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Aboveground biomass, productivity and carbon sequestration in *Rhizophora stylosa* mangrove forest of Southeast Sulawesi, Indonesia

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Abstract. *Analuddin K, Kadidae LO, Haya LOMY, Septiana A, Sahidin I, Syahrir L, Rahim S, Fajar LOA, Nadaoka K. 2020. Aboveground biomass, productivity and carbon sequestration in* Rhizophora *stylosa mangrove forest of Southeast Sulawesi, Indonesia. Biodiversitas 21: 1316-1325.* This study was aimed at analyzing the trends of aboveground biomass (AGB), productivity and carbon sequestration of *Rhizophora stylosa* Griff. forest in Rawa Aopa Watumohai National Park (RAWNP), Southeast Sulawesi, Indonesia. The DBH was the best predictor for partial and whole AGB of *R. stylosa* trees. The mean AGB was 562.76 ton ha^{-1}. The yearly biomass increment of living trees, biomass increment of whole stands, standing dead biomass, and litterfall in *R. stylosa* forest were estimated as 52.87, 50.09, 2.78 and 12.00 ton ha^{-1}, respectively, while its net primary production was about 64.88 ton ha^{-1} yr^{-1} indicating higher mangrove productivity. The total carbon stock in *R. stylosa* forest was 264.50 ton ha^{-1}, while the annual net carbon budget, carbon gain and carbon input in *R. stylosa* forest was 23.54, 24.85 and 5.64 ton ha^{-1}. However, the total CO_2 stored in *R. stylosa* forest was 969.83 ton ha^{-1}, while the annual of net CO_2 uptake, CO_2 gained and CO_2 input was 86.33, 91.12 and 20.86 ton ha^{-1}. The higher carbon sequestration and CO_2 uptake in *R. stylosa* forest indicate its significant role in the global carbon accumulation and reducing atmospheric CO_2.

Keywords: Carbon sequestration, carbon stock, mangrove biomass, mangrove productivity, *Rhizophora stylosa* forest

INTRODUCTION

Mangroves play an important role as source of carbon and nutrients in the coastal area (Clough 1992, 1998; Twilley et al, 1992; 1995). The mangroves are known to sequestrate organic matter and are capable of accumulating and storing carbon and nutrients in the soil (Spalding et al. 2010). Several studies have mentioned the mangrove litterfall as a major source of organic matter and nutrients for adjacent coastal areas (Twilley 1998; Alongi and Dixon 2000). Large amounts of mangrove litter are the most important sources of food and energy for all living organisms in coastal ecosystem (Hoque at 2015; Kristensen and Suraswadi 2002). Mangrove litter may enter into the rivers and streams when rain or tides inundate the forest, and decompose either in the source forest or in the river, with nutrients being retained or exported (Conacher et al. 1996).

High rate of primary production of mangroves has been verified on the coastlines, and biomass and productivity of mangroves are the two important parameters for elucidating the material and nutrient inputs in the mangrove ecosystem (Sherman et al 2003). Many studies have developed the biomass estimation methods for mangroves such as harvest method, mean-tree method and allometric method (Golley et al. 1975; Ketterings et al. 2001). The allometric method is the most frequently used method for estimating the mangrove forests biomass from measurable tree dimensions (Clough and Son 1989; Clough 1997, Komiyama et al. 2005, 2008; Mahmood et al. 2004, 2012). Meanwhile, allometric models for biomass estimation vary greatly among the species and sites, even in the mangroves grown in the same region (Analuddin et al. 2016b, 2018; Komiyama et al. 2008). Therefore, Ketterings et al. (2001) mentioned that it is preferable to use species and site-specific models for biomass estimation. Many allometric studies for mangroves biomass estimation have been reported (Deshar et al. 2012; Mahmood et al. 2012; Siddique et al. 2012). In some recent reports, allometric models and biomass estimation have been studied for mangroves growing in coral triangle ecoregion (Analuddin et al. 2016b, 2018).

Mangrove is one among the important coastal ecosystems in the coral triangle ecoregion Southeast Sulawesi, which play a very important role as a biofilter of heavy metals pollutants (Analuddin et al. 2017). Therefore, the mangroves maintain the health of coastal and marine ecosystems in coral triangle ecoregion. Although several studies in the coral triangle areas on mangroves allometric models and their biomass estimation (Analuddin et al 2016b, 2018), mangrove bioprospecting (Septiana et al. 2016; Analuddin et al. 2019) as well as the mangrove blue carbon stock (Analuddin et al. 2016a) have been undertaken so far, meager information is available regarding productivity and carbon sequestration of mangrove forests of this region. Therefore, the current study was undertaken in the coral triangle ecoregion, i.e. Rawa Aopa Watumohai National Park (RAWNP), Southeast Sulawesi, Indonesia with the objectives of estimation of aboveground biomass and productivity of *Rhizophora stylosa* mangrove forest, and elucidation of its carbon stock and carbon sequestration.

MATERIALS AND METHODS

Study site

This study was carried out at the mangrove forest of Rawa Aopa Watumohai National Park (RAWNP) of coral triangle ecoregion, Southeast Sulawesi, Indonesia (Figure 1), which is located at the eastern part of Kendari city (S: 04º33'12.1" and E: 122º0.3'20.4"). The mangrove tree species *Rhizophora stylosa* Griff. (Rhizophoraceae) has limited distribution in the coral triangle ecoregion. Its growth is restricted to the protected areas, but it was rarely present in unprotected areas. *R. stylosa* grows mostly in the soft muddy sites of the RAWNP (Analuddin et al. 2013). Mangroves at protected areas of Southeast Sulawesi, including RAWNP, have been recognized as an important conservation area and habitat for the endemic animal *Bubalus* sp. (Septiana et al. 2016).

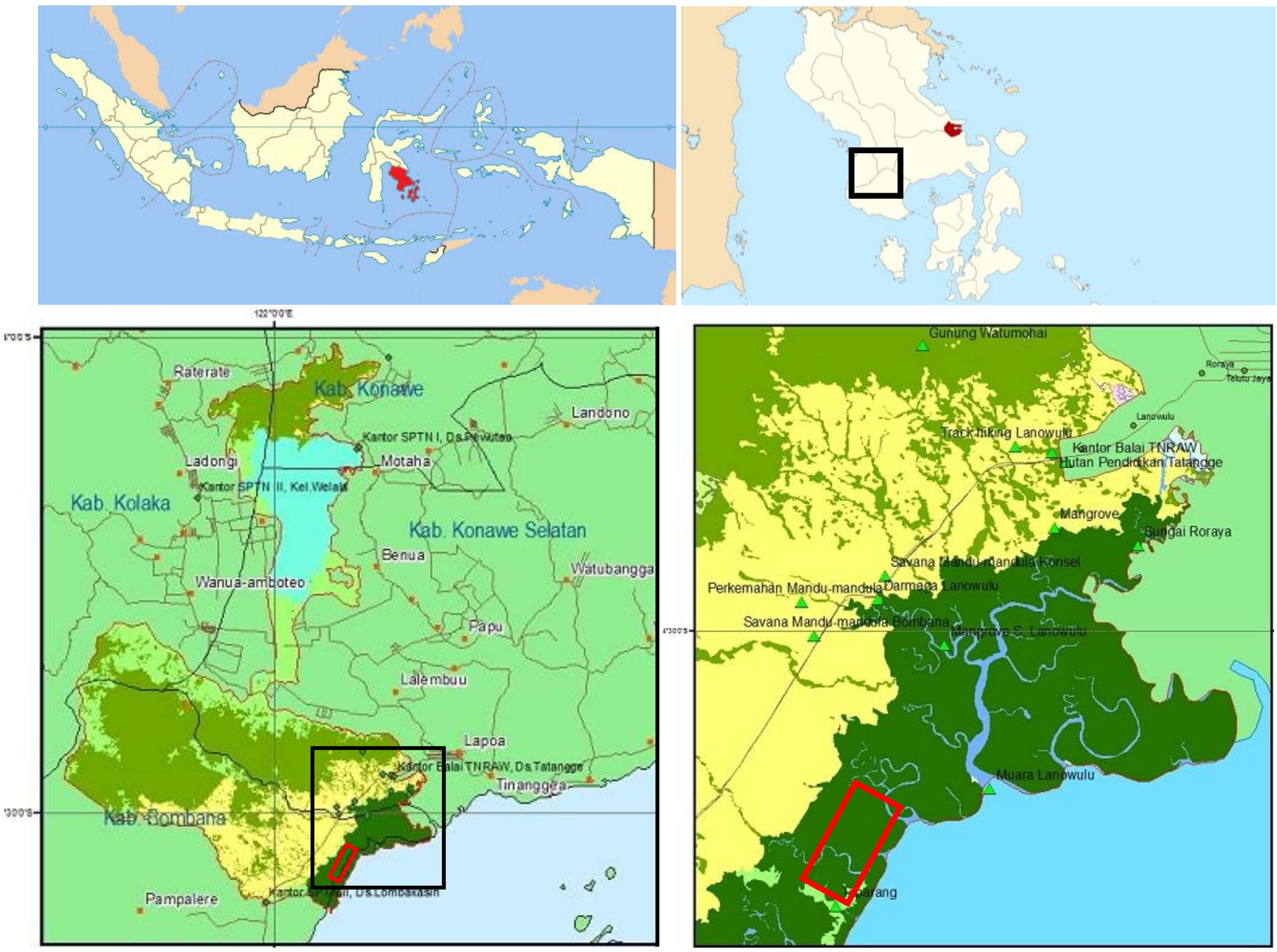

Figure 1. Map of mangrove forest of Rawa Aopa Watumohai National Park in Southeast Sulawesi, Indonesia (S: 04°33'12.1" and E: 122°0.3'20.4"). Red box: study location (*Rhizophora stylosa* forest)

Procedures

Sampling for allometric models

Allometric models were established by selecting eight individual trees in different size classes of *Rhizophora stylosa*. All selected trees were harvested, and divided into main stem, branch/twig, leaf as well as prop root components. The main stem was cut into pieces of 1 m length, from the base to the top. All fresh weight of tree components were measured of their weight at the sample plot. About 10 cm sized discs were cut from each 1m length main stem segments and taken together with branches/twigs, prop roots and leaves to the Biology Laboratory at Halu Oleo University. Samples were oven-dried to 80°C until mass remains constant. The dry mass of *Rhizophora stylosa* trees parts (stem, branch/twig, leaf and prop roots) were estimated as dry/fresh biomass ratios (Brown et al. 1997).

Sampling for biomass and productivity

Analysis of biomass and productivity of *Rhizophora stylosa* forest was carried out by marking 3 permanent plots, each of 300 m^2 wide. All individual trees in each plot were numbered, and tree census was conducted during 2014 and 2015. The stem diameter at breast height (DBH) was measured in the entire plot, using diameter tape. In addition, the litterfalls were collected from March 2014 to February 2015 by using 15 net traps (circle net trap with 0.5 cm of mouth diameter, and 1 mm mesh). The net traps were put 1.5 m above soil, while monthly litterfalls were collected at the end of every month. The litterfalls were collected in plastic bags and brought to the laboratory, and sorted according to leaf, branch/twig, and reproductive parts. Each litterfall part then placed in envelopes, dried at 80°C for two days, and then weighted separately.

Data analysis

Allometric models equations

Allometric models for estimation of stem weight w_S, branch weight w_B, leaf weight w_L and prop root weight w_R of *Rhizophora stylosa* trees were established using independent variables D_{30}, DBH, D_{30}^2H and DBH^2H. The equation forms were developed by using the method of Khan et al. (2018). The allometric models for estimation of w_S, w_B, w_L and w_R of *R. stylosa* trees were developed in the form of equations of one and two dimensions, as follows:

$w_S = a_0 D_{30}^{a1}$
$w_S = a_0 D_{BH}^{a1}$
$w_S = a_0 (D_{30}^2 \times H)^{a1}$
$w_S = a_0 (D_{BH}^2 \times H)^{a1}$
$w_B = b_0 D_{30}^{b1}$
$w_B = b_0 D_{BH}^{b1}$
$w_B = b_0 (D_{30}^2 \times H)^{b1}$
$w_B = b_0 (D_{BH}^2 \times H)^{b1}$
$w_L = c_0 D_{30}^{c1}$
$w_L = c_0 D_{BH}^{c1}$
$w_L = c_0 (D_{30}^2 \times H)^{c1}$
$w_L = c_0 (D_{BH}^2 \times H)^{c1}$
$w_R = t_0 D_{30}^{t1}$
$w_R = t_0 D_{BH}^{t1}$
$w_R = t_0 (D_{30}^2 \times H)^{t1}$
$w_R = t_0 (D_{BH}^2 \times H)^{t1}$

Where; D_{30} is stem diameter at 30 cm from the ground, DBH is stem diameter at breast height (1.3m from the ground), H is tree height, while the *c, a, b, t* are parameters. The values of *c, a, b, t* and coefficient determination R^2 for all allometric equations were estimated by least square method.

Partial and whole biomass estimation

The total stem biomass w_S, total branch biomass w_B, total leaf biomass w_L and total prop root biomass w_R of *R. stylosa* trees in each stand was estimated by summation method using the equations of Analuddin et al. (2016*b*) as follows:

$$w_S = \sum_{i=1}^{n} w_{S1} + w_{S2} + ... w_{Sn}$$

Where; w_S is individuals stem weight of mangrove trees.

$$w_B = \sum_{i=1}^{n} w_{B1} + w_{B2} + ... w_{Bn}$$

Where; w_B is individuals branch weight of mangrove trees.

$$w_L = \sum_{i=1}^{n} w_{L1} + w_{L2} + ... w_{Ln}$$

Where; w_L is individuals leaf weight of mangrove trees.

$$w_R = \sum_{i=1}^{n} w_{R1} + w_{R2} + ... w_{Rn}$$

Where; w_R is individuals prop root weight of *R. stylosa* trees.

Total aboveground biomass *w* of *R. stylosa* in each stand was estimated by summation method using the following equation:

$$w = \sum w_S + \sum w_B + \sum w_L + \sum w_R$$

Mangrove productivity analysis

The productivity of *R. stylosa* mangrove was estimated including biomass increment, standing dead biomass, litterfall, and net primary production. The biomass increment for living *R. stylosa* trees, $\Delta y'$ is estimated by using the following equation of Kira and Shidei (1967) as follows:

$$\Delta y' = \{(\sum_{i=1}^{n} w_{T2.1} + w_{T2.2} + w_{Tn.m}) - (\sum_{i=1}^{n} w_{T1.1} + w_{T1.2} + w_{Tn.m})\}$$

Where; $w_{T2.1}$ is the plant biomass at second harvest and $w_{T1.1}$ is the plant biomass at the first harvest, while $w_{Tn.m}$ is the plant biomass for the other time harvest. In addition, standing dead biomass was estimated by summation of individuals' dead biomass, *D* from the permanent plots. Biomass increment of whole stand, Δy is estimated by using the following equation:

$$\Delta y = \Delta y' - D$$

The aboveground net primary production ΔP_n was estimated by summation method (Kira and Shidei 1967) of the annual rate of biomass increment of living trees Δy and litterfall ΔL as follows:

$$\Delta P_n = \Delta y + \Delta L$$

Carbon stock and CO_2 uptake analysis

The carbon stock in partial and whole aboveground biomass was estimated following the method of IPCC (2006) as follows:

$$C = B \times 0.47$$

Where; C is carbon stock, B is biomass and the 0.47 is constant value of C in organic matter (IPCC 2006).

The CO_2 uptake in mangrove tissues was obtained by conversion of carbon stock to CO_2 that use the molecular relative mass of CO_2 (44) to the relative atomic mass ratio of C (12) following the method of Hidayah and Andriani (2019) as follows:

$$WCO_2 = C_n{*}\ (Mr.CO_2/Ar.C)$$

Where; WCO_2 is CO_2 absorption, Mr is molecular relative (44), Ar is atomic relative (12) and Cn is carbon stock.

RESULTS AND DISCUSSION

Allometric models of biomass

Table 1 represents the allometric models of partial and whole aboveground mass of *Rhizophora stylosa* trees. The allometric models of stem biomass w_S, branch biomass w_B, leaf biomass w_L, prop root weight w_R and aboveground biomass w of *R. stylosa* trees were established using independent variables D_{30}, DBH and quadratic parameters with tree height H ($D_{30}{}^2H$, DBH^2H). The constant values of a_0 and a_1 from allometric equations of w_S for *R. stylosa* trees were estimated as 3.15 × 10^{-2} and 3.04 (R^2 = 0.935) for D_{30}, 3.79× 10^{-2} and 3.04 (R^2 = 0.948) for DBH, 0.74 × 10^{-2} and 1.21 (R^2 = 0.963) for $D_{30}{}^2H$ and 0.91 × 10^{-2} and 1.20 (R^2 = 0.967) for DBH^2H, respectively. It seems that independent variables $D_{30}{}^2H$ and DBH^2H are more appropriate for estimating stem mass of *R. stylosa* trees. Meanwhile, the values of b_0 and b_1 from allometric equations of w_B for *R. stylosa* trees were estimated as 1.6 ×10^{-1} and 1.9 (R^2 = 0.983) for D30, 1.8 × 10^{-1} and 1.9 (R^2 = 0.991) for DBH, 6.65 × $10^{-2}$and 0.749 (R^2 = 0.973) for $D30^2H$ and 7.5× 10^{-2} and 0.745 (R^2 = 0.974) for DBH^2H, respectively. Thus, independent variables D_{30} and DBH are more precise for estimating the w_B of *R. stylosa* trees. However, the values of c_0 and c_1 from allometric equations of w_L in *R. stylosa* trees were estimated as 6.66 × 10^{-2} and 1.82 (R^2 = 0.96) for D_{30}, 7.49 × 10^{-2} and 1.81 (R^2 = 0.96) for DBH, 2.76× 10^{-2} and 0.725 (R^2 = 0.98) for $D_{30}{}^2H$ and 3.16 × 10^{-2} and 0.718 (R^2 = 0.969) for DBH^2H, respectively. It means that $D_{30}{}^2H$ is the best independent variable for estimating w_L of *R. stylosa* trees. Meanwhile, the values of t_0 and t_1 from allometric equations of prop root biomass (w_R) in *R. stylosa* trees were estimated as 8.99 × 10^{-2} and 2.53 (R^2 = 0.95) for D_{30}, 1.07 × $10^{-1}$and 2.51 (R^2 = 0.96) for DBH, 3.94 × 10^{-2} and 0.97 (R^2 = 0.94) for $D_{30}{}^2H$ and 4.16×10^{-2} and 0.96 (R^2 = 0.944) for DBH^2H, respectively. Thus, the independent variable DBH is the best predictor of prop root biomass w_R of *R. stylosa* trees. Although, various independent variables are applicable for estimation of partial and whole aboveground biomass of *R. stylosa* trees, the DBH is the best parameter for biomass estimation due to its easy measurement in the field.

In comparison with allometric models of mangroves from previous studies (Table 2), the allometric models of *R. stylosa* trees seemed to show different trends as compared with allometric models of several mangrove species grown at the same region (Analuddin et al. (2016*b*, 2018). Allometric models of stem weight, branch weight and leaf weight of *L. racemosa* trees well fitted with independent variables of DBH^2H, DB, and DBH, respectively, though DBH could be also applied (Analuddin et al. 2016b). Similarly, allometric models of branch weight and leaf weight of *R. apiculata* trees fitted well to independent variable DBH, while it stems weight well fitted to the independent variable of D30 (Analuddin et al. 2018). Furthermore, they also found that allometric models of partial and whole aboveground mass of *R. mucronata* trees fitted well to independent variables of DBH^2H, though DBH could be also applied. Same authors also found that allometric models of partial and whole aboveground biomass of *Ceriops tagal* were well fitted with independent variable of D30, though DBH could be also applied.

Table 1. The allometric equations for estimation of partial weights of *Rhizophora stylosa* trees

Independent variables	Dependent variables	Coefficient values		R^2 values
		a_0	a_1	R^2
D_{30}	Stem mass w_S	0.031493	3.0405	0.935
D_{BH}		0.0379	3.0382	0.948
$D_{30}{}^2H$		0.007372	1.2114	0.963
$D_{BH}{}^2H$		0.009127	1.201	0.967
D_{30}	Branch/twig	b_0	b_1	R^2
D_{BH}	mass w_B	0.1577	1.8956	0.983
$D_{30}{}^2H$		0.17488	1.8995	0.991
$D_{BH}{}^2H$		0.066485	0.7492	0.973
		0.074992	0.7445	0.974
D_{30}	Leaf mass w_S	c_0	c_1	R^2
D_{BH}		0.066595	1.8148	0.960
$D_{30}{}^2H$		0.074973	1.8098	0.957
$D_{BH}{}^2H$		0.027589	0.7251	0.975
		0.031596	0.7178	0.969
D_{30}	Prop root	t_0	t_1	R^2
D_{BH}	mass w_R	0.089946	2.5251	0.945
$D_{30}{}^2H$		0.10695	2.5143	0.960
$D_{BH}{}^2H$		0.039412	0.9705	0.940
		0.041556	0.9596	0.944

Table 2. Allometric equations for estimation of aboveground biomass of various mangroves based on D_{BH}

Mangroves	Allometric equations	References
Lumnitzera racemosa	Wtop = $0.184D_{BH}^{2.384}$ *R*= 0,98, n = 8	Analuddin et al. (2016*b*)
Rhizophora apiculata	Wtop = $0.268D_{BH}^{2.345}$ *R*= 0,93, n = 8	Analuddin et al. (2018)
Rhizophra mucronata	Wtop = $0.143D_{BH}^{2.519}$ *R*= 0,97, n = 8	Analuddin et al. (2018)
Avicennia germinans	Wtop = $0.140D_{BH}^{2.40}$ *R* = 0.97, n = 45	Fromard et al. (1998)
Avicennia marina	Wtop = $0.308D_{BH}^{2.11}$ *R* = 0.97, n = 22	Comley and McGuinness (2005)
Laguncularia racemosa	Wtop = $0.102D_{BH}^{2.50}$ *R* = 0.97, n = 70	Fromard et al. (1998)
Rhizophora apiculata	Wtop = $0.235DBH^{2.42}$ *R* = 0.98, n = 57	Ong et al. (2004)
Bruguiera gymnorrhiza	Wtop = $0.186DBH^{2.31}$ *R* = 0.99, n = 17	Clough and Scott (1989)
Ceriops australis	Wtop = $0.189D_{BH}^{2.34}$ *R* = 0.99, n = 26	Clough and Scott (1989)
Xylocarpus granatum	Wtop = $0.0823D_{BH}^{2.59}$ *R* = 0.99, n = 15	Clough and Scott (1989)
Rhizophora stylosa	Wtop = $0.1579D_{BH}^{2.593}$ *R*= 0,98, n = 8	Present study

Therefore, the consideration of different independent variables for estimation of partial aboveground biomass of mangroves is needed because the mangroves grown at the same region prefer different independent variables as the best predictor for estimation of partial or whole aboveground mass even when the parts mass, such as stem mass or branch, is same. These differences in the applicability of independent variables of allometric models among species might be indicative of the differences in their biological adaptation mechanisms for growth and withstanding various environmental circumstances. Several previous studies (Clough 1992; Steinke et al.1995) mentioned that the coefficient values of allometric models for the same species may vary with localities and it depends on-site quality, tree density, as well as species composition.

However, Komiyama et al. (2005) proposed a common allometric biomass model of mangroves by using DBH, though this allometric model is not applicable for *E. agallocha* trees as their DBH were less than 5 cm. Meanwhile, Mahmood et al. (2004) suggested the differences of coefficients in allometric models for estimation of aboveground biomass of mangroves. Many previous studies found suitability of independent variable DBH for estimation of aboveground biomass of various mangroves, including *Rhizophora apiculata* and *R. mucronata* (Analuddin et al. 2018), *Lumnitzera racemosa* (Analuddin et al. 2016b), *Avicennia germinans* and *Laguncularia racemosa* (Fromard et al. 1998), *Avicennia marina* (Comley and McGuinness 2005), *R. apiculata* (Ong et al. 2004), *Bruguiera gymnorrhiza*, *Ceriops australis* and *Xylocarpus granatum* (Clough and Scott 1989). Therefore, although different independent variables could be applied for calculating partial or whole aboveground biomass of *R. stylosa* trees, DBH and D30 are the two appropriate and easily measurable parameters. This is because tree height measurement is difficult in the field, though the DBH^2H well fitted.

Trends of partial and whole aboveground biomass

Table 3 shows the trends of partial and whole aboveground biomass of *R. stylosa* forest growing in Southeast Sulawesi. The first-year partial biomass calculation of *R. stylosa* stands showed that stem biomass ranges from 196.91 to 336.63 ton ha^{-1} (average of 248.98 ton ha^{-1}), branch biomass ranges 54.23 to 73.15 ton ha^{-1} (average of 61.88 ton ha^{-1}), leaf biomass ranges from 18.71 to 24.77 ton ha^{-1} (average of 21.19 ton ha^{-1}), and prop root biomass ranges 149.78 to 230.01 ton ha^{-1} (average of 180.61 ton ha^{-1}). The whole aboveground biomass of *R. stylosa* stands at the first year ranges from 419.64 to 664.55 ton ha^{-1} (average of 512.65 ton ha^{-1}).

The second-year partial biomass calculation of *R. stylosa* stands showed that stem biomass ranges from 216.27 to 371.65 ton ha^{-1} (average of 277.24 ton ha^{-1}), branch biomass ranges 57.16 to 76.89 ton ha^{-1} (average of 65.88 ton ha^{-1}), leaf biomass ranges from 19.89 to 25.791 ton ha^{-1} (average of 22.45 ton ha^{-1}), and prop root biomass ranges 161.36 to 248.48 ton ha^{-1} (average of 197.19 ton ha^{-1}). The whole aboveground biomass ranges from 454.45 to 722.92 ton ha^{-1} (average 562.76 ton ha^{-1}).

Aboveground biomass (AGB) of *R. stylosa* forest was much higher than AGB of various mangroves from different regions of the world (Table 4). The AGB of *R. stylosa* forest was much higher than AGB of *R. mangle* forest in Dominican (Sherman et al. 2003), Florida (Ross et al. 2001) and Mexico (Day et al. 1997). It was also much higher than that of *Rhizophora mucronata* and *Bruguiera gymnorrhiza* forests (Suzuki and Tagawa (1993), *Kandelia obovata* forest in Okinawa Japan and *Kandelia candel* forest in Hong Kong (Lee 1990). Similarly, the AGB of *R. stylosa* forest was much higher than that of *R. apiculata* (Putz and Chan 1986), *R. stylosa* forest (Chandra et al. (2011) and *B. parviflora* forest (Hossein et al. (2008) of Malaysia. In addition, AGB of *R. stylosa* was much higher than AGB of *Rhizophora* sp. in Thailand (Komiyama et al. 2000) as well as Oligohaline mangrove in Sundarbans, Bangladesh (Kamaruzzaman et al. 2017). The AGB of *R. stylosa* forest was much higher than that of *L. racemosa* forest (Analuddin et al. 2016*b*) and *R. mucronata* forest (Analuddin et al. 2018) growing in the same locations in Southeast Sulawesi, although it was lower as compared to AGB of *R. apiculata* forest of the protected area in Southeast Sulawesi (Analuddin et al. 2018).

Table 3. Trends of stem biomass w_S, branch/twig biomass w_B, leaves biomass w_L, prop root biomass w_R and whole aboveground biomass *w* of *Rhizophora stylosa* stands from two-year censuses

Years	Stands	w_S (ton ha^{-1})	w_B (ton ha^{-1})	w_L (ton ha^{-1})	w_R (ton ha^{-1})	w (ton ha^{-1})
2014	1	336.63	73.15	24.77	230.01	664.55
	2	213.40	58.25	20.07	162.02	453.75
	3	196.91	54.23	18.72	149.78	419.64
	Average	248.98	61.88	21.19	180.61	512.65
	SD	44.08	5.76	1.83	24.95	76.59
2015	1	371.65	76.89	25.91	248.48	722.93
	2	243.79	63.59	21.80	181.74	510.91
	3	216.27	57.16	19.66	161.36	454.45
	Average	277.24	65.88	22.45	197.19	562.76
	SD	82.91	10.06	3.176	45.57	141.55

Table 4. Comparison of aboveground biomass of mangrove forests in different region of the world

Countries region	Species	AGB (ton ha^{-1})	References
Neotropical countries			
Dominican	*Rhizophora mangle*	233	Sherman et al. (2003)
Florida, USA	*R. mangle* forest	56	Ross et al. (2001)
Mexico	*R. mangle* forest	135	Day et al. (1997)
Subtropical countries			
Japan (Okinawa)	*R. mucronata*	108.1	Suzuki and Tagawa (1983)
Japan (Okinawa)	*Bruguiera gymnorrhiza*	97.6	Suzuki and Tagawa (1983)
Japan (Okinawa)	*Kandelia obovata*	80.5	Khan et al. (2009)
Hong Kong	*Kandelia candel*	128.6	Lee (1990)
Tropical countries			
Malaysia (Matang)	*R. apiculata*	270-460	Putz and Chan (1986)
Kuala Selangor, Malaysia	*B. parviflora*	144.47	Hossein et al. (2008)
Lawas, Malaysia	*R. apiculata*	116.79	Chandra et al. 2011
Thailand (Satun Southern)	*Ceriops tagal*	92.2	Komiyama et al. (2000)
Bangladesh (Sundarbans)	Oligohaline mangrove	154.8	Kamaruzzaman et al. (2017)
Indonesia (Halmahera)	*B. gymnorrhiza* forest	436.4	Tamai et al. (1986)
Indonesia (Halmahera)	*R. apiculata* forest	356.8	Komiyama et al. (1988)
Indonesia (Halmahera)	*R. stylosa* forest	178.2	Kusmana et al. (1992)
Indonesia (East Sumatra)	*B. sexangula* stands	76.0	Kusmana et al. (1992)
Indonesia (Southeast Sulawesi	*Lumnitzera racemosa*	109.77	Analuddin et al (2016*b*)
SE, protected area	*R. apiculata*	651.60	Analuddin et al (2018)
	R. mucronata	232.11	Analuddin et al (2018)
SE, unprotected area	*R. apiculata*	139.30	Analuddin et al (2018)
	R. mucronata	189.32	Analuddin et al (2018)
Southeast Sulawesi (protected area)	*R. stylosa*	562.76	Current Study

These differences on aboveground biomass of various mangroves is due to differences in stand structure, climatic factors and habitat characteristics. However, higher biomass of mangroves might be indications of optimal habitat features, such as low salinity, high fertility and favorable climatic conditions (Saenger and Snedaker 1993). Therefore, the higher aboveground biomass of *Rhizophora stylosa* forest might be attributed to suitable conditions of soil structure, less anthropogenic disturbance, appropriate salinity and nutrient availability in the habitat.

Trend in productivity of *Rhizophora stylosa* forest

Table 5 shows the productivity of *Rhizophora stylosa* forest in Southeast Sulawesi. The yearly biomass increment of living $\Delta y'$ of *R. stylosa* stands ranges from 36 to 61.34 ton ha^{-1} (average of 52.87 ton ha^{-1}), while whole biomass increment of stand Δy ranges from 34.79 to 58.34 ton ha^{-1} yr^{-1} (average of 50.09 ton ha^{-1} yr^{-1}). On the other hand, the standing dead biomass *D* ranges from 1.40 to 4.20 ton ha^{-1} yr^{-1} (average of 2.78 ton ha^{-1} yr^{-1}), but litterfall ΔL production ranges from 10.63 to 14.10 ton ha^{-1} yr^{-1} (average of 12.00 ton ha^{-1}yr^{-1}). Aboveground ΔP_n in *R. stylosa* stands ranges from 45.42 to 72.44 ton ha^{-1} yr^{-1} (average of 62.09 ton ha^{-1} yr^{-1}). These trends indicate that productivity of *R. stylosa* stands varied across stands. Higher productivity of *R. stylosa* was found in stand 1, while it was the lower in stand 3. These differences in productivity might be due to differences in tree size and stand density. The mean DBH of trees at stand 1, stand 2 and stand 3 was 11.65 cm, 10.10 cm, and 9.43 cm, respectively. However, tree density at stand 1 was 3500 individuals per hectare, while both at stand 2 and stand 3 it was 3800 individuals per hectare. Thus, high rate of net primary production of *R. stylosa* forest in the present study might be attributed to the tree size rather than tree density. Similar result was reported by Kamaruzzaman et al. (2017) that there was significant correlation between mean DBH and aboveground biomass of Sundarbans mangroves.

This study is the first report on the productivity of mangrove forests in the coral triangle areas. Comparison with the production values of mangrove forests from different places of the world (Table 6), showed that Δy, and ΔP_n of *R. stylosa* forest in Southeast Sulawesi, Indonesia are much higher as compared with Δy and ΔP_n values of *Kandelia obovata* forest in Japan (Khan et al. 2009), *Rhizophora mangle* forest in Dominican (Sherman et al. 2003), *R. mangle* forest in Florida, USA (Ross et al. 2001), fringe mangrove forest in Australia (Alongi 2000) and Sundarbans mangrove forests in Bangladesh (Kamaruzzaman et al. 2019). However, the ΔL of *R. stylosa* forest obtained in the present study showed higher value than those of other mangroves, except the ΔL of *R. mangle* mangrove growing in Florida, USA (Ross et al 2001). Our study revealed that higher ΔP_n of *R. stylosa* forest was mostly contributed by Δy, while the ratio of ΔP_n to ΔL was 5.17: 1, indicating lower contribution of litterfall to the ΔP_n of *R. stylosa* forest. Thus, results of this study are contrary to the assumptions of Kamaruzzaman et al. (2017) and Teas (1979) that the total net primary production for mangroves is three times larger than the amount of total litterfall.

Trends of carbon sequestration

Table 7 indicates the trends of carbon stock, carbon sequestration (net carbon budget, carbon gain, carbon input, and net carbon production) and carbon loss in *Rhizophora stylosa* forest growing in Southeast Sulawesi. The carbon stock ranges from 213.59 to 339.78 ton ha^{-1} (average of 264.50 ton ha^{-1}), which was higher in stand 1 than other stands. However, the carbon stock was about 49.26% in stem and 35.04% in prop root, while it was about 11.17 % in branches/twigs and 3.99% in the leaf. The carbon stock in *R. stylosa* forest was much higher than that in mangrove at Peliat Island, Sumenep (10.80 ton/ha) as reported by Hidayath and Andriani (2019), as well as carbon stock of 115-225 ton/ha in many Asian coastal estuaries (IPCC 2006). These differences in carbon stock might be due to differences in biomass, tree size, etc. According to IPCC (2006), the concentration of carbon in vegetation depends on biomass, carbon absorption, soil fertility, plant diversity, and density. The mean annual of net carbon budget, carbon gain and carbon loss in *R. stylosa* forest was 23.54, 24.85 and 1.31 ton ha^{-1}, respectively. Moreover, mean annual carbon input and net carbon production of *R. stylosa* forest was 5.64 and 29.18 ton ha^{-1}. These trends indicate that this *R. stylosa* forest is high carbon sequestration, and is contributed to the global carbon budget.

Table 5. Trends in biomass increment of living trees $\Delta y'$, whole biomass increment of stand Δy, standing dead biomass *D*, litterfall ΔL and net primary production ΔP_n of *Rhizophora stylosa* forest in Southeast Sulawesi

Stands	$\Delta y'$ (ton ha^{-1}yr^{-1})	Δy (ton ha^{-1}yr^{-1})	*D* (ton ha^{-1}yr^{-1})	ΔL (ton ha^{-1}yr^{-1})	ΔP_n (ton ha^{-1}yr^{-1})
1	61.08	58.34	2.74	14.10	72.44
2	61.34	57.14	4.20	11.27	68.42
3	36.20	34.79	1.40	10.63	45.42
Average	52.87	50.09	2.78	12.00	62.09
SD	14.440	13.27	1.40	1.85	14.58

Table 6. The comparison of whole biomass increment of stand Δy, litterfall ΔL and net primary production ΔP_n of various mangrove species growing in different countries.

Country	Mangroves	Δy (ton ha^{-1}yr^{-1})	ΔL (ton ha^{-1}yr^{-1})	ΔP_n (ton ha^{-1}yr^{-1})	*References*
Okinawa, Japan	*Kandelia obovata*	19.3-21.5	10.6	29.9-31.2	Khan et al. (2009)
Rep. Dominican	*Rhizophora mangle*	9.7	11.4	19.7	Sherman et al. (2003)
Florida, USA	*R. mangle*	13.9	12.2	26.61	Ross et al. (2001)
Australia	*Mangrove fringe*	7.1	-	49.6	Alongi (2000)
Bangladesh	Mangrove of Sundarbans	-	10.1	17.2	Kamaruzzaman et al. (2019)
Southeast Sulawesi, Indonesia	*R. stylosa*	50.09	12.0	62.09	*This study*

Table 7. Trends of the trends of carbon stock, carbon sequestration (net carbon budget, carbon gain, carbon input and net carbon production) and carbon loss in *Rhizophora stylosa* forest growing in Southeast Sulawesi.

Stands	**C stock (ton ha^{-1})**	**Net C budget (ton ha^{-1} yr^{-1})**	**C gained (ton ha^{-1} yr^{-1})**	**C loss (ton ha^{-1} yr^{-1})**	**C input (ton ha^{-1} yr^{-1})**	**Net C production (ton ha^{-1} yr^{-1})**
1	339.78	27.42	28.71	1.29	6.63	34.05
2	240.13	26.86	28.83	1.97	5.30	32.15
3	213.59	16.35	17.01	0.66	5.00	21.35
Mean	264.50	23.54	24.85	1.31	5.64	29.18
SD	66.53	6.23	6.79	0.66	0.87	6.85

Table 8. Trends of CO_2 stock and CO_2 sequestration in *Rhizophora stylosa* forest

Stands	**CO_2 stored (ton ha^{-1})**	**Net CO_2 Uptake (ton ha^{-1}yr^{-1})**	**CO_2 gained (ton ha^{-1}yr^{-1})**	**CO_2 loss (ton ha^{-1}yr^{-1})**	**CO_2 input (ton ha-1yr-1)**
1	1245.84	100.54	105.26	4.72	24.30
2	880.48	98.48	105.71	7.23	19.42
3	783.17	59.95	62.38	2.41	18.32
Mean	969.83	86.33	91.12	4.79	20.68
SD	243.94	22.86	24.89	2.41	3.18

Table 8 shows trends of CO_2 stock and CO_2 sequestration in *Rhizophora stylosa* forest. The total CO_2 stored in mangrove stands ranges from 783.17 to 1245.84 ton ha^{-1} (average of 969.83 ton ha^{-1}). The yearly net CO_2 uptake by *Rhizophora stylosa* forest ranges from 59.95 to 100.54 ton ha^{-1}, while annual CO_2 loss due to trees death ranges from 2.41 to 7.23 ton ha^{-1} (average of 1.31 ton ha^{-1}). Annual CO_2 gained by living *R. stylosa* trees ranges from 62.38 to 105.26 ton ha^{-1} (average of 4.79 ton ha^{-1}), and annual CO_2 input by litterfall in *R. stylosa* forest range 18.32 to 24.30 ton ha^{-1} (average of 20.86 ton ha^{-1}). The concentrations of C and CO_2 in *R. stylosa* forest were about 49% and 35% stored in stems and prop root parts, respectively. Results of this study differ Hidayah and Andriani (2019) according to which the C and CO_2 concentrations in stems of mangroves of Peliat Island was about 76%. The higher carbon content in mangrove trees might be due to a high concentration of xylem and lignin in their stem and prop root tissues. Meanwhile, Hidayah and Andriani (2019) mentioned that with aging, the stems of trees tend to improve the cellulose substances and lignin. Krauss and Ball (2013) found that carbon content in cellulose and lignin is approximately 44.44% and 67.50%, respectively. Moreover, Effendi and Rusmana (2017) argued that mangrove ecosystems are capable of higher CO_2 absorption than terrestrial plants. In addition, Gilman et al. (2008) stated that the photosynthesis ability of mangroves is dependent on leaves capacity to absorb atmospheric CO_2, which in turn depends on the stomatal conductance and the enzymatic activity.

In conclusion, this study shows that although there are variations in suitability of independent variables for estimation of partial and whole aboveground biomass of *Rhizophora stylosa* forest, DBH is the best predictor for estimating the partial and whole biomass of *R. stylosa* trees, due to its easy measurement in the field. This study also confirms the high accumulation of aboveground biomass (562.76 ton ha^{-1} yr^{-1}) and productivity (62.09 ton ha^{-1} yr^{-1}) of *R. stylosa* forest in Southeast Sulawesi, which indicates the significant contribution of this forest to the global carbon and nutrients budget. Moreover, the higher carbon sequestration and CO_2 uptake in *R. stylosa* forest indicate its significant role in the global carbon accumulation and reducing atmospheric CO_2.

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