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Carbon Pools of Indigenous and Exotic Trees Species in a Forest Plantation, Prachuap Khiri Khan, Thailand

Ponthep Meunpong[1] Chongrak Wachrinrat[1,2]*, Bunvong Thaiutsa[1],
Mamoru Kanzaki[3] and Kongsak Meekaew[4]

ABSTRACT

The carbon pool was evaluated in a forest plantation in Kui Buri district, Prachuap Khiri Khan province, on peninsular Thailand. The study was conducted in native and exotic tree species plots, when the trees were aged 14-15 y. The above- and below-ground biomass of each tree species was evaluated. Plant and soil carbon concentrations and carbon pools were estimated. The total biomass of the stands aged 15 y ranged from 51.04 to 291.25 t ha^{-1}. On average, woody tissue (stem, branches and roots) made up 95% of the stand biomass. The fast-growing species, *Acacia crassicarpa* and *Azadirachta indica,* stored more carbon in biomass (177.12 and 91.37 t ha^{-1}). These results indicated that the efficiency of carbon storage for all stands of all tree species depended largely on the biomass. The carbon pool in the mineral soil layer (0-50 cm depth) ranged from 44.49 and 62.64 t ha^{-1}. In addition, the carbon content in the surface soil was higher than in sub-surface levels for every treatment. The results suggested that *A. crassicarpa* and *A. indica* were the most appropriate species for rapid carbon sequestration, with native tree species, such as *Tectona grandis* and *Xylia xylocarpa*, being alternative choices.

Keywords: carbon concentration, carbon pool, biomass, forest plantation

INTRODUCTION

The Earth's tropical region contains 758 million ha of depleted or degraded land that was once forested (Grainger, 1988). Reforestation of this area would capture significant amounts of atmospheric carbon and could be expected to contribute to soil quality and conservation (Schroeder, 1992). About 10% of the carbon stored globally in natural forest ecosystems has been lost through land conversion since industrialization commenced. Forestry activity designed to store carbon is often suggested for the tropics, as tropical climates support rapid rates of vegetative growth (Schroeder and Ladd, 1991). Forest plantations consisting primarily of introduced species make up an estimated 158.1 million ha (4% of total forest area). Productive forest plantations, primarily established for wood and fiber production, account for 78% of this area, with protective forest plantations, primarily established for conservation of soil and water, accounting for 22%. The area of forest plantations increased by about 14 million ha during 2000–2005, or 2.8 million ha $year^{-1}$, with 87% being productive forest plantation (FAO, 2005).

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[1] Department of Silviculture, Faculty of Forestry, Kasetsart University, Bangkok 10900, Thailand.
[2] Center for Advanced Studies in Tropical Natureal Resources, Kasetsart University, Bangkok 10900, Thailand.
[3] Laboratory of Tropical Forest and Environment, Graduate School of Agriculture, Kyoto University, Japan.
[4] Royal Forest Department, Bangkok 10900, Thailand.
* Corresponding authors, e-mail: fforcrw@ku.ac.th

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It is estimated that the world's forests store 283 gigatonnes (gt) of carbon in their biomass alone and 638 gt of carbon in the ecosystem as a whole (to a soil depth of 30 cm). Thus, forests contain more carbon than the entire atmosphere. Roughly, one half of the total carbon is found in the forest biomass and dead wood combined and the other half is in the combined soil and litter layer. Forestry activity has considerable potential to reduce the carbon concentration in the atmosphere (FAO, 2005). Although there have been several estimates of carbon storage in various forest types (Vogt, 1991; Lugo and Brown, 1992; Brown, 1993; Yusuke *et al.*, 2009), few studies on carbon storage and comparisons between species, including native and exotic species of Thailand, have been conducted (Nualngam, 2002). Furthermore, the soil carbon is not negligible and comparisons including the soil carbon pool are required. To allow informed choices between species when establishing carbon storage projects, it is important to characterize various traits which influence carbon storage on a per species basis. Such information would also be useful for inclusion in carbon storage/cycling models. The objectives of this study were to assess biomass productivity, biomass storage patterns, carbon concentration and storage over a 15-year period in a plantation established on degraded forest land in Prachuap Khiri Khan province, on peninsular Thailand.

MATERIALS AND METHODS

Site description

In 1993, the Prachuap Khiri Khan Silvicultural Research Station (PSRS) was established in Kui Buri district, Prachuap Khiri Khan province, in southern Thailand (Figure 1). Originally, PSRS was covered by dry evergreen forest. However, in 1980, it was disturbed by immigrants and converted to agricultural land dominated by pineapple plantations. The Royal Forest Department (RFD) acquired the land and established PSRS in 1990.

A study area of 1 ha was planted with 19 species include both native and exotic species, consisting of: *Acacia crassicapa*, *A. mangium*, *A. auriculaeformis*, *A. auriculaeformis* (A), *A. auriculaeformis* (B), *Acrocarpus fraxinifolius*, *Alstonia macrophylla*, *Azadirachta indica*, *Casuarina junghuniana*, *C. equisetifolia*, *C. equisetifolia* (no.13), *C. equisetifolia* (no.14), *C. equisetifolia* (no.21), *C. equisetifolia* (no.16), *Dalbergia cochinchinensis*, *Dipterocarpus. alatus*, *Eucalyptus camaldulensis*, *Fagraea fragrans*, *Fernandoa adenophylla*, *Intsia palembanica*, *Pterocarpus macrocarpus*, *Shorea roxburghii*, *Sterculia foetida*, *Tectona grandis* and *Xylia xylocarpa*. Each plot contained 25 trees at a spacing of 2 × 2m in a completely randomized block design (25 treatments and 4 replications). In the study period (August 2007-July 2008), the

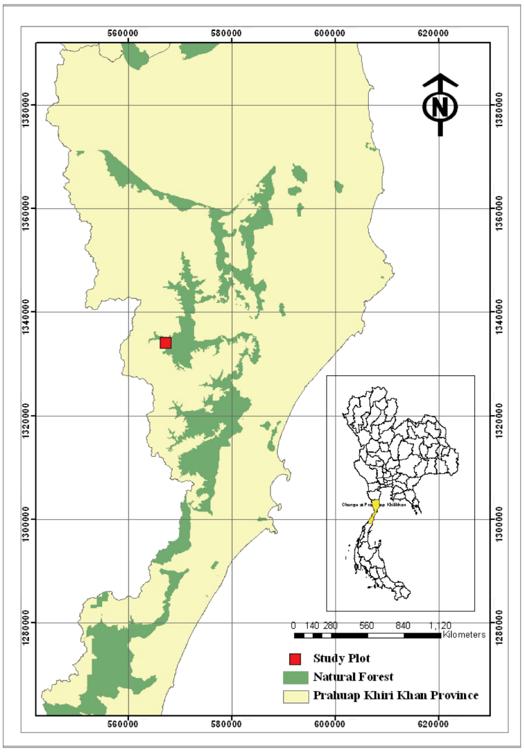

Figure 1 Location of the study site.

annual rainfall was 1,049 mm. The rainy season (when the average monthly rainfall exceeded 100 mm) occurred twice during the study period, firstly between August 2007 and October 2007, and then between March 2008 and May 2008. The average maximum and minimum temperature was 32.52 and 23.18°C, respectively. The average relative humidity was 83.81%. In order to evaluate the soil carbon pool without reforestation activities, an unplanted control plot was located in abandoned crop fields nearby the study plot; from 1990 onwards, the fields had been abandoned and developed into grasslands after the RFD acquired the land. The grasslands had been sustained by wildfires, which were mainly accidental. The study was carried out from August 2007 to July 2008, when the trees were aged 14-15 y.

Biomass measurement

After a tree census, the survival rate of all remaining trees of each species was calculated. Only six species with the highest survival rates, including native and exotic species, were selected for the following detailed studies. The diameter at ground level (D_0) and diameter at breast height over bark (DBH) were measured using a diameter tape, with total height (H) measured using a Haga hypsometer. A second tree census was repeated after 1 y, after which, five selected trees per species, distributed across all DBH size classes, were selected for the above- and below-ground biomass studies. Sample trees were felled and separated into stem, branches and leaves for evaluating above-ground biomass. The above ground biomass was studied using the stratified clip technique (Monsi and Saeki, 1953; cited by Sahunalu, 1995). The below-ground biomass measurement was used an excavation method, after Kanzaki *et al*. (1991) and Kraenzel *et al*. (2003). The root mass was separated into fine roots (diameter < 2 mm) and coarse roots (diameter > 2 mm).

Each element of the biomass was weighed and sub-sampled to determine the dry weight ratio and for chemical analyses. The samples were oven dried at 80°C for 72 h. The oven-dried samples were ground with a laboratory mill and sieved (0.5 mm). The sieved samples were used to analyze total N and total C, using a C/N corder (model MT-700).

Soil sampling

Soil samples were collected from soil pits excavated to study the below-ground biomass. Disturbed and undisturbed soil horizons were sampled from five depth layers (0-5, 5-10, 10-20, 20-30 and 30-50 cm) and taken back to the laboratory for analysis. Soil samples were air-dried and passed through a 2 mm soil sieve. Total C and total N were analyzed. Total carbon was calculated and expressed as weight per unit area (t ha^{-1}). Non-disturbed soil samples were also collected to estimate soil bulk density from each horizon of each pit.

Estimation of above- and below-ground biomass

An allometric relationship between the estimated component dry matter and the DBH was developed from the harvested trees and used to separate each component (Equation 1):

$$Y = aX^b \text{ or } \log Y = \log a + b \log X \quad (1)$$

where:

a and b are constants specific to each component of each species;

X is the diameter at breast height over bark (cm);

Y is the weight of the component (stem, branches or leaves) of a tree (kg $tree^{-1}$).

The total carbon contents of the biomass and soil were estimated on a unit-area basis for each species, based on the components of estimated biomass and their respective carbon concentrations. The soil carbon pool was calculated by multiplying soil bulk density by the nutrient concentration in each soil layer. Analysis of variance (ANOVA) was used to compare tree size, tree biomass, carbon concentration and the carbon pool in the soil and plant system between tree species. SPSS 10.0 for Windows computer software was used for all statistical analysis. Differences were evaluated as significant ($P < 0.05$) and highly significant ($P < 0.01$).

RESULTS

Survival rate

The tree survival rate was calculated at age 15 y. The survival rate ranking showed that two exotic tree species (*Azadirachta indica* and *Acacia crassicarpa*) had the highest survival rates, with 90 and 89%, respectively, while all native species had survival rates lower than 80%. Table 1 shows that the highest survival rate in the native tree species was 79% for *Tectona grandis*, followed by *Pterocarpus macrocarpus* (76%), *Shorea roxburghii* (74%) and *Xylia xylocarpa* (69%).

Tree growth

The mean sizes of six selected species age 15 y are shown in Table 2. The exotic tree species, *A. crassicarpa*, had the highest values for all parameters (25.01 cm, D_0; 18.66 cm, DBH; 16.01 m, H). A native species, *S. roxburghii*, had the smallest dimensions (9.71 cm, D_0; 6.96 cm, DBH; 7.57 m, H). The fastest growing species was *A. crassicarpa*, followed by moderate growth in *A. indica, T. grandis,* and *X. xylocarpa*, with the slowest growth in *P. macrocarpus* and *S. roxburghii*. All tree growth parameters (D_0, DBH and H) were highly significantly different between all tree species at age 15 y, the only age analyzed.

Table 1 Survival rates of 15-year-old tree species and their ranking.

Scientific name	Family	Survival rate (%)	Ranking	Source
Azadirachta indica (Ai)	Meliaceae	90	1	Exotic
Acacia crassicapa (Ac)	Fabaceae	89	2	Exotic
Tectonna grandis (Tg)	Labiateae	79	3	Native
Pterocarpus indicus (Pi)	Papilionoideae	76	4	Native
Shorea roxburghii (Sr)	Dipterocarpaceae	74	5	Native
Xylia xylocarpa (Xx)	Mimosaceae	69	6	Native

Table 2 Average diameter at ground level (D_0), diameter at breast height over bark (DBH) and total height (H) of 15-years-old trees in Kui Buri forest plantation (standard deviations in parentheses).

Species	D_0 (cm)	DBH (cm)	H (m)
A. crassicapa	25.01^{a} (10.99)	18.66^{a} (8.13)	16.01^{a} (3.08)
A. indica	17.37^{b} (6.29)	13.79^{b} (5.27)	13.42^{ab} (4.52)
P. macrocarpus	11.24^{cd} (5.35)	8.17^{cde} (4.49)	7.82^{c} (2.97)
S. roxburghii	9.70^{d} (4.80)	6.96^{e} (3.41)	7.57^{c} (2.77)
T. grandis	15.07^{bc} (4.77)	11.82^{bc} (4.16)	13.36^{ab} (3.23)
X. xylocarpa	16.20^{bc} (8.79)	11.24^{bcd} (6.50)	12.70^{b} (5.18)
F-value	11.39	9.71	10.12
Significant	**	**	**

ANOVA results: ** = significant at $P < 0.01$.

^{abcde} = the same letter in each column denotes groups that were not significantly different ($P > 0.05$).

Biomass

The relationships between the weight of tree components (kg tree^{-1}) and diameter at breast height over bark (DBH) were well defined by allometric equations of the form $Y = aX^b$, with high R^2 values (Table 3). The biomass estimates are shown in Table 4 and indicate that the total above-ground biomass for *A. crassicarpa* was the highest (272.71 t ha^{-1}), while the total above-ground biomass for *P. macrocarpus* was the lowest (36.38 t ha^{-1}). The average height for *A. crassicarpa* (16.01 m) resulted in its crown spread inhibiting other species in the plots. In contrast, the two native species, *S. roxburghii* and *P. macrocarpus*, had the two lowest values for total height and also the lowest above-ground biomass of only 57.06 and 36.38 t ha^{-1}, respectively. Overall, the differences in biomass among species plots were due primarily to the presence or absence of planted trees and also the growth performance of each tree species. *A. crassicarpa* showed the highest survival rate (89%), with its biomass productivity five to six times greater than that of *S. roxburghii* and *P. macrocarpus*, which had lower survival rates of 74 and 76%, respectively.

Total below-ground biomass to 50 cm soil depth ranged from 9.40 to 49.93 t ha^{-1} and was highest in the *A. indica* stand and lowest in the *X. xylocarpa* stand. Fine- and coarse-root biomass ranged from 6.22 to 24.92 t ha^{-1}, and from 1.07 to 25.01 t ha^{-1}, respectively. In contrast to the above-ground biomass, the total below-ground biomass of *A. crassicarpa* was only 18.54 t ha^{-1}. Overall, the average fine root mass was greater than that of the coarse roots, irrespective of tree species. *S. roxburghii* had the smallest amount of coarse roots (1.07 t ha^{-1}).

The root-to-shoot ratio (R:S) was lowest for *A. crassicarpa* (0.07) and *X. xylocarpa* (0.07), and highest for *P. macrocarpus* (0.40). The low root-to-shoot ratio for *A. crassicarpa* (Table 4) could be explained by many trees in the study area

Table 3 Biomass equation constants (*a* and *b*) and coefficients of determination (R^2) for estimating biomass components of individual tree species.

Tree species	Tree component	*a*	*b*	R^2
A. crassicarpa	Stem	0.27	2.10	0.98
	Branch	0.10	1.70	0.73
	Leaf	0.09	1.80	0.91
A. indica	Stem	0.28	2.11	0.97
	Branch	0.04	2.06	0.99
	Leaf	0.04	1.66	0.98
P. macrocarpus	Stem	0.08	2.33	0.98
	Branch	0.02	2.35	0.97
	Leaf	0.00	2.43	0.98
S. roxburghii	Stem	0.14	2.31	0.99
	Branch	0.04	2.25	0.91
	Leaf	0.05	1.70	0.92
T. grandis	Stem	0.06	2.59	0.99
	Branch	0.00	2.88	0.98
	Leaf	0.01	2.24	0.83
X. xylocarpa	Stem	0.11	2.47	0.98
	Branch	0.02	2.43	0.93
	Leaf	0.06	1.62	0.97

Table 4 Average above-ground and below-ground biomass of each tree species (all data in t ha^{-1}).

Species	Above-ground biomass			Below-ground biomass		Total above-ground biomass	Total below-ground biomass	Total biomass	R:S ratio
	Stem	Branch	Leaf	Fine root	Coarse root				
A. crassicarpa	231.53^{a}	26.84^{a}	14.34^{a}	15.48^{b}	3.06^{cde}	272.71^{a}	18.54^{cd}	291.25^{a}	0.07^{b}
A. indica	128.81^{b}	17.15^{b}	5.81^{b}	24.92^{a}	25.01^{a}	151.77^{b}	49.93^{a}	201.69^{b}	0.33^{a}
P. macrocarpus	27.76^{e}	7.29^{de}	1.33^{e}	9.04^{c}	5.62^{cd}	36.38^{e}	14.66^{cde}	51.04^{d}	0.40^{a}
S. roxburghii	42.83^{de}	10.60^{cde}	3.63^{d}	16.99^{b}	1.07^{de}	57.06^{de}	18.06^{cd}	75.12^{d}	0.32^{a}
T. grandis	76.83^{cd}	10.77^{cd}	5.25^{bc}	16.78^{b}	13.45^{b}	92.85^{cd}	30.23^{b}	123.07^{c}	0.33^{a}
X. xylocarpa	93.5^{bc}	15.28^{bc}	5.44^{bc}	6.22^{c}	3.18^{cd}	114.22^{bc}	9.40^{de}	123.62^{c}	0.07^{b}
F-value	46.07	67.97	48.60	21.80	104.58	48.96	48.04	40.95	17.65
Significant	**	**	**	**	**	**	**	**	**

ANOVA results: ** = significant at $P < 0.01$.

^{abcde} = the same letter in each column denotes groups that were not significantly different ($P > 0.05$).

having been damaged by wind snap and wind throw as a result of thunderstorms and strong winds, since *A. crassicarpa* trees were taller and had a greater canopy surface area and so were severely damaged.

Carbon concentration and pool in plant and soil

The values for plant and soil carbon concentration are summarized in Table 5. The results show that the average carbon concentration in the tree components (leaves, branches, stem, fine roots and coarse roots) of each species ranged from 43.68 to 51.49%. The above-ground biomass carbon concentrations varied from species to species. The highest carbon concentration was in the stem of all species (except for *A. crassicarpa*, which had a carbon concentration of 51.49% in the leaves). The below-ground plant carbon concentrations varied between the fine and coarse root components. *A. indica*, *P. macrocarpus* and *X. xylocarpa* showed a greater carbon concentration in the fine roots. On the other hand, the coarse root of *A. crassicarpa*, *S. roxburghii* and *T. grandis* had greater levels of carbon concentration.

The carbon concentration in the mineral soil from 0 to 50 cm depth was studied in every treatment and in the control plot. The results showed that the soil carbon content was highest in the surface horizon (0-10 cm depth) and declined with increasing soil depth. It was a common trend for soil carbon concentration to decrease with increasing depth, because the surface soil has more organic matter from litter than the subsoil. *A. crassicarpa* had the greatest value of carbon concentration (1.44%) in the first soil horizon, followed by *S. roxburghii* (1.24 %) and *P. macrocarpus* (1.13 %), probably due to the fact that *A. crassicarpa* had the greatest amount of leaves and branches whose components fell as litter and decomposed on the forest floor. Consequently, the litter decomposition affected the carbon concentration in the mineral soil, especially

Table 5 Carbon concentration (%) in plant and soil of different species (standard deviations in parentheses).

Species		Ac	Ai	Pm	Sr	Tg	Xx	Grassland
Tree part	Leaf	51.49^{a} (0.94)	44.89 (0.82)	44.86^{b} (0.78)	48.28 (0.37)	45.43^{bc} (0.13)	48.44^{a} (0.70)	na.
	Branch	48.34^{b} (0.34)	44.96 (0.25)	46.63^{a} (0.25)	47.40 (0.10)	46.78^{a} (0.19)	45.40^{c} (0.25)	na.
	Stem	48.01^{b} (0.82)	45.86 (1.53)	47.41^{a} (0.34)	48.52 (0.83)	47.20^{a} (0.26)	47.96^{ab} (0.17)	na.
	Fine root	45.18^{c} (0.93)	44.38 (1.20)	46.15^{ab} (0.94)	46.36 (1.43)	45.14^{c} (1.19)	47.65^{ab} (0.77)	na.
	Coarse root	47.83^{b} (0.36)	43.68 (1.10)	45.11^{b} (1.09)	47.59 (0.51)	46.28^{ab} (0.47)	46.44^{bc} (1.79)	na.
F-value		23.38	1.70	5.87	3.42	6.54	5.27	na.
Significant		**	ns	*	ns	**	*	
Soil depth (cm)	0-10	1.44^{a} (0.32)	1.01^{a} (0.25)	1.13^{a} (0.22)	1.24 (0.28)	1.03^{a} (0.08)	0.96^{a} (0.15)	0.80a (0.13)
	10-20	0.66^{b} (0.14)	0.67^{b} (0.16)	0.67^{b} (0.04)	0.93 (0.19)	0.91^{ab} (0.15)	0.64^{b} (0.09)	0.87^{a} (0.26)
	20-30	0.53^{b} (0.09)	0.49^{bc} (0.15)	0.49^{bc} (0.06)	0.73 (0.38)	0.68^{bc} (0.17)	0.50^{bc} (0.16)	0.66^{ab} (0.18)
	30-40	0.50^{b} (0.08)	0.43^{bc} (0.01)	0.39^{c} (0.10)	0.58 (0.15)	0.60^{c} (0.10)	0.45^{bc} (0.24)	0.46^{bc} (0.06)
	40-50	0.66^{b} (0.08)	0.28^{c} (0.14)	0.30^{c} (0.05)	0.64 (0.38)	0.19^{d} (0.11)	0.25^{c} (0.17)	0.33^{c} (0.12)
F-value		15.52	9.24	25.03	2.50	19.54	7.23	5.62
Significant		**	**	**	ns	**	**	*

Ac: *A. crassicarpa*, Ai: *Azadirachta indica*, Pm: *Pterocarpus macrocarpus*, Sr: *Shorea roxburghii*, Tg: *Tectona grandis*, Xx: *Xylia xylocarpa*, na.: data not available

ANOVA results; ns = treatment effect not significant; * = significant at $P < 0.05$; ** = significant at $P < 0.01$.

^{abc} = the same letter in each column denotes groups that were not significantly different ($P > 0.05$).

in the surface soil (0-10 cm depth). The soil carbon pool throughout the 50-cm depth ranged from 44.49 tC ha^{-1} in *A. indica* to 62.64 tC ha^{-1} for *S. roxburghii*. The soil carbon pool showed a distinctive difference between the grassland and plantation sites, especially in the top soil layer (0-10 cm depth). The results showed that the carbon pool in the upper soil of the grassland was less than in the soil under plantations.

The carbon pool in the biomass and mineral soil is estimated in Table 6. The carbon pool in the total biomass was highest in the plot of *A. crassicarpa* (177.12 tC ha^{-1}) followed by the plots of *A. indica* (91.37 tC ha^{-1}) and *X. xylocarpa* (58.85 tC ha^{-1}), respectively. The total carbon pool in the mineral soil layers was highest in the plot of *S. roxburghii* (62.64 t ha^{-1}) followed by *A. crassicarpa* (58.63 tC ha^{-1}) and was lowest in the *A. indica* plot (44.49 tC ha^{-1}). In addition, the carbon pool in the surface soil was higher than in the subsurface layers for every treatment (Figure 2).

DISCUSSION

Tree growth and biomass

A. crassicarpa had significantly greater DOB and height than the other species. It has been reported that *A. crassicarpa* has good wood properties, fast growth and can adapt to a wide range of site conditions (National Research Council, 1983). The results from this study showed there was a lower survival rate for native tree species when compared to the study by Nualngam (2002), which examined a 14-year-old plantation, located in northeastern Thailand, where survival rates of native tree species (*P. macrocarpus* and *X. xylocarpa*) were 94.5 and 80.0%, respectively. For native tree species, the narrow spacing of 2 × 2 m was an important factor that interrupted tree growth and affected the survival of the native tree species. *P. macrocarpus* and *S. rox*burghii had survival rates of only 76 and 74%, respectively, and total heights of only 7.82 and 7.57 m, respectively. These heights were lower than the

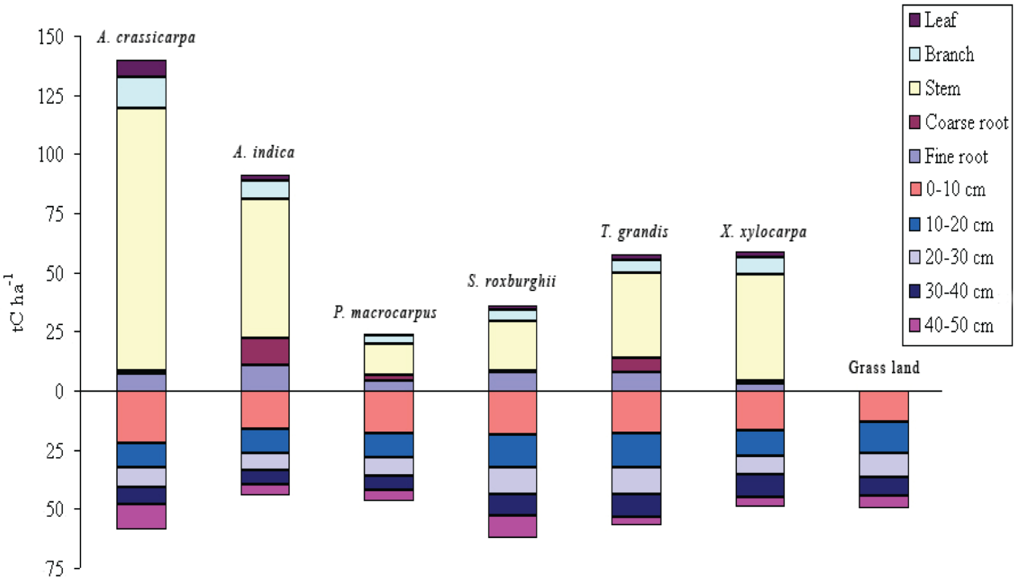

Figure 2 Carbon pool (tC ha^{-1}) of different species in the plant (above ground shown as stacked bars with a positive scale above the x-axis) and soil down to 50 cm depth (shown as stacked bars with a positive scale below the y-axis). **Note:** Carbon pool data for the plant component of the grassland site were not available.

Table 6 Carbon pool (tC ha^{-1}) in plant and soil of different species (standard deviations in parentheses).

Species		Ac	Ai	Pm	Sr	Tg	Xx	Grassland
Tree part	Leaf	7.39^{c} (0.78)	2.61^{b} (0.65)	0.60^{b} (0.31)	1.75^{bc} (0.65)	2.38^{b} (0.71)	2.63^{bc} (0.37)	na.
	Branch	25.38^{b} (1.85)	7.71^{b} (2.39)	3.40^{b} (1.69)	5.02^{bc} (2.33)	5.04^{b} (1.88)	6.94^{b} (1.05)	na.
	Stem	135.90^{a}(17.33)	59.07^{a} (18.67)	13.16^{a} (6.48)	20.78^{a} (9.83)	36.26^{a} (12.29)	44.84^{a}(6.85)	na.
	Fine root	6.99^{c} (0.59)	11.06^{b} (1.66)	4.17^{b} (1.30)	7.88^{b} (2.07)	7.58^{b} (0.94)	2.96^{bc}(0.20)	na.
	Coarse root	1.46^{c} (0.08)	10.92^{b} (0.86)	2.54^{b} (0.54)	0.51^{c} (0.22)	6.22^{b} (1.70)	1.48^{c}(0.19)	na.
	F-value	208.45	29.56	10.60	9.52	25.21	144.31	na.
	Significant	**	**	**	**	**	**	na.
	Total	177.12	91.37	23.86	35.94	57.49	58.85	na.
Soil depth (cm)	0-10	22.18^{a} (4.92)	16.12^{a} (4.12)	18.19^{a} (4.92)	18.56 (4.34)	17.81^{a} (1.43)	16.51^{a} (2.83)	12.94^{a} (3.14)
	10-20	10.51^{b} (2.18)	10.08^{b} (2.28)	10.11^{b} (2.44)	14.06 (3.35)	14.48^{ab} (3.23)	11.09^{ab} (2.08)	13.28^{a} (3.30)
	20-30	8.03^{b} (0.97)	7.32^{bc} (1.85)	7.44^{bc} (1.64)	10.90 (5.81)	11.26^{b} (3.14)	7.75^{b} (2.18)	10.65^{ab}(3.24)
	30-40	7.28^{b} (0.93)	6.18^{bc} (0.35)	6.40^{bc} (1.78)	9.10 (2.50)	9.93^{b} (2.15)	9.60^{ab} (7.92)	7.58^{bc} (1.23)
	40-50	10.63^{b} (1.58)	4.78^{c} (2.43)	4.64^{c} (0.90)	10.02 (5.75)	3.30^{c} (2.59)	4.06^{b} (2.59)	5.42^{c} (1.68)
	F-value	16.37	9.52	13.23	2.16	14.23	3.64	4.99
	Significant	**	**	**	ns	**	*	*
	Total	58.63	44.49	46.78	62.64	56.77	49.00	49.90

Ac: *A. crassicarpa*, Ai: *Azadirachta indica*, Pm: *Pterocarpus macrocarpus*, Sr: *Shorea roxburghii*, Tg: *Tectona grandis*, Xx: *Xylia xylocarpa*, na.: data not available

ANOVA results; ns = treatment effect not significant; * = significant at $P < 0.05$; ** = significant at $P < 0.01$.

^{abc} = the same letter in each column denotes groups that were not significantly different ($P > 0.05$).

heights of the exotic species planted in the same area, with values for *A. crassicarpa* and *A. indica* being 16.01 and 13.42 m, respectively (Table 2). Nualngam (2002) reported slow diameter growth for native tree species, with 11.6 cm for a 15-year-old *P. macrocarpus* stand and 9.8 cm for a 15-year-old *X. xylocarpa* stand. All results were different when compared to the results from the current study. For exotic tree species, Nualngam (2002) also found in 14-year-old plantations in northeastern Thailand that the exotic species, *Acacia auriculaeformis* and *A. mangium*, showed good growth, with mean DBH and height values of 15.5 cm and 17.39 m, and 19.9 cm and 20.32 m, respectively. The difference in the tree growth parameters between Nualngam (2002) and the present study could be due to many reasons. For example, one of the important factors that can affect tree growth is differences in spacing. Nualngam (2002) used two different spacing layouts of 2 × 3m and 2 × 4m that were wider than the 2 × 2m spacing used in the present study.

Above-ground biomass values from the present study, with the exception of the *A. crassicarpa* plot, were lower than reported by Nualngam (2002) who studied a 14-year-old plantation area in northeastern Thailand. The above-ground biomass of *P. macrocarpus*, *X. xylocarpa* and *Dalbergia cochinenesis* was 53.1, 88.3 and 84.2 t ha^{-1}, respectively. In contrast, the above-ground biomass of *Acacia* spp. in the same plot had values of only 119.5 to 195.2 t ha^{-1}, which were lower when compared to the value of 272.71 t ha^{-1} for *A. crassicarpa* in the present study. The difference was due to the greater tree density from the 2 × 2 m spacing in the present study versus the spacing of 2 × 3 m and also the higher survival rate of 89% in the present study compared to values of 69.5 and 52.6% reported by Nualngam (2002).

The below-ground biomass from the present study showed a similar trend to that of other exotic tree species plantations that were reported to have total below-ground biomass between 3.8 and 25.5 t ha^{-1} (Dutta and Madhoolika, 2003), and 26.54 t ha^{-1} reported by Singh (1994), who studied *Eucalyptus* spp. hybrid plantations. The differences in the below-ground biomass among tree species probably were due to genetic variation in and adaptation to each natural habitat. *A. crassicarpa*, which is naturally distributed in moist regions, had a lower value for below-ground biomass when compared to species that are naturally distributed in dry regions, such as *P. macrocarpus* and *X. xylocarpa*. The greater below-ground biomass of *A. indica* and *T. grandis* signifies their suitability for forest restoration on dry land due to their greater moisture and nutrient absorption capacity. *X. xylocarpa*, a native tree species, had the lowest survival rate of 69%, but nevertheless, the total biomass of this species was greater than some species with greater survival rates, such as *P. macrocarpus* (76%) and *S. roxburghi* (74%). The higher biomass was due to the larger growing space available to and the greater height of *X. xylocarpa* than the other species.

With the exception of *X. xylocarpa,* all the native tree species had an R:S ratio between 0.32 and 0.40 that was higher than the value of 0.07 for the exotic tree species *A. crassicarpa* (Table 4). The R:S values found in the present study were greater than the range 0.11- 0.23, with a mean of 0.16 reported by Kraenzel (2003) in a 20-year-old teak plantation. Cairns *et al.* (1997) found the average R:S for tropical forests was 0.24. Only a few articles have reported on the below-ground biomass allocation of individual tree species. Nevertheless, there has been a reported progressive decrease in the values of the R:S ratio with increasing plantation age (Hase and Foelster, 1983; Kraenzel, 2003). The uprooting of many trees caused by wind throw in the *A. crassicarpa* plot makes an interesting point on the silvicultural method necessary to solve this problem. Intensive plantation management is necessary in *A. crassicarpa* plantations, involving suitable initial spacing and intermediate cutting for canopy structure improvement. An appropriate wider spacing, such as 4 × 4 m or 2 × 4 m, could favor the growth rate in tree diameter, which would allow trees to reach a satisfactory diameter size to resist wind damage.

Carbon concentration and the carbon pool in the plant and soil

The carbon concentration in the above-ground biomass determined in the present study showed a similar trend to studies by Sakuntaluk (1999), Nualngam (2002) and Glumphabutr (2004), with the decreasing sequence being stem > leaves > branches. However, carbon concentrations in the soil for the present study were lower when compared to Sakurai *et al.* (1998) and Glumphabutr (2004), whose studies were in natural evergreen forest in the eastern and northeastern parts of Thailand. Their results ranged from 2.48 to 4.16% and 2.42 to 3.63%, respectively. Therefore, when compared with the results reported by Nualngam(2002) from a forest plantation established on abandoned crop fields originating from dry evergreen forest, the carbon concentration of the soil showed a similar trend to the present study. He also reported that the carbon concentration in the soil depth from 0 to 5 cm ranged from 1.23 to 1.95%, which was similar to the range in the present study from 0.96 to 1.44%. The results of carbon concentration in the present study are consistent with the research carried out by Tangsinmankong (2004) and Senpaseuth (2009). Under forest plantation, the soil carbon concentration was found to be higher than in grassland nearby and it agreed also with other reports (Hase and Foelster, 1983; Tangsinmankong, 2004). These results indicated that the efficiency of the above-ground carbon storage for all tree species depended largely on the above-ground biomass, because the concentrations of carbon in the plant tissues were comparable between species, which was consistent with the results of Nualngam (2002) and Glumphabutr (2004).

The largest new carbon store after the establishment of the plantation was in the trees themselves, as much of the tree's carbon is located above ground. For some species, such as *P. macrocarpus* and *S. roxburghii*, more carbon was stored in the soil than in the stand biomass. The above-ground mean carbon storage of each tree species in the present study was lower than 100 tC ha^{-1}, except for *A. crassicarpa*, which had more than 165.84 tC ha^{-1}. Carbon storage for native species in the present study was lower than in a 20-year-old teak (*T. grandis*) plantation in Panama, in which 120 tC ha^{-1} was stored (Kraenzel *et al.*, 2003). Petsri (2004) reported that the above-ground carbon pool in 6- to 24-year-old teak plantations ranged from only 29.76 to 37.58 tC ha^{-1}. Nualngam (2002) found that an *A. mangium* plantation stored the highest above-ground carbon content (94.45 tC ha^{-1}), followed by plantations of *A. auriculaeformis* (56.74 tC ha^{-1}), *Eucalyptus camaldulensis* (55.66 tC ha^{-1}), *X. xylocarpa* (41.89 tC ha^{-1}), *Dalbergia cochinchinensis* (38.46 tC ha^{-1}) and *P. macrocarpus* (24.72 tC ha^{-1}). His results appeared lower for *Acacia* spp. and *X. xylocarpa*, but were more or less the same for *P. macrocarpus,* compared to the results from the present study. This was probably because of the individual differences in growth rate, spacing, stand density or topography between the study sites.

It is of interest to compare the above-ground carbon pool estimated in the plantation of the present study with the carbon pool in a natural forest stand. The above-ground carbon pool for moist evergreen forest, dry evergreen forest and hill evergreen forest in eastern Thailand was reported to be 215.2, 170.1 and 51.9 tC ha^{-1}, respectively (Glumphabutr, 2004). Petsri (2004) reported that the above-ground carbon pool of mixed deciduous forest was 60.06 tC ha^{-1}. Compared to the results from the present study, the above-ground carbon pool in the plantation was lower than in the natural evergreen forest, but greater than that of dry land natural forest. The evergreen forest structure is composed of many tree layers that contain many life-forms, while on the other hand, a forest plantation contains only one species. Therefore, the carbon stored in the above-ground biomass would be expected to be different between a natural evergreen forest and a plantation.

Glumphabutr (2004) reported that the carbon pool to a soil depth of 100 cm in a natural forest ranged from 120.9 to 179.9 tC ha^{-1}. Kraenzel *et al*. (2003) reported the carbon content to a soil depth of 100 cm was 225 tC ha^{-1}. Nualngam (2002) reported that the soil carbon content (to 30 cm depth) in a plantation ranged from 37.2 to 48.9 tC ha^{-1}. The soil carbon content from the present study (to 50 cm depth), was lower compared to natural forest, but was similar to the results reported by Nualngam (2002) and (Tangsinmankong, 2004). The different results were probably due to the larger litterfall volume in the natural evergreen forest, as litterfall supplies the soil carbon store, with carbon being released from litter through the process of litter decomposition. When the soil carbon pools were compared between an unplanted control plot and the plantation areas, the results varied; *A. crassicarpa*, *S. roxburghii* and *T. grandis* had greater carbon contents, while on the other hand, *A. indica*, *P. macrocarpus* and *X. xylocarpa* had slightly lower results (Table 6). The litter volume and decomposition rate of each tree species might be the reason for the differences, with the high decomposition rate of the *S. roxburghii* litter and the production of a large amount of *A. crassicarpa* litter (data not shown).

According to the results from the present study, forest plantation plays a significant role in the carbon cycle. Both reforestation and afforestation can have a great influence on the reduction of CO_2 in the atmosphere. The climate can cause rapid tree growth, especially in tropical areas. Moreover, separating the estimates of carbon sequestration in plantations into individual species is useful to identify the potential of each species for projects involving carbon sequestration in plantations. This information will be very beneficial for global carbon sequestration database, and can be applied to establish carbon cycle models.

CONCLUSION

As all tree species were planted at the same site, the growing conditions, including environmental factors and management practices, must have been the same. Therefore, many results from this study indicated clear differences between species.

1. The exotic tree species, *A. crassicarpa*, showed the highest survival rate and the highest total biomass. On the other hand, *P. macrocarpus* showed the lowest amount of total biomass. The root-to-shoot ratio (R:S ratio) ranged from low in *A. crassicarpa* to high in *P. macrocarpus*. Many *A. crassicarpa* trees in the study area had blown over during strong winds or thunder storms. The *A. crassicarpa* canopy suffered from more damage in these storm events, as it was higher and dominated other species in the study plots.

2. There were indistinct differences between species in the carbon concentration in the plant and soil components. The carbon pool in a plantation ecosystem depends on the relative biomass of components. Fast growing species, such as *A. crassicarpa* and *A. indica*, can store more carbon compared to slow growing species, such as *P. macrocarpus* or *S. roxburghii*.

3. As the size of the carbon pool depends on biomass productivity, fast-growing tree species that can achieve greater levels of biomass productivity should be chosen for any nutrient conservation or carbon sequestration program. From the results of the present study, *A. crassicarpa* and *A. indica* appeared to be the

appropriate species for such programs. In addition, two native tree species, *T. grandis* and *X. xylocarpa*, were also alternative choices for such purposes.

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