Effect of agriculture on nitrogen flow in the coastal water environment at the Ariake Bay, Japan

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Abstract: We present an overview of the roles of cultivated land in the formation of the water environment, and suggest strategies for the conservation of this environment on the coast of the Ariake Bay, Kyushu, Japan. Various types of irrigation and drainage systems in this area form unique features of the water environment there. The waters in the Yabe River irrigation area and on the Shiroishi Plain are highly contaminated with nitrogen, which drains from tea plantations in the former and upland fields in the latter. Rush fields on the Yatsushiro Plain are another major source of nitrogen. Reusing agricultural drainage and domestic effluent for irrigation of paddy fields is an effective way to reduce the nitrogen load from such agricultural areas.

Key words: nitrogen, paddy field, upland field, water purification

Introduction

Various types of irrigation and drainage systems, including a recycling irrigation system that uses a dual-purpose canal, separate irrigation and drainage canals, and a pipe irrigation system, form unique features of the water environment on the coast of the Ariake Bay, Kyushu, Japan (Fig. 1).

More than 30,000 ha of paddy fields was developed by land reclamation projects along the seashore of the Ariake Bay between the early 14th and late 20th centuries (Matsumura et al. 1988). The natural water supply of $15 \times 10^6$ m$^3$ became inadequate for irrigation water by the end of 14th century because of rapid extension of paddy fields developed, so other water resources were developed. A unique method of tidal irrigation, locally called ‘awo water intake’, was devised to take irrigation water from the tidal reach of the Chikugo River, by which farmers abstract the top layer of fresh water lying above the saline layer in the

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Fig. 1. Location of the Ariake Bay.
river at high tide (Fig. 2). The use of this fresh water allowed the irrigation area to be extended to the area between the cities of Yanagawa, Kurume, and Saga.

However, as *awo* water intake depends entirely on tidal and hydrological conditions, this method is inconvenient, and water shortages often occur. Thus, farmers have developed a highly intense recycling system for paddy rice irrigation that uses creeks as irrigation and drainage canals and reservoirs. The water recycling system has caused deterioration of the water environment in rural areas and siltation in creeks, which might explain the malfunction of water flow (Yamamoto & Shiratani 1987). Especially in rural areas along the Ariake Bay coast where the water stays for a long time, the water environment is becoming increasingly polluted by an increase of inflowing pollutant load from cultivated land, farm yards, and domestic effluent. In recent years, the Chikugo–ohzeki head works has stabilized the water supply, allowing the irrigation and drainage system in the area to be restructured.

Our objective is to clarify the effects of cultivated land on water quality in these rural areas, and to suggest strategies for conservation of the water environment on the coast of the Ariake Bay.

**Roles of cultivated land in the water environment**

The major proportion of land in rural areas of Kyushu is occupied by paddy fields, upland fields, irrigation and drainage facilities, and wetlands. Although many previous studies (e.g. Tabuchi 2001) have tried to establish and quantify the roles of cultivated land in water purification and pollution, few have successfully quantified every process contributing to water quality, since chemical and biological reactions in water are complicated and vary with natural and social conditions.

**Nitrogen purification in paddy fields and wetlands**

Paddy fields remove nitrogen (N) when the irrigation water is highly contaminated with N (e.g., Miyoshi 1978; Kunimatsu 1983).

Shiratani et al. (2004b) reported the relationship between N removal in a paddy field in which N fertilizer was applied at a standard rate of 70 to 100 kg ha⁻¹ and the N concentration in the irrigation water. This is shown in Fig. 3.

The regression equation is as follows:

\[ R = 0.011 \cdot C_{\text{irrigation}} - 0.016, \]  \[ \text{[1]} \]

![Fig. 3. Relationship of nitrogen removal in paddy fields to nitrogen concentration of irrigation water (Shiratani et al., 2004b).](image)
where $R = \text{amount of N removed per cultivation day (g m}^{-2} \text{d}^{-1})$ and $C_{\text{inflow}} = \text{N concentration of irrigation water (mg L}^{-1})$. The amount of N removed per unit cultivation day was proportional to the N concentration in the irrigation water, with a proportional constant of 0.011 m d$^{-1}$, in paddy fields in which the N concentration of irrigation water was $\geq 1.45$ mg L$^{-1}$.

Kunimatsu (1983) reported that N runoff from a paddy field might be in balance with N inflow when the N concentration of irrigation water is more than 2.5 mg L$^{-1}$. Miyoshi (1978) reported a similar result at an N concentration of 2–3 mg L$^{-1}$. Only 3% of the data plotted in Fig. 3 for which the N concentration of irrigation water was more than 2.0 mg L$^{-1}$ had negative values of R. It seems reasonable to suppose that paddy fields remove N when the N concentration of irrigation water is higher than 2.0 mg L$^{-1}$, although there are exceptions.

When the N concentration of the irrigation water is lower than 2.0 mg L$^{-1}$, paddy fields may become N pollution sources, because the N loading rate, including elution from sediment and fertilizer, could exceed the N removal rate owing to denitrification, algal uptake, plant uptake, and sedimentation.

In general, the N concentration of standing surface water can be expressed as a 1 st -order differential equation (Tabuchi et al. 1987):

$$\frac{dC}{dt}h = -\alpha C,$$  \[2\]

where $C =$ N concentration of surface water (mg L$^{-1}$), $h =$ water depth (m), and $\alpha =$ rate constant (m d$^{-1}$).

The rate of N removal through a water area that has $T$ days’ retention time can be defined on the basis of eq. [2], and mathematically approximated by using an infinite series and omitting the terms higher than the 2 nd order:

$$D = \frac{h}{T} C_0 \left[ 1 - \exp \left( -\frac{\alpha}{h} T \right) \right]$$
$$= \frac{h}{T} C_0 \left[ 1 - \left( 1 - \frac{\alpha}{h} T + \frac{\alpha^2}{h^2} T^2 - \frac{\alpha^3}{h^3} T^3 + \ldots \right) \right] \quad [3]$$

where $D =$ N removal rate (g m$^{-2}$ d$^{-1}$) and $C_0 =$ N concentration of inflowing water (mg L$^{-1}$). When we take $C_0$ in eq. [3] to be the N concentration of irrigation water, eq. [3] is similar to eq. [1].

Rate constants of N removal in paddy fields where no fertilizer was applied and in wetlands, based on eq. [2] or [3], are listed in Table 1. The rate constant of N removal was twice the size under sunlit conditions (0.02–0.03 m d$^{-1}$) than under dark conditions (around 0.01 m d$^{-1}$). Plant uptake and algal growth might affect N removal under sunlit conditions, in addition to the effect of denitrification.

**Nitrogen pollution by upland fields**

The amount of N discharged from upland fields and orchards depends on the amount of applied fertilizer. Approximately 30% of N applied in fertilizer could effuse out of the field (Takeda 1997; Shiratani et al. 2004b).

Nitrogen flow through cultivated land in Japan is shown

<table>
<thead>
<tr>
<th>Site</th>
<th>Rate constant (m d$^{-1}$)</th>
<th>Conditions</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wetland with reed</td>
<td>0.024</td>
<td>Under sunlight</td>
<td>Calculated from Hosoi et al. (1995) on eq.[3].</td>
</tr>
<tr>
<td>Natural wetland</td>
<td>0.016</td>
<td>Under sunlight</td>
<td>Calculated from Hosomi &amp; Sudo (1991) on eq. [3].</td>
</tr>
<tr>
<td>Creek sediment</td>
<td>0.01</td>
<td>In dark room, 25°C</td>
<td>Shiratani et al. (2002a)</td>
</tr>
<tr>
<td>Paddy field soil</td>
<td>0.012</td>
<td>In dark room, 20°C</td>
<td>Tabuchi et al. (1993)</td>
</tr>
<tr>
<td>Paddy field soils</td>
<td>0.007–0.014</td>
<td>In dark room</td>
<td>Tabuchi (2001)</td>
</tr>
<tr>
<td>Fallow fields</td>
<td>0.02–0.03</td>
<td>Under sunlight</td>
<td>Yamaguchi &amp; Hata (1993)</td>
</tr>
<tr>
<td>Paddy fields</td>
<td>0.015–0.021</td>
<td>Under sunlight</td>
<td>Yoshimaga et al. (2003)</td>
</tr>
</tbody>
</table>
in Fig. 4 (Shiratani et al. 2004b). We estimated that approximately $360 \times 10^3$ t of fertilizer N and $175 \times 10^3$ t of farmyard manure N are applied to $2900 \times 10^3$ ha of upland fields and orchards. Assuming leaching of 30% of the applied N, approximately $152$ g ha$^{-1}$ d$^{-1}$ of N load was effused into the water environment.

Since 1,000 mm of annual rainfall drains out of the fields, the average N concentration in the drainage water from upland fields and orchards is $5.5$ mg L$^{-1}$ (Fig. 4). Ground or spring water in the area where vegetable cropping, tea cropping, and livestock farming are highly concentrated often has a nitrate/nitrite N concentration of more than $10$ mg L$^{-1}$ (water quality standard for human health, enacted by the Ministry of the Environment).

**Measures for water quality conservation on the coast of the Ariake Bay**

**Northern coast of the Ariake Bay**

Since 1970 many old, narrow, and complex agricultural canals have been replaced with wide, deep, and straight lined ones in land improvement projects such as the National Irrigation Projects of Kase-gawa and Chikugo-gawa and related lateral irrigation projects conducted by local government. The location and function of the main trunk canals have remained unchanged.

As shown in Fig. 5, the northern coast of the Ariake Bay can be divided into four areas in respect of irrigation water resources: the Yabe River-irrigated area (Yabe-sourced), the Chikugo River-irrigated area (Chikugo-sourced), the Kase River-irrigated area (Kase-sourced), and groundwater-irrigated area (Shiroishi Plain).

Before 1995, most of the irrigation water in the Chikugosourced area and a part of the Yabe-sourced area was supplied from the tidal reach of the Chikugo River by the awo water intake (Fig. 2), which was often subject to water shortages. The area of paddy fields irrigated from the awo water intake was $17,000$ ha (Matsumura et al. 1988). Since 1995, the Chikugo-ohzeki head works have supplied water at a maximum rate of $3.0$ m$^3$ s$^{-1}$, almost as much as the awo water intake supplies, making up the water shortage during the irrigation period.

In the Kase-sourced area, the Kase irrigation system, built in 1980, supplies enough irrigation water to irrigate the $11,000$ ha of paddy fields there.

The Shiroishi Plain has suffered from water shortages for hundreds of years, so farmers draw irrigation water from small reservoirs and ground water, and intensively recycle the agricultural drainage. Annually more than $10^{-15}$ million m$^3$ of ground water is pumped up, but this has caused serious subsidence of $3^{-5}$ cm year$^{-1}$ (Tanaka 1989).

In the Yabe-sourced area, the Chikugo-sourced area and the Kase-sourced area, the main summer crop is paddy rice, and winter crops are barley and wheat. In the Shiroishi Plain, the main crops are paddy rice or onion in summer, and onion or lotus root in winter.

Table 2 shows the quality of irrigation water in each area averaged from 1989 to 1996. The N concentrations...
were high in the Yabe-sourced area and the Shiroishi Plain. Approximately 66% of the irrigation water in the Yabe-sourced area and 49% in the Shiroishi plain had N concentrations of more than 2.5 mg L\(^{-1}\). The major pollutant source is agriculture, especially tea plantations in the Yabe area and onion cropping in the Shiroishi Plain. Approximately 1,560 ha of tea plantations, or 2.5% of the catchment area, occupies the upriver district of the Yabe River, where more than 500 kg ha\(^{-1}\) of N fertilizer is applied. In the Yabe-sourced area, nitrate leaching from tea plantations contaminates the Yabe River water, which is used for irrigation of 12,500 ha of paddy fields along the river (Matsumura et al. 1988), where some of the N in the water is removed (Fig. 6). On the Shiroishi Plain, approximately 6,000 ha is cultivated, of which 1,700 ha is planted with onion (Ministry of Agriculture, Forestry and Fisheries 2004), and 250 kg ha\(^{-1}\) of fertilizer N is applied to every onion crop. As farmers there intensively recycle the agricultural drainage (Fig. 7), the quantity of agricultural run-off
from the area is small, so the agricultural impact on the water quality at the periphery of the agricultural area might also be small.

Southern coast of the Ariake Bay
Rushes are grown on the Yatsushiro Plain on the southern coast of the Ariake Bay. As 640 kg ha\(^{-1}\) of N is applied and a large amount of N is effused out of the rush fields, this crop is one of the major pollution sources in the area.

Kubota (1999) examined the N flow in an agricultural area planted mainly with rushes and paddy rice (Fig 8), and found that the annual net effluent N load (eq. [4]) was approximately 26 kg ha\(^{-1}\). Kubota suggested that the effluent N load should be reduced during May to mid June, and that retaining ponded water in the rush fields for more than 5 days and reusing the drainage from the rush fields to irrigate the surrounding paddy fields might reduce the effluent load from the area. Kubota also showed that the rush fields reduced the N load, except during the 3 months after fertilization.

\[
\text{[Net effluent N load]} = \text{[gross effluent N load]} - \text{[inflowing N load]} - \text{[domestic and industrial N load]}. \quad [4]
\]

As a general rule, farmers try to retain ponded water for 3 days after fertilization. As the N concentration of the ponded water decreases to 40% or lower within 5 days according to the 1st-order kinetic equation (eq. [2]), extending the 3 days' retention time of ponded water by only 2 more days will achieve effective reduction.

Practical use of N removal in paddy fields for reduction of N load inflowing to the Ariake Bay
Recycling of gray water
In areas along the coast of the Ariake Bay where irrigation water is insufficient, a unique irrigation system called ‘paddy rice cultivation by creek’ has been developed. Farmers dug creek networks and used them as irrigation canals, drainage canals, and regulating ponds. Drainage from paddy fields and homes in the area was stored in a creek and reused for irrigation. This system was effective at purifying water before it was discharged into rivers.

Most domestic water is now supplied from taps and drains to sewage works. The sewage works planned around the cities of Kurume and Saga will discharge effluent from more than 500,000 people at over 1.7 m\(^3\) s\(^{-1}\), with no reuse.

To make better use of the limited water, it might be necessary to build small-scale sewage plants that make use of the ability of paddy fields to purify water. Although problems such as heavy metal contamination need to be solved, small-scale sewage plants have potential for water recycling because of ease of control. Kunimatsu et al. (1998) reported that the concentrations of Cd, Cu, Zn, Pb, and As in the harvested rice grains produced in a paddy field irrigated with effluent from a rural sewage treatment plant did not increase.
Recycling of paddy field drainage

As described above, paddy fields rarely purify water when the N concentration of the irrigation water is low. In that case, recycling of the paddy field drainage within the paddy field area, which could reduce the amount of field drainage and raise the N concentration of the irrigation water, is effective at reducing the effluent load in the area.

We developed a mathematical model to simulate water and nutrient flow in four 100-ha paddy fields with irrigation canals, drainage canals, and a regulating reservoir (1.5 m depth) with a pump (Fig. 9), and estimated the efficiency of recycling of paddy field drainage at reducing effluent N load (Shiratani et al. 2004a).

As shown in Fig. 10, the net effluent N load, defined as the balance between influent and effluent loads, was approximately 25 g ha\(^{-1}\) day\(^{-1}\) without recycling, and decreased with an increase of recycling rate (ratio of water introduced into the regulating reservoir to water drained from the paddy fields). At a 48% recycling rate, the net effluent N load was zero. This means that the paddy field area could purify N in water at a recycling rate of 48% or more.

On the other hand, the N concentration of irrigation water will increase and the water environment should therefore deteriorate as the recycling rate increases. Increased nutrient concentrations in irrigation water in agricultural areas where water recycling systems are constructed have been found in field examinations and model analyses (e.g., Kaneki 1991; Kudo et al. 1995; Feng et al. 2004).

Extending the water retention time in all agricultural areas and reusing water could enhance the capacity of agriculture to remove N.

Optimum land use for water quality conservation

Paddy fields and wetlands have N removal functions. On the other hand, upland fields release N. Nakasone et al. (1996) and Matsumori et al. (2004) examined the N removal functions of paddy fields in the N flow on agricultural catchments, and found that paddy fields located at the hill-bottom effectively removed N leached from upland fields located on the hill. To introduce the N flow from upland fields to paddy fields must be effective to reduce N load effluent from the agricultural catchment.

When the removal of N by paddy fields balances N pollution from upland fields, the state can be expressed by the following equation:
where $A_u$=area of upland fields (m$^2$), $A_p$=area of paddy fields (m$^2$), $R_u$=N loading rate of upland fields (g m$^{-2}$ d$^{-1}$), and $R_p$=N removal per unit cultivation day of paddy fields (g m$^{-2}$ d$^{-1}$).

The N loading rate of upland fields is expressed as $R_u=Q_{c_{N}}$, where $Q$=water drainage rate (m d$^{-1}$) and $C_{N}=N$ concentration of drainage water (mg L$^{-1}$). The N removal rate of paddy fields is expressed as $R_p=f C_{N}$ (approximated from eq. [1]). When $C_{N}=C_0$:

$$A_u/A_p=f/Q.$$  \hfill [6]

If $f=0.01$ m d$^{-1}$ and $Q=2.74\times10^{-5}$ m d$^{-1}$, where the water drainage rate is assumed to be the balance of daily average rainfall and evapotranspiration, then:

$$A_u/A_p=3.65.$$  \hfill [7]

That is, a unit area of paddy field could purify N-polluted drainage from 3.65 times that area of upland fields.

However, in reality, there are problems to be solved before we can apply this idea at actual sites. Although large upland field drainage occurs over a couple of days after rainfall, paddy fields never require irrigation water on those days, so we cannot directly recycle the field drainage for irrigation of paddy fields.

To solve this, an irrigation, drainage, and storage system is required. The system should have an adequate scale of regulating reservoirs to regulate the timing between upland field drainage and water requirement in paddy fields. Of course, consistent 100% reuse is not achievable.

Conclusions

We have explained the roles and features of agricultural areas in the water environment on the coast of the Ariake Bay, and suggested that recycling and reuse of agricultural discharge, including field drainage, and domestic and industrial drains for paddy irrigation can reduce the environmental impact on the periphery of an agricultural area.

However, the water environment in the paddy area deteriorates as pollutants accumulate with intensive recycling of run-off.

Water has multiple uses, including irrigation, conservation of rural amenity, bio-conservation, and household needs. Conservation of the water environment is essential for sustainable development of rural areas. Suitable water environments for respective water uses need to be clarified, and innovative water-use systems need to be developed to achieve a good rural environment.

References


