

The Effect of Microphytobenthic Resuspension on Suspended Particulate Matter Dynamics in a Shallow Lagoon in Hokkaido, Japan

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Abstract—Understanding suspended particulate matter (SPM) dynamics in coastal waters is crucial to assess changes in coastal sediment budgets and biogeochemical fluxes. It is known that characteristics of SPM are greatly influenced by the resuspension of sedimentary material including microphytobenthos, detritus, and inorganic minerals. However, there is little information on the individually identified components of resuspended materials that have major impact on SPM dynamics. In this study, we investigated the chemical composition of the water column, sediment and sinking particles in a shallow brackish lagoon (Hichirippu Lagoon) in eastern Hokkaido, Japan. The vertical flux of chlorophyll *a* (Chl-*a*), particulate organic carbon (POC) and nitrogen (PON) were directly estimated using sediment trap. The aim of this study is to identify the major components of resuspended materials contributing to the increase in SPM. The concentrations of Chl-*a*, POC and PON in water column correlated significantly with the resuspended flux of Chl-*a*. In contrast, we could not find significant relationship between POC/N concentration and resuspended POC/N flux. Our results suggest that the SPM increases were highly controlled by the resuspension of microphytobenthos. This finding might imply that microphytobenthos has longer residence time in water column than other resuspended materials.

Keywords: resuspension, microphytobenthos, particulate matter, detritus

INTRODUCTION

Suspended particulate matter (SPM) plays a crucial role in the complex dynamics of estuarine systems because of its links to biological and chemical processes. SPM can limit primary production (Tett *et al.*, 1993) and influence pollutant dispersal (Burton *et al.*, 1993). Resuspension of sedimentary material is generally the dominant determinant of SPM fluxes associated with chemical and biological processes on short time scales (Tett *et al.*, 1993; Millward *et al.*, 1998; Morris and Howarth, 1998). In estuaries, resuspension occurs because of tidal currents and

wave action (Baillie and Welsh, 1980; Lucas *et al.*, 2000), during which various sedimentary materials including inorganic mineral and organic matter (e.g., microphytobenthos, detritus) are resuspended. Therefore, the characteristics of SPM are greatly influenced by the components of resuspended material.

Despite the significant role of resuspended materials in determining geochemical, and biological processes in the water column of shallow areas, there have been few publications in which the individually identified components of resuspended materials are analyzed. Gust and Morris (1989) explained *in situ* estimates of bulk resuspended sediment fluxes. Wainright (1990) estimated the resuspension fluxes of particulate organic carbon (POC), nitrogen (POC), and bacteria. However, the resuspension flux of microphytobenthos has received less attention (Suga *et al.*, 2011a).

In this study, we conducted field measurements of the vertical fluxes of POC, PON, and microphytobenthos using sediment traps in a lagoon system (Hichirippu Lagoon) in eastern Hokkaido, Japan. This lagoon system is dominated by a tidal current, and its water depth is extremely shallow (Suga *et al.*, 2011b). Field sampling were conducted through a 36-h continuous survey in August 2003 and bimonthly field sampling from April 2008 to February 2009. Based on 36-h continuous survey, the tidal resuspension phenomenon was verified and the source of sinking particles collected in traps was tested using several methods. The aim of this study was to identify the major components of resuspended material contributing to the SPM increase in the lagoon system with the bimonthly field measurements.

MATERIALS AND METHODS

Field sampling

The study area, Hichirippu Lagoon, is located on the coast facing the Pacific Ocean in the eastern part of Hokkaido, Japan (43°02' N, 145°00' E, Fig. 1). The lagoon covers an area of 3.58 km² and its water depth is extremely shallow (mean water depth of *ca.* 1 m). We established four sampling stations in the subtidal zones of the lagoon (Stns A–C, Stn TL, Fig. 1).

We conducted a 36-h continuous survey from August 21 to 23, in 2003, at Stn B. Water samples were collected every 3 h from the surface and from 10 cm above the sea floor (bottom). Sinking particle samples were taken at 12-h intervals using a sediment trap system (Table 1, Fig. 2). Using a floating buoy, the sediment trap system at the surface layer was made to shift with the tidal rhythm, and the traps were kept in a position 20 cm below the water surface (Fig. 2). During this period, the tide level was monitored using a tide indicator every 10 minutes at Stn TL (Fig. 1). At 6:00 on 21 August 2003, we carried out the sampling of sediment at Stn B (Table 1). A grab sample of the sediment was collected with an Ekman-Berge grab sampler.

From April 2008 to February 2009, we conducted bimonthly sampling of water and sinking particles at Stns A, B and C (Table 1). These samples were collected in the same way as was done in August 2003. The sinking particle

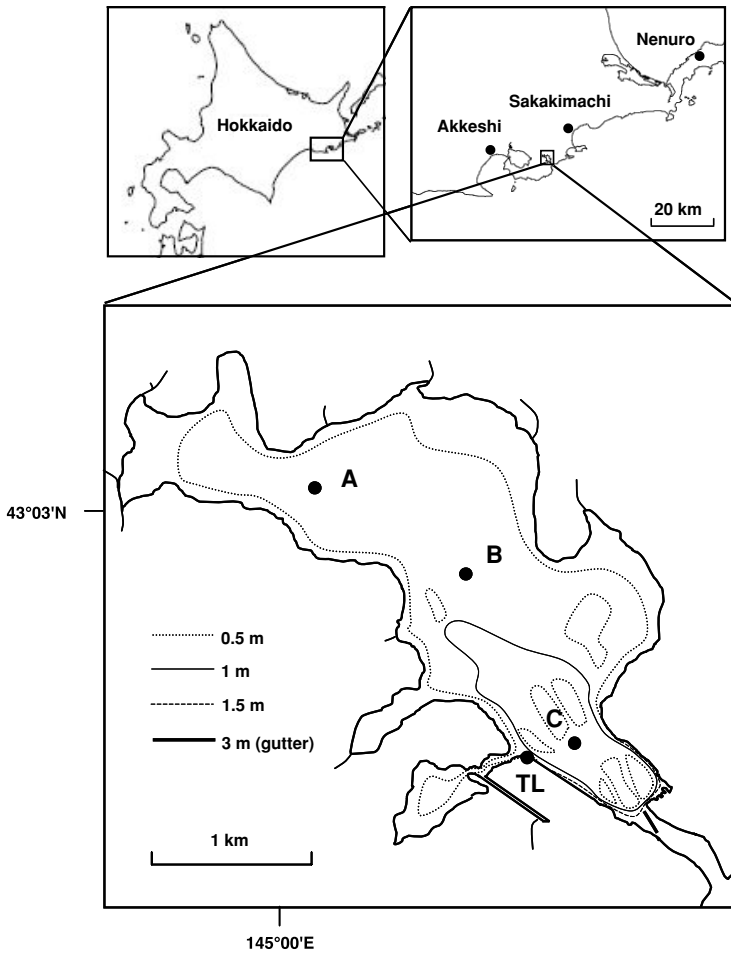


Fig. 1. Map of sampling stations in Hichirippu Lagoon.

samples at the bottom layer were collected for 24 h, once in a month during the sampling period (Table 1).

Analytical methods

The water samples collected in August 2003 were used for chlorophyll *a* (Chl-*a*), suspended particulate matter (SPM) weight, and particulate organic carbon and nitrogen (POC/N) analysis. For the determination of the Chl-*a* concentration of the water, 0.4 L of the water sample was filtered with a glass fiber filter. Chl-*a* on the filter was extracted in 7 mL of 90% acetone in a test tube. The concentrations of Chl-*a* ($\mu\text{g L}^{-1}$) in the supernatants were determined with a fluorophotometer (10-AU-5, Turner Designs). SPM weight (mg L^{-1}) was obtained

Table 1. Sampling regime.

	Water			Sinking particle			Sediment	
	Date time	Station	Depth	Date time	Station	Depth	Date time	Station
Aug 2003	21 12:00–23 00:00	B	Surface, Bottom	21 12:00–22 00:00	B	Surface, Bottom	21 06:00	B
	Collected every three hours			22 00:00–12:00	B	Surface, Bottom		
				22 12:00–23 00:00	B	Surface, Bottom		
Apr 2008	22 17:00	A, B, C	Surface	22 05:00–23 05:00	A, B, C	Bottom		
Jun 2008	17 14:00	A, B, C	Surface	17 04:00–18 04:00	A, B, C	Bottom		
Aug 2008	19 17:00	A, B, C	Surface	19 16:00–20 16:00	A, B, C	Bottom		
Oct 2008	28 13:00	A, B, C	Surface	27 16:00–28 16:00	A, B, C	Bottom		
Dec 2008	17 14:00	A, B, C	Surface	16 15:00–17 15:00	A, B, C	Bottom		
Feb 2009	23 15:00	B, C	Surface	23 14:00–24 14:00	B, C	Bottom		

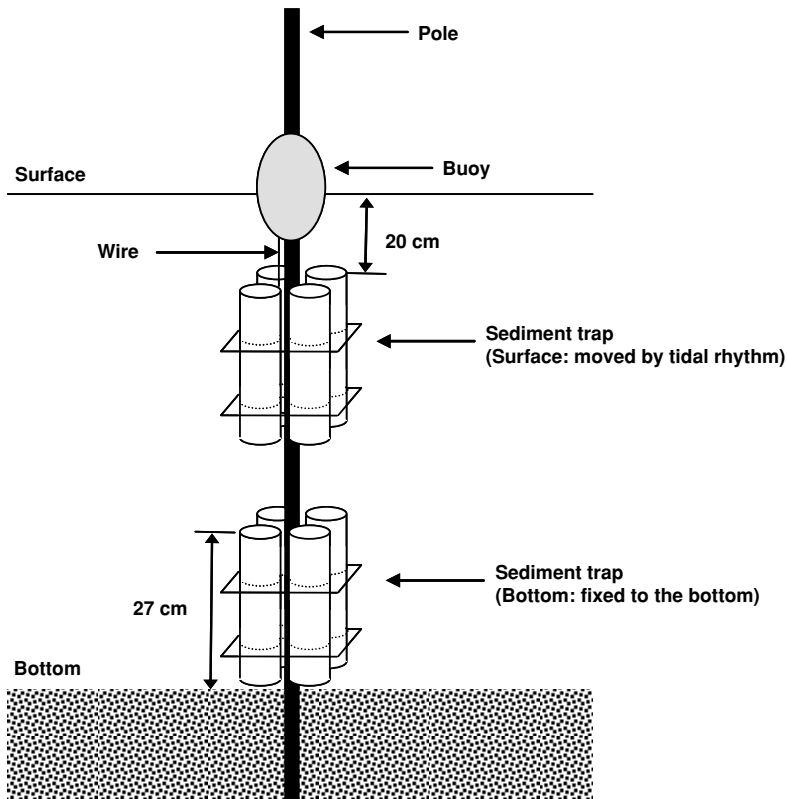


Fig. 2. Illustration of sediment trap system.

on the basis of the increase in the dry weight of the filter before and after filtration. The POC/N content on the filter was determined by high temperature oxidation using a CHN analyzer (Carbon, Hydrogen, and Nitrogen analyzer, MT-3, Yanaco) (for details, see Suga *et al.*, 2011a). The water samples collected during April 2008 and February 2009 were analyzed only for Chl-*a*, POC/N analysis.

The sinking particle samples collected in August 2003 were used for Chl-*a*, sinking particle weight and POC/N. Prior to filtration, the cylinder trap was kept stationary for 1 h and the supernatant was carefully discarded. The residues of all the three cylinders were filtered through pre-combusted filters. The concentrations of Chl-*a* ($\mu\text{g L}^{-1}$) and POC/N content (mg C g^{-1} , mg N g^{-1}) were analyzed in the same way as in the water samples. We calculated the sinking particle flux ($\text{g m}^{-2} \text{day}^{-1}$) using the following equation.

$$\text{Mass flux} = \text{sinking particle weight}/D/T$$

$$X \text{ flux} = \text{Mass flux} \times X \text{ content}$$

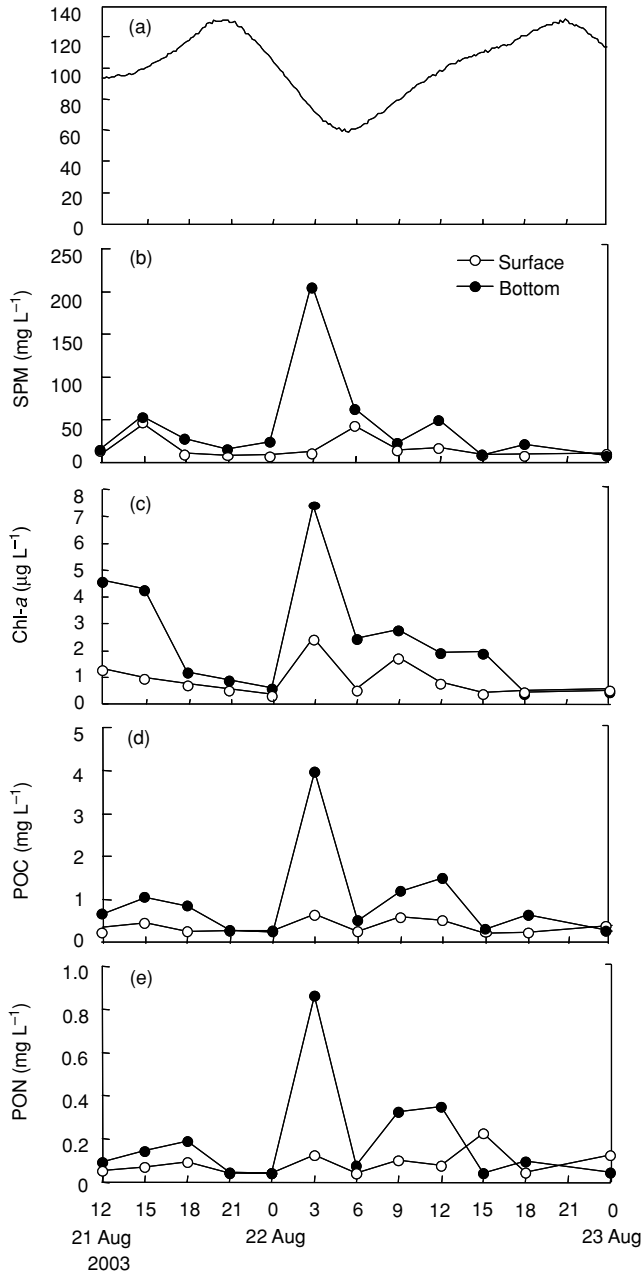


Fig. 3. Variations in (a) tide level (cm) at Stn TL, (b) suspended particle concentration (mg L^{-1}), (c) Chl-*a* concentration ($\mu\text{g L}^{-1}$), (d) particulate organic carbon concentration (mg L^{-1}), and (e) particulate organic nitrogen concentration (mg L^{-1}) in the surface and bottom waters observed every 3 h at Stn B during a 36-h period on August 21–23, 2003.

Table 2. The chemical composition of water, sinking particle and sediment samples. The *p* value is based on Student's *t*-test.

	Date time	Depth*	Chl- <i>a</i> ($\mu\text{g g}^{-1}$)	Carbon (mg g^{-1})	Nitrogen (mg g^{-1})	C/Chl- <i>a</i>		
Water	August 2003	21 12:00–22 00:00	Surface	96.1 \pm 71.3	34.0 \pm 18.8	6.3 \pm 3.6	400 \pm 111	<i>n</i> = 4
		Bottom	120.4 \pm 121.5	28.8 \pm 11.7	4.6 \pm 2.1	367 \pm 255	<i>n</i> = 4	
	22 00:00–12:00	Surface	104.8 \pm 94.1	38.2 \pm 23.1	6.4 \pm 4.4	474 \pm 232	<i>n</i> = 4	
		Bottom	55.5 \pm 44.1	22.9 \pm 20.3	5.3 \pm 6.0	406 \pm 137	<i>n</i> = 4	
	22 12:00–23 00:00	Surface	60.5 \pm 5.5	35.8 \pm 6.8	14.7 \pm 13.7	593 \pm 98	<i>n</i> = 4	
		Bottom	83.6 \pm 88.8	32.3 \pm 2.3	5.3 \pm 1.2	747 \pm 556	<i>n</i> = 4	
	Average		86.8 \pm 74.7**	32.0 \pm 14.8 ^{n.s.}	7.1 \pm 6.8 ^{n.s.}	498 \pm 282 ^{n.s.}	<i>n</i> = 24	
	Sinking particle	21 12:00–22 00:00	Surface	24.6	19.3	3.4	786	
			Bottom	8.4	10.6	1.8	1261	
		22 00:00–12:00	Surface	73.3	33.4	4.9	455	
Bottom			42.1	18.0	3.8	428		
8/22 12:00–23 00:00		Surface	31.0	28.7	4.3	925		
		Bottom	20.8	18.1	2.9	872		
Average			35.9 \pm 22.5**	21.4 \pm 8.2 ^{n.s.}	3.5 \pm 1.1 ^{n.s.}	788 \pm 313 ^{n.s.}	<i>n</i> = 6	
Sediment		21 06:00		32.4	13.8	1.8	427.5	

*Sampling layer: see text for more details.

***p* < 0.01.

^{n.s.}: not significant.

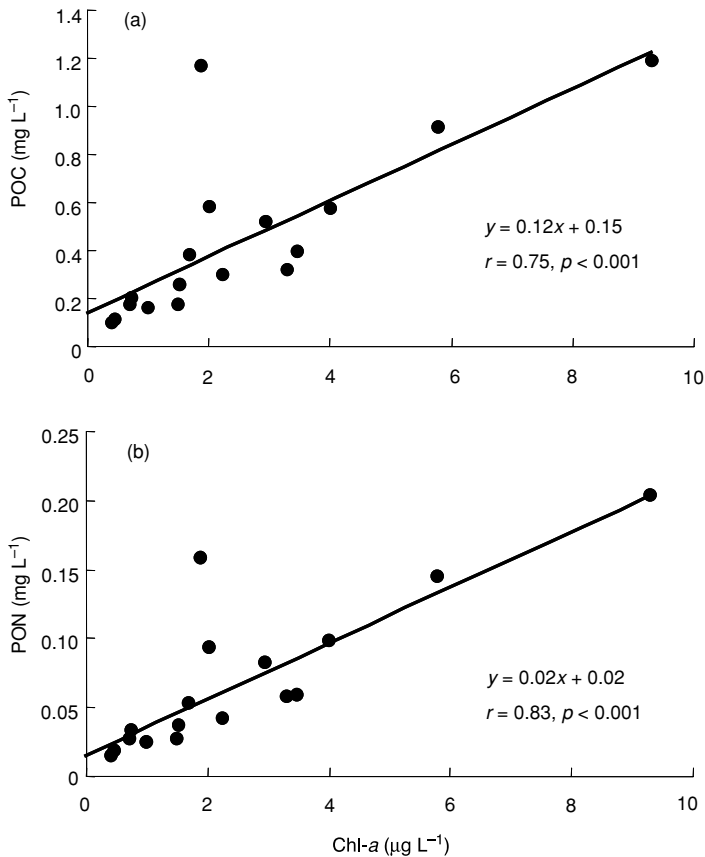


Fig. 4. Correlation between (a) POC concentration, (b) PON concentration and Chl-*a* concentration at Stns A, B, and C from April 2008 to February 2009.

where D = the dimensions of the cylinder trap (m^2), T = the installation time of the sediment trap (day), and individually identified X = Chl-*a*, POC or PON. The sinking particle samples collected during April 2008 and February 2009 were used for Chl-*a*, POC/N and sinking particle weight analysis in the same way as the samples collected in August 2003.

The sediment samples collected in August 2003 were analyzed for Chl-*a*, organic carbon and nitrogen analysis (for details, see Suga *et al.*, 2011a).

RESULTS

Thirty-six-hour continuous survey

The temporal variations in tide level and in SPM, Chl-*a*, and POC/N concentrations during August 21–23, 2003, are shown in Fig. 3. During this

Table 3. Temporal and spatial variations in the fluxes of sinking particles, Chl-*a*, particulate organic carbon, and particulate organic nitrogen at Stns A, B, and C from April 2008 to February 2009.

		Sinking particle flux (g m ⁻² day ⁻¹)	Chl- <i>a</i> flux (mg m ⁻² day ⁻¹)	POC flux (g m ⁻² day ⁻¹)	PON flux (g m ⁻² day ⁻¹)	C/Chl- <i>a</i>
Apr 2008	Stn A	298.0	10.3	14.1	1.9	1372
	Stn B	177.3	5.3	3.3	0.5	615
	Stn C	383.8	6.6	5.2	0.7	792
Jun 2008	Stn A	n.d.	10.0	n.d.	n.d.	n.d.
	Stn B	n.d.	1.6	n.d.	n.d.	n.d.
	Stn C	n.d.	10.0	n.d.	n.d.	n.d.
Aug 2008	Stn A	43.3	5.5	2.1	0.3	385
	Stn B	10.2	0.7	0.2	0.0	280
	Stn C	47.0	6.7	1.0	0.1	152
Oct 2008	Stn A	46.3	4.1	1.5	0.2	378
	Stn B	20.6	2.2	0.6	0.1	277
	Stn C	36.2	2.9	2.1	0.3	705
Dec 2008	Stn A	56.3	4.8	1.3	0.2	270
	Stn B	28.0	3.1	1.2	0.2	391
	Stn C	36.5	5.1	1.9	0.2	368
Feb 2009	Stn A	n.d.	n.d.	n.d.	n.d.	n.d.
	Stn B	134.9	4.3	1.3	0.2	307
	Stn C	55.8	8.5	3.5	0.4	407

period, there were two high tides and one low tide. The lowest low tide was at 06:00 hrs on August 22, 2003 (58.5 cm). Concentrations of SPM peaked at 205 mg L⁻¹ at 03:00 hrs on August 22, that is before the lowest low tide. The SPM concentrations of the bottom water tended to be higher than those of the surface water. The temporal and spatial variations of Chl-*a* and POC/N concentrations occurred at the same time with those of SPM.

The average Chl-*a* content and carbon content of the SPM in the water column ranged between 55.5 and 120 µg g⁻¹ and between 22.9 and 38.2 mg g⁻¹, respectively (Table 2). The average content of Chl-*a* of the sinking particles was significantly lower than that of the suspended particles in the water column (Student's *t*-test $p < 0.01$, Table 2). In contrast, the average carbon, and nitrogen content of the sinking particles showed no significant difference from that of the SPM in the water column (Table 2). The ratio of POC to Chl-*a* (C/Chl-*a*) in SPM were from 367 to 747.

SPM concentration in the water column and sinking particle fluxes

From April 2008 to February 2009, the concentration of SPM and Chl-*a* in the water column ranged from 12.4 to 28.2 mg L⁻¹ and from 0.4 to 9.3 µg L⁻¹, respectively. Concentrations of POC and PON were 0.1 to 1.2 mg L⁻¹ (0.4 ± 0.3, mean ± SD) and 0.02 to 0.20 mg L⁻¹ (0.07 ± 0.05, mean ± SD), respectively. The concentrations of POC and PON in water column highly correlated with Chl-*a* concentration ($r > 0.75$, $p < 0.001$, Fig. 4).

Table 4. The Pearson's product-moment correlation coefficient. The *p* value is based on significance test for the correlation coefficient.

	SPM conc.	Chl- <i>a</i> conc.	POC conc.	PON conc.	Sinking particle flux	Chl- <i>a</i> flux	POC flux	PON flux
SPM conc.	1							
Chl- <i>a</i> conc.	-0.02	1						
POC conc.	0.18	0.75***	1					
PON conc.	0.17	0.83***	0.99***	1				
Sinking particle flux	0.45	0.69***	0.31	0.43	1			
Chl- <i>a</i> flux	0.30	0.58*	0.57*	0.62**	0.58*	1		
POC flux	0.49	0.32	0.32	0.39	0.73**	0.76**	1	
PON flux	0.49	0.33	0.31	0.39	0.74***	0.76**	1.00***	1

p* < 0.05; *p* < 0.01; ****p* < 0.001.

Table 3 shows the spatial and temporal variations in the mass, Chl-*a* and POC/N fluxes of the sinking particles at Stns A–C. The mass fluxes of the sinking particles ranged from 10.2 (Stn B, August) to 383 (Stn C, April) $\text{g m}^{-2} \text{day}^{-1}$. The temporal and spatial variations of Chl-*a* and POC/N fluxes occurred in parallel with mass fluxes. The POC and PON fluxes were 0.2 to 14.1 and 0.03 to 1.9 $\text{g m}^{-2} \text{day}^{-1}$, respectively. The ratio of POC to Chl-*a* (C/Chl-*a*) in sinking particles varied widely from 152 to 1370.

Concentrations of Chl-*a*, POC and PON in the water column correlated significantly with Chl-*a* flux. In contrast, we could not find significant relationship between POC/N concentration and POC/N flux (Table 4).

DISCUSSION

Source of sinking particles collected in sediment traps

Resuspension occurs because of tidal currents and wave action (Baillie and Welsh, 1980; Lucas *et al.*, 2000). Although the waves in shallow water may not be very large, in general, they can still cause considerable resuspension (De Jonge and van Beusekom, 1995). The physical structure in Hichirippu Lagoon is dominated by a tidal current, and its water depth is extremely shallow (mean water depth of *ca.* 1 m, Suga *et al.*, 2011b). In this lagoon, resuspension seemed to have an effect on SPM in the surface water. Using microscopic examination, Lucas (2003) observed resuspension phenomenon at the turbid edge of the water, particularly in the trailing edge of the ebb tide in Molenplaat tidal flat (maximum water depth 1 m). Although Hichirippu Lagoon is well mixed vertically (Suga *et al.*, 2011b), the SPM, Chl-*a*, and POC concentrations of the bottom water were higher than those of the surface water, and peaked at the trailing edge of the ebb tide at 03:00 hrs on August 22, 2009 (Fig. 3).

These results would imply that the Chl-*a* and POC/N collected in sediment traps consisted of resuspended materials. To test this hypothesis, we focused on the source of the sinking particles. The average Chl-*a* content in the sinking particles was significantly lower than that in the water column, and the Chl-*a* content in the sediment was in the same range as that in the sinking particles. In addition, using the two-source linear mixing model with $\delta^{13}\text{C}$, Suga *et al.* (2011a) reported that the rates of contribution of microphytobenthos and phytoplankton in sinking particles were 63 to 74% and 26 to 37%, respectively, which would imply that the contribution of microphytobenthic resuspension to Chl-*a* collected in the traps is much higher than that of phytoplankton. Our results thus confirm that the contribution of the phytoplankton present in the water column to the Chl-*a* collected in the traps is likely to be negligible, and the source of Chl-*a* collected in the traps was mainly due to microphytobenthos.

The average carbon and nitrogen content in the sinking particles was not significantly different from the water and sediment samples. Accordingly, we could not describe the source of carbon and nitrogen in sinking particles based on chemical composition. However, we confirmed that the source of Chl-*a* in sinking particles were sedimentary materials (microphytobenthos). Unless

microphytobenthos are resuspended selectively, the source of carbon and nitrogen is likely to be sedimentary materials. This hypothesis is supported by the low standing stock of carbon in the water column. According to the results of bimonthly field measurements, the standing stock of carbon ranged from 0.1 to 1.2 g m⁻² (water depth 1 m), and the daily POC fluxes were 0.2 to 14.1 g m⁻² day⁻¹. These results show that carbon standing stock in the water column indicate 9% to 50% of daily POC flux, and were not enough to support the daily sinking fluxes. Therefore, the source of sinking particles collected in traps seemed not to be the water column but rather resuspended sedimentary materials. Consequently, we assumed that all the sinking particle fluxes in this study were resuspended material fluxes.

Effect of microphytobenthic resuspension on SPM increases

The concentrations of POC and PON in water column had a high correlations with Chl-*a* concentration (Fig. 4). The intercept of regression line between POC and Chl-*a* was 0.15 mg L⁻¹ (Fig. 4), which indicates that POC in the water column consist of both materials which contain Chl-*a* (i.e., phytoplankton, microphytobenthos) and which do not contain Chl-*a* (i.e., detritus). For instance, the intercept (0.15 mg L⁻¹) indicates approximately 38% of average POC concentration (0.4 mg L⁻¹) in the water column. This finding shows that SPM in the lagoon usually contains considerable amount of detritus. Therefore, it is reasonable that the values of C/Chl-*a* in SPM tend to be higher than the general value of microalgae (C/Chl-*a* = 59, Antia *et al.*, 1963, Table 2). However, the positive correlation between POC/N and Chl-*a* indicates that SPM increase were highly controlled by the material which contain Chl-*a* (Fig. 4). Accordingly, these result suggest that the component which have a major impact on the SPM increase were not detritus but the materials which contain Chl-*a*.

We assumed that all the sinking particle fluxes measured by sediment traps in this study were resuspended material fluxes, therefore Chl-*a* flux in this section indicates resuspended microphytobenthic flux. The ratio of POC to Chl-*a* (C/Chl-*a*) in resuspended particle varied apparently (Table 3). It showed that the components of resuspended materials have temporal and spatial variations such as content rate of microphytobenthos and detritus. We could not find significant relationship between POC/N concentrations in water column and resuspended POC/N flux. In contrast, the concentrations of Chl-*a*, POC/N in water column correlated significantly with the resuspension flux of Chl-*a* (Table 4). These results suggest that the changes of SPM concentrations did not occur in parallel with resuspended POC/N fluxes which contain detritus, however the resuspended Chl-*a* fluxes have an affect on SPM concentration in water column. This finding is consist with the hypothesis that the component which have a major impact on the SPM increase were not detritus but the materials which contain Chl-*a*. Consequently, we conclude that the resuspension of microphytobenthos have a major impact on the SPM increases in the water column, and the resuspended materials which do not contain Chl-*a* have little effect on the SPM dynamics.

Most of marine microalgae have a large surface area to volume ratio to avoid sinking (Taniguchi, 1986). Our finding might imply that resuspended microphytobenthos has longer residence time in water column than other suspended material.

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