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 sequesterate 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 al. 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 forest 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: 04°33'12.1" and E: 122°0.3'20.4°). 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 at their weight at the sample plot. About 10 cm sized discs were cut from each 1 m 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 m² 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, $D_{30}^2/H$ and $DBH^2/H$. 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:

\[
\begin{align*}
    w_s &= a_0 D_{30}^{a_1} \\
    w_s &= a_0 D_{30}^{a_1} \\
    w_s &= a_0 (D_{30}^2 \times H)^{a_1} \\
    w_s &= a_0 (D_{30}^2 \times H)^{a_1} \\
    w_b &= b_0 D_{30}^{b_1} \\
    w_b &= b_0 D_{30}^{b_1} \\
    w_b &= b_0 (D_{30}^2 \times H)^{b_1} \\
    w_b &= b_0 (D_{30}^2 \times H)^{b_1} \\
    w_l &= c_0 D_{30}^{c_1} \\
    w_l &= c_0 D_{30}^{c_1} \\
    w_l &= c_0 (D_{30}^2 \times H)^{c_1} \\
    w_l &= c_0 (D_{30}^2 \times H)^{c_1} \\
    w_r &= t_0 D_{30}^{t_1} \\
    w_r &= t_0 D_{30}^{t_1} \\
    w_r &= t_0 (D_{30}^2 \times H)^{t_1} \\
\end{align*}
\]

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 $a$, $b$, $c$, $t$ are parameters. The values of $a$, $b$, $c$, $t$ 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. (2016b) as follows:

\[
\begin{align*}
    w_s &= \sum_{i=1}^{n} W_{si} + W_{s2} + \ldots + W_{sn} \\
    w_s &= \sum_{i=1}^{n} W_{si} + W_{s2} + \ldots + W_{sn} \\
    w_b &= \sum_{i=1}^{n} W_{bi} + W_{b2} + \ldots + W_{bn} \\
    w_b &= \sum_{i=1}^{n} W_{bi} + W_{b2} + \ldots + W_{bn} \\
    w_l &= \sum_{i=1}^{n} W_{li} + W_{l2} + \ldots + W_{ln} \\
    w_l &= \sum_{i=1}^{n} W_{li} + W_{l2} + \ldots + W_{ln} \\
    w_r &= \sum_{i=1}^{n} W_{ri} + W_{r2} + \ldots + W_{rn} \\
    w_r &= \sum_{i=1}^{n} W_{ri} + W_{r2} + \ldots + W_{rn} \\
\end{align*}
\]

Where: $w_s$ is individuals stem weight of mangrove trees.

Where: $w_b$ is individuals branch weight of mangrove trees.

Where: $w_l$ is individuals leaf weight of mangrove trees.

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:

\[
\Delta y' = \left[ (\sum_{i=1}^{n} W_{T1,1} + W_{T2,2} + W_{Tn,m} \right) - (\sum_{i=1}^{n} W_{T1,1} + W_{T2,2} + W_{Tn,m})]
\]

Where: $w_{T1,1}$ 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, $\Delta y$ is estimated by using the following equation:

\[
\Delta y = \Delta y' - D
\]
The aboveground net primary production $\Delta P_{\text{n}}$ was estimated by summation method (Kira and Shidei 1967) of the annual rate of biomass increment of living trees $\Delta y$ and litterfall $\Delta L$ as follows:

$$\Delta P_{\text{n}} = \Delta y + \Delta L$$

**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 biomass of CO$_2$ to CO$_2$ using 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:

$$\text{WCO}_2 = C_n \times (\text{Mr.CO}_2/\text{Ar.C})$$

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 presents the allometric models of partial and whole aboveground biomass 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 estimated as $3.15 \times 10^{-2}$ and $3.04 (R^2 = 0.935)$ for $D_{30}$, $3.79 \times 10^{-2}$ and $3.04 (R^2 = 0.948)$ for DBH, $0.74 \times 10^{-2}$ and $1.21 (R^2 = 0.963)$ for $D_{30}H$ and $0.91 \times 10^{-2}$ and $1.20 (R^2 = 0.967)$ for DBFH, respectively. It seems that independent variables $D_{30}^2H$ and DBFH are more appropriate for estimating stem mass of *R. stylosa* trees. Meanwhile, the values of $b_0$ and $b_1$ from allometric equations of $w_S$ for *R. stylosa* trees were estimated as $3.15 \times 10^{-2}$ and $3.04 (R^2 = 0.935)$ for $D_{30}$, $3.79 \times 10^{-2}$ and $3.04 (R^2 = 0.948)$ for DBH, $0.74 \times 10^{-2}$ and $1.21 (R^2 = 0.963)$ for $D_{30}H$ and $0.91 \times 10^{-2}$ and $1.20 (R^2 = 0.967)$ for DBFH, respectively. Therefore, the independent variables $D_{30}H$ and DBFH are more appropriate for estimating stem mass 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 $8.99 \times 10^{-2}$ and $2.53 (R^2 = 0.95)$ for $D_{30}$, $1.07 \times 10^{-2}$ and $2.51 (R^2 = 0.96)$ for DBH, $3.94 \times 10^{-2}$ and $0.97 (R^2 = 0.94)$ for $D_{30}H$ and $4.16 \times 10^{-2}$ and $0.96 (R^2 = 0.944)$ for DBFH, 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. 2016b, 2018). Allometric models of stem weight, branch weight and leaf weight of *L. racemosa* trees well fitted with independent variables of DBFH, 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 DBFH, 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 |
|-----------------------|---------------------|--------------------|--------------|
| $D_{30}$ Stem mass $w_S$ | $a_0$ $a_1$ | | $R^2$ |
| $D_{30}$ | 0.031493 | 3.0405 | 0.935 |
| $D_{30}$ | 0.0379 | 3.0382 | 0.948 |
| $D_{30}^2H$ | 0.007372 | 1.2114 | 0.943 |
| $D_{30}^2H$ | 0.009127 | 1.201 | 0.967 |
| $D_{0}$ Branch/twig mass $w_B$ | $b_0$ $b_1$ | | $R^2$ |
| $D_{30}$ | 0.1577 | 1.8956 | 0.983 |
| $D_{30}$ | 0.17488 | 1.8995 | 0.991 |
| $D_{30}^2H$ | 0.066485 | 0.7492 | 0.973 |
| $D_{30}^2H$ | 0.074992 | 0.7445 | 0.974 |
| $D_{30}$ Leaf mass $w_L$ | $c_0$ $c_1$ | | $R^2$ |
| $D_{30}$ | 0.066595 | 1.8148 | 0.960 |
| $D_{30}$ | 0.074973 | 1.8098 | 0.957 |
| $D_{30}$ | 0.027589 | 0.7251 | 0.975 |
| $D_{30}$ | 0.031596 | 0.7178 | 0.969 |
| $D_{30}$ Prop root mass $w_R$ | $t_0$ $t_1$ | | $R^2$ |
| $D_{30}$ | 0.089946 | 2.5251 | 0.945 |
| $D_{30}$ | 0.10695 | 2.5143 | 0.960 |
| $D_{30}H$ | 0.039412 | 0.9705 | 0.940 |
| $D_{30}H$ | 0.041556 | 0.9596 | 0.944 |
Table 2. Allometric equations for estimation of aboveground biomass of various mangroves based on DBH

| Mangroves                          | Allometric equations                      | References                      |
|------------------------------------|-------------------------------------------|---------------------------------|
| Lumnitzera racemosa               | Wtop = 0.184DBH^{2.384} R^2 = 0.98, n = 8 | Analuddin et al. (2016b)        |
| Rhizophora apiculata               | Wtop = 0.268DBH^{3.45} R^2 = 0.93, n = 8 | Analuddin et al. (2018)         |
| Rhizophora mucronata               | Wtop = 0.143DBH^{2.59} R = 0.97, n = 8  | Analuddin et al. (2018)         |
| Avicennia germinans                | Wtop = 0.140DBH^{2.9} R = 0.97, n = 45   | Fromard et al. (1998)           |
| Avicennia marina                   | Wtop = 0.308DBH^{1.11} R = 0.97, n = 22  | Comley and McGuinness (2005)    |
| Laguncularia racemosa              | Wtop = 0.102DBH^{3.9} 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^{3.1} R = 0.99, n = 17   | Clough and Scott (1989)         |
| Ceriops australis                  | Wtop = 0.189DBH^{3.4} R = 0.99, n = 26   | Clough and Scott (1989)         |
| Xylocarpus granatum                | Wtop = 0.0823DBH^{2.59} R = 0.99, n = 15 | Clough and Scott (1989)         |
| Rhizophora stylosa                 | Wtop = 0.1579DBH^{2.59} 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. azalalocha 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), Lumnitzer 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 DBFH1 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 Dominica (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. pinnifolia 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. 2016b) 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).
ions of optimal

appropriate salinity and nutrient availability in

condition

Rhizophora stylosa

1993). Therefore, the higher aboveground biomass of

favorable climatic

biomass of mangroves might be indicat

factors and habitat characteristics. However, higher

mangroves

Tropical countries

Subtropical countries

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)

Brouquieria 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 (2016b)

SE, protected area

R. apiculata

651.60

Analuddin et al (2018)

SE, unprotected area

R. mucronata

232.11

Analuddin et al (2018)

Southeast Sulawesi

R. stylosa

562.76

Current Study

(protected area)

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)   | Brouquieria 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 (2016b) |
| SE, protected area | R. apiculata | 651.60 | Analuddin et al (2018) |
| SE, unprotected area | R. mucronata | 232.11 | Analuddin et al (2018) |
| Southeast Sulawesi | 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 Rhizophora stylosa stands ranges from 36 to 61.34 ton ha⁻¹ (average of 52.87 ton ha⁻¹), while whole biomass increment of stand \( \Delta y \) 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 \( L \) production ranges from 10.63 to 14.10 ton ha⁻¹ yr⁻¹ (average of 12.00 ton ha⁻¹ yr⁻¹). Aboveground \( \Delta P_s \) in Rhizophora 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 \(\Delta y\) and \(\Delta P_n\) of \(R.\ stylosa\) forest in Southeast Sulawesi, Indonesia are much higher as compared with \(\Delta y\) and \(\Delta P_n\) 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 (Kamaruzaman et al. 2019). However, the \(AL\) of \(R.\ stylosa\) forest obtained in the present study showed higher value than those of other mangroves, except the \(AL\) of \(R.\ mangle\) mangrove growing in Florida, USA (Ross et al 2001). Our study revealed that higher \(\Delta P_n\) of \(R.\ stylosa\) forest was mostly contributed by \(\Delta y\), while the ratio of \(\Delta P_n\) to \(AL\) was 5.17:1, indicating lower contribution of litterfall to the \(\Delta P_n\) 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.

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**Table 5.** Trends in biomass increment of living trees \(\Delta y'\), whole biomass increment of stand \(\Delta y\), standing dead biomass \(D\), litterfall \(AL\) and net primary production \(\Delta P_n\) of \(Rhizophora\ stylosa\) forest in Southeast Sulawesi

| Stands | \(\Delta y'\) (ton ha\(^{-1}\)yr\(^{-1}\)) | \(\Delta y\) (ton ha\(^{-1}\)yr\(^{-1}\)) | \(D\) (ton ha\(^{-1}\)yr\(^{-1}\)) | \(AL\) (ton ha\(^{-1}\)yr\(^{-1}\)) | \(\Delta P_n\) (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 \(\Delta y\), litterfall \(AL\) and net primary production \(\Delta P_n\) of various mangrove species growing in different countries.

| Country                  | Mangroves               | \(\Delta y\) (ton ha\(^{-1}\)yr\(^{-1}\)) | \(AL\) (ton ha\(^{-1}\)yr\(^{-1}\)) | \(\Delta P_n\) (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 growing forest 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\(^{-1}\) yr\(^{-1}\)) |
|--------|----------------------------------|-----------------------------------------------|-----------------------------------------------|------------------------------------------|---------------------------------------------|
| 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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