NUTRIENT BALANCE IN A PADDY FIELD WITH A RECYCLING IRRIGATION SYSTEM

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ABSTRACT

We studied nutrient balance in a paddy field that had a recycling irrigation system and evaluated the effect of the irrigation system on nutrient balance during the irrigation period, from April to August 2002. Chemical fertilizer was the main input of phosphorus; the soil absorbed about 56% of it. The amount of nitrogen supplied by the irrigation system was higher than in a representative paddy field, and the amount of nitrogen fertilizer used was decreased because of the reuse of irrigation water was partly reused. About 20% of applied nitrogen was lost by denitrification. The net outflows of phosphorus and nitrogen were –0.37 and –3.98 kg ha^{-1}, respectively. These results indicate that our study paddy field performed well in removing phosphorus and nitrogen compounds from runoff water. A recycling irrigation system can be considered an effective way of reducing the amounts of water and fertilizer used and reducing the outflow nutrients.

KEY WORDS: Nutrient balance; net outflow; paddy field; irrigation system

INTRODUCTION

There is considerable worldwide concern about the eutrophication of waters. One of the most important factors contributing to this problem is the large amount of nutrients from non-point sources, especially agricultural catchments. In agricultural catchments, excessive chemical fertilizer application increases the concentration of nitrate nitrogen in groundwater, which in turn results in the eutrophication of public water areas.

In Japan, paddy fields cover 55% of all land used for agriculture; they require abundant amounts of water, accounting for 95% of the total agricultural water use (Tabuchi and Hasegawa, 1995), and demand of a lot of chemical fertilizer for rice production. Therefore, they play a significant role in catchment environments. Depending on the amounts of water and fertilizer used and how they are applied, some paddy fields remove nutrients (Takeda et al, 1997). The recycling of irrigation water may reduce both irrigation water and nutrient use in agricultural catchment (Kudo et al., 1995). Because water that drains from paddy fields is reapplied to the same fields, it is important to measure the movement of nutrients in paddy field areas.

The objects of our study were to elucidate nutrient balance in a paddy field catchment in which a recycling irrigation system was implemented, and to evaluate the effects on water quality in the catchment.

METHODS

Study site

The investigation was carried out during an irrigation season from April to August 2002 in the Yoshinuma region, about halfway down the Kokai River in Ibaraki Prefecture (Fig. 1). The study paddy field site has an area of 7.3 ha, and is equipped with a system to recycle irrigation water. Figure 2 shows the irrigation and drainage systems, the flow of river water to paddy fields (43.2 ha) upstream on the Kokai River, the drainage of water from there to our study paddy field where it is reused, the reuse of water drained from the study paddy field, and the release of some drainage water to the Kokai River through a drainage canal.

From farmers' records, we found that the mean amounts of fertilizer applied to paddy fields in this region are 32 kg ha^{-1} N in late April and 30 kg ha^{-1} N in mid July, and 25 and 3 kg ha^{-1} at same time.

Hydrological measurement

The flow rates at points S1, S2 and S3 were determined from continuous records of water levels recorded with self-registers, and the flow rate was measured when the water was sampled. The flow rate of pump 1 was measured with a portable radio liquid flow meter (transport model PT 868, Panametrics, Japan). Precipitation was estimated from the rainfall recorded at Tsukuba Mountain (far from 3 km) by an Automated Meteorological Data Acquisition System (AMeDAS). Evapotranspiration was estimated by the Makkink method (Nagai, 1993). We assumed soil percolation to be negligible compared with runoff, because this region is a flat, low-lying basin, the surface of the study site is lower than the river's level, and most percolated water reached the nearest drainage canals.

Fig 1. Location of the paddy field study area

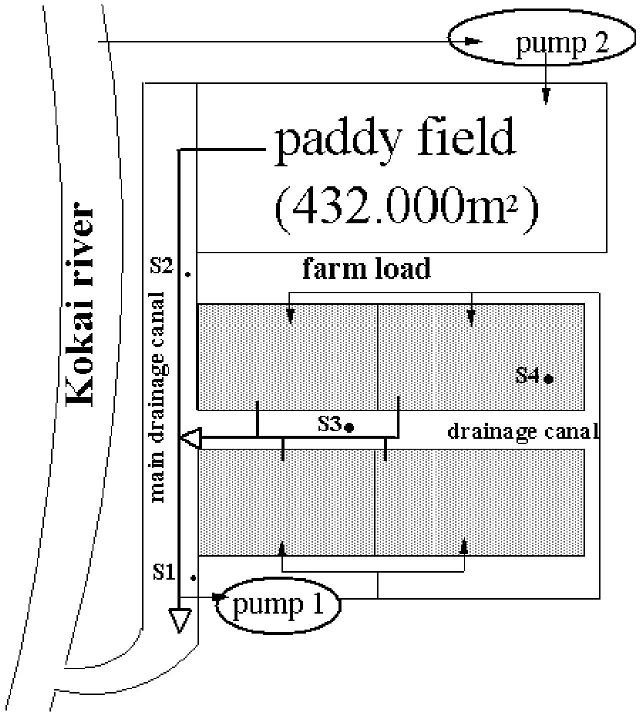

*Fig 2. Schematic representation of irrigation and drainage systems in paddy field areaArrows with solid heads: irrigation water Arrows with outlined heads: outflow water Grey shading: study area;S1: irrigation water sampling point; S2, S3: outflow sampling point; S4: flooding water sampling point; * The large upstream paddy field is not drawn to scale*

SAMPLING AND SAMPLE ANALYSES

Irrigation water (at point S1) and runoff water (at point S3) were sampled once a week from April to August 2002. In addition, during the puddling period, from 25 April to 5 May, samples of irrigation and outflow water were collected at approximately 4-h intervals with an automatic sampler (ISCO 6700, ISCO, USA). The concentration of total nitrogen (TN) was measured with a TN analyser (TN-301P, Yanaco, Japan). The concentrations of NH_4-N, NO_3-N and NO_2-N were measured by ion chromatography (IC 20, Dionex, USA), and the concentrations of total phosphorus (TP) were measured by standard methods, as described in the JIS (Japanese Industrial Standard) (Namiki, 1986). Samples of soil and rice plants were collected on 15 August. The rice yield was 5160 kg ha^{-1} – higher than the average yield in Ibaraki Prefecture (4800 kg ha^{-1}). The concentrations of total nitrogen and total phosphorus in the rice and soil were measured as above.

RESULTS AND DISCUSSION

Water balance

The water balance equation in a paddy field has the following form (Shiratani et al., 2002):

$$W_t = W_{t-1} + I_t + P_t - E_{t}, \qquad (1)$$

where W is the depth of ponding (in mm), I is the amount of irrigation water (mm), P is the amount of precipitation (mm), E is the amount of evapotranspiration (mm), and t is time (days).

The total amount of irrigation water was 1781 mm, which amounted to 77% of the total inflow (Fig. 3). The total amount of outflow was 2227 mm, of which 75% was runoff from the paddy field via canals. The paddy field showed a net water loss of 76 mm, which amounted to 3% of the total outflow, presumably because of rice evapotranspiration and interception losses from the rice seedlings (Feng et al, 2003).

The average flow rate of irrigation water in this field was 14 mm day^{-1}, which is about 30% lower than the standard rate of irrigation in Japan. Therefore, this paddy field was concluded as a saving water paddy field.

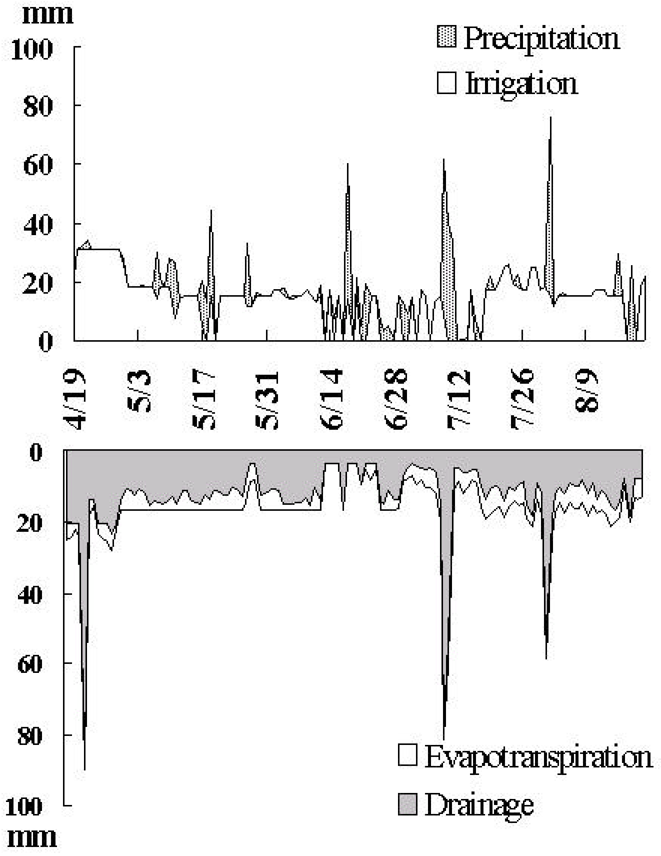

Figure 3. Water balance in the paddy field

Nutrient balance

Phosphorus.

The amounts of phosphorus added were 28 kg ha^{-1} (90%) in chemical fertilizer, 0.47 kg ha^{-1} (1%) in precipitation and 2.66 kg ha^{-1} (9%) in irrigation water (Table 1). The output loads were 2.74 kg ha^{-1} (14%) in drainage water and 18.3 kg ha^{-1} in rice grains (86%). The output was much smaller than the input. About 56% of phosphorus fertilizer was absorbed by paddy field soil.

Table 1 Phosphorus loads in the study paddy-field area

unit: kg ha^{-1}

	Inflow		Outflow	Net outflow*		
Period	Precipitation	Irrigation	Runoff		Fertilizer	Rice uptake
April	0.00	0.86	0.99	0.13	25.0	
May	0.04	0.49	0.46	-0.07		
June	0.18	0.35	0.42	-0.11		
July	0.06	0.68	0.58	-0.16	3.0	
August	0.19	0.28	0.31	-0.16		18.3
Total	0.47	2.66	2.76	-0.37	28.0	18.3

*: Net outflow: Outflow-Inflow

The net outflow load of nutrients (the outflow load minus the inflow load) is one of the most important factors in evaluating the role of paddy fields in water conservation (Tabuchi and Takamara, 1985). A negative value for the net outflow load means that the catchment is a nitrient sink, and a positive value means it is a nutrient source. The net outflow load of phosphorus in this study paddy field was –0.37 kg ha^{-1}. Therefore, we conclude that this study paddy field removes phosphorus during the irrigation period.

Nitrogen.

The nitrogen balance in the paddy field can be divided into input, internal and output systems. Chemical fertilizer, nitrogen fixation, precipitation and irrigation water are inputs. The nitrogen mineralization in the soil is an internal factor. Removal of rice grains, runoff and nitrogen loss by denitrification are outputs.

The nitrogen balance in a paddy field has the following form (Takeda et al, 1991).

$$\ddot{A}S = F \text{ x } Cr \text{ x } LR \text{ x } LI \text{ x } LD \text{ x } FN \text{ x } DN \qquad (2)$$

Where $\ddot{A}S$ is the amount of nitrogen mineralization in soil, F is the amount of fertilizer, Cr is the amount of rice uptake, LR is the amount of rain load, LI is the amount of irrigation load, LD is the outflow load in drainage, FN is the amount of nitrogen fixation, DN is the amount of denitrification and all units are kg ha^{-1}.

The amounts of nitrogen added were 62 kg ha^{-1} in chemical fertilizer; 3.68 kg ha^{-1} T-N, 1.99 kg ha^{-1} NH_4-N, 1.68 kg ha^{-1} NO_x-N in precipitation; and 45.7 kg ha^{-1} T-N, 7.21 kg ha^{-1} NH_4-N and 28.6 kg ha^{-1} NO_x-N in irrigation water. Over a whole irrigation period, the amounts of nitrogen fixation and denitrification were comparable (Takeda et al 1991). Therefore, we calculated the amount of nitrogen fixation as 12.6 kg ha^{-1}, the amount of denitrification (Eq. 3, below).

The outflow loads were 41.7 kg ha^{-1} T-N, 8.48 kg ha^{-1} NH_4-N and 19.7 kg ha^{-1} NO_x-N. The outflow loads of nitrogen were much greater in April and July than in the other months, in accordance with the schedule for applying fertilizer to paddy fields. The amount of rice uptake during the cultivation period was 94.1 kg ha^{-1} (Fig 4).

Nitrogen loss by denitrification was calculated according to the equation of Tabuchi et al (1993):

$$D = (0.000011T^2 + 0.005)\times N \qquad (3)$$

where D is the amount of denitrification (kg ha^{-1}), T is water temperature (10 °C < T < 40 °C) and N is nitrogen concentration in paddy water (mg l^{-1}). The nitrogen loss from the paddy field by denitrification was 12.6 kg ha^{-1}, or about 20% of applied chemical fertilizer. Datta (1987) reported that 28%–33% of applied urea was lost. Datta and Buresh (1989) stated that 12% of nitrogen was lost by denitrification in flooded paddy soil. The nitrogen loss by denitrification was large during the irrigation period. The differences in the nitrogen losses between the studies were derived from the differences in fertilizers, methods of fertilizer application, duration of fertilizer application, soil pH and meteorological conditions in each study.

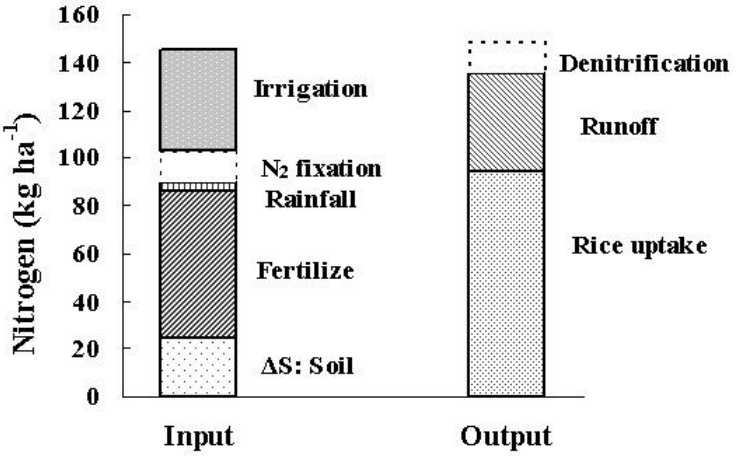

Figure 4. Nitrogen balance in the paddy field

The amount of nitrogen mineralization in the soil was 24.4 kg ha^{-1}. The net total outflow load for T-N was –3.98 kg ha^{-1}. The input load of nitrogen was 124 kg ha^{-1} (50% by fertilizer, 36% by irrigation water, 3% by precipitation). The output load was 148 kg ha^{-1} (64% by rice uptake, 27% by drainage water, 9% by denitrification). The nitrogen balance in this study paddy field and in a representative paddy field (Yuyama and Hata, 2000) are presented in Table 2. Irrigation water supplied much more nitrogen in our field than in the representative field. In our study area, a recycling irrigation system had been implemented, and the runoff water from the paddy field was reused for irrigation. Therefore, the nitrogen concentration in the irrigation water was higher, reached 4.91 mg l^{-1}, and the average concentration was 2.31 mg l^{-1}. Kunimatsu (1983) reported the possible purification functions of paddy fields in which the concentration of nitrogen in the irrigation water was higher than 2 mg l^{-1}. Therefore, we conclude that our study paddy field seems to have functioned well in removing nutrients, and required less fertilizer because of the amount supplied in the irrigation water.

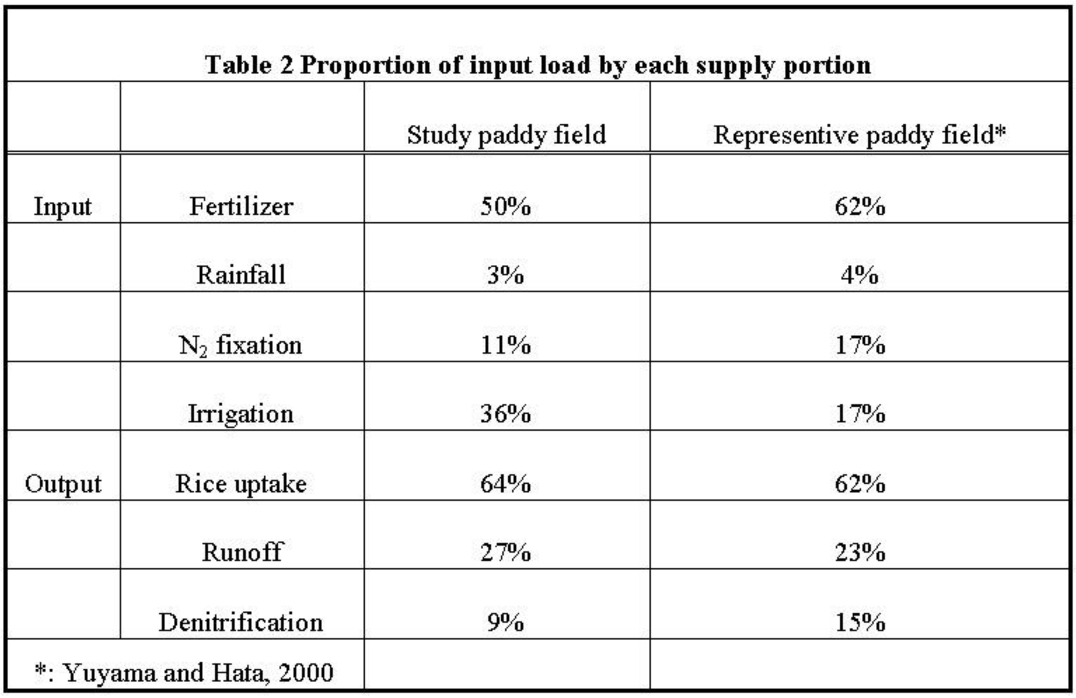

Table 2 Proportion of input load by each supply portion

		Study paddy field	Representive paddy field*
Input	Fertilizer	50%	62%
	Rainfall	3%	4%
	N_2 fixation	11%	17%
	Irrigation	36%	17%
Output	Rice uptake	64%	62%
	Runoff	27%	23%
	Denitrification	9%	15%
*: Yuyama and Hata, 2000			

Retention time in the field is one of the most important factors in pollutant removal by artificial wetlands and paddy fields. Gersberg et al. (1986) and Takeda et al. (1997) indicated that retention times for relatively good performances are 5~7 days, since sufficient retention time in the watershed allows the main purification mechanisms (nitrification-denitrification and phosphorus adsorption by the soil) to proceed sufficiently. The retention time was calculated according to the equation of Takeda et al. (1997).

$$RT = V / (P_t + I_t) \tag{4}$$

Where RT is the retention time (in days), V is the volume of water retained in the watershed (mm), P_t is precipitation (mm), and I_t is the amount of irrigation water (mm).

In our study, except in May, which was the period of transplanting rice seedling and required large amounts of irrigation water, the retention time ranged from 5 to 7 days and was comparable to the result of Takada et al. (1997). Therefore, our study paddy field should have sufficient retention time for pollutant removal. From these results, our study paddy field, which used a recycling irrigation system, seemed to function well in removing nutrient pollutants, considering the relatively high concentrations of nutrients in the irrigation water, and the sufficient retention time.

The recycling irrigation system was originally designed to save water, but it can also reduce nutrient loads in agricultural catchment and the amount of fertilizer used. From the viewpoint of preserving water quality in a catchment, the use of a recycling irrigation system is an effective way of reducing levels of non-point-source nutrients.

CONCLUSIONS

In a paddy field area using a recycling system, we assessed the water quality, the supply of nutrients by fertilizer and the amount of nutrients taken up by rice. We also estimated the input and output loads of nutrients and clarified the characteristics of nutrient balance during the observation period. We draw the following conclusions.

About 56% of phosphorus fertilizer was absorbed by paddy field soil, and the net outflow load of phosphorus was -0.37 kg ha^{-1}. The negative shows the paddy field's capacity to remove phosphorus.

The irrigation water supplied more nitrogen to the crop than in a representative paddy field. This decreased the amount of fertilizer used

The loss of nitrogen by denitrification was large during the irrigation period, accounting for about 20% of the applied chemical fertilizer.

The net outflow load of nitrogen was -3.98 kg ha^{-1}. This result indicates this paddy field's capacity to remove nitrogen compounds.

Recycling of irrigation water not only saves irrigation water but can also be considered an effective way of reducing the amount of fertilizer used and the levels of non-point-source nutrients in paddy field areas.

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