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ORIGINAL PAPER

Carbon storage potential of avenue trees: a comparison of *Barringtonia racemosa*, *Cyclobalanopsis glauca*, and *Alnus formosana*

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Abstract Trees in cities play a valuable public health role for they are able to use photosynthesis to absorb atmospheric carbon dioxide (CO_2), which is then stored as tree biomass. The present study compared the potential for carbon storage in the aboveground tree biomass of 3-year-old specimens of *Barringtonia racemosa*, *Cyclobalanopsis glauca,* and *Alnus formosana* grown in Chiayi City, Taiwan. Assessment of the carbon storage of avenue trees was based on measurement of the photosynthetic rate and leaf area, as well as the biomass of timbers, from October 2008 to 2009. Based on photosynthetic rates and leaf area, the estimated carbon stocks of *B. racemosa*, *C. glauca*, and *A. formosana* are 756, 615, and 2738 kg Cha^{-1} a^{-1}, respectively. In addition, carbon storage can be estimated based on timber volume, and these results are 1170, 720, and 1995 kg Cha^{-1} a^{-1} for *B. racemosa*, *C. glauca*, and *A. formosana*, respectively. Based on these findings, *A. formosana* has the highest carbon fixation potential of these three trees. Although the photosynthetic rate measurements can provide detailed data on the diurnal changes in carbon stocks, this requires more time and labor. In contrast, timber volume measurements provide a rapid and convenient way to estimate carbon stocks.

Keywords Carbon dioxide · Carbon stock · Greenhouse gas · Leaf area · Timber volume

Introduction

Carbon sequestration is the capacity of trees to absorb carbon dioxide (CO_2) and other greenhouse gases from the atmosphere. Increases in the CO_2 concentration in the atmosphere are mounting concern because it is the predominant greenhouse gas responsible for global warming. The Intergovernmental Panel on Climate Change (IPCC) (2009) predicted that the CO_2 concentration is about of 385–410 ppm in 2014. Moreover, human activities contribute the growth rate of atmospheric carbon dioxide (Canadell et al. 2007). Thus, much effort has been focused on reducing these emissions.

Many reports have suggested that forest ecosystems can be a substantial terrestrial sink for carbon fixation (Birdsey et al. 1993; Ciais et al. 2000; Dixon et al. 1994; Fan et al. 1998; Kirschbaum 1996; Rayner et al. 1999; Warran and Patwardhan 2008). Furthermore, the Kyoto Protocol also suggested that both afforestation and reforestation are promising mitigation strategies because trees are able to absorb a considerable amount of CO_2 through photosynthesis, while wood production is recognized as a form of carbon (C) storage (IPCC 2007).

Directly estimating the amount of carbon sequestered in a forest ecosystem is complex and costly (de Gier 2003). In addition, the storage potential of different species varies significantly (Negi and Chauhan 2002), requiring tree biomass components and biomass expansion factors (BEFs) for predicting forest growth and estimating how much carbon can be stored in a forest ecosystem as well as for use as inventory data (Brown 2002; Somogyi et al. 2007; Teobaldelli et al. 2009). Tree BEFs vary depending on tree species (Pajtík et al. 2011), tree age (Lehtonen et al. 2004; Tobin and Nieuwenhuis 2007), timber volume (Fang et al. 2001), weather conditions, and plantation location

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(Negi et al. 2003; Singh 2003), making tree-level biomass data a better way to estimate the carbon storage potential.

Carbon storage, as estimated based on tree biomass production, is an efficient method for reducing the amount of greenhouse gases in the atmosphere (Ritson and Sochacki 2003; Schulze et al. 2000). Gucinski et al. (1995) noted that fast-growing species, such as conifers are major carbon depositories in forests, and so have a great deal of potential with regard to mitigating climate change (Laclau 2003).

Although most studies of carbon storage in forests are carried out at the regional, national, and global levels (Birdsey et al. 1993; Dixon et al. 1994; Nowak 1993, 1994), there is growing recognition of the importance of urban trees. Urban activities affect local climate through both CO_2 emissions and the creation of what are known as urban heat islands (Abdollahi et al. 2000; Gill et al. 2007; Lal and Augustine 2012; Nowak 2010). However, there are as yet few studies examining the potential of urban trees for carbon sequestration and storage, although they are clearly able to reduce atmospheric CO_2 by their photosynthetic ability and accumulation of carbon in the form of biomass (Chavan and Rasal 2010). During photosynthesis, trees are able to convert CO_2 and water into sucrose and oxygen (O_2), and while some of this sugar is stored, most of it is used as energy and to form the structure of the tree. It has been reported that the national average of carbon storage by urban forests in the United States is 25.1 Mg $ha^{-1}a^{-1}$, resulting in 705 million tons of carbon sequestration annually (Nowak and Crane 2002). In addition, the level of carbon sequestration in three South Korean cities ranged from 0.41 to 0.62 kg m^{-2} a^{-1} of tree cover (Jo 2002). Furthermore, carbon storage ranged from 1.53 to 9.67 kg m^{-2} a^{-1} in Barcelona, Spain (Chaparro and Terradas 2009), and from 0.68 to 9.85 kg m^{-2} a^{-1} reported in Leipzig, Germany (Strohbach and Haase 2012).

The objective of this study was to compare the carbon storage capacities of three different urban trees of similar age overtime, using *B. racemosa*, *Cyclobalanopsis glauca*, and *Alnus formosana*. We employed our estimates of photosynthesis in conjunction with leaf area and timber volume to quantify the accumulation of carbon in the aboveground tree biomass for all three species. The results can be used as inventory data to assess the potential of urban trees with regard to carbon storage in Chiayi City, Taiwan.

Materials and methods

Plant growth conditions

The research area was an open space located in National Chiayi University in Chiayi City, Taiwan, (lat. 23.46°N, long. 120.48° E, elevation 150 m). The experimental trees included six specimens each of 3-year-old of *B. racemosa*, *C. glauca,* and *A. formosana* (total 18 trees), grown in 5.0-L vinyl pots (one plant/pot) under natural photoperiod and with daily watering, with an average height of 2.3 m. This area has a whole-year freeze-free growing period and average annual precipitation of approximately 1.69 m.

Light intensity

The photosynthesis and photosynthetic photon flux (*PPF*) were measured on a selected clear, sunny day. Measurements were made hourly (from 0800 to 1600 h) 1 day per month during the experimental period (from October 2008 to 2009). Data were recorded using a portable photosynthesis system (LI-6400; LI-COR, Lincoln, NE) equipped with a constant-area insert (12 cm^2) chamber attached to a fully expanded leaf. Five leaves were chosen randomly per tree, with three replications.

Aboveground biomass

Leaf-area measurements were made with a portable leaf area meter (Li-3000A; LI-COR, Lincoln, NE). One of the six specimens of each species was chosen for leaf-area measurement. The length (L) (cm) and middle width (W) (cm) of each leaf was measured with a digital electronic calipers ruler (Ets-Dig150R; Annex Depot Corp, Sacramento, CA), and the total leaf area was then calculated. Each leaf area was measured with the following equation:

$$A_r = W \times L \tag{1}$$

where A_r represents the rectangular leaf area. Because deciduous trees lose their leaves each fall, no carbon storage was calculated during this period.

Timber volume was calculated based on the girth and length of the segments of the limbs and branches. To calculate timber volume, the branches and limbs were subdivided into a series of segments with an equal length (10 cm) from the bottom to top. The timber volume was then calculated according to the following formula:

$$V = \sum G^2/4\pi \times H \times F \tag{2}$$

where V is timber volume; π (Pi) is a constant (3.14); G is the girth (cm); H is the length of a limb or branch (cm); and F is the form factor, which is set at 0.33 for the young trees in our study. The fresh biomass as a proportion of the timber volume was calculated by multiplying by a conversion factor (e.g. specific gravity) according to Penman et al. (2003). Timber dry weight was calculated by multiplying the timber volume by 0.57 (IPCC 2006).

Carbon storage

McPherson and Simpson (1999), and Miyazawa and Terashima (2001) used photosynthetic rate to calculate the level of carbon sequestration. The net photosynthetic rate (A_{on}) on a leaf-area basis was measured for 8 h/day (from 08:00 AM to 16:00 PM), assuming no internal CO_2 transfer resistance. Total CO_2 absorption per tree per month was calculated as follows:

$$A_n = A_{on} \times CO_2 \times A_r \times d \qquad (3)$$

where A_n is the net photosynthetic rate on a leaf area basis at a CO_2 condition of 360 mmol mol^{-1} per tree per month; $A_{\rm on}$ is the net photosynthetic rate on a leaf-area basis; CO_2 is a constant (CO_2 molecular weight = 44); $A_{\rm r}$ is the rectangular leaf area; and d is days per month. Total carbon sequestration is estimated as follows:

$$C_{leaf} = A_n \times 0.272 \qquad (4)$$

where $C_{\rm leaf}$ is the amount of carbon stored in leaves; A_n is the net photosynthetic rate on a leaf-area basis per tree per month; and 0.272 is the percentage of carbon (C) in carbon dioxide (CO_2).

The timber dry-matter biomass was converted to carbon storage by multiplying by 0.5 (Nowak and Crane 2002). The various equations were then used in combination to estimate the total carbon sequestration of each species.

Data analysis

Data were collected and subjected to analysis of variance (ANOVA) using SAS (version 9.2; SAS Institute, Cary, NC). Mean values and standard errors of six replications for each species (i.e., a total of 18 specimens) are presented below.

Results

Photosynthetic photon flux

A seasonal variation of *PPF* was recorded during the experimental period; the level of sunlight *PPF* ranged from 401 to1018 µmol m^{-2} s^{-1}, and the average sunlight *PPF* was 692 µmol m^{-2} s^{-1}. The amount of *PPF* recorded from different species declined from December 2008 to March 2009 and from June to October in 2009. However, there are no data from February for *B. racemosa* because this is a deciduous species that loses its leaves during dormancy (Fig. 1). Although an increase of *PPF* was recorded from March to June, different species had varying levels of photosynthetic photon interception. The maximum *PPF* was recorded at 1095, 1063, and 897 µmol m^{-2} s^{-1} for *B. racemosa*, *C. glauca*, and *A. formosana*, respectively (Fig. 1), with *B. racemosa* having the highest average *PPF* (739 µmol m^{-2} s^{-1}). Thereafter, the *PPF* declined, and it fell below 500 µmol m^{-2} s^{-1} in September 2009.

Calculation of leaf area and timber volume

A linear regression with a high coefficient of determination (R^2) between the leaf area and rectangular leaf area (*A*r) was found in all three species. The R^2 was 0.96 in *B. racemosa*, 0.97 in *C. glauca*, and 0.95 in *A. formosana*. *A*r is thus very similar to the photosynthetic area and can be used to calculate the monthly leaf area growth curve and further estimate leaf carbon sequestration. The leaf area of *B. racemosa* decreased from 1729.93 cm^2 in October 2008 to 27.89 cm^2 in February 2009 and then increased to 11,319.56 cm^2 in October 2009. There was an increase in the leaf area of *C. glauca* from 2304.32 cm^2 in October 2008 to 12,541.18 cm^2 in October 2009. Interestingly, there were two peaks in the leaf-area growth curve for *A. formosana*. In this species, the leaf area increased from 14,156.26 cm^2 in October 2008 to 24,372.16 cm^2 in March 2009, then it decreased to 18,865.26 cm^2 in May 2009, saw a slight increase to 22,000.32 cm^2 in July 2009, and finally dropped to 13,856.58 cm^2 in September 2009 (Fig. 2).

Similarly, a high coefficient of determination (R^2) between circumference and timber volume was seen in all three trees. The R^2 was 0.99 in *B. racemosa*, 0.99 in *C. glauca*, and 0.99 in *A. formosana*. The timber volume was measured every month. An increase in timber volume was recorded for all three species during the study period, and for *B. racemosa*, *C. glauca*, and *A. formosana*, this rose from 204.52 to 401.95 cm^3, from 118.15 to 238.59 cm^3, and from 477.83 to 697.77 cm^3, respectively, over the 13 months, with *A. formosana* showing the largest increase (Fig. 3).

Photosynthetic rate

The average photosynthetic rates of *B. racemosa*, *C. glauca,* and *A. formosana* were 5.69, 5.26, and 5.73 µmol m^{-2} s^{-1}, respectively. Both *B. racemosa* and *C. glauca* had their highest photosynthetic rates, 9.62 and 8.61 µmol m^{-2} s^{-1}, respectively, in June 2009, while *A. formosana* had its highest photosynthetic rate of 9.01 µmol m^{-2} s^{-1} in July 2009 (Fig. 4). In contrast, the lowest photosynthetic rate (i.e., 0.52 µmol m^{-2} s^{-1}) was seen in *B. racemosa* in January 2009, while a low of 3.12 µmol m^{-2} s^{-1} was measured in *C. glauca* in October 2009, and 4.37 µmol m^{-2} s^{-1} was recorded from *A. formosana* in September 2009. As noted above, *B. racemosa* is a deciduous species that drops leaves during dormancy,

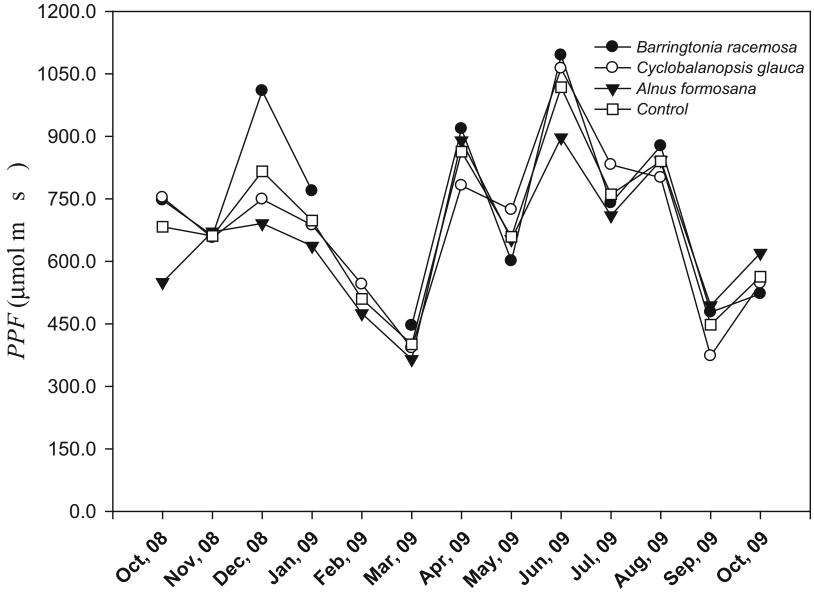


Fig. 1 The average photosynthetic photon flux (*PPF*) of *Barringtonia racemosa*, *Cyclobalanopsis glauca,* and *Alnus formosana* recorded during the study period

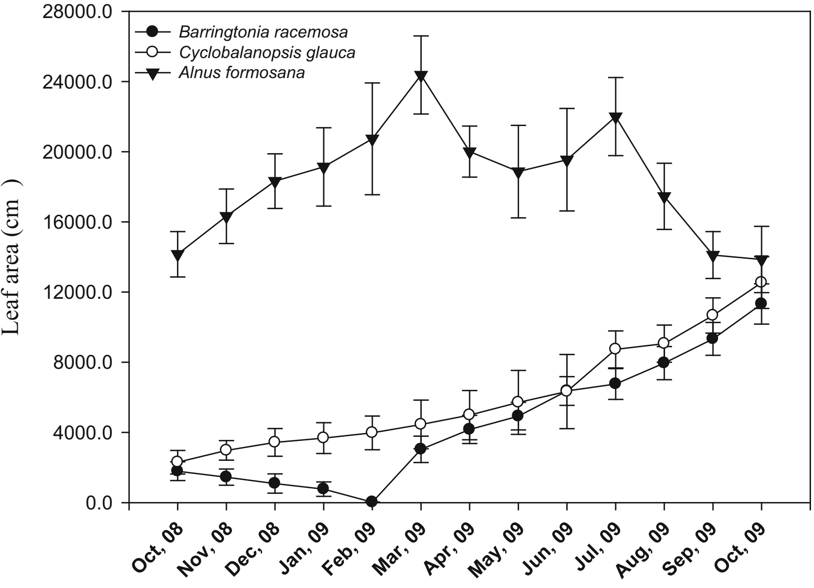


Fig. 2 The monthly leaf area variation of *Barringtonia racemosa*, *Cyclobalanopsis glauca,* and *Alnus formosana*

and so no photosynthetic rate was recorded for those trees in February 2009.

Carbon storage

Carbon storage in these urban trees was calculated based on C_{leaf} every month. The highest carbon stock in *B. racemosa* was recorded in July and August 2009 with an average of 89.6 g C plant^{-1} month^{-1}, but the lowest carbon stock (0.0 g C plant^{-1} month^{-1}) was seen in February 2009 because the trees had lost their leaves. The highest carbon storage in *C. glauca* was found in July 2009, with the average of 67.0 g C plant^{-1} month^{-1}, while the lowest carbon storage (10.0 g plant^{-1} month^{-1}) was measured in November and December 2008. Interestingly, carbon storage in *A. formosana* varied dramatically, from 70.0 to 220.0 g C plant^{-1} month^{-1}.

The amount of carbon stock decreased from March to April and from July to September in 2009 (Fig. 5). In addition, the annual gross carbon accumulation of *B. racemosa*, *C. glauca*, and *A. formosana* was 504.0, 410.0, and 1825.0 g C plant^{-1} a^{-1} on a leaf-area basis, respectively. The gross carbon storage per square meter per year thus depends on tree density, and the ideal tree density per hectare is suggested to be 1500 plant ha^{-1} in Taiwan. This leads to 756, 615, and 2738 kg C ha^{-1} a^{-1} carbon being stored in the leaves of *B. racemosa*, *C. glauca*, and *A. formosana*, respectively. Carbon storage can also be estimated on the

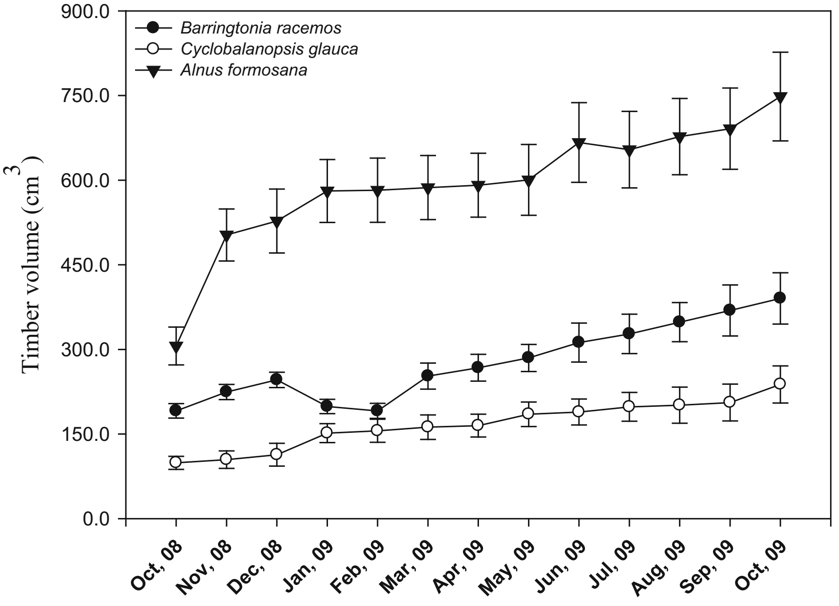


Fig. 3 The monthly timber volume of *Barringtonia racemosa*, *Cyclobalanopsis glauca,* and *Alnus formosana*

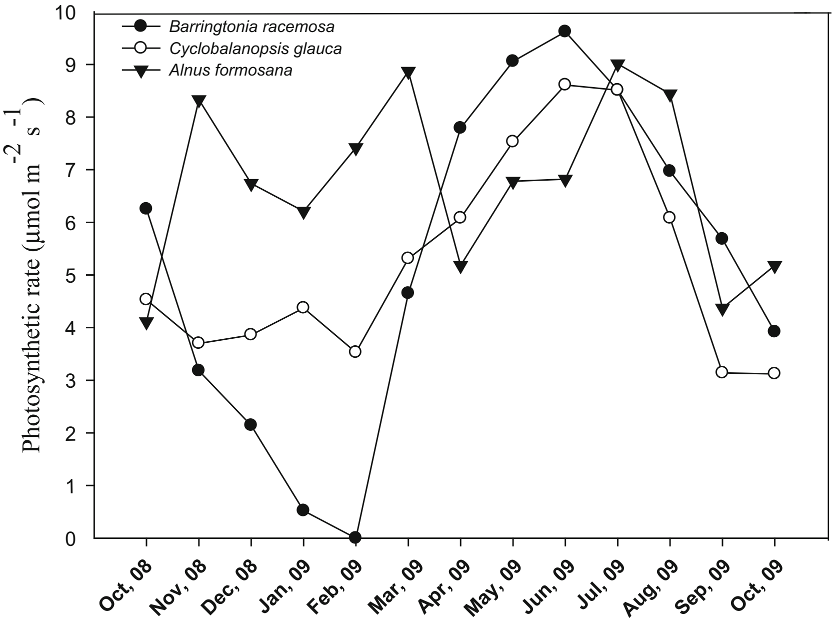


Fig. 4 The average photosynthetic rate variation of *Barringtonia racemosa*, *Cyclobalanopsis glauca,* and *Alnus formosana* during the study period

basis of timber volume. The average carbon storage of tree timber per month varied by tree species. *A. formosana* had the highest carbon storage, of between 52.7 and 129.0 g C plant^{-1} a^{-1}, while *C. glauca* had the lowest carbon content, between 40.8 and 83.4 g C plant^{-1} a^{-1} (Fig. 6). The annual gross carbon storage of *B. racemosa*, *C. glauca*, and *A. formosana* was 780.0, 480.0, and 1330.0 g C plant^{-1} a^{-1} on a timber basis, respectively, which equals 1170, 720, and 1995 kg C ha^{-1} a^{-1}. In addition, a power regression of branch and limb circumference and carbon storage in timber was performed; the result showed high coefficients of determination (R^2), 0.92, 0.66, and 0.92, for *B. racemosa*, *C. glauca*, and *A. formosana*, respectively.

The annual estimated gross carbon storage of *B. racemosa*, *C. glauca*, and *A. formosana* is equivalent to the amount of carbon stored in the aboveground biomass (including leaf), which resulted in 1926, 1335, and 4733 kg C ha^{-1} a^{-1}, respectively.

Discussion

In general, BEFs (e.g. leaf area and photosynthetic rate, DBH, and tree volume) are used as non-destructive methods to predict biomass production and carbon storage in forestland (Aboal et al. 2005; de Gier 2003); these criteria

Fig. 5 The average carbon storage in leaves of *Barringtonia racemosa*, *Cyclobalanopsis glauca,* and *Alnus formosana* from 10/2008 to 10/2009

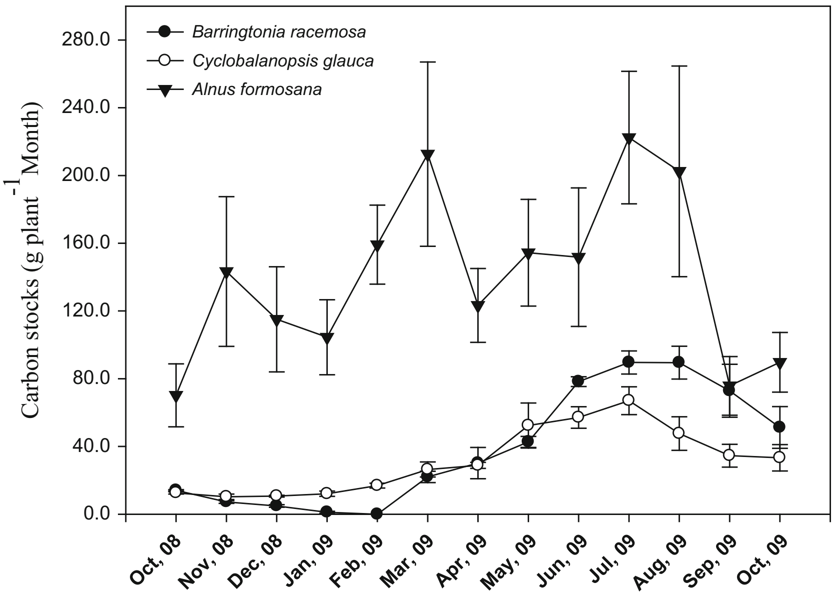
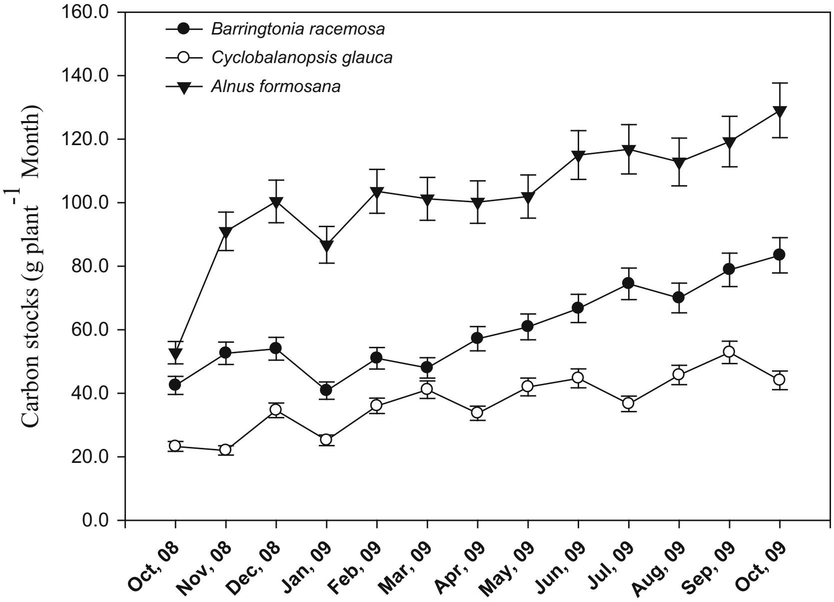


Fig. 6 The average carbon storage in timber of *Barringtonia racemosa*, *Cyclobalanopsis glauca,* and *Alnus formosana* from 10/2008 to 10/2009



can also be used for predictions about urban trees (Nowak and Crane 2002). The results for carbon storage obtained in this study varied substantially among species from 1335 to 4733 kg C ha^{-1} a^{-1}. Species with a greater leaf area and timber volume seem to store larger amounts of carbon, based on the BEF criteria.

Additionally, the photosynthetic rate increased from March to June in 2009 in response to variations in *PPF* (Figs. 1, 4) leading to increased photosynthesis and thus greater carbon storage by the *B. racemosa* and *C. glauca* specimens. However, this pattern was not found for *A. formosana*, due to the decreased leaf area and photosynthetic rate from March to June in 2009 (Figs. 2, 4, 5).

The living wood tissues are the major storage compartments of carbon in trees, and thus the amount of carbon that is sequestered in wood is highly correlated to timber volume (e.g. R^2 is 0.92, 0.66, and 0.92, for *B. racemosa*, *C. glauca*, and *A. formosana*, respectively). Echoing the findings of a previous report that stem circumference can be used to accurately estimate the total aboveground yield of some eucalyptus species in Central Queensland, Australia (Burrows et al. 2000). Results of our current work indicated that, of the three species studied, *A. formosana* has the highest potential to store carbon, followed by *B. racemosa* and then *C. glauca*.

This study examined the potential carbon storage of three avenue trees species at 3 years of age, but it should be noted that the long-term carbon storage depends on the growth characteristics of the tree species, the environmental conditions, the density of tree plantation, and it is more important to plant the right species. Therefore, more research is needed on variations in these factors among urban trees to obtain better estimates of their related carbon storage abilities.

Conclusion

This study provides details about the aboveground carbon storage potential of young *B. racemosa*, *C. glauca*, and *A. formosana*. The total gross aboveground biomass carbon stock per hectare for these trees measured were 1926, 1335, and 4733 kg $Cha^{-1}\ a^{-1}$, respectively. However, our estimated results were limited by the pot growth conditions, the youth of the plants, and the consideration of only the aboveground biomass carbon. To evaluate the true extent to which these species are appropriate urban trees for use in carbon sequestration, and how well they are able to store extra carbon within their biomass, every year of carbon production (e.g. plant decomposition and burning) and reduction (i.e., sequestration) is needed, as this will yield a better understanding of carbon cycling within a city.

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