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The origin of the suspended particulate matter in the seagrass meadow of tropical waters, an evidence of the stable isotope signatures

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Abstract

Suspended particulate matter (SPM) has been known as an important variable in the organic matter flow of coastal ecosystem. Half of burial carbon in seagrass meadows is contributed by allochthonous sources that compose the SPM such as phytoplankton, seagrass detritus, marine snow aggregates and terrestrially derived particles. Each composition of the SPM contributes different roles and is important to be identified, for instance, the exact contribution of seagrass detritus will be useful for determination of carbon export through the detritus form in seagrass meadows. Here, the SPM of seagrass meadows is studied in Bintan Island and the Selayar Archipelago. The aim of this research is to determine the source origin of the SPM using a stable isotope signature. In order to fulfill this aim, the objectives are defined as: (1) to specify the stable isotope signature (δ^{13}C and δ^{15}N) of the SPM, and (2) to determine the proportional distribution of the SPM's prospectus sources. The result shows that the possibility of the source origin of the SPM includes a seagrass fraction (*Enhalus acoroides* and *Thalassia hemprichii*), terrestrial C4 plant, macroalgae, and terrestrial C3 plant. The SPM lies between the marine- and terrigenous-end members. However, it seems that the SPM is more to be terrigenous-end and allochthonous. According to a Bayesian mixing model, the terrestrial C4 has the highest contribution of the SPM at all sites except Barugaia and Pasi Island in Selayar (i.e., the highest contribution of the SPM is from the detritus of *E. acoroides*). The second contribution has been contributed by either seagrass detritus (*E. acoroides* or *Th. hemprichii*) or terrestrial C3 plant. The finding of this study indicates that there is a strong influence of the terrigenous sources in the SPM of the seagrass meadows.

Key words: suspended particulate matter, stable isotope, source origin, seagrass ecosystems

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1 Introduction

Seagrass meadows as a coastal ecosystem play an important role such as organic carbon production and export (due to primary production), nutrient cycling, sediment stabilization, enhanced biodiversity, and trophic transfers to adjacent habitats (Orth et al., 2006). The seagrass meadows altogether with mangrove and coral reef ecosystems provide ecosystem services for the nursery function, e.g., coral reef fishes (Nagelkerken et al., 2000). The seagrass ecosystem is also an important part of global carbon cycles since this ecosystem acts as a carbon sink (Duarte et al., 2013). A seagrass and mangrove ecosystem has been reported to contribute up to 50% top-down carbon sequestration, i.e., 216 Tg/a (Duarte et al., 2004). Furthermore, the global seagrass carbon pool lies up to 8.4 Pg (Fourqurean et al., 2012). Despite its high carbon pool, a seagrass decomposition rate is relatively low. Therefore, the seagrass meadows are potential to be carbon sequester generating surplus of organic carbon production (Duarte et al., 2013) and are crucial for the global carbon cycle (Wahyudi et al., 2016 and references therein).

The carbon cycle in the seagrass meadows is not merely contributed by seagrass species but also by all components such as particulate matter, correspond organisms, chemical and physical factors (Mateo and Romero, 1997; Duarte et al., 2010, 2013; Lavery et al., 2013). Suspended particulate matter (SPM) in the seagrass meadows is expected to have an important contribution in the carbon cycle. As suggested by Kennedy et al. (2010), seagrass vegetation contributes only ~50% carbon burial. The remaning half are contributed by the allochthonous sources such as phytoplankton, marine snow aggregates and terrestrially derived particles (Wahyudi et al., 2016). The important contribution of particulate matter is specifically reported by Wahyudi et al. (2016) that the vertical flux of the aggregates in the seagrass meadows is two orders of magnitude larger than other ecosystems such as coral reef and pelagic.

As previously suggested (e.g., Dalu et al., 2016; Middelburg and Nieuwenhuize, 1998), and according to the result of a marine snow-isotopic profile by Wahyudi et al. (2013), the SPM is not merely composed by a conventional proportional of marine and terrigenous materials. It is expected that the origin/sources of the SPM are either autochthonous or allochthonous. The sources can be from the seagrass detritus, macroalgae, plankton, organisms' s fecal pellet, sediment, terrestrial plant, and so on (Sarma et al., 2012; Hou et al., 2013). One of the approach to determine the SPM origin is using stable isotope analysis. The stable isotope

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analysis is a widely used approach in ecology and biogeochemistry, such as determining the food web, diet sources, or the origin of the organic matter pools (Post, 2002; Kennedy et al., 2010; Wahyudi et al., 2013, 2016; Dalu et al., 2016). The use of carbon and nitrogen isotopic-natural-abundance depends on the relative enrichment of ^{13}C and ^{15}N in the organic matter pools (e.g., the SPM in this case) relative to the different sources (Thornton and McManus, 1994; Graham et al., 2001; Dalu et al., 2016).

The study of a SPM’ s isotopic profile is important because the SPM contributes the carbon burial in the seagrass ecosystems (Kennedy et al., 2010; Wahyudi et al., 2016), thus unraveling the origin of the SPM will enhance our knowledge of the proportion of each component that compose the SPM. The evaluation of organic matter contribution to the SPM also provide a baseline assessment of potential diet sources for consumer (Dalu et al., 2016). Since the SPM is expected to be important part of carbon burial, this study will provide the information in carbon sequestration pathways. Furthermore, such kind of study and assessment has not been conducted within Indonesia waters. Thus, we select two study site which represent both pristine (less influenced by anthropogenic activities) and anthropogenic-influenced site. The aim of this study is evaluating the SPM properties that useful to understand the influence factors around the seagrass ecosystem. The objectives of this study are (1) to determine the source of the SPM in the seagrass meadows using natural abundance of carbon and nitrogen stable isotope signature, and (2) to determine the proportions of each prospectus sources of the SPM. By determining the SPM’ s source origin, we expect that the result will be useful to understand the holistic carbon flow in the seagrass ecosystem especially SPM contribution in the carbon sequestration pathways. The SPM’ s source origin can also be used as a good proxy to indicate the stress from terrestrial activities.

2 Materials and methods

2.1 *Field sampling*

The sampling was carried out in three locations of the seagrass meadows (Fig. 1), i.e., the coast of Bintan Island, the Selayar Archipelago (Selayar Island and Pasi Island), and Weh Island (Sabang). The first sampling in Bintan was conducted in August 2014, followed by the second sampling in May 2016. The Bintan’ s sites consist of Pengudang, Berakit, Malangrapat and Teluk Bakau. The field sampling in Selayar was conducted in May and August 2015. The Selayar’ s sites consist of Barugaia and Pasi Island. The field sampling in Weh Island (Sabang area) was conducted in May 2016. The methods for collecting marine snow aggregates as explained by Wahyudi et al. (2016) were applied in this research. Water samples were collected in 50 mL of centrifuge tubes. The trap formation sampling followed 2×3 and 3×6 matrix in Bintan and Selayar, respectively. The tissue samples of seagrass were also collected, i.e., the most dominant species, *Enhalus acoroides* (Ea) and *Thalassia hemprichii* (Th) during sampling in Bintan Island.

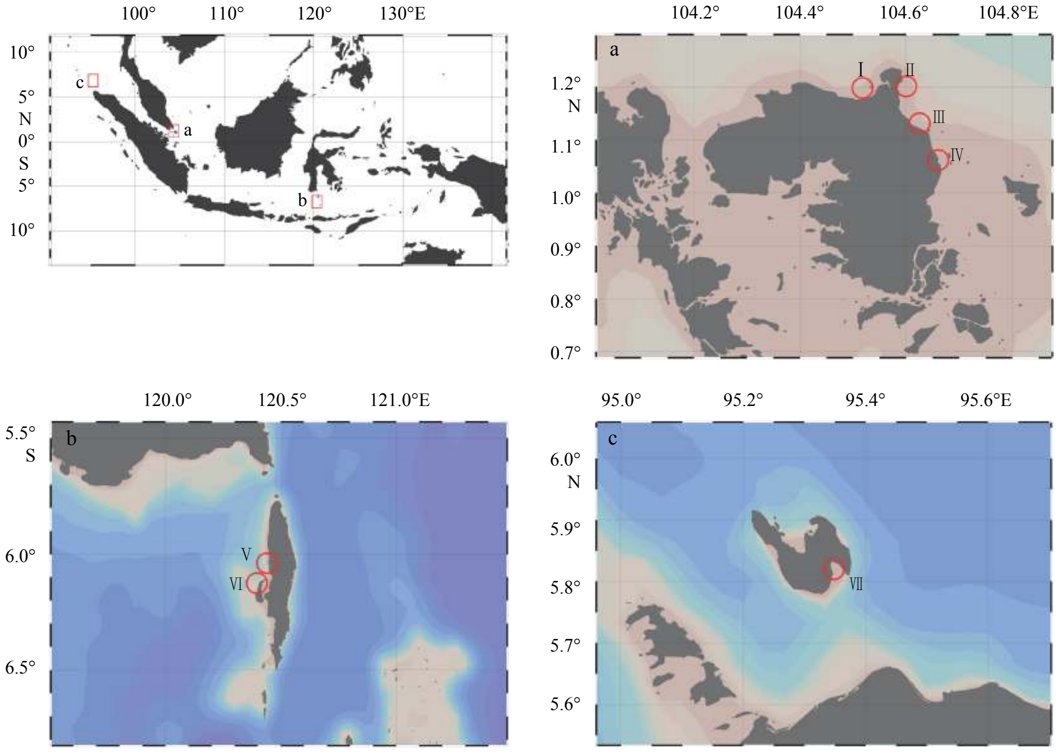

Fig. 1. Sampling sites in Bintan Island (a), Selayar (b) and Weh Island (c). Ⅰ Pengudang, Ⅱ Berakit, Ⅲ Malangrapat, Ⅳ Teluk Bakau, Ⅴ Barugaia, Ⅵ Pasi Island, Ⅶ Sabang. The map was generated by using Ocean Data View v4.7.10.

2.2 *Stable isotope analysis*

The filtrate of the SPM was acidified to remove inorganic carbon using HCl fume for 1 min and neutralized by placing it in a vacuum desiccator with concentrated NaOH for 24 h. The dry weight was measured after oven drying process at 60°C up to constant weight. Each filtrate sample (in glass fiber filter GF/F) was then packed into a tin capsule (Lüdiswiss Sn 98, d 9/10 mm) and stored for further analysis.

The tissue samples of seagrass species were oven-dried at 60°C up to constant weight. The sample was then homogenized using mortar and pestle. About 2–3 mg of homogenized sample was then packed into tin capsule and stored in the vacuum desiccator for further analysis.

The stable isotope analysis was conducted using an isotope ratio mass spectrometer, i.e., thermo delta plus XP coupled to a trace GC ultra with a combi PAL autosampler. The analysis was conducted at the Iso-trace Research, University of Otago (New Zealand).

The stable isotope ratios of $^{13}C/^{12}C$ and $^{15}N/^{14}N$ are expressed as $\delta^{13}C$ and $\delta^{15}N$, respectively. The isotopic ratios were normalized using Vienna-pee dee belemnite (VPDB) limestone-standard and atmospheric nitrogen (N_2). An isotope ratio (R) calculation, given as per-million (‰) deviation from the standard value, was calculated as follows:

$$R = {}^{13}\mathrm{C}/{}^{12}\mathrm{C} \text{ or } R = {}^{15}\mathrm{N}/{}^{14}\mathrm{N}$$

$$\delta = [(R_{\mathrm{sample}}/R_{\mathrm{standard}}) - 1] \times 1\,000.$$

Isotopic and elemental values were determined using laboratory reference materials (USGS-40 and USGS-41). Control materials, namely EDTA-OAS, IAEA-414: algae and IAEA MA-A-1: copepod were used to determine precision and accuracy for Selayar and Bintan samples, respectively. Details information for the stable isotope analysis can be found in, e.g., Carter and Barwick (2011), Lara et al. (2010), Liu et al. (2007a, b), and Wahyudi et al. (2013).

2.3 *Determination of proportional distribution*

In order to determine the proportional distribution of prospectus sources of the SPM (later the term “source” will be used), we used several secondary data (Table 1). The primary data are the SPM that collected during field sampling. SPM’ s stable isotope values would be the “mixture”.

The proportional contribution of the sources was determined using a hierarchal Bayesian mixing model analysis using MixSIAR (Stock and Semmens, 2013) within 95% credible interval (95% CI). The detail of the analysis was “residual” and “uninformative/generalist” for the error structure and the prior, respectively. The mixing model was run using “long” run length of Markov chain Monte Carlo/MCMC (Stock and Semmens, 2013). Some prospectus sources from secondary data were not included in mixing model analysis after evaluation of the preliminary result of iso-space plot of $\delta^{13}C$ against $\delta^{15}N$. The preliminary iso-space plot shows that some of the prospectus sources lie out of the SPM’ s isotopic data range (data not shown). We use discrimination factors namely 1‰ and 1.7‰ for carbon and nitrogen isotopes, respectively. The discrimination factor 1.7‰ for nitrogen was used with the assumption that all the sources and mixture can be categorized as a primary producer (or their proxy). Thus the discrimination factor is half of the discrimination factor from primary producer to the first trophic level which is 3.4‰ (Post, 2002). The MixSIAR’s Bayesian mixing model was performed using R v3.3.1 (http://www.R-project.org/).

3 Results

The comparison of organic carbon and nitrogen mole ratios (C/N) with carbon and nitrogen isotopes shows the data dispersion of the SPM isotopic and C/N mole ratios values. The minimum C/N mole ratios of the SPM is 9.7 and the maximum value is 25.0. These values lie within the range of marine to terrigenous end-member (Fig. 2). The carbon isotope values ranged from –15.36‰ to –5.15‰ and the nitrogen isotope values ranged from –2.31‰ to 5.54‰. Bi-plot of stable carbon and nitrogen isotopes (Fig. 3) shows that some of the prospectus sources may contribute to the SPM origin. Those sources consist of C4 terrestrial plant, macroalgae, particulate organic matter (POM), and seagrass species (*E. acoroides* and *Th. hemprichii*). According to the bi-plot (iso-space plot), the SPM isotopic values distribute scatteringly that show high variability of the source origin.

The stable nitrogen isotope of the SPM shows two groups with

Table 1. The isotopic profile of the prospectus sources of the SPM

Source	Code	Mean $\delta^{13}C$	SD $\delta^{13}C$	Mean $\delta^{15}N$	SD $\delta^{15}N$	n	Reference	Included in MixSIAR
Periphyton	periphyton	–15.60	1.65	4.87	1.41	36	Wahyudi et al. (2013)	yes
Green macroalgae	macroalgae	–12.30	2.18	2.18	0.85	32	Wahyudi et al. (2013)	yes
Mangrove SPM	MSPM	–25.32	0.26	2.41	0.60	7	Kaiser et al. (2014)	no
C3 terrestrial plant	C3	–27.70	1.70	–4.70	1.20	8	Liu et al. (2007b)	yes
C4 terrestrial plant	C4	–13.70	1.10	–3.40	1.10	2	Liu et al. (2007b)	yes
Aquatic plant	AquPlant	–29.70	2.50	–3.97	0.40	4	Liu et al. (2007)	no
Soils	soils	–25.50	1.30	–0.01	1.30	7	Liu et al. (2007a)	yes
Estuary SPM	ESPM	–25.56	0.03	3.97	0.03	2	Kaiser et al. (2014)	no
Bay SPM	BSPM	–22.21	1.32	8.81	1.47	14	Kaiser et al. (2014)	no
River sediment	RiverSed	–25.20	0.20	3.90	0.10	3	Liu et al. (2007b)	no
All seagrass species	seagrass-all	–11.50	3.20	5.15	0	unknown	Hemminga and Mateo (1996), Wahyudi et al. (2013)	no
Enhalus acoroides	Ea1	–9.80	0.90	NA	NA	6	Kennedy et al. (2010)	no
Enhalus acoroides	Ea2	–5.80	1.20	NA	NA	2	Hemminga and Mateo (1996)	no
Enhalus acoroides (Abg)	Ea3-Abg	–6.76	0.29	7.10	0.15	2	this study	yes
Enhalus acoroides (Blg)	Ea3-Blg	–6.83	0.14	3.32	0.80	2	this study	yes
Thalassia hemprichii	Th1	–11.80	0	NA	NA	unknown	Kennedy et al. (2010)	no
Thalassia hemprichii	Th2	–6.90	1.20	NA	NA	6	Hemminga and Mateo (1996)	no
Thalassia hemprichii	Th3	–7.10	0.65	3.72	1.62	2	this study	yes
POM	POM	–15.80	0.66	4.23	1.41	36	Wahyudi et al. (2013)	yes
Marine SPM	MSPM1	–23.37	1.24	8.84	1.55	117	Kaiser et al. (2014)	no
Marine SPM (East China Sea)	MSPM2	–20.10	1.50	4.20	1.00	5	Liu et al. (2007a)	no

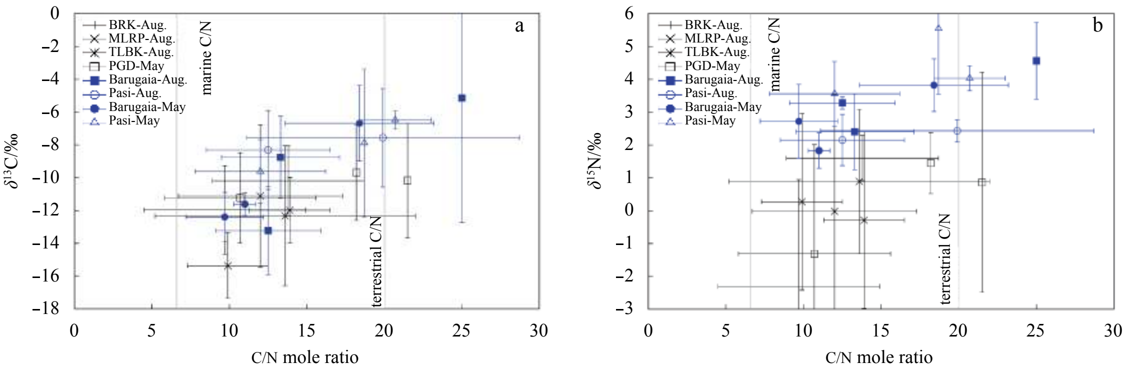

Fig. 2. Comparison of organic carbon and nitrogen mole ratio (C/N) to carbon (a) and nitrogen (b) isotopes. The right and left gray lines show typical C/N values for marine- (less than 6.6 in Martiny et al. (2014)) and terrestrially-derived organic matters (greater than 20.0 in Gilhooly et al. (2008)).

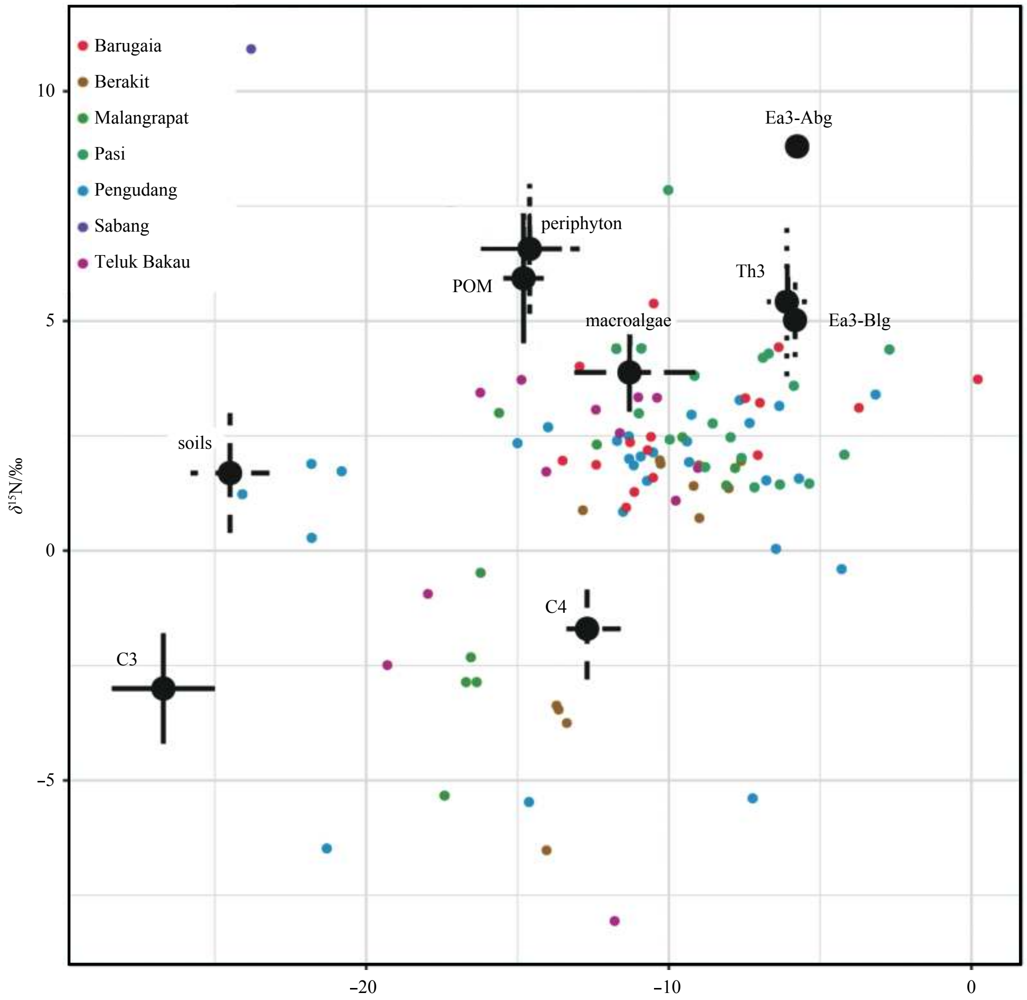

Fig. 3. Bi-plot of stable carbon and nitrogen isotopes of the SPM (MixSIAR output). The prospectus sources (closed big circle ●) are obtained from the primary and secondary data presented in Table 1.

distinct differences. About a third of the SPM collected in Bintan have depleted δ^{15}N (negative value), meanwhile almost all of the SPM collected in Selayar have more enriched δ^{15}N (positive value). Almost all depleted δ^{15}N from Bintan were collected in August (during the southwest monsoon). Furthermore, the δ^{13}C values of the SPM collected in Selayar tend to be homogen (lies between –12.00‰ and –2.00‰) compared with the SPM from Bintan which have wider range values.

The iso-space plot of the δ^{13}C againts the δ^{15}N (Fig. 3) shows the possibility of the source origin of the SPM including the seagrass fraction (*E. acoroides* and *Th. hemprichii*), terrestrial C4 plant, macroalgae, and terrestrial C3 plant. However, the contribution of each fraction to the mixture cannot be understood merely from the iso-space plot.

The Bayesian mixing model performed using the MixSIAR shows the estimate of the source origin of the SPM (Figs 4 and 5). The statistic summary (data not shown), suggests that according to Figs 4 and 5, the sources origin of the SPM is dominated by the C4 plant followed by the seagrass (*E. acoroides*) for all sites except for Barugaia, Pasi Island and Sabang. The SPM origin in Barugaia and Pasi Island is dominated by *E. acoroides* instead. This seagrass species contributes about 24% and 33% in total above- and below-ground habitus for Barugaia, Pasi Island and Sabang, respectively. The C4 plant contributes minimum 8.8% of the total SPM in Sabang (Weh Island) and maximum 64% of total SPM in Berakit. *Thalassia hemprichii,* as the second dominant species at all sites, contributes 8%–44% of the total SPM, which is comparable with other sources (e.g., macroalgae or POM), except in Sabang that have major contribution. Overall, there is no seasonal variation of the proportional contribution of each source as shown by Fig. 5 (i.e., C4 plant dominant as SPM source followed by *E. acoroides*). Table 2 shows the highest three contributors of the SPM in the seagrass ecosystem of Bintan, Selayar and Weh Island.

4 Discussion

The C/N mole ratio of SPM ranged from 9.7 to 25.0. According to Gilhooly et al. (2008) and Martiny et al. (2014), these values lie within the range of marine to terrigenous end-members. Antonio et al. (2012) and Fu et al. (2014) suggested that the C/N mole ratio of SPM which elevated more than 8 indicates the increased-freshwater and/or terrestrial sources contributions. Either Antonio et al. (2012) or Fu et al. (2014) assessed the SPM in estuaries. Thus cannot be compared directly with the seagrass ecosystem' s SPM in the present study. However, according to the evaluation by comparing the present study with the study by Antonio et al. (2012) or Fu et al. (2014), it is clear that the SPM in the present study tends to be terrigenous by means the increased terrestrial sources contributions.

It has been expected that the stable carbon and nitrogen isotope values show high variability, since the SPM composed by many sources/materials. As suggested by Sarma et al. (2012) and Hou et al. (2013), the sources can be from the seagrass detritus, macroalgae, plankton, organisms' s fecal pellet, sediment, terrestrial plant, and so on. Wahyudi et al. (2016) also explained that

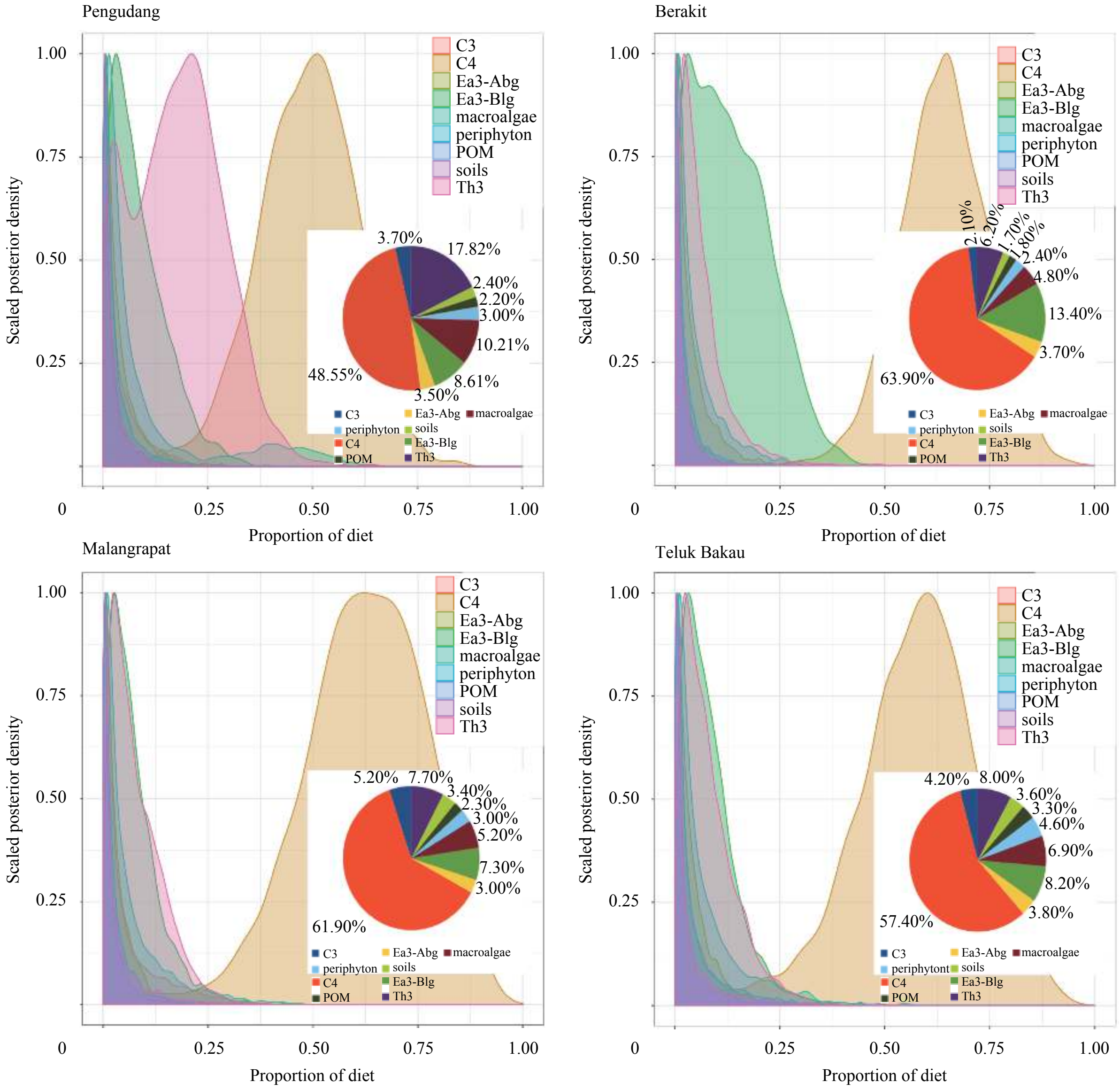

Fig. 4.

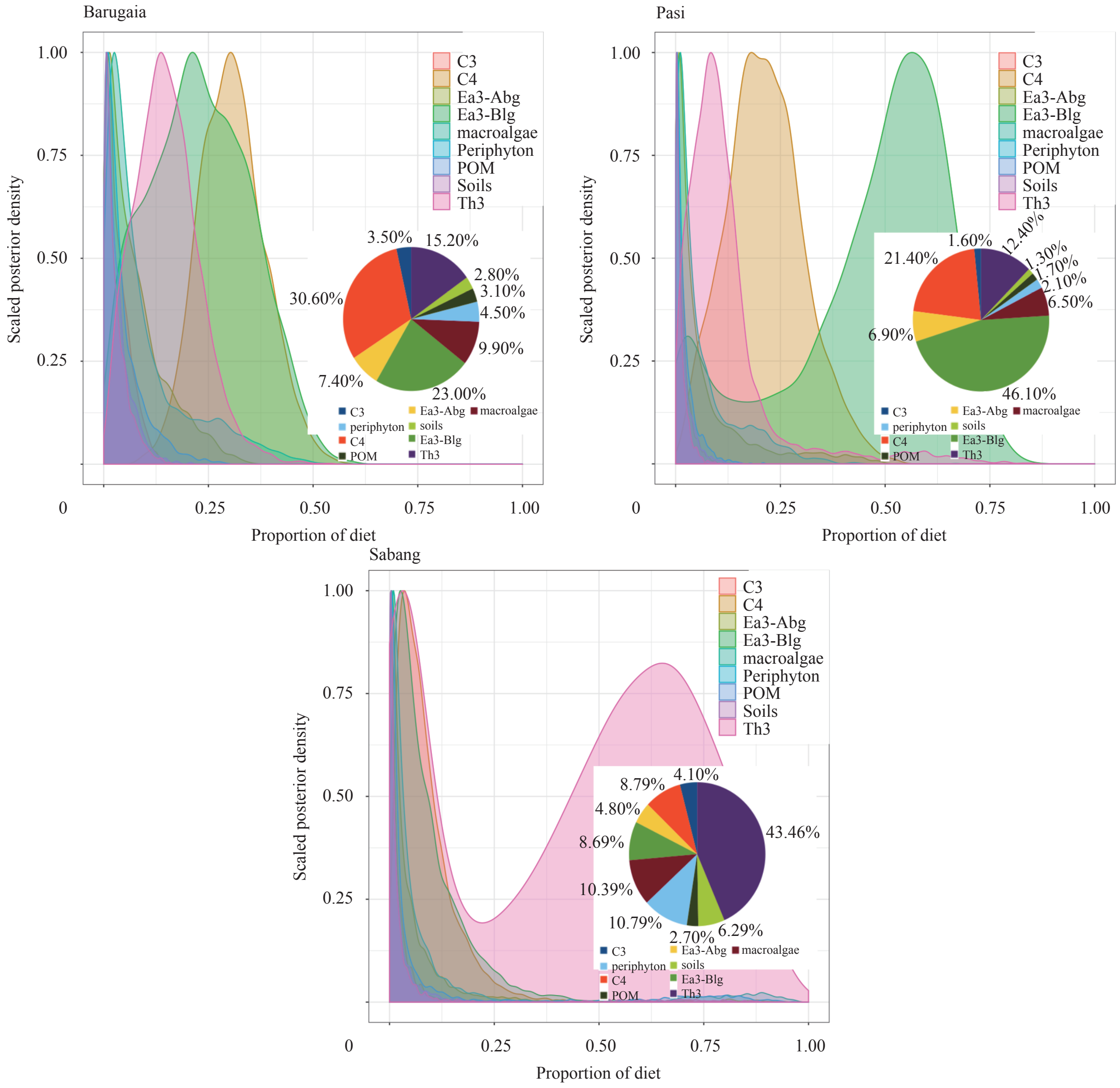

Fig. 4. Posterior plot (MixSIAR output) of all sources according to the location that shows the proportions each source to the mixture (SPM).

the marine snow (another typical name of the SPM) is composed by the POM, mesograzer fecal pellet and seagrass detritus. Therefore, the wide range SPM's isotopic values indicate the different major compositions of each SPM sample.

A mixing model shows that the sources origin of the SPM is dominated by the C4 plant followed by the seagrass (*E. acoroides*) for all sites in Bintan. Meanwhile, the SPM in Selayar' s seagrass meadows that represent by sites in Barugaia and Pasi Island, is dominated by the seagrass detritus (*E. acoroides*). The SPM in Sabang is dominated by *Th. hemprichii* detritus (Fig. 4). The seagrass meadows in Selayar can be categorized more pristine ecosystem compared with those in Bintan (unpublished data). This may affect the composition of the SPM in both areas, Bintan and Selayar. The C4 plant that dominates the SPM composition in Bintan may be caused by the high amount of the terrestrial loading, i.e., detritus export from terrestrial plantations or grassland to the coastal ecosystem. This finding suggests that the SPM in the seagrass meadows that located in island with high anthropogenic stress (i.e., land use change) will be likely composed mainly by terrigenous materials.

On the contrary, the seagrass meadows of Pasi Island and Barugaia in Selayar and also Sabang shows different SPM profiles. The stable isotope profile of the SPM shows the dominance of the seagrass detritus (i.e., *E. acoroides*) on the SPM composition. Another autochthonous source of the SPM, e.g., *Th. hemprichii*, has medium proportions (except for Sabang which is majority), since this species is the second dominant species following *E. acoroides*.

This study suggests that there is no different trends obtained in May and August. However, there is still no data obtained from the periods of October to March. Therefore, we expect there is still a minor or insignificant differences due to the seasonal changes. Previous studies of the seagrass ecosystem, suggested that there are seasonal variabilities of the net productivity in the seagrass meadows caused by physical factors such as temperature and light (Herzka and Dunton, 1997), environmental stress (Carr et al., 2012), or anthropogenic activities (Fourqurean et al., 2001). The seasonal variability of the seagrass production may af-

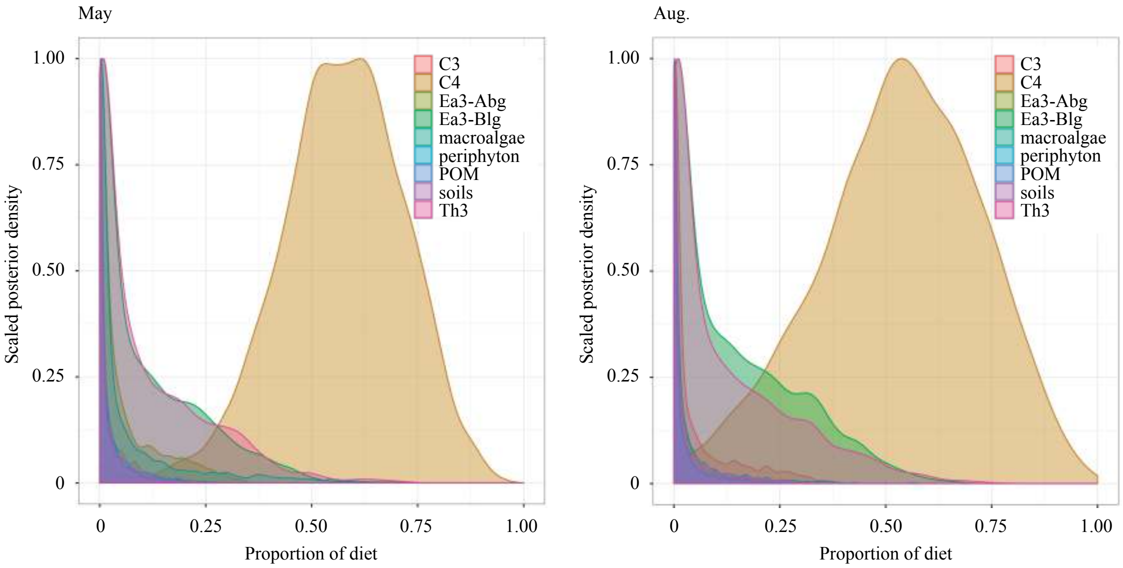

Fig. 5. Posterior plot (MixSIAR output) of all sources according to the different sampling time that shows the proportions each source to the mixture (SPM).

Table 2. The highest three contributors of SPM in seagrass ecosystem

Location	Highest three contributor	Proportion/%
Pengudang (Bintan)	C4 plant	49
	Th. hemprichii	18 (above and below ground)
	E. acoroides	12
Berakit (Bintan)	C4 plant	64
	soils	13 (above and below ground)
	Th. hemprichii	8
Malangrapat (Bintan)	C4 plant	62
	E. acoroides	10 (above and below ground)
	Th. hemprichii	8
Teluk Bakau (Bintan)	C4 plant	57
	E. acoroides	12 (above and below ground)
	Th. hemprichii	8
Barugaia (Selayar)	*E. acoroides*	30 (above and below ground)
	C4 plant	30
	Th. hemprichii	15
Pasi Island (Selayar)	*E. acoroides*	53 (above and below ground)
	C4 plant	21
	Th. hemprichii	12
Sabang (Weh Island)	*Th. hemprichii*	44
	E. acoroides	14 (above and below ground)
	Periphyton	11

fect the detritus production that contribute to the SPM composition. Furthermore, an SPM concentration may be changes seasonally, as suggested by Mityaev and Berger (2014), mainly due to abiotic factors such as water temperature and tide events. Although our result shows the similar SPM composition indifferent seasons, the possibility of the seasonal changes in the SPM composition should be evaluated for the future direction of SPM studies.

Kennedy et al. (2010) suggested that the seagrass vegetation contributes only ~50% carbon burial in the sediment. We can assume that the other half are contributed by the other sources, such as detritus, fecal pellet, planktonic organisms, marine snow aggregates or particulate matter. Wahyudi et al. (2016) suggested that the particulate matter can be exported downward to the sediment as much as 5.4 kt/a C within 964.2 hm^2 seagrass meadows. This value is equal to 5.6 t/(hm^2·a). Altogether with the seagrass detritus, the particulate matter can be deposited or buried in the bottom of the seagrass meadows. This process can be distinguished as the contribution in the carbon sequestration. However, as mentioned by Wahyudi et al. (2016) there is a dissonance in the estimation of the vertical flux of the SPM (or marine snow aggregates) compared with the carbon storage capacity in the seagrass meadows. Duarte et al. (2013) also explained that only half of the seagrass net production are buried downward. Therefore, in order to determine the exact SPM contribution in the carbon sequestration, we need to know the fate of the SPM after exported downward. One of the key process that can be assessed is the decomposition rate of the SPM in both water column and bottom of the seagrass meadows.

5 Conclusions

The SPM lies between the marine- and terrigenous-end member but tends to be be terrigenous and allochthonous. The terrestrial C4 plant has the highest contribution of the SPM at all sites of Bintan. The highest contribution of SPM in Barugaia and Pasi Island is from the detritus of *E. acoroides*. The second contribution has been made by either seagrass detritus (*E. acoroides* or *Th. hemprichii*), terrestrial C3 plant or even soil materials. There is no different trends obtained in the different time periods (May and August). Our finding indicates that there is a strong influence of the terrestrial sources in the SPM of seagrass meadows. However, the influences seem to be site specific. The seagrass contribution would be the highest at pristine seagrass meadows (e.g., Pasi Island) compared with the disrupted areas (e.g., east coast of Bintan).

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References

Antonio E S, Kasai A, Ueno M, et al. 2012. Spatial-temporal feeding dynamics of benthic communities in an estuary-marine gradient. Estuarine, Coastal and Shelf Science, 112: 86–97, doi: 10.1016/j.ecss.2011.11.017

Carr J A, D'Odorico P, McGlathery K J, et al. 2012. Stability and resilience of seagrass meadows to seasonal and interannual dynamics and environmental stress. Journal of Geophysical Research, 117(G1): G01007

Carter J, Barwick V. 2011. Good Practice Guide for Isotope Ratio Mass Spectrometry, FIRMS. https://www.lgcgroup.com/LGCGroup/media/PDFs/Our%20science/NMI%20landing%20page/Publications%20and%20resources/Guides/IRMS_Guide.pdf [2015–1–1]

Dalu T, Richoux N B, Froneman P W. 2016. Nature and source of suspended particulate matter and detritus along an austral temperate river-estuary continuum, assessed using stable isotope analysis. Hydrobiologia, 767(1): 95–110, doi: 10.1007/s10750-015-2480-1

Duarte C., Middelburg J, Caraco N 2004. Major role of marine vegetation on the oceanic carbon cycle. Biogeosciences Discussions, 1(1): 659–679, doi: 10.5194/bgd-1-659-2004

Duarte C M, Kennedy H, Marbà N, et al. 2013. Assessing the capacity of seagrass meadows for carbon burial: current limitations and future strategies. Ocean & Coastal Management, 83: 32–38

Duarte C M, Marbà N, Gacia E, et al. 2010. Seagrass community metabolism: assessing the carbon sink capacity of seagrass meadows. Global Biogeochemical Cycles, 24(4): GB4032

Fourqurean J W, Willsie A, Rose C D, et al. 2001. Spatial and temporal pattern in seagrass community composition and productivity in south Florida. Marine Biology, 138(2): 341–354, doi: 10.1007/s002270000448

Fourqurean J W, Duarte C M, Kennedy H, et al. 2012. Seagrass ecosystems as a globally significant carbon stock. Nature Geoscience, 5: 505–509, doi: 10.1038/ngeo1477

Fu Y C, Tang C G, Li J, et al. 2014. Sources and transport of organic carbon from the Dongjiang River to the Humen outlet of the Pearl River, southern China. Journal of Geographical Sciences, 24(1): 143–158, doi: 10.1007/s11442-014-1078-2

Gilhooly W P, Macko S A, Flemings P B. 2008. Data report: isotope compositions of sedimentary organic carbon and total nitrogen from Brazos-Trinity Basin IV (Sites U1319 and U1320) and Ursa Basin (Sites U1322 and U1324), deepwater Gulf of Mexico. In: Proceedings of the Integrated Ocean Drilling Program, 308: 1–11

Graham M C, Eaves M A, Farmer J G, et al. 2001. A study of carbon and nitrogen stable isotope and elemental ratios as potential indicators of source and fate of organic matter in sediments of the Forth estuary, Scotland. Estuarine, Coastal and Shelf Science, 52(3): 375–380, doi: 10.1006/ecss.2000.0742

Hemminga M A, Mateo M A. 1996. Stable carbon isotopes in seagrasses: variability in ratios and use in ecological studies. Marine Ecology Progress Series, 140: 285–298, doi: 10.3354/meps140285

Herzka S Z, Dunton K H. 1997. Seasonal photosynthetic patterns of the seagrass Thalassia testudinum in the western Gulf of Mexico. Marine Ecology Progress Series, 152: 103–117, doi: 10.3354/meps152103

Hou W, Gu B H, Lin Q Q, et al. 2013. Stable isotope composition of suspended particulate organic matter in twenty reservoirs from Guangdong, southern China: implications for pelagic carbon and nitrogen cycling. Water Research, 47(11): 3610–3623, doi: 10.1016/j.watres.2013.04.014

Kaiser D, Unger D, Qiu G L. 2014. Particulate organic matter dynamics in coastal systems of the northern Beibu Gulf. Continental Shelf Research, 82: 99–118, doi: 10.1016/j.csr.2014.04.006

Kennedy H, Beggins J, Duarte C M, et al. 2010. Seagrass sediments as a global carbon sink: isotopic constraints. Global Biogeochemical Cycles, 24(4): GB4026

Lara R J, Alder V, Franzosi C A, et al. 2010. Characteristics of suspended particulate organic matter in the southwestern Atlantic: influence of temperature, nutrient and phytoplankton features on the stable isotope signature. Journal of Marine Systems, 79(1–2): 199–209, doi: 10.1016/j.jmarsys.2009.09.002

Lavery P S, McMahon K, Weyers J, et al. 2013. Release of dissolved organic carbon from seagrass wrack and its implications for trophic connectivity. Marine Ecology Progress Series, 494: 121–133, doi: 10.3354/meps10554

Liu K K, Kao S J, Hu H C, et al. 2007a. Carbon isotopic composition of suspended and sinking particulate organic matter in the northern South China Sea—From production to deposition. Deep Sea Research Part II: Topical Studies in Oceanography, 54(14–15): 1504–1527, doi: 10.1016/j.dsr2.2007.05.010

Liu K K, Kao S J, Wen L S, et al. 2007b. Carbon and nitrogen isotopic compositions of particulate organic matter and biogeochemical processes in the eutrophic Danshuei Estuary in northern Taiwan. Science of the Total Environment, 382(1): 103–120, doi: 10.1016/j.scitotenv.2007.04.019

Martiny A C, Vrugt J A, Lomas M W. 2014. Concentrations and ratios of particulate organic carbon, nitrogen, and phosphorus in the global ocean. Scientific Data, 1: 140048, doi: 10.1038/sdata.2014.48

Mateo M, Romero J. 1997. Detritus dynamics in the seagrass Posidonia oceanica: Elements for an ecosystem carbon and nutrient budget. Marine Ecology Progress Series, 151: 43–53, doi: 10.3354/meps151043

Middelburg J J, Nieuwenhuize J. 1998. Carbon and nitrogen stable isotopes in suspended matter and sediments from the Schelde Estuary. Marine Chemistry, 60(3–4): 217–225, doi: 10.1016/S0304-4203(97)00104-7

Mityaev M V, Berger V Y. 2014. Seasonal variability of the suspended particulate matter concentration in Chupa inlet of the white Sea. Oceanology, 54(3): 338–347, doi: 10.1134/S0001437014020180

Nagelkerken I, van der Velde G, Gorissen M W, et al. 2000. Importance of mangroves, seagrass beds and the shallow coral reef as a nursery for important coral reef fishes, using a visual census technique. Estuarine, Coastal and Shelf Science, 51(1): 31–44, doi: 10.1006/ecss.2000.0617

Orth R J, Carruthers T J B, Dennison W C, et al. 2006. A global crisis for seagrass ecosystems. BioScience, 56(12): 987–996, doi: 10.1641/0006-3568(2006)56[987:AGCFSE]2.0.CO;2

Post D M. 2002. Using stable isotopes to estimate trophic position: models, methods, and assumptions. Ecology, 83(3): 703–718, doi: 10.1890/0012-9658(2002)083[0703:USITET]2.0.CO;2

Sarma V V S S, Arya J, Subbaiah C V, et al. 2012. Stable isotopes of carbon and nitrogen in suspended matter and sediments from the Godavari estuary. Journal of Oceanography, 68(2): 307–319, doi: 10.1007/s10872-012-0100-5

Stock B C, Semmens B X. 2013. MixSIAR GUI User Manual (Version 3.1). https://github.com/brianstock/MixSIAR/[2015–10–1]

Thornton S F, McManus J. 1994. Application of organic carbon and nitrogen stable isotope and C/N ratios as source indicators of organic matter provenance in estuarine systems: evidence from the Tay Estuary, Scotland. Estuarine, Coastal and Shelf Science, 38(3): 219–233, doi: 10.1006/ecss.1994.1015

Wahyudi A J, Rahmawati S, Prayudha B, et al. 2016. Vertical carbon flux of marine snow in Enhalus acoroides-dominated seagrass meadows. Estuarine, Coastal and Shelf Science, 5: 27–34

Wahyudi A J, Wada S, Aoki M, et al. 2013. Stable isotope signature and pigment biomarker evidence of the diet sources of Gaetice depressus (Crustacea: Eubrachyura: Varunidae) in a boulder shore ecosystem. Plankton and Benthos Research, 8(2): 55–67, doi: 10.3800/pbr.8.55