Economic valuation of reduction in nitrogen outflow from a paddy field area equipped with a recycling irrigation facility

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Abstract We estimated the reduction in nitrogen outflow load from a paddy field that had a recycling irrigation facility and, by using a replacement cost method, evaluated the economic effect of nitrogen removal by the paddy field during the irrigation period in the Yoshinuma region of Tsukuba City, Japan. The recycling ratio of outflow water (proportion of outflow reused) was 13.5%. The nitrogen (N) outflow load was reduced by about 45 $kg\,ha^{-1}$ by the N removal function of the paddy field and by about 39 $kg\,ha^{-1}$ by the recycling irrigation facility. The paddy field equipped with a recycling irrigation facility as an N removal facility was valued at 32.6 million Japanese yen (JPY) ha^{-1} and 0.72 million JPY ha^{-1} per year, which compare it with the construction and maintenance costs, respectively, of a water quality improvement facility. The recycling irrigation facility was costed at 17.3 million JPY ha^{-1} for construction and 0.21 million JPY ha^{-1} for maintenance per year. The cost for constructing and maintaining a recycling irrigation facility was 53% of the value of the paddy field area equipped with a recycling irrigation facility as an N removal facility.

Keywords Effective; nitrogen; outflow load; replacement cost method

Introduction

In Japan, paddy fields cover 55% of all land used for agriculture. They require fertilizers with an N at 70 $kg\,ha^{-1}\,y^{-1}$ and abundant amounts of water, accounting for 95% of the total agricultural water demand (Tabuchi and Hasegawa, 1995). Most paddy fields use streams and lakes as their main water sources and discharge the outflow back into them. Therefore, outflow water containing nitrogen from fertilizer application is a causative factor in the deterioration of water quality of streams and lakes. To reduce the nitrogen outflow from paddy fields, many approaches are called for, including improvement of soil properties and of methods of fertilizer application, and the introduction of a recycling irrigation facility. A recycling irrigation facility is often constructed in some paddy fields along the lower parts of rivers; river water is reused within the paddy to make better use of limited amounts of water. The introduction of a recycling irrigation facility has received much attention, because it may not only save irrigation water, but also reduce nutrient outflow loads from agricultural areas (Misawa, 1987; Kudo *et al.*, 1995). Some investigations have shown that a paddy field area equipped with a recycling irrigation facility reduces the nutrient outflow loads (Takeda *et al.*, 1997; Feng *et al.*, 2004; Shiratani *et al.*, 2004a), but the economic effect has not been evaluated.

The objectives of our study were to elucidate the reduction in nitrogen outflow load in a paddy field equipped with a recycling irrigation facility and to evaluate the economic effect by using the replacement cost method.

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Methods

Study site

This investigation was carried out during the irrigation period from April to September 2002 in the Yoshinuma region (36°8′N, 140°0′E), which is located about halfway down the Kokai River, Tsukuba City, Ibaraki Prefecture (Figure 1). The paddy field area we studied belongs to a larger area of paddies and is equipped with a system to recycle the irrigation water. Figure 2 shows the irrigation and drainage systems and water sampling points. Water from the Kokai River is pumped into the upper paddy field (43.2 ha) via pump station 2. The outflow water from that field drains into the main drainage canal. Water from this canal is pumped into the study paddy (7.3 ha) via pump station 1. The outflowing water from the study paddy field also discharges into the main drainage canal, which drains into the Kokai River. The soil is a Gray Lowland soil, which has good permeability.

From farmers' records, we found that the usual amounts of fertilizer applied to paddy fields in this region are 32 and 30 kg N in late April and mid July, respectively.

For this study, we used hydrological data and concentrations of N in irrigation water, outflow water, and precipitation from Feng *et al.* (2004) to calculate the amounts of reduction in nitrogen outflow load.

Economic valuation method

The replacement cost method (RCM) is often used to evaluate the multifunctional roles of paddy fields. In RCM, goods and services traded on the market are substituted for the functions to be valued. The functions are then evaluated according to the market prices of these goods and services. This method has two advantages. First, it is possible to evaluate each function separately, and second, the valuation is easy to understand, since goods and services are used instead of functions. Several studies using RCM have evaluated the nutrient reduction by tidal flats or wetlands on the basis of the costs of construction and maintenance of sewage treatment plants (Barbier *et al.*, 1997; Sasaki, 1998). However, it is difficult to apply this method to paddy field areas because sewage treatment plants treat water containing a high concentration of nitrogen (N: 15–40 mg L^{-1}), while paddy field areas equipped with a recycling irrigation facility use water containing a low concentration of nitrogen (N: < 3 mg L^{-1}). In this study, we evaluated the economic effect of reduction in nitrogen outflow load from a paddy field equipped with a recycling irrigation facility on the basis of the costs of construction and maintenance of

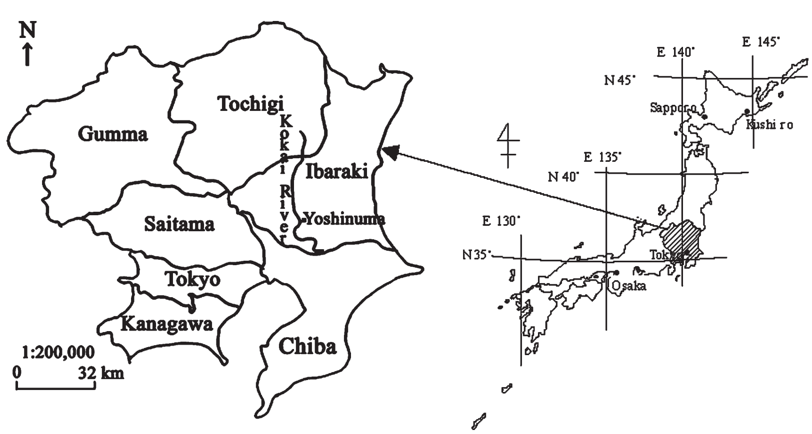

Figure 1 Location of the paddy field

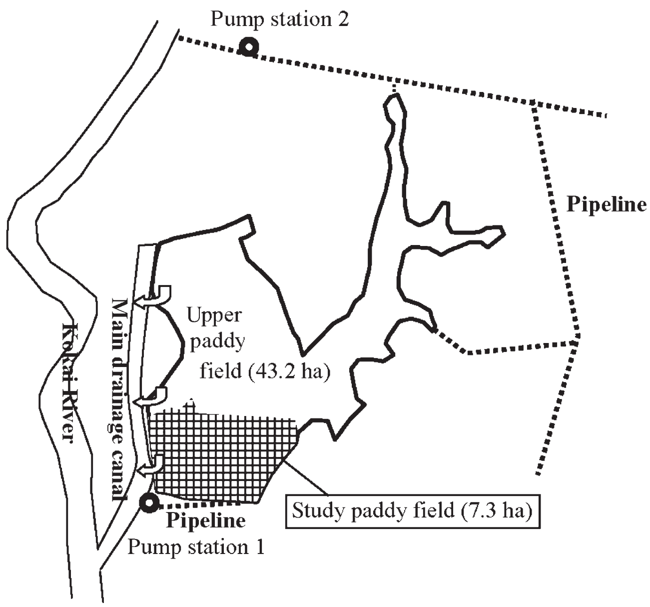

Figure 2 Schematic representation of irrigation and drainage system

a water quality improvement facility, that has been constructed throughout Japan to directly purify river water, irrigation water, and field outflow water.

Results

Reduction in nitrogen outflow load

The reduction in N outflow load from a paddy field equipped with a recycling irrigation facility is caused not only by the reuse of N for irrigating a paddy field by a recycling irrigation facility, but also by the paddy field's removal functions, e.g. the denitrification of NO_x–N and sedimentation of particulate N.

Kunimatsu (1983) reported the possible removal functions of paddy fields irrigated with water containing N at concentrations higher than $2\,\mathrm{mg\,L^{-1}}$. In our study area, a recycling irrigation facility was implemented to reuse the outflow water from the upper paddy field for irrigation. The N concentration in the irrigation water averaged $2.31\,\mathrm{mg\,L^{-1}}$ and reached $4.91\,\mathrm{mg\,L^{-1}}$. This paddy field can remove N because it uses irrigation water with a relatively high concentration of N and has a good retention time, both of which factors facilitate N removal (Feng *et al.*, 2004). The N concentration decrease in the ponded water can be expressed by the following first-order-kinetic reaction formula according to Shiratani *et al.* (2004a).

$$C = C_0 \exp^{-\frac{\alpha}{h}t} \tag{1}$$

where C is the concentration in the ponded water ($\mathrm{mg\,L^{-1}}$), C_0 is the initial N concentration in the ponded water ($\mathrm{mg\,L^{-1}}$), α is the rate constant for N removal ($\mathrm{m\,d^{-1}}$), h is the depth of the ponded water (m), and t is time (in days). Although ponded depth in the paddy field was not always constant, h was taken to be 0.05 m, in accordance with the standard paddy field conditions in Japan. α was $0.016\,\mathrm{m\,d^{-1}}$, similar to the findings of another investigation in the same paddy field area (Yoshinaga *et al.*, 2003).

The N removal rate in our study area was calculated according to Tabuchi *et al.* (1993):

$$R = 10{,}000\alpha C_{irrigation} \tag{2}$$

where R is the nitrogen removal rate ($g\,ha^{-1}\,d^{-1}$), $C_{irrigation}$ is the N concentration in the ponded water ($mg\,L^{-1}$), α is the rate constant for N removal ($m\,d^{-1}$). The resulting N removal rate was $370\,g\,ha^{-1}\,d^{-1}$. The area of the study paddy field was 7.3 ha and there were 121 days of irrigation. The amount of N removed from our study paddy field area during the irrigation period was calculated to be 326 kg.

The amount of N reused for irrigating the paddy field by the recycling irrigation facility was calculated with the following formula.

$$M = 10{,}000 Q_i C_{irrigation} \tag{3}$$

where M is the amount of reused N ($g\,ha^{-1}\,d^{-1}$) and Q_i is the average daily water requirement (m). The results indicate that the amount of reused N was $323\,g\,ha^{-1}\,d^{-1}$, when the average daily water requirement was 0.014 m and the N concentration was $2.31\,mg\,L^{-1}$. About 285 kg N was reused for irrigating the paddy field during the irrigation period.

Economic valuation

Paddy field. The average daily rate of water (Q, $m\ s^{-1}$) flowing into a water quality improvement facility is required for calculating the construction and maintenance costs. This rate was calculated with the following equation:

$$Q = \frac{(M + R) \times A}{C_{in} \times r \times 86{,}400} \tag{4}$$

where M is the amount of reused N for irrigating the paddy field by the recycling irrigation facility ($g\,ha^{-1}\,d^{-1}$), R is the N removal rate by the paddy field removal function ($g\,ha^{-1}\,d^{-1}$), A is the area of the paddy field (7.3 ha), C_{in} is the N concentration of flowing water ($mg\ L^{-1}$), r is the N removal rate of a water quality improvement facility. The range of r is from 4% to 18.2%, depending on the different treatment methods used by the water quality improvement facility. In this study, r was 12.1% (the average value reported by the Ministry of Construction of Japan, 1994) and C_{in} was equated with $C_{irrigation}$ ($2.31\,mg\,L^{-1}$). $Q = 0.21\,m\,s^{-1}$ when the water quality improvement facility removed the same N load in the paddy field.

The paddy field's valuation (E_c and E_m, JPY) as an N removal facility can be expressed by the following equations, which compare it with the construction and maintenance costs, respectively, of a water quality improvement facility:

$$E_c = Q \times W_c \tag{5}$$

$$E_m = Q \times W_m \tag{6}$$

where W_c and W_m are the construction and maintenance costs per unit flowing water of the water quality improvement facility, respectively, and Q is the average daily rate of flowing water ($m\,s^{-1}$). W_c and W_m were 1,132 million JPY m^{-3} and 25 million JPY m^{-3} per year (the Ministry of Construction of Japan, 1994), respectively. As an N removal facility, the paddy field was valued at 238 million JPY for the construction cost and 5.25 million JPY for the maintenance cost per year.

Recycling irrigation facility. The construction and maintenance costs of a recycling irrigation facility were calculated according to the Japan Sewage Works Association (1994) as:

$$E_p = 85.51 \times Q_p^{0.598} \times (113.2/90.1) \tag{7}$$

$$E_i = 1 \times Q_p^{0.690} \times (113.2/90.1) \tag{8}$$

where E_p and E_i are construction and maintenance costs, respectively, of a recycling irrigation facility and Q_p is pumpage ($m^3\,min^{-1}$). The resulting costs were 126 million JPY for construction and 1.52 million JPY per year for maintenance. The cost for constructing and maintaining a recycling irrigation facility was 53% of the value of the paddy field area equipped with a recycling irrigation facility as an N removal facility. Shiratani *et al.* (2004b) calculated the average paddy field's valuation in Japan as an N removal facility as 6 to 10 million JPY ha^{-1} and 0.20 million JPY ha^{-1} per year, respectively, by RCM when compared with the costs of construction and maintenance of water quality improvement facilities. In our study, the paddy field as an N removal facility was valuated at 112 million JPY for the construction cost and 3.73 million JPY for the maintenance cost per year, if we subtract the costs for constructing and maintaining a recycling irrigation facility, respectively. The studied paddy field area was 7.3 ha; therefore, the paddy field as an N removal facility was valued at 15.3 million JPY per unit area (ha) for the construction cost and 0.51 million JPY per unit area (ha) for the maintenance cost per year. These are 1.5 to 2.5 times and 2.6 times higher than the valuations reported by Shiratani *et al.* (2004b), when compared with costs of construction and maintenance, respectively. Because the paddy field reported by Shiratani *et al.* (2004b) was a normal irrigation paddy field area without a recycling irrigation facility, the reduction in N outflow loads appeared just as the paddy field's N removal function. The above results indicate that a recycling irrigation facility can be considered an economic and effective way to reduce nutrients flowing out from a paddy field area.

Recycling ratio

To reduce the N outflow load from a paddy field area, it is necessary to reuse as much of the outflow water as possible as irrigation water. The recycling ratio (R_{rp}) of outflow water is defined as the ratio of the volume of irrigation water applied to the paddy field (reused water by a recycling irrigation facility, V_p) to the sum of that of the upstream outflow (V_d) and the outflow from the paddy field (V_s).

$$R_{rp} = \frac{V_p}{V_d + V_s} \times 100 \tag{9}$$

$R_{rp} = 13.5\%$. The area of paddy field able to be irrigated with the total outflow water increased as the recycling ratio increased (Figure 3). This is because the volume of irrigation water increased, but the water requirement per unit paddy field remained the same.

The N concentration in ponded water at the ith day was simulated with Shiratani's model (2004a):

$$N_{paddy,i} = \frac{(h_{i-1} - O_i)N_{irrigation,i-1}\exp\left(-\frac{\alpha}{h_{i-1}}\right)\Delta t + W_i N_{irrigation,i} + R_i N_{rain,i} + L_i/10}{h_i} \tag{10}$$

where N_{paddy}, $N_{irrigation}$, and N_{rain} are the N concentrations ($mg\,L^{-1}$) in ponded water, irrigation water, and precipitation, respectively. L is the amount of applied N fertilizer ($kg\,ha^{-1}$), h is the depth of ponded water (m), O is the amount of outflow water (m), W is the amount of irrigation water (m), R is the amount of precipitation (m), α is the rate constant for N removal ($m\,d^{-1}$), and $\Delta t = 1$ day. The N concentration in ponded water appears to have a significant exponential correlation with the recycling ratio ($r^2 = 0.99$) (Figure 3). Hidaka (1990) reported that ponded water harmed rice growth when the N concentration was higher than $3\,mg\,L^{-1}$. The simulation results indicate that when the N concentration in ponded water is $3\,mg\,L^{-1}$, at a 30% recycling ratio the area of paddy field that can be irrigated with outflow water is 15.5 ha. The valuations of paddy field

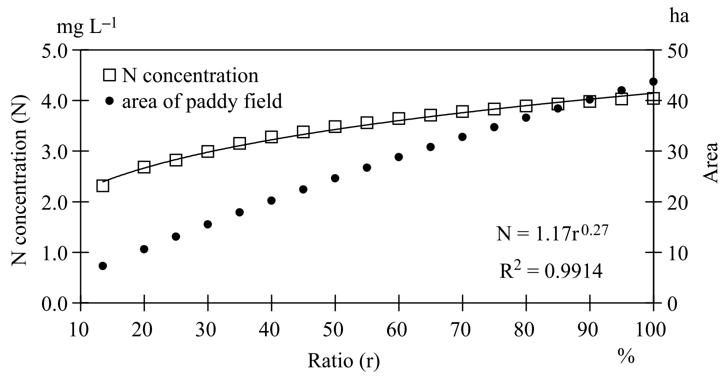

Figure 3 The relationship between the recycling ratio and nitrogen concentration

Table 1 The recycling ratio and construction and maintenance costs

Ratio %	Construction cost million JPY	Maintenance cost million JPY
13.5	238	5.2
20	344	7.6
25	426	9.4
30	504	11.1
35	581	12.8
40	656	14.5
45	728	16.1
50	799	17.6
55	867	19.2
60	936	20.7
65	1,001	22.1
70	1,065	23.5
75	1,127	24.9
80	1,189	26.3
85	1,249	27.5
90	1,306	28.8
95	1,364	30.1
100	1,420	31.4

areas equipped with a recycling irrigation facility as an N removal facility and recycling ratios are shown in Table 1. The results indicate that the most economic and effective recycling ratio in this study paddy field area is 30%, while the paddy field as an N removal facility is valued at 504 million JPY in comparison with the construction cost and at 11.1 million JPY per year in comparison with the maintenance cost of a water quality improvement facility. The costs of construction and maintenance of a recycling irrigation facility are 199 million JPY and 2.40 million JPY per year, respectively. The cost for constructing and maintaining a recycling irrigation facility is 39% of the value of a paddy field area equipped with a recycling irrigation facility as an N removal facility. The effective construction of a recycling irrigation facility not only saves abundant amounts of irrigation water, but also reduces nutrient outflow loads from paddy field areas. A recycling irrigation facility can be considered an economic and effective way to reduce non-point source nutrients.

Conclusions

We evaluated the reduction in nitrogen outflow load from a paddy field area equipped with a recycling irrigation facility and estimated the paddy field's valuation as an N removal facility. We calculated the recycling ratio of outflow water and proposed the most economic and effective recycling ratio. We drew the following conclusions.

1. The recycling ratio of outflow water was 13.5%, and the N outflow load was reduced by 326 kg by the study paddy field's removal function and by 285 kg by the recycling irrigation facility.
2. The value of the paddy field area equipped with a recycling irrigation facility as an N removal facility was 112 million JPY for construction and 3.73 million JPY for maintaining per year, subtracting the cost of the recycling irrigation facility, when replaced by a water quality improvement facility.
3. The N concentration in ponded water appeared to have a significant exponential correlation with the recycling ratio.
4. The most effective and economic recycling ratio of outflow in this study paddy field area would be 30%, the paddy field would have an economic value of 515 million JPY when replaced by the sum of the construction and maintenance costs of a water quality improvement facility.

The effective construction of a recycling irrigation facility not only saves abundant amounts of irrigation water and reduces nutrient outflow loads from paddy field area, but also has a huge economic effect. A recycling irrigation facility can be considered an economic and effective way to reduce non-point source nutrients.

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