Research paper

Stand Development and Aboveground Biomass Carbon Accumulation with Cropland Afforestation in Taiwan

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【Summary】

Afforestation in low-carbon-density areas has been proposed for mitigating climate change, because it leads to a reduction in the atmospheric carbon dioxide concentration. However, afforestation can be conducted for numerous purposes, and the complexity of tree species may render accurate estimation of the carbon (C) sequestration potential difficult. In this study, 22 cropland afforested plantations among 12 tree species and 4 study sites were investigated. We investigated stand development and aboveground biomass C accumulation of cropland afforestation in Taiwan, and examined how tree species and site conditions affected stand growth and yields. Results showed that average values of the mean diameter at breast height, tree height, stand density, and aboveground biomass C stocks for all studied plantation at 8~10 yr after planting were 12.1 cm, 8.5 m, 1272 trees ha^{-1}, and 32.1 Mg C ha^{-1}, respectively. The results also revealed that fast-growing tree species such as S*wietenia macrophylla* and *Melia azedarach* attained the highest growth rates and accumulated the most biomass C stocks, whereas slow-growing tree species such as *Zelkova serrata* exhibited the lowest growth rate and C accumulation potential. Trees grown at sites with deep soils outperformed those grown at sites with shallow and rocky soils. Overall, current cropland afforestation in Taiwan can enhance C sequestration, and also generate economic and ecological benefits.

Key words: afforestation, cropland, carbon sequestration, stand characteristics, soil depth.

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研究報告

台灣農地造林之林分發展與地上部林木碳量蓄積

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摘 要

低碳濃度地區的造林提供了減緩氣候變遷的有效方法，因為造林林木可固定引起氣候變遷的大氣二氧化碳。但除固碳效益外，造林仍具有其它生態或生產效益，使得不同樹種與不同地點間的造林計畫可能增加固碳效益推估上的難度。本研究總共調查台灣22個農地造林樣區，包含12種樹種與4個研究地點，研究目的主要為調查現有台灣農地造林的林分發展與地上部林木碳量蓄積，並分析不同數種與不同地點的差異如何影響林木生長。調查結果顯示經過8~10年的造林，所有調查樣區的平均胸高直徑、樹高、林分密度與地上部林務碳量分別為12.1 cm、8.5 m、1272 trees ha^{-1}與32.1 Mg C ha^{-1}，並以速生的大葉桃花心木(*Swietenia macrophylla*)與苦楝(*Melia azedarach*)有最高的生長速率與林木碳量蓄積，櫸樹(*Zelkova serrata*)則呈現最低的生長速率與林木碳量蓄積。生長於土層深厚的造林林木，也較生長於土層薄淺且含石量高的造林林木有較佳的林木生長。整體而言，農地造林可增加林地碳吸存，也具有增加林木經濟與生態效益。

關鍵詞：造林、農地、碳吸存、林分特性、土壤厚度。

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INTRODUCTION

Forest plantation areas are rapidly increasing worldwide, and numerous global, regional, and national forest restoration and afforestation goals like the 2011 Bonn Challenge (www.bonnchallenge.org) and the 2014 New York Declaration on Forests (www.un.org/climatechange/summit) have recently been promoted (FAO 2006, Jacobs et al. 2015). Afforestation of low-carbon (C)-density areas such as croplands and pastures can lead to accumulation of C in the terrestrial ecosystem and has been proposed as an effective means of mitigating climate change, because it reduces the atmospheric carbon dioxide (CO_2) concentration (IPCC 2003, Pan et al. 2011). In addition to enhancing C sequestration, afforestation can generate other economic and ecological benefits such as wood production, habitat restoration, soil protection, and social services (Lamb et al. 2005, Chazdon 2008). Thus, the purposes of afforestation in modern times can be numerous, and tree species planted in such plantations are more diverse than those in plantations intended for wood production that are generally composed of a few fast-growing tree species (FAO 2006). A wider diversity of tree species was also proposed to strengthen the adaptive capacity of forest plantations in response to environmental changes (Newton and Cantarello, 2015). Because of the complexity of tree species, accurately estimating the C sequestration potential due to afforestation can be difficult. In addition, differences in site conditions and management practices may pose additional challenges to attaining accurate estimates over larger areas. Several studies have evaluated the differences in C sequestration potentials among tree species, site conditions, and management practices to make predictions using these variables as model modifiers (Niu and Duiker 2006, Schroder and Pesch 2010). However, field data are still limited and must be obtained to better understand how these variables affect stand development and C sequestration potentials (Orihuela-Belmonte et al. 2013).

Since 2002, the government of Taiwan has implemented the Plain Afforestation Project in response to calls for an opening of the local agricultural market after joining the World Trade Organization. In total, 25,100 ha of cropland (approximately 3% of total cropland) was earmarked to be converted through afforestation, and more than 13,000 ha of croplands have been converted (Forestry Bureau 2012). Plantations were mainly established in the west-central, southwestern, and east-central plains of Taiwan, and a wide range of tree species including 5 coniferous tree species and 30 broadleaf tree species were recommended and planted for various purposes (Forest Bureau 2009). Such cropland afforestation promises opportunities for C sequestration and also economic and ecological benefits. However, information about stand development and C accumulation with cropland afforestation is still fragmented, and the complexity of plantations containing different tree species and site conditions was not considered in such information (Lin 2008, Lee 2009, Liao et al. 2011). A more comprehensive study is necessary to obtain information about stand development and C accumulation with different tree species and site conditions.

In this study, we investigated 22 afforested plantations among 12 tree species and 4 study sites. Our objectives were (1) to investigate stand development and aboveground biomass C accumulation of cropland afforestation at 8~10 yr after planting, and (2) to examine how tree species and site conditions affect stand growth and yields.

MATERIALS AND METHODS

Study areas

The study was conducted in lowland plain areas of Taiwan. We examined afforested sites in Changhua, Chiayi, Hualien, and Pingtung Counties (Fig. 1); plantation areas in these counties constitute 70% of the total cropland plantation areas (Chen and Ho 2008). The mean annual temperature is 23~25℃, and the mean annual precipitation is 1700~2100 mm (Table 1). According to the Holdridge life-zones system, the climatic condition corresponds to tropical or subtropical moist forests.

The topography of the study sites is flat and elevations range 20~160 m above sea level (Table 1). All soils were derived from alluvial sediments originating from the Central Mountain Range; however, soil properties significantly varied according to the landscape location. Study sites in Hualien and Pingtung are near river banks, and their soil profiles are shallow (< 40 cm depth) with a coarse (sandy loam) and rocky texture (Soil Information System 2012). In contrast, soil profiles in Changhua and Chiayi are deep (> 150 cm) with a loam or silty-loam soil texture. Soil profile photos of Changhua, Chiayi-A, Chiayi-B, and Pingtung are shown in the appendix (Fig. 2) and clearly indicate shallow and rocky soils in Pingtung but deep soils in Changhua, Chiayi-A, and Chiayi-B. The pH of the soil at the 4 study sites was approximately 6.5. The Chiayi-A site is located in a coastal area and exhibits saline soil characteristics.

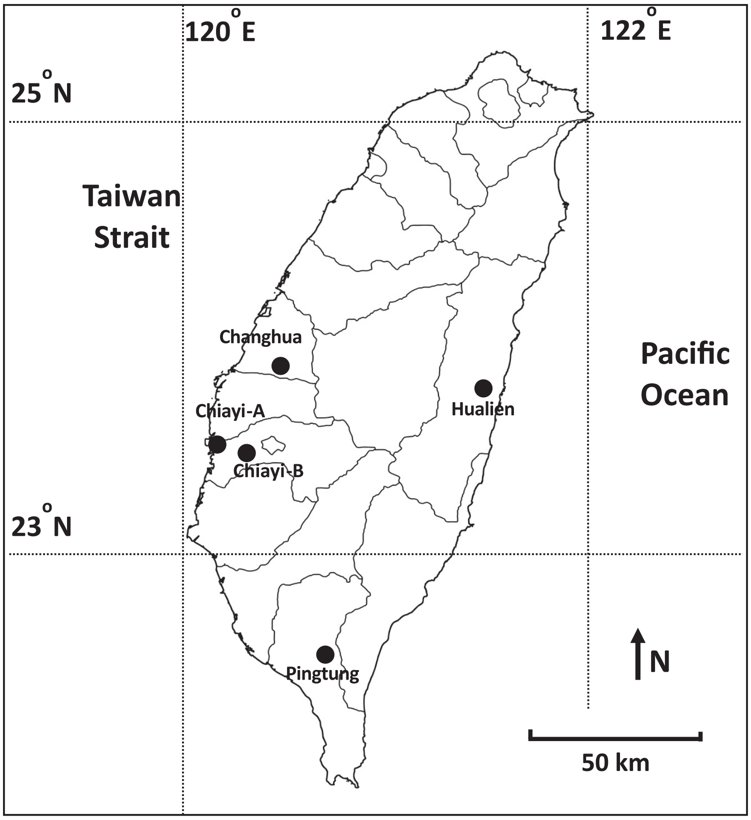

Fig. 1. Map of the study sites. Black circles indicate locations of study sites in Changhua, Chiayi, Hualien, and Pingtung.

Plantations

Plantations at the 4 study sites were all converted from sugarcane fields managed by the Taiwan Sugar Corporation. A wide range of tree species with various purposes were planted. For example, the exotic species *Swietenia macrophylla* and native fast-growing species *Melia azedarach* were planted for their wood production. The native slow-growing species *Zelkova serrata* was planted for its high-quality timber. *Koelreuteria henryi*, *Millettia pinnata*, and *Cassia fistula* were planted as ornamental tree species for enhancing aesthetic values. Salt-tolerant tree species *Casuarina equisetifolia*, *Eucalyptus citriodora*, and *Melaleuca leucadendra* were planted at Chiayi-A because this site is characterized by saline soils. Numerous native tree species, such as *Cinnamomum spp*., *Fraxinus formosana*, *Liquidambar formosana*, and *Terminalia catappa*, were also planted to provide both economic and ecological benefits. A monoculture stand with a size in the range of 0.2~1 ha was typically established for each tree species. Trees were planted at a spacing of 3.6×1.8 m, corresponding to a tree density of 1500 trees ha^{-1}. Mechanical weeding and irrigation were applied to all stands, particularly in the first 5 yr. Fertilization was also performed using a chemical compound fertilizer at an annual N-P_2O_5-K_2O rate of approximately 45-23-34 kg ha^{-1} (personal communication). Plantations in Chiayi-A, Hualien, and Pingtung were established in contiguous zones, and the afforesta-

Table 1. Site characteristics and selected tree species used for cropland afforestation in Changhua, Chiayi, Hualien, and Pingtung in Taiwan

	Changhua	Chiayi		Hualien	Pingtung
		A	B		
Latitude/longitude	23°50'39"N 120°29'44"E	23°30'28"N 120°09'32"E	23°28'34"N 120°19'41"E	23°36'48"N 121°24'51"E	22°31'25"N 120°36'57"E
Elevation (m)	13~45	3	12	170	77
Temperature (℃)	23.3	23.1	23.1	23.4	25.1
Precipitation (mm)	1773	1774	1774	2176	1885
Previous land use	Sugarcane field	Sugarcane field	Sugarcane field	Sugarcane field	Sugarcane field
Initial seedling density	1500 trees ha^{-1}	1500 trees ha^{-1}	1500 trees ha^{-1}	1500 trees ha^{-1}	1500 trees ha^{-1}
Soil series	Ershui series	Chengchung series	Tsochia series	Sungpu series	Shashuipu series
Profile depth (cm)	> 150 cm	> 150 cm	> 150 cm	< 40 cm; Rocky	< 40 cm; Rocky
Texture	Loam	Silty loam	Silty loam	Sandy loam	Sandy loam
Selected tree species	*Cassia fistula* (阿勃勒) *Fraxinus formosana* (光臘樹) *Koelreuteria henryi* (台灣欒樹) *Melia azedarach* (苦楝) *Millettia pinnata* (水黃皮) *Swietenia macrophylla* (大葉桃花心木)	*Casuarina equisetifolia* (木麻黃) *Eucalyptus citriodora* (檸檬桉) *Melaleuca leucadendra* (白千層)	*Swietenia macrophylla* (大葉桃花心木) *Zelkova serrata* (櫸樹)	*Cinnamomun spp.* (樟屬) *Fraxinus formosana* (光臘樹) *Koelreuteria henryi* (台灣欒樹) *Liquidambar formonsana* (楓香) *Zelkova serrata* (櫸樹)	*Cassia fistula* (阿勃勒) *Fraxinus formosana* (光臘樹) *Melia azedarach* (苦楝) *Swietenia macrophylla* (大葉桃花心木) *Terminalia catappa* (欖仁樹) *Zelkova serrata* (櫸樹)

tion of these plantations resembled a mosaic parqueted with various stands of tree species. Plantations at Changhua and Chiayi-B were discretely distributed, and individual plantation stands containing a monoculture or comprising 2 or 3 tree species were scattered among agricultural fields.

In this study, we selected the most dominant tree species with planting ages of 8~10 yr at each study site (Table 1). They were *F. formosana*, *Mel. azedarach*, *Mil. pinnata*, *K. henryi*, *Cas. fistula*, and *S. macrophylla* in Changhua; *S. macrophylla*, *Z. serrata*, *M. leucadendra*, *E. citriodora*, and *Cas. equisetifolia* in Chiayi; *Cinnamomum* spp., *F. formosana*, *L. formosana*, *Z. serrata*, and *K. henryi* in Hualien; and *S. macrophylla*, *Z. serrata*, *F. formosana*, *Mel. azedarach*, *T. catappa*, and *Cas. fistula* in Pingtung (Table 1). We surveyed 3 stands for each tree species to represent replicates; however, when 3 replicates were not possible, we used 2 stands. In each stand, 3 sampling plots with dimensions of 20×20 or 10×10 m (if the tree density was higher than 1200 trees ha^{-1}) were investigated. The diameter at breast height (DBH, to the nearest 0.5 cm at 1.3 m above ground surface) and tree height (to the nearest 0.5 m) for each tree were measured using a measuring tape and a clinometer or range pole, respectively. Stand density (trees ha^{-1}) was determined by counting the number of trees in a plot. For trees that were split into several stems, the DBH was calculated as the square root of the sum of all squared stem DBHs (Hairiah et al. 2010).

We examined approximately 1500 individuals of 12 tree species. Cutting all of the trees or applying species-specific allometric equations to estimate the biomass of trees

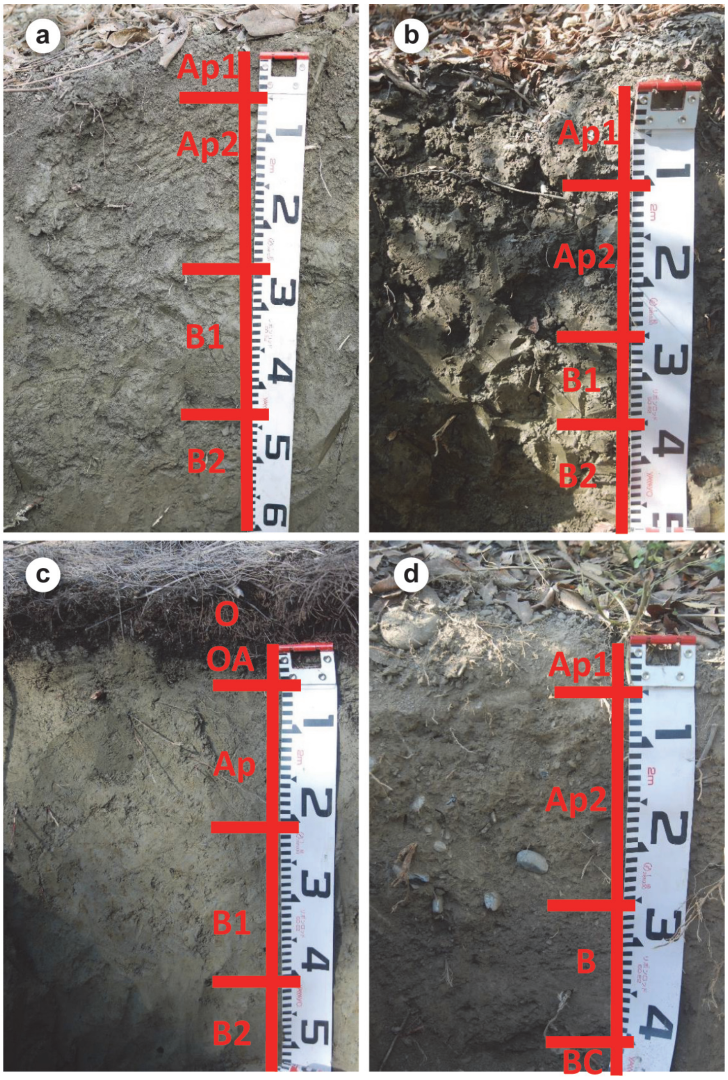

Fig. 2. Soil profile photos in (a) Changhua, (b) Chiayi-A, (c) Chiayi-B, and (d) Pingtung. Shallow and rocky soils were found in Pingtung, while deep soils were found in Changhua, Chiayi-A, and Chiayi-B. The Ap horizon contains mixed upper soil by ploughing. The Ap1 horizon displays higher soil organic matter and aggregate structures than the Ap2 horizon.

was not possible. Considering models developed by Brown et al. (1989), Chave et al. (2005), and the FAO (2006), the allometric equation established by Chave et al. (2005) was used to estimate the aboveground tree biomass for species lacking an allometric equation (Table 2). This allometirc equation has been recommended in other tropical or subtropical forests/plantations where no specific equation for biomass estimations was developed (Hairiah et al. 2010, Kanowski and Catterall. 2010, McEwan et al. 2011):

$$\text{Aboveground biomass} = 0.0509 \times \rho \times DBH^2 \times H; \quad (1)$$

where aboveground biomass is expressed in kg, ρ is the wood density in g cm^{-3}, DBH is

Table 2. Allometric equations used for estimating aboveground biomass

Species	Allometric model	Reference
Fraxinus formosana	Aboveground biomass = $0.057785 \times DBH^{1.645} \times H^{1.146}$	Lin (2008)
Melia azedarach	Aboveground biomass = $0.0286386 \times DBH^{2.163} \times H^{0.74}$	Lin (2008)
Others species	Aboveground biomass = $0.0509 \times \rho \times DBH^2 \times H$	Chave et al. (2005)

DBH, diameter at breast height; H, tree height; ρ, wood density.

the stem diameter at breast height in cm, and H is the tree height in m. Wood density values were obtained from Lin et al. (2002), the IPCC (2003), and the Global Wood Density Database (www.agroforestrycenter.com). Genus wood density data were applied when species wood density data were unavailable. Biomass per sampling plot was measured by summing the biomass of all trees inside the sampling plot, and this was eventually converted to aboveground biomass per hectare. A C fraction rate of 0.5 was applied for calculating C stocks in the aboveground biomass (IPCC 2003).

Statistics

An analysis of variance (ANOVA) and least significant difference (LSD) were used to test for differences in the mean DBH, tree height, stand density, and aboveground biomass C stock values among the tree species at each site, and were performed using SAS 9.1 software (SAS Institute, Cary, NC, USA).

RESULTS

Eight to 10 yr after planting, the mean DBH significantly varied among tree species, ranging from 8.0 cm in *Z. serrata* plantations in Pingtung to 17.0 cm in *S. macrophylla* plantations in Changhua (Table 3). Fast-growing species such as *S. macrophylla* and *Mel. azedarach* generally exhibited higher mean DBH values, whereas medium-sized tree species such as *Mil. pinnata* or tree species intended for high-quality wood production such as *Z. serrata* showed lower mean DBH values. Tree heights also considerably varied among tree species, ranging from 5.7 m in *Z. serrata* plantations in Pingtung to 11.5 and 11.6 m in *S. macrophylla* and *Mel. azedarach* plantations, respectively, in Changhua. Fast-growing tree species, such as *S. macrophylla*, were also taller than other tree species. Among the 4 study sites, the highest mean DBH values for each study site were 2.3~5.4 cm greater than the lowest mean DBH values, and the heights of the tallest trees were 3.0~4.4 m greater than the heights of the shortest trees.

The 4 study sites exhibited similar stand densities (i.e., 1100~1400 trees ha^{-1}). At the Chiayi, Hualien, and Pingtung sites, differences in stand densities among tree species were not significant ($p > 0.05$); however, stand densities significantly varied in Changhua ($p < 0.05$). In Changhua, fast-growing tree species (e.g., *Mel. azedarach* and *S. macrophylla*) exhibited lower stand densities than those of other tree species (1050 vs. 1300 trees ha^{-1}).

Aboveground biomass C stocks ranged from 9.0 Mg C ha^{-1} in *Z. serrata* plantations in Pingtung to 74.4 Mg C ha^{-1} in *S. macrophylla* plantations in Changhua (Table 3). At the Chiayi, Hualien, and Pingtung sites, differences in aboveground biomass C stocks among tree species were not significant ($p >$ 0.05); however, differences were significant at the Changhua site ($p < 0.05$). The fast-growing tree species *S. macrophylla* and *Mel.*

Table 3. Mean diameter at breast height (DBH), tree height, stand density, and aboveground biomass C stocks with cropland afforestation in Taiwan

Site	Dominant tree species	No. of Stands	Stand age (yr)	Mean DBH (cm)	Tree height (m)	Stand density (no. ha^{-1})	Aboveground Biomass C (Mg C ha^{-1})
Changhua	*Cassia fistula*	3	10	14.8±1.4bc	10.7±0.8a	1044±96c	49.0±4.3bc
	Fraxinus formosana	3	10	14.1±1.3c	10.7±0.6a	1267±100b	47.8±8.6c
	Koelreuteria henryi	3	10	13.9±0.5c	7.8±0.2b	1283±29ab	33.5±2.5d
	Melia azedarach	3	10	16.2±0.9ab	11.6±0.6a	1089±19c	59.5±8.2b
	Millettia pinnata	3	10	11.6±0.3d	7.2±0.4b	1389±51a	25.0±2.7d
	Swietenia macrophylla	3	10	17.0±1.5a	11.5±0.5a	1083±56c	74.4±8.2a
Chiayi	*Casuarina equisetifolia*	3	9	12.3±1.7a	10.2±1.2ab	1267±88a	41.2±11.8a
	Eucalyptus citriodora	3	9	11.0±0.9a	8.7±0.2cd	1206±173a	18.7±7.2a
	Melaleuca leucadendra	3	9	13.8±2.5a	6.9±1.2d	1400±88a	42.1±20.6a
	Swietenia macrophylla	2	8	14.8±0.2a	11.2±0.3a	1375±35a	60.4±5.7a
	Zelkova serrata	2	8	11.5±0.5a	7.9±0.2cd	1283±24a	32.0±3.8a
Hualien	*Cinnamomum spp.*	3	10	12.4±1.1a	7.4±0.9b	1367±153a	28.3±9.6a
	Fraxinus formosana	3	10	10.1±0.9bc	8.5±1.6ab	1300±100a	21.7±6.7a
	Koelreuteria henryi	2	10	12.2±0.1a	7.9±0.1ab	1100±141a	27.0±5.6a
	Liquidambar formosana	3	10	11.5±0.8ab	9.6±0.5a	1333±153a	26.7±5.6a
	Zelkova serrata	3	10	9.3±1.0c	6.6±0.4b	1383±161a	21.7±5.8a
Pingtung	*Cassia fistula*	3	9	10.3±0.3ab	7.2±0.3ab	1333±153a	19.1±1.8a
	Fraxinus formosana	3	9	8.9±0.7bc	6.6±0.3bc	1333±58a	11.5±1.7a
	Melia azedarach	2	9	8.8±0.4bc	7.3±0.7ab	1550±354a	15.9±7.7a
	Swietenia macrophylla	3	9	11.6±2.1a	8.6±1.2a	1142±101a	21.0±8.8a
	Terminalia catappa	3	9	11.3±0.8a	8.2±1.3ab	1233±306a	21.3±5.8a
	Zelkova serrata	3	9	8.0±0.6c	5.4±0.4c	1133±115a	9.0±0.9a
Average			9.4	12.1	8.5	1272.4	32.1

Values are the means±standard deviation. Means and standard deviations followed by different letters significantly differ ($p < 0.05$) at each site.

azedarach grown in Changhua exhibited the greatest aboveground biomass C stock values (i.e., 74.4 and 59.5 Mg C ha^{-1}, respectively), whereas *K. henryi* and *Mil. pinnata* demonstrated the lowest values (i.e., 33.5 and 25.0 Mg C ha^{-1}, respectively).

Among the 4 study sites, trees grown in Changhua and Chiayi were taller and larger than those grown in Hualien and Pingtung. For example, the mean DBH, height, and aboveground biomass C stock values of *S. macrophylla* plantations in both Changhua and Chiayi were greater than those of plantations in Pingtung by approximately 3.2 cm, 2.6 m, and 46 Mg C ha^{-1}, respectively. The mean DBH, height, and aboveground biomass C stock values of *F. formosana* plantations in Changhua were also greater than those of plantations in Hualien and Pingtung by 4 cm, 2.2 m, and 26.1 Mg C ha^{-1} and 5.2 cm, 2.2 m, and 36.3 Mg C ha^{-1}, respectively. In addition, averages of the mean DBH, tree height, and aboveground biomass C stocks from all of the selected tree species in Changhua and Chiayi were greater than those of species in Hualien and Pingtung (Fig. 3). Averages of the mean DBH, tree height, and aboveground biomass C stocks in Changhua were 4.8 cm, 2.7 m, and 32 Mg C ha^{-1}, respectively, higher than those in Pingtung.

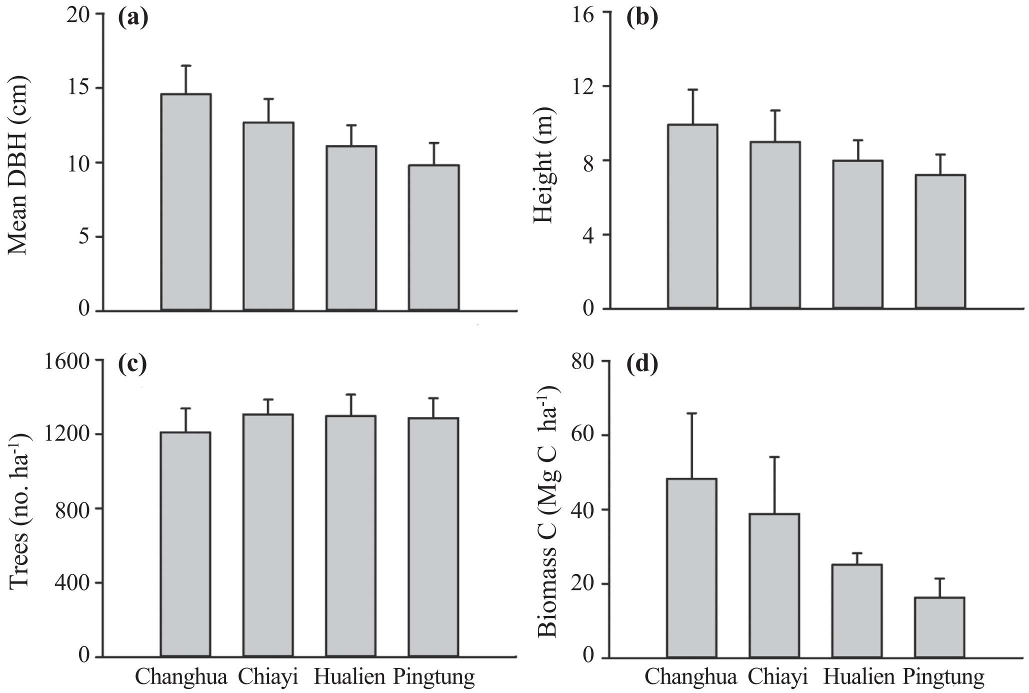

Fig. 3. Average values (mean±standard deviation) of (a) mean diameter at breast height (DBH), (b) tree height, (c) stand density, and (d) aboveground biomass C stocks with cropland afforestation in Changhua, Chiayi, Hualien, and Pingtung.

DISCUSSION

Stand characteristics of cropland plantations in Taiwan

This study assessed the stand development and aboveground biomass C accumulation with cropland afforestation in Taiwan. Results revealed that stand development and aboveground biomass C accumulation varied with tree species and site conditions. Among the tree species examined in this study, *S. macrophylla* and *Mel. azedarach* plantations exhibited the highest growth rates. Previous studies reported similar results concerning the fast growth rate of *S. macrophylla* (Shono and Snook 2006, Wadsworth and Gonzalez 2008). *Melia azedarach* is also a fast-growing tree species in Taiwan (Lin 2008), but the rapid growth rate was valid in Changhua (but not in Pingtung) because of its favorable soil conditions (Tables 1, 3). In contrast, *Z. serrata* exhibited the lowest growth rate compared to other tree species. *Zelkova serrata* is considered a high-quality wood and its slow-growing rate could limit stand development (Cheng et al. 2011). *Millettia pinnata* also showed a relatively low growth rate compared to other species, which could be attributed to it being a medium-sized tree species. Other tree species demonstrated moderate growth rates; that is, their growths were between fast- and slow-growing tree species.

Tree heights recorded in this study were similar to those reported by Lin et al. (2008), Lin et al. (2011), Cheng et al. (2013a), and Lin and Lin (2013), who indicated that tree heights were 9.3~13.2 m in other plain and lowland forests of Taiwan. Although tree heights may differ among species (Table 3), we suppose tree heights of 10~12 m are valid for stands on plain areas in Taiwan. Such tree heights appear to be less than those of trees in other moist forests in the tropics and subtropics (Lefsky 2010, Simard et al. 2011), because these stands in Taiwan are exposed to frequent typhoon disturbances (on average 3.1 typhoons per year), and typhoon-force winds may cause considerable damage to tree canopies and suppress their heights (Vandermeer et al. 2004, Chao et al. 2010). For example, Chao et al. (2010) reported that the canopy height in lowland rainforests in southern Taiwan can be greatly suppressed under the influence of wind. Nevertheless, canopy heights of > 30 m were reported in other parts of Taiwan, and such canopies are located in the mountainous areas and adequately protected from typhoon disturbances (McEwan et al. 2011, Cheng et al. 2013b).

The similar stand densities observed in cropland afforestation reflected similarities in silvicultural practices. Density variations were observed in fast-growing tree species such as the *S. macrophylla* and *Mel. azedarach* plantations in Changhua. Their lower stand densities were attributed to a natural self-thinning process, in which subcanopy trees began to die because of severe inter-tree competition (Table 3).

The aboveground biomass C stocks with cropland afforestation at 8~10 yr after planting ranged 9~74 Mg C ha^{-1} (Table 3), which equaled mean annual C sequestration rates of 0.9~7.4 Mg C ha^{-1} yr^{-1} or an average mean value of 3.4 Mg C ha^{-1} yr^{-1} for all studied stands (Table 3). Although the estimation can be improved by applying updated species-specific allometric equations, using Chave et al.'s (2005) allometric equation is still an effective method since this equation is recommended for determining tree biomass of tree species for which a species-specific equation is not available in tropical or subtropical forests and plantations (Hairiah et al. 2010, Kanowski and Catterall 2010, McEwan et al. 2011, Rutishauser et al. 2013). Comparing our results to those of other plantations in the tropics and subtropics, our estimate was within the lower range (Laclau et al. 2003, Swamy et al. 2004, Redondo-Brenes and Montagnini 2006, Kanowski and Catterall 2010, Matsumura 2011, Bonner et al. 2013). For example, Bonner et al. (2013) performed a meta-analysis and reported that aboveground biomass accumulation rates in tropical plantations ranged 2~8 Mg C ha^{-1} yr^{-1}, with an average of approximately 6 Mg C ha^{-1} yr^{-1} (calculated from the aboveground biomass using a C fraction rate of 0.5). The low C sequestration rates with cropland afforestation in Taiwan can be attributed to the diverse tree species planted, in which C sequestration rates were a balance between fast- and slow-growing tree species. In contrast, other studies usually examined plantations that were purposely established using certain fast-growing tree species to produce maximum C sequestration, which would lead to fast and high yields. In addition, typhoon disturbances in Taiwan might serve as a climatic constraint that hampers aboveground biomass C accumulation with cropland afforestation, because trees can be damaged by typhoon-force winds (Mascaro et al. 2005, McEwan et al. 2011).

Effects of the study sites on stand growths and developments were profound. Trees grown in Changhua and Chiayi outperformed those grown in Hualien and Pingtung (Table 3, Fig. 3). Because of small differences in climatic conditions and management practices, differences in stand growth and development were likely caused by differences in soil conditions, particularly differences in soil depths (Table 1). Many studies also reported a high correlation between soil depths and growth rates (Romanya and Vallejo 2004, Geyer and Ponder Jr 2013), in which deep soils could provide optimal soil moisture and nutrient retention and have sufficient space for root development. Moreover, favorable soil conditions enable fast-growing tree species to achieve optimal growth, and differences in growth rates between fast- and slow-growing tree species were greater in Changhua and Chiayi compared to those in Hualien and Pingtung.

Policy implications

We further used the mean annual C sequestration rate developed in this study to estimate the total C sequestration potential of cropland afforestation in Taiwan. According to the Plain Afforestation Project in which 25,100 ha of cropland was intended to be converted, the annual C sequestration potential in cropland afforestation was estimated to be 0.85×10^5 Mg C yr^{-1}. Hence, the annual C sequestration in cropland afforestation offsets 9.8% of the annual fossil fuel consumption from the agricultural sector (8.59×10^5 Mg C yr^{-1}, Environmental Protection Administration 2012) or offsets only 0.2% of the entire fossil fuel consumption in Taiwan (6.84×10^7 Mg C yr^{-1}, Environmental Protection Administration 2012). This low proportion is attributed to the substantial amounts of fossil fuels used for combustion in Taiwan (Ko et al. 2010). The C sequestration by cropland afforestation is too small to exert a major effect on the national emission budget, and a direct reduction in CO_2 emissions by improving energy efficiency may be more effective (Fissore et al. 2010). However, cropland afforestation can provide multiple economic and ecological benefits in addition to C sequestration (Cannell 1996, Lamb et al. 2005). Information about these benefits of cropland afforestation to the ecosystem is limited and future research is necessary.

Conclusions

The study assessed cropland afforestation in Taiwan. By assessing 22 afforested plantations among 12 tree species and 4 study sites, our results indicate that stand development and aboveground biomass C accumulation varied according to the tree species and site conditions. In general, fast-growing tree species exhibited a higher growth rate and accumulated more C than did other tree species, whereas slow-growing tree species exhibited the lowest growth rate and C accumulation. Our results indicated that average values of the mean DBH, tree height, stand density, and aboveground biomass C stocks for all studied plantation at 8~10 yr after planting were 12.1 cm, 8.5 m, 1272 trees ha^{-1}, and 32.1 Mg C ha^{-1}, respectively. Hence, cropland afforestation in Taiwan may play an important role in C sequestration and also generate economic and ecological benefits.

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