Effects of residence time and nutrient load on eutrophic conditions and phytoplankton variations in agricultural reservoirs

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Abstract The effects of residence time and nutrient load on eutrophic conditions and phytoplankton variations were examined on six ponds highly influenced by agricultural activity in western Japan. Estimated residence times ranged from 7 to 2348 days, which decreased from summer to winter. The nutrient condition was totally in a N-rich and P-limited condition compared with the Redfield ratio in both summer and winter. The estimated budget of DIN, DIP and dissolved silica (DSi) suggests that the ponds acted as a sink of nutrients to the downstream environment throughout the year. Fluorescence was clearly higher in the shorter residence time ponds. It suggests that cyanobacteria with relatively low chlorophyll content were dominant in the longer residence time while other phytoplankton was dominant in the shorter residence time. The opposite trend in residence time and fluorescence from August to December suggests that the dominant primary producer changed from cyanobacteria to diatoms.

Key words agricultural reservoirs; eutrophic condition; phytoplankton; residence time; nutrient load

INTRODUCTION

Reservoirs and ponds have been used as important water resources in agriculture areas of little rain. Moreover, their importance will increase along with the worldwide climate change in the future. Intensive agriculture generally increase the load of nutrients such as nitrate (NO_3^-) to surface water and groundwater (Burt *et al*., 1993), which causes serious eutrophication and phytoplankton blooms in small-scale reservoirs and ponds. Consequently, it sometimes induces clogging of irrigation facilities such as sprinklers. However, effective countermeasures against the problem are not taken in most agricultural regions. For sustainable water use in agricultural areas, it is important to clarify the trigger of eutrophication and control it based on the characteristics of the respective ponds and reservoirs. Previous studies reported that physical and morphometric characteristics of reservoirs, such as water level fluctuations (Garcia de Emiliani, 1997), changes in flushing rate (Garcia de Emiliani, 1993; De M. Huszar & Reynolds, 1997), and water residence time (Olding *et al*., 2000) play a role of influencing the phytoplankton-community composition. Valiela *et al*. (2000) discussed the relation between residence time and primary producers in several estuaries. They estimated that the contribution of phytoplankton to primary production will increase in longer residence time water, while macroalgae and seagrasses will act as main primary producers in shorter residence time water. Regarding the effect of nutrient condition on the lower trophic ecosystem, Harlin (1993) and Burkholder *et al*. (2007) generalized the shift in the biomass of major groups of primary producers from seagrass to phytoplankton and macroalgae with increasing nutrient in coastal marine ecosystems. However, factors controlling the nutrient condition and mechanisms of phytoplankton variation in agricultural reservoirs were not well examined in the previous studies. In the present paper, we aim to examine the effects of residence time and nutrient load on the eutrophic condition and phytoplankton variation in ponds highly influenced by agricultural activity.

STUDY AREA

The study area is located on Ikuchijima Island, which is one of the islands in the Seto Inland Sea, western Japan (Fig. 1). The study area is characterized by a temperate, marine climate with annual mean precipitation and temperature of 1100 mm and 15.6°C, respectively; it is one of the lowest precipitation areas in Japan. The annual precipitation ranged from 400 to 1700 mm over the last four decades. Onodera *et al*. (2007) reported that annual precipitation has been decreasing by about 40 mm per decade over the last five decades and suggests increased frequency of drought in the future. The study island is characterized by steep terrain underlain by granite rocks; the total area is 32.7 km^2 (Fig. 1(b)). Citrus trees such as orange and lemon are widely cultivated over more than 30% of the total area of the island. However, estimated average transpiration exceeds the rainfall during the summer period. The annual input of nitrogen fertilizer to the citrus farm is estimated to be 2400kg ha^{-1} $year^{-1}$ (Saito *et al*., 2008).

Small-scale ponds and reservoirs in the island are used for the irrigation and crop protection in the citrus farms. However, most of these ponds are in a eutrophic condition and significant phytoplankton blooms occur in the summer period. Six ponds (P1–P6) constructed from 150 to 200 years ago, with different volume, watershed area and citrus farm area were included for the field survey (Fig. 1(c), Table 1). The watershed area ranges from 5 to 222 ha, and citrus farm covers from 14 to 82% of the total watershed area.

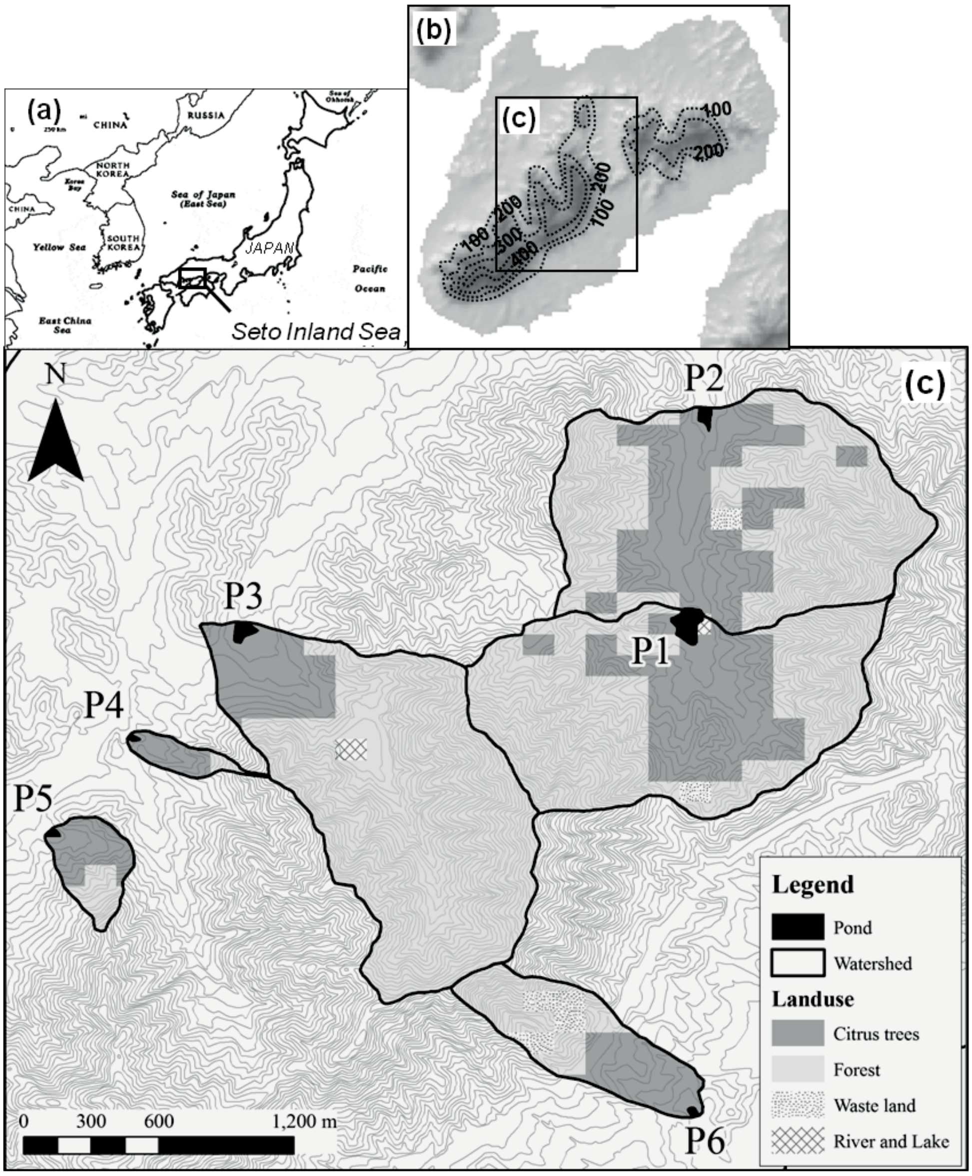

Fig. 1 Study area (a) location of study area, (b) Ikuchijima island, and (c) study ponds and their watersheds).

Table 1 Morphometry and geographical information of the ponds.

	Watershed area (ha)	Land use				Volume (m^3)		Residence time (day)	
		Citrus farm (%)	Forest (%)	River & lake (%)	Waste land (%)	August 2012	December 2012	August 2012	December 2012
P1	110	32	66	66	66	31 140	10 863	93	31
P2	222	35	64	64	64	4 156	4 317	24	7
P3	117	14	85	85	85	11 189	6 775	75	29
P4	5	82	18	18	18	1 602	910	17	-
P5	10	65	35	35	35	1 578	1 321	-	2348
P6	28	41	43	43	43	3 161	3 263	-	378

METHOD

We conducted measurements of water depth, volume of inflow and outflow of surface water through the channels, and vertical profiles of water temperature, salinity and fluorescence in the central part of ponds in August and December 2012. The pond volume was estimated from water depths and topography using a GIS calculation tool. The residence time of pond water was estimated from dividing the volume of ponds by the inflow or outflow. However, it could not be estimated for P5 and P6 in August, and P4 in December, because neither the inflow nor outflow were confirmed. Water samples were collected from the surface in the central part of the ponds, and channels of inflow and outflow. The samples were filtered by 0.2 μm cellulose ester filters in the field and stored in a freezer until the analysis of dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP) and dissolved silica (DSi) using a spectrophotometric auto analysing system (SWAAT, Bl-tec).

RESULTS AND DISCUSSION

Residence time

Estimated residence times are from 7 to 93 days, which tends to be longer with the increase of volume in P1, P2, P3 and P4 (Table 1). In P5 and P6, it could only be estimated in December and was 2348 and 378 days, respectively. The result suggests these two ponds are in a significantly stagnant condition throughout the year and possibly the main inflow source is groundwater discharge from the bottom or side of the ponds.

The volume of pond water in December decreased from 16 to 65% of that in August, except for P2 and P6. Residence time decreased by about 1/3 from August to December in P1, P2 and P3. This suggests that the increase of water withdrawal for irrigation and crop protection from summer to winter influenced the reduction of residence time. However, the P4, residence time could be significantly long in December because both the inflow and outflow were not confirmed. P4 is characterized by the smallest catchment area and the highest citrus farm ratio among the study ponds. It suggests that decrease of inflow and increase of withdrawal caused a significant drop of water level below the outlet.

Nutrient condition and budget

The relation between dissolved DIN and DIP in the pond water is shown in Fig. 2. The broken lines represent the Redfield ratio (N:P = 16:1) (Redfield, 1934) which is the molar ratio of nitrogen and phosphorus for uptake by phytoplankton. The solid arrows show the variation from August to December in the respective ponds. The result shows that the ponds, except for P4 and P3, were in a significant nitrogen-rich and phosphorus-limited condition compared with the Redfield ratio in both summer and winter. It suggests these ponds are significantly influenced by the nitrogen load from citrus farms. In P3, the nutrient condition changed from N-limited to P-limited from summer to winter. P4 shows P-limited conditions in both summer and winter, which is a different trend to the other ponds. On the variation of nutrient concentrations from August to December, only DIN showed a clear increasing trend in P1 and P2, both DIN and DIP increased in P3, P5 and P6, and only DIP decreased in P4.

The budget of DIN, DIP and DSi were evaluated on the respective ponds in August and December (Table 2). The influx and outflux of nutrients were estimated by the inflow and outflow volume of surface water and its nutrient concentration. Influx of nutrients was much higher in P1, P2 and P3 than the other ponds. Regarding variation from August to December, DIN influx increased in P2 and P3, while it decreased in P1. DIP influx decreased and DSi influx increased in

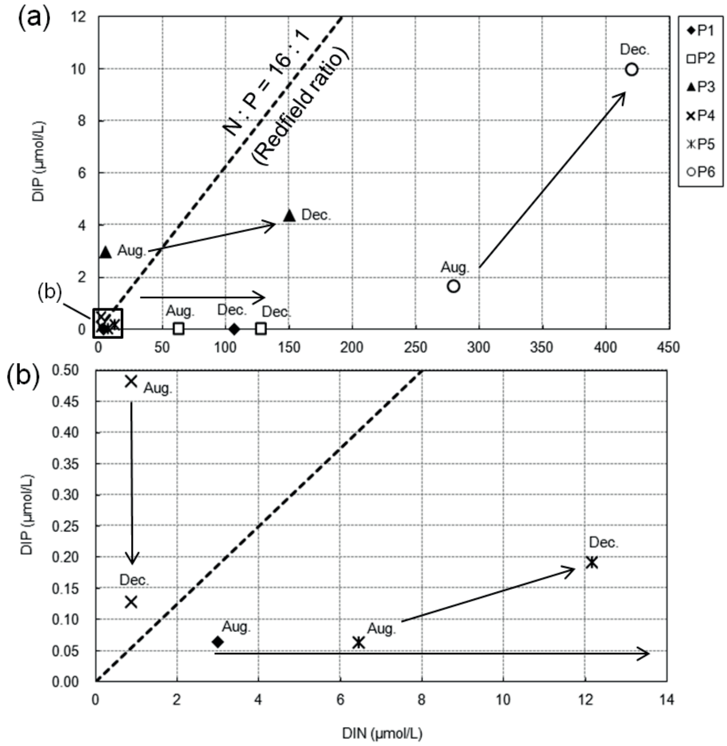

Fig. 2 Relation between concentrations of DIN and DIP in pond water.

Table 2 Budget of DIN, DIP and DSi at the ponds in August and December 2012.

	DIN			DIP			DSi		
	Influx (kg/y)	Outflux (kg/y)	Attenuation (%)	Influx (kg/d)	Outflux (kg/d)	Attenuation (%)	Influx (kg/y)	Outflux (kg/y)	Attenuation (%)
August 2012									
P1	608	5	99	21	0.3	99	1749	132	92
P2	239	42	82	6	2.7	52	611	260	57
P3	635	2	99	5	3.2	32	874	270	69
P4	31	16	49	6	1.5	75	433	272	37
P5	-	-	-	-	-	-	-	-	-
P6	-	23	-	-	0.2	-	-	67	-
December 2012									
P1	440	331	25	7	0.7	90	1875	274	85
P2	783	213	73	2	0.7	64	1630	392	76
P3	832	61	93	4	2.2	38	1360	228	83
P4	-	-	-	-	-	-	-	-	-
P5	-	0.1	-	-	0.01	-	-	1.5	-
P6	1.1	-	-	0.04	-	-	0.3	-	-

P1, P2 and P3. The difference between the influx and outflux was estimated as nutrient attenuation in the ponds. The results suggest that from 25 to 99% of DIN, from 32 to 99% of DIP and from 37 to 92% of DSi inflows to the ponds were removed in the ponds before it outflows to the downstream. This indicates that the ponds acted as a nutrient sink to the downstream environment throughout the year.

Variation of fluorescence

The vertical profiles of water temperature and fluorescence in the respective ponds in December are shown in Fig. 3(a) and (b), respectively. The temperature profile (a) indicates the pond water is well mixed vertically except for just under the surface (<0.2 m) in P4 and P6. Meanwhile the fluorescence profile (b) shows the different trend among the ponds. P1 shows the highest value, about 60 μg L^{-1} at 0.1 to 0.8 m. P3 shows the lowest value, less than 6.2 μg L^{-1} from the surface to the bottom. In the other ponds, the peak values of 40 to 74 μg L^{-1} were found in the middle layer from 0.5 to 2.1 m.

The variation of fluorescence from August to December is shown in Fig. 3(c). The value is shown as the average concentration from surface to bottom in the respective ponds. P1 and P2 show an increasing trend from summer to winter, while the other ponds show a decreasing trend or little change.

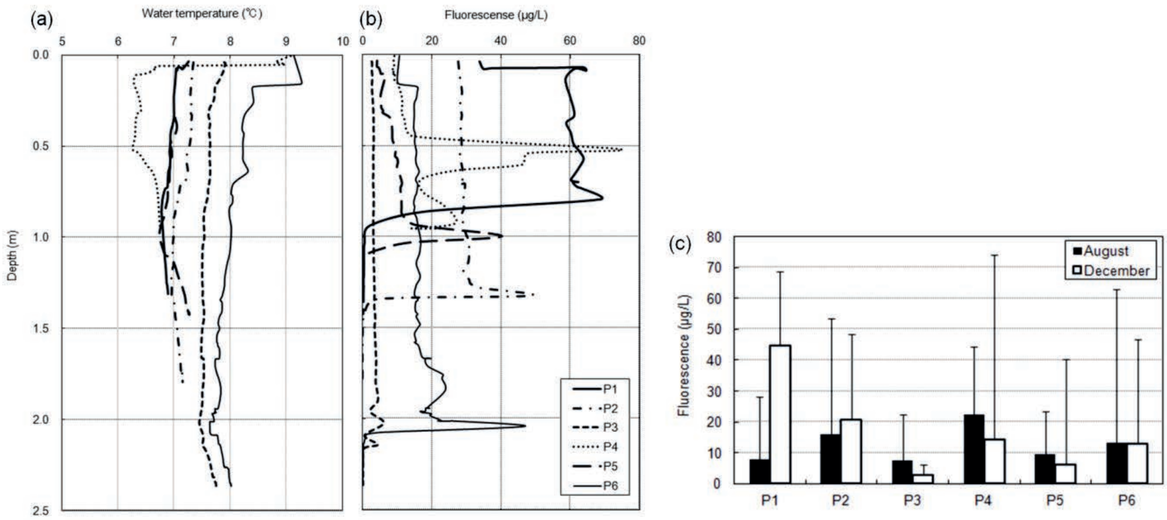

Fig. 3 Vertical profiles of water temperature (a), fluorescence (b) in December and seasonal variations of fluorescence from August to December (c).

Effect of residence time on the phytoplankton variation

Figure 4 shows the relation between residence time and fluorescence of the ponds in August and December. Fluorescence is shown as the vertical averaged value (Fig. 4). Solid arrows in the figure represent the variation from summer to winter. Fluorescence clearly shows an increasing trend with the decrease of residence time. Olding *et al.* (2000) reported the dominance of cyanobacteria in longer residence time conditions in the several lakes, reservoirs and ponds in the heavily urbanized Greater Toronto Area, Ontario, Canada. The content of chlorophyll is generally lower in cyanobacteria than that in the other phytoplankton such as diatoms and green algae. These suggest the possibility that cyanobacteria with lower chlorophyll content were dominant in the ponds with longer residence time such as P5 and P6, while other phytoplankton (diatom, green algae, etc.) were dominant in the shorter residence time ponds, such as P2 and P4 in our study area. Especially in P4 with the shortest residence time in August, floating plants as well as phytoplankton covered all around the water surface, which suggests a different ecosystem structure from the other ponds.

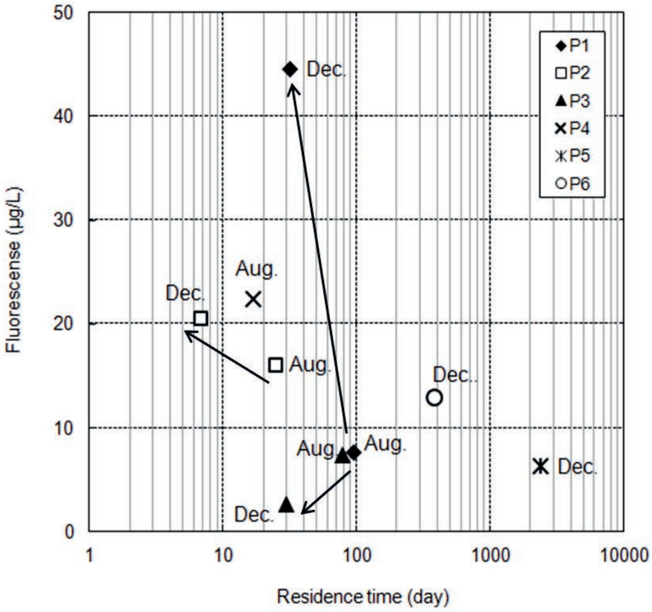

Fig. 4 Relation between residence times and averaged fluorescence in the ponds.

On the seasonal variation, residence time decreased while fluorescence increased in P1 and P2 from August to December. The result suggests that the dominant species of primary producer changed from cyanobacteria to other phytoplankton, such as diatoms, from summer to winter. Especially in P1, a significant change of water colour from green to brown was confirmed. These results suggest that residence time is one of the critical factors for controlling the phytoplankton variation in the ponds.

CONCLUDING REMARKS

The residence times of water in the six ponds (P1–P6) were estimated to be from 7 to 2348 days in the study area, and decreased by about 1/3 from August to December in P1, P2 and P3. The nutrient condition of the pond water in both summer and winter was wholly in the significant N-rich and P-limited condition compared with the Redfield ratio. The estimated budget of DIN, DIP and DSi suggests that the ponds act as a sink of nutrients to the downstream environment throughout the year. Fluorescence was clearly higher in the ponds with shorter residence time. It suggests the possibility that cyanobacteria with relatively low chlorophyll content were dominant in the longer residence time ponds, while other phytoplankton such as diatoms and green algae were dominant in the shorter residence time ponds in the study area. On the seasonal variation, residence time decreased while fluorescence increased in P1 and P2 from August to December. It suggests that the dominant species of primary producer changed from cyanobacteria to diatoms from summer to winter. These results suggest that residence time is one of the critical factors for controlling the phytoplankton variation in the ponds.

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