Characteristics of Phosphorus in Sediments in Drainage Canals in Paddy-Field Districts around Lake Biwa

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ABSTRACT

Phosphorus (P) is a limiting factor of eutrophication in many lakes. Paddy-field districts are major non-point sources of P; water pollution prevention measures are to be implemented in these districts. However, sediment in drainage canals has a large P buffering capacity and can release P to the water column when input of P from paddy fields is reduced. Therefore, it is necessary to evaluate the amounts of P in the sediment in drainage canals. In this study, the sediments in drainage canals in paddy-field districts around Lake Biwa were investigated. The amounts and fractions of P in the sediments during both the irrigation period and the non-irrigation period were analyzed. Results showed that the mean value of total P in the sediment was 0.6 g/kg in both periods, but total P in non-irrigation periods tends to be greater than that during irrigation periods for each site in the study. Furthermore, over 70% of total P was inorganic on the average. Moreover, the fractions of organic and inorganic P exhibited seasonal variability. The potential contribution of water-extractable P in the sediment to total P in drainage water increased from June to November.

Keywords: drainage canal, paddy field, phosphorus, sediment

INTRODUCTION

Rice paddy fields, which use about 60% of the total water resources of Japan, are the most important non-point sources of phosphorus (P). The effluent load of P from a paddy-field district has large impacts on downstream ecosystems: eutrophication, algal blooms, and freshwater red tides.

Recently, increased interest in environmental problems has led to the implementation of many environmentally friendly farming practices. Paddy-field-scale practices include reducing the amount of chemical fertilizer used by applying slow-release fertilizer (Choi and Nelson, 1996; Fan and Li, 2010). District-scale practices include restructuring of vegetation and the reuse of drainage water through irrigation recycling, which can reduce the load of suspended solids (SS) (Hama *et al.*, 2010) and nutrients (Takeda *et al.*, 1997; Feng *et al.*, 2004, 2005; Takeda and Fukushima, 2006). However, increased implementation of these measures may cause ponding of water with high SS and P loads in drainage canals. For example, when water is reused, water with high SS load flows in drainage canals. As a result, P bound or adsorbed to suspended solids may accumulate in the bottom of these drainage canals. Reduction of effluent loads in the canals is important because the canals may act as sources of P when water flowing into the drainage canals contains no P. In particular, it is essential for the appropriate management of drainage canals to quantify the amount of P in the sediments because P tends to be adsorbed or desorbed to sediments easily. Christophoridis and Fytianos (2006) revealed that the rates of release of P from lake sediment increased under reductive conditions and high pH values. It is reported that lake sediment P release

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mainly relates to P bound to iron and aluminum, and total organic carbon (Pant and Reddy, 2001; Wang *et al.*, 2005; Dong *et al.*, 2011). However, there is little research to date that has investigated the amount of P in drainage canals. Therefore, in this paper, we clarified the amount and fraction of P in the sediments in drainage canals in low-lying paddy-field districts.

MATERIALS AND METHODS

Study sites

We investigated 6 paddy-field districts around Lake Biwa in Shiga Prefecture, Japan (Fig. 1). Lake Biwa is the largest lake in Japan and the most important water resource for the Kinki region, which includes Osaka and Kyoto. Around Lake Biwa, two main types of irrigation practices, namely, lake water irrigation and river water irrigation are employed.

An outline of each study site is shown in Table 1. Mean annual temperature around all sites is 14°C. Most sites have separate irrigation and drainage canals, except St. F. Drainage canals are considered to have wall lining when only the walls are lined with concrete, while considered to have concrete lining when both the walls and the bottom are lined with concrete.

We focused on two periods, irrigation period and non-irrigation period. During the irrigation period, from late April to the middle of September, the irrigation water is supplied to paddy fields. As a result, highly loaded water may flow into the drainage canal. During the non-irrigation period, less P containing water may flow or pond in the drainage canal. Therefore, we investigated the study districts in June (irrigation period) and in November (non-irrigation period) of 2011.

Phosphorus measurement in the sediments and paddy soils

Sediments in drainage canals and paddy soils in nearby fields were sampled in June and November 2011 at each of the study sites.

Fig. 1 - Study sites.

Table 1 - Outline of study sites and canals.

St.	District	Coordinate	Water Catchment Area [ha]	Mean Annual Rainfall [mm] ^a
A	Enoki Town, Nagahama City	35° 24' N, 136° 18' E	9.4	1,800
B	Yagihama Town, Nagahama City	35° 24' N, 136° 13' E	13.0	
C	Shimo-Aso Town, Higashi-Ohmi City	35° 02' N, 136° 11' E	48.7	1,600
D	Nomura Town, Ohmi-Hachiman City	35° 08' N, 136° 02' E	7.9	
E	Adogawa Town, Takashima City	35° 21' N, 136° 00' E	9.1	2,500
F	Adogawa Town, Takashima City	35° 20' N, 136° 04' E	52.5	

St.	Nearby River	Location ^b	Irrigation Water	Canals ^c	Lining on Drainage Canal
A	Anegawa River	Upstream (9km)	River	Separated	Wall lining
B	Anegawa River	Downstream	Lake	Separated	Wall lining
C	Hinogawa River	Upstream (23km)	River	Separated	Concrete lining
D	Hinogawa River	Downstream	Lake	Separated	Wall lining
E	Adogawa River	Upstream (9km)	River	Separated	Concrete lining
F	Adogawa River	Downstream	River	Not-separated	No lining

^a Mean annual rainfall data are estimated from the Japan Meteorological Agency (2011).

^b The location column indicates whether the site is in the upstream or downstream part of the associated river; numbers in parentheses indicate the distance upstream.

^c The canals column indicates whether irrigation and drainage canals are separated.

Sediment samples were classified as those corresponding to upper, middle, and lower layers. The upper layer extended to about 1 cm depth from the sediment surface, the middle layer from around 1 cm to 5 cm, and the lower layer from around 5 cm to 10 cm depth. At St. E, however, because of low sedimentation rates, E-L (the lower layer of the St. E sample) could not be sampled. Samples were taken to the laboratory in airtight bags and kept in cool conditions. Then, samples were dried in a refrigerator and sieved through a 125- μ m sieve (Ruttenberg, 1992) wherein the waste material, gravel, and other constituents over 2 mm in diameter were removed.

Sediments and paddy soils were analyzed for ignition loss, weight ratio of particles smaller than 125- μ m, total P (TP), and some P fractions. Analyzable forms of P are divided into the following fractions: total inorganic P (TIP); water-extractable P (WE-P); P bound to iron, aluminum, and calcium carbonate (Fe-P, Al-P, and CaCO₃-P, respectively); P including detrital apatite (Detrital-P); and total organic P (TOP). In this study, TIP was extracted from oven-dried sediments and paddy soils using 1 M HCl solution for 16 h and TP was extracted using the same method after ignition at 550°C for 2 h. The WE-P and Fe-P + Al-P fractions were dissolved out of naturally dried sediments and paddy soils: WE-P was determined to be PO₄-P dissolved out using distilled water for 2 h, and Fe-P + Al-P was determined to be the difference between PO₄-P extracted by 1 M sodium hydroxide (NaOH) solution for 16 h and WE-P.

After extraction, all these samples were filtrated through a 0.45- μ m cellulose acetate membrane filter. Phosphorus concentration measurements were made using a spectrophotometer (UV-1200; Shimadzu Corp., Kyoto, Japan) using the molybdenum blue method. Furthermore, the CaCO₃-P + Detrital-P fraction was calculated as the

difference between TIP and $\text{PO}_4\text{-P}$ extracted using NaOH. Total OP was calculated by subtracting TIP from TP. Traditionally, fractionation of P has employed a sequential extraction method (SEDEX, Ruttenberg, 1992).

Phosphorus measurement in the drainage water

The water in the drainage canals was sampled at the same time as the sediments and soils. These sampled drainage water were analyzed for TP, dissolved total P (DTP), and phosphate P ($\text{PO}_4\text{-P}$). Dissolved P was distinguished by filtering the sample with a 1- μm filter prior to analysis. Total P and DTP concentrations were measured by a spectrophotometer using the molybdenum blue method after potassium-peroxydisulfate digestion, while $\text{PO}_4\text{-P}$ concentration was measured by the molybdenum blue method.

RESULTS AND DISCUSSION

Weight ratio of particles smaller than 125 μm

Table 2 shows the ratios of the weights of sediments and paddy soils that were sampled in November and passed through a 125- μm sieve to the total weight of the sediments and paddy soils (< 2 mm sieve).

The weight ratio of the sediment ranged from 0.17 to 0.93, and the average of all stations and layers was 0.70. Compared to the trends for paddy soils, those of sediments differ remarkably among sites. Variations in weight ratios were small at St. B, D, E, and F, with a range of less than 0.08. This was particularly noticeable at St. F, where it was assumed to be a result of the lack of separation of the canals and the lack of lining. In contrast, at St. A and St. C, the weight ratios were three or four times higher in lower layers than in upper layers. This is thought to reflect not the weight ratio of paddy soil, which is a main origin of the sediment, but the physical conditions such as current velocity. At St. A, a high current velocity of 55 cm/s was observed in September (after harvesting), which may have resulted in the removal of fine fractions in the top layer. In addition, at St. C and St. E, of which the drainage canal receives water from the outside even during the non-irrigation period, the base flow of more than 2 cm/s caused the removal in the top layer (St. C) and prevented sedimentation of fine particles (St. E).

Table 2 - Weight ratio of particles smaller than 125 μm and water depth and current velocity in the drainage canals in November.

St.	Sediment ^a				Paddy soil	water	current
	Layer			Average		depth	velocity
	Upper	Middle	Lower			cm	cm/s
A	0.31	0.67	0.86	0.73	0.67	13	0
B	0.53	0.55	0.48	0.51	0.85	26	2
C	0.17	0.55	0.67	0.57	0.70	16	2
D	0.85	0.78	0.77	0.78	0.64	NS	NS
E	0.45	0.43	NS ^b	0.44	0.74	12	3
F	0.85	0.87	0.93	0.90	0.91	11	0

^a 100% (1.00) represents a sample from which waste and other particles over 2 mm have been removed. The average was calculated considering the thickness of the upper, middle, and lower layers to be 1 cm, 4 cm, and 5 cm, respectively.

^b NS means no sample.

Although it has not been possible to specify all factors affecting the ratios, these results show that the weight ratio of the sediment is strongly affected by the conditions in the drainage canal.

Quantification of phosphorus and its fractions in the sediments

Figure 2 shows TP in June and November for every station. Average values of TP were 0.62 gP/kg (range: 0.14 – 1.19 gP/kg) in June and 0.67 gP/kg (range: 0.24 – 1.94 gP/kg) in November. For both periods and in all stations, TP values in the sediments were higher in the upper layer than in the lower layer. TP in paddy soils tends to be similar to that of the upper sediment layer, perhaps as a result of accumulation of phosphorus from drainage water or SS in the water on the surface of the sediments. Therefore, sediment in the drainage canals contained large amount of P depending on the amount of P in the paddy soil. In addition, P is easy to dissolve in lower layers, where reducing conditions are more prevalent. The sediments in the lower layer show black or gray color, indicating that they are under reducing conditions.

Total P was greater in November than in June for all samples, with the exception of B-M (middle layer of the sample from St. B), E-M, F-M, and F-L. In other words, TP tended to be higher in the non-irrigation period.

Table 3 shows the quantities of the various P fractions that make up TP of the sediment. The sum of $\text{CaCO}_3\text{-P}$ + Detrital-P, Fe-P + Al-P, and WE-P is TIP, and the sum of TOP and TIP is TP. The average was calculated considering the thickness of each layer in the same way as the weight ratio. The average amount of TOP was 0.14 gP/kg in June and 0.17 gP/kg in November. Total IP was 0.47 gP/kg in June and 0.50 gP/kg in November on the average. The amounts of all fractions tend to decrease from the upper layer to the lower layer, both in June and in November.

Figure 3 shows the proportions of P fractions in paddy soil and sediment (average and by layer). In both June and November, TIP accounts for more than 70% of TP in the

Fig. 2 - Site-specific TP in June and November. The plots show the amount of TP on the horizontal axes and the types of sample on the vertical axes: paddy soil (P), upper layer (U), middle layer (M), and lower layer (L).

Table 3 - Quantities of TP and phosphorus fractions.

St.	Layer	TOP		CaCO ₃ -P Detrital-P		Fe-P Al-P		WE-P	
		Jun.	Nov.	Jun.	Nov.	Jun.	Nov.	Jun.	Nov.
A	Upper	0.17	0.16	0.23	0.41	0.27	0.16	0.01	0.02
	Middle	0.15	0.32	0.19	0.27	0.22	0.16	0.01	0.01
	Lower	0.16	0.12	0.09	0.40	0.24	0.13	0.01	0.01
B	Upper	0.18	0.24	0.15	0.71	0.77	0.78	0.00	0.00
	Middle	0.13	0.09	0.20	0.30	0.64	0.17	0.01	0.00
	Lower	0.14	0.12	0.17	0.41	0.45	0.37	0.00	0.00
C	Upper	0.12	0.25	0.06	0.52	0.69	0.53	0.02	0.01
	Middle	0.02	0.07	0.03	0.15	0.15	0.16	0.01	0.00
	Lower	0.02	0.06	0.02	0.10	0.10	0.09	0.01	0.00
D	Upper	0.25	0.38	0.02	0.28	0.35	0.25	0.00	0.02
	Middle	0.19	0.27	0.04	0.19	0.39	0.19	0.02	0.02
	Lower	0.15	0.22	0.01	0.18	0.32	0.20	0.00	0.02
E	Upper	0.36	0.45	0.11	0.47	0.72	0.41	0.01	0.01
	Middle	0.24	0.21	0.05	0.13	0.57	0.15	0.00	0.01
F	Upper	0.22	0.41	0.13	0.77	0.70	0.76	0.00	0.01
	Middle	0.16	0.13	0.12	0.37	0.45	0.21	0.00	0.01
	Lower	0.18	0.12	0.17	0.29	0.43	0.16	0.01	0.00
Average		0.14	0.17	0.10	0.28	0.37	0.21	0.01	0.01

The values of the fractions are shown as the weight per unit oven-dried sediment (gP/kg).

Fig. 3 - Proportion of phosphorus fractions to TP. The error bars indicate upper and lower limits among all sites. The average was calculated considering the thickness of each layer.

sediment on the average. The mean proportion of CaCO₃-P + Detrital-P is 16% in June and 42% in November. The mean proportion of Fe-P + Al-P is 61% in June and 31% in November. The mean proportion of WE-P to TP is less than 2% on the average, in both

June and November. On the other hand, the proportions of all fractions vary greatly among the sites. For example, in June, TIP of St. C accounts for 88% of TP, but that of St. D accounts for 68% of TP.

From June to November, the amount (Table 3) and the proportion (Fig. 3) of Fe-P + Al-P decreased while that of $\text{CaCO}_3\text{-P}$ + Detrital-P increased. However, there was a little difference in TIP, TOP, and WE-P between June and November. Therefore, it is suggested that seasonal variation of P in the sediment is mainly affected by the fractions of $\text{CaCO}_3\text{-P}$ + Detrital-P and Fe-P + Al-P.

Influence of phosphorus in the sediment on the overlying drainage water

Water-extractable P, which is extracted by water containing no P, is believed to indicate the quantity of P dissolved by drainage water containing no or low P without resulting in chemical changes such as in pH or ORP. Therefore, in order to evaluate the potential of the sediment to contribute P, we calculated the potential WE-P in the overlying drainage water. The potential concentration of P released from the sediment, C_{sed} , can be estimated by the following equation:

$$C_{\text{sed}} = (\text{WE-P}) \rho_s V_s / V_d = (\text{WE-P}) \rho_s (1 - n) h_{\text{sed}} / h_d \quad (1)$$

where WE-P is the amount of water-extractable P per unit sediment in the upper layer (g/kg); ρ_s is the density of soil (kg/m^3); V_s is the volume of the sediment (m^3); V_d is the volume of overlying drainage water (m^3); h_{sed} is the depth of the sediment (m); h_d is the depth of drainage water (m); and n is the porosity of the sediment. Here, we assigned a value of 2.65 to ρ_s , which is a commonly used value for soil. Because we could not measure the porosities of the sediments in this study, the values of 0, 0.25 and 0.5 are assigned to n to estimate the range of C_{sed} .

Figure 4 shows the ratios of C_{sed} to TP concentration in drainage water (C_d). Because drainage water did not exist at St. D in November, this result is not shown. The ratios of C_{sed} to C_d increased considerably from June to November at all sites except St. C. This

Fig. 4 - Contribution of water-extractable phosphorus to phosphorus in drainage water.

may be because the drainage water in November contained less P, which suggested that the influence of P in the sediments is greater in November than in June.

However, at St. C the percentage was decreased; this may be a result of the inflow into the drainage of domestic wastewater from the neighboring settlement, which has higher P concentration than the agricultural drainage water.

CONCLUSIONS

Results showed that sediment in the drainage canals contained significant amount of P depending on the amount of P in the paddy soil, although the weight ratio varied among paddy-field districts. The mean amounts of TP in the sediments were 0.62 gP/kg in June and 0.67 gP/kg in November, and TP in the sediments increased in November. The P in the sediment consisted mainly of inorganic P (over 70% of TP on the average). It implied that the seasonal variations of TP in the sediments are determined by those of specific P fractions: $\text{CaCO}_3\text{-P}$, Detrital-P, Fe-P, and Al-P. The contribution of P in the sediment to P in drainage water increased from June to November. Therefore, the fractions of P should also be considered when implementing water quality conservation measures.

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