J For Res (2015) 20:1–8
DOI 10.1007/s10310-014-0455-0

ORIGINAL ARTICLE

Comparing aboveground structure and aboveground carbon storage of an age series of moso bamboo forests subjected to different management strategies

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Received: 8 January 2013 / Accepted: 15 May 2014 / Published online: 27 June 2014

Abstract The purpose of this study was to compare aboveground carbon storage capacities of different management strategies of an age series of moso bamboo (*Phyllostachys pubescens*) forests. The study site was located in the lower mountain area of central Taiwan. Stand structure and aboveground carbon storage were compared between moso bamboo stands that were subjected to two management strategies, intensive management (IM) and extensive management (EM). The Chi squared (χ^2) test was utilized to examine the frequency distribution of culms among the age classes in each stand. All the IM stands passed the χ^2 test, while only 41.7 % of the EM stands passed the test. This result suggests that the IM stands contain culms that are homogeneously distributed within an age series, while more than one-half of the EM stands did not follow this distribution. In addition, the relative root mean square errors (RRMSEs) of carbon storage in the age classes were calculated as an indicator of the variations of carbon storage in the age classes of each stand. A non-parametric test (Wilcoxon Scores) was utilized to compare the RRMSEs of the IM and EM stands; the results indicated that the RRMSEs were significantly different between these two management strategies. The IE stands displayed a smaller RRMSE than the EM stands, suggesting that the IE stands had stable carbon storage in the age series.

Keywords Carbon storage · Extensive management · Intensive management · Moso bamboo (*Phyllostachys pubescens*) · Stand structure

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Introduction

The bamboo plant has multiple uses, and it is widely distributed around the world, especially in Asia (Scurlock et al. 2000; Shanmughavel et al. 2001; Yang et al. 2004; Yen et al. 2010; Yen and Lee 2011; Inoue et al. 2013). Most bamboo species are woody, tree-like grasses that possess a woody vascular bundle and a hollow culm (Lu 2001; Yen et al. 2010; Yen and Lee 2011). Bamboo is a resource that is widely utilized by humans, and is used as a food and material source by Asian people (Lu 2001; Yen et al. 2003a, b; Yang et al. 2004; Chen et al. 2009; Lin 2011; Yen and Lee 2011; Inoue et al. 2013). Interestingly, the growth patterns of bamboo plants differed from those of timber trees (Yen and Lee 2011). In general, the developments of new culms were continuously supplemented using horizontal rhizome systems (Lu 2001). Therefore, the bamboo forests contained a series of culms of different ages; this property caused the forests to demonstrate unevenly aged stand structures (Yen and Lee 2011). Based on this growth phenomenon, two growth periods were identified for bamboo plants; the first period determined the culm height and diameter at breast height (DBH) within 2–3 months, while the second period occurred after the first period until the time of harvesting (4–5 years) (Lu 2001; Yen 2003; Yen et al. 2010; Yen and Lee 2011).

Since the new culms sprout each year in bamboo groves, the older culms (over 4–5 years old) should be harvested via selective cutting (thinning) (Yen and Lee 2011). Improving the productivity of bamboo stands usually relies on the management strategies, such as thinning and fertilizing (Lu 2001; Yen et al. 2003a, b, 2010; Wang et al. 2009; Yen and Lee 2011; Zhou et al. 2011). Thinning is a necessary and essential method to maintain the vigor and productivity of bamboo forests (Yen and Lee 2011). If bamboo stands are not thinned, their asexual reproduction capacity will decline with heavy stand density (Lu 2001; Yen et al. 2010; Yen and Lee 2011). In addition, a negative correlation was found between the mean DBH of culms and stand density for bamboo forests regardless of elevation (Yen and Lee 2011). This suggests that stand density is a primary factor that affects the mean DBH of bamboo stands, and that DBH is restrained in dense stands.

Due to the effects of global warming in relation to elevating atmospheric CO_2, understanding the carbon storage of forest ecosystems helps in assessing the processes of global carbon cycles (Yen and Wang 2013). Large-bodied woody plants in forest ecosystems are known to make dominant contributions to carbon storage of global carbon cycles (e.g., Gifford 2000; Lamolom and Savidge 2003; Smith et al. 2006; Kindermann et al. 2008; Yen et al. 2009, 2010; Lin et al. 2011; Yen and Lee 2011). In recent years, following the adoption of the Kyoto Protocol, the capacity of CO_2 fixation is widely accessed at woody plants, and bamboo forests were found to possess a high potential for carbon sequestration due to the high productivity of bamboo over a short period (Chen et al. 2009; Nath et al. 2009; Wang et al. 2010; Yen et al. 2010; Yen and Lee 2011; Zhou et al. 2011; Yen and Wang 2013).

Moso bamboo (*Phyllostachys pubescens*) is one of the most valuable giant bamboo species which is widely distributed in China, Japan and Taiwan, and covers over 3 million ha around Asia (Watanabe 1985; Fu 2000; Lu 2001; Chen et al. 2009; Yen and Lee 2011). Because moso bamboo forests are highly productive, it has been targeted for research on a variety of aspects such as physiology, ecology, and economics (Watanabe 1985; Fu 2000; Lu 2001; Chen et al. 2009; Yen and Lee 2011). Most previous studies have demonstrated that the productivity of moso bamboo stands is strongly correlated with management strategies (Watanabe 1985; Lu 2001; Yen 2003; Yen and Lee 2011; Zhou et al. 2011). Watanabe (1985) surveyed 9 sites of long-term unmanaged moso stands in Japan and found a positive correlation between the new culms (new culms/total live culms) and the dead culms (dead culms/toal culms). A same trend was also found in the basal area per ha of the new culms (new culms basal area/total live culms basal area) and the dead culms (dead culms basal area/total live culms basal area). Based on these findings, Watanabe (1985) further suggested biomass–density regulation for unmanaged moso stands.

Li et al. (1998a) observed the dynamics of moso bamboo groves during a period of 20 years and found that production appeared to alternate yearly. Many shoots emerged during the rich years while only a few shoots emerged during the poor years, showing a clear biennial cycle (Li et al. 1998a). Koike et al. (2001) evaluated CO_2 fixation capacity for three bamboo plants and found that the longevity of culms and their net photosynthetic rate are negatively correlated. The study also investigated photosynthetic rate, respiration rate and net primary production (NPP) in order to evaluate the carbon sequestration capacity of the bamboo stands. They found that the NPP was 11–18 Mg ha^{-1} $year^{-1}$ for bamboo stands (Koike et al. 2001). Li et al. (1998b) analyzed carbon and nutrient dynamics for moso bamboo groves and found that nutrient concentrations (N, P, and K) were higher in the leaves and lower in the roots. In addition, the new leaves were found to have higher nutrient concentration than the older leaves. Chen et al. (2009) reported that moso bamboo stands processed high biomass stocks (159.86 ± 137.50 Mg ha^{-1}) that are higher than those of other bamboo species (95.36 ± 82.21 Mg ha^{-1}) in China, suggesting that moso bamboo had a high potential for carbon storage. Compare to man-made forests, moso bamboo displayed a high carbon sequestration capacity, which even exceeds that of timber tree forests. For example, Yen and Lee (2011) demonstrated that moso bamboo forests had a higher mean aboveground carbon sequestration value (8.13 ± 2.15 Mg ha^{-1} $year^{-1}$) than China fir plantations (3.35 ± 2.02 Mg ha^{-1} $year^{-1}$) in Taiwan.

More than 150,000 ha of bamboo forests are distributed around Taiwan (Yen et al. 2010; Yen and Lee 2011). Bamboo resources have been important income sources in Taiwan's rural and mountain villages for a long time (Yen et al. 2010; Lin 2011). Moso bamboo, which is widely distributed at elevations of 700–1,600 m, is an important bamboo species that has multiple commercial uses in Taiwan (Lu 2001; Yen 2003; Yen and Lee 2011). The culms possess an excellent woody property, and moso bamboo forests are very productive (Yen 2003; Yen et al. 2003a; Yen and Lee 2011). Most moso bamboo forests are man-made plantations managed by farmers, and financial income is their main interest in bamboo forest management (Lu 2001; Yen and Lee 2011). Since 1990, the benefits from moso bamboo forest management have declined due to rising labor costs and replacements of raw materials (such as plastics) (Lin 2011). On the other hand, farmers still benefit from bamboo shoot production. As a result, the purpose of current bamboo forest management mainly focuses on bamboo shoot production for vegetable foods in Taiwan. The managed moso bamboo forests can be classified into two main categories in Taiwan, that is, intensive management (IM) stands and extensive management (EM) stands. The former are bamboo stands that were normally thinned and fertilized, and the latter are thinned but not fertilized (Lu 2001; Hu 2002; Yen and Lee 2011). In general, the same pattern of thinning was performed in both stands, including thinning method, thinning intensity and thinning period. Because fertilization can significantly improve the productivity for moso bamboo forests, the IM stands usually have higher productivity than the EM stands (Hu 2002; Yen 2003).

Because the bamboo forests contain culms of different ages, the carbon storage of the entire stand includes the storage capacity of each age series. Interestingly, the carbon storage value may vary with age class and management strategy. These factors influenced the sustained management of the bamboo forests. This study analyzed the stand structure and aboveground carbon storage values of culms of different ages in moso bamboo forests, and these values were compared between different management strategies. Our objectives were as follows: (1) to examine the homogeneity of the culm distribution among the age series in different management strategies, (2) to predict the aboveground carbon storage of each age class in the bamboo stands, (3) to compare the carbon storage of different management strategies at the stand level, and (4) to compare the carbon storage of the age classes of different management strategies in moso bamboo stands.

Materials and methods

Study areas

The study site was located in the lower mountain area (at an elevation of 600–1,500 m) of central Taiwan (between 120°15′ and 120°48′E and 23°29′ and 24°29′N). This area contains abundant bamboo resources, and the moso bamboo forest is a key bamboo forest that is widely distributed around this region. In addition, most of the moso bamboo forests are private forests that are managed by farmers; this study area has a long history of bamboo management (over 60 years) (Yen and Lee 2011). The experimental site had a temperature range of 12–22 °C and a rainfall range of 1,800–2,400 mm $year^{-1}$ (Yen and Lee 2011). Soil was yellow of depth over 60 cm, and soil nutrient contents were 0.40–0.45 % for N, 14.35–22.32 mg kg^{-1} for P and 95.62–102.05 mg kg^{-1} for K (Hu 2002).

Because bamboo shoot production had higher benefits, the current management of bamboo forests focused on bamboo shoot production for vegetable foods and this is a common phenomenon in Taiwan. The IM stands were normally thinned and fertilized while the EM stands were only thinned but not fertilized as mentioned above. Although different management strategies were shown between IM and EM stands, a same pattern of thinning was performed in both types of stands. The thinning intensity was approximately one-fifth of the entire stands based on thinning older culms and the thinning period was from October to December, one time per year.

All the bamboo stands were surveyed in late autumn and early winter (October and November) because the bamboo shoots were harvested in this period. On the other hand, the new culms (below 1 year old) have grown and the older culms were still not harvested in the stands. Moreover, all the IM and EM were pure stands. Each management level forest surveyed contained 12 stands, and 24 bamboo stands were included in this study. The survey was conducted from 2004 to 2008. The stands range in area from 0.78 to 2.46 ha, an average slope was 10°–25° and all belong to private owners.

Methods

As described previously, the bamboo forests contained a series of culms of different ages; this property caused the forests to demonstrate unevenly aged stand structures. The different culm ages are distributed randomly and older culms (over 4–5 years old) should be harvested to maintain the productivity of the stands (Lu 2001; Yen and Lee 2011). New culms sprout via horizontal rhizome systems, and some of these new culms were harvested as bamboo shoots. The other new culms in the stands gradually matured over time. Failing to harvest older culms will prevent new culms from sprouting. Harvesting older culms from stands is called ‘thinning’ or ‘selective cutting’ and is necessary to improve the vigor of bamboo stands (Yen et al. 2010). Selective cutting was also performed annually; therefore, a similar stand structure appeared in the stands each year in the well-managed stands.

A total of 12 IM and 12 EM bamboo stands was examined, and six 0.01-ha (10 × 10 m) sub-plots were installed on each stand. In order to obtain relatively homogeneous samples, the six subareas were equally divided for each stand, and a sub-plot was randomly sampled from each subarea. The age of culms was defined as followings. The culms of ‘current year old’ indicated that the new culms were sprouted and grown in the current year of data measures (<1 year old). The culms of ‘1 year old’ indicated that the culms were sprouted in the last year (the culms of more than 1 year old but <2 year old). Likewise, the culms of 3 and 4 year olds were based on this rule. The 4-year-old age class included culms that were more than 4 years old.

The culm age and diameter at breast height (DBH) were measured within the sub-plots, and these six sub-plots were then pooled as a sample for analysis; i.e., one stand comprised 0.06 ha that contained six sub-plots as a sample unit.

Bamboo age is determined based on features of the culms, such as external color, branch and leaf development, and the status of the culm sheaths (Lin 1961; Fu 2000; Yen et al. 2010; Yen and Lee 2011). For instance, the culm is light green with a white powder and has sheaths in the younger bamboo (current–2 years old), while the culm turns dark green to brownish green, the sheath has dropped, and culm surface is covered with moss and mold in the older bamboo (3–5 years old) (for details, see Lin 1961; Fu 2000; Yen et al. 2010; Yen and Lee 2011).

Using this method, five age classes of current to 4 years old were utilized in this study. Using stands as a unit, the culm number was calculated and compared among different age classes in each stand. The Chi squared (χ^2) test was used to examine the frequency distribution of culms among age classes. The hypothesis (H_0) is that the culm number is equally distributed in each age class; in other words, the culm number in current-year bamboos is equal to those of age classes 1, 2, 3, and 4 if the χ^2 test is not significant at $P = 0.05$. After all the stands were examined using the χ^2 test, the pass ratios were measured, and the IM and EM stands were compared.

At a genet (individual plant) level, DBH was correlated with the biomass of the leaves, branches, culms and underground tissues, and many studies that predict biomass via the allometric function ($Y = a \times DBH^b$) were based on the DBH in bamboo forests (e.g., Nath et al. 2009; Yen et al. 2010; Yen and Lee 2011). Therefore, this study also followed this method and the allometric function has been calculated for the study area by Yen and Lee (2011). After aboveground biomass was obtained, the prediction of carbon storage in bamboo forests was based on biomass and percent carbon content (PCC); that is, carbon storage = biomass × PCC. The processes of predicting carbon storage are illustrated in Table 1. In the previous studies concerning moso bamboo forests, the PCCs of different sections (leaves, branches and culms) was determined by Wang et al. (2009), and the relationships between DBH and aboveground biomass were calculated by Yen and Lee (2011). These PCCs and allometric functions were cited to predict aboveground carbon storage for moso bamboo forests in this study.

The carbon storage for each age class was predicted for each stand, and the root mean square error (RMSE) for the carbon storage of the different aged classes was calculated for each stand. The formula for RMSE is as follows:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}\left(\mathrm{CS}_i - \mathrm{CS}_{\mathrm{average}}\right)^2}{n}} \qquad (1)$$

where CS_i is the carbon storage of the i age, $\mathrm{CS}_{\mathrm{average}}$ is the average carbon storage of n ages, and n is the number of ages.

The RMSE was standardized as relative RMSE (RRMSE), and the RRMSE was defined as $\mathrm{RMSE}/\mathrm{CS}_{\mathrm{average}}$. This indicator was used to measure the relative differences of the carbon storage among aged classes for each moso bamboo forest. In order to understand the RRMSE of carbon

Table 1 The processes of predicting carbon storage for moso bamboo forests in this study

Step and item	Description
1. Field survey	The culm age and diameter at breast height (DBH) were determined and measured for each culm of all sample plots of moso bamboo stands
2. Predicting biomass	The allometric functions that based on DBH to predict aboveground biomass have been calculated for different age bamboo plants in this study site by Yen and Lee (2011). According to these models, aboveground biomass of each bamboo plant was obtained in this study
3. The percent carbon content (PCC)	The PCCs of each section of moso bamboo have been determined to be 45.44, 48.15 and 46.28 % for the leaves, branches and culms, respectively, by Wang et al. (2009). These PCCs were directly cited in this study
4. The proportion of each section's biomass to the aboveground biomass	The proportion of each section's biomass to the aboveground biomass was measured by Yen and Lee (2011), and was cited in this study. For example, for the current-year bamboo, the proportion of foliage, branches and culms to the aboveground biomass were 0.04, 0.12 and 0.84, respectively
5. The average PCC of aboveground biomass ($\mathrm{PCC}_{\mathrm{average}}$)	According to steps 3 and 4, the average PCC of aboveground biomass was calculated for different age bamboo plants. For example, for the current-year bamboo, the aboveground PCC was calculated as follows: (0.04 × 45.44 %) + (0.12 × 48.15 %) + (0.84 × 46.28 %) = 46.48 %. Likewise, the aboveground PCCs of the current- to 4-year-old bamboo plants were determined to be 46.48, 46.47, 46.48, 46.48 and 46.49 %, respectively
6. Aboveground carbon storage	Aboveground carbon storage was equal to aboveground biomass × $\mathrm{PCC}_{\mathrm{average}}$

storage between the IM and EM stands, a non-parametric test of analysis of variance (Wilcoxon Scores) was used.

Results

Stand characteristics

The mean DBH and culms per ha were similar between the IM and EM stands (Table 2), and these two terms were not significantly different (at the $P = 0.05$ level) using a t test. Moreover, the relationships between the mean DBH and culms per ha were negatively correlated for the IM ($R = -0.600$, $P = 0.039$) and EM stands ($R = -0.906$, $P = 0.000$) (Fig. 1), where the IM stands were reported in a previous study (Yen and Lee 2011). This negative correlation between the mean DBH and culms per ha was also found in the combined data that was pooled from the IM and EM stands ($R = -0.607$, $P = 0.002$). It implicated that a negative correlation commonly existed in the moso bamboo stands.

Table 2 The stand characteristics of moso bamboo stands in different management levels

Item	Management level	
	Intensive management	Extensive management
Mean DBH (cm)	8.75 ± 0.86	8.49 ± 0.42
Culms per ha (culms ha^{-1})	7,077.8 ± 417.9	7,045.8 ± 407.9

Mean ± standard deviation

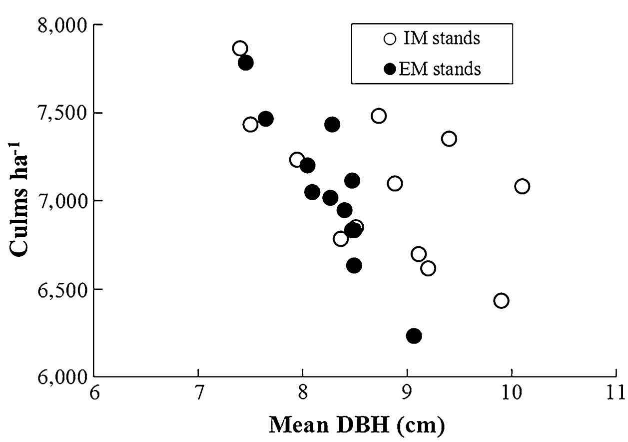

Fig. 1 Relationships between the mean DBH and culms per ha in the intensive management (*IM*) and extensive management (*EM*) moso bamboo stands

Comparing culm distributions among age classes between the IM and EM stands

An obvious difference was identified between the IM and EM stands using the χ^2 test (Table 3). All the IM stands passed the χ^2 test, suggesting that the IM stands accepted H_0 (that the culms were equally distributed among the age classes). These results also suggested that the IM stands follow the sustained model of bamboo forests. Only 41.7 % of the EM stands passed the χ^2 test, indicating that more than half of the EM stands do not follow the sustained model of bamboo forests; their culm distributions were unequal among the age classes. To promote the sustained management of bamboo forests, it is essential to maintain equal culms within the stands. In this study, all the IM stands followed this concept; their culm numbers were equally distributed in each age class, which was confirmed via the χ^2 test. However, over half of the EM stands (58.3 %) did not follow the sustained model of bamboo forests. From the above comparison, the IM stands were confirmed to follow the sustained growth and yield model of bamboo forests, while the stand structure of most of the EM stands should be improved to follow the sustained model.

Comparing carbon storage for the IM and EM stands at the stand level

The IM stands had higher average aboveground biomass values than the EM stands (Table 4). However, the aboveground biomass values were not significantly different between the management levels according to the Wilcoxon Scores test ($P = 0.102$), suggesting that these two stands had no significant difference in aboveground biomass. A similar pattern was observed for aboveground carbon storage because aboveground carbon storage was conducted from the aboveground biomass. Consequently, these two stands were also not significantly different in aboveground carbon storage ($P = 0.126$).

Table 3 The χ^2 test examining the frequency distribution of culms among the different age classes for moso bamboo stands with different management levels

Management level	No.	χ^2 value				Accept at $P = 0.05$	Reject at $P = 0.05$
		Average	Standard derivation	Maximum	Minimum		
Intensive management	12	1.024	0.360	1.718	0.614	12	0
Extensive management	12	18.742	17.694	53.878	2.005	5	7

Table 4 The aboveground biomass and carbon storage values for the intensive management (*IM*) and extensive management (*EM*) stands and test by a non-parametric test of analysis of variance (Wilcoxon Scores)

Item	Management level	No.	Average (Mg ha^{-1})	Standard deviation (Mg ha^{-1})	Maximum (Mg ha^{-1})	Minimum (Mg ha^{-1})	*Z* value (*P* value)
Biomass	IM	12	86.49	21.99	131.19	54.33	1.703
	EM	12	73.68	5.45	79.20	62.89	(0.102)
Carbon storage	IM	12	40.64	10.73	60.69	25.13	1.587
	EM	12	34.25	2.53	36.81	29.23	(0.126)

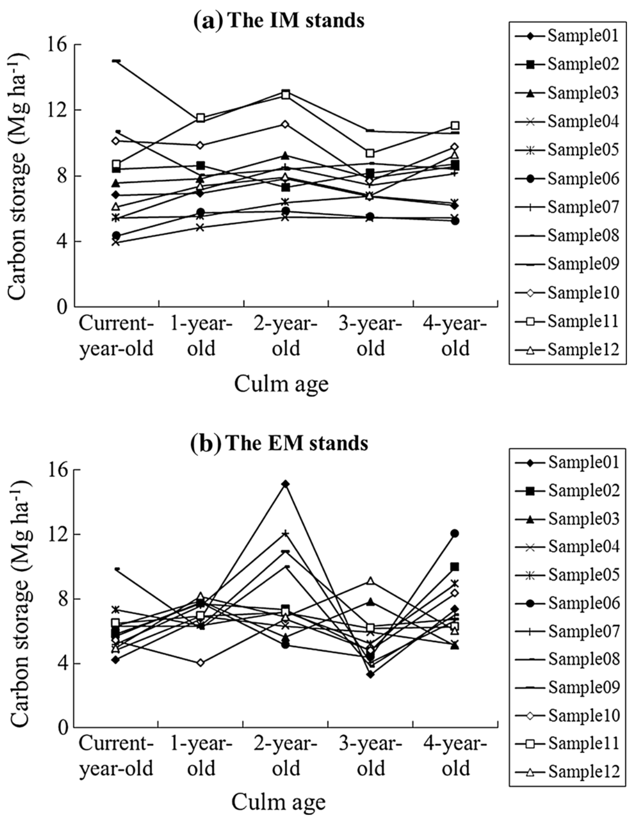

Fig. 2 The carbon storage values of the different age classes of each stand for intensive management (*IM*) and extensive management (*EM*)

On the other hand, the IM stands had larger standard deviations than the EM stands both for aboveground biomass and carbon storage, indicating that the IM stands had large variations in aboveground biomass and carbon storage for moso bamboo forests.

Comparing carbon storage for the IM and EM stands in each age series

The distributions of the carbon storage values among the age classes revealed obvious differences between the management levels (Fig. 2). In general, the carbon storage values were homogeneously distributed in the IM stands, while the carbon storage values exhibited wide variations among the ages in some of the EM stands. To make comparisons of carbon storage among the ages, the RRMSE was used as an indicator to compare the different management levels (Table 5). The IM stands displayed a smaller average RRMSE than the EM stands, and the values of these two management levels were significantly different according to the Wilcoxon Scores two-sample test (Z value = −3.204, P = 0.004). The RRMSE of the IM stands was only 10.89 %, indicating ∼11 % of the variation in carbon storage among the age classes. Conversely, a larger RRMSE (26.42 %) was found in the EM stands. In addition, the ratio of the RRMSE values for the IM stands to the EM stands was ∼2.4, indicating that the variation in the carbon storage of the EM stands was 2.4 times higher than that of the IM stands among the different ages. These results further explain the differences in carbon storage among the age series of the different management levels of moso bamboo forests.

Table 5 The summary of the relative root mean square error (RRMSE) carbon storage values of the different age groups in the IM and EM stands

Management level	No.	Average	Standard deviation	Maximum	Minimum
Intensive management	12	0.1089	0.0285	0.1479	0.0617
Extensive management	12	0.2642	0.1315	0.5676	0.0577

Discussion

Bamboo forest ecosystems can usually be classified into two main categories, that is, natural bamboo forests and man-made bamboo plantations (Lu 2001). Natural bamboo forests play an important role in forest succession; for instance, bamboo invasion was found in forest gaps (Griscom and Ashton 2003) and after forest fires (Lu 2001). Lu (2001) pointed out that secondary bamboo forests were usually developed from the destroyed forests and bamboo plants play a pioneer species role after forest fires. The target of man-made bamboo plantations has focused on their productivity, and most bamboo plantations display pure stands in Taiwan because these are easy to manage by farmers (Yen et al. 2010; Yen and Lee 2011). Various management styles have been found in man-made bamboo forests including unmanaged plantations. Although the capacity of carbon storage can also be predicated for the unmanaged bamboo stands, they were not included in this research due to their declining productivity over time and irregular distribution of culms of different ages.

In previous studies, many trails concerning the productivity with treatments (e.g., thinning and fertilization) were examined for moso bamboo plantations (e.g., Li et al. 2000; Hu 2002; Yen 2003). In those trails, all processes of the treatments are usually designed and controlled by the researchers. To some extent, the study findings represented the optimized thinning intensity and fertilization or combinations of thinning intensity and fertilization. Different from those previous studies, the management strategy of moso bamboo forests was determined by farmers in this study. Therefore, this study intended to represent the current status of moso bamboo plantation management. From the field surveys of different management levels, the aboveground carbon storage in the aged series was compared between IM and EM moso bamboo plantations.

Farmers used to follow the conception of benefit–cost ratio in determining their management strategies for moso bamboo stands in Taiwan. Although higher productivity has been confirmed for IM stands in previous studies, more bamboo shoots were also harvested in the IM stands (Lu 2001; Zhou et al. 2011). The current aboveground carbon storage of moso bamboo forests was collectively influenced by productivity and bamboo shoot harvest. Consequently, the aboveground carbon storage was not significantly different at statistical level between the IM and EM stands in this study area.

Bamboo forests that were previously researched and which contained various bamboo species and occupied various sites around the world were found to have superior capacities for productivity (e.g., Veblen et al. 1980; Shanmughavel and Francis 1996; Isagi et al. 1997; Lin et al. 1998; Chen et al. 2009; Wang et al. 2009; 2010; Yen et al. 2010; Lin 2011; Lin et al. 2011; Yen and Lee 2011, Zhou et al. 2011). Among these bamboo species, moso bamboo forests possessed a high capacity of carbon storage that has been reported worldwide, but little work has been done on this capacity in relation to age (e.g., Chen et al. 2009; Zhou et al. 2011; Yen and Lee 2011; Yen and Wang 2013). Yen and Lee (2011) predicted the aboveground carbon storage for moso bamboo plantations based on the allometric model, and they assumed that the carbon storage in each age class was equal. However, those studies did not further examine this assumption whereas it is important to the measure stability of carbon storage in different age classes.

In order to control the factor of selective cutting, this study selected the stands in which selective cutting was consistently performed each year in both IE and ME stands. However, the amount of selective cutting was decided by farmers and their decisions were mainly based on their personal experience. Since the decisions of the farmers were complex and hard to understand, this raised the concerns of objectiveness and randomization in the experimental design. This study examined the homogeneity of culm distribution among the age series to explain the current status of different management levels, and further examined aboveground carbon storage in age classes for moso bamboo plantations. The results revealed that the EM stands displayed large variations of carbon storage among the age series, while only slight variations of carbon storage were observed in the IM stands. Interestingly, this result suggested that the assumption that carbon storage is equally distributed among the age series cannot be applied to all bamboo stands. I found that this assumption may only be applicable to bamboo forests with intensive management, because the EM stands displayed large variations in carbon storage among the age series, and their culm distributions exhibited differences between the age classes. This suggests that the structures of EM stands should be improved to attain a sustained model of bamboo forest management. This study provided concrete information regarding the carbon storage of age series of moso bamboo forests.

Since moso bamboo is one of important bamboos worldwide, many characteristics have been revealed in this species including the biennial variations in shoot production, nutrient dynamics of individual culms and stands, and the management strategies for productivity (Watanabe 1985; Li et al. 1998a, b; Koike et al. 2001; Chen et al. 2009; Yen and Lee 2011; Zhou et al. 2011). Those results indicated that the productivity of moso bamboo stands was mainly affected by environmental factors and management strategies, such as thinning and fertilization. In addition, carbon storage had a correlation with productivity, especially in current stocks of culms. This study focused on aboveground carbon storage of moso bamboo forests subjected to different management strategies. However, variations of environmental factors and mechanisms of nutrient dynamics for individual bamboo plants were not addressed, and thus might be a limitation for this study.

References

Chen X, Zhang X, Zhang Y, Booth T, He X (2009) Changes of carbon stocks in bamboo stands in China during 100 years. For Ecol Manag 258:1489–1496

Fu J (2000) "Moso Bamboo" in China. Abs Mag 21(6):12–17

Gifford RM (2000) Carbon contents of above-ground tissues of forest and woodland trees. National Carbon Accounting System Technical Report no. 22. Canberra: Australian Greenhouse Office

Griscom BW, Ashton PM (2003) Bamboo control of forest succession: *Guadua sarcocarpa* in Southeastern Peru. For Ecol Manag 175:445–454

Hu HL (2002) Studies on management cost and growth of moso bamboo in Chu-Sun area. Master thesis of National Chung-Hsing University. (in Chinese with English summary)

Inoue A, Sakamoto S, Suga H, Kitazato H, Sakuta K (2013) Construction of one-way volume table for the three major useful bamboos in Japan. J For Res 18:323–334

Isagi Y, Kawahara T, Kamo K, Ito H (1997) Net production and carbon cycling in a bamboo *Phyllostachys pubescens* stand. Plant Ecol 130:41–52

Kindermann GF, McCallum I, Fritz S, Obersteiner M (2008) Aglobal forest growing stock, biomass and carbon map based on FAO statistics. Silva Fenn 42:387–396

Koike T, Sasa K, Matsuura Y (2001) A trial for evaluating CO_2 fixation capacity in the plant communities of bamboo and dwarf bamboo, *Sasa* sp. Bamboo J 18:1–14 (in Japanese with English summary)

Lamolom SH, Savidge RA (2003) A reassessment of carbon in wood: within and between 41 North American species. Biomass Bioenergy 25:381–388

Li R, Werger MJA, During HJ, Zhong ZC (1998a) Biennial variation in production of new shoots in groves of the giant bamboo *Phyllostachys pubescens* in Sichuan, China. Plant Ecol 135:103–112

Li R, Werger MJA, During HJ, Zhong ZC (1998b) Carbon and nutrient dynamics in relation to growth rhythm in the giant bamboo *Phyllostachys pubescens*. Plant Soil 201:113–123

Li R, Werger MJA, de Kroon H, During HJ, Zhong ZC (2000) Interactions between shoot age structure, nutrient availability and physiological integration in the giant bamboo *Phyllostachys pubescens*. Plant Biol 2:437–446

Lin WC (1961) Studies on the classification of Bambusaceae in Taiwan. Report No. 69 of Taiwan Forestry Research Institute

Lin YJ (2011) Review, current status, and prospects of the bamboo industry in Taiwan. Taiwan J For Sci 26:99–111

Lin Y, Lin P, Wen W (1998) Studies on dynamics of carbon and nitrogen elements in *Dendrocalamopsis oldhami* forest. J Bamboo Res 17(4):25–30 (in Chinese)

Lin YJ, Wang CH, Wu S (2011) Analyzing carbon conversion factors of four species of Taiwanese bamboo. Taiwan J For Sci 26:341–355

Lu CM (2001) Cultivation and management of bamboo forests. Taiwan For Res Inst Ext Ser 135:29 (in Chinese)

Nath AJ, DasG Das, Das AK (2009) Above ground standing biomass and carbon storage in village bamboos in North East India. Biomass Bioenergy 33:1188–1196

Scurlock JMO, Dayton DC, Hames B (2000) Bamboo: an overlooked biomass resource? Biomass Bioenergy 19:229–244

Shanmughavel P, Francis K (1996) Above ground biomass production and nutrient distribution growing bamboo(*Bambusa bambos* (L.) Voss). Biomass Bioenergy 10:383–391

Shanmughavel P, Peddappaiah RS, Muthukumar T (2001) Biomass production in an age series of *Bambusa bambos* plantations. Biomass Bioenergy 20:113–117

Smith JE, Heath LS, Skog KE, Birdsey RA (2006) Methods for calculating forest ecosystem and harvested carbon with standard estimates for forest types of the United States. General Technical Report NE-343. USDA Forest Service, Washington, DC

Veblen TT, Schlegel FM, Escobar BR (1980) Dry matter production of two species of bamboo (*Chusquea culeou* and *C. tenuiflora*) in South-Central Chile. J Ecol 68:397–404

Wang J, Chen TH, Chen SY, Chung HY, Li TI, Liu CP (2009) The structures, aboveground biomass, carbon storage of *Phyllostachys pubescens* stands in Huisun experimental forest station and Shi-Zhuo. Q J Chin For 31(4):17–26 (in Chinese with English summary)

Wang J, Chen TH, Chen SY, Chung HY, Liu EU, Li TI, Liu CP (2010) Estimating aboveground biomass and carbon sequestration of moso bamboo growth under selection cutting after 2 years. Q J Chin For 32(3):35–44 (in Chinese with English summary)

Watanabe M (1985) Studies on the ecological characteristics of bamboo stand (II) Stand sturcture of long term unmanaged *Phylostachys pubescens* stands. Bamboo J 3:7–17 (in Japanese)

Yang Y, Wang K, Pei S, Hao J (2004) Bamboo diversity and traditional uses in Yunnan, China. Mt Res Dev 24(2):157–165

Yen TM (2003) Three growth models for Moso bamboo (*Phyllostachys heterocyala*) culm height growth. Q J Chin For 36(3):285–296 (in Chinese with English summary)

Yen TM, Lee JS (2011) Comparing aboveground carbon sequestration between moso bamboo (*Phyllostachys heterocycla*) and China fir (*Cunninghamia lanceolata*) forests based on the allometric model. For Ecol Manag 261:995–1002

Yen YM, Wang CT (2013) Assessing carbon storage and carbon sequestration for natural forests, man-made forests, and bamboo forests in Taiwan. Int J Sustain Dev World Ecol 20:455–460

Yen TM, Hu HL, Lee JS (2003a) An economic study on culms of Moso bamboo (*Phyllostachys heterocycla*) in Chu-Sun area. Q J For Res 25(1):25–36 (in Chinese with English summary)

Yen TM, Hu HL, Lee JS (2003b) The shoots of Moso bamboo (*Phyllostachys heterocycla*) management in Chu-Shan area. Q J For Res 25(2):43–54 (in Chinese with English summary)

Yen TM, Ai LM, Li CL, Lee JS, Huang KL (2009) Aboveground carbon contents and storage of three major Taiwanese conifer species. Taiwan J For Sci 24:91–102

Yen TM, Ji YJ, Lee JS (2010) Estimating biomass production and carbon storage for a fast-growing makino bamboo (*Phyllostachys makinoi*) plant based on the diameter distribution model. For Ecol Manag 260:339–344

Zhou G, Meng C, Jiang P, Xu Q (2011) Review of carbon fixation in bamboo forests in China. Bot Rev 77:262–270