Plant Archives Volume 20 No. 2, 2020 pp. 4301-4311 **e-ISSN:2581-6063 (online), ISSN:0972-5210**

SEASONAL FLUXES OF CO_2, CH_4 AND N_2O GREENHOUSE GASES IN VARIOUS MANGROVE SPECIES ON THE COAST OF WEST MUNA REGENCY, SOUTHEAST SULAWESI, INDONESIA

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Abstract

Seasonal fluxes of CO_2, CH_4 and N_2O greenhouse gases in each mangrove species on the coast of West Muna Regency - Southeast Sulawesi, Indonesia conducted in 2019. The largest CO_2 gas flux occurred in April (rainy season) in *B. cylindrica* species with a flux value of 79.29 mg m^{-2} h^{-1}, while the lowest CO_2 gas flux occurred in July (the dry season) in *S. alba* species with a flux of 6.32 mg m^{-2} h^{-1}. The largest CH_4 gas flux occurred in April (rainy season) in *R. mucronata* species at 57.16 mg m^{-2} h^{-1}, while the lowest occurred in July (dry season) in species *B. gymnorrhiza* at 11.38 mg m^{-2} h^{-1}. The largest N_2O gas flux occurred in June (dry season) in *S. alba* species at 6.08 mg m^{-2} h^{-1} and the lowest occurred in July (dry season) in *B. cylindrica* species at 0.43 mg m^{-2} h^{-1}. Rain duration has a high correlation with CO_2 gas flux in *B. cylindrica* and *B. gymnorrhiza* species and on CH_4 gas flux in *R. mucronata* and *S. alba* species with correlation values of r = 0.6318, r = 5071, r = 0, 6371 and r = 0.5076. Rain duration does not correlate with N_2O gas flux in *S. alba* and *B. gymnorrhiza* species with correlation values of r = 0,0002 and r = 0.0003, respectively.

Key words: Greenhouse gases, Mangrove species, Seasonal fluxes.

Introduction

Global warming is one of the natural phenomena that can occur because it is triggered by an increase in greenhouse gases in the atmosphere. Global warming or commonly known as climate change can have an impact on aspects of fisheries (Badjeck *et al*., 2010; Shawket *et al*., 2019). Some changes that arise as a result of climate change such as rising water temperatures, increased deposition, pH, salinity, oxygen, wind speed, waves and sea level rise that significantly affect ecological conditions or decreased ecosystem services in the sea and freshwater (Cheung *et al*., 2009; Brander, 2010; Drinkwater *et al*., 2009; Jones, 2013; Wang *et al*., 2016) and had an impact on the decline in fisheries production and community livelihoods (Coulthard, 2008; Belhabib *et al*., 2016; Ohwayo *et al*., 2016; Rosegrant *et al*., 2016; Valmonte-Santos *et al*., 2016; Asch *et al*., 2017; Shaffril *et al*., 2017a) and can affect food security based on the level of food security vulnerability to climate change (Ding *et al*., 2017), so social adaptation and policy processes must be adapted both spatially and temporally (de Salamanca *et al*., 2017; Shaffril *et al*., 2017b; Singh *et al*., 2017).

The biggest contributors to global warming were carbon dioxide (CO_2) and methane (CH_4) which are produced by various human activities such as burning fossil fuels, motor vehicles and industrial machinery that causes carbon gas to accumulate in the atmosphere (IPCC, 2001; Lang *et al*., 2011; Oertel *et al*., 2016). There are three main greenhouse gases identified in the atmosphere, namely CO_2, CH_4 and N_2O (Turunen *et al*., 2001); Houghton, 2003; Archard *et al*., 2004; Adi *et al*., 2009). According to the IPCC, (2007), the percentage

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increase in greenhouse gas emissions between 1970 and 2004 has reached 70%.

Mangrove ecosystems are unique ecosystems with puddles that cause high substrate salinity, as well as flooding by tides. Mangrove ecosystems have a high content of organic matter derived from leaves, flowers, branches, twigs and some other tree parts commonly called litter. Besides the litter from mangroves, the input of organic matter from the outside as a result of pressure from anthropogenic activity is also a material to be processed by various decomposer organisms (Giani *et al.*, 1996; Tam and Wong, 2000; Trott and Alongi, 2000; Chang and Yang, 2003; Lovelock *et al.*, 2004). Decomposition of litter and organic matter and various other reactions such as methanogenic, nitrification and denitrification that occur in the mangrove substrate produces the main gases in increasing greenhouse gas emissions, in this case, are CO_2, CH_4 and N_2O (Mosier, 1994; Purvaja and Ramesh, 2001; Hincapie *et al.*, 2002; Kreuswiezer *et al.*, 2003; Alongi *et al.*, 2005; Wang *et al.*, 2009; Chen *et al.*, 2012; Konnerup *et al.* 2014; Nobrega *et al.* 2016).

CO_2, CH_4 and N_2O gases produced by microbial activities that occur in the soil or substrate will mostly be released into the atmosphere either diffused through the soil or fluxed by plants so that it will increase the concentration of greenhouse gases that affect increasing the temperature of the earth's surface (De Wilde and De Bie, 2000; Allen *et al.*, 2007; Biswas *et al.*, 2007; Davidson, 2009; Dunne *et al.*, 2013; Harley *et al.*, 2015; Castillo *et al.*, 2017; Tullberg *et al.*, 2018) includes fluxes that occur in grasslands (Li *et al.*, 2015). The rate of carbon gas flux (CO_2 and CH_4) originating from mangrove litter is generally influenced by litter type, litter degradation rate, salinity, temperature, tides, pH and freshwater input (Purvaja and Ramesh, 2001; Kreuzwieser *et al.*, 2003; Arnold *et al.*, 2005; Barnes *et al.*, 2006; Rusmana, 2006; Kristensen *et al.*, 2008a,b; Kone and Borges, 2008; Dutta *et al.*, 2013; Rahman *et al.*, 2018). Besides that, bulk soil density is also a factor influencing the formation of

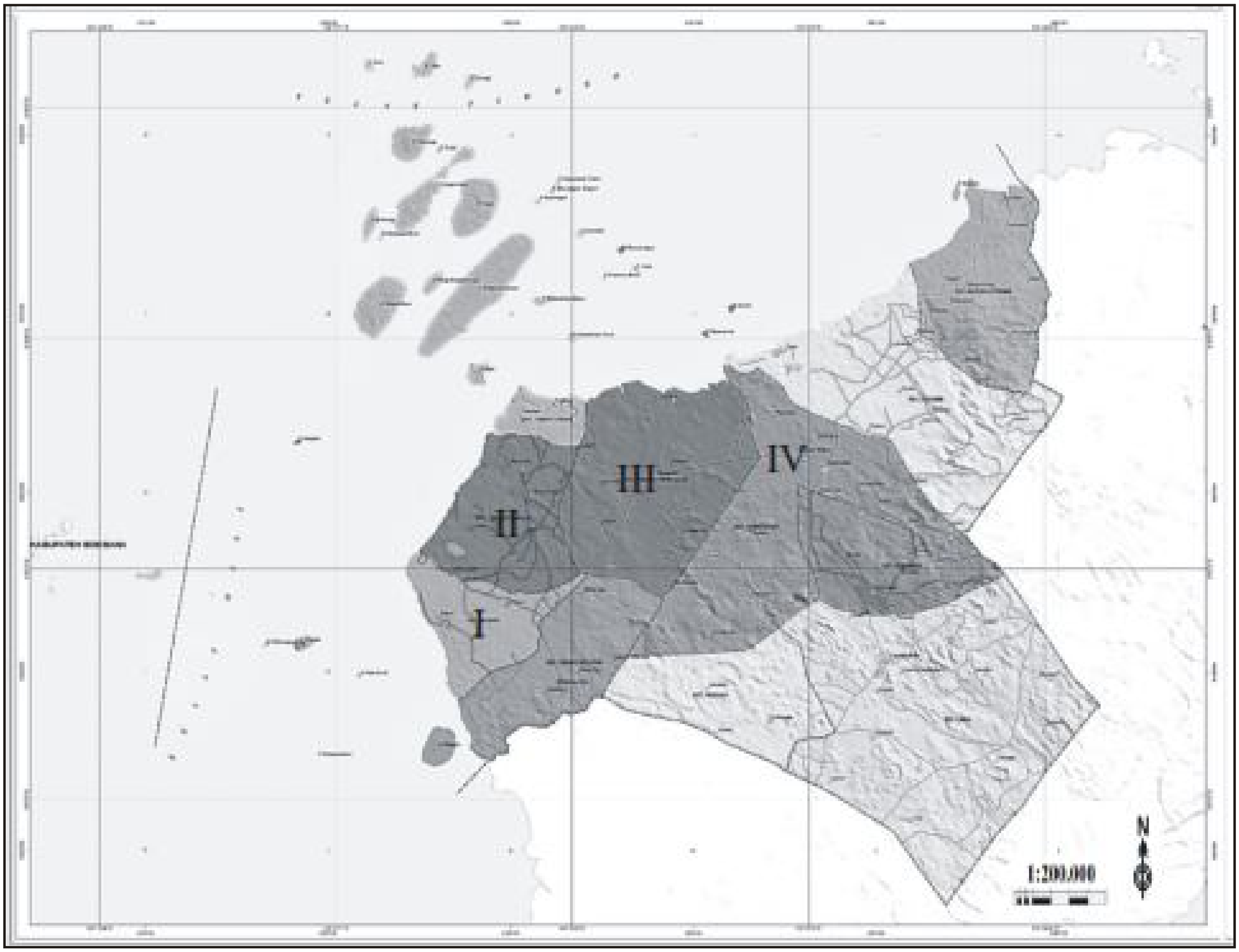

Fig. 1: Geographical location of the mangrove in the present study. I: Maginti mangrove; II: Central Tiworo mangrove; III: Archipelago Tiworo mangrove; IV: Sawerigadi mangrove.

methane gas in wetlands including mangrove ecosystems (Giani *et al*., 1996; Chang and Yang, 2003).

The study related to greenhouse gas flux in various types of ecosystems have been carried out, for example, Ye *et al*., (2000); Kreuzwieser *et al*., 2003; Arnold *et al*., (2005); Rusmana, 2006; Chen *et al*., (2010); Konnerup *et al*., (2014); Chauhan *et al*., (2015); Nobrega *et al*. (2016); Cabezas *et al*., (2017) and Rahman *et al*., (2018) in mangrove ecosystems, Midderlburg *et al*., (2002); Harley *et al*., (2015); Nirmal-Rajkumar *et al*., (2008); and Upstill-Goddard and Barnes, (2016) respectively in estuarine waters and Ostrovsky, (2003); Ferron *et al*., (2007); and Osudar *et al*., (2015) respectively on the lake, bay and sea waters. However, a study related to greenhouse gas flux to the type of litter from some mangrove species is still very least, especially if it is related to the temperature, salinity, frequency and duration of rain which is a representation of the season.

Indonesia in general consists of two seasons, the dry season and the rainy season. The rainy season occurs in November - May while the dry season occurs in June - October. Information related to greenhouse gas fluctuations from litter of various mangrove species in the dry and rainy seasons, especially in Indonesia, has not yet been found. Whereas the frequency and duration of rain that occurs can influence changes in temperature and salinity, causing fluxes of greenhouse gases to fluctuate. Therefore it is necessary to research to obtain information related to it.

One of the mangrove ecosystem habitats is on the coast of West Muna Regency - Southeast Sulawesi. Mangrove species in this region consist of Bruguiera cylindrica, Bruguiera gymnorrhiza, Rhizophora apiculata, Rhizophora mucronata, Rhizophora stylosa, Sonneratia alba and other species (Rahman *et al*., 2014) that are still classified as natural because their waters have not been contaminated by industrial waste or domestic waste overload. This is because the majority of the community on the coastal area of West Muna work as farmers and only a small proportion work as fishermen or cultivators. Ecosystem natural conditions supported by low anthropogenic activity stresses and dominant mangrove species are representative enough to illustrate seasonal analysis of greenhouse gas fluxes (CO_2, CH_4 and N_2O) in various mangrove species in other natural ecosystems in Indonesia.

Fig. 2: Schematic of greenhouse gases samplings in each mangrove species.

Material and Methods

Description of study area

This research was conducted in January - December, 2019 as a representation of the rainy season and the dry season. The study sites are in four areas which are mangrove ecosystem habitats. These areas are Maginti District (Station I), Central Tiworo District (Station II), Tiworo Kepulauan District (Station III) and Sawerigadi District (Station IV), West Muna Regency (Fig. 1).

Rahman *et al*., (2014) reported that mangrove species in this region were dominated by *Bruguiera cylindrica, Bruguiera gymnorrhiza, Rhizophora apiculata, Rhizophora mucronata, Rhizophora stylosa* and *Sonneratia alba* with a total densities ranging from 760-1000 trees.ha^{-1} and Rahman *et al*., 2019) mangroves with density values are included in the low category. These species live in different habitat types. *Bruguiera cylindrica* and *Bruguiera gymnorrhiza* live in mud-substrate habitats, *Rhizophora apiculata*, *Rhizophora mucronata* and *Rhizophora stylosa* live in sandy-mud-habitats, while *Sonneratia alba* lives in mud-sand substrate habitats (Bengen, 2004; Noor *et al*., 2006; Hogarth, 2007; Rahman *et al*., 2014; Martuti *et al*., 2019).

Furthermore, Rahman *et al*., (2014) states that each mangrove ecosystem has a relatively similar utilization pattern, namely as a fishing ground, timber, ecotourism and around 250 ha of traditional aquaculture ponds, especially in the coastal areas of Maginti District. The conversion of land as ponds, docks, boat moorings and settlements has triggered a decrease in the area and density of mangroves in Indonesia (Ilman *et al*., 2016) including on the coast of West Muna (Rahman *et al*., 2019).

Greenhouse gases samplings and flux measurements

Gas sampling begins by first storing the litter of each mangrove species. Litter collection is done by placing litter traps measuring 2 × 4 m^2 under the canopy of each mangrove species. Next take each of the 600 grams of the wet weight of the litter to be placed and allowed to stand on a square plate (1 × 1 × 1 m^3) for 30 days when the litter begins to decay and decompose. When litter begins to decompose, a chamber (0.5 × 0.5 × 1 m^3) was placed in a square plate to take gas that results from litter decomposition (Mosier, 1994; Purvaja and Ramesh, 2001; Ye *et al*., 2000; Hincapie *et al*., 2002; Kreuswiezer *et al*., 2003; Alongi *et al*., 2005; Wang *et al*., 2009; Chen *et al*., 2012; Konnerup *et al*., 2014; Nobrega *et al*., 2016). Gas samples were taken for 8 hours at intervals of 2 hours (08.00, 10.00, 12.00, 14.00, 16.00). Gas was taken through a syringe tube and put into a 10 ml glass bottle and analyzed using gas chromatography (GC) methods. The litter collection and gas sampling can be presented in fig. 2.

Measurement of rainy day and daily duration

Measurement of rain frequency and duration was manually carried out by recording its amount and duration in a month using a stopwatch. This is aimed to categorize the summer and the rainy season, so that it can be the analysis of the correlation between the season to greenhouse gas flux of each mangrove species found on the coast of West Muna.

Data analysis

- **Greenhouse gases fluxes:**

Greenhouse gas fluxes (CO_2, CH_4 and N_2O) are analyzed based on differences in mangrove species and seasons represented by the frequency and duration of rainfall. The flux analysis was calculated with the following formula (IAEA, 1992):

$$F = \frac{dc}{dt} \times \frac{Vch}{Ach} \times \frac{mW}{mV} \times \frac{273,2}{273,2 + T}$$

Notes: F = flux (mg m^{-2} h^{-1}), = change in gas concentration per unit of time (ppm hr^{-1}), Vch = volume of chamber (m^3), Ach = area of chamber (m^2), mW = molecular weight (g.$mole^{-1}$), mV = mole volume constant (22.4 L), T = average temperature during gas sampling (p C), 273.2 = Kelvin temperature constant.

- **Seasonal analysis**

In general, the difference between the rainy season and the summer season can be represented by the frequency and rain duration that occurred each month. The season was analysis descriptively-quantitative.

- **Seasonal relationship to greenhouse gases fluxes**

The relationship between season and greenhouse gas flux was analyzed using the regression method. This is aimed to see the level of season correlation with the flux of greenhouse gases in each mangrove species. The analysis of correlation level of the season and greenhouse gas flux refers to the classification according to Sarwono, (2009) as in table 1.

Result and Discussion

Greenhouse gases fluxes

Appendix 1. shows that the greatest CO_2 gas flux is found in *B. cylindrica*, *B. gymnorrhiza, R. mucronata* and *R. apiculata*, which are 38.28 mg m^{-2} h^{-1}, 29.92 mg m^{-2} h^{-1}, 29.02 mg m^{-2} h^{-1} and 25.70 mg m^{-2} h^{-1}. The lowest CO_2 gas flux is found in *R. stylosa* and *S. alba*, namely 18.93 mg m^{-2} h^{-1} and 16.44 mg m^{-2} h^{-1}. CH_4 gas flux the largest are found in *R. mucronata, B. cylindrica, R. stylosa* and *B. gymnorrhiza* were 37.37 mg m^{-2} h^{-1},

Appendix 1: Flux of greenhouse gases in various mangrove spesies.

Time (Month)	***Flux of greenhouse gases*** **(mg m^{-2} h^{-1})**																	
	B. cylindrica			***B. gymnorrhiza***			***R. apiculata***			***R.mucronata***			***R. stylosa***			***S. alba***		
	CO_2	**CH_4**	**N_2O**	**CO_2**	**CH_4**	**N_2O**	**CO_2**	**CH_4**	**N_2O**	**CO_2**	**CH_4**	**N_2O**	**CO_2**	**CH_4**	**N_2O**	**CO_2**	**CH_4**	**N_2O**
Jan.	35,01	45,65	4,43	27,72	42,85	2,09	13,30	29,30	5,60	16,46	29,34	5,38	12,50	21,30	3,31	8,58	19,61	3,48
Feb.	47,96	49,33	1,46	42,43	35,06	1,32	34,64	25,71	1,72	31,93	29,71	4,70	24,00	28,64	2,99	20,15	28,05	1,58
March	64,53	40,37	1,34	57,17	37,75	1,26	32,58	31,54	5,22	38,59	40,11	4,23	29,80	28,24	1,99	18,17	31,28	4,25
April	79,29	54,76	0,43	62,90	47,83	5,88	43,36	31,57	1,89	51,88	57,16	4,26	35,51	34,80	1,74	23,76	34,18	2,68
May	53,60	48,42	0,93	41,86	37,86	1,60	27,47	22,71	1,83	37,81	51,66	1,26	32,72	49,41	3,13	42,06	29,40	2,26
June	40,80	37,49	2,49	11,65	24,79	5,07	21,07	26,77	5,04	16,09	41,52	5,17	6,52	33,52	2,48	10,43	28,05	6,08
July	7,00	32,93	2,59	13,14	24,14	4,47	18,67	17,29	5,67	10,71	35,39	4,36	15,15	24,58	5,39	6,32	14,95	2,66
Aug.	15,15	27,90	1,28	9,69	28,73	1,81	7,30	20,70	6,25	8,74	32,58	2,71	18,07	33,58	3,95	25,98	21,81	3,13
Sept.	18,07	27,86	3,19	23,52	11,38	5,99	15,18	16,96	4,96	23,99	23,58	1,91	7,46	20,82	3,51	14,24	19,68	5,84
Oct.	7,46	25,88	3,58	10,22	14,83	4,50	35,01	21,79	3,61	45,83	27,47	3,42	16,55	19,41	5,51	6,22	22,30	3,74
Nov.	40,95	21,26	5,95	27,95	20,94	3,53	27,16	22,22	5,22	28,81	36,65	3,92	12,41	28,57	2,61	8,52	17,01	2,01
Dec.	49,49	32,56	1,85	30,83	16,81	4,34	32,65	27,22	3,79	37,41	43,23	3,53	16,46	35,99	2,45	12,87	19,08	1,38
Average	**38,28**	**37,03**	**2,46**	**29,92**	**28,58**	**3,49**	**25,70**	**24,48**	**4,23**	**29,02**	**37,37**	**3,74**	**18,93**	**29,90**	**3,25**	**16,44**	**23,78**	**3,26**

Table 1: Clasification of correlation level (Sarwono, 2009).

R	*Correlation level*
0	No correlation
0,00 – 0,25	Low correlation
0,25 – 0,50	Moderat
0,50 – 0,75	High correlation
0,75 – 0,99	Very high correlation
1	Perfect

37.03 mg m^{-2} h^{-1}, 29.90 mg m^{-2} h^{-1} and 28.58 mg m^{-2} h^{-1}, respectively. The lowest CH_4 gas flux is found in *R. apiculata* namely 24.48 mg m^{-2} h^{-1} and *S. alba* namely 23.78 mg m^{-2} h^{-1}. The largest N_2O gas flux is *R. apiculata, R. mucronata* and *B. gymnorrhiza* were 4.23 mg m^{-2} h^{-1}, 3.74 mg m^{-2} h^{-1} and 3.49 mg m^{-2} h^{-1}, respectively. The lowest N_2O gas flux is found in *B. cylindrica, R. stylosa* and *S. alba* were 2.46 mg m^{-2} h^{-1}, 3.25 mg m^{-2} h^{-1} and 3.26 mg m^{-2} h^{-1}, respectively.

Rainy days and daily duration

In 2019/2020 the rainy season experienced a time shift from April-August and January-June 2019, in several regions in Sulawesi. Based on the analysis of the rain frequency and duration throughout 2019, it was found that West Muna Regency was one of the regions that experienced a shift in season, with rainfall from January to July followed by the dry season which started in August. The peak of the rainfall occurred in April with a frequency of 17 days $month^{-1}$ with a duration of 2.03 hours day^{-1} and the lowest in September with a frequency of 1 day $month^{-1}$ and a duration of 0.01 hours day^{-1}.

However, there was low-frequency rainfall in September, November and December, therefore, it was concluded that subsequent months were called "wet-dry season" (Fig. 3).

Seasonal relationship to greenhouse gases fluxes

The correlation of rain duration to greenhouse gas flux in each species is relatively different. Rain duration has a low correlation with CO_2 gas flux in *S. alba* and a strong correlation with CO_2 gas flux in *B. cylindrica* and *B. gymnorrhiza.* Rain duration has a low correlation with CH_4 gas flux in *R. stylosa*, but has a low correlation with CH_4 gas flux in *R. mucronata* and *S. alba*. While the correlation of rain duration to N_2O gas flux is low in *B. gymnorrhiza, R. apiculata, R. mucronata a*nd *S. alba*, but moderately correlated with N_2O gas flux in *B. cylindrica* and *R. stylosa* (Table 2).

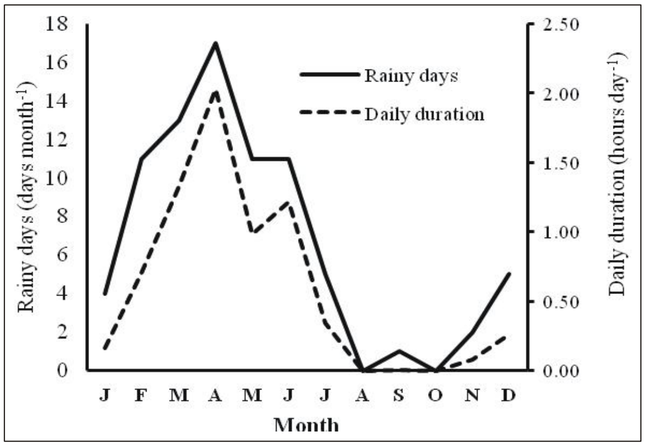

Fig. 3: Rainy days and daily duration in 2019.

CO_2

In general, CO_2 gas fluxes for each mangrove species are relatively different and their fluctuations tend to follow fluctuations in rain duration throughout 2019 (Fig. 4). In January 2019 which is the rainy season, it rains for 4 days with an average duration of 0.17 hour day^{-1}. Species with the largest CO_2 gas flux this month are *B. cylindrica* and *B. gymnorrhiza* with values of 35.01 mg m^{-2} h^{-1} and 27.72 mg m^{-2} h^{-1}, respectively. While the species with the smallest flux is *S. alba* with a value of 8.58 mg m^{-2} h^{-1}. CO_2 gas flux in the *B. cylindrica* species, *B. gymnorrhiza, R. mucronata, R. apiculata* and *R. stylosa* increased to reach the largest values in April, with values of 79.29 mg m^{-2} h^{-1}, 62.90 mg m^{-2} h^{-1}, 51.88 mg m^{-2} h^{-1}, 43.36 mg m^{-2} h^{-1} and 35.51 mg m^{-2} h^{-1}, respectively. The flux is in line with the frequency and duration of rain, namely 17 days $month^{-1}$ and 2.03 hour day^{-1}, which is the peak of the rainy season. Entering the dry season (June-October) the frequency and duration of raindrops dramatically, especially in August and October where rain does not occur at all. This causes the CO_2 gas flux to also experience a significant decrease in each mangrove species. The lowest CO_2 gas flux for *R. apiculata, R. mucronata* and *B. gymnorrhiza* species occurred in August with values of 7.30 mg m^{-2} h^{-1}, 8.74 mg m^{-2} h^{-1} and 9.69 mg m^{-2} h^{-1}, respectively. While the

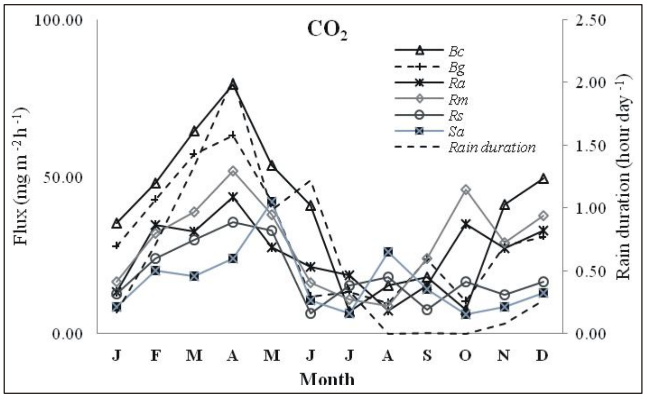

Fig. 4: Seasonal fluxes of CO_2 gases in various mangrove spesies on the coast of West Muna Regency. *Bc = Bruguiera cylindrica, Bg = Bruguiera gymnorrhiza, Ra = Rhizophora apiculata, Rhizophora mucronata, Rhizophora stylosa, Rs = Sonneratia alba.*

Tabel 2: Seasonal relationship to greenhouse gases fluxes.

Green house gases	Daily duration	Species											
		B.cylindrica		***B.gymnorrhiza***		***R.apiculata***		***R.mucronata***		***R. stylosa***		***S. alba***	
		Flux	***r***	**Flux**	***r***	**Flux**	***r***	**Flux**	***r***	**Flux**	***r***	**Flux**	***r***
CO_2	0,00	35,01	0,6318	27,72	0,5071	13,30	0,1426	16,46	0,3051	12,50	0,3356	8,58	0,0925
	0,00	47,96	a	42,43	a	34,64	c	31,93	b	24,00	b	20,15	c
	0,01	64,53		57,17		32,58		38,59		29,80		18,17	
	0,08	79,29		62,90		43,36		51,88		35,51		23,76	
	0,17	53,60		41,86		27,47		37,81		32,72		42,06	
	0,26	40,80		11,65		21,07		16,09		6,52		10,43	
	0,34	7,00		13,14		18,67		10,71		15,15		6,32	
	0,71	15,15		9,69		7,30		8,74		18,07		25,98	
	0,98	18,07		23,52		15,18		23,99		7,46		14,24	
	1,22	7,46		10,22		35,01		45,83		16,55		6,22	
	1,33	40,95		27,95		27,16		28,81		12,41		8,52	
	2,03	49,49		30,83		32,65		37,41		16,46		12,87	
CH_4	0,00	45,65	0,4788	42,85	0,3609	29,30	0,4253	29,34	0,6371	21,30	0,2244	19,61	0,5076
	0,00	49,33	b	35,06	b	25,71	b	29,71	a	28,64	c	28,05	a
	0,01	40,37		37,75		31,54		40,11		28,24		31,28	
	0,08	54,76		47,83		31,57		57,16		34,80		34,18	
	0,17	48,42		37,86		22,71		51,66		49,41		29,40	
	0,26	37,49		24,79		26,77		41,52		33,52		28,05	
	0,34	32,93		24,14		17,29		35,39		24,58		14,95	
	0,71	27,90		28,73		20,70		32,58		33,58		21,81	
	0,98	27,86		11,38		16,96		23,58		20,82		19,68	
	1,22	25,88		14,83		21,79		27,47		19,41		22,30	
	1,33	21,26		20,94		22,22		36,65		28,57		17,01	
	2,03	32,56		16,81		27,22		43,23		35,99		19,08	
N_2O	0,00	4,43	0,2820	2,09	0,0003	5,60	0,2120	5,38	0,1075	3,31	0,3781	3,48	0,0002
	0,00	1,46	b	1,32	c	1,72	c	4,70	c	2,99	b	1,58	c
	0,01	1,34		1,26		5,22		4,23		1,99		4,25	
	0,08	0,43		5,88		1,89		4,26		1,74		2,68	
	0,17	0,93		1,60		1,83		1,26		3,13		2,26	
	0,26	2,49		5,07		5,04		5,17		2,48		6,08	
	0,34	2,59		4,47		5,67		4,36		5,39		2,66	
	0,71	1,28		1,81		6,25		2,71		3,95		3,13	
	0,98	3,19		5,99		4,96		1,91		3,51		5,84	
	1,22	3,58		4,50		3,61		3,42		5,51		3,74	
	1,33	5,95		3,53		5,22		3,92		2,61		2,01	
	2,03	1,85		4,34		3,79		3,53		2,45		1,38	
a: high correlation, b: moderat, c: low correlation, unit of greenhouse gases = mg m^{-2} h^{-1}													

lowest flux for *R. stylosa, B. cylindrica* and *S. alba* species respectively occurred in June, July and October with flux values of 6.52 mg m^{-2} h^{-1}, 7.00 mg m^{-2} h^{-1} and 6.23 mg m^{-2} h^{-1}, respectively. CO_2 gas fluxes in each species then increase again when entering the rainy season, especially in December 2019 with a value of 49.49 mg m^{-2} h^{-1} for *B. cylindrica*, 30.83 mg m^{-2} h^{-1} for *B. gymnorrhiza*, 32.65 mg m^{-2} h^{-1} for *R. apiculata*, 37.41 mg m^{-2} h^{-1} for *R. mucronata*, 16.46 mg m^{-2} h^{-1} for *R. stylosa* and 12.87 mg m^{-2} h^{-1} for *S. alba*. The value of CO_2 gas flux is relatively low when compared to the report of Arnold *et al*., (2005); Chen *et al*., (2010, 2012) and Rahman *et al*., (2018).

The difference in CO_2 gas flux in each species is in line with the value of its correlation with the seasons. Seasonal correlation to CO_2 gas flux in *B. cylindrica* and *B. gymnorrhiza* species is relatively strong. The correlation value of these species was r = 0.6318 for *B. cylindrica* and r = 5071 for *B. gymnorrhiza.* Seasonal correlation to CO_2 gas flux is low in species *R. apiculata* (r = 0.1426) and *S. alba* (r = 0.0925) and moderate in species

R. mucronata (= 0.3061) and *R. stylosa* (r = 0.3051).

The occurrence of differences in gas flux in the rainy season and the dry season is caused by temperature and salinity fluctuations caused by freshwater input (Kreuzwieser *et al*., 2003; Barnes *et al*., 2006; Kristensen *et al*., 2008ab; Kim, 2015), especially during heavy rain. In the rainy season the temperature and salinity of the waters decreases making it possible for microorganisms to carry out microbiological processes especially in litter decomposition (Yunasfi, 2006; Alongi *et al*., 2000, 2001; 2004; Alongi, 2009; Afdal *et al*., 2012) so that gas flux the resulting yield also increases, on the contrary, the dry season temperature and salinity of the waters increase which causes pressure for microorganisms so that they cannot carry out the decomposition process optimally. Chen *et al*., (2010) state that the production of greenhouse gases is significantly influenced by microbiological processes.

Furthermore, differences in CO_2 gas flux in each species are also caused by zoning systems and differences in vegetation. *B. cylindrica* and *B. gymnorrhiza* species have a greater flux than other species because they are in a closed zone with mud habitat, *R. apiculata*, *R. mucronata* and *R. stylosa* species are in the middle zone with sandy-mud habitat, while *S. alba* species are in an open zone with muddy-sand habitat (Bengen, 2004; Noor *et al*., 2006; Hogarth, 2007; Rahman *et al*., 2014; Martuti *et al*., 2019). Substrate differences show differences in soil total carbon, soil bulk density and salinity (Corredor *et al*., 1999; Purvaja and Ramesh, 2001; Kreuzwieser *et al*., 2003; Lekphet *et al*., 2005; Huang *et al*., 2009).

CH_4

CH_4 gas fluctuations are relatively the same as CO_2 gas fluctuations. The largest gas flux occurs in the rainy season and the lowest in the dry season. At the peak of the rainy season that occurred in April, the species with the largest gas flux were *R. mucronata*, *B. cylindrica* and *R. stylosa* with gas flux were 57.16 mg m^{-2} h^{-1}, 54.76 mg m^{-2} h^{-1} and 49.41 mg m^{-2} h^{-1}, respectively. In the dry season the lowest gas flux occurs in September in *B. gymnorrhiza*, *R. apiculata* and *R. mucronata* species with the gas flux were 11.38 mg m^{-2} h^{-1}, 16.96 mg m^{-2} h^{-1} and 23.58 mg m^{-2} h^{-1}, respectively. The lowest gas flux also occurred in July in *S. alba* (flux = 14.95 mg m^{-2} h^{-1}), in October at *R. stylosa* (flux -19.41 mg m^{-2} h^{-1}) and in November in *B. cylindrica* (flux = 21.26 mg m^{-2} h^{-1}) (Fig. 5). This shows that the season influences methane gas emissions that occur in mangrove ecosystems.

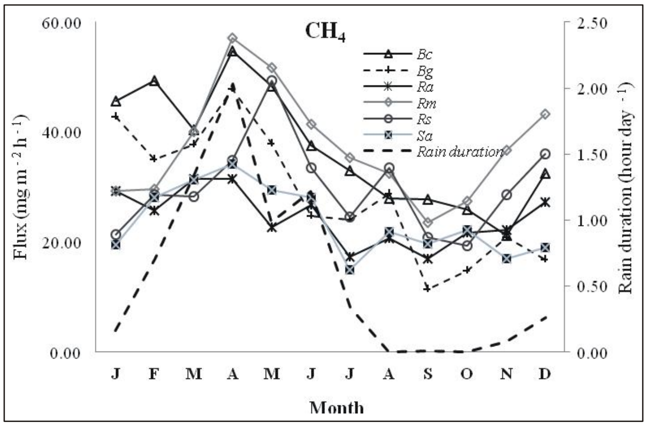

Fig. 5: Seasonal fluxes of CH_4 gases in various mangrove spesies on the coast of West Muna Regency. *Bc = Bruguiera cylindrica, Bg = Bruguiera gymnorrhiza, Ra = Rhizophora apiculata, Rhizophora mucronata, Rhizophora stylosa, Rs = Sonneratia alba.*

Table 2 shows that the influence of seasons on CH_4 gas flux tends to be different for each mangrove species. Season has a strong correlation to flux in species *R. mucronata* (*r* = 0.6371) and *S. alba* (*r* = 0.5076), moderate correlation to flux in species *B. cylindrica* (*r* = 0.4788), *B. gymnorrhiza* (*r* = 0.3609) and *R. apiculata* (*r* = 0.4253), as well as a low correlation with flux in the *R. apiculata* species (*r* = 0.2244). Furthermore, the correlation of seasons to CH_4 flux in each species tends to be different when compared to CO_2. Season is highly correlated to CO_2 gas flux in *B. cylindrica* and *B. gymnorrhiza* species, but moderate to CH_4 gas flux. Season is low correlated to CO_2 gas flux in *R. apiculata* species but moderate to CH_4 gas flux. Season is moderately correlated with CO_2 gas flux in *R. apiculata* species and low in *S. alba* species, but high in CH_4 gas flux in the same species. In the same species (*R. stylosa*), the season has a moderate correlation with CO_2 gas flux, but it has a low correlation with CH_4 gas flux. This shows that many factors influence the occurrence of CO_2 and CH_4 gas flux, especially related to microorganisms producing these gases or other factors. The formation of

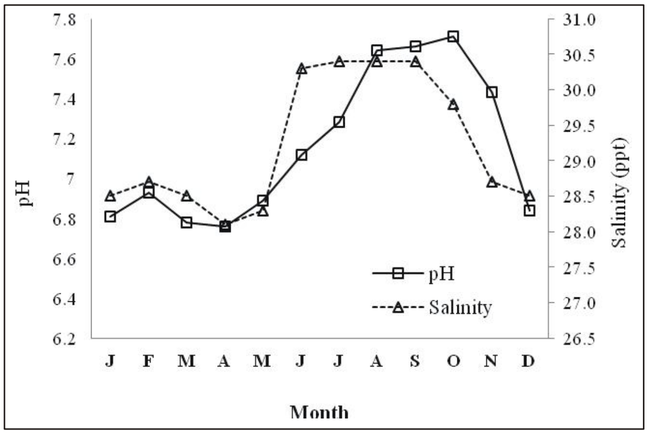

Fig. 6: pH and salinity in mangrove ecosystem on the coast of West Muna Regency.

methane gas in mangrove ecosystems is strongly influenced by the activity of methanogenic bacteria. Methanogenic bacteria are strongly influenced by bulk soil density and are sensitive to pH in the range of 6-8 (Giani *et al*., 1996). In this study, waters pH ranged from 6.8-7.6 and was the maximum pH for methane formation in wetlands (Giani *et al*., 1996; Chang and Yang, 2003). Another factor that triggers methane gas formation in wetlands is salinity. The best salinity to methane formation was from 15-20 ppt (Purvaja and Ramesh, 2001; Arnold *et al*., 2005; Kone and Borges, 2008; Dutta *et al*., 2013). In this study, salinity ranged from 28.31-30.11 ppt (Fig. 6) and is a poor salinity in the formation of methane gas (Chen *et al*., 2010).

In general, CH4 gas flux in each species is lower than the report of Ye *et al*., (2000); Arnold *et al*., (2005); Chen *et al*., (2010); Konnerup *et al*., (2014); Chauhan *et al*., (2015); Cabezas *et al*., (2017) and Rahman *et al*., (2018) which are also carried out in mangrove ecosystems. Methane gas flux is also lower than that of Midderlburg *et al*., (2002); Harley *et al*., (2015); Nirmal-Rajkumar *et al*., (2008) and Upstill-Goddard and Barnes (2016) in estuarine waters, respectively, Mastepanov *et al*., (2008) and Kim, (2015) in the tundra, as well as report by Ostrovsky (2003); Ferron *et al*., (2007); and Osudar *et al*., (2015) each conducted in a lake, bay and sea waters.

N_2O

In contrast to CO_2 and CH_4 gas, N_2O gas flux occurs higher in the dry season compared to the rainy season. In the rainy season, the smallest N_2O gas flux was found in *B. cylindrica* (flux = 0.43 mg m^{-2} h^{-1}) in April, *R. apiculata* (flux = 1.25 mg m^{-2} h^{-1}) in May, *B. gymnorrhiza* (flux = 1.26 mg m^{-2} h^{-1}) in March, *S. alba* (flux =1.38 mg m^{-2} h^{-1}) in December, *R. apiculata* (flux= 1.72 mg m^{-2} h^{-1}) in May and *R. stylosa* (flux = 1.74 mg m^{-2} h^{-1}) in April. In the dry season, the largest gas flux is found in the *R. apiculata* species (flux = 6.25 mg m^{-2} h^{-1}) in August, *S. alba* (6.08 mg m^{-2} h^{-1}) in June, *B. gymnorrhiza* (flux = 5.99 mg m^{-2} h^{-1}) in September, *B. cylindrica* (flux = 5.95 mg m^{-2} h^{-1}) in November, *R. stylosa* (flux = 5.51 mg m^{-2} h^{-1}) in October and *R. mucronata* (flux = 5.17 mg m^{-2} h^{-1}) in January (Fig. 7). Thus indicates that the frequency and duration of rain did not have a significant effect on N_2O gas flux in each mangrove species. The results of the analysis show that rain duration has a low correlation with N_2O gas flux in *S. alba* species (r = 0.0002), *B. gymnorrhiza* (r = 0,0003), *R. mucronata* (r = 0.1075) and *R. apiculata* (r = 0.2120), as well as moderate correlations with *B. cylindrica* (r = 0.3781) and *R. stylosa* (r = 0.2820). The N_2O flux value is lower than report of Pathak, (1999); Zheng *et al*., (2000); Dalal *et al*., (2003); Kreuzwieser *et al*., (2003); Arnold *et al*., (2005); Nirmal-Rajkumar *et al*., (2008); Huang *et al*., (2014); Konnerup *et al*., (2014); and Rahman *et al*., (2018) both in mangrove ecosystems and in other ecosystems and higher when compared with Chen *et al*., (2010) reports in mangrove ecosystems in South China with a flux range of 5.6-224.14 mg m^{-2} h^{-1}.

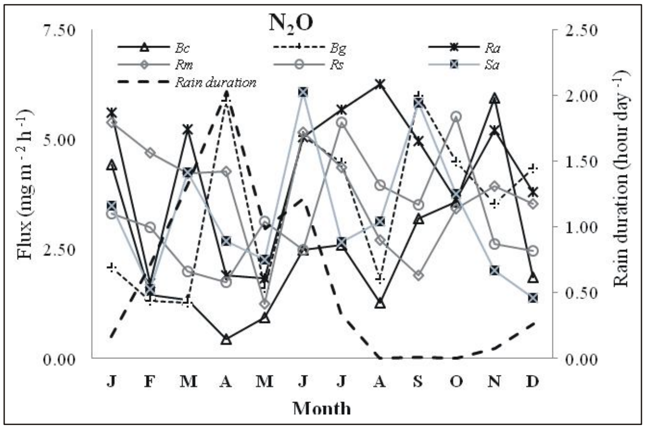

Fig. 7: Seasonal fluxes of CH_4 gases in various mangrove spesies on the coast of West Muna Regency. *Bc = Bruguiera cylindrica, Bg = Bruguiera gymnorrhiza, Ra = Rhizophora apiculata, Rhizophora mucronata, Rhizophora stylosa, Rs = Sonneratia alba.*

This difference occurs because in this study the type and amount of litter is limited to each mangrove species that has been trapped in a closed manner so that, no input of organic matter from the outside is mixed and is part of the litter decomposition process, consequently the resulting gas flux is purely from 600 g decomposition litter wet weight of each mangrove species. The low greenhouse gas flux in each mangrove species also occurs because the mangrove ecosystem on the coast of West Muna is still natural and has not been contaminated by industrial waste, except by small amounts of domestic waste. Domestic wastes that enter the mangrove ecosystem waters are more susceptible to dilution with the tides, so that there is no long-term waste left in the ecosystem water bodies.

Also, the low N_2O flux value indicates that temperature and salinity are negatively correlated to N_2O gas production. Chen *et al*., (2010) reported that N_2O production was positively correlated to NH_4^+ and negatively to NO_3^-. This indicates that N_2O gas production is dominated by nitrification and denitrification process which is supported by oxygen and inorganic nitrogen content (Corredor *et al*., 1999; Purvaja and Ramesh, 2001; Kreuswiezer *et al*., 2003; Rusmana, 2006; van den Heuvel *et al*., 2009; Chen *et al*., 2010). According to Huang *et al*., (2014) the combination of the availability of ammonium (NH_4^+), nitrate (NO_3^-) and oxygen is positively correlated to the production of N_2O gas (r = 0.764).

Acknowledgment

The author would like to express the highest gratitude to the Indonesian Endowment Fund for Education (LPDP) as the main sponsor of this research so that the research could be conducted successfully.

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