Assessment of the Effect of Cyclic Irrigation on Reducing Nitrogen Effluent Loading from a Paddy-Field District

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ABSTRACT

Nitrogen (N) effluent loading discharged from paddy fields has a large impact on water quality in downstream areas. Cyclic irrigation, which reuses drainage water for irrigation purposes, is considered an effective water pollution prevention measure in paddy fields. In this study, we evaluated the effectiveness of cyclic irrigation in the reduction of N loading from a paddy-field district. We measured temporal variations in N concentration in drainage water and estimated the N mass balance for the study district for three consecutive years since 2007. We found that cyclic irrigation reduced N loadings. Mean N effluent loadings during the cyclic irrigation were 4.4 kg/ha and were smaller compared to lake water irrigation (non-cyclic irrigation). The hydrological structure and effect of a cyclic irrigation system can be characterized by using three parameters: ratio of the N concentration in drainage water to that in irrigation water; intensity at which drainage water is reused; and ratio of surplus irrigation water to the total amount of irrigation water. We conclude that the efficient use of irrigation water is important for reducing N effluent loadings from the paddy-field district because N in drainage water may not be qualitatively purified.

Keywords: nitrogen, paddy field, water reuse

INTRODUCTION

The removal of pollutants such as suspended solids, nutrients, and organic matter from non-point sources is an important issue in water quality management, especially in downstream watersheds. Paddy-field districts, which use large quantities of water, are major non-point sources for these types of pollutants. Cyclic irrigation, which reuses drainage water for irrigation, is considered an effective water management technique for reducing pollutants from these areas. Cyclic irrigation can reduce pollutant loadings in multiple ways. For example, with this technique, more water is retained within paddy fields, thus reducing the volume of run-off carrying potential pollutants. In addition, water that does leave the fields is partially purified because longer hydraulic retention time allows for the increased absorption of nutrients within fields, reducing the amount that is released as pollutants (Takeda *et al.*, 1997; Feng *et al.*, 2004, 2005; Takeda and Fukushima, 2004, 2006). The effectiveness of cyclic irrigation is directly proportional to the amount of water that is reused (Kaneki, 2003) and to the intensity of cyclic irrigation (Shiratani *et al.*, 2004; Hitomi *et al.*, 2006). However, because high intensity cyclic irrigation requires the use of large quantities of freshwater to reduce the risks

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associated with pathogens and heavy metals (Zulu *et al.*, 1996), there is a low upper limit to the intensity used in many paddy-field districts that attempt to capture industrial or domestic wastewater from upstream areas. Accordingly, little is known about the effectiveness of using high intensity cyclic irrigation to reduce nutrient effluent loadings from paddy-field districts.

Our objectives in this study were to understand the characteristics of nitrogen (N) effluent loading in a low-lying paddy-field district currently implementing cyclic irrigation with high intensity and to evaluate the effectiveness of that technique in reducing the loadings. We focused our analysis, over three years (2007 – 2009), on a low-lying paddy-field district neighboring Lake Biwa, the largest lake in Japan.

MATERIALS AND METHODS

Study Site

We focused our analysis on a low-lying paddy-field district located on the southeastern edge of Lake Biwa (35° 05' N, 135° 56' E, Fig. 1). The district covers an area of about 1.5 km², with more than 90% of that area comprised of paddy fields. Rotation crops, specifically wheat and soybean, are grown in about one-third of the paddy area on a three-year cycle.

Within the district, a complex drainage and irrigation system in which canals are separate for each process were employed. Furthermore, industrial or domestic wastewater from outside the district does not flow into the drainage and irrigation canals. The drainage portion of the system contains one main and 14 lateral canals, and drainage water is discharged through floodgates at both ends of the main canal. During our study period, the floodgate at the northern end of the main drainage canal was closed, forcing the outflow of all drainage water through the southern floodgate. Two pump stations are located at the northern and southern ends of the main drainage canal with maximum capacities of approximately 2.5×10^3 and 0.2×10^3 m³/h, respectively. The northern pump station has two water inlets that connect to Lake Biwa and to the main drainage canal, whereas the southern pump station has a single water inlet that only connects to the main drainage canal. Because there are no water sources other than Lake Biwa, the maximum amount of available water for irrigation depends solely on the capacity of these pumps.

In this region, two irrigation techniques are used at specific times of the year during a four-month irrigation period (Table 1). Cyclic irrigation is employed for the first half of the season and uses recycled drainage water to flood the paddy fields. When the drainage water level falls by evapotranspiration, water flows from the lake to the drainage canal through the floodgate. Lake water irrigation is then used for the second half of the irrigation period, when cool water is needed for maximum rice quality, in which irrigation water is pumped directly from Lake Biwa through the northern pump. A 10-day mid-summer drainage season separates the use of these irrigation techniques.

Water Quality and Hydrological Measurements

We measured the quality of drainage, irrigation, and lake water at weekly intervals from 2007 to 2009. Samples of drainage and irrigation water were obtained from the southern

Fig. 1 - Layout of paddy fields, pump stations, and irrigation and drainage canals in the study district (35° 05' N, 135° 56' E).

Table 1 - Irrigation schedule in the study district.

Irrigation schedule	2007	2008	2009
Start of irrigation	April 25	April 26	April 24
Cyclic irrigation period	April 25 – June 23	April 26 – June 24	April 24 – June 25
Mid-summer drainage season	June 24 – July 5	June 25 – July 6	June 26 – July 9
Lake water irrigation period	July 6 – August 28	July 7 – August 26	July 10 – September 2
End of irrigation	August 28	August 26	September 2

end of the main drainage canal and the outlet of the pump, respectively, and samples of inner lake water were obtained. In addition, a programmable automatic water sampler (3700 Sampler, Teledyne Isco Inc., Lincoln, NE, USA) was installed at the southern end of the main drainage canal to sample drainage water daily at noon. Rainwater collected in a small plastic tank at the northern pump station was sampled during weekly field visits. All sampled water was analyzed for total nitrogen (TN) using an ultraviolet spectrophotometer (UV-1200, Shimadzu Corp., Kyoto, Japan) after alkaline potassium-peroxydisulfate digestion.

We installed meteorological instruments for measuring rainfall, air temperature, wind velocity, relative humidity, and solar radiation in an open area at the southern pump

station. We estimated evapotranspiration during the irrigation period by the Penman method (Penman, 1948) using the data measured at the southern pump station and the crop coefficient value for rice (Sakuratani and Horie, 1985). We measured the flow rates of discharged drainage water (lake water irrigation period) and of inflowing lake water (cyclic irrigation period) using flow meters (2150 Area Velocity Flow Module, Teledyne Isco Inc.) installed at both ends of the main drainage canal. We estimated the volume of pumped water by multiplying the amount of time the pumps were in operation by their capacities. We did not measure the subsurface percolation from the district but assumed it to be negligible because it is a low-lying district and is close to the lake with high groundwater levels. We calculated the water balance over a fixed portion of each part of the irrigation period in order to compare values across years; water balance for the cyclic irrigation period was measured from 20 April to 30 June and from 1 July to 30 September for the lake water irrigation period.

Simple Model for Assessment of Cyclic Irrigation

In this study, we determined the net N export as a way of assessing the effect of irrigation techniques on the reduction in effluent loading in the district, where the net N export is defined as N export subtracting N input. Because N loading is dependent on both N concentration and water flow volume, we define the net N export, L_{net} (kg/ha/d), as:

$$L_{\text{net}} = C_{\text{out}} Q_{\text{out}} - C_{\text{in}} Q_{\text{in}} \quad (1)$$

where C is the N concentration (mg/L) and Q is the water flow volume (mm/d). The subscripts *out* and *in* refer to the outflow from and inflow into the district, respectively. In this case, C_{out} is the N concentration of the drainage water; Q_{out} is the amount of drainage water discharged from the district; C_{in} is the N concentration of the lake water; and Q_{in} is the amount of lake water intake. A value of L_{net} greater than zero indicates that the district is adding to N effluent loading downstream (contamination) while a value less than zero indicates that the district is reducing it (purification). Considering the neutral condition, where $L_{\text{net}} = 0$, this relationship can be shown as follows:

$$C_{\text{out}} / C_{\text{in}} = Q_{\text{in}} / Q_{\text{out}} \quad (2)$$

where we define $C_{\text{out}} / C_{\text{in}}$ as the concentration ratio, χ_c .

We were able to determine the values of each variable needed to calculate net N export through a conceptual understanding of the relationships between water flows in this system (Fig. 2). Because this system uses a closed irrigation canal, we derived the volume of irrigation water (Q_p) directly from the volume of water that is passed through the pump. The inflow of water from the lake (Q_{in}) can then be calculated by multiplying the volume of irrigation water by the proportion of water that is not reused through cyclic irrigation:

$$Q_{\text{in}} = (1 - \alpha_{\text{CI}}) Q_p \quad (3)$$

where α_{CI} is the cyclic irrigation ratio, defined as the ratio of the amount of reused water to the total amount of irrigation water (Hama *et al.*, 2010). However, equation 3 is not

necessarily true for the district. If the inlet to the lake at the northern pump is closed, lake water does not directly flow into the pump but into the main drainage canal under cyclic irrigation; in other words, equation 3 may be true when the lakeside inlet is opened. The amount of drainage water that is discharged from the district (Q_{out}) can be calculated as a function of both the ratio of water that is considered surplus irrigation water not used in the paddy fields (α_{SW}) and the ratio of water that is reused in the process of cyclic irrigation:

$$Q_{out} = (\alpha_{SW} - \alpha_{CI}) Q_p \quad (4)$$

This model does not consider temporary deficits in the inflow of water, which can lead to a decrease in the amount of drainage water stored in the drainage canal. As noted previously, when the amount of drainage water in the canal falls (alternatively when $\alpha_{SW} < \alpha_{CI}$ in equation 4), water must be brought in from the lake. In this case, when the lakeside inlet at the northern pump is closed as was the case during cyclic irrigation periods in 2008 and 2009, the net N export can be described as a negative net export:

$$L_{net} = -(1 - \alpha_{SW}) C_{in} Q_{in} < 0 \text{ for any } \alpha_{CI} \quad (5)$$

and cyclic irrigation may always show a net purification effect.

Knowing the relationships between water flows in our model (Fig. 2) as described above, we can replace the variables on the right side of equation 2 with the relationships established in equations 3 and 4:

$$\beta = (1 - \alpha_{CI}) / (\alpha_{SW} - \alpha_{CI}) \quad (6)$$

where β varies as a function of both α_{CI} and α_{SW} . Using this information, we can show the effect of irrigation on L_{net} for a given α_{SW} value (Fig. 3). The irrigation system has a net contamination effect when χ_c is above the β curve and a net purification effect when χ_c is below that curve. In addition, when χ_c is less than one, irrigation for any α_{CI} may show a net purification effect of irrigation because β is greater than or equal to 1 for any combination of α_{CI} and α_{SW} . This simple model allows us to establish the effect of cyclic irrigation on N effluent loadings considering various irrigation intensities, assuming the conditions of our particular irrigation system.

Fig. 2 - Conceptual diagram of water flow under cyclic irrigation in the paddy-field district. Upper-case "P" represents a pump and arrows indicate flow direction.

Fig. 3 - Neutral effect curve for net effluent loadings at a given surplus irrigation ratio. The colored area represents the conditions under which irrigation has a purification effect on net nitrogen effluent loadings downstream for any α_{CI} or χ_c .

RESULTS AND DISCUSSION

Water Balance

We found that the amount of discharged water was smaller during cyclic irrigation periods compared to lake water irrigation periods (Table 2). Higher volumes of discharged water during lake water irrigation periods may partly be the result of the discharge of surplus irrigation water on fine days. We confirmed that the reuse of drainage water can reduce the inflow of water by lake water intake, because the amount of lake water intake was smaller during the cyclic irrigation period than during the lake water irrigation period.

We can estimate the amount of drainage water that was reused through cyclic irrigation from the difference between the volume of irrigation water and the volume of lake water intake. We found that the volume of reused drainage water was 792 mm, 864 mm, and 878 mm with mean cyclic irrigation ratios of 0.82, 0.90, and 0.84 in 2007, 2008, and 2009, respectively, during cyclic irrigation periods (Table 2). Because the lakeside inlet at the northern pump was closed in 2008 and 2009, ratios for these years represent estimates for a situation in which irrigation water had been taken from both water resources (the lake and the drainage canal) under cyclic irrigation. Lake water intake approximately equaled the volume of irrigation water during the lake water irrigation period, although the volume of reused drainage water by the operation of the southern pump was 50 mm, 47 mm, and 22 mm in 2007, 2008, and 2009, respectively (Table 2).

Table 2 - Water balance for the study district during irrigation periods.

Year	Period ^a	Inflow ^b		Outflow ^c		Irrigation water (Pumped water)
		R [mm]	LI [mm]	ET [mm]	D [mm]	
2007	Cyclic irrigation	405	173	277	277	965
	Lake water irrigation	565	677	376	919	727
2008	Cyclic irrigation	481	100	277	285	964
	Lake water irrigation	347	648	442	610	644
2009	Cyclic irrigation	280	168	287	124	1046
	Lake water irrigation	331	605	365	583	618

^a Cyclic irrigation = April 20 – June 30; Lake water irrigation = July 1 – September 30.

^b R, rainfall; LI, lake water intake. ^c ET, evapotranspiration; D, discharged water.

Nitrogen Effluent Loadings

Our results show that, during the cyclic irrigation period, N effluent loadings increased mainly in association with rainfall events. During the lake water irrigation period, drainage water was discharged even on fine days (Fig. 4).

Nitrogen inputs and exports by rainfall, lake water intake, and discharged drainage water during the irrigation periods are listed in Table 3. We found that the N export during the cyclic irrigation period was smaller than during the lake water irrigation period, although weather conditions especially rainfall events during each irrigation period had a large influence on the amount of N exported. Mean N exports during the cyclic and lake water irrigation periods were 4.4 kg/ha and 11.2 kg/ha, respectively.

Effect of Cyclic Irrigation

Nitrogen concentration ratios ranged from 1.6 to 5.5 under lake water irrigation ($\alpha_{CI} = 0 - 0.16$) and from 0.8 to 13.6 under cyclic irrigation ($\alpha_{CI} = 0.62 - 1.0$; Fig. 5), with χ_c typically higher under cyclic irrigation compared to lake water irrigation. Because χ_c is larger than one regardless of α_{CI} in almost all of our measurements, our results suggest that N concentration in water flowing through the district is not purified qualitatively and increases under both irrigation techniques. We believe this occurs because N is released from the sediment in the drainage canal. In the district, dredging of the sediments in the main drainage canal, other than in the southern area (about 100 m long), has not been conducted since 2004 when the canal was constructed. Therefore, we infer that the capacity of the drainage canal for storing new sediment has been reduced.

However, our results also suggest that the use of cyclic irrigation with high α_{CI} has a net purification effect for any χ_c , whereas the use of lake water irrigation has a net contamination effect when the surplus irrigation water ratio (α_{SW}) is large (e.g., $\alpha_{SW} \geq 0.7$). The surplus amount or ratio of irrigation water could not be estimated because there were no hydrologic measurements for the paddy fields during this study. However, a previous study (Hama *et al.*, 2010) suggested that the ratio of surplus irrigation water to total irrigation water was about 70% on the average during the irrigation period, varying from 30% to 90% daily. Therefore, lake water irrigation in the district may lead to net N contamination, even when α_{SW} is low during the irrigation period. In contrast, cyclic irrigation has a net purification effect on N for possible α_{SW} .

Fig. 4 - Daily variations in nitrogen effluent loadings during cyclic irrigation (CI) and lake water irrigation (LWI) periods in (a) 2007, (b) 2008 and (c) 2009.

Table 3 - Nitrogen inputs through rainfall (R) and lake water intake (LI) and exports through discharged water (D) during irrigation periods.

Year	Period ^a	Inputs		Exports	
		R [kg/ha]	LI [kg/ha]	D [kg/ha]	net N export [kg/ha]
2007	Cyclic irrigation	3.2	2.8	5.9	-0.1
	Lake water irrigation	4.5	4.6	16.1	7.0
2008	Cyclic irrigation	2.8	1.2	4.6	0.6
	Lake water irrigation	2.0	2.1	8.8	4.7
2009	Cyclic irrigation	1.9	1.4	2.6	-0.7
	Lake water irrigation	2.2	3.3	8.7	3.2

^aCyclic irrigation = April 20 – June 30; Lake water irrigation = July 1 – September 30.

Fig. 5 - Relationship between the cyclic irrigation ratio and the concentration ratio considering various β curves. Subscripts of β represent the surplus irrigation ratio.

CONCLUSIONS

We determined that the use of cyclic irrigation techniques, in which drainage water is reused, can effectively reduce N effluent loadings from paddy-field districts. The hydrological structure and the effect of cyclic irrigation systems can be characterized using three parameters: N concentration ratio (χ_c), cyclic irrigation ratio (α_{CI}), and surplus irrigation water ratio (α_{SW}). Furthermore, levels of α_{CI} and α_{SW} can act as strong indicators of the efficiency of water use in a paddy-field district. Our simple model may be applicable for assessing the effect of irrigation techniques on nutrient or suspended solid effluent loadings in other paddy-field districts.

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