Universal Journal of Agricultural Research 10(4): 305-330, 2022 http://www.hrpub.org
DOI: 10.13189/ujar.2022.100401

The Aboveground Biomass Allometry and Carbon Stocks of Serial Age Planted *Rhizophora apiculata* in Northern Sumatra, Indonesia

Bambang Suprayogi[1], Joko Purbopuspito[2], Meilinda S. Harefa[3], Grace Y. Panjaitan[1], Zulkifli Nasution[4]

[1]Yagasu Aceh Foundation, Medan, Indonesia
[2]Department of Soil, Faculty of Agriculture, Sam Ratulangi University, Menado, Indonesia
[3]Department of Geography, Faculty of Social Sciences, Universitas Negeri Medan, Medan, Indonesia
[4]Department of Biology, Universitas Sumatera Utara, Medan, Indonesia

Received February 15, 2022; Revised June 18, 2022; Accepted July 17, 2022

Cite This Paper in the Following Citation Styles

***(a):** [1] Bambang Suprayogi, Joko Purbopuspito, Meilinda S. Harefa, Grace Y. Panjaitan, Zulkifli Nasution , "The Aboveground Biomass Allometry and Carbon Stocks of Serial Age Planted Rhizophora apiculata in Northern Sumatra, Indonesia," Universal Journal of Agricultural Research, Vol. 10, No. 4, pp. 305 - 330, 2022. DOI: 10.13189/ujar.2022.100401.*

***(b):** Bambang Suprayogi, Joko Purbopuspito, Meilinda S. Harefa, Grace Y. Panjaitan, Zulkifli Nasution (2022). The Aboveground Biomass Allometry and Carbon Stocks of Serial Age Planted Rhizophora apiculata in Northern Sumatra, Indonesia. Universal Journal of Agricultural Research, 10(4), 305 - 330. DOI: 10.13189/ujar.2022.100401.*

Abstract The biomass and carbon stocks of 2, 6 and 10 year planted mangroves were studied through destructive method of weighting each tree component. The objective was to establish new allometries and carbon production of *R. apiculata.* Two aboveground biomass allometries of *R. apiculata* have been developed based on D_{30} ($AGB_D = 0.1224\ D_{30}^{2.3380}$) and D_{30}^2H ($AGB_{DH} = 0.1508\ D_{30}^2H^{0.7793}$). Accuracy level of aboveground biomass estimation was 85.40% to the actual values of destructive calculation. Each biomass allometric equation can be applied accurately when the estimated mangrove ecosystem has similarity in species, age, tree-density, wood-density and growth factors of mangrove ecosystem where allometry is established. The allometric equation of above-ground carbon stock $AGC_D = 0.0368D_{30}^{2.5996}$ (based on stem diamater) and $AGC_{DH} = 0.0422D_{30}^2H^{0.8730}$ (based on combined stem diameter and tree height) can be used to estimate the *R. apiculata* carbon stocks of non-destructive measurement. However, the accuracy level of AGC_D and AGC_{DH} allometries used to estimate non-destructive *R. apiculata* carbon stocks was 60.14% and 79.72% to the actual carbon value of destructive study. The average aboveground carbon stocks of 2 – 10 year *R. apiculata* were 37.2 MgC ha^{-1} (destructive actual value), 30.2 MgC ha^{-1} (D_{30}^2H), and 29.9 MgC ha^{-1} (D_{30}) respectively. It is concluded that the estimated allometric values of aboveground biomass and carbon productions of restored mangroves are closely related to the growth of stem diameter and tree height, but its values are lower than destructive actual value.

Keywords Aboveground Biomass, Allometry, Carbon Stocks, Restored Mangroves, Carbon Sequestration. Rhizophora Apiculata

---

1. Introduction

Rhizophora apiculata species was mostly used to restore degraded mangroves in Northern Sumatra, Indonesia for global climate change mitigation program. Biomass study based on individual species and serial age of mangrove plays an important role in tracking changes of the vegetation carbon stock. Allometries to estimate biomass of mangrove species- and site specific have been established in many countries. Most of biomass, allometry and carbon studies were carried out in un-known ages and in natural mangrove forests [1]; [2]; [5]; [6]; [10] - [14]. However, there was little known about biomass and carbon stocks of serial age restored mangroves and only a few studies on restored or replanted mangroves [15]. A study on single age of replanted mangroves in Kenya showed the 12-year *Rhizophora mucronata* producing standing biomass of 106.7 ± 24.0 ton ha^{-1} with accumulation rate of 8.9 ton ha^{-1} yr^{-1} [16].

Mangrove ecosystem can store more carbon (C-stocks) than other plantations because mangrove can grow faster than other species and the *ecosystem* has more underground organic materials [17]. Mangrove ecosystem has almost double amount of carbon stocks compared to the other tropical forest ecosystems. The high productivity of old trees shows the ability of mature mangroves to accumulate and store carbon in vegetation and sediment.

CO_2 in atmosphere as well as water and nutrients from the soil are absorbed by mangroves. Within a help of sunlight for photosynthesis those components are converted into carbohydrates for tree growth. Photosynthesis in mangroves *involves* a complex process and is strongly influenced by physical-chemical factors of sediment and local climate. The mangrove C-stocks resulting from photosynthetic process and its sequestration are needed for identification of long-term dynamic of coastal-land management that contribute to global climate change mitigation. However, mangrove ecosystem is also fragile facing land-use change and produce CO_2 emissions when the trees are cut and cleared [19]; [20].

Global climate change also threatens mangrove ecosystems with the rising sea levels, changes in sea wave intensity and tropical storms, and changes in river flow towards mangrove ecosystems [21]. An increase in air temperature of 0.9°C will limit mangrove growth and change the composition of mangrove species, as well as affect microbial decomposition and decrease sedimentation processes [22]. The productivity of plant biomas in the estuarine area will also change as it has to respond to changes in time and the amounts of fresh water, nutrients and sediments.

The process of accumulating C in leaves, fruits, flowers, stems, branches, twigs, stumps and proop-roots is called the sequestration process of carbon. This sequestration involves carbon capture and storage of carbon dioxide (CO_2) for a long time [23]. The CO_2 sequestration of mangrove ecosystem stored in the biomass of plant components is called vegetation carbon stock.

Rhizophora apiculata was a majority species used for mangrove restoration in the Northern Sumatra, Indonesia. After several years of restoration, the natural *succession* of other species has grown on restoration sites. However, the field observation on each sub-plot showed the *R. apiculata* was the mostly dominant species. Therefore, this species was chosen for this destructive study.

The destructive method was applied to the 2, 6 and 10-year planted *R. apiculata*. Each trees' component such as leaves/fruits/flowers, stems, branches, twigs, stumps and proop-roots was separately weighed in the field. The collected samples were analysed for carbon fractions in the laboratory. Two allometries with independent variable tree Diameter (D_{30}) and combined quadratic D_{30} and Height (D_{30}^2H) were established. Those allometries were used as references for non-destructive biomass and carbon stock estimation that was carried out parallely with this destructive study. Moreover, the carbon stocks estimated by destructive allometry were compared with direct calculation through destructive data in order to understand an accuracy level of estimation.

2. Materials and Method

Study sites

The 2, 6 and 10-year planted mangroves in the East Coast of North Sumatra province – Indonesia were selected for destructive study. Two sites in Sei Meran village of Langkat district that lie at the GPS site of 04°06'41.01"N - 098°12'18.39"E and 04°05'14.37"N - 098°10'40.91"E were chosen representing 2-year and 6-year restored mangroves; while one site in Tanjung *Rejo* village that geographically locates at 03°45'20.70"N - 098°45'27.58"E representing 10-year mangroves (Annex 1).

Secondary data on climate parameters during the last 30 years in study sites were collected from local climate institution. The air temperature ranged from 26.4 ± 0.2 to 27.3 ± 0.2^{0}C; average air humidity from 83.3 ± 0.6 to 84.8 ± 0.5%; sun radiation intensity from 52.7 ± 1.6 to 57.5 ± 2.6% and annual precipitation from 1,927.8 ± 345.8 to 2,245.7 ± 371.0 mm yr^{-1}.

Plant culture

To obtain plant materials for field measurement, mangrove seedlings of equal age were propagated and transplanted into ponds prior to field samplings. Propagules of *Rhizophora apiculata* were collected from the nearest planting sites. When seedlings were 3 – 4 months old, then they were transplanted into study sites. The mangrove seedlings were planted in the middle of ponds to ensure all plants were covered by intertidal zones. The planted trees were designed in the same distance between one to another to ensure each plot had similar density at the beginning of planting time. After several years, each site of planted mangroves performed a variety of vegetation compositions and structures.

Sampling, measurement and data analysis

To represent each mangrove age, 5 plots were established along randomly transect in which the size of each plot was 100 m^2 (5.64 m radius), and tree component of each plot can be seen in Annex 2. Species composition, tree density, basal *area* and important value index were measured at each plot. Four species of *Avicennia marina*, *Bruguiera sexangula*, *Sonneratia alba* and *Sonneratia caseolaris* grew naturally where each plot had a variety natural growth species. The important value index of 6-year (260.9%) is the highest compared to 10-year (220.1%) and 2-year (123.7%) planted *R. apiculata*. All tree species inside the plots were measured for stem diameter, tree height, basal area and root/shoot ratio for destructive method applied (Annex 3).

Field findings showed *R. apiculata* dominating in all sub-plots (Annex 4). Only two trees of 2-year *Sonneratia caseolaris* were found among 197 trees in the destructive sub-plots. Therefore, the destructive study was focused on *R. apiculata* only. Biomass samplings were conducted at 3 sub-plots (on the size of ¼ plot or 25 m^2) at the *destructive* plot number 2, 3 and 4. The stem diameter 30 cm above the highest prop-roots (D_{30}) was recorded for each tree. Each multi-stemmed tree was treated individually. Each tree was measured for its height - from land-base to the top of canopy. Then, each vegetation component (leaves/fruits/flowers, twigs, branches, stems, stumps and proop-roots) were collected for separated wet-weight measurement. Dead woods were also collected and measured for above-ground biomass calculation.

The wet-weight samples (± 250 g) of each vegetation component were collected and put into plastic bags before oven-dried at 70 - 80^0C for *constant* weight. Samples from all tree components were collected proportionally to the sub-plots and trees. Therefore, representatives of all ages and tree components were available.

In the laboratory, carbon fraction of each *tree* component from 45 selected trees was analysed using *wet method* of Walkley & Black and *dried method* of Dry Combustion. The wet method was conducted at the RISPA laboratory – Medan, while the dried method was conducted at IPB Soil Biotechnology laboratory - Bogor. Then, the wet and dried weight ratio was calculated to obtain total dry weight estimation for each biomass portion.

All data collected from the field were calculated using Excel software package. Linear and multiple regression were established for further data analysis. Comparisons between mean data ($p<0.05$) were analysed using the Excel Statistical package. Two types of allometric formulas were established: (a) $AGB_D = a (D_{30})^b$ for independent variable tree Diameter and (b) $AGB_{DH} = a (D_{30}{}^2H)^b$ for combined quadratic of tree Diameter and tree Height. Wood density was not included in those allometric equations because the dry-wight of each component was measured directly through destructive method and its value was assumed equal to 1.00.

3. Results and Discussion

Growth parameters

Stem diameter, tree height and tree age were *significantly* correlated. Therefore, the tree age can be used to estimate stem diameter and tree height, and vice-versa (Table 1).

Correlation between stem diameter and tree age was high (97.40%). Therefore, the linear regression $D_{30} = 0.36A + 3.22$ was preferably used to estimate tree biomass. In addition, the regression $H = 0.59D_{30} + 2.89$ was worthy of being considered to estimate the tree height when we have stem diameter data of the dense vegetation in the field. Even though the correlation between the tree height and tree age was the highest (98.20%), the tree height regression $H = 0.58A + 0.70$ was rarely used due to wide variation of tree high growth among species and individual tree at different locations.

Table 1. Correlative equations among *R. apiculata* growth parameters and tree age

(Determination coefisien, R^2)	Linear regression of each variable
0.97	D_{30} (stem Diameter, cm) = 0.36A (tree Age, yr) + 3.22; n = 197
0.98	H (tree Height, m) = 0.58A (tree Age, yr) + 0.70; n = 197
0.91	H (tree Height, m) = 0.59D_{30} (stem Diameter, cm) + 2.89; n = 197

Carbon fraction of R. apiculata

Carbon is an essential nutrient for tree growth and its existence mostly comes from air. Carbon fractions of each *R. apiculata* tree component were analysed through Walkley & Black and Dry Combustion methods and the results are shown in Annex 6, Annex 7 and Annex 8. The wet analysis results of each tree component based on Walkley & Black method varied from 53.7 ± 0.7 to 56.1 ± 0.2%, while the Dry Combustion analysis were from 38.6 ± 0.09 to 41.9 ± 0.04%.

The average carbon fractions of each tree component analysed by Dry Combustion method varied with the tree ages, such as 39.8% at 2- year, 40.8% at 6- year and 40.7% at 10-year old. The average carbon fraction of *R. apiculata* on this study (40.4%) was smaller than average dry weight of general trees used as recent references in tropical species that consists of 41.9–51.6% carbon [24].

The correlation between Walkley & Black and Dry Combustion carbon fractions based on tree ages and tree components can be seen in Annex 8. Both graphs produced linear regression $Y = 1.3064 X – 0.3151$ with coefficient of determination $R^2 = 0.99$ or 99% confident level that used to determine biomass regression.

Biomass allometry of R. apiculata

Allometric regressions in predicting above-ground biomass can be derived based on tree Diameter and tree Height variables. The above-ground biomass allometric equations for dry weight of each vegetation component of *R. apiculata* based on stem Diameter (D_{30}) and combined quadratic of tree Diameter and tree Height (D_{30}^2H) were established through destructive study (Table 2).

The aboveground biomass of mangrove species was highly related to the stem diameter growth. The $AGB_D = 0.1224\ D_{30}^{2.3380}$ regression means that the above-ground biomass (kg) of *R. apiculata* can be estimated by 0.1224 * (D_{30}, cm) ^2.3380 with relationship between variables of 89%. Aboveground biomass regressions of this study had various determination coefficients (0.70 to 0.89). More than 80% of the biomass estimation for leaves/fruits/flowers, twigs, branches and stems can be explained by their allometry formula. Additional component of the dead wood biomass will not much influence the determination pf the totally above ground biomass.

The biomass of *R. apiculata* can also be estimated by the quadratic diameter and tree height and the total biomass allometry was $AGB_{DH} = 0.1508\ D_{30}^2H^{0.7793}$. Based on the R^2 comparison in Table 2, the D_{30} allometry may be more feasible and applicable compared to the D_{30}^2H allometry because the D_{30} determination coefficients at all tree components are higher than its values in D_{30}^2H.

The aboveground biomass estimation for each tree component in this study had various allometric regressions that were significantly different with the finding of Kusmana [1] on *R. apiculata* biomass regressions in mangrove forest in Talidendang Besar–Riau: $Y = 0.90232X^{0.08070}$ $R^2 = 0.99$ for stems; $Y = 0.90380X^{0.02940}$ R2 = 0.97 for twigs; $Y = 0.74774X^{0.00208}$ $R^2 = 0.96$ for fruits and flowers; $Y = 0.40441X^{0.33853}$ $R^2 = 0.92$ for leaves; and $Y = 0.81637X^{0.03594}$ $R^2 = 0.95$ for proop-roots. It can conclude that the estimation of above-ground biomass varies from one to the other places due to the differences in growth factors, sediment condition, local climate and site-specific where the mangroves grow.

Table 2. Allometric equations for above ground biomass (AGB, kg) of *R. apiculata* tree components based on D_{30} and D_{30}^2H variables

	D_{30} allometry		D_{30}^2H allometry	
Tree component	$AGB = b\ D_{30} \wedge ^a$	R^2	$AGB = b\ D_{30}^2H \wedge ^a$	R^2
Leaves/fruits/flowers	$AGB = 0.0151\ D_{30}^{2.3400}$	$R^2 = 0.87$	$AGB = 0.0198\ D_{30}^2H^{0.7667}$	$R^2 = 0.77$
Twigs	$AGB = 0.0038\ D_{30}^{2.8944}$	$R^2 = 0.88$	$AGB = 0.0052\ D_{30}^2H^{0.9521}$	$R^2 = 0.78$
Branches	$AGB = 0.0093\ D_{30}^{2.6188}$	$R^2 = 0.83$	$AGB = 0.0124\ D^2H^{0.8616}$	$R^2 = 0.74$
Stems	$AGB = 0.0220\ D_{30}^{2.6972}$	$R^2 = 0.83$	$AGB = 0.0261\ D_{30}^2H^{0.9139}$	$R^2 = 0.78$
Stumps	$AGB = 0.0241\ D_{30}^{1.9958}$	$R^2 = 0.70$	$AGB = 0.0305\ D_{30}^2H^{0.6528}$	$R^2 = 0.62$
Proop-roots	$AGB = 0.0711\ D_{30}^{1.5736}$	$R^2 = 0.72$	$AGB = 0.0894\ D_{30}^2H^{0.5005}$	$R^2 = 0.61$
AGB	$\mathbf{AGB = 0.1224\ D_{30}^{2.3380}}$	$\mathbf{R^2 = 0.89}$	$\mathbf{AGB = 0.1508\ D_{30}^2H^{0.7793}}$	$\mathbf{R^2 = 0.82}$
Dead woods	$AGB = 0.0109\ D_{30}^{1.8273}$	$R^2 = 0.54$	$AGB = 0.0167\ D_{30}^2H^{0.5559}$	$R^2 = 0.42$
AGB + Deadwoods	$AGB = 0.1231\ D_{30}^{2.3401}$	$R^2 = 0.89$	$AGB = 0.1520\ D_{30}^2H^{0.7797}$	$R^2 = 0.82$

AGB = Above ground dry weight biomass (kg); R^2 = determination coefficient; n = 45

Aboveground biomass

The density of planted mangroves at destructive plots varied at different ages, such as 5,733 ind ha^{-1} at 2 year; 12,133 ind ha^{-1} at 6 year and 8,400 ind ha^{-1}. The development of mangrove trees induced an increase in stem diameter (2.4; 3.3 and 5.6 cm) and a corresponding increase in biomass. The aboveground biomass of *R. apiculata* based on destructive actual values from laboratory analysis increased from 42.0 kg at 2-year to 152.5 kg at 6 year and 490.9 kg at 10-year old. This study shows an increase of biomass productivity at different age level is more determined by stem diameter rather than mangrove density and this condition is consistent with Ellison [25] finding. An increase of mangrove carbon biomass in this study is also consistent with *Rhizophora apiculata* biomass (Table 3) and stem diameter study in the Mekong delta, Vietnam that trees still increase until 40-years old [26].

Average estimated aboveground biomass of *R. apiculata* was 64.77% by D$_{30}$ allometry and 69.15% by D$_{30}^{2}$H allometry to the actual destructive value (91.4 Mg ha^{-1}). The estimated values are less than actual destructive values because the calculation of both allometries only use stem diameter and don't include the other trees' components such as leaves/flowers/fruits, twigs, branches, stumps and roots.

Table 3. Aboveground biomass of *R. apiculata* based on destructive actual values, D$_{30}$ allometry and D$_{30}^{2}$H allometry

	Aboveground biomass (Mg ha^{-1})							
	2 years		6 years		10 years		(2-10 years)	
Description	X	± *sd*	X	± *sd*	X	± *sd*	X	± *sd*
Destructive Actual Values	16.8	± 3.6	61.0	± 3.0	196.4	± 35.5	91.4	± 18.6
D$_{30}$ allometry	20.7	± 3.3	62.4	± 3.1	94.6	± 16.3	59.2	± 7.6
D$_{30}^{2}$H allometry	18.3	± 3.2	69.6	± 3.0	101.6	± 15.1	63.2	± 7.1

Table 4. Above ground biomass (AGB) of *Rhizophora species* of worldwide

Location	Condition/age	AGB (Mg ha^{-1})	D (cm)	H (m)	BA (m^2 ha^{-1})	Density (ind ha^{-1})	References
North Sumatra, Indonesia	*R. apiculata* (2 – 10 years)	91.4	4.8	4.6	11.5	8.755	Destructive value of this study
Riau, Indonesia	*R. apiculata* stand	40.9		29.5	2.5		Kusmana *et al*. (1992)
Lawas, Malaysia	*R. apiculata* stand	116.8		12.2		840	Chandra *et al*. (2011)
Phuket, Thailand	*R. apiculata* forest (15 years)	159.0		11.0			Christensen (1978)
Matang, Malaysia	Forest	183.3					Gong and Ong (1990)
Matang, Malaysia	*R. apiculata* stand (28 years)	211.8		15.0			Ong *et al*. (1982)
Matang, Malaysia	*R. apiculata* forest (>80 years)	270.0					Putz and Chan (1986)
Halmahera, Indonesia	*R. apiculata* primary forest	356.8		21.2	25.1		Komiyama *et a*l. (1988)
Florida, USA	*R. mangle* stand	7.9					Lugo &Snedaker (1974)
Florida, USA	*R. mangle* stand	12.5					Coronado-Molina *et al*. (2004)
Sri Lanka	*Rhizophora* island habitat	71.0		3.9	11.4		Amarasinghe & Balasubramaniam (1992)
Estero Pargo, Mexico	*A.germinans fringe forest*	83.4		6,0	23.3	7,510	Day *et al.* (1996)
Okinawa, Japan	*R. mucronata* forest	108.1		5.5	31.0		Suzuki and Tagawa (1983)
Boca Chica, Mexico	*A.germinans riverine forest*	125.2		20.0	34.2	3,360	Day *et al.* (1996)
Halmahera, Indonesia	*R. stylosa* forest	178.2		22.3	14.0		Komiyama *et al*. (1988)
Andaman Island, India	*Rhizophora* forest	214.0		22.5	15.7		Mall *et al*. (1991)
Kenya	R. mucronata forest	249.0		12.0			Slim *et al*. (1996)
Ranong, Thailand	*Rhizophora spp* forest	281.2		10.6	24.0	1,246	Tamai *et al*. (1986)
Ranong, Thailand	*Rhizophora spp* forest	298.5			31.3		Komiyama *et al*. (1987)

Table 4 provides that the average aboveground biomass of destructive value (2-10 years) in this study (91.4 Mg ha^{-1}) was higher than aboveground biomass of 9 and 12 year *R. apiculata* at Tambol Yisan, Samut Songram province, Thailand that were consisted of 65.96 ton ha^{-1} and 78.22 Mg ha^{-1} [27]. However, it was lower than the aboveground biomass (>500 Mg ha^{-1}) of mangroves growing in the rivers in the Indo-Pacific [29]. Mangrove ecosystem have a high biomass productivity (2 Mg ha^{-1} yr^{-1}) for vegetation carbon stocks [31].

Compared to the other species, the aboveground biomass of this study was higher than biomass of 10-year *Bruguiera cylidrica* (28.8 Mg ha^{-1}) planted at the ex-pond in Khanom, Thailand [32], *Lagucularia* pioneer stage (31.5 Mg ha^{-1}) and *Avicennia* pioneer stage (35.1 Mg ha^{-1}) in French Guiana [33], *Ceriops tagal* forest (40.1 Mg ha^{-1}) in Kenya [34], *Avicennia marina* dominated forest (54.9 Mg ha^{-1}) in Thane creek, Maharashtra, India [35], riverine mixed forest (57.0 Mg ha^{-1}) in Sri Lanka [36], and secondary mixed forest (62.2 Mg ha^{-1}) in Southern Pang-nga, Thailand [37].

However, the aboveground biomass of this study was lower than the other studies on *Ceriops tagal* secondary forest (92.2 Mg ha^{-1}) in Southern Satun, Thailand [9], *Bruguiera gymnorhiza* & *Avicennia marina* (94.5 Mg ha^{-1}) in South Africa [38], *B. gymnorhiza* primary forest (97.6 Mg ha^{-1}) in Okinawa, Japan [39], *B. gymnorhiza* and *Ceriops* primary forest (124.0 Mg ha^{-1}) in Andaman Island, India [40], *A. marina* primary forest (144.5 Mg ha^{-1}) in Australia [41], *Sonneratia* primary forest (169.1 Mg ha^{-1}) in Halmahera, Indonesia [8], and 50 year mixed forest of *R. mangle*, *Lagucularia* and *A. germinans* (233.0 Mg ha^{-1}) in Dominican Republic [42].

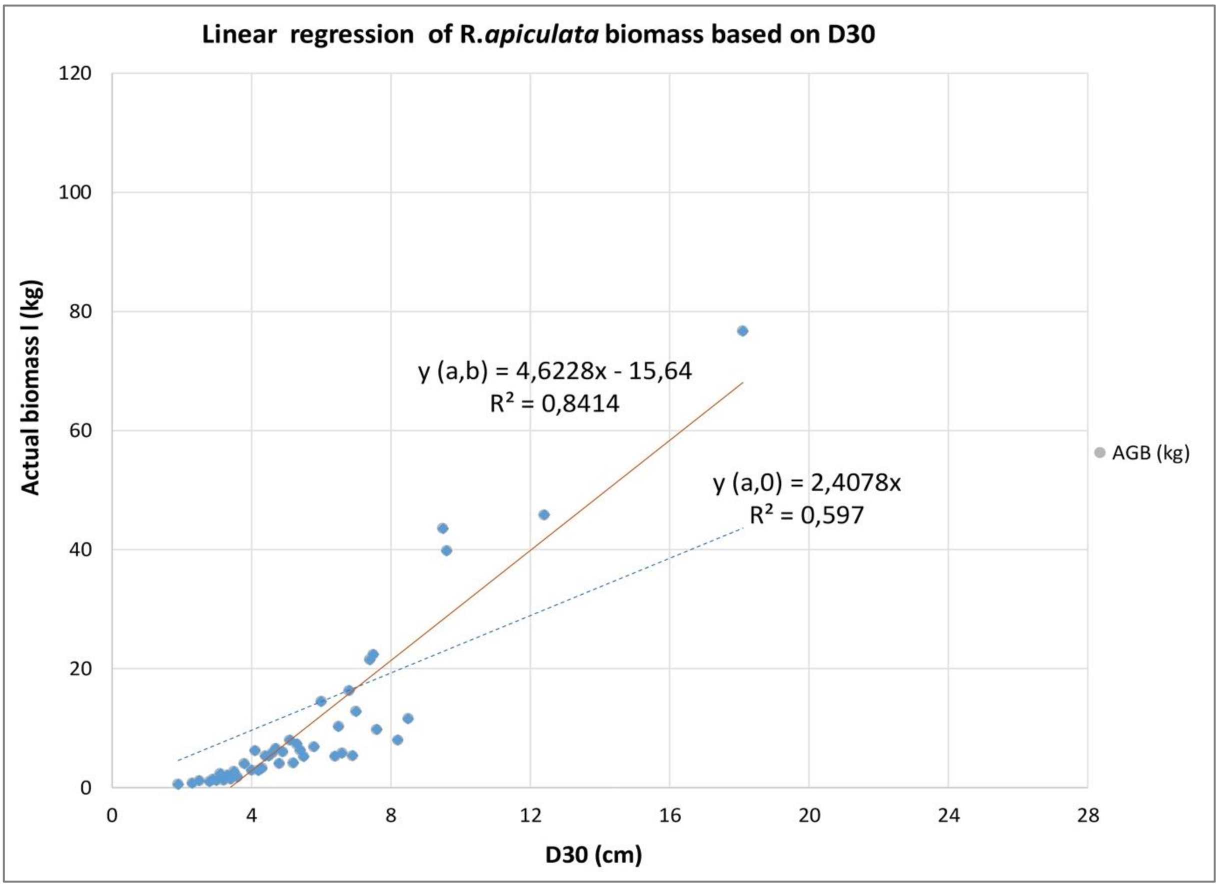
The ability of producing biomass of each mangrove in different locations may be influenced by their photosynthetic capacities. Clough [43] found that 22 years old of *R. apiculata* in Malaysia had showed a photosynthetic rate of 155 kgC ha^{-1} day^{-1}. The similar study conducted by Clough [44] in China showed the net canopy production *R. 310piculate* growing until 25 – 30 years in which the old trees were able to maintain an average speed of carbon fixation.

With an average biomass productivity of 2 Mg ha^{-1} yr^{-1} the mangrove ecosystem was able to support food chains of pelagic organisms and benthos present in coastal areas and contribute organic carbon to fisheries life [31]; [47]; [48]. Mangroves also played a role in responding to various risks of climate change, such as increased rainfall, rising temperatures and rising sea levels [26]. Altered mangrove ecosystems to function intensive fish ponds or shrimp ponds or abandon will affect the quantity and quality of organic soil carbon [32].

Field biomass estimation

An annual net production of aboveground mangrove biomass can be obtained from multiple regression or simple linear regression. Based on the data on dry-weight biomass from destructive study, two simple linear regressions based on stem diameter and tree height were established for quick assessment in the field (Figure 1).

The aboveground mangrove biomass can be estimated by simple linear regression based on diameter measurement: $Y = 4{,}6228X – 15{,}6404$; $R^2 = 0{,}8414$. This regression is equal to free variable linear regression $y(a,0) = 2{,}4078X$; $R^2 = 0.5970$. It means an additional 1 cm stem diameter will produce 2.41 kg aboveground biomass per tree. However, this estimation will not be recommended for accurate calculation because of low level of determination coefficient (59.70%). Similar study was carried out in Southern Mexican mangrove forest for 7 years record to measure randomly the tagged dbh of 25 trees of *Avicennia germinans* using regression equation $Y = 2.302X – 1.5852$ [49]. The tree height linear regression of $Y(a,0) = 0.0286X$ means that an additional 1 m of tree height will produce 0.03 kg aboveground biomass per tree.



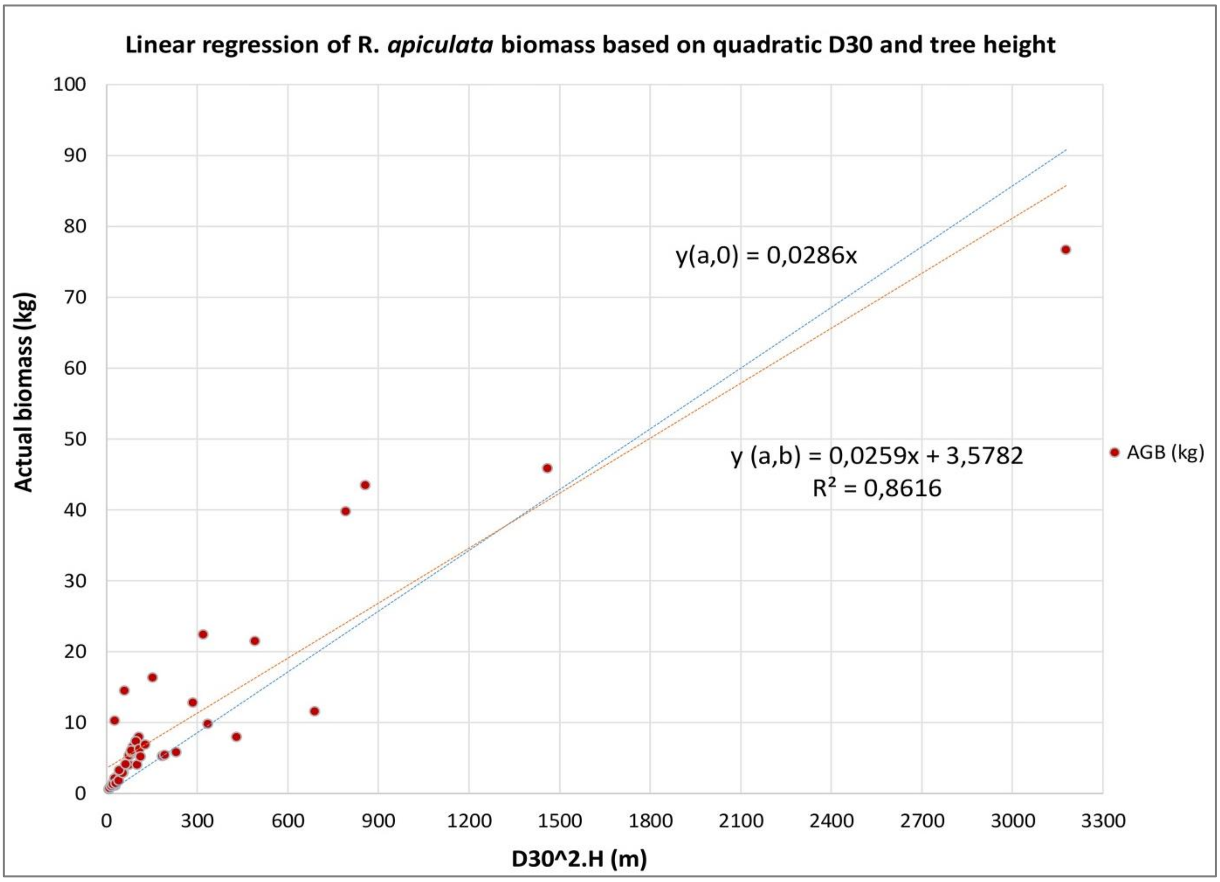


Figure 1. Linear regressions of R. apiculata biomass estimation based on D_{30} linear regression and D_{30}^2H linear regression

Accuracy level of biomass estimation

Total aboveground biomass is the sum of biomass of all tree components (leaves/fruits/flowers, twigs, branches, stems, stumps and proop-roots). The uncertainty of each biomass component was calculated in order to understand the uncertainty of total biomass (Figure 2). This graph showed the level accuracy of biomass allometric estimation to the destructive actual values for each *R. apiculata* tree component.

Relative Error (RE) of each tree component in this study varied from -38.5 to +24.0%. The actual stump and dead wood biomass were higher than its values estimated by allometries, while the twig and stem actual calculation were lower than regression values. The most accurate allometric estimation was above-ground roots with over-estimate level of +3.0% only (y = 1.033x). The accuracy level of estimated biomass was 85.4% to the actual values calculated by destructive method.

The RE level of aboveground *R. apiculata* biomass in this study (-14.6%; Y = 0.854X) was less accurate compared to the RE of other *Rhizophora spp* studies, such as -9.8 to +10.3% (Clough and Scott, 1989) and +6.8 to +10.8% [4]. The production variaties of aboveground biomass *Rhizophora* species may depend on the basal area, tree diameter, tree height and density of individual trees. Moreover, the findings of [8] and [1] reported that the mangrove biomass production was influenced by annual air temperature and precipitation. The different REs between this study and other findings may imply that each allometric equation can be applied accurately when the estimated mangrove ecosystems have similar species, age, tree-density, wood-density, growth factors, sediment condition, site-specific, sub-ecosystem type and local climate parameters.

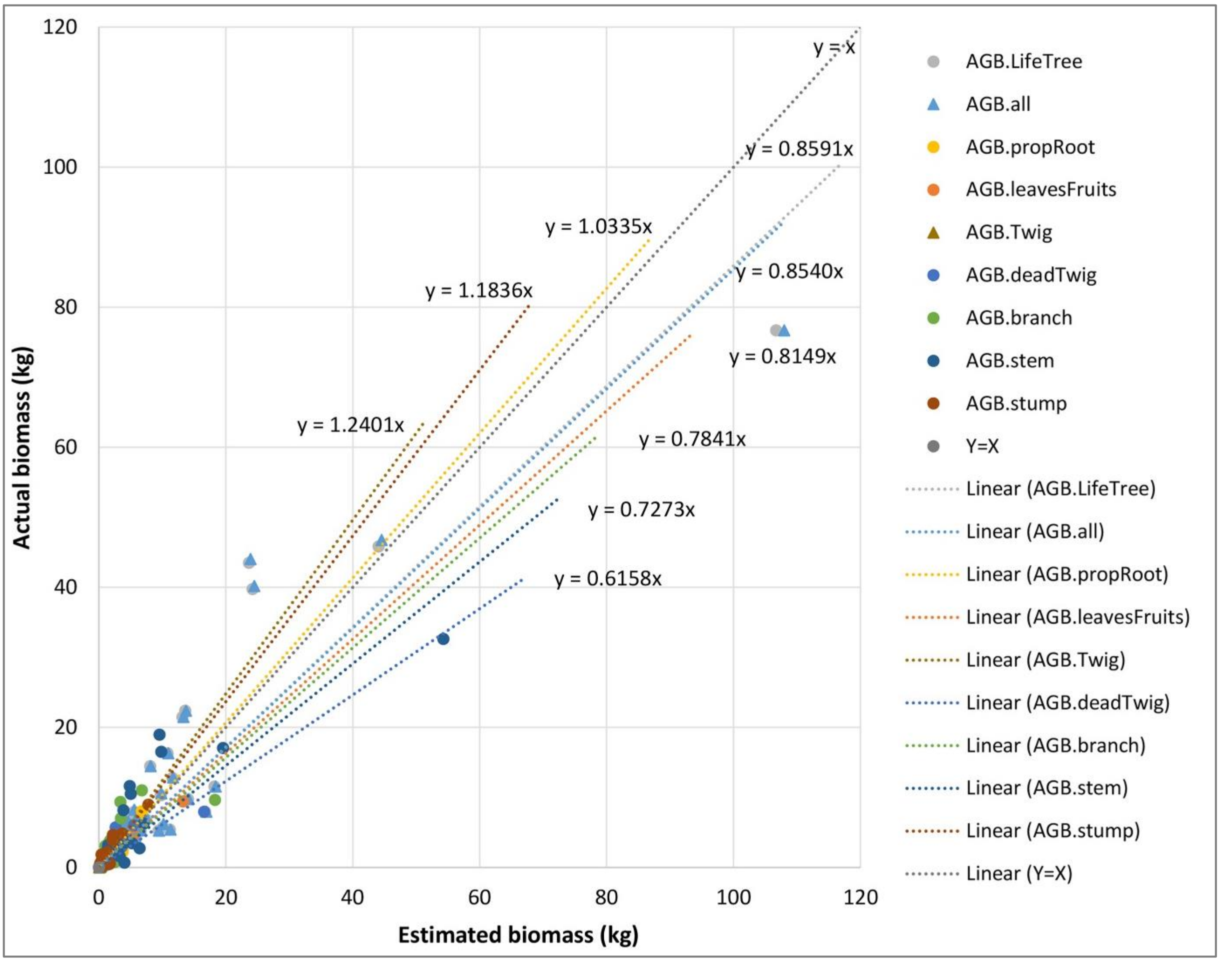


Figure 2. An accuracy level of biomass allometric estimation compared to actual biomass destructive measurement

Carbon stocks of R. apiculata

Mangrove is a good carbon assimilator that capture CO_2 and process it into the carbohydrates needed for its growth. Mangroves have C4 pathways in carbon fixation process for photosynthesis [46], in which mangrove biomass productivity increases with the increasing atmospheric CO_2 concentrations [50]. The amount of carbon stored in each plant component is affected by individual's ability of tree, species composition, vegetation structure and the support of environmental factors in processing CO_2 from atmosphere through photosynthetic process. Allometric regressions for carbon stocks of each *Rhizophora apiculata* tree component based on stem diameter and stem diameter - tree height has been shown in Table 5.

Allometric regressions of carbon stocks varied among tree component of *R. apiculata*. Additional component of dead woods didn't give impacts to the total aboveground carbon stocks that were shown by same value of coefficient determination. The R^2 = 0.93 means that 93% of aboveground *R. apiculata* carbon stocks can be estimated by the regression of $AGC_D = 0.0368D_{30}^{2,5996}$. This allometric regression will be used as a reference in calculating carbon stocks of non-destructive *R. apiculata* estimation in which the field data were compiled in parallel with this destructive study.

Preliminary study on carbon stocks of restored mangroves at Percut and Sicanang villages was conducted in 2008 - 2009 through non-destructive method on 4 and 12 years old mangroves. Mangroves at Percut can store aboveground carbon of 9.98 MgC ha^{-1}, while the carbon stock at Sicanang was 11.14 MgC ha-1 [51]. Taking into account the long-term scenario, the total areas of 26,458 ha had carrying capacity of carbon stocks of 264,050 - 294,742 MgC.

It is necessary to measure biomass of each mangrove component in order to determine the above ground carbon stocks. The stocks were obtained by multiplying the above-ground biomass component with the percentage of carbon concentration which was usually less than 50% [30]. The aboveground carbon stocks of all tree components increase along with the increase of tree age. The highest carbon stock at all ages (2 – 10 years) estimated by D_{30} allometry was stems (28.2 MgC ha^{-1}), then followed by branches (10.8 MgC ha^{-1}), proop-roots (8.7 MgC ha^{-1}), leaves/fruits/flowers (8.3 MgC ha^{-1}), stumps (7.5 MgC ha^{-1}) and twigs (6.9 MgC ha^{-1}). This sequence of carbon stocks at 2, 6 and 10 years was similarly comparable to the other findings [30]; [18]. The 10-year aboveground destructive actual value (200 MgC ha^{-1}) was higher than the stocks estimated by D_{30} allometry (128.0 MgC ha^{-1}) due to high range of stem diameter of D_{30} allometry from 0.4 to 18.1 cm.

However, the proportion sequence of aboveground carbon stocks will change when the trees get older, as seen in 10-year *R. apiculata*: stems (43.2%), branches (16.1%), leaves/fruits/flowers (11.1%), twigs (10.8%), stumps (9.5%) and proop-roots (9.2%). The highest carbon stock proportion on stems in this study was consistent with other studies on *R. apiculata* [4] and on *R. stylosa* [6].

Table 5. Allometric equations for aboveground carbon stocks of *R. apiculata* based on D_{30} and D_{30}^2H

Tree component	$AGC = b\ D_{30}$ ^ ^{a} (kg)	R^2	Accuracy %	$AGC = b\ D_{30}^2\ H$ ^ ^{a} (kg)	R^2	Accuracy %
Leaves/fruits/flowers	$AGC = 0.0046D_{30}^{2.5685}$	0.91	58.84	$AGC = 0.0054D_{30}{}^2H^{0.8565}$	0.85	78.56
Twigs	$AGC = 0.0011D_{30}^{3.1624}$	0.92	41.47	$AGC = 0.0014D_{30}^2H^{1.0596}$	0.87	59.92
Branches	$AGC = 0.0026D_{30}^{2.9651}$	0.89	45.40	$AGC = 0.0031D_{30}^2H^{0.9968}$	0.83	67.08
Stems	$AGC = 0.0065D_{30}^{2.9717}$	0.88	49.59	$AGC = 0.0072D_{30}^2H^{1,0078}$	0.84	70.30
Stumps	$AGC = 0.0071D_{30}^{2.2671}$	0.78	85.14	$AGC = 0.0089D_{30}^2H^{0.7376}$	0.69	109.04
Proop-roots	$AGC = 0.0295D_{30}^{1.5843}$	0.64	100.48	$AGC = 0.0344D_{30}^2H^{0.5171}$	0.57	108.33
AGC	$\mathbf{AGC_D = 0.0368D_{30}^{2.5996}}$	**0.93**	**60.14**	$\mathbf{AGC_{DH} = 0.0422}D_{30}^{\mathbf{2}}\mathbf{H^{0.8730}}$	**0.88**	**79.72**
Dead woods	$AGC = 0,0039D_{30}^{1,9329}$	0.56	122.50	$AGC = 0.0079D_{30}^2H^{0.5265}$	0.38	136.21
AGC + Deadwoods	$AGC = 0,0369D_{30}^{2,6042}$	0.93	59.58	$AGC = 0.0425D_{30}^2H^{0.8738}$	0.88	79.49

AGC = Aboveground carbon stock (kg); R^2 = determination coefficient; n = 197

Table 6 shows the average of aboveground carbon stock of *R. apiculata* that estimated by the D_{30} allometry (29.9 MgC ha^{-1}) and by the D_{30} allometry (30.2 MgC ha^{-1}) was lower than the actual destructive value (37.2 MgC ha^{-1}). The actual destructive value of aboveground carbon stock of 6-year *R. apiculata* (24.8 MgC ha^{-1}) and its estimated indicator by the D_{30} allometry (29.1 MgC ha^{-1}) in this study was lower than above-ground stocks of 6-year *R. apiculata* (54.0 MgC ha^{-1}) in Southern Vietnam but it was smaller than aboveground stocks of 5-year *R. apiculata* (87 MgC ha^{-1}) in Peninsular Malaysia [26].

The actual destructive value of 10-year *R. apiculata* aboveground carbon stock (80.0 MgC ha^{-1}) this study was higher than 20-year *R. apiculata* (72 MgC ha^{-1}) in Southern Vietnam and carbon stock of *Kandelia obovata* (48.47 Mg C ha^{-1}) growing at natural mangrove forest in Mako Wetland-Japan (Hoque, *et al*., 2010). However, it was lower than the aboveground carbon stocks of 18-year *R. apiculata* (193 MgC ha^{-1}) in Peninsular Malaysia, 35-year *R. apiculata* (153 MgC ha^{-1}) in Southern Vietnam and 25-year *R. apiculata* (138 MgC ha^{-1}) in Southern Thailand [26].

Degree of accuracy of carbon estimation

The degree of accuracy of carbon stock estimation by allometric equations compared to the actual values of destructive measurement for each *R. apiculata* tree component can be seen in Figure 3.

Table 6. Carbon stocks of *R. apiculata* based on destructive actual values, D_{30} allometry and D_{30}^2H allometry

	Carbon stocks (MgC ha^{-1})							
	2 years		6 years		10 years		(2-10 years)	
Description	X	± *sd*	X	± *sd*	X	± *sd*	X	± *sd*
Destructive Actual Values	6.8	± 1.5	24.8	± 1.2	80.0	± 14.5	37.2	± 5.7
D_{30} allometry	9.5	± 1.7	29.1	± 1.6	51.2	± 10.0	29.9	± 4.5
D_{30}^2H allometry	7.8	± 1.6	30.7	± 1.5	52.3	± 8.5	30.2	± 3.9

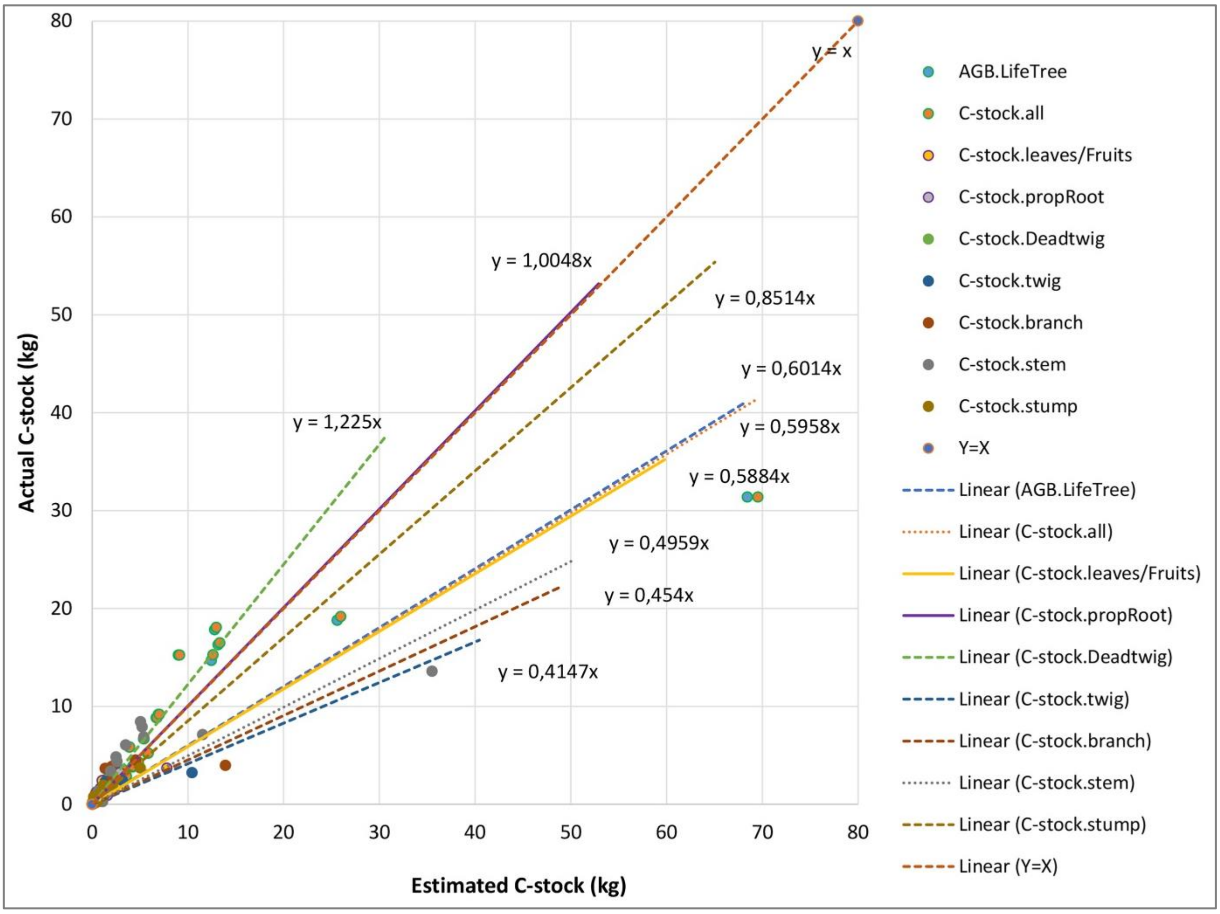


Figure 3. An accuracy level of carbon estimation compared to actual measurement of each tree component based on D_{30} regression

The accurate levels of aboveground biomass estimation by allometric regressions for stems, twigs, leaves/fruits/flowers and stumps were ranging from 41.47 to 85.14% to actual values of destructive measurement. The deadwoods allometry was 25.50% exceed estimates from the actual destructive carbon measurement. Only proop-roots ($y = 1,0048x$) allometry had an accurate allometric estimation (almost 100%) compared to the actual destructive value. Moreover, the *R. apiculata* aboveground carbon estimation ($y = 0.6014x$) was only 60.14% accurate to the actual destructive values. It is concluded that the estimated values based on stem diameter is always lower than the actual destructive values because some tree components such as leaves/flowers/fruits, twigs, branches, stumps and proop-roots are not yet calculated.

Application of destructive allometry

The allometric equation $AGC_D = 0.0368D_{30}^{2.5996}$ can used to estimate the *R. apiculata* carbon stocks based on stem diameters from field non-destructive measurement. For non-*R. apiculata* species, several allometric references from previous studies were used by Kauffman [28] *Sonneratia caseolaris* $AGC = 0.3841D_{30}^{2.1000}$, *Sonneratia alba* $AGC = 0.3841D_{30}^{2.1000}$, *Bruguiera sexangula* $AGC = 0.0754D_{30}^{2.5000}$ and by Comley [6] *Avicennia marina* $AGC = 0.3080D_{30}^{2.1100}$.

Two scenarios of aboveground carbon stock estimation were established using allometry resulted from this destructive study as provided on Table 7.

Based on the scenario 1, the actual aboveground carbon stocks of 2, 6 and 10-year *R. apiculata* only were 5.94; 26.85 and 37.35 MgC ha^{-1}. Compared to their ideal condition the carbon loss of this species were 0.04; 0.12 and 3.60 MgC ha^{-1}. In addition, the scenario 2 showed the aboveground carbon stocks of 2; 6 and 10 year *R. apiculata* plus other species in actual condition 15.5; 26.9 and 40.2 MgC ha^{-1}. Compared to their ideal condition, the carbon loss of all species were 0.2; 0.1 and 4.5 MgC ha^{-1}. The carbon loss in ideal- and actual condition increases when the trees grow older. These evidences showed that the older restored mangroves were fragile from carbon loss because local communities preferred to cut trees for several purposes. These carbon losses can not be avoided but it can be minimized through awareness program and law-enforcement.

The average (2-10 years) aboveground carbon stocks of all species in actual condition (27.53 MgC ha^{-1}) were higher than the *R. apiculata* only (23.38 MgC ha^{-1}). Carbon productivity of planted mangroves per year can be estimated by its carbon sequestration and its comparative values are in opposite with their carbon stocks. The average (2-10 years) actual carbon sequestration of all species (11.29 $MgCO_2e$ ha^{-1} yr^{-1}) was lower than the sequestration in *R. apiculata* only (14.42 $MgCO_2e$ ha^{-1} yr^{-1}). It is important to conduct further study to identify how old this species can still effectively sequester carbon. The biomass production of *Rhizophora apiculata* in the Mekong delta, Vietnam still increase until 40 years old [44]. Similarly, mangrove forests in French Guiana effectively accumulated carbon at the ages of 15 to 70-years [33].

Acknowledgements

We thank to the USAID Indonesia Program who finance this research and to Livelihoods Fund in supporting long-term mangrove carbon project. We also thank to the Yagasu field team and volunteers from various university students in Medan that involve on the field data collection. We appreciate to the RISPA laboratory - Medan, IPB Soil Biotechnology - Bogor who allow us to use their laboratory for carbon fraction analysis. The special thanks are given to the research partners (Rahayu Subekti, Melanton Haloho, Hasri Abdilah, Rangga Bayu Basuki, Dhany Saragih and Ricky Stiawan) who assist in providing secondary data, mapping study sites, drawing illustrations and analysing statictical data. We also appreciate and thank to Prof. Zulkifli Nasution and Nirmal Beura for proof-reading and critical review of this manuscript.

Table 7. Aboveground carbon stocks (MgC ha^{-1}) of non-destructive *R. apiculata* and other species in ideal- and actual condition

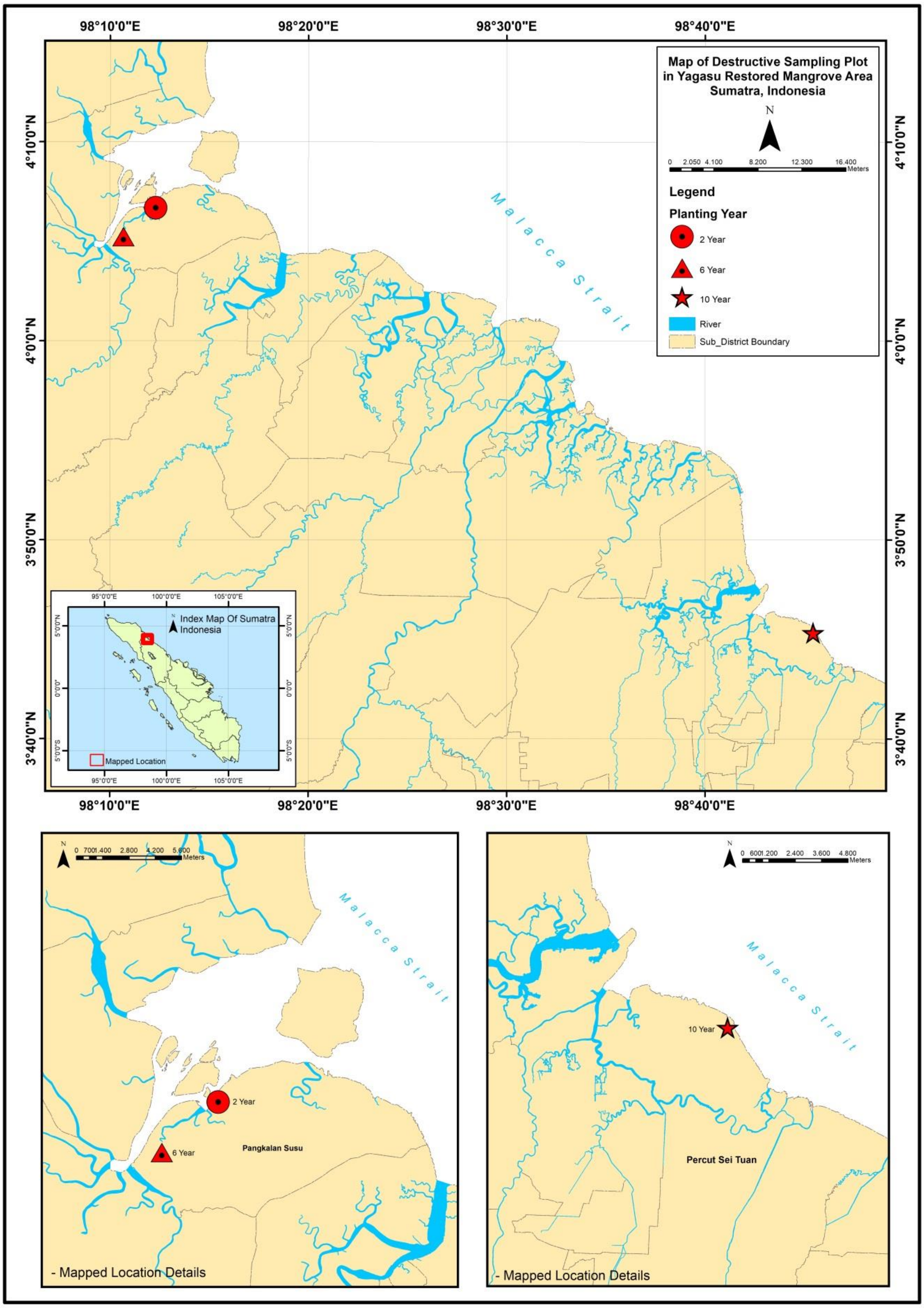
Tree age (years)	Scenario 1 AGC-stocks *R. apiculata* only			Scenario 2 AGC-stocks *R. apiculata* + other species		
	Ideal condition	Actual condition	Carbon lost	Ideal condition	Actual condition	Carbon lost
2	5.98	5.94	0.04	15.70	15.50	0.20
6	26.96	26.85	0.12	27.00	26.90	0.10
10	40.95	37.35	3.60	44.70	40.20	4.50
Av. AG C-stocks	24.63	23.38	1.25	29.13	27.53	1.60
AG Seq-CO_2		14.42			11.29	

Av. AGC C-stocks = Average aboveground C-stocks (MgC ha^{-1}); AGB Seq-CO_2 = Aboveground carbon sequestration ($MgCO_2e$ ha^{-1} yr^{-1}); Ideal condition = all tree components are estimated in intact condition; Actual condition = parts of tree components are in actual condition in which there are field evidences of cut trees, dried branches, no-leaves and no branches or twigs; n - R. apiculata only = 1.357;

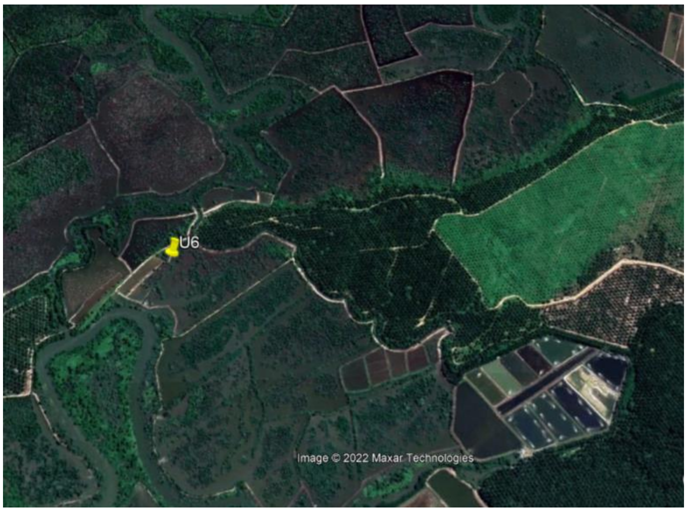
n – R.apiculata + other species = 1,456.

Annexes

Annex 1. Destructive sites



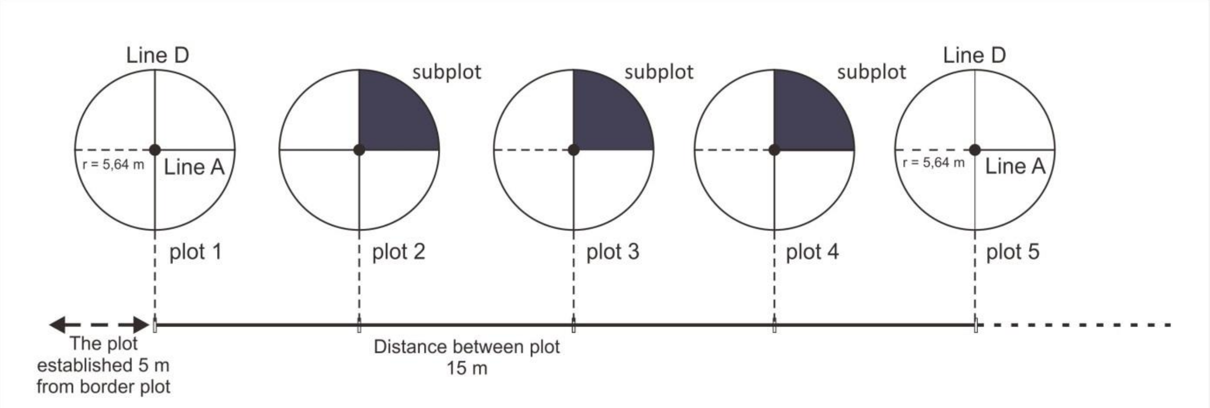
2 year (Sei Meran)
04 °06'41.01"N; 098 °12'18.39"E

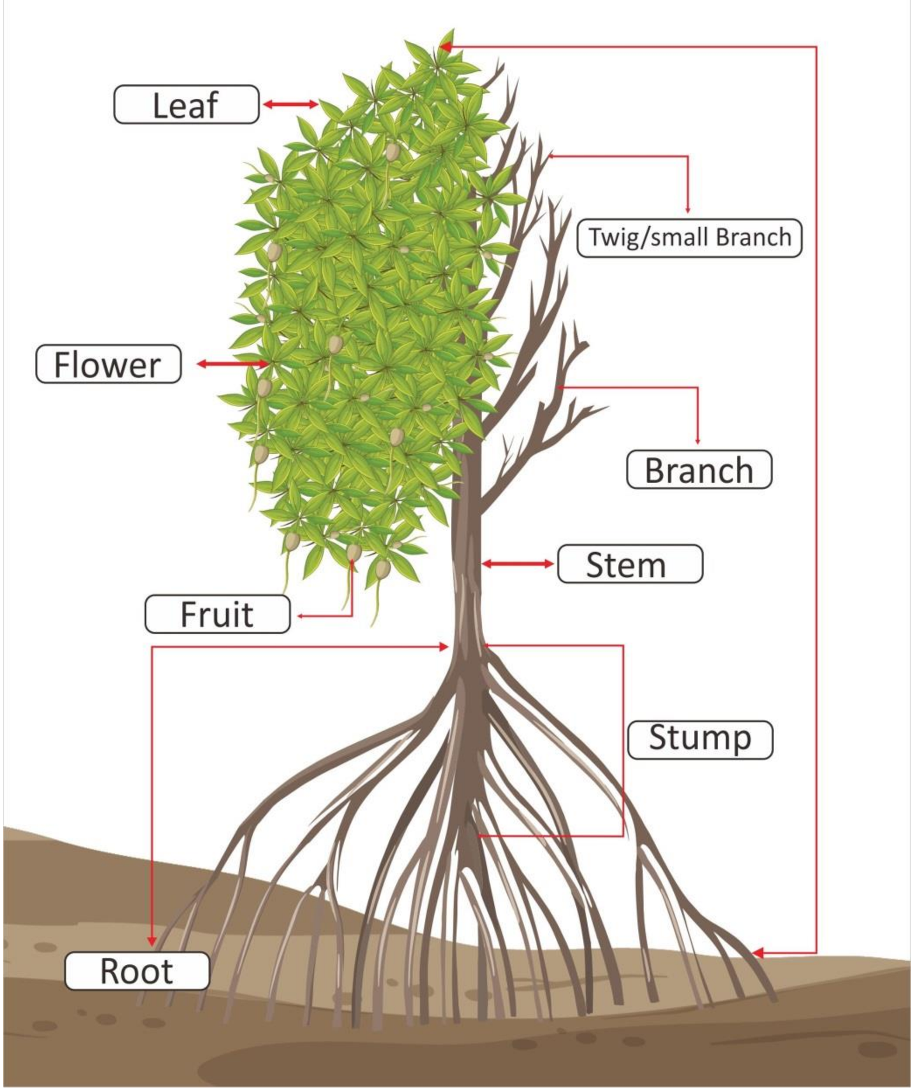


6 year (Sei Meran)
04 °05'14.37"N; 098 °10'40.91"E

10 year (Tanjung Rejo)
03 °45'20.70"N; 098 °45'27.58"E

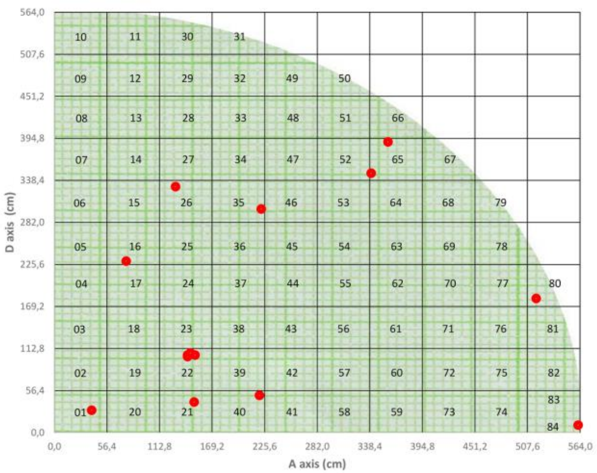
Collecting tree components in sub-plot (1/4 plot) at Plot 2, Plot 3 and Plot 4



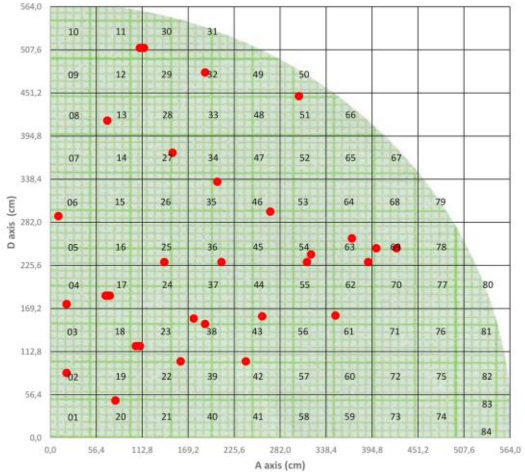


Annex 2. Transect and sub-plots of destructive tree distribution for collecting samples from each tree component of R. apiculata

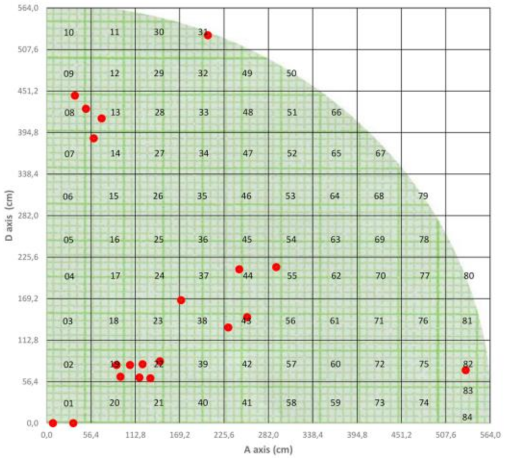
Subplot 2 of U02



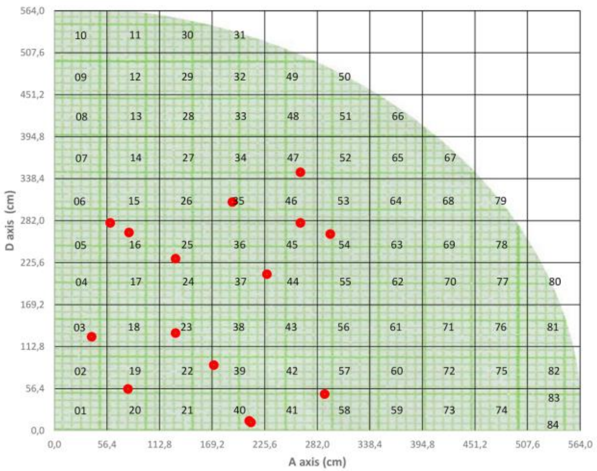
Subplot 2 of U06



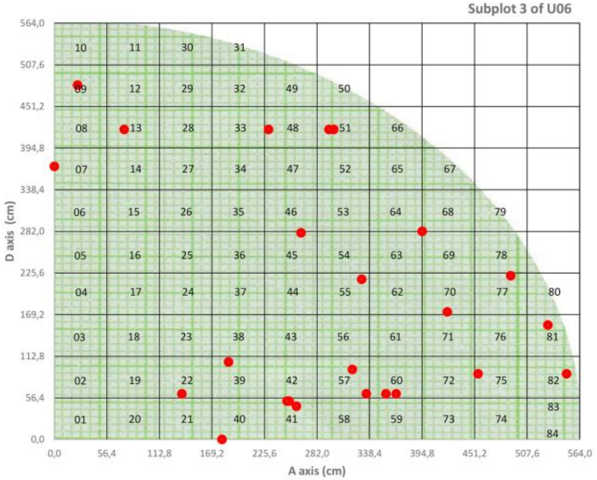
Subplot 2 of U10



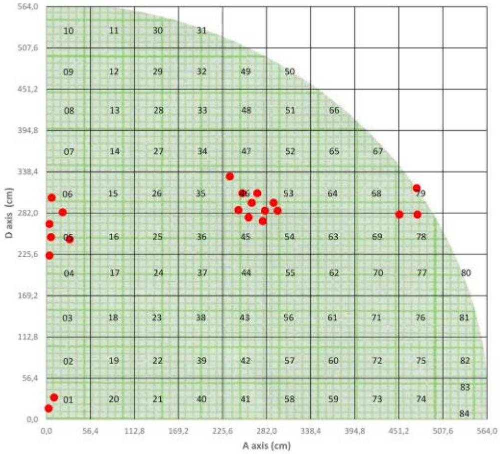
Subplot 3 of U02

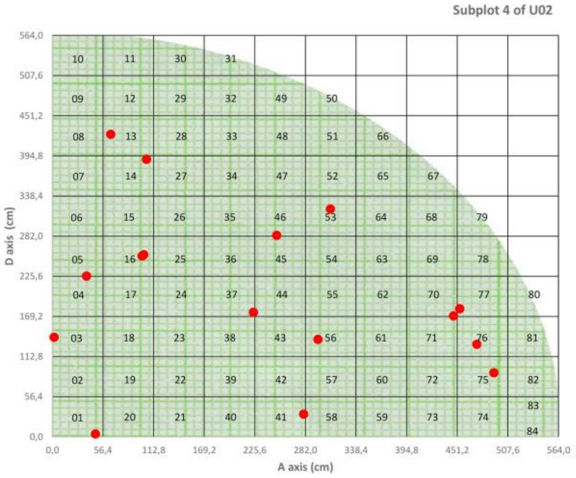


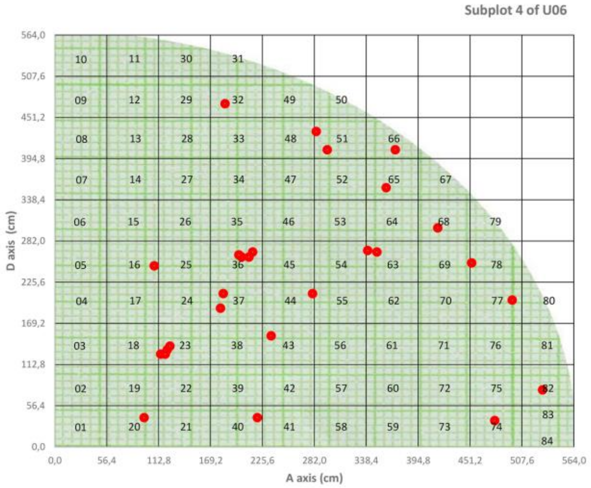
Subplot 3 of U06

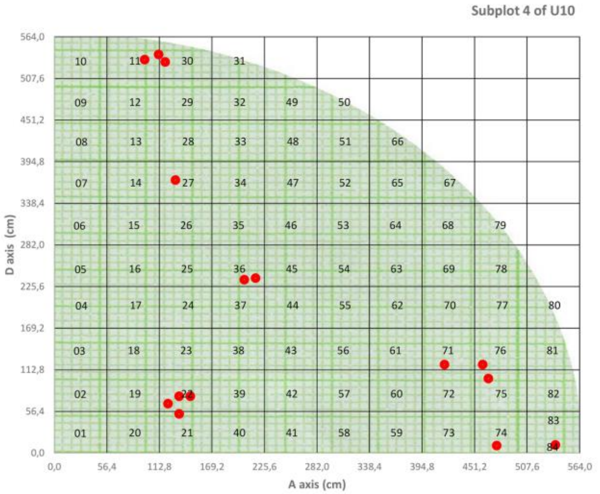


Subplot 3 of U10




Subplot 4 of U02
D axis (cm)
A axis (cm)
0,0
56,4
112,8
169,2
225,6
282,0
338,4
394,8
451,2
507,6
564,0


Subplot 4 of U06
D axis (cm)
A axis (cm)
0,0
56,4
112,8
169,2
225,6
282,0
338,4
394,8
451,2
507,6
564,0


Subplot 4 of U10
D axis (cm)
A axis (cm)
0,0
56,4
112,8
169,2
225,6
282,0
338,4
394,8
451,2
507,6
564,0

Annex 3. Number of trees and important value index of all species at destructive plots

Age and spesies	NT per plot	BA ($m^2 ha^{-2}$)	RDs (%)	RF (%)	RDm (%)	IVI (%)
2 years						
R. apiculata	440	0.18	83.5	31.3	9.0	123.7
S. caseolaris	27	1.03	5.1	31.3	50.3	86.7
Sonneratia alba	59	0.78	11.2	31.3	38.4	80.9
Avicennia marina	1	0.05	0.2	6.3	2.2	8.7
6 years						
R. apiculata	653	0.47	99.7	71.4	89.8	260.9
Avicennia marina	1	0.04	0.2	14.3	7.3	21.7
B. sexangula	1	0.02	0.2	14.3	2.9	17.4
10 years						
R. apiculata	264	1.39	96.4	71.4	52.3	220.1
Avicennia marina	5	0.68	1.8	14.3	25.7	41.8
S. caseolaris	5	0.59	1.8	14.3	22.0	38.1

NT = Number of Trees; BA = Basal Area; RDs = Relative Density; RF = Relative Frequency; RDm = Relative Dominance; IVI = Important Value Index (%). maximum 300%; n-plot = 15

Annex 4. Number of trees, stem diameter, tree height, basal area and shoot/root ratio of all species at destructive plots

Tree age	Number of trees per plot		Stem diameter (cm)		Tree height (m)		Basal area ($m^2 ha^{-2}$)		Shoot/root ratio	
	X	±sd	X	±sd	X	±sd	X	±sd	X	±sd
2 years	105 a	± 29	2.4 c	± 0.3	2.34 c	±1.0	6.3 b	± 3.1	0.91 ab	± 0.15
6 years	131 a	± 18	3.3 b	± 0.2	4.09 b	±1.1	12.2 a	± 1.4	0.84 b	± 0.02
10 years	55 b	± 11	5.6 a	± 0.5	7.33 a	±2.4	16.0 a	± 2.0	1.11 a	± 0.11
SL	**		**		**		**		**	

x = mean; sd = deviasion standard: SL = Significant Level; NS = Not Significant; * = Significant at α 5%;

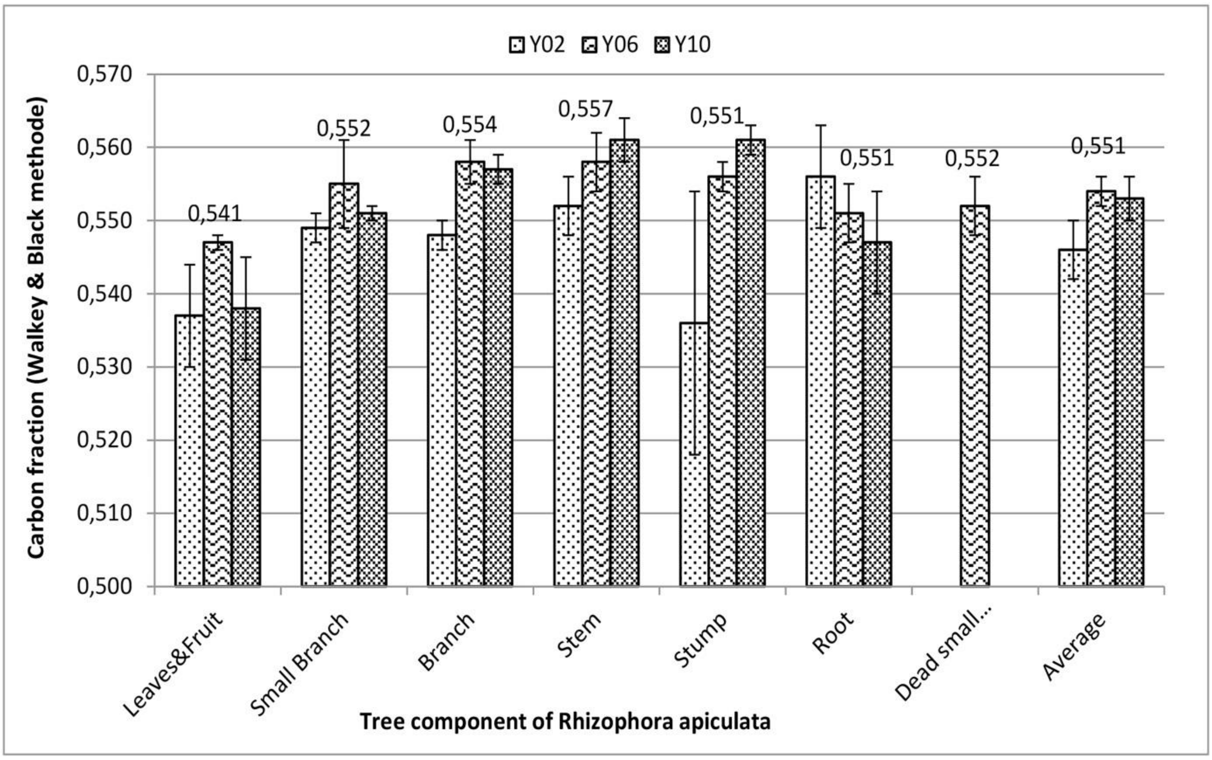
** = Significant at α 1%; n-plot = 15

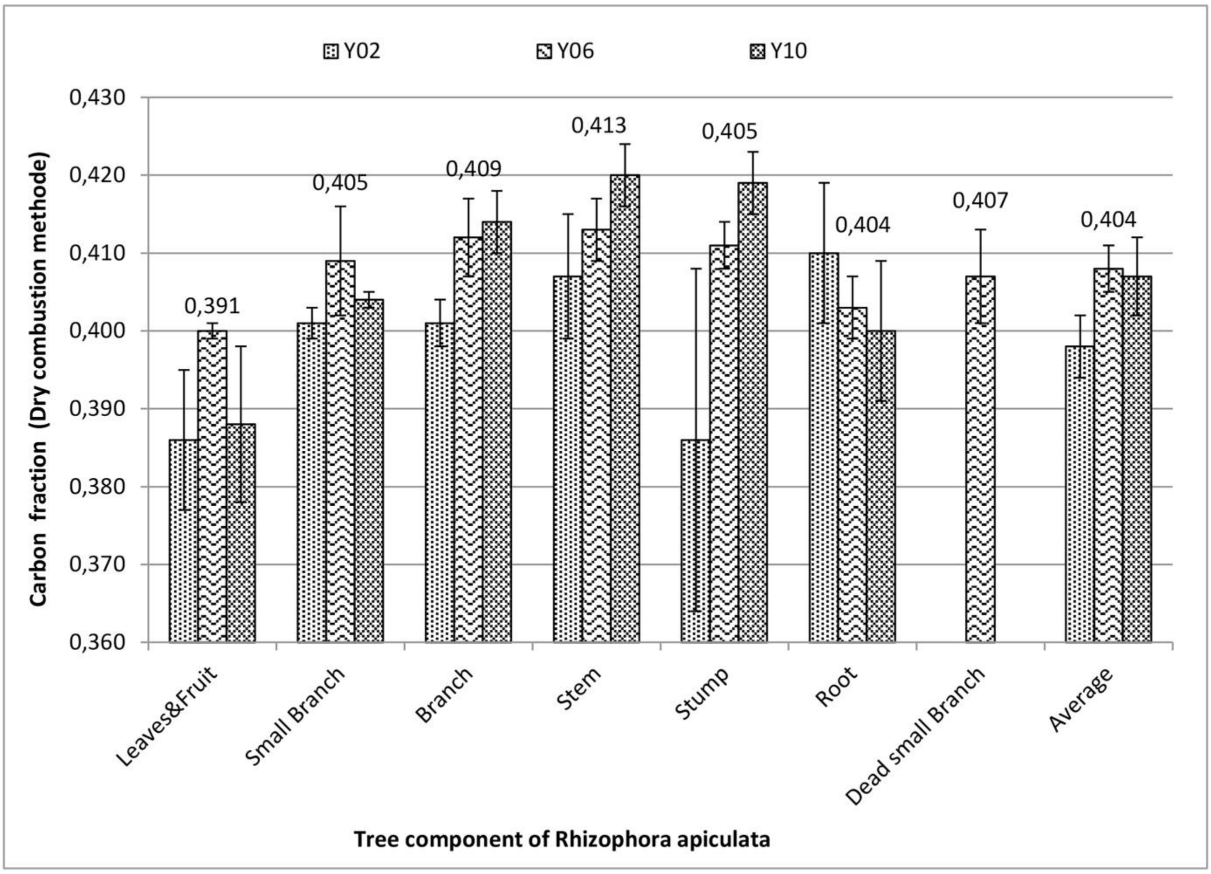
Annex 5. Number of trees and its diameter at destructive sub-plots

Species	Number of trees and average stem diameter		
	2 years	6 years	10 years
Rhizophora apiculata	43 ind (4.0 cm)	91 ind (4.7 cm)	63 ind (5.8 cm)
Sonneratia caseolaris	2 ind (3.0 cm)		
Total	45 ind	91 ind	63 ind

n- trees = 197

Annex 6. Carbon fraction of R. apiculata through Walkley & Black and Dry Combustion





Y02 = 2 years; Y06 = 6 years; Y10 = 10 years

Annex 7. Carbon fractions of *R. apiculata* through Walkley & Black method

	2 years		6 years		10 years	
Tree component	x	± *sd*	x	± *sd*	x	± *sd*
Leaves/fruits/flowers	0.537	± 0.007	0.547	± 0.001	0.538	± 0.010
Twigs	0.549	± 0.002	0.555	± 0.006	0.551	± 0.001
Branches	0.548	± 0.002	0.558	± 0.003	0.557	± 0.004
Stems	0.552	± 0.004	0.558	± 0.004	0.561	± 0.004
Stumps	0.536	± 0.018	0.556	± 0.002	0.561	± 0.004
Roots	0.556	± 0.007	0.551	± 0.004	0.547	± 0.009
Dead woods			0.552	± 0.004		
Average	0.546	± 0.004	0.554	± 0.002	0.553	± 0.005

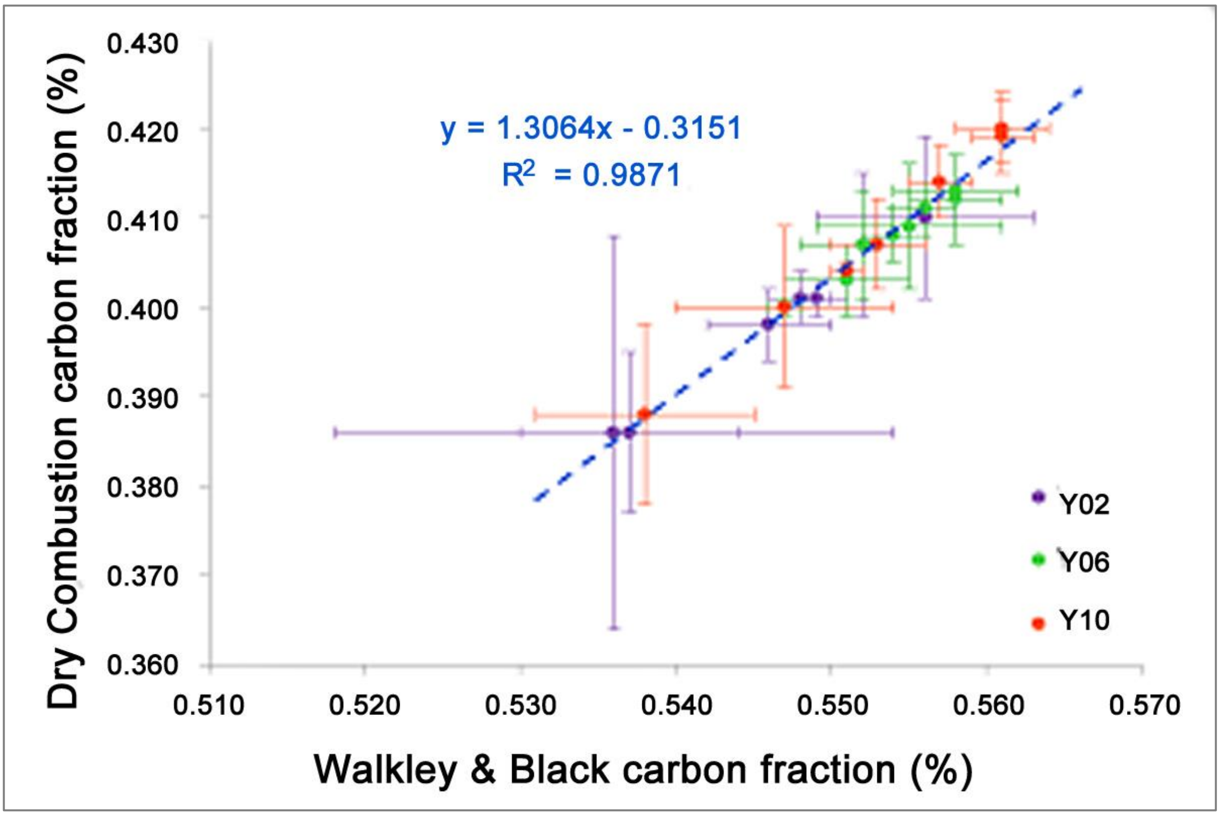
x = mean; sd = deviasion standard; n = 197

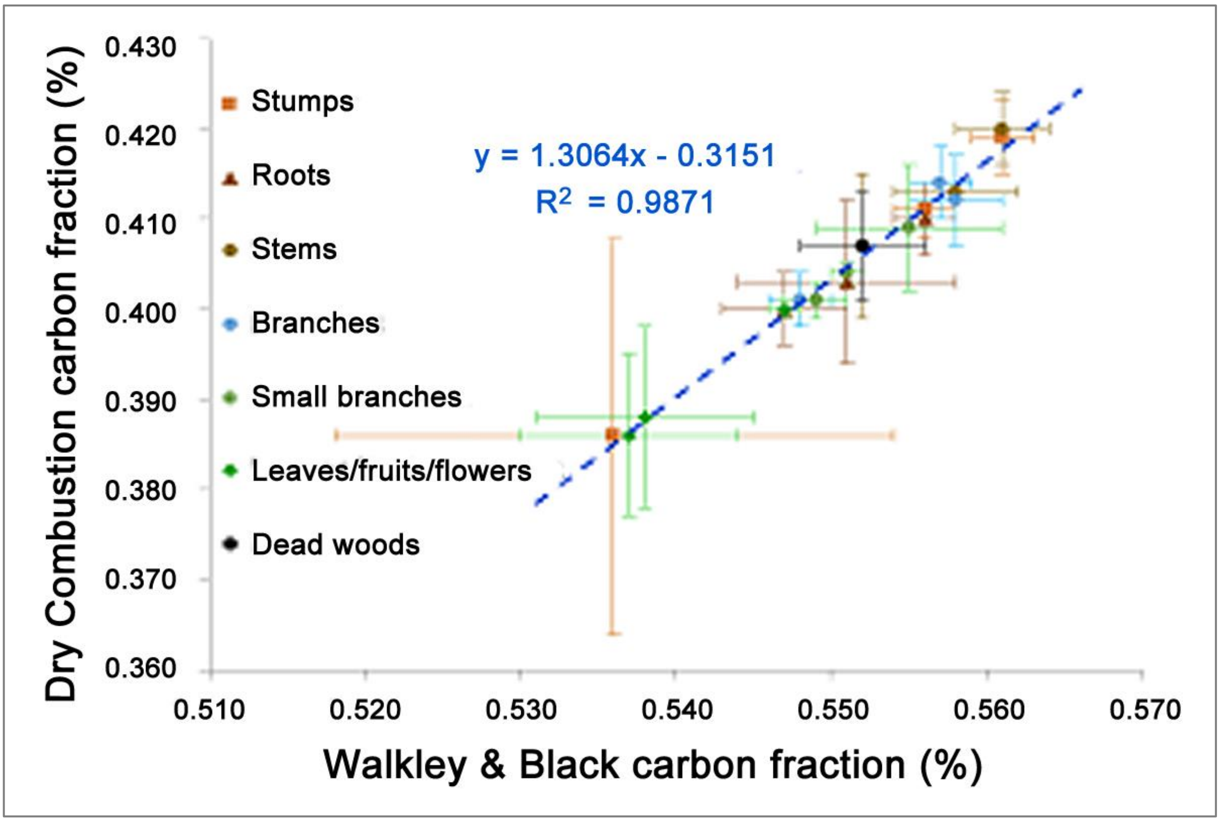
Annex 8. Carbon fractions of *R. apiculata* through Dry Combustion method

	2 years		6 years		10 years	
Tree component	D30	± *sd*	D30	± *sd*	D30	± *sd*
Leaves/fruits/flowers	0.386	± 0.009	0.400	± 0.001	0.388	± 0.010
Twigs	0.401	± 0.002	0.409	± 0.007	0.404	± 0.001
Branches	0.401	± 0.003	0.412	± 0.005	0.414	± 0.004
Stems	0.407	± 0.008	0.413	± 0.004	0.420	± 0.004
Stumps	0.386	± 0.022	0.411	± 0.003	0.419	± 0.004
Roots	0.410	± 0.009	0.403	± 0.004	0.400	± 0.009
Dead woods			0.407	± 0.006		
Average	0.398	± 0.004	0.408	± 0.003	0.407	± 0.005

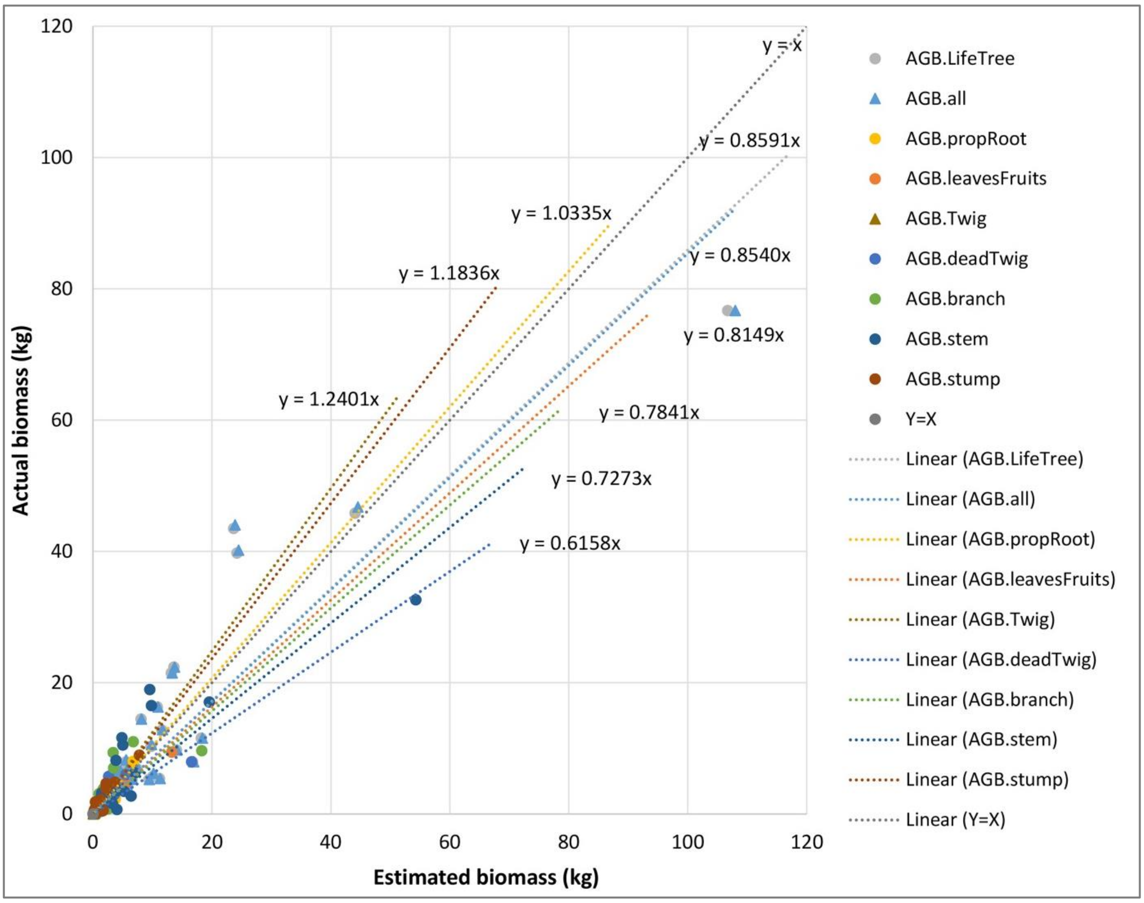
x = mean; sd = deviasion standard; n = 197

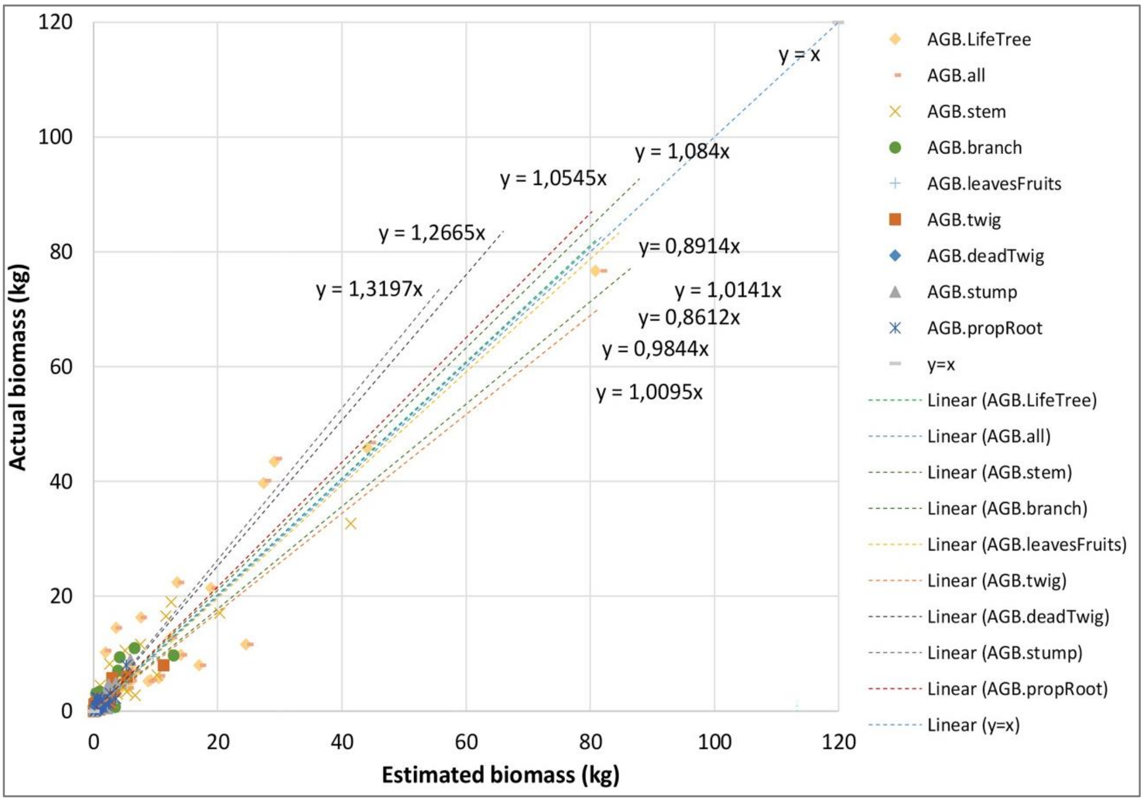
Annex 9. Correlation between Walkley & Black and Dry Combustion carbon fraction based on tree ages and tree components





Annex 10. Allometric regressions of aboveground R. apiculata biomass based on (D_{30}) and $D_{30}{}^2H$





Annex 11. Aboveground biomass of each tree component of *R. apiculata* (kg) based on destructive actual values from laboratory analysis

	2 years			6 years			10 years			(2-10 years)		
Tree components	X	± *sd*	%	X	± *sd*	%	X	± *sd*	%	X	± *sd*	%
Stems	11.0	± 1.2	26.3	47.6	± 1.0	30.7	195.1	± 14.1	39.5	84.6	± 7.5	36.7
Branches	6.5	± 0.9	15.4	17.3	± 0.5	11.1	80.6	± 7.4	16.3	34.8	± 3.9	15.1
Proop-roots	8.9	± 0.5	21.2	34.6	± 0.9	22.3	53.5	± 4.2	10.8	32.4	± 2.0	14.1
Leaf/fruit/flowers	7.3	± 0.5	17.4	18.8	± 0.5	12.1	48.3	± 4.3	9.8	24.8	± 2.2	10.8
Stumps	4.2	± 0.3	10.1	21.5	± 0.7	13.9	65.4	± 5.1	13.2	30.4	± 2.7	13.2
Twigs	4.1	± 0.4	9.7	12.7	± 0.4	8.2	47.9	± 4.6	9.7	21.6	± 2.4	9.4
AGB	**42.0**	**± 3.6**		**152.5**	**± 3.0**		**490.9**	**± 35.5**		**228.5**	**18.6**	
Deadwoods	0.0			2.5	± 0.2		2.8	± 0.7		1.8	± 0.4	
AGB+deadwoods	42.0	± 3.6		155.0	± 3.1		493.6	± 35.7		230.2	± 18.7	

AGB = Above Ground Biomass (MgC ha^{-1}); X = average C-stocks; sd = deviation standard; n = 197

Annex 12. Aboveground biomass of each tree component of *R. apiculata* (kg) based on desructive allometric estimation of D_{30} variable

	2 years			6 years			10 years			(2-10 years)		
Tree components	X	± *sd*	%	X	± *sd*	%	X	± *sd*	%	X	± *sd*	%
Stems	16.6	±1.3	31.6	50.7	±1.2	32.2	95.1	±8.1	39.8	54.1	±4.0	36.2
Branches	6.2	±0.5	11.8	18.8	±0.4	11.9	31.4	±3.0	13.1	18.8	±1.5	12.6
Proop-roots	9.3	±0.4	17.8	25.7	±0.3	16.3	26.7	±1.2	11.2	20.6	±0.5	13.8
Leaf/fruit/flowers	6.4	±0.4	12.3	18.8	±0.4	11.9	26.5	±2.3	11.1	17.3	±1.1	11.5
Stumps	6.0	±0.3	11.4	17.4	±0.3	11.1	22.0	±1.3	9.2	15.1	±0.6	10.1
Twigs	3.9	±0.3	7.5	12.2	±0.3	7.8	24.3	±2.8	10.2	13.5	±1.4	9.0
AGB	**51.8**	**±3.3**		**156.0**	**±3.1**		**236.5**	**±16.3**		**148.1**		
Deadwoods	0.0			2.1	±0.1		1.8	±0.3		1.3		
AGB+deadwoods	52.3	±3.4		157.4	±3.1		239.0	±16.5		149.6		

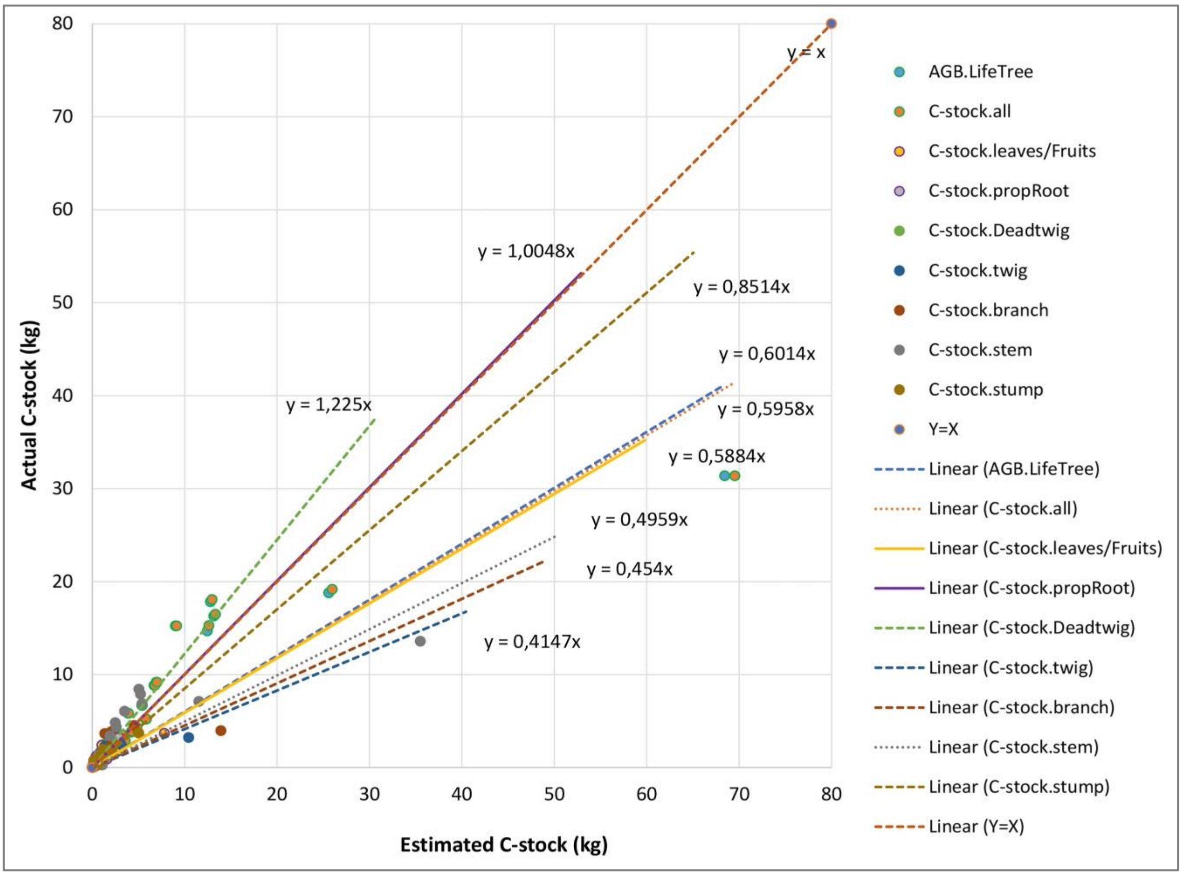
AGC = Above Ground Carbon (kg); X = average C-stocks; sd = deviation standard; n = 197

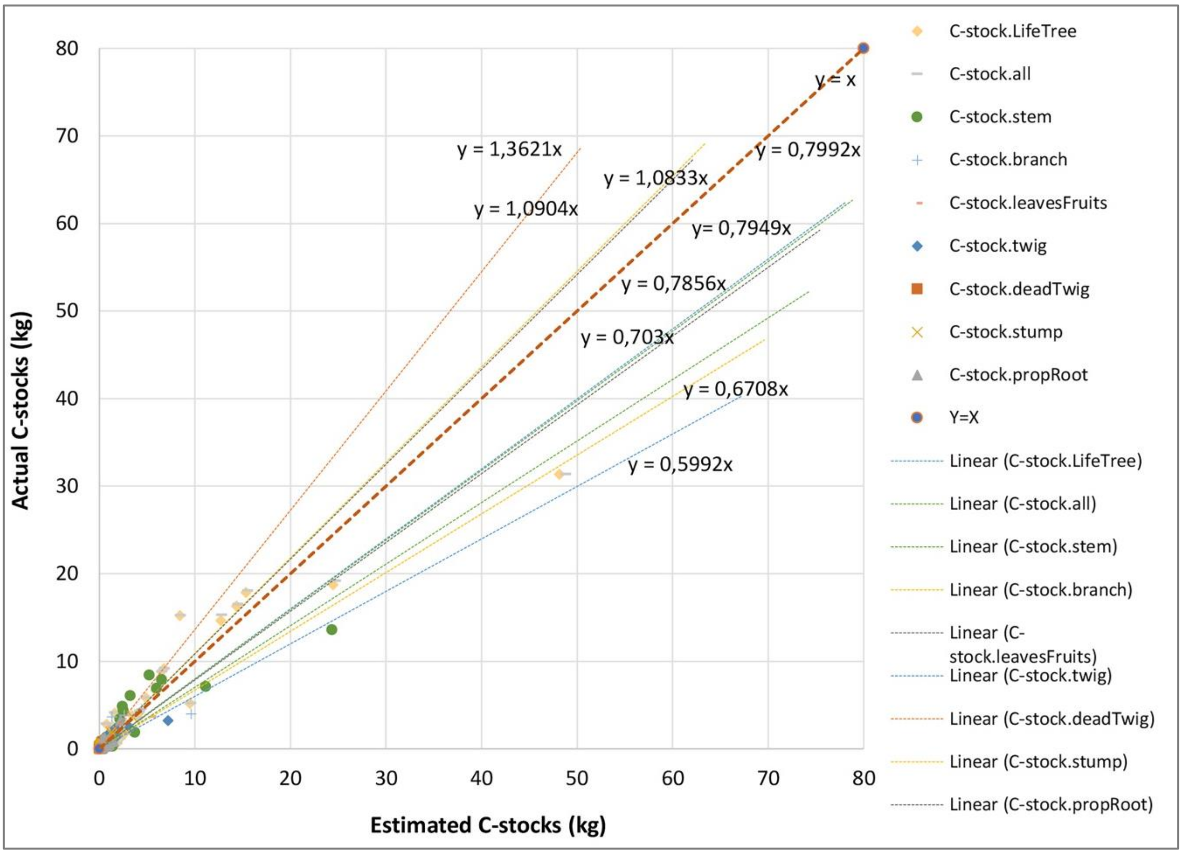
Annex 13. Aboveground biomass of each tree component of *R. apiculata* (kg) based on desructive allometric estimation of D_{30}^2H variable

	2 years			6 years			10 years			(2-10 years)		
Tree components	X	± *sd*	%	X	± *sd*	%	X	± *sd*	%	X	± *sd*	%
Stems	14.4	±1.2	31.1	57.3	±1.2	32.6	105.7	±7.3	41.2	59.1	±3.2	37.1
Branches	5.4	±0.4	11.7	21.1	±0.4	12.0	35.1	±2.4	13.7	20.5	±1.1	12.9
Proop-roots	3.4	±0.3	7.4	13.8	±0.3	7.8	26.7	±2.1	10.4	14.6	±0.9	9.2
Leaf/fruit/flowers	5.7	±0.4	12.3	21.0	±0.4	11.9	29.7	±1.9	11.6	18.8	±0.9	11.8
Stumps	5.4	±0.3	11.7	19.1	±0.3	10.9	23.0	±1.2	8.9	15.8	±0.6	9.9
Twigs	8.6	±0.3	18.6	27.8	±0.3	15.8	27.1	±1.1	10.6	21.2	±0.6	13.3
AGB	**45.8**	**±3.2**		**174.0**	**±3.0**		**254.0**	**±15.1**		**157.9**	**±7.1**	
Deadwoods				2.5	±0.1		1.9	±0.3		1.5	±0.2	
AGB+deadwoods	46.2	±3.2		175.7	±3.0		256.7	±15.2		159.5	±7.2	

AGC = Above Ground Carbon (kg); X = average C-stocks; sd = deviation standard; n = 197

Annex 14. Allometric regressions of aboveground R. apiculata carbon stocks based on (D_{30}) and D_{30}^2H





Annex 15. Aboveground C-content of each tree component of *R. apiculata* (kg) based on destructive actual values from laboratory analysis

	2 years			6 years			10 years			(2-10 years)		
Tree components	X	± *sd*	%	X	± *sd*	%	X	± *sd*	%	X	± *sd*	%
Stems	4.6	±0.5	26.5	19.6	±0.4	31.2	80.6	±5.8	40.1	34.9	±2.2	37.3
Branches	2.7	±0.4	15.4	7.1	±0.2	11.2	33.0	±3.0	16.4	14.2	±1.2	15.2
Proop-roots	3.6	±0.2	20.9	14.0	±0.4	22.2	21.6	±1.7	10.8	13.1	±0.7	13.9
Leaf/fruit/flowers	2.9	±0.2	16.6	7.4	±0.2	11.7	18.9	±1.7	9.4	9.7	±0.7	10.3
Stumps	1.7	±0.1	10.0	8.7	±0.3	13.8	26.5	±2.1	13.2	12.3	±0.8	13.1
Twigs	1.6	±0.2	9.6	5.2	±0.2	8.2	19.4	±1.9	9.6	8.7	±0.7	9.3
AGC	**17.0**	**±1.5**		**61.9**	**±1.2**		**200.0**	**±14.5**		**93.0**	±5.7	
Deadwoods	0.0			1.0			1.1					
AGC+deadwoods	17.2	±1.5		62.9	**±1.2**		201.1	**±14.5**		93.7	±5.7	

AGC = Above Ground Carbon (MgC ha^{-1}) calculated by total of tree components; X = average C-stocks;
sd = deviation standard; n = 197

Annex 16. Aboveground C-content of each tree component of *R. apiculata* (kg) based on desructive allometric estimation of D_{30} variable

	2 years			6 years			10 years			(2-10 years)		
Tree components	X	± *sd*	%	X	± *sd*	%	X	± *sd*	%	X	± *sd*	%
Stems	7.7	± 0.7	32.1	23.9	±0.6	32.5	53.1	±5.2	40.9	28.2	±2.1	37.3
Branches	3.0	± 0.3	12.7	9.5	±0.2	12.9	19.8	±2.2	15.3	10.8	±0.9	14.2
Proop-roots	3.9	± 0.2	16.4	10.9	±0.1	14.8	11.3	±0.5	8.8	8.7	±0.3	11.5
Leaf/fruit/flowers	2.8	± 0.2	11.8	8.4	±0.2	11.5	13.7	±1.3	10.6	8.3	±0.6	11.0
Stumps	2.7	± 0.2	11.3	8.0	±0.2	10.9	11.7	±0.8	9.0	7.5	±0.4	9.9
Twigs	1.8	± 0.2	7.4	5.6	±0.2	7.6	13.3	±1.7	10.3	6.9	±0.7	9.1
AGC	**23.7**	**± 1.7**		**72.7**	**± 1.6**		**128.0**	**± 10.0**		**74.7**	**± 4.5**	
Deadwoods				0.9	± 0.0		0.8	± 0.1		*0.6*	± *0.1*	
AGC+deadwoods	23.9	± 1.8		73.5	± 1.6		129.7	± 10.2		75.7	± 4.5	

AGC = Above Ground Carbon (kg) estimated D_{30} allometry; X = average C-stocks; sd = deviation standard;
n = 197

Annex 17. Aboveground C-content of each tree component of *R. apiculata* (kg) based on desructive allometric estimation of $D_{30}^{2}H$ variable

	2 years			6 years			10 years			(2-10 years)		
Tree components	X	± *sd*	%	X	± *sd*	%	X	± *sd*	%	X	± *sd*	%
Stems	6.1	±0.6	31.1	25.1	±0.6	32.4	54.5	±4.1	41.2	28.6	±1.8	37.3
Branches	2.5	±0.2	71.5	10.2	±0.2	13.2	21.6	±1.7	16.3	11.4	±0.7	15.0
Proop-roots	1.5	±0.2	7.7	6.3	±0.1	8.1	14.9	±1.3	11.2	7.6	±0.5	9.9
Leaf/fruit/flowers	2.3	±0.2	11.8	8.9	±0.2	11.4	14.6	±1.0	11.1	8.6	±0.5	11.2
Stumps	2.3	±0.1	11.5	8.4	±0.1	10.8	11.5	±0.7	8.7	7.4	±0.3	9.6
Twigs	3.5	±0.1	17.8	11.3	±0.1	14.6	11.2	±0.5	8.5	8.7	±0.3	11.3
AGC	**19.4**	**±1.6**		**76.7**	**±1.5**		**130.8**	**±8.5**		**75.6**	**±3.9**	
Deadwoods				1.0	±0.0		0.7	±0.1		0.6	±0.1	
AGC+deadwoods	19.6	±1.6		77.6	±1.5		132.5	±8.6		76.5	±3.9	

AGC = Above Ground Carbon (kg) estimated D_{30} allometry; X = average C-stocks; sd = deviation standard;
n = 197

REFERENCES

[1] Kusmana, C., S. Sabiham, K. Abe and H. Watanabe. An estimation of above ground tree biomass of a mangrove forest in East Sumatra, Indonesia. Tropics, Vol. 1(4): 243-257. 1992.

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

[3] Ong, J.E., Gong, W.K., Wong, C.H. Studies on nutrient levels in standing biomass, litter and slash in a mangrove forest. BIOTRP, Bogor, p.44. 1982.

[4] Ong, J.E., Gong, W.K., Wong, C.H. Allometry and partitioning of the mangrove, *Rhizophora apiculata*. Forest Ecol. Manage. 188: 395-408. 2004.

[5] Ketterings, Q.M., R. Coe, M. Van Nordwijk, Y. Ambagau and C.A. Palm. Forest Ecology and Management 146: 199 – 209. 2001.

[6] Comley, B.W.T. and K.A. McGuiness. Above- and below ground biomass, and allometry, of four common northern Australian mangroves. Australian Journal of Botany, 53: 431-436. 2005.

[7] Komiyama, A., Ogino, K., Akasornkoae, S. Sabhasri, S. Root biomass of a mangrove forest in Southern Thailand. 1. Estimation by the trench method and zonal structure of root biomass. J. Trop. Ecol. 3 : 97-108. 1987.

[8] Komiyama, A., Moriya, H., Prawiroatmodjo, S., Toma, T., Ogino, K. Forest primary productivity. In: Ogino, K., Chihara, M. (Eds.), Biological System of Mangrove, Ehime University, pp. 97-117. 1988.

[9] Komiyama, A., Havanond, S., Srisawatt, W., Mochida, Y., Fujimoto, K., Ohnishi, T., Ishihara, S., Miyagi, T. Top/root biomass ratio of a secondary mangrove (*Ceriops tagal* (Perr.) C.B. Rob.) forest. Forest Ecol. Manage. 139: 127-134. 2000.

[10] Komiyama, A., J.E. Ong, and S. Poungparn. Allometry, biomass, and productivity of mangrove forests: A review. Aquat.Bot. 89:128-137. 2008.

[11] Chandra, I.A., Seca, G., Abu Hena, M.K. Aboveground biomass production of *Rhizophora apiculata* Blume in Sarawak mangrove forest. American Journal of Agricultural and Biological Sciences 6 (4): 469-474. 2011.

[12] Rutishauser, E., F. Noor'an, Y. Laumonier, J. J. Halperin, Rufi'e, K. Hergoualch and L. Verchot. Generic allometric models including height best estimate forest biomass and carbon stocks in Indonesia. Forest Ecology and Management, 307: 219-225. 2013.

[13] Sitoe, A.A., L.J.C. Mandlate and B.S. Guedes. Biomass and carbon stocks of Sofala Bay mangrove forests. Forest, 5: 1967-1981. 2014.

[14] Alemayehu, F., Richard, O., James, K.M., Wasonga, O. Assessment of mangrove covers change and biomass in Mida Creek, Kenya. Open Journal of Forestry 4: 398-413. 2014.

[15] Tamooh, F., J.G. Kairo, M. Huxham, B. Kirui, M. Karachi, M. Mencuccini. Biomass accumulation in a rehabilitated mangrove forest at Gazi Bay. In Advances in Coastal Ecology : People, Processes and Ecosystems in Kenya., 138-147. African Studies Centre. 2008.

[16] Kairo, J.G., J.K.S. Lang'at, F. D. Guebas, J. Bosire and M. Karachi. Structural development and productivity of replanted mangrove plantions in Kenya. Forest Ecology and Management 255: 2670 – 2677. 2008.

[17] Murdiyarso, D.K., Hairiah, K., and Van Noorwidjk. Modelling and Measuring Soil Organic Matter Dynamic and Greenhouse gas Emission After Forest Conversion. Report of Workshop, Training Course. August 8-15. 1994.

[18] Murdiyarso, D., Purbopuspito, J., Kauffman, J. B., Warren, M. W., Sasmito, S. D., Donato, D. C. & Kurnianto, S. The potential of Indonesian mangrove forests for global climate change mitigation. Nature Climate Change. DOI: 10.1038/NCLIMATE2734. 2015.

[19] Page SE, Rieley JO, Banks CJ. Global and regional importance of the tropical peatland carbon pool. Glob. Change Biol. 17:798–818. 2011.

[20] Hooijer, A., Silvius, M., Wösten, H. and Page, S. PEAT-CO_2, Assessment of CO_2 emissions from drained peatlands in SE Asia. Delft Hydraulics report Q3943. 2006.

[21] Gilman, E.L., J. Ellison, N.C. Duke and C. Field. Threats to mangroves from climate change and adaptation options. Aquatic Botany. 2008.

[22] UNEP. Assessment and Monitoring of Climatic Change Impacts on Mangrove Ecosystems. UNEP Regional Seas Reports and Studies No 154. Nairobi, Kenya: United Nations Environment Programme: 62 pp. 1994.

[23] *Sedjo. Roger; Sohngen. Brent.* "Carbon Sequestration in Forests and Soils". Annual Review of Resource Economics. Annual Reviews . 4:127–144. doi:10.1146/annurev-resource-083110-115941. *2012.*

[24] Thomas, S.C. and Martin, A.R. Carbon Content of Tree Tissues: A Synthesis. Forests 2012, 3, 332-352; doi:10.3390/f3020332. 2012.

[25] Ellison, A.M. Managing Mangroves with Benthic in Mind: Moving Beyond Roving Banditry. Journal of Sea Research. 59: 2-15. 2008.

[26] Alongi. Mangrove forests: resilience, protection from tsunamis, and responses to global climate change. Estuarine, Coastal and Shelf Science, Vol 75 (1): 1-13. 2011.

[27] Christensen, B. Biomass and productivity of Rhizophora apiculata B1 in a mangrove in Southern Thailand. Aquat. Bot. 4: 43-52. 1978.

[28] Kauffman J.B. and T. Cole. Micronesian mangrove forest structure and tree response to a severe typhoon. Wetlands 30: 1077 - 1084. 2010.

[29] Kauffman J.B., C. Heider, T. Cole, K.A. Dwire, D.C. Donato. Ecosystem Carbon Stocks of Micrinesian mangrove forests. Wetlands 31: 343 – 352. 2011.

[30] Kauffman J. B. and D.C. Donato. Working Paper: Protocols for the measurement, monitoring and reporting of structure,

biomass and carbon stocks in mangrove forests. Center for International Forestry Research. Bogor. 2012.

[31] Manson, F.J., Loneragan, N.R., Harch, B.D., Skilleter, G.A., Williams, L. A broad-scale analysis of links between coastal fisheries production and mangrove extent: a case-study for northeastern Australia. Fish. Res. 74, 69–85. 2005.

[32] Matsui, N., K. Morimune, W. Meepol and J. Chukwamdee. Ten years evaluation of carbon stock in mangrove plantation reforested from an abandoned shrimp pond. 2012.

[33] Fromard, F., Puig, H., Mougin, E., Marty, G., Betoulle, J.L., Cadamuro, L. Structure above-ground biomass and dynamics of mangrove ecosystems: new data from Frech Guiana. Oecologia 115: 39-53. 1998.

[34] Slim, F.J., Gwada, P.M., Kodjo, M. Kemminga, M.A. Biomass and litterfall of *Ceriops tagal* and *Rhizophora mucronata* in the mangrove forest of Gazy Bay, Kenya. Mar. Freswater Res. 47: 999-1007. 1996.

[35] Pachpande, S.C. and M. Pejaver. Natural carbon sequestration by dominant mangrove species *Avicennia marina* var. accutissima ex staf & Modelke ex Modelke found across Thane creek, Maharashtra, India. International Journal of Scientific & Engineering Research, Vol 6(2). 2015.

[36] Amarasinghe, M.D. and Balasubramaniam, S. Net primary productivity of two mangrove stands on the Northwest coast of Sri Lanka. Hydrobiologia 247: 37-47. 1992.

[37] Poungparn, S. Commmon allometric relationships for estimating the biomass of mangrove forests. PhD. Dessertation, Gifu Univerisity, 87pp. 2003.

[38] Steinke, T.D., Ward, C.J., Rajh, A. Forest structure and biomass of mangroves in the Mgeni estuary, South Africa. Hydrobilogia 295: 159-166. 1995.

[39] Suzuki, E., Tagawa, E. Biomass of a mangrove forest and a sedge marsh of Ishigaki island, South Japan. Jpn. J. Ecol. 33: 231-234. 1983.

[40] Mall, L.P., Singh, V.P., Garge, A. Study of biomass, litter fall,litter decomposition and soil respirationin monogenetic mangrove and mixed mangrove forets of Andaman island. Trop. Ecol. 32: 144-152. 1991

[41] Briggs, S.V. Estimates of biomass in a temperate mangrove community. Aust. J. Ecol. 2: 369-373. 1977.

[42] Sherman, R.E., Fahey, T.J. Martinez, P. Special patters of biomass and aboveground net primary productivity in a mangrove ecosystem in the Dominican Republic. Ecosystems 6: 384-398. 2003.

[43] Clough, B.F., Ong, J.E. and W.K. Gong. Estimating Leaf Area Index and Photosynthetic Production in Canopies of the Mangrove *Rhizophora apiculata*. Marine Ecology Progress Series. 159: 285 – 292. 1997.

[44] Clough, B.F., D.T. Tan, D.C. Buu and D.X. Phuong. Mangrove Forest Structure and Growth. Canberra, Australia. pp 235 – 251. 1999.

[45] Clough, B.F. and Scott, K. Allometric relationships for estimating aboveground biomass in six mangrove species. Forest Ecol. Manage. 27: 117-127. 1989.

[46] Clough, B.F., Andrews, T.J., Cowan, I.R. Physiological processes in mangroves. In: Clough, B.F. (ed) Mangrove Ecosystems in Australia: Structure, Function and Management. ANU Press, Canbera, pp 193-210. 1982.

[47] Wilkie, M.L. and S. Fortuna. Status and Trends in Mangrove Area Extent Worldwide. Food and Agriculture Organization of the United Nations, Rome, Italy. 2003.

[48] Sathiratai, S. and E.B. Barbier. Valuing Mangrove Conservation in Southern Thailand. Contemp. Econ. Policy. 19: 109-122. 2001.

[49] Day Jr, J.W., C.C. Molina, F.R.V. Herrera, R. Twilley, V.H.R. Monroy, H.A. Guillen, R. Day and W. Corner. A 7 years record of above-ground primary production in a southern Mexican mangrove forest. Aquatic Botany 55: 39 – 60. 1996.

[50] Warrick, R.A. Carbon dioxide, climatic change and agriculture. Geogr. J. 154:221–233. doi:10.2307/633848. 1988.

[51] Suprayogi, B., Hamy, S., Suriani, M., Rahayu, S. and Suharto, B. Preliminary Research: Carbon, Community and Biodiversity (CCB) Study. Medan-Indonesia. 2010.

[52] Hoque, A.T.M.R., S. Sharma and A. Hagihara. Carbon Acquisition of mangrove Kandelia obovate trees. Proc. Of International Conference on Environmental Aspects of Bangladesh (ICEAB10), Japan. 2010.

[53] Coronado-Molina, C., Day, J.W., Reyes, E., Perez, B.C. Standing crop and aboveground biomass partitioning of a dwarf mangrove forest in Taylor River Slough, Florida. Wetlands Ecology and Management 12: 157 - 164. 2004.

[54] Gong, W.K. and J.E. Ong. Plant biomass and nutrient flux in a managed mangrove forest in Malysia. Estuarine, Coastal and Shelf Science, 31: 519-530. 1990.

[55] Lugo, A.E. and S.C. Snedaker. The Ecology of Mangroves. Annual Review of Ecology and Systematic, 5: 39 - 63. 1974.

[56] Putz, F., Chan, H.T. Tree growth, dynamics, and productivity in mature mangrove forest in Malaysia. Forest Ecol. Manage. 17: 211-230. 1986.

[57] Tamai, S. S., Nakasuga, T., Tabuchi, R., Ogino, K. Standing biomass of mangrove forests in Southern Thailand. J. Forest Soc. 68: 384-388. 1986.