JARQ 42 (4), 285 – 289 (2008) http://www.jircas.affrc.go.jp

Economic Valuation of the Agricultural Impact on Nitrogen in the Water Environment by a Newly Proposed Replacement Cost Method

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Abstract

Agriculture is multifunctional, and the value of each function should be expressed in a form that is easy for anyone to understand. One function, for example, is water purification, and recently much effort has been expended to quantify this function. The author proposed a new replacement cost method for the economic valuation of the nitrogen (N) removal function of paddy fields and of the N effusing function of upland fields, and then economically valuated cultivated lands Japan-wide. The N removal function of cultivated paddy fields and fallow paddy fields was valued at approximately 0.3 JPY m^{-2} d^{-1} and 0.6 JPY m^{-2} d^{-1}, respectively, when replaced by the sum of maintenance and depreciation costs of water quality improvement facilities. Upland fields have a negative economic value of approximately 0.08 JPY m^{-2} d^{-1}. However, paddy fields function effectively in N removal only when the irrigation water is strongly contaminated with N. Consequently, 85% of the area used for paddy fields does not function in N removal. The use of N-contaminated water from upland fields for paddy field irrigation throughout the year might be environmentally and economically effective with respect to the conservation of water quality in agricultural areas.

Discipline: Agricultural environment
Additional key words: Japanese yen, paddy field, upland field, wetland

Introduction

Much effort has been expended to index the multifunctionality of agricultural and other rural areas and to calculate their economic value, to make it possible to compare functionalities among countries of the world[3,9]. One function of agriculture is water purification. In general, paddy fields effectively improve water quality by removing nitrogen (N) when the irrigation water is strongly contaminated with N. On the other hand, upland fields might pollute ground and surface waters with N leached from N-containing fertiliser applied to the fields.

Feng et al.[1] valuated the economic effect of N removal by a paddy field equipped with a recycling irrigation facility by replacing the amount of the N removal to the cost for artificial N removing. However, cultivated lands have a variety of effects on the water environment, and the external economy of the role of cultivated lands in the water environment has hardly been valuated, perhaps because the degree to which they purify or pollute the water varies greatly depending on the cultivation conditions. Shiratani et al.[8] newly proposed a replacement cost method (RCM), and valuated the external economies, in terms of Japanese yen (JPY ≈ $ 0.008), of cultivated lands and fallow paddy fields as N removal/effusion sites[8]. However, as the multifunctionality of agriculture is incidentally brought out with everyday farming, when we valuate the impact of agriculture on the environment, it is considered to be befitting to valuate the everyday performance of the multifunctionality than to valuate the site of it.

In this paper, the external economies of the N removal rate in cultivated and fallow paddy fields and external economies of the N effusing rate in upland fields and orchards are valuated by the newly proposed RCM.

Nitrogen removal/effusion by agricultural lands

The newly proposed RCM is grounded in the following features of the N removal/effusion rate of cultivated paddy fields, fallow paddy fields and upland fields.

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Received 27 July 2007; accepted 4 April 2008.

1. Cultivated paddy fields

It is commonly known that paddy fields have an N purification function when the irrigation water is strongly contaminated with N. Shiratani et al.[6] reported that the N removal rate in paddy fields to which N fertiliser had been applied at the standard level, 5.0–14.7 g m^{-2}, was related to the N concentration of irrigation water (Fig. 1) by the following equation:

$$R = 0.0107C_{irrigation} - 0.0156 \quad (1)$$

where R = N removal rate, defined as the balance between the N input load in irrigation water and rainfall and the N output load in surface and underground drainage (g m^{-2} d^{-1}), and $C_{irrigation}$ = N concentration of irrigation water (mg L^{-1}).

2. Fallow paddy fields

Shiratani et al.[7] reported that the change in the N concentration of standing water in wetlands and paddy fields over time can be expressed as a first-order kinetic as follows:

$$\frac{dC}{dt}h = -\alpha C \quad (2)$$

where C = N concentration of the standing water (mg L^{-1}), t = N reaction time (d), h = water depth (m) and α = N removal rate constant (m d^{-1}). Shiratani et al.[7] reviewed the N removal rate constants reported by researchers in the past, and summarised that the N removal rate constant was apparently about twice as high under natural solar radiation (0.02–0.03 m d^{-1}) as under dark conditions (around 0.01 m d^{-1}) because uptake by plants and algal growth, in addition to denitrification, was considered to contribute to N removal under natural solar radiation.

Fallow paddy fields, in which no crop is cultivated and no fertiliser is applied, are supposed to remove N in inflowing water in accordance with eq. (2). Roughly assuming that surface water in the fallow paddy field moves under plug flow conditions from inlets through outlets, the water retention time can be considered to be the N reaction time in the water, then the N removal rate per unit area and unit time is calculated by eq. (3):

$$E = \frac{h}{T}C_{in}\left[1 - \exp\left(-\frac{\alpha}{h}T\right)\right] \quad (3)$$

where E = N removal rate (g m^{-2} d^{-1}), T = water retention time (d) and C_{in} = N concentration of inflowing water (mg L^{-1}).

3. Upland fields and orchards

The amount of N effused out of upland fields and orchards depends on the amount of fertiliser applied. Shiratani et al.[6] investigated the relationship between the amount of N in effluent from upland fields and the amount of applied N fertiliser (Fig. 2) and found that approximately 30% of applied N was effused from the fields. Thus the N effusing rate from upland fields can be approximately estimated as follows:

$$\Delta R = 0.3\ F \quad (4)$$

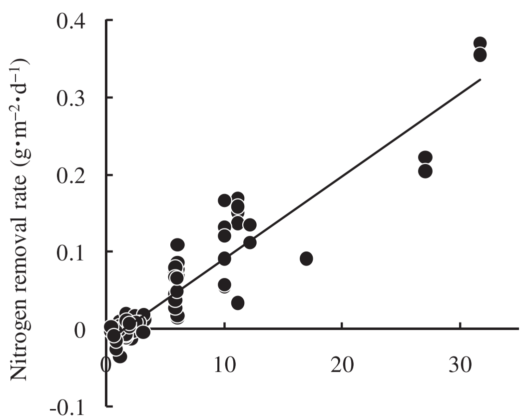

Fig. 1. Relationship of nitrogen removal rates in paddy fields to nitrogen concentrations of irrigation water in paddy fields (Shiratani et al.[6])

Regression equation: [N removal rate] = 0.0107 × [N concentration] – 0.0156, n = 91, r = 0.930 ± 0.014.

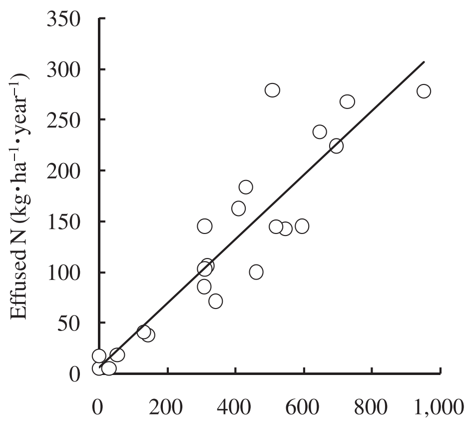

Fig. 2. Relationship of nitrogen effused from upland fields and orchards to applied nitrogen fertiliser (Shiratani et al.[6])

Regression equation: [Effused N] = 0.317 × [Applied N] + 5.887 ≈ 0.3 × [Applied N], n = 22, r = 0.910 ± 0.037.

where ΔR = N effusing rate (g m^{-2} d^{-1}) and F = N fertilisation rate (g m^{-2} d^{-1}).

As the N effusing rate from upland fields depends on the fertilisation, the anamnestic RCM which has been commonly used to estimate the external economies based on the N effusing rate is inapplicable.

Economic valuation method

While it was difficult to apply the RCM, by which the external economies of the multifunctionality of agriculture were valuated, to water purification in cultivated lands where the amounts of water purification vary greatly depending on both natural conditions and farming practices, the newly proposed RCM by Shiratani et al.[8] conquered this difficulty. In this paper, based on this method, the N removal rate of paddy fields and the N effusing rate of upland fields are replaced by the sum of the maintenance and depreciation costs of water quality improvement facilities (WQIFs).

The same equations derived in Shiratani et al.[8] can be used to calculate the external economies of the N removal rate and/or effusing rate in cultivated paddy fields, upland fields and fallow paddy fields, by simply using the sum of the maintenance and depreciation costs of WQIF in place of the construction cost, where we assume that the life of a WQIF is 15 years and that during its life, with the receipt of appropriate maintenance, the facility steadily improves the water quality. The construction and maintenance costs of WQIFs are based on evaluation documents that we obtained from the Ministry of Construction of Japan.

The external economies of the N removal rate of a cultivated paddy field and a fallow paddy field can be respectively calculated by the following equations:

$$S_{paddy} = \frac{f}{r} P \tag{5}$$

$$S_w = -\frac{\alpha}{\ln(1-r)} P \tag{6}$$

where S_{paddy} = external economic value of the N removal rate of a cultivated paddy field (JPY m^{-2} d^{-1}), S_w = external economic value of the N removal rate of a fallow paddy field (JPY m^{-2} d^{-1}), P = sum of the maintenance and depreciation costs per unit capacity of water purification (JPY m^{-3}), f = rate constant of N removal (m d^{-1}) and r = N removal rate by a WQIF (–).

On the other hand, the external diseconomy of the impact of N effusion from upland fields on the water environment can be calculated on the basis of the cost and performance of the WQIF only, without taking into account either the N effusing rate or the N concentration in the upland field drainage. Thus;

$$\Delta S_{upland} = \frac{HP}{r} \tag{7}$$

where ΔS_{upland} = external diseconomic valuation of N pollution per unit area of upland fields (JPY m^{-2} d^{-1}) and H = field drainage rate (m d^{-1}).

Results and discussion

The results of the external economies of N removal/effusion rate from cultivated paddy fields, fallow paddy fields and upland fields for eight kinds of WQIFs are shown in Table 1, taking f = 0.01 (m d^{-1}), α = 0.025 (m d^{-1}) and H = 1/365 (m d^{-1}) in eq. (5), eq. (6) and eq. (7),

Table 1. Economic value of nitrogen removal/effusion in cultivated paddy fields, fallow paddy fields and upland fields when replaced by the maintenance and depreciation costs of eight types of water quality purification facilities

	R* (–)	P** (JPY m^{-3})	Economic valuation (JPY m^{-2} d^{-1})		
			Paddy field	Fallow paddy field	Upland field
Reactor with textile contactor	0.133	1.56	0.12	0.27	Δ 0.03
Multi-tank oxidation reactor	0.040	3.26	0.82	2.00	Δ 0.22
Reactor with lace contactor	0.182	3.01	0.17	0.37	Δ 0.05
Reactor with charcoal	0.232	2.14	0.09	0.20	Δ 0.03
Oxidation reactor with plastic contactor	0.066	3.16	0.48	1.16	Δ 0.13
Anaerobic– aerobic reactor	0.006	5.50	9.17	22.85	Δ 2.51
Reactor with bio-filter	0.173	3.69	0.21	0.49	Δ 0.06

*: Nitrogen removal rate by a water quality improvement facility.
**: Cost per unit capacity of water purification.

respectively.

The external economic value of the N removal rate of a paddy field ranged from 0.1 to 0.8 JPY m^{-2} d^{-1} (0.3 JPY m^{-2} d^{-1} on average; excepting the anaerobic–aerobic reactor, the performance of which is extremely low) when compared with the sum of the maintenance and depreciation costs of the WQIF. Although paddy fields potentially have an N removal function, more than 85% of paddy fields do not effectively remove N because approximately 85% of irrigation waters have an N concentration of less than 2.5 mg L^{-1}, which is the minimum level required for a paddy field to function in N removal[2,4]. If we set the economic value of N removal rate by a paddy field at 0.3 JPY m^{-2} d^{-1} referring to Table 1, and the paddy cultivation period at 140 days, the total annual external economic value of N removal rate by paddy fields in Japan, the 15% of fields with irrigation water with sufficiently high N, can be estimated as approximately 106 billion JPY.

The external economic value of the N removal rate of fallow paddy fields and wetlands ranged from 0.2 to 2.0 JPY m^{-2} d^{-1}, or 0.6 JPY m^{-2} d^{-1} on average. Thus, the external economic value of fallow paddy fields for N removal rate is double that of paddy cultivated fields. At present in Japan, more than 25% of paddy fields lie fallow each year because of rice overproduction. Fallow fields and paddy fields during the non-growing season do not function in N removal, because no irrigation water is supplied to them. However, fallow paddy fields have high potential for N removal, as shown above, and give full play to their ability when N-contaminated water is introduced into them.

Sasaki[5] calculated the external economic value of the water purification function of the Mikawa-wan tidal flat by a RCM. The amount of N removal by the tidal flat was replaced by the amount of N removal by a sewage treatment plant. The result showed that the external economic value of N removal by the tidal flat, in comparison with the maintenance cost of the plant, was 0.3 JPY m^{-2} d^{-1} (Sasaki did not consider the depreciation cost of the sewage treatment plant). The external economic value of N removal rate by cultivated paddy fields was approximately equal to that of the tidal flat, and the external economic value of N removal rate by fallow paddy fields was about double that of the tidal flat.

On the other hand, the N effusing rate from upland fields had a negative external economic cost of approximately 0.08 JPY m^{-2} d^{-1} on average, and ranged from 0.03 to 0.22 JPY m^{-2} d^{-1}. Assuming the external diseconomic value of the N effusing rate from upland fields at 0.08 JPY m^{-2} d^{-1}, the annual external diseconomy of the N effusing rate from upland fields can be estimated as approximately 850 billion JPY Japan-wide.

From the results, the net external economy of N removal/effusion of cultivated lands, paddy fields and upland fields Japan-wide, is calculated at approximately minus 744 billion JPY annually. Therefore, on balance, cultivated lands could harm the water environment from the aspect of N pollution.

To enhance the N removal function of paddy fields, the use of strongly N-contaminated water — such as groundwater from beneath intensively farmed fields, drainage from upland fields, and grey water moderately diluted with unpolluted water — for paddy field irrigation might be cost effective. In addition, supplying N-contaminated waters to fallow paddy fields and to paddy fields during the non-growing season could also be environmentally and externally economically effective. Particularly, more than 25% of paddy fields lie fallow each year. The economic valuation of the potential for N removal in such fields into which N-contaminated water is introduced gives us a useful piece of information on how to make good use of fallow paddy fields as N removal sites.

Conclusion

In the newly proposed RCM by Shiratani et al.[8] which is applicable to land cultivated in various conditions, the external economic values of the N removal rate of cultivated paddy fields and fallow paddy fields, and the negative economic value of N effusing rate from upland fields were calculated, by replacing the fields with WQIFs. The results showed the following:

1. The N removal function of cultivated paddy fields and fallow paddy fields had an external economic value of 0.3 JPY m^{-2} d^{-1} and 0.6 JPY m^{-2} d^{-1}, respectively, when replaced by the sum of the maintenance and depreciation costs of WQIFs.
2. Upland fields had an external negative economic value of approximately 0.08 JPY m^{-2} d^{-1}.
3. Cultivated lands, comprising paddy fields and upland fields Japan-wide, can be externally economically valuated at approximately minus 744 billion JPY annually.

To conserve water quality in a watershed, a sound nutrient and water cycle must be developed. It could be cost effective to use strongly N-contaminated water and grey water moderately diluted with unpolluted water for paddy field irrigation and to supply N-contaminated waters to cultivated paddy fields during the non-growing season and to fallow paddy fields.

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