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Some Aspects of the Variation of Particulate Phosphorus in a Eutrophic Coastal Environment

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(Figs. 1–6; Tables 1–8)

In a previous paper we have reported on the seasonal variation in the concentrations of particulate phosphorus (PP), dissolved inorganic phosphorus (DIP) and dissolved organic phosphorus (DOP) in the water column in the central part of the Seto Inland Sea, Japan, and referred to the correlation between PP and sestonic chlorophyll *a* (MATSUDA et al.[1]).

In this paper, which is based on the same material, we examine the variation in PP in relation to such data pertaining to the particulate matter as particulate carbon (PC), particulate nitrogen (PN), sestonic chlorophyll *a* (chl. *a*) and the dry weight of total particulate matter for the purpose of understanding the origin of PP and gaining further insight into the phosphorus cycle in this eutrophic environment.

Although it is well known that high concentrations of particulate matter are characteristic of eutrophic waters, it does not appear that the variation in PP has been studied as intensively as that in PC and PN in those waters, especially in such waters where dense phytoplankton bloom is of frequent occurrence.

MATERIAL AND METHODS

Field Observation and Collection of Samples

The same seawater samples that were described in the previous paper (MATSUDA et al.[1]) were used in this study. They were collected from April 1972 to February 1974 at roughly monthly intervals at St. 2 (34°24.1'N, 133°24.1'E) and St. BG-1 (34°18.5'N, 133°26.3'E) situated in the northern Bingo-nada region of the Seto Inland Sea. The methods of field observation and of collecting samples, the hydrographical conditions at both stations and the system of dividing an annual cycle into seasons were already reported.

Measurements on the Concentration of Particulate Matter

The methods for determining PP and chl.*a* were described in the previous paper. The concentration of the total particulate matter ("seston weight" or SW) was determined gravimetrically with the method of STRICKLAND and PARSONS[2] by filtering a known volume of sample water through a tared Millipore HA-47 filter, washing it free from salts and drying it for 1 hr at 75°C. The concentrations of PC and PN were determined by recovering the particulate material from the sample water on a pre-combusted glass-fiber filter paper (Whatman GF/C) and analysing it by use of an automated C.H.N. analyser (Yanagimoto C.H.N. Corder) which involved dry combustion of organic matter in a stream of oxygen.

The concentration of the particulate organic matter was estimated at by multiplying PC by 2, which factor was adopted by considering the results obtained by GORDON[3], PARSONS et al.[4] and RILEY[5]. The concentration of inorganic particulate matter was, therefore, obtained by subtracting twice PC from SW.

RESULTS AND DISCUSSION

Concentration of Total Particulate Matter

The seston weight (SW), expressed in mg/1, varied seasonally as shown in Fig. 1. The arithmetic means for high and low temperature seasons and for different depths are shown in Table 3.

At the inshore (St. 2) as well as at the offshore station (St. BG-1) SW was greater in the high temperature season (May to October; water temp. above 15° C) than in the low temperature season (November to April; water temp. below 15°C), and its variation was more remarkable in the former season. SW remained at higher level at the inshore station than at the offshore station throughout the year.

Vertical difference in SW was not remarkable at St. BG-1 except in one occasion (i.e., August 1972). At St. 2 SW was usually greater at 5 m layer than at 0 m, because the former layer was usually within 2 m of the sea bottom.

In Fig. 2 SW for 0 m layer is plotted against the visual range of the 30 cm Secchi disk ("transparency" or Tr, expressed in meters). The plots are distributed within an arbitrary range of (SW)(Tr) = 9~20 except in three cases (September 1972 and August 1973 at St. 2; August 1973 at St. BG-1). They are distributed near the empirical curve derived from the seston weights (pore size of the filter, 1.6 μm) and Secchi disk visibilities (disk diameter, 20 cm) measured in and off the Thames River estuary by JONES and WILLS[6].

Seston weights for 5, 10 and 20 m layers are also plotted in Fig. 2. They are distributed within a range of (SW)(Tr) = 8.5 ~ 32 with three exceptions.

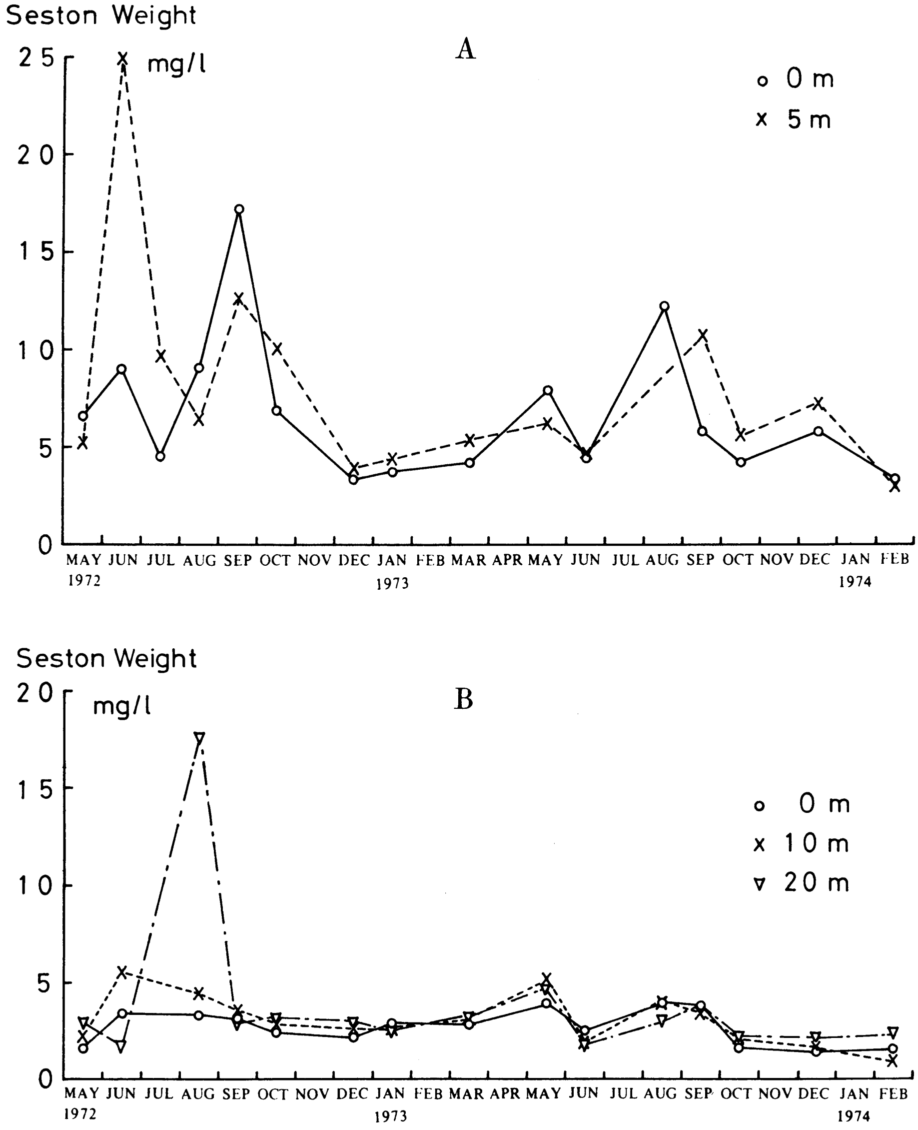


Fig. 1. Variation of seston weight:(A) St. 2; (B) St. BG-1.

Since SW represents the combined weight of organic and inorganic particles mixed in various ratios, and since these particles have various sizes, shapes and light reflectivity, one can not expect a clear-cut relationship between SW and Tr. Nevertheless, Fig 2 may serve to indicate certain physical properties of the particulate matters dealt with in this study.

Particulate Carbon

We would be able to describe more accurately the origin of the particulate phosphorus if we could tell what proportion of the total particulate matter is represented

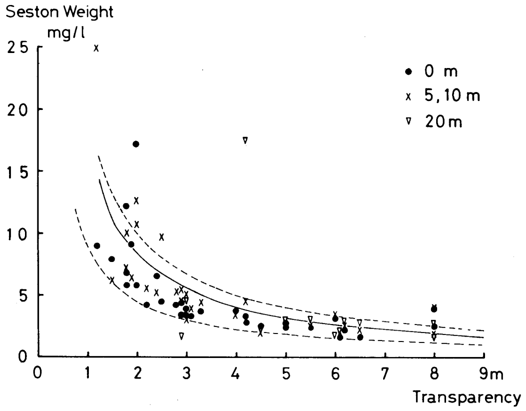


Fig. 2. Relation between the transparency and the seston weight for different layers. Broken curves represent (SW) (Tr) = 9 and 20. Solid curve shows the empirical curve obtained by JONES and WILLS[6].

by the organic matter. The analytical method we employed does not warrant that our particulate carbon data (Tables 1 and 2) represent specifically the organic carbon.

Correlation between particulate carbon and particulate nitrogen is illustrated in Fig. 3. A high correlation coefficient of 0.996 was obtained for St. 2, while the correlation was considerably high (r = 0.770) at St. BG-1. Moreover, in the regression PC = *a* + *b* (PN), *a* takes small values, and *b* approximates 7 which agrees with the C/N ratio of phytoplankton proposed by STRICKLAND[7] or reported by PARSONS et al.[4] Therefore it seems justifiable to postulate that PC approximates the particulate organic carbon (POC).

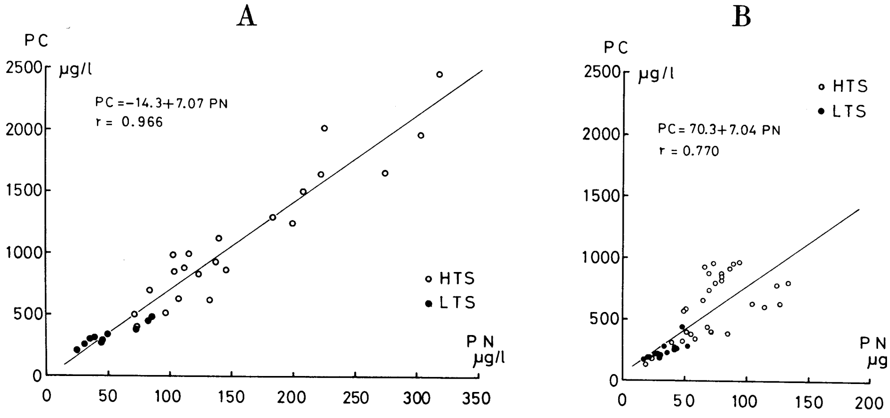
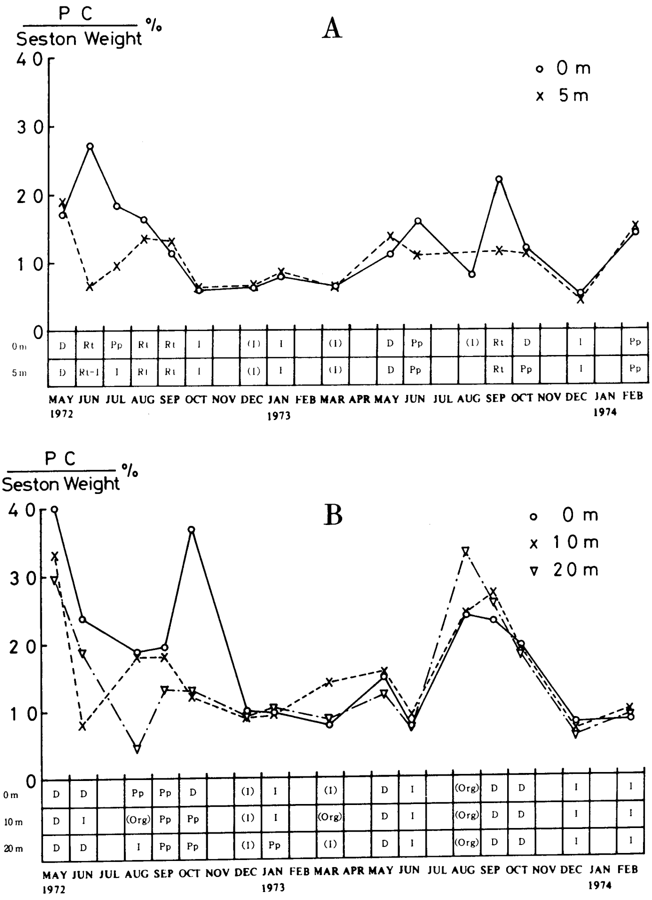


Fig. 3. Relation between particulate carbon (PC) and particulate nitrogen (PN) for all layers: (A) St. 2; (B) St. BG-1. HTS, high temperature season; LTS, low temperature season.

Then the ratio PC/SW, expressed in percentage, may be regarded as a meaningful index of the organic or inorganic feature of the sampled particulate matter. Fig. 4 shows the seasonal variation of the ratio. As can be seen in the figure and in Table 3, the arithmetic mean of the ratio is greater at the offshore station than at the shallow inshore station; this is probably because the distribution of the silt and clay carried in by the discharge of the Ashida River, as well as the resuspension of fine sediment particles from the sea bottom, was more prevalent at the latter station. The ratio also showed the tendency of being comparatively small during the low temperature season when vertical circulation of water was prevalent. During the high temperature season the ratio was comparatively high, especially at 0 m layer. As will be mentioned later, high values of the ratio were usually caused by high PC values, which in turn were associated with high chlorophyll *a* values in some cases.

For the purpose of estimating the contribution of the phytoplankton to particulate carbon, the relation between particulate carbon and sestonic chlorophyll *a* was examined.



	MAY 1972	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN 1973	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN 1974	FEB
0 m	D	Rt	Pp	Rt	Rt	I		(I)	I		(I)		D	Pp		(I)	Rt	D		I		Pp
5 m	D	Rt-I	I	Rt	Rt	I		(I)	I		(I)		D	Pp			Rt	Pp		I		Pp

	MAY 1972	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN 1973	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN 1974	FEB
0 m	D	D		Pp	Pp	D		(I)	I		(I)		D	I		(Org)	D	D		I		I
10 m	D	I		(Org)	Pp	Pp		(I)	I		(Org)		D	I		(Org)	D	D		I		I
20 m	D	D		I	Pp	Pp		(I)	Pp		(I)		D	I		(Org)	D	D		I		I

Fig. 4. Variation in the percentage of particulate carbon to seston weight and the classification of particulate material: (A) St. 2; (B) St. BG-1.
Rt, Red tide type; Pp, Phytoplankton type; D, Detritus type; I, Inorganic type.

In 61 sets of measurements the PC/chl.*a* ratio varied over a wide range of 53-425 with large values over 100 mostly occurring at St. BG-1.

The data were stratified with regard to station and depth, and the correlation and the linear regression of PC to chl.*a* was computed for each stratum (Table 4).

At St. 2 the correlation was high ($r = 0.925$ and 0.872) and statistically significant at either depth; the regression coefficient (c_1) approximated 60, and the portion of PC independent of chl.*a* (C_0) accounted for 20.5 and 27.6 % of the mean of PC. These results indicate that phytoplankton accounted for considerable portions of particulate carbon at this station.

In contrast, the correlation was not significant at St. BG-1. This result, together with the fact that the PC/chl.*a* ratio was often very high, suggests that large proportions of particulate carbon were often represented by detrital matter at this offshore station. Comparatively large values of C_0 and $C_0/\langle PC \rangle$, although their statistical significance is not warranted, may be a result of the same fact.

Considering the value of c_1 obtained at St. 2, we postulate that phytoplankton carbon can be estimated at by 60 × chl. *a* for 0 m layer of St. 2 during the high temperature season and by 30 × chl. *a* in the other cases. As for the ratio of phytoplankton carbon to chlorophyll *a*, 30 was proposed by STRICKLAND(7); according to NISHIZAWA(8), 30-50 have usually been preferred although the ratio reported from different parts of oceans has varied from 30 to 270.

Phosphorus Content of Particulate Matter

Although we have determined particulate phosphorus on 81 samples of particulate matter, the ratio PP/SW (i.e., the phosphorus content of the particulate material on dry weight basis) was available only on 76 samples (Tables 1 and 2). The arithmetic mean of the ratio was calculated for each depth of each station by making distinction between high and low temperature seasons (Table 3). These means varied between 0.13 and 0.27 %. Largest and smallest means were obtained at St. BG-1 in the high and the low temperature season respectively. At St. 2, the means were of intermediate magnitude and showed a slight tendency of being larger in the high temperature season than in the low temperature season. The means did not show a marked tendency of vertical variation.

It is suspected, however, that some important information has been masked in the process of averaging, because the ratio varied irregularly over a wide range of 0.06–0.57 %.

Correlation between Phosphorus and Carbon Contents

An attempt has then been made to relate the phosphorus content to the organic content of the particulate matter. In Fig. 5 the phosphorus content is plotted against the carbon content of the particulate matter. The general trend appears to be that the increase in carbon content is accompanied by a gradual increase in phosphorus content,

Table 1. Results of measurements on particulate material at St. 2

Date	Tr* (m)	Layer (m)	Seston weight (mg/l)	PP	PC	PN	Chl.*a* (μg/l)
					(μg/l)		
Apr. 25, 1972	2.0	0		2.8			9.03
		5		4.3			7.89
May 23	2.4	0	6.6	14.9	1120	140	7.17
		5	5.2	14.9	994	116	6.47
Jun. 29	1.2	0	9.0	29.1	2450	319	30.74
		6	24.9	28.2	1640	223	19.46
Jul. 28	2.5	0	4.5	17.7	830	124	13.14
		7	9.7	18.3	930	138	10.30
Aug. 30	1.9	0	9.1	32.9	1500	209	25.00
		5	6.4	30.1	865	147	16.38
Sep. 26	2.0	0	17.2	32.9	1960	304	22.95
		6	12.6	31.3	1650	275	20.84
Oct. 24	1.8	0	6.8	9.0	403	74	3.73
		6	10.0	13.6	623	133	6.04
Dec. 19	3.1	0	3.3	4.3	209	25	
		6.5	3.9	5.3	255	31	
Jan. 27, 1973	3.3	0	3.7	7.8	293	46	5.50
		5	4.4	9.6	379	73	5.34
Mar. 20	2.8	0	4.2	5.6	272	45	
		5	5.3	9.6	336	49	
May 2	1.5	0	7.9	7.8	882	112	6.92
		5	6.2	6.8	852	104	6.19
Jun. 17	2.9	0	4.4	5.3	704	84	8.26
		5	4.6	5.3	502	72	6.90
Aug. 24	1.8	0	12.2	13.0	983	103	
		4			2011	226	
Sep. 13	2.0	0	5.8	13.3	1285	184	22.36
		5	10.7	13.3	1241	200	20.44
Oct. 2	2.2	0	4.2	13.6	514	97	4.02
		5	5.6	11.8	629	108	6.69
Dec. 24	1.8	0	5.8	6.5	301	36	2.61
		6	7.2	6.8	308	40	2.70
Feb. 23, 1974	3.0	0	3.4	8.7	484	86	5.65
		5	3.0	9.0	453	83	6.99

* Tr: Transparency or visible range of 30 cm diam. Secchi disk.

although some exceptional cases have been noticed.

At St. 2 (Fig. 5–A) the two highest values of carbon content were 22.0 and 27.0%, with which the phosphorus contents of 0.23 and 0.32% were respectively associated. These data were obtained at 0 m layer in June 1972 and September 1973 respectivley. In both cases the sea was discolored by a dense bloom of phytoplankton (i.e., the red tide), and sestonic chlorophyll *a* was as high as 30.7 and 22.4 μg/l, respectively.

At St. BG-1 (Fig. 5–B) the upper range of carbon content was higher than at St. 2. Highest carbon contents of 36.9 and 40.1 % were recorded at 0 m layer in May and October of 1972, with which considerably high phosphorus contents of 0.32 and 0.45 %

Table 2. Results of measurements on particulate material at St. BG-1

Date	Tr* (m)	Layer (m)	Seston weight (mg/l)	PP	PC	PN	Chl. *a* (μg/l)
				(μg/l)			
Apr. 25, 1972	7.0	0		4.3			1.39
		10		5.3			2.37
		20		3.7			2.92
May 23	6.5	0	1.6	7.4	658	65	1.61
		10	2.2	9.0	740	70	1.74
		20	2.9	9.0	850	80	2.62
Jun. 29	2.9	0	3.4	9.3	815	80	6.06
		10	5.5	8.4	444	68	3.55
		20	1.7	9.6	316	49	2.34
Aug. 30	4.2	0	3.3	11.8	627	104	7.46
		10	4.5	15.8	803	133	
		19	17.6	17.7	785	124	3.52
Sep. 26	6.0	0	3.1	13.3	602	114	8.91
		10	3.5	15.5	632	127	9.36
		20	2.9	10.5	382	85	5.77
Oct. 24	5.0	0	2.4	7.4	877	70	4.60
		10	2.8	6.5	343	59	3.89
		20	3.1	7.8	402	71	4.42
Dec. 19	6.2	0	2.2	2.8	218	27	
		10	2.6	3.1	233	36	
		20	3.0	3.1	276	34	
Jan. 27, 1973	5.0	0	2.9	5.0	280	53	4.55
		10	2.7	4.0	253	42	3.38
		20	2.5	3.7	261	44	3.43
Mar. 20	4.2	0	2.8	3.4	218	29	
		10	3.1	4.3	437	48	
		20	3.2	4.3	273	43	
May 2	3.0	0	3.9	3.4	578	50	2.33
		10	5.1	4.7	798	75	4.56
		20	4.7	3.4	572	49	3.72
Jun. 17	8.0	0	2.5	3.4	190	22	1.28
		10	1.9	3.4	177	24	1.44
		20	1.8	2.5	133	19	1.34
Aug. 24	8.0	0	3.9	6.5	929	66	
		10	4.0	7.8	963	73	
		20	2.9	6.5	959	89	
Sep. 13	4.0	0	3.8	8.4	872	81	2.99
		10	3.4	8.4	918	86	2.72
		20	3.8	8.7	973	94	2.57
Oct. 2	6.1	0	1.6	4.7	311	40	2.28
		10	2.0	5.6	381	55	2.90
		20	2.2	5.9	395	51	3.05
Dec. 24	5.5	0	2.4	3.4	192	22	2.49
		10	2.5	6.8	172	17	2.34
		20	3.1	1.9	190	21	2.48
Feb. 23, 1974	4.5	0	2.5	4.0	207	31	1.64
		10	1.9	4.3	186	30	1.55
		20	2.3	4.3	207	30	1.49

* Tr is as in Table 1.

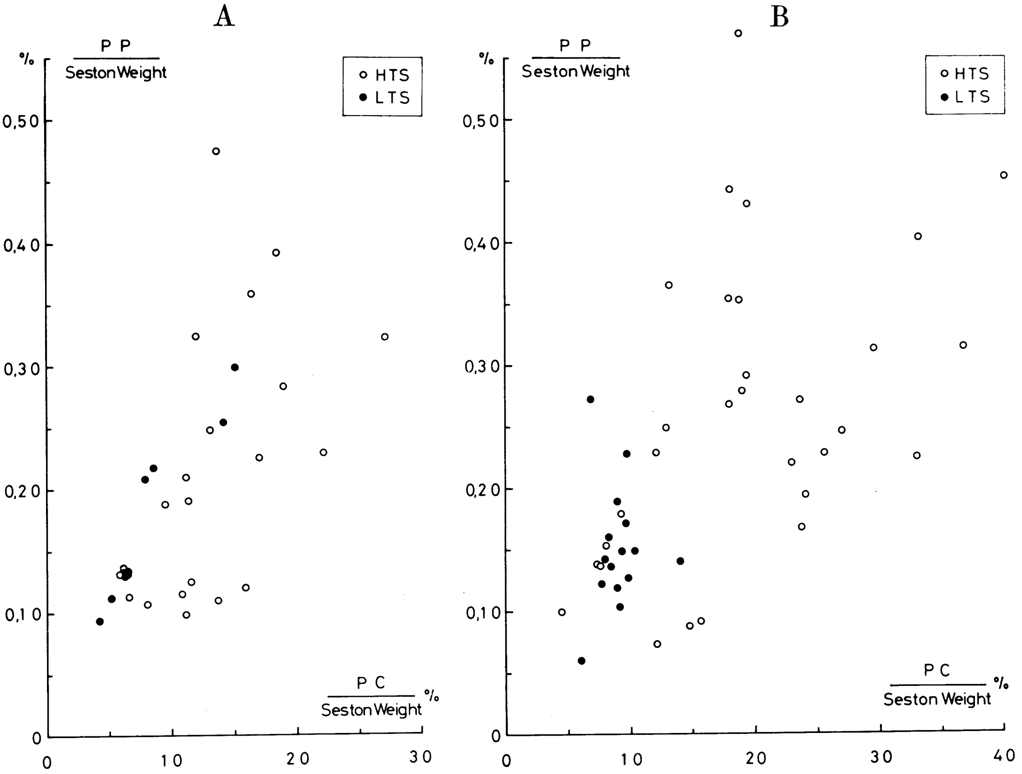


Fig. 5. Relation between carbon and phosphorus percentages to seston weight for all layers: (A) St. 2; (B) St. BG-1. HTS, high temperature season; LTS, low temperature season.

Table 3. Means of seston weight and PP, PC, PN percentages to seston weight

Station	Season	Layer (m)	Sample size	Seston weight (mg/l)	PP (%)	PC (%)	PN (%)
2	HTS*	0	11	7.98	0.23	15.06	2.11
		5	10	9.59	0.20	11.55	1.74
	LTS**	0	5	4.08	0.17	8.03	1.24
		5	5	4.76	0.19	8.17	1.34
BG-1	HTS	0	10	2.96	0.27	22.76	2.45
		10	10	3.49	0.26	18.45	2.29
		20	10	4.36	0.25	17.51	2.16
	LTS	0	5	2.81	0.14	8.73	1.24
		10	5	3.14	0.18	9.82	1.36
		20	5	3.85	0.13	8.66	1.24

* High temperature season (water temp. ≧ 15°C)

** Low temperature season (water temp. < 15°C)

were associated respectively. If we take twice the carbon content for a rough estimate of the organic content, it follows that 74 and 80 % of the dry weight of total particulate matter should have been accounted for by the organic matter in these examples. These

Table 4. Regression[a] of particulate carbon (PC) to chlorophyll *a*

Station	Layer (m)	n^b	$\langle PC \rangle^c$	$\langle chl.a \rangle^d$	r^e	C_0	c_1	$C_0/\langle PC \rangle$
2	0	13	979	12.15	0.925	201	64	0.205
	5	13	851	10.36	0.872	235	60	0.276
BG-1	0	12	478	3.85	0.429	339	46	0.709
	10	11	459	3.40	0.332	320	51	0.697
	20	12	456	3.06	0.174	335	39	0.735

[a] Regression equation: $PC(\mu g/l) = C_0 + c_1 \cdot chl.a(\mu g/l)$.

[b] Sample size.

[c] Mean of particulate carbon ($\mu g/l$).

[d] Mean of chlorophyll *a* ($\mu g/l$).

[e] Correlation coefficient.

percentages are extremely high as compared with the data reviewed by RILEY,[5)] and this fact may be regarded as a characteristic feature of the sea region under study.

In both Fig. 5-A and 5-B, the lower range of the carbon content is represented by the data obtained during the low temperature season. At St. 2 low carbon contents between 4.2 and 6.5 % were recorded at 0 m and 5 m, with which low phosphorus contents of 0.095-0.14 % were associated. At St. BG-1 lowest carbon contents of 4.46 and 6.13 % were observed at the bottom layer, with which the low phosphorus contents of 0.06 and 0.10 % were associated respectively.

It is suggestive that the particulate matter settling into a sedimentation trap (1-2 m above the sea bottom) showed the phosphorus contents between 0.03 and 0.20 % in another year and that the lowest phosphorus contents plotted in Fig. 5 lie within this range. The distribution of plots in Fig. 5 suggests that the phosphorus content depended to a considerable degree upon the carbon or organic content of the particulate matter. However, the correlation between phosphorus and carbon contents was not high, the correlation coefficient r being 0.607 and 0.598 respectively for St. 2 and St. BG-1.

Correlation of Particulate Phosphorus to Organic and Inorganic Particulate Matter

The seston weight (SW) was divided into two portions, namely, the organic particulate matter (2·PC) and the inorganic particulate matter (SW – 2·PC), and the dependence of particulate phosphorus upon these two variables were evaluated by multiple regression analysis for each depth of each station (Table 5). The multiple correlation coefficient R was always significant at 1 or 5 % level. The *t*-test of partial regression coefficients showed that p_1 (correlating PP to organic particulate matter) was always positive and statistically significant, while p_2 was comparatively small and insignificant with the exception of 20 m layer of St. BG-1.

The values of p_1, when their confidence limits are neglected, indicate that PP increased by 6-7.4 $\mu g/l$ at St. 2 and by 3-3.8 $\mu g/l$ at St. BG-1 for a unit (one mg/l) increase of particulate organic matter. The difference is probably referrable to the tendency that large portions of the particulate organic matter were accounted for by phytoplankton at St. 2 and by detrital matter at St. BG-1.

Table 5. Multiple regression[a] of particulate phosphorus (PP) to organic (Org) and inorganic (Inorg) particulate matter

Station	Layer (m)	n^b	$\langle PP \rangle^c$	P_0	p_1	p_2	R^d
2	0	16	13.9	1.05	5.98^{**}	0.45	0.879^{**}
	5	15	14.3	2.08	7.37^{**}	0.11	0.796^{**}
BG-1	0	15	6.3	2.55	3.85^{**}	-0.18	0.726^{**}
	10	15	7.2	2.45	3.75^{*}	0.45	0.563^{*}
	20	15	6.6	1.99	2.97^{*}	0.63^{**}	0.778^{**}

[a] Regression equation: $PP(\mu g/l) = P_0 + p_1 \cdot Org(mg/l) + p_2 \cdot Inorg(mg/l)$.

[b] Sample size.

[c] Mean of particulate phosphorus ($\mu g/l$).

[d] Coefficient of multiple correlation.

** Significant at 1 % level.

* Significant at 5 % level.

Correlation of Particulate Phosphorus to Phytoplankton and Non-Phytoplankton Particulate Carbon

Since it has become clear that the concentration of PP in the seawater depended chiefly on the abundance of particulate organic matter, particulate carbon is subdivided into two portions, namely, the phytoplankton carbon and the non-phytoplankton carbon. The dependence of PP upon these two variables were evaluated by the multiple regression analysis (Table 6). Data were stratified with regard to station, season and depth. Phytoplankton carbon was calculated by multiplying chl. *a* by 60 or 30 as described before. The difference between particulate carbon and phytoplankton carbon was designated as the non-phytoplankton particulate carbon.

The partial regression coefficient p'_2 was always insignificant, indicating that the concentration of non-phytoplankton particulate carbon was not related linearly to that of PP.

The coefficient p'_1 (relating PP to phytoplankton carbon) was positive and significant in the high temperature season in the upper layers of both stations; this result is not surprising because the growth of phytoplankton was active on these occasions. In the low temprature season, p'_1 was significant only at St. 2, reflecting the growth of phytoplankton occurring chiefly in the shallow inshore waters.

The coefficient of multiple correlation R was significant at 1 or 5 % level when p'_1 was significant.

In a previous paper (Matsuda et al.[1], p. 234–235) we tentatively examined the relation between PP and sestonic chlorophyll *a* by combining all the data except those

Table 6. Multiple regression[a] of particulate phosphorus (PP) to phytoplankton carbon (C_{pp}) and non-phytoplankton particulate carbon (C_{npp})

Station	Season	Layer (m)	n	⟨PP⟩	P_0'	p_1'	p_2'	R
2	HTS†	0	10	17.6	3.55	14.1^{**}	6.25	0.826^{**}
		5	10	17.4	1.90	31.3	6.69	0.764^{*}
	LTS††	0,5	6	8.1	3.57	24.0^{**}	4.59	0.868^{**}
BG-1	HTS	0	9	7.7	1.54	38.1^{**}	2.80	0.917^{**}
		10	9	4.2	1.79	39.0^{*}	3.34	0.795^{*}
		20	8	7.7	0.86	43.4	7.40	0.563
	LTS	0,10,20	9	8.3	5.21	2.2	-8.47	0.151

[a] Regression equation: $PP(\mu g/l) = P_0' + p_1' \cdot C_{pp}(mg/l) + p_2' \cdot C_{npp}(mg/l)$.

† High temperature season.

†† Low temperature season.

Other symbols are as in Table 5.

of 20 m layer of St. BG-1, and obtained a high correlation coefficient of 0.836. In the present analyses, we have examined the dependence of PP upon chlorophyll *a* for each stratum of the data taking into account the possible effect of chlorophyll-free particulate organic matter.

In Table 6, p_1' takes values between 14 and 39 when it is statistically significant. Since C_{pp} (phytoplankton carbon) has been derived by multiplying chlorophyll *a* by a factor of 30 or 60, these values of p_1' are equivalent to an increase of 0.72 to 1.17 µg/l in PP per unit (µg/l) increase in chlorophyll *a*. These figures are perhaps reasonable, but we postpone any definite conclusion until more information is gathered on this subject.

From the statistical analyses in this and the preceding section we may conclude that the concentration of particulate phosphorus in the seawater depended chiefly on that of the organic particulate matter in all layers of both stations, and that it depended particularly on the concentration of sestonic chlorophyll *a* in the upper layers during the high temperature season. We also point out that in the shallow inshore waters the dependence of PP upon chl. *a* prevailed in the season of convective cooling.

Classification of Particulate Material

As we have pointed out, the lowest phosphorus contents shown by our particulate materials were comparable with the phosphorus contents of the particulate matter settling in a sedimentation trap placed near the sea bottom, and red tide seawaters gave particulate materials which were very high in both carbon and phosphorus contents.

We are then led to imagine two prototypes of suspended matter for the coastal waters under study. One is something similar to the bottom mud, being characterized by high contents of inorganic constituents such as silt and clay; the other is the living phytoplankton population. We further noticed that some of our carbon-rich materials were exceedingly low in chlorophyll contents. This has led us to imagine the third prototype, i.e., the detritus or an aggregate of particulate organic matter very low in both mineral and chlorophyll contents.

Though our definition of the chemical properties of each prototype is imperfect as yet, we postulate that the suspended matter in the sea, hence the particulate material recovered by filtering the seawater, is usually a mixture of such particulate matters whose origins are referrable to these prototypes and that its chemical composition varies with the mixing ratio.

A tentative scheme of classifying the recovered particulate materials is presented in Table 7. A particulate sample with chl. *a* less than 15 μg/l is assigned to one of the three types shown in the middle line, namely, "phytoplankton type", "detritus type" and "inorganic type", according to its carbon content and PC/chl. *a* ratio. Each type is named after the prototype to which a close alliance is supposed. The boundary values of 100 (for PC/chl. *a* ratio) and 10 % (for carbon content) are chosen by the rule of thumb. The carbon content of 10 % is equivalent to the inorganic content of 80 %, if two times of PC is accepted as the estimate of organic particulate matter.

The fourth type, i.e., "red tide type", is set up since the particulate material usually satisfied the indicated criteria (chl. $a \geqq 15$ μg/l, carbon content>10 %, PC/chl.$a<100$) on the occasions of the red tide, a phenomenon characterizing the eutrophic state of the sea region under study. This type, however, is nothing but a special case of the phytoplankton type in which the particulate matter is exceedingly concentrated in the sea.

Table 7. Classification of particulate materials according to their chemical composition and the chl. *a* concentration in seawater

	Carbon content >10 %		Carbon content $\leqq 10$ %
	PC/Chl. $a<100$	PC/Chl. $a \geqq 100$	
Chl. $a<15$ μg/l	1. Phytoplankton type [Pp]	2. Detritus type [D]	3. Inorganic type [I]
Chl. $a \geqq 15$ μg/l	4. Red tide type [Rt]	*	** Red tide type with high inorganic content [Rt-I]

* Not observed in this study.
** Only one example.

At the bottom of Fig. 4-A and 4-B the occurrences of each type are indicated with such symbols as Pp, D, I and Rt as defined in Table 7.

Every plot representing a carbon content below 10 % in the body of Fig. 4 is matched by the symbol "I" at the bottom. This is due to the definition of the inorganic type. The symbol "(I)" refers to particulate materials with carbon contents below 10 % and with the chlorophyll data lacking; judging from the circumstances, their chlorophyll

Table 8. Mean and variability of various ratios in four types of particulate material

Ratio	Red tide type	Phytoplankton type	Detritus type	Inorganic type
PC/SW (%)	15.3[a] *0.43*[b]	14.7 *0.22*	21.5 *0.39*	7.6 *0.23*
PP/SW (%)	0.258 *0.44*	0.278 *0.41*	0.257 *0.50*	0.158 *0.32*
PC/Chl. *a*	70.0 *0.19*	77.4 *0.14*	215 *0.49*	106 *0.36*
PP/Chl. *a*	1.22 *0.36*	1.42 *0.27*	2.45 *0.51*	2.26 *0.43*
PC/PP	64.8 *0.37*	60.4 *0.44*	98.0 *0.40*	50.7 *0.29*
PN/PP	9.61 *0.36*	9.90 *0.25*	10.28 *0.30*	7.47 *0.27*
PC/PN	6.73 *0.10*	5.92 *0.17*	9.34 *0.21*	6.98 *0.20*
Sample size	8[c]	13	20	20

[a] Mean.

[b] The ratio of standard deviation to the mean.

[c] Includes one example to the Rt-I type.

values were probably below 15 μg/l.

In the low temperature season, particulate materials were usually low in carbon content and assigned mostly to I- or (I)-type; the low carbon contents resulted probably from depleted crop of particulate organic matter (phytoplankton and/or poorly pigmented organic matter) rather than from an increase of silty matter, because the seston weight remained low during the season (Fig. 1). The occurrence of Pp-type in late February, 1974 at St. 2 reflects the tendency of the phytoplankton population in the inshore waters to grow even in the low temperature season.

In the high temperature season, particulate materials were mostly assigned to Pp-, Rt- or D-type because their carbon content usually exceeded 10 %. The symbol "(Org)" refers to those materials which showed high carbon contents over 10 % but the chlorophyll contents of which were not determined. The occurrences of I-type in the bottom layer in summer (July 1972 at St. 2; August 1972 at St. BG-1) were probably due to the fact that the sampling layer was within a few meters of the sea bottom.

Admitting the incompleteness of the foregoing classification scheme which is based on several chemical parameters and not on plentiful biological and/or mineralogical information, we calculated means and standard deviations of chemical parameters for each type (Table 8). The ratio of the standard deviation (SD) to the mean is shown to indicate the variability of the parameters within each type.

SD/mean was usually as large as 0.2 – 0.5 for all parameters except the PC/PN ratio. The comparatively small SD/mean for PC/PN (i.e., 0.1 – 0.2) probably reflects the high correlation between PC and PN as indicated in Fig. 3.

The small mean for PC/SW in the inorganic type and the large mean for PC/chl. *a* in the detritus type are primarily due to the criteria used for classification.

A hexagonal diagram was devised in order to visualize the chemical characteristics of each particulate material. Fig. 6 shows the examples of the diagram illustrating the means presented in Table 8. The scale on each axis is chosen in such a way as a rather balanced hexagon may result from a particulate material of the phytoplankton type.

The large hexagon illustrating the mean parameter values of the red tide type is nearly homologous to the hexagon representing the phytoplankton type, because the particulate materials of these two types are alike in C, N, P and chlorophyll *a* contents. The diagram illustrating the mean parameter values of the detritus type visualizes such features as relatively low chlorophyll *a* content and remarkably high carbon content. The hexagon representing the inorganic type is characterized by lower contents of C, N, P and chlorophyll *a* and by higher inorganic content, as compared with the one representing the phytoplankton type.

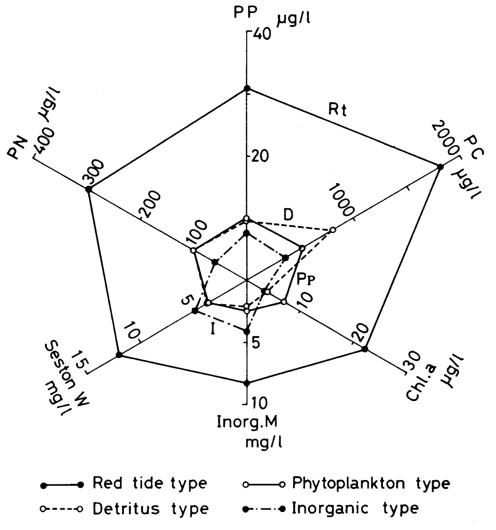


Fig. 6. Hexagonal diagrams characterizing different types of particulate material. Means for St. 2 and St. BG-1 combined are used to construct each hexagon.

SUMMARY

On the particulate materials collected at two stations in the central part of the Seto Inland Sea, Japan, at roughly monthly intervals from April 1972 to February 1974, particulate phosphorus (PP), particulate carbon (PC), particulate nitrogen (PN), sestonic chlorophyll *a* (chl. *a*) and dry weight of total particulate matter ("seston weight", SW) were determined.

PC was regarded as particulate organic carbon from the regression of PC to PN. The ratio PC/SW, i.e., the carbon content of the particulate material, was regarded as an index of organic feature of the particulate matter. The mean of this ratio was greater at the offshore station than at the inshore station, and was generally great during the high temperature season especially at 0 m layer.

The phosphorus content of the particulate material increased generally with the carbon content. The highest carbon contents were observed on the occasions of the red tide and also at 0 m layer of the offshore station, with phosphorus contents amounting to 0.32 – 0.45 % of SW. Low phosphorus contents were observed mainly in the bottom layer or in the low temprature season.

The regression analysis of PC to chl. *a* indicates that living phytoplankton accounted for major portions of PC at the inshore station; in contrast, large proportions of PC were represented by detrital carbon at the offshore station.

SW was divided into the organic and the inorganic matter by calculation, and their contributions to PP was evaluated by multiple regression analysis. The multiple correlation of PP to these two variables was always significant, and this significant correlation derived chiefly from the positive contribution made by particulate organic matter. Therefore, it is concluded that the abundance of PP depended mostly on that of particulate organic matter in all layers of both stations.

PC was subdivided into the phytoplankton carbon and the non-phytoplankton carbon by calculation, and their contributions to PP was evaluated also by multiple regression analysis. The result shows that the abundance of PP depended on the abundance of phytoplankton carbon especially in the upper layers of both stations during the high temperature season. In the shallow inshore waters the dependence of PP upon phytoplankton carbon prevailed also in the low temperature season.

Recovered particulate materials were classified into four types on the basis of C, N and chlorophyll *a* contents. The occurrence of each type was discussed with regard to the season, station and depth.

A hexagonal diagram was devised to illustrate the chemical characteristics of individual particulate material.

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富栄養沿岸海域における懸濁態リンの変動要因

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前報で瀬戸内海備後灘におけるリンの存在様式とその季節変動を，海水中のリンを懸濁態リン (particulate phosphorus, PP)，溶存態無機リン (DIP)，溶存態有機リン (DOP) の 3 態に分別定量する方法により明らかにし，PP と chlorophyll *a* の相関について考察を加えた。本研究は前報に報告した PP について，その内容と変動要因を，同時に測定した懸濁態炭素 (particulate carbon, PC)，懸濁態窒素 (particulate nitrogen, PN)，全懸濁物乾重量 (seston weight, SW)，chlorophyll *a* (chl. *a*) および透明度の値を用いて解析したものである。

1. SW は，暖季には値が大きく変動も大きいが，低温期には値が小さい場合が多かった。地点別では，沖合の St. BG-1 に比べ，沿岸の浅所の観測点 St. 2 で値が大きく特に海底に接近した 5 m 層では大きい値が観測された (Fig. 1, Table 3) 。
2. 透明度 (Tr, m) と 0 m 層における SW (mg/l) との関係は，極めて特殊な 3 例を除き，ほぼ双曲線的で分布範囲は (Tr)·(SW) ＝9 ～ 20 であった (Fig 2)。
3. PC が PN と非常に高い相関を示したこと，回帰式から得られた PC/PN 比が約 7.0 であったことから (Fig. 3)，今回測定した PC, PN はともに主として有機懸濁物成分であったと考えられた。
4. PC/SW 比は，懸濁物の有機性の強弱（懸濁物中に有機物が占める割合の大小）の指標として考えることができる。この比の平均値から判断すると，懸濁物の有機性は暖季の沖合点 St. BG-1 で最も強く，低温期（鉛直循環期）の St. 2 で最も弱かった (Table 3) 。この比の変動は植物プランクトンによる PC の生成と，河川水の流入や底質の再懸濁に伴う無機懸濁粒子の増加とによって，ほぼ説明できた。
5. 懸濁物のリン含有率は，無機的性質の強い懸濁物では一般に低く，一方，有機性の強い懸濁物ではリン含有率の高い例が相当数あった (Fig. 5)。最も有機性の強い懸濁物は赤潮時や St. BG-1 の 0 m 層で観測され，その際，リン含有率は 0.32 ～ 0.45 %に達した。最小値は St. BG-1 の底層で観測され 0.06%であった。
6. PC の chl. *a* に対する回帰および PC/chl. *a* 比の値から，St. 2 の懸濁有機物は主として植物プランクトンであり，一方 St. BG-1 にはデトリタス状の懸濁有機物が多かったと考えられた。
7. 有機懸濁物量 (Org) を 2·PC と見積り，従って無機懸濁物量 (Inorg) を SW−2·PC と計算して，PP の Org, Inorg に対する重回帰を調べると，一般に PP の増減は Org のそれに強く依存していた (Table 5)。PP が Inorg と有意の回帰を示したのは St. BG-1 の 20 m 層においてのみであった。
8. 前項の関係をさらに理解するため，懸濁態炭素 (PC) を計算によって植物プランクトン態炭素（chl. *a* 量の 30 または 60 倍）と非植物プランクトン態炭素に二分し，両者に対する PP の重回帰を季節・深度別に解析したところ，St. 2 においては暖季の底層を除いて，また St. BG-1 では暖季の 0，10 m 層において，PP の変動は植物プランクトン態炭素に強く依存しており，非植物プランクトン態炭素とは明瞭な関係になかった (Table 6)。
9. PP と他の懸濁物成分との共存状態を把握するため，この研究で取扱った懸濁物をその分析測定値にもとづいて，赤潮型，植物プランクトン型，デトリタス型，無機懸濁物型の 4 種類に分類し，各類型毎に出現状況および PP の関係する成分比を整理した (Table 7, 8; Fig. 6)。