Blue carbon dynamics in mangroves and conservation of their services in the Coral Triangle Ecoregion, Southeast Sulawesi, Indonesia

Kangkuso Analuddin¹, La Ode Kadidae², La Ode Muhammad Yasir³, Andi Septiana¹, La Syahrir⁴, Saban Rahim⁵, David Pratama⁶, LD Abdul Fajar⁷ and Kazuo Nadaoka⁸

¹Biotechnology Study Program, Halu Oleo University, Kendari, Indonesia
²Chemistry Study Program, Halu Oleo University, Kendari, Indonesia
³Marine Science Study Program, Halu Oleo University, Kendari, Indonesia
⁴Fisheries Science Postgraduate Program, Halu Oleo University, Kendari, Indonesia
⁵Geography Study Program, Halu Oleo University, Kendari, Indonesia
⁶Chemistry Science Postgraduate Program, Halu Oleo University, Kendari, Indonesia
⁷Marine & Fisheries Faculty, Sebelas November University, Kolaka, Indonesia
⁸Dept. of Trans-disciplinary Science and Engineering, Tokyo Institute of Technology, Japan

zanzarafli@gmail.com (corresponding author)

Abstract. Coral triangle eco-region is hotspot of coastal blue carbon, and contributes to the global carbon cycling. This study aimed to elucidate the blue carbon dynamics in mangroves and their importance services as source of blue carbon in the coastal zone of coral triangle ecoregion. The blue carbon content in mangrove sediment was analyzed, while blue carbon production and its export from mangroves leaf litterfall was estimated. The results showed that the blue carbon content in mangrove sediment was significantly higher in depth of 40-50 cm than other layers (P < 0.05). The annual blue carbon production (g C/m²/year) was 495.80 for R. mucronata, 572.52 for C. tagal and 335.56 for R. apiculata. Moreover, the annual blue carbon export (g C/m²/year) was 148.74 for R. mucronata, 171.76 for C. tagal and 100.68 for R. apiculata. Overall, carbon production and carbon export from these mangrove species were 1403.88 and 421.18 g C/m²/year, respectively. Therefore, huge blue carbon production and export by mangroves in this region contribute to the global carbon cycling in the coastal and marine environments. Thus, conservation of mangroves and their services is very important for maintenance the coastal productivity in the coral triangle eco-region.

1. Introduction
Coastal blue carbon ecosystems including mangroves, salt marsh and seagrass are known to constitute on the global carbon cycling and are large carbon sinks [1, 2] and therefore, they are potential ecosystems for sequestrations and contribution large carbon stocks in coastal environment[1-3]. Mangrove ecosystem is very productive [4] and contributes as a source of organic carbon in the coastal areas [5-9]. Mangroves litterfall is calculated around 50% - 78% of the total production of a mangrove forest and is an important source of organic matter in the food chain to maintain the fecundity of the surrounding waters[10]. However, the production of mangrove leaf litter is about 10% will be deposited (burial), 9% is consumed directly (direct consumption), 40% will be decomposed and 30% is exported, while about 11% is unknown[11].
The mangrove litter is transported by mangroves in the form of macro-particulates such as mangrove leaf litter [12] that contains high carbon [7]. Moreover, about 70% of mangrove litter is exported to offshore areas[13], while other studies report that around 30-80% of mangrove litterfall is exported to the surrounding waters [14-16]. Meanwhile, the average carbon export by mangroves to the coastal waters was about 210 g C/m2/year[17]. It estimated that approximately of 30% carbon was exported to the surrounding environment[18]. The export of carbon from mangrove leaf litter is influenced by various factors including the amount of rainfall, the type of season [19] and the type of mangrove [20]. The amount of carbon exported by mangroves during the rainy season is higher than in the dry season[7].

Mangrove forests in Southeast Sulawesi is one of the most huge diversity in coral triangle eco-region, Indonesia, and are dominated by mangroves of Rhizophora apiculata, Ceriopa tagal, Bruguiera gymnorrhiza, Lumnitzera racemosa, Xylocarpus granatum, and Sonneratia alba [21]. These mangroves are stocked higher abovegroundblue carbon[22] and potential source of antioxidants [23,24] as well as acting as bio-filter of heavy metal pollutants [25]. To date, there was no report on blue carbon dynamics in mangrove forest at the coral triangle area, knowledge of which important for understanding mangroves ecosystem services and their sustainable management. Therefore, the objectives of this study were (1) to assess the blue carbon content in mangrove sediment, (2) to quantify the blue carbon production and blue carbon exported by mangroves, and (3) to elucidate the conservation of mangroves and their services as blue carbon source for maintenance productivity of coastal zone in the coral triangle eco-region, Southeast Sulawesi.

2. Material and methods

2.1. Study site

The mangrove forest was carried out at the mangrove forest of RawaAopa Watumohai National Park, Southeast Sulawesi, which is located at 04°29'38.4 LS) and (122°05'06.5 LU), and at 04°29'42.6 LS and 122°05'13.4 LU 2). The mangrove forests are pristine stands, and show good growth and development. This mangrove forest provides nice site for elucidation the mangrove capability as blue carbon source in coastal and marine environments. There are several mangrove dominants in this site including Rhizophoramucronata, R. apiculata and Ceriopstagal. These mangroves are unique characteristics as they show clear zonation, while the R. mucronata and R. apiculata are grown in the same zonation, while Ceriopstagalis grown at different zonation [21].

2.2. Analysis of carbon accumulation in mangrove sediment

The mangrove sediment was collected from 200 meter inside mangrove up to the edge or border area. The samples of sediment were collected by using sediment core of 2 meters length. The soil sediment samples up to one meter depth were collected and divided into several layers of 0-10, 20-30, 40-50, 60-70 and 80-100 cm. The soil samples were placed in plastic bag, labeled and then brought to the Forensic Laboratory at Halu Oleo University, Kendari. The determination of organic carbon content was carried out as follows:

- **Soil dried processed**

  The soil samples were dried by oven dry method and after that soil sample (5.0 g) was placed in an aluminum dish with known weight and put it in an oven. The oven was then heated at 105 °C for 3 hours. After that, the dish was taken out with tongs and put it in a desiccator to cool it down. The cold sample was then weighed and the missing weight was counted as the weight of water.

- **Soil organic carbon analyses**

  The basis for determination of organic C content is the reduction of Cr$^{6+}$ (orange color) to Cr$^{3+}$ (green) in acid atmosphere. Into a 100 mL of volumetric flask containing 0.5 g of soil sample with size <0.5 mm, as much as 5 mL of K$_2$Cr$_2$O$_7$ 1 N was added then shaken, followed by the addition of 7.5 mL of concentrated H$_2$SO$_4$, shaken and left it for 30 minutes. The flask was then topped it up with ion free water to be 100 mL, and cooled it to the room temperature overnight. The next day, the absorbance of
the resulted clear solution was measured with a spectrophotometer at 561 nm wavelength and it was compared to standard solutions of 0 and 250 ppm. These standard solutions were made by diluting 0 and 5 mL of 5,000 ppm of standard solution to 100 mL using volumetric flask, exactly using the same procedure for the sample assessment but without sample. The calculation of organic C content (%) follows the formula established by [26].

2.3. Analysis of blue carbon production and its export

The blue carbon production and export by mangroves were calculated from leaf litterfall. The leaf litters of *Rhizophoraceae* and *Ceriopstagal* were powdered by using mortal. Then, entering 10 grams of sample into a porcelain dish then oven for 2 hours at 1050 °C. After that taken back the porcelain cup containing the sample and cooled. After that weighting 5 g of sample then put in porcelain cup and inserted it into the furnace. Further processing: a porcelain cup the sample then blotted out at a temperature of 3000 °C for 1.5 hours and then raised the temperature to 550-6000 °C for 2.5 hours, and finally the sample was cooled into the excitatory and weighed again.

Calculation of organic carbon content was done by following method:

- Ash content (%) = \( \frac{W_2}{W_1} \times 100\% \)     \( (1) \)
- Organic matter content (%) = \( \frac{W_1 - W_2}{W_1} \times 100\% \)     \( (2) \)
- Organic carbon content (%) = organic matter content \( \times 0.58 \)     \( (3) \)

where the \( W_1 \) and \( W_2 \) are the weights of sample and weigh of ash, respectively, while the 0.58 is conversion factor of organic matter to organic carbon.

The calculation of carbon production and carbon exports are as follows:

- Total carbon production = total leaf litter production \( \times \) carbon content (%).
- Total carbon exports = total carbon production \( \times \) 30% [11].

3. Results

3.1. Blue carbon content in mangroves sediment

Blue carbon content in soil sediment of mangroves varied according to the sediment layer (Table 1). The blue carbon content in mangrove sediment ranges from 2.40 to 4.55 (%), which was higher in depth of 40-50 cm, and lower in surface layer. The carbon content was significantly different among layers (\( p < 0.05 \)). This trend indicated that organic carbon accumulates in the middle layer of mangrove sediment, while low organic carbon deposition in surface layer might be due to water leaching during high tide as well as rainy season.

| Soil depth (cm) | C content (%) |
|----------------|--------------|
| 0-10           | 2.397±0.296<sup>a</sup> |
| 20-30          | 3.343±0.792<sup>ab</sup> |
| 40-50          | 4.533±0.550<sup>c</sup> |
| 60-70          | 4.345±1.037<sup>bcd</sup> |
| 80-100         | 2.692±0.782<sup>abe</sup> |

3.2. Blue carbon production by mangroves

Table 2 depicts the mean monthly blue carbon production and carbon export by *Rhizophoraceae* mangroves grown in the coral triangle ecoregion, Southeast Sulawesi. Mean monthly blue carbon production was estimated as 41.32 g C/m² for *R. mucronata*, 27.96 g C/m² for *R. apiculata* and 47.71 g C/m² for *Ceriopstagal*, respectively. However, the annual blue carbon production by mangrove of *R. mucronata* was estimated as 495.80 g C/m²/year, and it was estimated as 572.52 g C/m²/year by *C. tagal*. On the other hand, annual blue carbon production by *R. apiculata* was estimated 335.56 g
Therefore, the mangrove *C. tagal* seems to produce much higher blue carbon as compared to other mangroves. Meanwhile, total annual production from these mangrove species was estimated as 1403.88 g C/m²/year.

Mean monthly blue carbon export was estimated as 12.4 g/m² for *R. mucronata*, 8.39 g/m² for *R. apiculata* and 14.11 g/m² for *C. tagal*, respectively. The annual blue carbon organic exported by mangrove leaf litter of *R. mucronata* was estimated as 148.74 g C/m²/year, and it was estimated as 171.76 g C/m²/year by leaf litter of *C. tagal*. However, annual blue carbon exported by *R. apiculata* was estimated 100.68 g C/m²/year. Thus, total annual carbon exported by these mangroves was estimated about 421.18 g C/m²/year. Moreover, the mangrove of *C. tagal* exports much higher blue carbon as compared to other mangroves, while the *R. apiculata* seemed to show the lower blue carbon exports to the coastal environment.

**Table 2.** Mean monthly and annual carbon production and carbon export by mangroves grown in the coral triangle eco-region, Southeast Sulawesi.

| Mangroves       | Carbon production (g C/m²) | Carbon export (gC/m²) |
|-----------------|----------------------------|-----------------------|
|                 | Mean monthly | Annual    | Mean monthly | Annual    |
| *R. mucronata*  | 41.32         | 495.8     | 12.40        | 148.74    |
| *R. apiculata*  | 27.96         | 335.56    | 8.39         | 100.67    |
| *Ceriopstagal*  | 47.71         | 572.52    | 14.11        | 171.76    |

**4. Discussion**

The mangroves sediment showed different content of organic carbon from surface area to the 100 cm depth (Table 1). The organic carbon accumulation in the middle layer (40-50 cm depth) of mangrove sediment tended to be higher, while low deposition in surface layer might be due to water leaching during high tide as well as rainy season. However, high blue carbon production was found in family rhizophoraceae mangroves (Table 2), which was higher than that reported by [27] that studied in Papua New Guinea (380 g C / m² / year), and also reported by [28] that studied in Australia (400 g C/m²/year), and therefore, mangroves in Southeast Sulawesi produce huge blue carbon and they play very important roles for maintenance the productivity of the coastal environment in coral triangle area, Southeast Sulawesi.

Higher blue carbon export by mangroves in the present study (Table 2) plays an important role in supporting aquatic productivity in the coral triangle ecoregion, and therefore it has been widely used as a strong argument in conserving mangroves [15]. Mangrove ecosystem exports a number of organic carbon in the form of macro-particulates such as mangrove leaf litter to coastal areas around mangrove areas [6, 29, 30]. The annual export of organic carbon from several mangroves rhizophoraceae family grown in Southeast Sulawesi was 421.18 g C/m²/year. This value is higher when compared to organic carbon exported by several mangrove forest throughout the world, such as reported by [31] that studied in Malaysia (176 g C / m² / year), by [15] that studied Brazil (193 g C / m² / year), by [19] that studied in Florida (64 g C / m² / year), by [23] studied in New Zealand (110 g C / m² / year), by [15] studied in Brazil (144 g C / m² / year). These trends indicate high variations of blue carbon exports by mangroves in different region of the world. Nevertheless, the potentially important amount of detritus for export to the coastal areas might be influenced by many environmental factor including tidal fluctuations and the amount of rainfall, mangrove structure, climatic factor, etc. Thus, the results of this study highlight the important role of mangroves as source of blue carbon for nearby coastal ecosystem in the coral triangle areas, Southeast Sulawesi. Therefore, conservation of mangroves in this region is very important to ensure their ecological role as blue carbon source, habitat for various organisms as well as other essential services including biofilter of heavy metals pollutant [25], sources nutrition and antioxidants [23, 24] etc., at the coastal zone of coral triangle eco-region.
5. Conclusions
This study provides important analysis for elucidation the blue carbon dynamics in mangroves, and their services for maintenance the productivity of coastal zone in Southeast Sulawesi, Indonesia. The concentration of blue carbon was much higher in middle layer of sediment, while the blue carbon production and blue carbon export varied among mangroves. However, mangroves at the coral triangle eco-region produce and export huge amount of blue carbon. Thus, conservation of mangroves is very important to ensure their essential role and services at the coastal zone of coral triangle eco-region.

Acknowledgements
This research was supported by the Ministry of Research, Technology and Higher Education Republic of Indonesia with grant nos. 0100/E5.1/PE/2015 and T/140/E3/RA.00/2019, in collaboration with Tokyo Institute of Technology, Japan. We also like to thank Rector of Universitas Halu Oleo Kendari, Indonesia and President of Tokyo Tech, Japan.

References
[1] Nellemann C, Corcoran E, Duarte CM, Valdés L, De Young C, Fonseca L and Grimsditch G 2009 Blue carbon - the Role of Healthy Oceans in Binding Carbon. United Nations Environment Programme, GRID-Arendal
[2] Duarte CM, Losada JJ, Hendrik IE, Mazarroa I and Marbà N 2013 The role of coastal plant communities for climate change mitigation and adaptation, Nature Climate Change 3 961–968
[3] JW, Duarte CM, Kennedy H, Marbà N, Holmer M Mateo MA, Apostolaki ET, Kendrick GA, Krause-Jensen D, McGlathery KJ and Serrano O 2012 Seagrass ecosystems as a globally significant carbon stock, Nature Geoscience 5 505–509
[4] Woodroffe C D 1985 Studies of a mangrove basin, Tuff Crater, New Zealand: II. Comparison of volumetric and velocity-area methods of estimating tidal flux, Estuarine and Coastal Shelf Science 20 431–445
[5] Benner R and Hodson RE 1985 Microbial degradation of the leachable and lingo-cellulosic components of leaves and wood from Rhizophora mangle in a tropical mangrove swamp, Journal of Marine Ecology Progress Series 23 221-230
[6] Alongi D M 1996 The dynamics of benthic nutrient pools and fluxes in tropical mangrove forests, Journal of Marine Research 54 123-148
[7] Young M, Gonnea ME, SilveiraJH and Paytan A 2005 Export of dissolved and particulate carbon and nitrogen from a mangrove-dominated Lagoon, Yucatan Peninsula, Mexico, Journal of Ecology and Environmental Sciences 31 (3) 189-202
[8] Alongi DM, Clough BF and Robertson AI 2005 Nutrient-use efficiency in arid-zone forests of the mangroves Rhizophorastylusa and Avicennia marina. Aquatic Botany 82 121–131
[9] Hogarth P 2007 The Biology of Mangroves and Seagrass 2nd Ed Oxford; Oxford University Press, England.
[10] Tomascick T, Mah AI, Nontji A and KasimMoosa MK 1997 The Ecology of the Indonesia Seas, Part One. Periplus Edition (HK) Ltd., Singapore.
[11] Duarte CM and Cebrián J 1996 The fate of marine autotrophic production, Journal of Limnology and Oceanography 41(8) 1758-1766
[12] Boto KG and Bunt JS 1981 Tidal Export of Particulate Organic Matter from a Northern Australian Mangrove System. Estuarine, Coastal and Shelf Science 13 247-255
[13] Boto KG and Bunt JS 1982 Carbon Export from Mangroves, In: Galbally I E and Freney J R Cycling of carbon, nitrogen, sulfur and phosphorus in terrestrial and aquatic ecosystems, Australian Academy of Science, Canberra
[14] Spitzly A and Leenheer J 1991 Dissolved organic carbon in rivers. In: Degens ET, Kempe S, Richey J E (Eds.), Biogeochemistry of major world rivers Scope 42. Wiley, U.K., pp. 214–232
[15] Dittmar A and Lara R 2001 Do mangroves rather than rivers provide nutrients to coastal environment South of the Amazon River? Evidence from long-term flux measurement, *Journal of Marine Ecology Progress* **213** 67-77

[16] Jennerjahn TC and Ittekkot V 2002 Relevance of mangroves for the production and deposition of organic matter along tropical continental margins, *Journal of Naturwissenschaften* **89** 23-30

[17] Ewel KC, Twilley RR and Ong JE 1998 Different kind of mangrove forests provide different goods and services, *Journal of Global Ecology and Biogeography Letters* **7** 83-94

[18] Boto KG and Wellington J T 1988 Seasonal variations in concentrations and fluxes of dissolved organic and inorganic materials in a tropical tidally dominated by mangrove waterway, *Journal of Marine Ecology Progress* **50**(1) 151-160

[19] Twilley RR 1985 The Exchange of organic carbon in basin mangrove forests in a Southwestern Florida estuary, *Estuarine, Coastal and Shelf Science* **20** 543–557

[20] Gattuso JP, Frankignoulle M and Wollast R 1998 Carbon and carbonate metabolism in coastal aquatic ecosystem, *Journal of Annual Review of Ecology and Systematics* **29** 405-434

[21] Analuddin K, Jamili, Septiana A, Raya R and Rahim S 2013 The spatial trends in the structural characteristics of mangrove forest at the RawaAopaWatumohai National Park, Southeast Sulawesi, Indonesia, *International Journal of Plant Science* **4**(8) 214-221

[22] Analuddin K, Jamili, Septiana A, HarlisWd, Sahidin I, Usman R, Saban R, Sharma S and Nadaoka K 2016 Blue carbon stock and green tea potential in mangroves of coral triangle eco-region, Southeast Sulawesi, Indonesia, *International Journal of Environment* **125**-132

[23] Septiana A, Jamili, HarlisWd, Analuddin K. 2016. Mangroves bioprospecting: Antioxidant source and habitat of endemic animal *Buballus* sp. in RawaAopaWatumohai National Park, Southeast Sulawesi, Indonesia, *Malaysian Applied Biology* **45**(1) 23–34

[24] Analuddin K, Septiana A, Nasaruddin, Yusuf S and Sharma S 2019 Mangrove Fruit Bioprospecting: Nutritional and Antioxidant Potential as a Food Source for Coastal Communities in the RawaAopaWatumohai National Park, Southeast Sulawesi, Indonesia, *International Journal of Fruits Science* **19**(4) 423-436

[25] Analuddin K, Sharma S, Jamili, Septiana, Sahidin I, Usman R and Nadaoka K 2017 Heavy metal bioaccumulation in mangrove ecosystem at the coral triangle ecoregion, Southeast Sulawesi, Indonesia, *Marine Pollution Bulletin* **125** 472–480

[26] Eviati and Suleman 2009 Technique for Chemical Analysis of Soil, Plants, Water and Organic Fertilizer (*Analisis Kimia Tanah, Tanaman, Air dan Pupuk. Petunjuk Teknis*) Edisi 2.BalaiPenelitian Tanah, Bogor.

[27] Bunt JS 1995 Continental scale patterns in mangrove litterfall, *Hydrobiologia* **295**(1–3)135–140

[28] Mann KH 2000 *Ecology of Coastal Waters*: with Implications for Management, Second edition, Library of Kongress Cataloging, Amerika.

[29] Robertson AI, Alongi DM and Boto KG 1992 Food chains and carbon fluxes, In: Robertson AI and Alongi DM, *Tropical Mangrove Ecosystems, Coastal and Estuarine Studies* 41, Washington, D.C.

[30] Ayukai T, Miller D, Wolanski E and Spagnol S 1998 Fluxes of nutrients dissolved and particulate organic matter in two mangrove creeks in Northeastern Australia, *Journal of Mangrove and Salt Marsh* **2**(4) 223-230

[31] Gong KW and Ong JE 1990 Plant biomass and nutrient flux in a managed mangrove forest in Malaysia, *Estuarine, Coastal and Shelf Science* **102**(5) 519-530