Effects of Cyclic Irrigation on Water and Nitrogen Mass Balances in a Paddy Field

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Abstract

Cyclic irrigation is considered an effective water management practice for reducing pollutant loads from a paddy-field district. The objective of this study was to clarify the effects of cyclic irrigation on mass balance in paddy plots. At the study site, cyclic irrigation with a high cyclic irrigation ratio (% reused water in irrigation water) was conducted from late April to late June. We found a complementary relationship between the volume of irrigation water and rainfall, which together totaled about 1400–1600 mm during the irrigation period each year. We concluded that a cyclic irrigation system that enables the paddy-field district to use a high cyclic irrigation ratio may lead to more efficient use of rainfall for crop irrigation. Nitrogen concentrations in both irrigation water and ponded water tended to be higher during the cyclic irrigation period than during the lake water irrigation period. Nitrogen input from irrigated water accounted for about 8–16% of the total input of nitrogen. It is suggested that fertilizer application of nitrogen can be reduced by its return through cyclic irrigation.

Keywords:
Nitrogen; Cyclic irrigation; Water reuse; Paddy field

1. Introduction

The reduction of pollutants such as nitrogen (N), phosphorus, organic matter, and suspended solids discharged from non-point sources is an important aspect of improving water quality of downstream water areas (Reinelt et al., 1992; Gunes, 2008; Collins et al., 2010). Paddy fields, which produce rice as staple food in many countries, especially in the Asian monsoon region, and use large amounts of water during the rice growing season, are a major non-point source of pollution.

Cyclic irrigation (CI) is considered an effective water management practice for saving irrigation water resources. In a CI system, drainage water discharged from the paddy field is partially reused as irrigation water, so that the actual downstream effluent volume is decreased. Cyclic irrigation is also expected to decrease pollutant loads both because less water leaves the district and because some of the pollutants in the drainage water will be returned to the paddy field. In addition, CI system may increase the hydraulic retention time of nutrients in the paddy field and thereby enhance the purity of water leaving the field (Takeda et al., 1997; Feng et al., 2004, 2005; Takeda and Fukushima, 2006). It has been suggested that the effect of CI on reducing nutrient loads is proportional to the ratio of reused water to drainage water (Shiratani et al., 2004; Hitomi et al., 2006). However, the CI ratio, that is defined as the ratio of reused water to irrigation water, in paddy-field districts that have upstream areas is limited to low values due to large amount of uncontrollable inflow of water to the districts.

Little is known about the ability of CI conducted with high CI ratios to reduce pollution loads in runoff from paddy-field districts. We reported the ability of CI to reduce suspended solids load from the district (Hama et al., 2010). In this paper, we aimed to clarify the effects of CI with high CI ratio on water and N mass balances in paddy plots in the district.

2. Materials and methods

2.1. Study site

The study site is low-lying paddy field district (35°05′N, 135°56′E), located on the southeastern side of Lake Biwa, which is the largest lake in Japan. The mean temperature and rainfall during the rice growing season (May-August) for three decades (1980-2009) are 23.1±0.7°C and 765±205mm (Japan Meteorological Agency, 2010), respectively. The district covers about 1.5 km^2, of which more than 90% is used as paddy fields. There is no inflow of industrial wastewater from outside the study area into the drainage and irrigation canals. Two types of irrigation have been practiced in the district: lake water irrigation (LWI) and cyclic irrigation. In LWI, irrigation water is pumped from Lake Biwa into the irrigation canals. Under CI, drainage water in the main drainage canal is pumped and reused as irrigation water. The irrigation period is about four months, including a mid-summer drainage season of about ten days (Table 1). Cyclic irrigation is used from the beginning of the irrigation period to the mid-summer drainage season (referred to as the CI period), then lake water irrigation is used until the end of the irrigation period (the LWI period). The CI and lake water irrigation periods are both about two months long. The CI ratio during the CI period was 79% (reused water/irrigation water = 800mm/1010mm) in 2004, 78% (1370mm/1760mm) in 2005, and 88% (980mm/1110mm) in 2006, respectively.

2.2. Field investigation

From 2004 through 2006, we performed weekly water quality measurement at two paddy plots in the district during the irrigation period each April to September. The area of each paddy plot is about 30 m × 100 m. The two study plots were cultivated in normal farming methods for paddy rice, as other paddy fields in Japan or other countries (e.g., Liu et al., 2001; Kim et al., 2006). Each week, ponded water was sampled at the outlet of the paddy plots, and irrigation water was sampled. A small plastic tank was set in the study site to collect rainfall water, which was sampled during the weekly field investigation. The manually sampled water was analyzed for total nitrogen (TN). Total nitrogen was measured using an ultraviolet spectrophotometer after alkaline potassium-peroxydisulfate digestion.

Hydrological measurement instruments for rainfall, air temperature, wind velocity, relative humidity and solar radiation were installed in the study sit. Evapotranspiration was estimated by the Penman method (Penman, 1948) and crop coefficient value for rice (Sakuratani and Horie, 1985). We measured the irrigation and runoff water flow rates delivered to and drained from each paddy plot using a Parshall flume set at the inlet and a triangular weir set at the outlet.

Daily inputs and outputs of N in water were estimated by multiplying water N concentrations by flow volumes. Averaged data of the field measurements in the plots were used for the estimation. Inputs of N from fertilizer were estimated from the records of fertilizer application in the paddy plots. Outputs of N in the harvested rice were estimated by multiplying the content of N by the harvested yield. Rice N content was measured by Shiga Agricultural Technology Center. Rice straw was not considered as output component because rice straw was kept in the plots after harvesting rice.

3. Results and discussion

3.1. Water balance

Table 1 shows the water balances for the paddy plots during the irrigation periods in 2004–2006. The water level of the plot at the begging and the end of each period was zero. A complementary relationship was seen between irrigation water and rainfall because the irrigation pump was not operated on rainy days. The sum of rainfall and irrigation water during each irrigation period was fairly constant (about 1400–1600 mm each year). The sum of rainfall and irrigation water minus runoff water was used to estimate the potential water demand of the paddy field in the district. Using this calculation, about

1100–1200 mm was estimated as the potential water demand during the irrigation period (without the mid-summer drainage season). In addition, the reason that the difference in water management practices in 2004–2006 was not reflected in the water balances of each irrigation period is because irrigation water was supplied only from the pumps, and the irrigation schedule for each plot depended on the pump operation. In other words, supply-side water management practices seemed to have a greater influence on water balance in the paddy plots than did individual farmers' management practices. An irrigation system with a closed irrigation canal (receiving no inflow of water from outside the area) that enables the paddy-field district to conduct cyclic irrigation with a high CI ratio, combined with supply-side water management (e.g., stopping the pump during rainfall events), can provide efficient use of rainfall for crop irrigation, though such an irrigation system is less flexible for meeting the water use demands of individual farmers.

3.2. Mass balance of nutrients

Figure 1 shows the temporal variations of concentration in TN of irrigation water and ponded water during the 2006 irrigation period. Nitrogen concentrations in irrigation water were the highest during the puddling season and higher during the CI period than during the LWI period. Nitrogen concentrations in the ponded water were higher than in irrigation water during the puddling season and fertilizer application. The high N concentration in irrigation water during the puddling season is likely due to dissolution and leaching of nutrients from paddy soil. In contrast, nitrogen concentrations in the ponded water were similar to those in irrigation water during the irrigation period following the puddling season. The trends for each N component in irrigation water and ponded water were similar over the study years, except for lower concentration of TN during the puddling season in 2004, which may have been caused by dilution in successive rainfall events during that season.

Nitrogen balances for the paddy plots during the irrigation period are shown in Fig.2. The difference between total input and total output is attributed to adsorption to soil or dissolution from soil, with mass transfer between soil and atmosphere (N fixation, volatilization, and denitrification). Fertilizer application of N was reduced in 2004 because rotation crops had been cultivated and much fertilizer had been input in the previous year. Nitrogen input by fertilizer and output of harvesting were approximately balanced in 2005 and in 2006. Irrigated water of N accounted for 8–16% of the total input of N (Fig.2). In each of the three years of this study, the inflow of N from irrigation water was greater during the CI period than during the LWI period (Table 2). Outflow of N during the CI period was also larger than that during the LWI period. Net outflow of N from a paddy plot, which is estimated as outflow (= runoff water and percolation water) minus inflow (= rainfall and irrigation water), indicates whether the water management practices associated with that plot may increase or decrease the N load. A negative value of net outflow means that the paddy plots decreased N load during the calculation period. Net outflow of N was negative during all LWI periods. Our data indicate that LWI may remove N from the outside water area (e.g., Lake Biwa). A similar situation was observed for a paddy field adjacent to Kasumigaura Lake (the second largest lake in Japan), a region that is aiming to remove N from river water (Zhou and Hosomi, 2008). Cyclic irrigation using a high CI ratio probably does not remove N from the lake water because almost all the N in CI water was originally input as fertilizer. In this case, the major benefit of CI is considered to be the return of nitrogen to the paddy field, which leads to a reduction in fertilizer usage. The result that N fertilizer and harvesting were balanced suggests that fertilizer application can be reduced by the return with CI.

4. Conclusions

A complementary relationship was found between amount of irrigation water applied and amount of rainfall each year. It is concluded that a CI system that enables the paddy-field district to use a high CI ratio may lead to more efficient use of rainfall for crop irrigation. Irrigated water of nitrogen accounted for 8–16% of the total input of nitrogen. Nitrogen input from fertilizer and output from harvesting were approximately balanced. Therefore, it is suggested that fertilizer application of N can be reduced by its return through cyclic irrigation.

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Tables

Table 1. Mean water balances for the paddy plots during the irrigation period

Year	Period[a]	Inflow (mm)		Outflow (mm)		
		Rainfall	Irrigated water	Evapotranspiration	Runoff water	Percolation
2004	CI period (28 April - 20 June)	313	377	213	178	299
	Mid-summer drainage season[b]	73	0	37	8	28
	LWI period (1 July - 21 August)	139	624	252	65	446
	Total	525	1001	502	251	773
2005	CI period (25 April - 30 June)	210	563	210	71	492
	Mid-summer drainage season	115	0	7	14	94
	LWI period (6 July - 28 August)	139	379	179	46	293
	Total	464	942	396	131	879
2006	CI period (24 April - 25 June)	277	275	212	72	268
	Mid-summer drainage season	102	0	37	8	57
	LWI period (8 July - 31 August)	400	500	241	213	446
	Total	779	775	490	293	771

[a] CI, cyclic irrigation; LWI, lake water irrigation.

[b] From the end of CI period to the beginning of LWI period.

Table 2. Nitrogen loads in the paddy plots during the irrigation period

Year	Period[a]	Inflow (kg ha^{-1})		Outflow (kg ha^{-1})		
		Rainfall	Irrigated water	Runoff water	Percolation	Net[c]
2004	CI period (28 April - 20 June)	1.8	7.2	6.7	5.3	3.0
	Mid-summer drainage season[b]	0.7	0.0	0.1	0.0	-0.6
	LWI period (1 July - 21 August)	1.4	2.8	0.9	2.4	-0.9
	Total	3.9	10.0	7.7	7.7	1.5
2005	CI period (25 April - 30 June)	1.6	10.0	2.3	10.1	0.8
	Mid-summer drainage season	0.9	0.0	0.1	0.0	-0.8
	LWI period (6 July - 28 August)	1.0	3.4	0.8	2.2	-1.4
	Total	3.5	13.4	3.2	12.3	-1.4
2006	CI period (24 April - 25 June)	1.4	7.1	2.2	4.9	-1.4
	Mid-summer drainage season	0.8	0.0	0.3	0.0	-0.5
	LWI period (8 July - 31 August)	3.9	3.5	2.0	2.3	-3.1
	Total	6.1	10.6	4.5	7.2	-5.0

[a] CI, cyclic irrigation; LWI, lake water irrigation.

[b] From the end of CI period to the beginning of LWI period.

[c] (Runoff water + Percolation) －(Rainfall + Irrigated water).

Figures

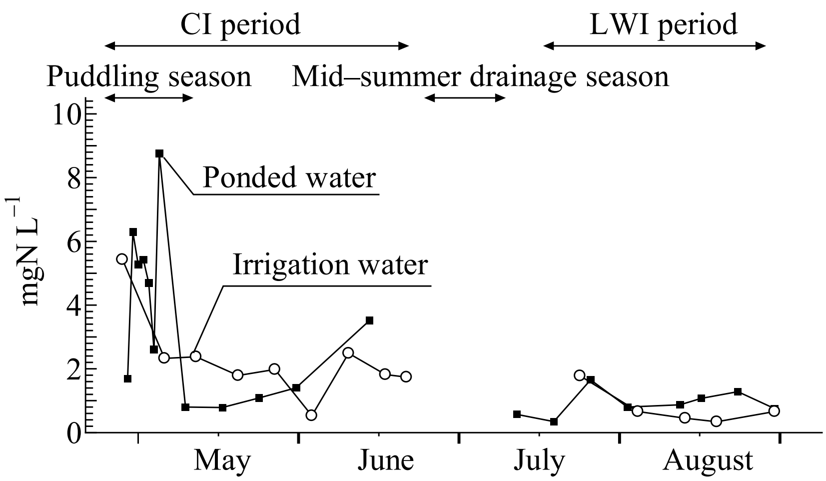

Fig. 1 Temporal variations of total nitrogen in irrigation water and ponded water during the irrigation period in 2006.

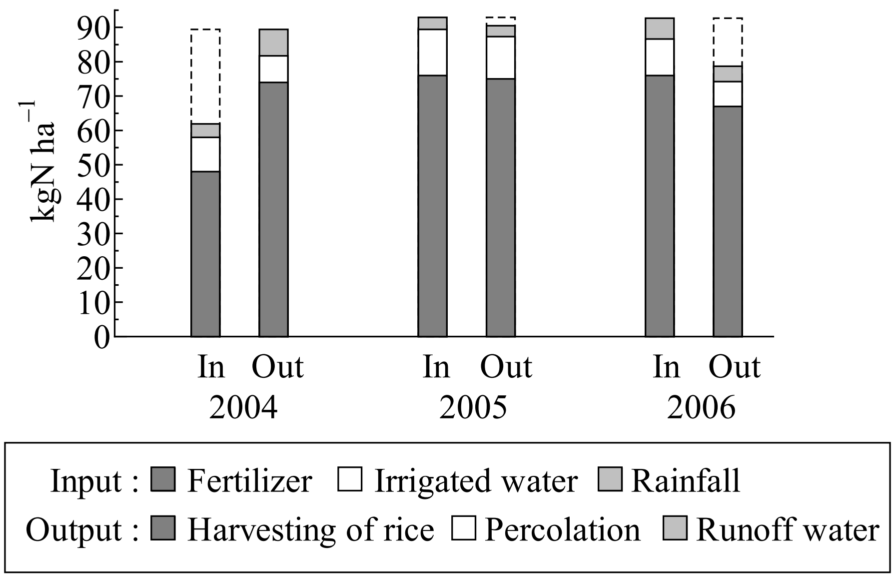

Fig. 2 Nitrogen mass balances for total nitrogen in the paddy plot during the irrigation period in 2004 - 2006.