Management Practices and Aboveground Biomass Production Patterns of *Rhizophora apiculata* Plantation: Study from a Mangrove Area in Samut Songkram Province, Thailand

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Rhizophora spp. are grown for wood charcoal production in many tropical estuaries and coastal areas. However, a lack of species-level information stands in the way of promoting this resource for sustainable practices. The present study investigated management practices and aboveground biomass (AGB) production patterns of *Rhizophora apiculata* plantations in the Yeesarn area of Samut Songkhram Province, Central Thailand. Interviews of farmers and a field survey were main instruments for collecting and analyzing of the data. It was found that farmers collect mature propagules locally and use traditional knowledge for maintenance of the plantation including site preparation and planting. Beating-up and weeding are the main operations applied in establishing a plantation; otherwise, little effort is directed towards post-planting maintenance. The plantation was reforested in a harvesting rotation of 8 to 15 years. Observed stand growth in terms of annual turnover rate (ATR) of height and diameter was highest in a 12-year old plantation; 0.82 m/year and 0.46 cm/year, respectively. Highest AGB production, stem wood volume (SWV), and commercial wood volume (CWV) were observed in a 14-year old plantation; 201.95 tonnes/ha, 181.49 m^3/ha, and 178.98 m^3/ha, respectively. Growth and productivity patterns indicate that the plantation has a high yield potential in terms of wood biomass production.

Keywords: Rhizophora apiculata; Plantation management; Aboveground biomass; Growth pattern; Biomass estimation model;

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INTRODUCTION

Mangroves are an incredible ecosystem that can be found in tropical and subtropical deltas, estuaries, lagoons, and islands. Mangrove forests grow ubiquitously on a relatively narrow fringe between land and sea, and their distribution is mostly restricted between latitudes of 25° N and 30° S (Valiela *et al.* 2001). They often provide a wide range of ecosystem functions, goods, and services (Kathiresan 2012). Mangrove forests protect coastlines from wave actions, storms, and surges (Mukherjee *et al.* 2010); slowing beach erosion and flood actions (Iftekhar and Islam 2004); form nursery grounds for numerous fish and other numerous aquatic animals (Lee *et al.* 2014); provide habitat for diverse vertebrates and invertebrates (Cannicci *et al.* 2008); and supply food, fuel and traditional medicine to local communities (Bandaranayake 1998). Mangroves play an important role in coastal wetland management under rapid climate-driven shifts, especially in relation to carbon cycling and shoreline stabilization, and they form an important link between terrestrial and aquatic ecosystems (Gillis *et al.* 2017). Mangroves are of great importance in muting the impact of storm surges on coastal communities, which especially affects those who live along tropical shorelines. However, most of the existing mangrove forests across the world are under human population and development pressures, which often lead to forest degradation and deforestation (Valiela *et al.* 2001; Giri *et al.* 2011). Various anthropogenic pressures have reduced the global range of these forests to less than 50% of their original size (Spalding *et al.* 2010). These anthropogenic drivers include indiscriminate harvest of forest products for local (*e.g.* timber, charcoal, woodfuel, and tannin) and industrial (*e.g.* woodchips and lumber) purposes (Goessens *et al.* 2014); conversion of mangrove forests into aquaculture, agricultural land, industrial and urban areas (Abuodha and Kairo 2001; Paul and Vogl 2011); and damage to riverine hydrology (Wolanski *et al.* 2000). Various international agencies, governments, non-governmental organizations, coastal communities, and scientists have recognized the ecological, environmental, and socio-economic importance of mangrove forests (Bandaranayake 1998). Based on satellite imagery data, the mangrove forests cover an estimated area of 137,760 km^2 worldwide of which about 42% of them are concentrated in Asia and Pacific region (Giri *et al.* 2011).

In Thailand, mangrove forests have shrunk from 372,350 ha in 1961 to 229,600 ha in 2007 (Pumijumnong 2014). Intensive shrimp farming was recognized as one of the major causes of mangrove destruction in the country (Aksornkoae 1993). Samut Songkram is one of the provinces of Thailand where pristine mangrove forests exist, and the local people manage the forests for goods and services such as fisheries and wood charcoal production. In Yeesarn of Ampawa District, Samut Songkram Province, where about 1276 ha of private mangrove area is known to cultivate for intensive mangrove plantation, mainly with *Rhizophora apiculata* for charcoal production (Kridiborworn *et al.* 2012). Mangrove plantation based charcoal production system has been practiced in Yeesarn for more than a half century and is one of the few examples in the Asia Pacific region where local people conserve and manage mangrove plantation sustainably.

Rhizophora spp. (mainly *R. apiculata, R. mucronata*) are collected for wood charcoal production in many coastal areas of Asia and Pacific region including Thailand, Vietnam, Malaysia, Indonesia, the Philippines, Myanmar, and Bangladesh (Nam *et al.* 1993; Garcia *et al.* 2014; Giri *et al.* 2015). In many parts of these regions, *Rhizophora* wood is harvested from natural mangrove forests (Goessens *et al*. 2014); however, the wood is often collected from man-made plantations (Nam *et al.* 1993; FAO 1994; Primavera and Esteban 2008; Hashim *et al.* 2010; Quy and Nam 2014), *e.g.* in the Can Gio District and the Yeesarn sub-district of Samut Songkhram Province where wood from *R. apiculata* plantations is collected and processed for charcoal production (Nam *et al.* 1993; FAO 1994). Because of specific characteristics *e.g.* strength, straight stem, hardness, and high wood density, *R. apiculata* wood is highly preferred for manufacturing premium quality charcoal (Chantarasena 1985). Apart from the Asia Pacific region, *Rhizophora* trees (*e.g. R. mucronata*, *R. mangle*) play an important role in changing rural demographic livelihood patterns and meeting the needs of urban citizens in many coastal areas in tropical Africa, Latin America, and Caribbean regions (Lugo 2002; Bosire *et al*. 2008; Din *et al.* 2008).

R. apiculata is mostly grown in tropical mudflats. This species is known as a fast growing tree species that is suitable for planting in coastal landward zones where natural regeneration is often inadequate after clear-felling (FAO 1994). Many farms are located in the coastal areas of the Asia Pacific region, including Thailand, Indonesia, Malaysia, and

Vietnam where the local farmers grow this tree in mangrove land for charcoal production (Nam *et al.* 1993; Giri *et al.* 2015). *R. apiculata* plantation based tree farming is considered one of the key sources of income for many mangrove dwellers in this region (Giri *et al.* 2015). Despite the ecological and socio-economic importance of these trees, little is known about their management, growth, and biomass production patterns, which are imperative for popularizing this tree for mangrove restoration, rehabilitation, afforestation, and development of sustainable mangrove plantation-based livelihood programmes (*e.g.* charcoal making, wood fuel, small timber log and tannin production). To date, there are few scientific studies published on management practices, age-wise growth, and productivity patterns of *R. apiculata* plantation. Only a few publications are available, which mainly focus on the productivity of certain age-group of *R. apiculata* plantation (Komiyama *et al.* 1988; Ong *et al.* 1995; Kathiresan and Rajendran 2002) and to a lesser extent on their carbon sequestration (Kridiborworn *et al.* 2012). Moreover, lack of appropriate plantation establishment techniques such as planting and post-planting management techniques are identified as one of the major barriers for undertaking mangrove restoration, rehabilitation, and afforestation programmes across the tropical coastal regions (Kaly and Jones 1998; Lugo 2002; Hashim *et al.* 2010).

In addition, recent interest is growing in the assessment of net primary production (NPP) and net ecosystem production (NEP) to judge carbon fixation from mangroves (Komiyama *et al.* 2008). However, little information is available for species-level biomass estimation specifically for tropical mangrove ecosystems in Southeast Asian region, as the forest conditions are changing rapidly over time (Majid and Nurudin 2015). Moreover, the collection of forest inventory data from mangroves is hampered by a lack of standard model for converting tree measurements to AGB estimation, carbon stock measurement, and subsequent growth estimation (Ong *et al.* 2004; Komiyama *et al.* 2008). The paucity of study cases is one of the major obstacles in developing an allometric relationship for biomass estimation of mangrove species (Komiyama *et al.* 2008). Thus, this research was carried out to fill in these knowledge and information gaps. The study aimed to collect valuable information on management practices, growth, and biomass production patterns of *R. apiculata* mangrove plantations, and to develop a site-specific biomass estimation model to predict above ground biomass production. The outcomes of this study could aid many small scale (*i.e.* household, farm), small and medium scale forestry operators (*i.e.* companies), mangrove plantation based charcoal producers, renewable energy entrepreneurs, scientific communities, governmental and non-governmental agencies in developing and implementing of agriculture, forestry, coastal land management, energy and combat climate change related programmes at local, regional and national levels.

EXPERIMENTAL

Study Area

The study was conducted in a low-lying mangrove area in the Yeesarn sub-district in Amphawa District of Samut Songkhram Province, located approximately 80 km southwest of Bangkok, Thailand and 5 km from inner part of the Gulf of Thailand (Fig. 1). The study area lies between latitude 13º 16´ and 13º 19´ South, longitude 99º 52´ and 99º 56´ East. The area is a flat coastal zone with an area of 6090 ha and is situated along one of the largest artificial canal named Yeesarn. It receives deposition of alluvial soil and sediment from bank erosion and from the Maeklong River estuary. The sampling sites for this study are shown in Fig. 2.

Aquaculture, mangrove forest plantations, coconut plantations, residential areas, and infrastructure development are the major land-use categories in this area. The mangrove plantations (mainly with *R. apiculata* for charcoal production) are a unique feature of this area. However, scarcity of fresh water, polluted water from shrimp ponds, and poor management of solid wastes are major environmental threats in the area. The climate of the study area is designated as *tropical climate*, which is characterized by moderate temperatures and hot summers. Based on weather data from the nearest meteorological station (Bangkok Metropolis Meteorological Station), the cold weather lasts between November and February (TMDB 2016). The weather data for 2016 showed that the coldest month was January with a mean monthly temperature of 26.5 °C and the hottest month was April with a mean monthly temperature of 32.7 °C. The annual rainfall was 1390.8 mm and most of the precipitation fell between May and October. The highest amount of monthly rainfall occurred in September (269.3 mm). However, the soil of this mangrove area is clay in texture with moderate salinity and low proportion of organic matter (Wechakit 1987).

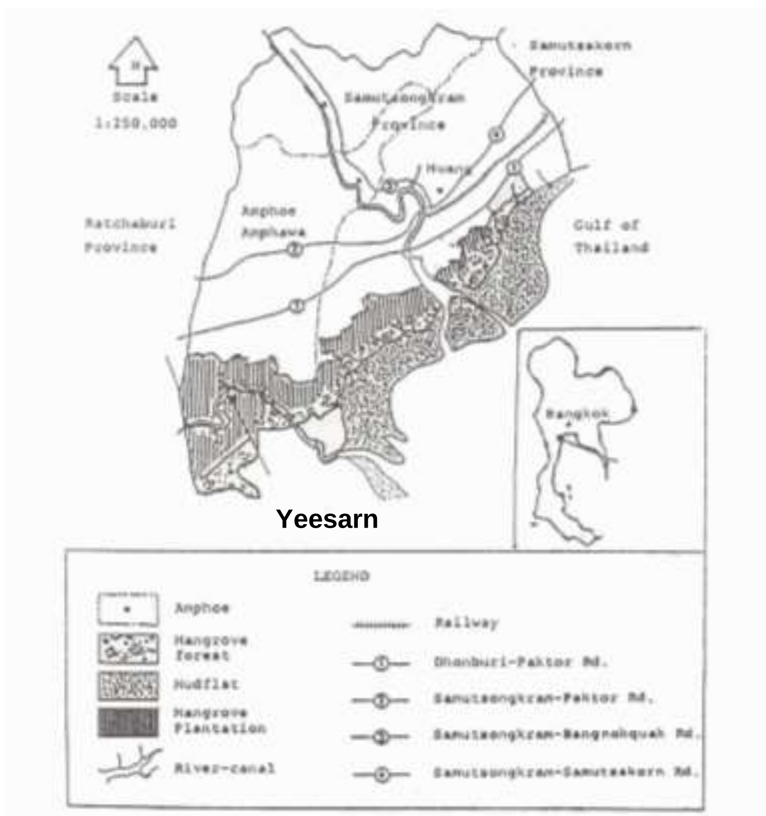

Fig. 1. Map of Samut Songkram Province of Thailand; showing the location of study area Yeesarn

Study Materials

Prior to the start of the field work, the authors examined local area maps to determine the locations of the mangrove plantations. Various equipment, such as measuring tapes and ropes, were used for measuring the sampled plots in the plantations.

Electronic calipers (Scangrip SDC 150 Digital Caliper 6″, Svendborg, Denmark) were used for measuring tree diameter, and Haga altimeter (Vertex III, Haglöf, Långsele, Sweden) and poles were used for measuring stand heights. Electronic devices, *i.e*. camera and laptop were used for documenting the sites.

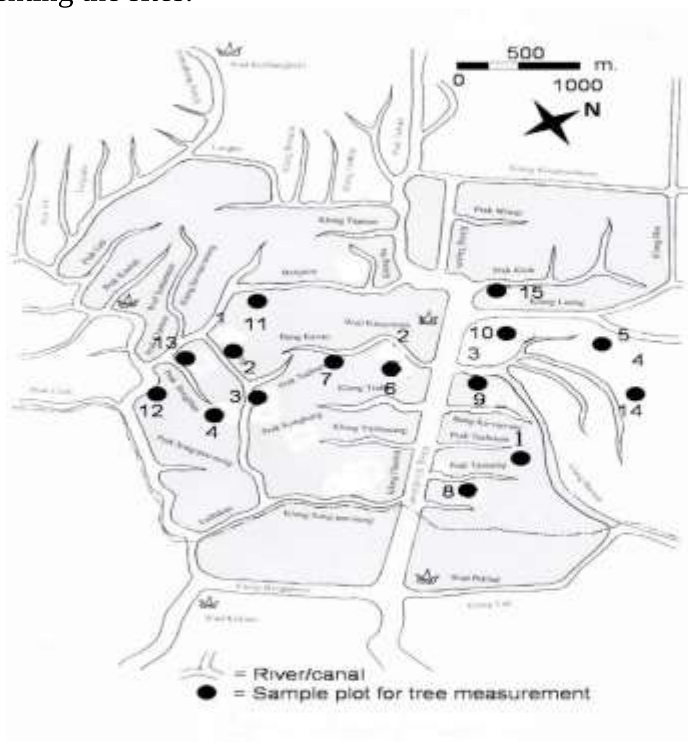

Fig. 2. Map of Yeesarn area; showing the location of tree measurement sampling sites

Methods

Data collection

Data on management practices of *R. apiculata* plantations were collected by interviewing with the local plantation owners, as well as by personal observation. During these events, the following parameters were recorded:

- Site preparation by interviewing with the local farmers and direct observation from the field.
- Seedling collection and seedling processing by interviewing with the local farmers.
- Planting techniques by interviewing the local farmers and direct observation from the field.
- Post-planting maintenance such as beating-up/vacancy filling (*beating-up is a type of replanting operation and the term is often used in mangrove silviculture. Beating-up is also called 'vacancy filling'. The operation is mainly done where the previously planted seedling died*), weeding (*weeding is a type of silvicultural operation that is used for removing unwanted plants*), thinning (*thinning is a type of silvicultural operation that is used to remove some plants/trees in order to make room for the improvement of growth and health of the remaining plants/trees*) and pruning (*pruning is a type of silvicultural operation that is used to remove*

certain parts such as branches and buds of a plant in order to rid them from any possible risk e.g. injury and infection as well as to allow them for better health and growth in the future) operations by interviewing the local farmers.

- Harvesting (*a harvesting system is the coordinated package of activities and methods to fell trees, snig and haul logs, and transport them to a portable location*), wood processing and replanting operations by interviewing with the local farmers and directly observation from the field.

For data on growth and biomass production, a purposive sampling technique was adopted to select 15 temporary sampling plots from different aged *R. apiculata* plantations in the Yeesarn area. The selection of each age-year sample plot was based on personal judgment, accessibility and on site conditions, which are representative of conditions in an average stand. The size of each sample plot was 10 m × 10 m. Similar sampling techniques for assessing growth and productivity of *R. apiculata* stands have also been applied in other studies (Wechakit 1987; Kridiborworn *et al.* 2012). Within each plot, the following parameters were recorded:

- Number of individuals of *R. apiculata* by actual count.
- Diameter at breast height (DBH; 1.30 m above ground) for 3- to 15-year-old plantations and diameter at ground level (Do) for 1- and 2-year-old *R. apiculata* stands.
- Diameter of trees was measured with a Digital-Caliper with 0.01 mm accuracy.
- Height (H) of the stands was measured using poles and a Haga altimeter.
- The age of the plantations were confirmed by the respective plantation owner.

Moreover, available relevant published and unpublished literature were explored for comparing and validating of the collected data.

Data processing

This study applied the following equations for computing the stand density (SD) and stand survival percentage (SSP):

$$SD = N / A \quad (1)$$

where *SD* is the stand density, *N* is the number of living individual trees, and *A* is the area (ha).

$$SSP = (N / n) * 100 \quad (2)$$

where *SSP* is the stand survival percentage, *N* is the number of living individual trees per unit area (ha), and *n* is the number of individual propagule (seedling material) per unit area (ha) during first planting. In this study, both SD and SSP was calculated based on an initial planting of 25000 seedlings/ha.

A non-destructive method was applied for biomass and volume estimation, *i.e.* the allometric term $y = a \times x^h$. The allometric relationship between diameter square (cm^2) and height (m) for the estimation of biomass and volume for 3- to 15-year-old *R. apiculata* stands applied in this study follows Wechakit (1987).

Trees with a stem diameter of 2 cm were considered for the estimation of stem wood volume (SWV), while trees with a DBH of 2 cm or more were considered for the estimation of commercial wood volume (CWV). The annual growth was estimated from the average diameter (D_o, DBH) and H growth of the stand divided by the age of the respective stand. In this study, the following equations were used for an estimation of the productivity of above ground biomass (AGB):

$$W_S\text{: } \text{Log } W_S = 2.0576 + 0.8124 \log D^2H,\ r = 0.9954 \quad (3)$$

$$W_B\text{: } \text{Log } W_B = 1.9928 + 0.4866 \log D^2H,\ r = 0.859 \quad (4)$$

$$W_L\text{: } \text{Log } W_L = 1.9655 + 0.3865 \log D^2H,\ r = 0.7562 \quad (5)$$

$$W_R\text{: } \text{Log } W_R = 1.6630 + 0.5806 \log D^2H,\ r = 0.9385 \quad (6)$$

$$V_T\text{: } \text{Log } V_T = 1.8515 + 0.9100\ D^2H,\ r = 0.9990 \quad (7)$$

$$V_M\text{: } \text{Log } V_M = 1.8198 + 0.9195 \log D^2H,\ r = 0.9977 \quad (8)$$

where W_S is the biomass yield of stem (gm/tree), W_B is the biomass yield of branches (gm/tree), W_L is the biomass yield of leaves (gm/tree), W_R is the biomass yield of prop roots (gm/tree), V_T is the stem wood volume (cm^3/tree), V_M is the commercial wood volume (cm^3/tree), D is the diameter (cm) at breast height, and H is the height (m).

The tree parts were considered, namely the stem, branches, leaves, and prop roots (that grow above the ground) when estimating AGB. During estimation, all biomass components were considered on a dry weight basis. The AGB and SWV for 1 and 2-year plantations were estimated by the harvest technique. Details of the technique are described by Whittaker and Woodwell (1971).

The D_o and H of all sampled plots in a stand were measured, and the average D_o and H values were used as coefficient values for the indirect estimation of AGB and SWV in 1- and 2-year-old plantations. Annual turnover rate (ATR) of Do, H, AGB, SWV, and CWV of each plantation age cohort was calculated from the corresponding values of each component divided by the corresponding age of the stands.

Data analysis

The data analyses were performed with the statistical package SPSS (version 25.0, IBM Corporation, Armonk, NY, USA) and Microsoft Excel software (Redmond, WA, USA). Simple descriptive statistics such as cross tabs and percentages were used to compute the average rating of the growth, biomass productivity, and yield data. As an inferential statistical method, correlation was applied to determine the relationships between different variables, H, DBH, stem, branch, leaf, prop root, AGB, SWV, CWV, and age of stands. Finally, linear regression analyses were performed to construct allometric relationships between H, DBH, and dry biomasses of 3- to 15-year-old stands.

In this study, the allometric equations (referred as *biomass estimation models*) for 3- to 15-year-old *R. apiculata* stands were categorized into two age-class groups; firstly, biomass estimation models for 3 to 7 age-class group of which age-class group was considered as *growing and sapling phase stands*, secondly, biomass estimation models for 8 to 15 age-class group of which age-class group was considered as *developing and mature phase stands.*

RESULTS AND DISCUSSION

Management of *R. apiculata* Plantation

The study observed that farmers cultivated *R. apiculata* trees in private-owned mangrove lands and they often applied their traditional knowledge in the development and establishment of the plantation. The major interventions applied in the management of *R. apiculata* plantations are as follows.

Silvicultural practices

The clear-felling system was applied in the *R. apiculata* plantation in Yeesarn with a cutting rotation between 8 and 15 years. Indeed, the cutting rotation depends on the objectives, end-use of the planted trees, and on the financial return needed by the plantation owner. The study found that production of wood charcoal is the main management objective for cultivating *R. apiculata* plants in mangrove lands in Yeesarn. In addition to wood-charcoal, small quantities of *R. apiculata* tree products such as sapwood is used for pole and logging residues (branches, leaves, and bark) for wood vinegar production. The clear-felling silvicultural system is also reported to apply in many mangrove plantation areas in Thailand with different cutting rotations and management objectives. For instance, in Pattani Province, the silvicultural systems of *Rhizophora* plantations (mainly *R. apiculata* and *R. mucronata*) is a clear-felling, and the cutting rotation is usually set at 15 years. The plantation is mainly used for the production of charcoal (FAO 1994). In Trang, Nakorn Si Thammarat, Pattani and Krabi Provinces, the cutting rotation of *Rhizophora* plantations varied between 6 and 20 years (Komiyama *et al.* 1992). In Chumporn Province, the cutting rotation of mixed *R. apiculata* stands (mainly with *Ceriops tagal* and *Bruguiera* spp.) was fixed at 4 years; the plantation is mostly used for firewood production and stick making for mussel culture (Aksornkoae 1993). However, Thailand declared logging ban from all types of natural forests including natural mangrove forests since 1989.

Nevertheless, the natural *Rhizophora* mangrove forests are managed for both coastal protection and sustainable forestry purposes in many parts of the Asia and Pacific region. For instance, in the Sundarbans mangrove forest of Bangladesh, *Rhizophora* spp. grow naturally in mangrove forests as mixed stands, and the forest is managed for coastal protection from wave actions and storms (Iftekhar and Islam 2004). However, in the Matang mangrove forests of Malaysia, the *Rhizophora-Bruguiera* mixed mangrove forest is managed to maximize a sustained yield of wood, particularly for charcoal production with a felling cycle of 30 years (Chan 2014). The silviculture system applied in Matang for *R. apiculata* mixed stands is clear felling with two thinning operations (Goessens *et al.* 2014). During final felling, about 7 to 10 trees/ha are left in the forest as 'mother trees' for post-harvest regeneration. A different type of silvicultural system has also been reported to apply in man-made *Rhizophora* mangrove plantations; for instance, in Can Gio District of Southern Vietnam it was revealed that the silvicultural system applied in *R. apiculata* plantations in that area is a two-stage selective felling system where the *R. apiculata* plantation is managed for charcoal and woodfuel production with a cutting rotation of 14 years (Nam *et al.* 1993). For understanding the effectiveness of clear-felling system in the *R. apiculata* plantation in Yeesarn area, more investigation on the impact of this felling system on site conditions particularly on soils, flora and fauna are needed to be done.

Site preparation

The farmers put very little effort into site preparation before planting. The logging residues that include bark, branches, and leaves from the previous felling were generally left in the logging sites. It was observed that if the logging residues were excessive, then the residues were chopped and heaped in rows perpendicular to the waterway or burned area. Exploitable slash was collected from the felling areas, gathered near the waterway, and often carried away by boat. If the plantations were over 12 years old, the plantation owner generally allowed interested groups to collect the slash and uproot the remaining parts of the stands after felling. It was noted that the slash was not clearly removed from the planting sites. It is assumed that such practices may provide partial shade in the primary stage of new-planted *R. apiculata* propagules during post-planting development and subsequently may provide nutrients through the decomposition of the slash. In areas where *Acanthus ilicifolius*, *Acrostichum aureum*, *A. speciosum*, *Pluchea indica*, and other undesirable shrubs were abundant, site preparation including cleaning and weeding is needed before planting. In areas above the normal tide level, a small canal (usually 2 to 3 m wide, 50 to 500 m long, and 0.75 to 1.50 m depth) is dug to facilitate seawater flooding and dispersal over the planted areas.

Muddy areas with frequent tides along the coastline or riverine banks are considered the most suitable sites for planting *Rhizophora* spp., and under these conditions, planting is quite successful (FAO 1994). In the Can Gio District of Southern Vietnam, site preparation prior to planting is not necessary if the area is open swampy land, whereas, in areas with scattered shrubs and bushes, site preparation prior to planting is necessary and is mainly carried out by removal of undesirable plants and heaping them in rows (Chan 1990). However, in degraded interior areas and elevated mangrove lands with predominantly *A. aureum* and mixed stands, extensive cleaning work is required prior to planting of *R. apiculata* propagules (FAO 1994).

Source of planting material

The fruiting season of *R. apiculata* in Yeesarn was observed to occur from July to September. The mature propagules become pale green in color with a distinctive reddish abscission collar between the fruit and hypocotyls. The length of propagules (hypocotyls together with cotyledon) is about 25 to 35 cm. The local farmers, who collect propagules from local tree sources, did not practice the establishment of a nursery for *R. apiculata* seedlings; often they collect propagules directly from the mature trees, forest floors, as well as those floating on the water. The farmers collect propagules one month before planting and the propagules are stored under a shed and kept in a horizontal position, covered with *Nypa fruticans* leaves to prevent excessive loss of moisture, and are watered twice a day (*e.g.* in the morning and afternoon) with seawater. Usually, the farmers construct seedlings storage areas, which are adjacent to their houses and/or at the planting sites depending on the handling convenience of the propagules. In many cases, it was observed that the plantation owners kept some mother trees in suitable locations, particularly near their houses or near waterways, as a source of propagules. From discussions with local farmers, it is clear that sources of premium quality propagules for planting have become scarce over the course of time, mainly due to the destruction of the natural habitat of *R. apiculata* and the loss of mother trees. The propagules are transported to the planting sites by long-tail boat. Planting of local propagules could be the right choice since it is cost-effective and is representative of local genetic materials.

The study suggested that the use of local propagules for *R. apiculata* plantations has many advantages since it ensures the survival and adaptation of young plants to the new planting sites and also reduces seedling damage during transportation. In Klong Khon village of Muang District, located approximately 20 km northeast of the Yeesarn sub-district, *R. apiculata* seedlings are grown in a nursery where propagules were directly sown in black plastic bags in a vertical position. The seedlings are watered daily with seawater and subsequently transported to the planting sites (Paphavasit *et al.* 1997). Such nursery practices and tree improvement programmes have yet to be implemented in the Yeesarn area. Nevertheless, in the Can Gio mangrove forests of Southern Vietnam, about 200 ha of mature *R. apiculata* mangrove plantations are managed as a 'specialized area' as a source of propagules; planting of such propagules resulted in more healthy and straight stemmed trees (Nam *et al.* 1993). However, establishment of a seed production area in Yeesarn with mature *R. apiculata* plantation needs to be done.

Spacing and planting techniques

Planting is carried out after site preparation. The farmers plant approximately 25,000 propagules per ha with a spacing of 0.6 × 0.6 m. The main planting technique in the Yeesarn area was observed to be the direct planting of mono-species *R. apiculata* propagules. The planting period was from July to September, with August the peak month for planting. Excavation of pits was done manually by hand, as planting equipment was not used during planting. The planter carried a small bundle of propagules and at every step he/she stacked one propagule about one-third of its length in a vertical position into the soft mud. One interesting finding of this study was that the planting density was quite similar to the previous study by Wichakit (1987) and had remained unchanged over the past 20 years. This would indicate that the farmers are not eager to change their planting techniques, as they would like to ensure a sufficient number of stands per unit of area. It could be inferred that using a high planting density also provides some advantages, for instance by providing straight stems to augment the wood assortment for charcoal production and to maximize the yield/economic gain to the growers. It was suggested that planting at 1 × 1 m and 1.5 × 1.5 m spacing could provide the highest productivity and lowest rate of mortality (FAO 1994). A recent study from southern Thailand showed that lower planting density of *R. apiculata* seedlings could reduce the mangrove restoration cost and decrease the stand mortality (Pranchai 2017). In the Can Gio District of Vietnam, where three types of planting techniques, *i.e.* direct showing, transplanting nursery-raised seedlings and transplanting wildings are applied for *R. apiculata* plantation (FAO 1994). The planting operation is usually carried out between August and November with an approximate spacing of 1 × 1 m or 10,000 seedlings per ha.). However, discussions with the local farmers, it was known that such types of planting techniques have yet to be practiced in the Yeesarn area. Long-term research and development concerning planting techniques, spacing and planting density are needed in the Yeesarn area.

Post-planting maintenance

Beating-up (vacancy filling) and weeding were observed the main post-planting maintenance activities for *R. apiculata* plantations in the Yeesarn area. Due to early stage mortality of planted propagules, two beating-ups were practiced in the area. The first is undertaken within six months from the first planting, with the second one done simultaneously with weeding in the second year. However, plantations that are located in comparatively higher elevations and inundated during medium to medium-high tides require two weedings (the first in the second year and the second in the third year). Neither thinning nor pruning is carried out in *R. apiculata* plantations in Yeesarn, most likely due to the high labor costs associated with those practices, which may involve work in the deep muddy soil that is thickly interwoven with prop roots of the *R. apiculata* stands. However, natural pruning and thinning may occur in the plantations due to the high planting density. Similar phenomena are also reported by other study (Pranchai 2017).

It was observed that weeding is rarely carried out in *R. apiculata* plantations and never in the first year (although in some plantations, it is done in the second year). A weeding operation is reported to require about 18 labor-days/ha. However, it was recommended that the first thinning should apply a spacing of 1 × 1 m after five to six years where the rotation is set at 15 years (FAO 1994). In the Can Gio District of Southern Vietnam, two thinning and pruning operations are carried out in a 14-year rotation of *R. apiculata* plantations, where the first and second thinnings are carried out between 6–7, and 9–10 years, respectively. A third one is also recommended between the years 14–15, where the rotation of the plantation was set for a 20 years (Nam *et al.* 1993). However, two artificial thinnings are carried out in *R. apiculata* mixed stands forests in Matang Mangrove Forest Reserve in Peninsular Malaysia, which are based on a spacing technique called stick-methods. The first thinning is carried out for any tree within a 1.2 m radius of the selected central tree during the fifteenth year, and the second thinning is carried out for any tree within a 1.8 m radius during the twentieth year (Goessens *et al.* 2014). Trial, experiment, or demonstration plots need to be established to examine the effect of planting space and thinning on the growth and productivity of *R. apiculata* plantations in the Yeesarn area.

Harvesting, wood processing, and replanting operations

The farmers usually start to harvest *R. apiculata* plantations when the trees reach between eight and 15 years old. Home-made hand-axes and small chainsaws are used for felling the trees. Such type of manual feeling is reported to be quite effective for small-scale wood harvesting from mangroves, since it generates less impact on the existing vegetation and sites (Walters 2005; Bosire *et al.* 2008; Hashim *et al.* 2010). In general, the plantation owner sells the plantation to charcoal kiln operators if he/she has no kilns. Most often, harvester purchases the plantation from the plantation owners and subsequently harvests the stand manually or with a small chainsaw. Harvesters were also seen to employ local labor to process the tree stems into billets (*i.e.* 1.30 to 1.42 cm long pieces of wood) and directly supply them to the kiln operators. Harvesting operations take place all year round. In general, harvesting and post-harvesting tasks include debarking (peeling of bark), carrying and piling up the billets at the kiln site. Such tasks are done mainly on a contractual basis with the local workers. However, in some cases, contracts are made separately with the tree feller, de-barker, transporter, and pile-maker groups. In all cases, the wages are paid based on the age of stands and location of the plantations.

The harvesting operation is commonly carried out by a team of 2 to 4 members. On some occasions, one or more couples perform the harvesting operation. On average, each couple produces 300 to 400 billets per day, depending on the age of the plantation and the size of the billets. The workers receive an average of $4/100 billets. Debarking and billet-making take place near the harvesting site, and the billets are piled near to the waterways for ease of transportation. Small country boats are the only convenient means for transportation of the billets to the kiln sites. To facilitate transportation of the billets, small canals are often dug. These are up to 100 m long, 2 m wide, and about 1 m deep and it is assumed that these canals also provide a means for regular seawater dispersal and flooding of the area and to facilitate replanting. A replanting operation is started immediately after harvesting that take place during monsoon; otherwise, it is delayed until the following planting season.

Preparation of extraction canals for mangrove wood harvest is commonly used in many parts of the world, notably Malaysia, Indonesia, the Philippine, Vietnam, and Cuba (FAO 1994; Walters 2005). However, other harvesting systems such as wheelbarrow method and portable cable winch are also known to be used for *Rhizophora* wood extraction from Matang mangrove forest of Malaysia and in the Sierpe-Terraba mangrove forest of Costa Rica (FAO 1994). Nevertheless, it was observed that harvesting, wood processing, transportation, and replanting operations were the major labor-oriented activities in the management of *R. apiculata* plantations in Yeesarn area. In fact, the forestry operations are reported to be very labor intensive, and in particular it becomes more frequent for felling and extraction of wood from mangroves in Asia and Pacific region (FAO 1994). There is a need to adopt an appropriate felling, and cost-effective harvesting systems are important which could reduce wood harvesting cost without impairing the site. Moreover, the study found that during wood processing, the tree barks are left as waste either in the field or in the kiln site. The bark of *Rhizophora* tree is known a prime resource for various renewable materials (*i.e.* tannin, adhesive) and valuable chemicals (Vetter *et al.* 1996). The study envisaged that there is a need for conducting research on the utilization of *R. apiculata* wood for value added products (*i.e.* tannin, adhesive, pyrolysis oil, and biochemical) production which could maximize the economic benefit of this plantation.

Growth and Biomass Production Patterns

This study examined SD, D_o/DBH, and *H* as a step in the assessment of growth and biomass production patterns of 15 different age groups of *R. apiculata* plantations in Yeesarn.

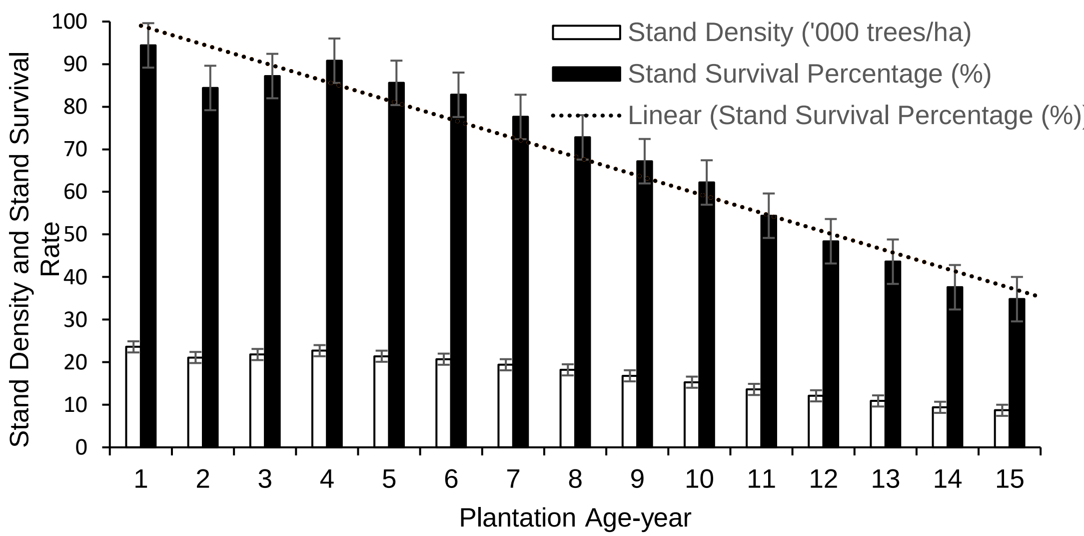

Fig. 3. Stand Density (SD) and Stand Survival Percentage (SSP) of *R. apiculata* Plantations in Yeesarn of Samut Songkram Province

Stand density and stand survival percentage

The study found that SD significantly decreased with the increased age of the *R. apiculata* plantation (R = 0.97). The initially planting density was found to be about 25,000 seedlings/ha. However, the number of seedlings decreased with the increased age of the plantation. SD decreased to 23,600/ha at the end of first year of planting and further dropped to 21,100/ha by the end of second year (Fig. 3).

During the first and second years, stand mortality was high due to the death of the newly-planted propagules. However, in the third and fourth years, the SD had increased slightly due to beating-up practices and new coppice from planted seedlings (propagules). Between 5 and 15 years, the SD gradually decreased due an increase in the mortality rate, and had dropped to about 8700/ha by the fifteenth year. Indeed, *R. apiculata* SD varies considerably with forest types, *i.e.* primary/natural, secondary/plantation (pure stand plantation; mixed stand plantation), and concession mangrove area. For instance, in the Ranong natural mangrove forests of Thailand, the average *R. apiculata* SD is 812 trees/ha (FAO 1994), whereas in *R. apiculata* plantation in Hoa mangrove area of Can Gio district, Vietnam, the SD is about 5220 trees/ha (Quy and Nam 2014); however, in a concession area of Matang mangrove forest, Malaysia, the average *R. apiculata* SD is reported to be about 2425 trees/ha (Ong 1995).

Concerning SSP, the study found that it dropped from 94.4% in the first year to 34.8% in the fifteenth year (Fig. 3). Between the first and fifth year, the average SSP rate was 88.5%, and it plunged to 72.5% between the sixth and tenth years. In the eleventh and fifteenth years, it had dropped to 50% and 33%, respectively. The SSP rate decreased with increased age of the plantation as the competition within the stands for light and nutrients increased, coupled with imperfectly planted propagules, and infestation of the seedlings by crabs, barnacles, and other pests. Similar phenomena were also reported by other studies (Du 1962; Chaiglom 1982; Wechakit 1987).

Diameter and height growth

The D_o of 1- and 2-year old *R. apiculata* plantations was found to be about 1.73 cm and 2.91 cm, respectively (Table 1). The ATR of D_o of 2-year old plantations was 1.45 cm/yr (Table 2). The DBH of 3 to 15-year old *R. apiculata* stands varied between 1.16 and 6.54 cm, and the corresponding ATR of DBH of the stands varied between 0.38 and 0.46 cm/yr. Between the third and fifth years, DBH increased from 1.16 to 2.23 cm, and the ATR was 0.43 cm/yr. Between the sixth and tenth years, the DBH increased from 2.46 to 4.36 cm, while the ATR dropped at 0.41 cm/yr. However, between the eleventh and fifteenth years, the DBH steadily increased from 4.87 to 6.54 cm with a ATR of 0.45 cm/yr. The ATR of DBH was highest in a 14-year old plantation (0.46 cm/yr) and lowest in a 3-year old plantation (0.39 cm/yr). The study found that diameter growth significantly correlated with the height and age of the plantation (R = 0.99 and R = 0.99, respectively); however, it was negatively correlated with stand density (R = -0.99). Similar patterns of DBH growth were also reported by other studies (Wechakit 1987; Kridiborworn *et al.* 2012). Indeed, the DBH growth depends on site conditions, stand density as well as orientation of the silvicultural operations (Aksornkoae 1993). For instances, the DBH of a-3 year old *R. apiculata* plantation in Thua Thien Hue Province of Central Vietnam was observed to be about 4.2 cm (Do *et al.* 2015), whereas in Matang natural mangrove forest in Malaysia, the DBH of a-20 year old *R. apiculata* stand was about 39.0 cm, where the tree grows as mixed stands with a cutting rotation of 30 years (Ong *et al.* 1995).

Table 1. Diameter, Height, and Aboveground Biomass Yield of *R. apiculata* Plantations in Yeesarn of Samut Songkram Province

Age of stands (year)	Do/DBH (cm)	H (m)	AGB (tonnes/ha)					SWV (m^3)	CWV (m^3)
			Stem	Branch	Leaf	Prop root	Total AGB		
1	1.73*	0.51	0.30	0.19	0.28	-	0.77	0.72	-
2	2.91*	1.27	0.87	0.45	0.93	0.31	2.56	1.82	-
3	1.16	1.83	5.76	3.39	2.86	1.76	13.77	4.06	-
4	1.78	2.69	15.35	6.38	4.80	3.67	30.20	11.92	4.73
5	2.23	3.78	27.92	8.84	6.14	5.50	48.40	23.57	17.69
6	2.46	4.51	35.57	10.11	6.78	6.50	58.96	30.98	27.85
7	2.84	5.28	48.52	11.77	7.53	7.91	75.73	44.36	41.59
8	3.25	5.94	62.70	13.52	8.33	9.41	93.96	59.32	57.44
9	3.83	6.65	82.00	15.45	9.13	11.19	117.77	80.74	78.50
10	4.36	7.93	106.57	17.38	9.83	13.12	146.90	109.63	107.04
11	4.87	8.74	121.17	18.00	9.88	13.96	163.01	128.00	125.29
12	5.48	9.87	144.91	19.07	10.1	15.32	189.39	158.80	156.00
13	5.72	10.4	147.40	18.37	9.58	14.98	190.33	164.43	161.81
14	6.38	11.3	159.11	18.29	9.27	15.28	201.95	181.49	178.98
15	6.54	11.5	155.36	17.50	8.81	14.71	196.38	178.20	175.84

*Measurement of D_o instead of DBH

Table 2. ATR (Annual Turnover Rate) of *R. apiculata* Plantations in Yeesarn of Samut Songkram Province

Age of stands (year)	ATR of Do/DBH (cm/yr)	ATR of H (m/yr)	ATR of AGB (ton/ha/yr)					ATR of SWV (m^3/ha/yr)	ATR of CWV (m^3/ha/yr)
			Stem	Branch	Leaf	Prop root	Total		
1	1.73**	0.51	0.30	0.19	0.28	-	0.77	0.72	-
2	1.45**	0.64	0.44	0.23	0.47	0.16	1.28	0.91	-
3	0.39	0.61	1.92	1.13	0.95	0.59	4.59	1.35	-
4	0.44	0.67	3.84	1.60	1.20	0.92	7.55	2.98	1.18
5	0.45	0.76	5.58	1.77	1.23	1.10	9.68	4.71	3.54
6	0.38	0.75	5.93	1.69	1.13	1.08	9.83	5.16	4.64
7	0.40	0.75	6.93	1.68	1.13	1.13	10.82	6.33	5.94
8	0.41	0.74	7.83	1.69	1.04	1.18	11.75	7.41	7.18
9	0.43	0.74	9.11	1.72	1.01	1.24	13.08	8.97	8.72
10	0.44	0.79	10.65	1.73	0.98	1.31	14.69	10.96	10.70
11	0.44	0.79	11.02	1.64	0.90	1.27	14.82	11.64	11.39
12	0.46	0.82	12.08	1.59	0.84	1.28	15.78	13.23	13.00
13	0.44	0.80	11.34	1.41	0.74	1.15	14.64	12.65	12.45
14	0.46	0.80	11.37	1.30	0.66	1.09	14.43	12.96	12.78
15	0.44	0.77	10.36	1.17	0.59	0.98	13.09	11.88	11.72

**ATR of Do instead of DBH

With regard to *H* growth, the study found that it varied between 0.51 and 11.49 m, and the ATR varied between 0.64 and 0.82 m/yr. Between the first and fifth years, *H* increased with a ATR of 0.64 m/yr, and was 0.75 m/yr between the sixth and tenth years. However, between the eleventh and fifteenth years, height growth became stunted, and the ATR was 0.8 m/yr. The highest ATR (0.82 m/yr) was observed in a 14-year old plantation. The study found that H of *R. apiculata* stands significantly correlated with DBH growth

(R = 0.99) and the age of the plantation (R = 0.99); however, it was negatively correlated with stand density (R = -0.98). *H* growth depends on site conditions, stand density, intra and extra-species competition for light and nutrients (Whittaker and Woodwell 1971). Nevertheless, our findings correspond with H growth patterns of *R. apiculata* plantations in many parts of Thailand and Vietnam, however, slightly higher H growth observed in a *R. apiculata* concession area in Matang mangroves of Malaysia (Table 3).

AGB production

Biomass allocation patterns of 1 to 15-year old *R. apiculata* stands are shown in Table 1. The AGB of 1 to 15-year old plantations varied between 0.77 and 201.95 tonnes/ha. The highest AGB production (201.95 tonnes/ha) was observed in a 14-year old plantation. The ATR of AGB varied between 1.28 and 15.78 tonnes/ha/yr and was highest in a 12-year old plantation. Between the first and fourteenth years, the AGB production steadily increased and reached its maximum level. Thereafter, the AGB production trend plunged, indicating that the plantation rotation could be between 14 and 15 years. The AGB production patterns of *R. apiculata* stands in Yeesarn revealed that the plantations have high biomass production potential. The study found that AGB production was significantly correlated with *H*, DBH and age of the stands (R = 0.99, R = 0.99, and R = 0.98 respectively), but was negatively correlated with sand density (R = -0.97).

The AGB consists of stem, branch, leaf, and prop root biomass. In almost all stands, stem comprised the largest proportion, nearly 33-80% (stand average 62.8%) of the total AGB. Stem biomass in 1 to 15-year-old *R. apiculata* stands varied between 0.30 and 159.11 tonnes/ha. Highest stem biomass production was observed in a 14-year old plantation. The ATR of stem biomass production varied from 0.44 to 12.08 tonnes/ha/yr and was greatest in a 12-year old plantation. Between the first and fifth years, the production of stem biomass increased from 0.30 to 27.92 tonnes/ha with an ATR of 2.42 tonnes/ha/yr. Between the sixth and tenth years, stem biomass accumulated at an ATR of 8.09 tonnes/ha/yr, while it was 11.23 tonnes/ha/yr between the eleventh and fifteenth years. The stem biomass production patterns indicated that harvest before 11-years-old may affect the final assortments. Thus, this study argues that the final harvest should not take place before 12 years. However, it was found that stem biomass production significantly correlated with diameter, height, and age of the plantation (R = 0.99, R = 0.99 and R = 0.98, respectively). Similar patterns of stem biomass production in *R. apiculata* plantations were observed by other studies (Table 3).

Furthermore, the volumetric measurement showed that SWV of 1- to 15-year-old plantations varied between 0.72 and 181.5 m^3/ha. The ATR of SWV was 2.13 cm^3/ha/yr between the first and fifth years, and it steadily increased at a rate of 7.77 m^3/ha/yr until 10 years old. Moreover, the study found that between the first and fifth years, SWV production was quite low due to the age and size of the stands, while it steadily increased between the sixth and tenth years, and this latter period can be considered the growing period of the stand. However, the ATR of SWV was 12.47 m^3/ha/yr between the 11^{th} and 15^{th} years. The highest SWV production was observed in a 14-year-old plantation, while the highest ATR of SWV (13.23 m^3/ha/yr) was observed in a 12-year-old plantation. In contrast, the SWV production trend dropped from 181.5 m^3/ha in the 14^{th} year to 178.2 m^3/ha in 15^{th} year, possibly due to natural mortality rates and stunted growth functions of the stands, which would indicate that the plantation becomes mature at 15 years old. Similar patterns of SWV production were also reported in other studies (Table 3). The present study found that SWV production was significantly correlated with DBH, H, and age of the stands (R = 0.99, R =

0.98, and R = 0.97 respectively); however, it was negatively correlated with stand density (R = -0.99).

On the other hand, measurement of *R. apiculata* stands is important for prediction of wood exploitation for charcoal and other end-use products, as well as economic gain to the growers. The CWV of *R. apiculata* stands form an important feedstock supply especially to the farmers who further process the raw wood for charcoal production. In Yeesarn, the farmers exploited *R. apiculata* stands of > 2 cm DBH and this study, therefore, considered this value the threshold level for the estimation of CWV. It was observed that no tree was >2 cm DBH before the age of three years. By four years, only 39.7% of the stands were >2 cm DBH, while by five, six, and seven years, 59.8, 87.9, and 91.2%, respectively, were >2 cm DBH and accounted for 75.1, 89.9, and 93.8% of the stem wood volume in the stands, respectively. However, by the age of 8, 9, 10, 11, 12, 13, 14, and 15 years, the CWV constituted about 96.8, 97.2, 97.6, 97.9, 98.2, 98.4, 98.6, and 98.7% of the stem wood volume of the stand, respectively. The highest CWV production (179.0 m^3/ha) was observed in a 14-year-old plantation, whereas, the highest ATR of CWV (13.23 m^3/ha/yr) was observed in a 12-year-old plantation. This study revealed that CWV in *R. apiculata* stands was significantly correlated with SWV production, DBH, *H*, and age of the stands (R = 1.00, R = 0.99, R = 0.98, and R = 0.97, respectively); however, it was negatively correlated with stand density (R = -0.99). Similar patterns of CWV production in *R. apiculata* stands have been observed by other studies (Wechakit 1987; Kongsangchai *et al.* 1990).

Branches constituted about 9 to 25% (stand average 15.11%) of the total AGB. The largest share of branch biomass (25%) was observed in a 3-year-old plantation, whereas the greatest branch biomass production (19.07 tonnes/ha) was observed in a 12-year-old plantation. The highest ATR of branch biomass (1.77 tonnes/ha/yr) was in a 5-year-old plantation. Between the first and fifth years, the ATR of branch biomass production was 0.98 tonnes/ha/yr, and it steadily increased at an ATR of 1.70 tonnes/ha/yr until 10 years of age. Between the 11^{th} and 15^{th} years, branch biomass production fluctuated between 19.07 and 17.50 tonnes/ha with an ATR of about 1.42 tonnes/ha/yr. Nevertheless, the present study revealed that branch biomass production was significantly correlated with *H*, age, and DBH of the stands (R = 0.95, R = 0.95, and R = 0.93, respectively); however it was negatively correlated with stand density (R = -0.98), indicating that the higher the stand density, the lower the branch biomass production

Nevertheless, the leaf made an amount of 4 to 37.54% (stand average 12.9%) of the total AGB. The leaf biomass in 1- to 15-year-old plantations varied between 0.28 and 10.09 tonnes/ha, and the highest leaf biomass was observed in a 12-year-old plantation. The ATR of leaf biomass varied from 0.47 to 1.23 tonnes/ha/yr and was highest in a five-year-old plantation. Between the first and fifth years, leaf biomass production steadily increased from 0.28 to 6.14 tonnes/ha, with an ATR of 0.83 tonnes/ha/yr, and was 1.06 tonnes/ha/yr between the sixth and 10^{th} years. However, between the 11^{th} and 15^{th} years, the leaf biomass production fluctuated between 8.81 and 10.09 tonnes/ha with an ATR of 0.75 tonnes/ha/yr. The study found that leaf biomass production was significantly correlated with branch, height, age, and DBH of the plantation (R = 0.98, R = 0.90, R = 0.90, and R = 0.89, respectively); however, it was negatively correlation with stand density (R = -0.78). Similar patterns of leaf biomass production in *R. apiculata* plantations were reported by other studies (Table 3).

Indeed, several studies consider prop roots of *R. apiculata* trees a part of AGB (Wechakit 1987; Ong *et al.* 1995; Komiyama *et al.* 2008). This study found that prop roots accounted for 8 to 12% (stand average 9.18%) of the total AGB. Highest prop root biomass production (15.3 tonnes/ha) was observed in a 12-year-old plantation while highest ATR (1.31 tonnes/ha/yr) was observed in a 10-year-old plantation. The results indicate that prop root production is high in young plantations; however, it decreases with increased maturity of the plantation. Similar patterns of prop root biomass production were reported for *R. apiculata* plantations in Nakorn Sri Thammarat Province (Kongsangchai *et al.* 1990).

Table 3. Growth and Aboveground Biomass Yield of *R. apiculata* Pure Stands Reported in the Literature

Parameter of growth/yield	Age of stands (year)	Corresponding value(s)	Study site(s)	Reference(s)
Diameter growth (cm)	3 - 15	0.94 - 6.26	Samut Songkram, Thailand	Wechakit 1987; FAO 1994
	1 - 12	0.69 - 3.41	Samut Songkram, Thailand	Kridiborworn *et al.* 2012
	3	4.2	Thua Thien Hue Province, Vietnam	Do *et al.* 2015
	20	39.0	Matang mangroves, Malaysia	Ong *et al.* 1995
Height growth (m)	1 - 15	0.45 - 12.36	Samut Songkram, Thailand	Wechakit 1987; FAO 1994
	1 - 12	0.47 - 11.39	Samut Songkram, Thailand	Kridiborworn *et al.* 2012
	5 - 20	3.56 - 14.23	Pattani, Thailand	Tanapermpool 1989
	6 - 11	7.73 - 9.76	Nakorn Sri Thammarat, Thailand	Kongsangchai *et al.* 1990
	15	8.0	Phuket, Thailand	Christensen 1978
	3	1.88	Thua Thien Hue Province, Vietnam	Do *et al.* 2015
	20	15.0	Matang mangroves	Ong *et al.* 1995
	Not known	29.5	East Sumatra, Indonesia	Kusmana *et al.* 1992
Stem (tonnes/ha)	1 - 15	0.25 - 199.58	Samut Songkram, Thailand	Wechakit 1987
	9 - 14	93.59 - 174.71	Trang, Thailand	Kongsangchai *et al.* 1990
	20	169.0	Matang mangroves, Malaysia	Ong *et al.* 1995
Branch (tonnes/ha)	1 - 15	0.16 - 20.74	Samut Songkram, Thailand	Wechakit 1987
	5 - 20	3.02 - 21.79	Pattani, Thailand	Tanapermpool 1989
	20	18.4	Matang mangroves, Malaysia	Ong *et al.* 1995
Leaf (tonnes/ha)	1 - 15	0.23 - 11.12	Samut Songkram, Thailand	Wechakit 1987
	6 - 11	6.29 - 10.56	Nakorn Sri Thammarat, Thailand	Kongsangchai *et al.* 1990
	20	6.0	Matang mangroves, Malaysia	Ong *et al.* 1995
Prop root (tonnes/ha)	2 - 15	0.26 - 18.49	Samut Songkram, Thailand	Wechakit 1987

	6 - 11	9.98 - 19.05	Nakorn Sri Thammarat, Thailand	Kongsangchai *et al.* 1990
	20	23.0	Matang mangroves, Malaysia	Ong *et al.* 1995
AGB (tonnes/ha)	1 - 15	0.64 - 239.25	Samut Songkram, Thailand	Wechakit 1987; FAO 1994
	15	159.0	Phuket, Thailand	Christensen 1978
	20	216.4	Matang mangroves	Ong *et al.* 1995
	Not known	216.8	Halmahera, Indonesia	Komiyama *et al.* 1988
SWV (m^3/ha)	4 - 15	0.60 - 233.56	Samut Songkram, Thailand	Wechakit 1987
	5 - 20	14.33 - 197.16	Pattani, Thailand	Tanapermpool 1989
	9 - 14	97.18 - 170.63	Trang, Thailand	Kongsangchai *et al.* 1990
	30	153.0	Matang mangroves, Malaysia	FAO 1994
CWV (m^3/ha)	4 - 15	2.15 - 231	Samut Songkram, Thailand	Wechakit 1987
	9 - 14	91.72 - 170.21	Trang, Thailand	Kongsangchai *et al.* 1990

For any woodland, the assessment of AGB is of great importance because it is relevant for the estimation of carbon storage in the trunk (often called the stem), branches, leaves, and roots. It also provides a measure of net primary production, the efficiency of vegetation to fix energy in different components of the ecosystem (Devi and Yadava 2009). In comparison to inland forests, the estimation of tree biomass for mangrove species is rather difficult due to muddy soil conditions, inaccessibility, and highly labor-intensive work (Komiyama *et al.* 2008). Until now little data on biomass yield and productivity of *R. apiculata* plantations has been available. Table 3 represents the most relevant available data on growth and yield of *R. apiculata* stands reported in the literature, which correspond with the current findings. Indeed the AGB of *R. apiculata* plantation and forest varied considerably with site conditions and forest types (Komiyama *et al.* 2008). For instances, the AGB in a *R. apiculata* dominated natural forest was reported to be about 460 tonnes/ha in Malaysia (Putz and Chan 1986), whereas about 300 tonnes/ha was reported in mangrove forests in Indonesia (Komiyama *et al.* 1988) and French Guiana (Fromard *et al.* 1998). Komiyama *et al.* (2008) stated that the AGB in most *R. apiculata* secondary forests and concession areas is nearly 100 tonnes/ha. In these contexts, *R. apiculata* plantations in Yeesarn area provides a high AGB production if the cutting rotation (8 to 15 years) is taken into consideration. However, comparatively a lower AGB is also reported in primary mangrove forests in high latitude areas (above 24° 23´ N or S) and low temperate areas might be due to climatic conditions, such as temperature, solar radiation, precipitation, and frequency of storms (Komiyama *et al.* 2008).

The partitioning of biomass allocation of different organs of *R. apiculata* stands vary with age, stand density, and site conditions. Ong *et al.* (1995) found that the stem, branches, leaf, prop roots, and fine roots in a typical 20-year-old *R. apiculata* tree accounted for 74%, 8%, 3%, 10%, and 5% of the total biomass, respectively. The fine roots are generally considered as below ground biomass. However, this study did not measure the biomass of fine roots, since the focus was on the AGB estimation. Apart from fine roots, is was found that the stem, branches, leaf, and prop roots constituted about 79%, 9%, 4%, and 8% of the total AGB in a 15-year-old *R. apiculata* plantation, respectively, which are consistent with the findings of Ong *et al.* (1995). Previous studies revealed that leaf biomass comprised the small portion, ranged from 0.4 to 29.8 tonnes/ha (Komiyama *et al.* 1988). The ratio of leaf biomass and stem biomass in mature *R. apiculata* stands is quite low, and the ratio decreases with increases the age of the stands (Komiyama *et al.* 1988; Ong *et al.* 1995). It was found that the ratios of leaf biomass and stem biomass were 13.3, 11.1, 9.2, 8.2, 7.0, 6.5, 5.8, and 5.6 in 8-, 9-, 10-, 11-, 12, 13-, 14-, and 15-year-old stands, respectively, which corresponded with the previous findings.

Biomass Estimation Models

Allometric equations are quite useful to estimate biomass and subsequent growth for mangroves because tree weight measurement in mangrove forests is labor-intensive. The allometric equations could be developed for estimating the whole or partial weight of a tree from measurable tree dimensions, including *H* and DBH. Along with *H* and DBH, other parameters such as age and stand density could have an effect in the estimation of AGB and biomass of other organs of *R. apiculata* stands. Inclusion of these parameters in the biomass estimation models could be important. However, the linear regression analysis showed that some of the parameters, such as *H* and DBH, are critically important parameters for estimation of stem biomass, branch biomass, leaf biomass, prop root biomass, AGB, SWV, and CWV. Based on *H* and DBH measurement of the stands, we constructed biomass estimation models for *growing and sapling phase stands i.e.* 3 to 7 age-class group (Table 4a), and for *developing and mature phase stands i.e.* 8 to 15 age-class group (Table 4b).

Table 4a. Results of Allometric Relationships between Dry weight of Biomasses, H and DBH of 3- to 7-year-old *R. apiculata* Stand

Biomass part	Models (Allometric equations)	R	R^2	p-value
Stem biomass	13.316 *H* + (-2.653 DBH) + 0.995	0.997	0.993	0.007
Branch biomass	0.289 *H* + (4.456 DBH) + 1.000	0.999	0.999	0.001
Leaf biomass	-0.419 *H* + (3.716 DBH) + 0.994	0.998	0.995	0.005
Prop root biomass	0.813 *H* + (1.992 DBH) + 1.000	1.000	1.000	0.000
AGB	14.000 *H* + (7.510 DBH) + 1.000	0.999	0.998	0.002
SWV	14.985 *H* + (-7.794 DBH) + 0.990	0.994	0.987	0.013
CWV	24.007 *H* + (-25.644 DBH) + 0.976	0.994	0.988	0.012

Table 4b. Results of Allometric Relationships between Dry weight of Biomasses, H and DBH of 8- to 15-year-old *R. apiculata* Stand

Biomass part	Models (Allometric equations)	R	R^2	p-value
Stem biomass	34.142 *H* + (-29.873 DBH) + 0.985	0.990	0.980	0.000
Branch biomass	3.897 *H* + (-5.579 DBH) + 0.798	0.845	0.714	0.044
Leaf biomass	3.737 *H* + (-5.760 DBH) + 0.851	0.698	0.487	0.000
Prop root biomass	3.407 *H* + (-4.285 DBH) + 0.918	0.938	0.879	0.005
AGB	43.243 *H* + (-42.745 DBH) + 0.977	0.983	0.966	0.000
SWV	36.413 *H* + (-25.196 DBH) + 0.992	0.995	0.991	0.000
CWV	35.599 *H* + (-23.913 DBH) + 0.993	0.996	0.991	0.000

The construction of biomass estimation models in accordance to age-class groups could be useful because such models could provide better accurate estimation and even could help in forest biomass estimation in future by means of subsequent measurements due to temporal changes of the forest conditions.

In the biomass estimation models (Tables 4a and 4b), each model represents the corresponding R (correlation coefficient), R^2 (coefficient of determination), and level of significance (p-value), indicating their fitness. Most of the models seemed to have performed well since all they provided high R and R^2 values. However, the AGB estimation models for both age groups were quite relevant, since the models are highly significant (p-values < 0.01 at a 95% confidence level). The applicability of these models are quite practical since they are non-destructive in nature and less tedious for statistical evaluation. Nevertheless, this study did not employ biomass estimation models for 1 and 2-year old *R. apiculata* stands because they were not seen to be exploited for charcoal production or any other commercial purpose.

Several studies have developed allometric equations to estimate biomass and carbon sequestration from mangrove tree species, and most of them have focused on allometric equations for single-stemmed trees (Komiyama *et al.* 2008). This study developed allometric equations for single stemmed trees since most of *R. apiculata* stands in Yeesarn area produce single-stemmed tree. Perhaps one of the reason might be that the farmers plant initially a high number of seedlings per unit area so that the seedlings do not have much room for branching and/or multi-stemmed tree form. Nevertheless, the allometric models often show site and/or species-specific dependency (Smith III and Whelan 2006).

Clough *et al.* (1997) found that the allometric equations of a particular mangrove species revealed different relationships in different sites. Ong *et al.* (2004) reported that similar allometric equations applied in two different sites for *R. apiculata* produced different relationships, which indicates that site-specific trait of allometric equations remains contentious. Further, a recent study found that allometric equations can differ substantially for primary (natural forest) and secondary forest (regenerated/ plantation forest) in AGB estimations (Majid and Nurudin 2015). Thus, these issues need to be taken into account while applying the above allometric equations for AGB estimations of *R. apiculata* tree or other *Rhizophora* species in different sites.

The present study had some limitations, such as limited number of sampling sites, and the absence of allometric equation for root biomass estimation. The latter is important for determining the NPP and NEP to estimate carbon fixation model in the mangrove plantation.

Thus, further studies on the allometric relationship of *R. apiculata* tree roots are still needed. Nevertheless the results obtained from our study will directly aid in the prediction of yields, forecasts of raw wood supply, and in the formulation of strategies on mangrove plantation/wood charcoal production dynamics from an end-user perspective. Furthermore, the study is useful in the development of micro-plans for coastal wetland management, mangrove restoration, sustainable farm-forestry, and renewable energy promotion at local, regional, and national levels in Thailand and in other tropical countries in the world.

CONCLUSIONS

1. The silvicultural system adopted in the *R. apiculata* mangrove plantations in the Yeesarn area is a clear-felling system with a cutting rotation between 8 and 15 years. The main objective for growing this mangrove plantation is to produce wood charcoal. The farmers apply their local (traditional) knowledge in the establishment and harvesting of this plantation. They often collect seedlings locally and plant them with a high initial planting density, aiming to ensure the presence of sufficient tree numbers during final harvesting as well as to maximize the wood biomass yield. Beating-up and weeding are the main post-planting maintenance activities of the plantation. Thinning operations are not practiced until the final harvest since they involve high labor costs, less sales from thinning products, inaccessibility, and unsuitable site conditions. Nevertheless, this study envisaged that the establishment of a seed production area with mature *R. apiculata* trees for supply of seedlings; demonstration of long-term field trials with appropriate planting densities; and examining the effectiveness of thinning operations are some of interventions that could promote more effective management of *R. apiculata* mangrove plantations in the Yeesarn area.
2. This plantation was found to have a high yield potential in regard to AGB, SWV and CWV production. The growth and productivity patterns reveal that the ATR of *H* and DBH of *R. apiculata* stands become highest at 12 years old, while the AGB SWV and CWV maximize when the stands attain 14 years of age. Thus, wood harvesting before 11 years old could affect the growth and productivity of the wood biomass and volume. Therefore, an appropriate cutting cycle should be considered in order to allow the trees to grow and to maximize the yield. This study envisages that the cutting rotation for *R. apiculata* plantations in Yeesarn area could be the best in between 12 and 15 years.
3. The study constructed biomass estimation models for 3 to 7 age-class and 8 to 15 age-class groups, which could provide more accurate estimation. The allometric models produced in this study could be useful since the model fitted well to the data. The models could be useful in forecast of raw wood supply as well as estimation of AGB, SWV, CWV, and different parts of R. *apiculata* tree not only in the Yeesarn area but also to other areas. However, species-specific and site-specific traits as well as type forest (*i.e.* natural or plantation, *etc.*) need to be considered while applying these allometric equations to other sites.

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REFERENCES CITED

Abuodha, P. A. W., and Kairo, J. G. (2001). "Human-induced stresses on mangrove swamps along the Kenyan coast," *Hydrobiologia* 458(1-3), 255-265. DOI: 10.1023/A:1013130916811

Aksornkoae, S. (1993). *Ecology and Management of Mangroves*, International Union for Conservation of Nature & Natural Resources, Bangkok, Thailand.

Bandaranayake, W. M. (1998). "Traditional and medicinal uses of mangroves," *Mangroves and Salt Marshes* 2(3), 133-148. DOI: 10.1023/A:1009988607044

Bosire, J. O., Dahdouh-Guebas, F., Walton, M., Crona, B. I., Lewis III, R. R., Field, C., Kairo, J. G., and Koedam, N. (2008). "Functionality of restored mangroves: A review," *Aquat. Bot.* 89(2), 251-259. DOI: 10.1016/j.aquabot.2008.03.010

Cannicci, S., Burrows, D., Fratini, S., Smith III, T. J., Offenberg, J., and Dahdouh-Guebas, F. (2008). "Faunal impact on vegetation structure and ecosystem function in mangrove forests: A review," *Aquat. Bot.* 89(2), 186-200. DOI: 10.1016/j.aquabot.2008.01.009

Chaiglom, D. (1982). "Biological and ecological studies of insects in mangrove forests," in: *Proceedings of NRCT- JSPS Rattanakosin Bicentennial Joint Seminar on Science and Mangrove Research*, Phuket, Thailand, pp. 227-229.

Chan, H. T. (1990). *Proposed Establishment and Management of Mangrove Plantation in the Duyen Hai District, South Vietnam* (Report No. VIE/86/027), FAO, Rome, Italy.

Chan, H. T. (2014). "Some topic of research interest in the Matang Working Plan (2010–2019)," *ISME/GLOMIS Electronic Journal* 12(2), 6–8.

Chantarasena, T. (1985). *Charcoal Making and Quality of Charcoal from Mangrove Timbers by Small Brick Kiln*, Master's Thesis, Kasetsart University, Bangkok, Thailand.

Christensen, B. (1978). "Biomass and primary productivity of *Rhizophora apiculata* BI. in a mangrove in southern Thailand," *Aquat. Bot.* 4, 43-52. DOI: 10.1016/0304-3770(78)90005-0

Clough, B. F., Dixon, P., and Dalhaus, O. (1997). "Allometric relationships for estimating biomass in multi-stemmed mangrove trees," *Aust. J. Bot.* 45, 1023-1031.

Devi, L. S., and Yadava, P. S. (2009). "Aboveground biomass and net primary production of semi-evergreen tropical forest of Manipur, northeastern India," *J. Forestry Res.* 20(2), 151-155. DOI: 10.1007/s11676-009-0026-y

Din, N., Saenger, P., Jules, P. R., Siegried, D. D., and Basco, F. (2008). "Logging activities in mangrove forests: A case study of Douala Cameroon," *African Journal of Environmental Science and Technology* 2(2), 22-30.

Do, T. V., Dung, P. N., Kozan, O., and Thang, N. T. (2015). "Nursery techniques and primary growth of *Rhizophora apiculata* plantation in coastal area, Central Vietnam," *Annual Research & Review in Biology* 6(6), 401-408. DOI: 10.9734/ARRB/2015/16843

Du, L. V. (1962). "Ecology and silviculture of mangrove," *Yale University School of Forestry*, 28.

FAO (1994). *Mangrove Forest Management Guidelines* (FAO Forestry Paper 117), FAO Forestry Department, Rome, Italy.

Fromard, F., Puig, H., Mougin, E., Marty, G., Betoulle, J. L., and Cadamuro, L. (1998). "Structure aboveground biomass and dynamics of mangrove ecosystems: New data from French Guiana," *Oecologia* 115, 39-53.

Garcia, K., Malabrigo, P., and Gevaña, D. (2014). "Philippines' mangrove ecosystem: Status, threats and conservation," in: *Mangrove Ecosystems of Asia*, I. Faridah-Hanum, A. Latiff, K. R. Hakeem, and M. Ozturk (eds.), Springer, New York, NY, pp. 81-94.

Gillis, L. G., Belshe, E. F., and Narayan, G. R. (2017). "Deforested mangroves affect the potential for carbon linkages between connected ecosystems," *Estuar. Coast.* 40(4), 1207–1213. DOI: 10.1007/s12237-017-0210-9

Giri, C., Long, J., Abbas, S., Murali, R. M., Qamer, F. M., Pengra, B., and Thau, D. (2015). "Distribution and dynamics of mangrove forests of South Asia," *J. Environ. Manage.* 148, 101-111. DOI: 10.1016/j.jenvman.2014.01.020

Giri, C., Ochieng, E., Tieszen, L. L., Zhu, Z., Singh, A., Loveland, T., Masek, J., and Duke, N. (2011). "Status and distribution of mangrove forests of the world using earth observation satellite data," *Global Ecol. Biogeogr.* 20(1), 154-159. DOI: 10.1111/j.1466-8238.2010.00584.x

Goessens, A., Satyanarayana, B., Van der Stocken, T., Zuniga, M. Q., Mohd-Lokman, H., Sulong, I., and Dahdouh-Guebas, F. (2014). "Is Matang mangrove forest in Malaysia sustainably rejuvenating after more than a century of conservation and harvesting management?" *PLoS One* 9(8). DOI: 10.1371/journal.pone.0105069

Hashim, R., Kamali, B., Tamin, N. M., and Zakaria, R. (2010). "An integrated approach to coastal rehabilitation: Mangrove restoration in Sungai Haji Dorani, Malaysia," *Estuar. Coast. Shelf-S.* 86(1), 118-124. DOI: 10.1016/j.ecss.2009.10.021

Iftekhar, M. S., and Islam, M. R. (2004). "Managing mangroves in Bangladesh: A strategy analysis," *J. Coast. Conserv.* 10, 139-146.

Kaly, U. L., and Jones, G. P. (1998). "Mangrove restoration: A potential tool for coastal management in tropical developing countries," *Ambio* 27(8), 656-661.

Kathiresan, K. (2012). "Importance of mangrove ecosystem," *International Journal of Marine Science* 2(10), 70-89. DOI: 10.5376/ijms.2012.02.0010

Kathiresan, K., and Rajendran, N. (2002). "Growth of a mangrove (*Rhizophora apiculata*) seedlings as influenced by GA_3, light and salinity," *Rev. Biol. Trop.* 50(2), 525-530.

Komiyama, A., Kongsangchai, J., Patanaponpaiboon, P., Aksornkoae, S., and Ogino, K. (1992). "Socio-ecosystem studies on mangrove forests – Charcoal industry and primary productivity of secondary stands," *Tropics* 1(4), 233-242.

Komiyama, A., Moriya, H., Prawiroatmodjo, S., Toma, T., and Ogino, K. (1988). "Forest primary productivity," in: *Biological System of Mangrove*, K. Ogino, and M. Chihara (eds.), Ehime University, Matsuyama, Japan, pp. 97–117.

Komiyama, A., Ong, J. E., and Poungparn, S. (2008). "Allometry, biomass, and productivity of mangrove forests: A review," *Aquat. Bot.* 89(2), 128-137. DOI: 10.1016/j.aquabot.2007.12.006

Kongsangchai, J., Tanapermpool, P., Havanond, S., and Jintana, V. (1990). *Report on Productivity of Mangrove Forest Plantation in Thailand*, Royal Forest Department, Bangkok, Thailand.

Kridiborworn, P., Chidthaisong, A., Yuttitham, M., and Tripetchkul, S. (2012). "Carbon sequestration by mangrove forest planted specifically for charcoal production in Yeesarn, Samut Songkram," *Journal of Sustainable Energy & Environment* 3, 87-92.

Kusmana, C., Sabiham, S., Abe, K., and Watanabe, H. (1992). "An estimation of above ground tree biomass of a mangrove forest in East Sumatra, Indonesia," *Tropics* 1(4), 243-257. DOI: 10.3759/tropics.1.243

Lee, S. Y., Primavera, J. H., Dahdouh-Guebas, F., McKee, K., Bosire, J. O., Cannicci, S., Diele, K., Fromard, F., Koedam, N., Marchand, C., *et al*. (2014). "Ecological role and services of tropical mangrove ecosystems: A reassessment," *Global Ecol. Biogeogr.* 23(7), 726-743. DOI: 10.1111/geb.12155

Lugo, A. E. (2002). "Conserving Latin American and Caribbean mangroves: Issues and challenges," *Madera y Bosques* 8, 5-25. DOI: 10.21829/myb.2002.801289

Majid, S. A., and Nurudin, A. A. (2015). "Aboveground biomass and carbon stock estimation in logged-over lowland tropical forest in Malaysia." *International Journal of Agriculture, Forestry and Plantation* 1, 1-13.

Mukherjee, N., Dahdouh-Guebas, F., Kapoor, V., Arthur, R., Koedam, N., Sridhar, A., and Shanker, K. (2010). "From bathymetry to bioshields: A review of post-tsunami ecological research in India and its implications for policy," *Environ. Manage.* 46(3), 329-339. DOI: 10.1007/s00267-010-9523-1

Nam, V. N., My, T. V., and Jensen, M. (1993). *Mangrove for Production and Protection. A Changing Resource System: Case Study in Can Gio District, Southern Vietnam* (Field Document No. 43), FAO, Bangkok, Italy.

Ong, J. E., Gong, W. K., and Clough, B. F. (1995). "Structure and productivity of a 20-year-old stand of *Rhizophora apiculata* B1 mangrove forests," *J. Biogeogr.* 22, 417-427.

Ong, J. E., Gong, W. K., and Wong, C. H. (2004). "Allometry and partitioning of the mangrove, *Rhizophora apiculata*," *Forest Ecol. Manag.* 188(1-3), 395-408. DOI: 10.1016/j.foreco.2003.08.002

Paphavasit, N., Nishihira, M., Piuumsomboon, A., and Sudtongkong, C. (1997). "Historical aspect of Samut Songkhram mangrove swamp: From natural forest to mangrove plantations," in: *Benthic Communities and Biodiversity in Thai Mangrove Swamps*, M. Nishihira (ed.), Tohoku University, Sendai, Japan, pp. 205-218.

Paul, B. G., and Vogl, C. R. (2011). "Impacts of shrimp farming in Bangladesh: Challenges and alternatives," *Ocean Coast. Manage.* 54(3), 201-211. DOI: 10.1016/j.ocecoaman.2010.12.001

Pranchai, A. (2017). "Regeneration and self-thinning processes in a restored *Rhizophora apiculata* plantation in southern Thailand," *Agriculture and Natural Resources*. DOI: 10.1016/j.anres.2017.11.004

Primavera, J. H., and Esteban, J. M. A. (2008). "A review of mangrove rehabilitation in the Philippines: Successes, failures and future prospects," *Wetl. Ecol. Manag.* 16(5), 345-358. DOI: 10.1007/s11273-008-9101-y

Pumijumnong, N. (2014). "Mangrove forests in Thailand," in: *Mangrove Ecosystems of Asia*, I. Faridah-Hanum, A. Latiff, K. R. Hakeem, and M. Ozturk (eds.), Springer, New York, NY, pp. 61-79.

Putz, F. E., and Chan, H. T. (1986). "Tree growth, dynamics, and productivity in a mature mangrove forest in Malaysia," *Forest Ecol. Manag.* 17(2-3), 211-230. DOI: 10.1016/0378-1127(86)90113-1

Quy, P. V., and Nam, V. N. (2014). "Effects of thinning on CO_2 absorption capacity of *Rhizophora apiculata* plantations in Can Gio Mangroves," in: *Studies in Can Gio Mangrove Biosphere Reserve, Ho Chi Minh City, Vietnam*, H. T. Chan, and M. Cohen (eds.), Tohoku University, Sendai, Japan, pp. 47-49.

Smith III, T. J., and Whelan, K. R. T. (2006). "Development of allometric relations for three mangrove species in south Florida for use in the Greater Everglades Ecosystem restoration," *Wetl. Ecol. Manag.* 14(5), 409-419. DOI: 10.1007/s11273-005-6243-z

Spalding, M., Kainuma, M., and Collins, L. (2010). *World Atlas of Mangroves*, Routledge, Abingdon, UK.

Tanapermpool, P. (1989). *Productivity of Rhizophora apiculata Plantation in Changwat Pattani*, Master's Thesis, Kasetsart University, Bangkok, Thailand.

TMDB (2016). "Annual weather summary over Thailand in 2016," *Thai Meteorological Department-Bangkok (TMDB),* (https://www.tmd.go.th/programs/uploads/yearlySummary/weather2016.pdf), Accessed 31 January 2018.

Valiela, I., Bowen, J. L., and York, J. K. (2001). "Mangrove forests: One of the world's threatened major tropical environments," *Bioscience* 51(10), 807-815.

Vetter, R. E., Barbosa, A. P. R. (1995). "Mangrove bark: A renewable resin source for wood adhesives," *Acta Amazonica* 25(1/2), 69-72.

Walters, B. B. (2005). "Patterns of local wood use and cutting of Philippine mangrove forests," *Econ. Bot.* 59(1), 66-76.

Wechakit, D. (1987). *Growth and Survival of Private Mangrove Plantation (Rhizophora apiculata) at Amphoe Amphawa, Changwat Samut Songkram,* Master's Thesis, Kasetsart University, Bangkok, Thailand.

Whittaker, R. H., and Woodwell, G. M. (1971). "Measurement of net primary production of forest," in: *Productivity of Forest Ecosystems. Proceedings of the Brussels Symposium Organized by Unesco and the International Biological Programme*, Brussels, Belgium, pp. 159-175.

Wolanski, E., Spagnol, S., Thomas, S., Moore, K., Alongi, D. M., Trott, L., and Davidson, A. (2000). "Modelling and visualizing the fate of shrimp pond effluent in a mangrove-fringed tidal creek," *Estuar. Coast. Shelf-S.* 50(1), 85-97. DOI: 10.1016/ecss.1999.0535

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