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Chun G. Yoon · Jong-Hwa Ham · Ji-Hong Jeon

Mass balance analysis in Korean paddy rice culture

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Abstract A field experimental study was performed during the growing season of 2001 to evaluate water and nutrient balances in paddy rice culture. Three plots of standard fertilization (SF), excessive fertilization (EF, 150% of SF), and reduced fertilization (RF, 70% of SF) were used and the size of treatment plot was 3,000 m^2, respectively. The hydrologic and water quality was field monitored throughout the crop stages. The water balance analyses indicated that approximately half (47–54%) of the total outflow was lost through surface drainage, with the remainder consumed by evapotranspiration. Statistical analysis showed that there was no significant effect of fertilization rates on nutrient outflow through the surface drainage or rice yield. Reducing fertilization of rice paddy may not work well to mitigate the non-point source nutrient loading in the range of normal farming practices. Instead, the reduction in surface drainage could be important to controlling the loading. Suggestive measures that may be applicable to reduce surface drainage and nutrient losses include water-saving irrigation by reducing ponded water depth, raising the weir height in diked rice fields, and minimizing forced surface drainage as recommended by other researchers. The suggested practices can cause some deviations from conventional farming practices, and further investigations are recommended.

Keywords Paddy field · Rice culture · Nutrient loading · Surface drainage · Fertilization

C. G. Yoon (✉)
Rural Engineering Department,
Konkuk University,
1 Hwayang-dong, 143-701 Kwangjin-gu, Seoul, Korea
e-mail: chunyoon@konkuk.ac.kr

J.-H. Ham · J.-H. Jeon
Graduate Program, Rural Engineering Department,
Konkuk University,
1 Hwayang-dong, 143-701 Kwangjin-gu, Seoul, Korea

Introduction

Paddy rice culture is an important agricultural practice in many countries of the Asian monsoon region, and paddy fields often dominate extensive portions of the landscape. Rice is a principal staple food for half of mankind and a major portion of the world's population obtains more than half of its daily calories from rice (Counce et al. 2000). More than 75% of the world's rice supply comes from 79 million ha of irrigated rice production in Asia (Cabangon et al. 2002), and rice (*Oryza sativa*) is grown during a single crop season on about 1.1 million ha in Korea. Field water input during a growing season may vary from 500–800 mm (De Datta et al. 1973) to more than 3,000 mm (Hukkeri and Sharma 1980), and about 1,250 mm typically is supplied in Korea, in most cases by irrigation. Among the water uses, irrigation for paddy rice culture ranks first and it takes about half of the total water consumption in Korea.

Korea is a densely populated country with about 47 million people in about 100,000 km^2 and has an average annual precipitation of 1,274 mm (Yoon et al. 2001). The Korean environment suffered seriously during rapid industrialization up to the late 1980s, but it has been improving since then due to ongoing restoration efforts. As of 2000, over 70% of domestic wastewater generated nationally was collected and treated by public sewers. However, the water quality of many streams and lakes often exceeds the established standards, and periodic algal blooms in most reservoirs imply that further efforts to safeguard quality are still needed.

It was realized recently that water quality improvement is hardly achievable without proper control of non-point source pollution, which, in turn, is closely related to land use and rainfall events. The land use in Korea includes about 65% forest and 20% farmland, where runoff from forest is thought to be natural, but drainage water from farmland is suspected as a key pollution source. Although urban areas cover a substantial portion of the country, much of the urban runoff is collected by stormwater treatment systems, and receives less attention except for first flush. The rainfall of the Asian monsoon region, including Korea, is concentrated and intensive during the growing season for rice, when fertilizer runoff into rivers and lakes may therefore be quite high.

Rice, like other crops, needs 16 essential elements that must be present in optimum amounts and in forms available by rice plants for proper growth. Among these elements, nitrogen, phosphorus, and potassium are most commonly applied as fertilizer by rice farmers, and a major portion of these nutrients is taken up by rice plants as they grow to harvest size (Lee 2001). An important question is whether or not substantive amounts of nutrients are lost in runoff water from paddy rice fields, and whether this runoff contributes to lake eutrophication and algal bloom problems. Some studies have suggested that paddy fields can have beneficial effects, including water quality attenuation, air cooling and refreshing, groundwater recharge, and soil erosion control (Eom 2001).

Water is one of the most essential prerequisites for sustaining natural ecosystems and human development. Increasing human population and economic development require more water and competition occurs among the water uses. Furthermore, the available fresh water is not always satisfactory for intended water uses due to water quality problems. Therefore, securing not only water quantity but also water quality protection is important. Nitrogen and phosphorus are a focus of this study because of their effects on algal blooms in surface waters that also are used for domestic water supply and other uses. Rice culture requires large amounts of water and nutrients, and substantial amounts of both can be lost through surface drainage, unless there is a careful balance between inputs and what actually is used by rice plants. Nutrients lost in surface drainage water can cause eutrophication and excessive algal growth in receiving water bodies. Of particular concern are P and N, because these essential plant nutrients also limit algal growth in most fresh waters. A field experiment was performed at experimental plots to examine the effects of fertilization and rainfall on the nutrient export from paddy rice fields, and results are presented in this paper to provide an insight into nutrient movement during paddy farming.

Materials and methods

Site characteristics

The experiment was performed during the growing season of 2001 at the Konkuk University Agricultural Research Farm in Yojoo (37°14′N, 127°33′E), Korea, approximately 85 km southeast of Seoul. The elevation of the study site (Fig. 1) is 70 m above mean sea level and the surrounding area has a typical rural community involved in paddy rice farming. The average annual rainfall for the last 10 years is about 1,265 mm and groundwater irrigation is usually practiced.

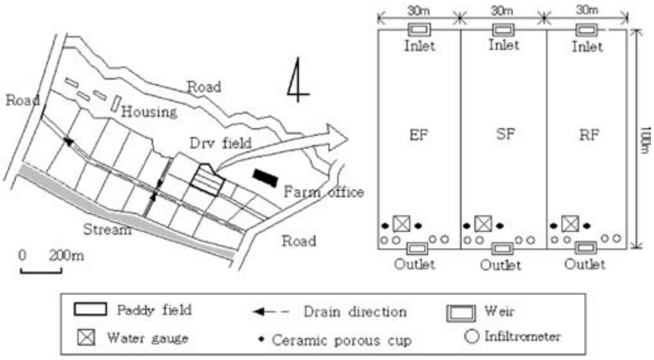

Fig. 1 Layout of the study area and location of sampling stations. *EF* Excessive fertilization; *SF* standard fertilization; *RF* reduced fertilization

Table 1 Fertilization rates (in kg/ha) for the treatments

Treatments	N	P_2O_5	K_2O
EF	165.0	67.5	85.5
SF	110.0	45.0	57.0
RF	77.0	31.5	39.9

Table 2 Soil characteristics of experimental plots

Properties	EF	SF	RF
Sand (%)	42.2	35.1	34.0
Silt (%)	35.8	40.8	45.1
Clay (%)	22.0	24.1	20.9
Textural class	Clay loam	Clay loam	Clay loam
Particle density (Mg/m^3)	2.68	2.66	2.67
pH (soil:water=1:5)	5.20	5.09	5.14
CEC ($cmol_c/kg^1$)	7.05	7.30	7.65
EC (μs/cm)	2,193	2,833	2,167
Organic carbon (%)	1.62	1.60	1.72
Total N (mg/kg^1)	1,078	1,197	1,463
Total P (mg/kg^1)	284.28	346.01	413.49
P_2O_5 (mg/kg^1)	15.68	24.31	16.91

Treatments and cropping

SpringTreatments included three fertilization rates (Table 1) and the standard cultivation practices of the local district. Fertilizers to the standard fertilization (SF) plot were applied according to the standard practice of rice cultivation in the central part of Korea prior to ploughing at the standard rates of 110, 45, and 57 kg/ha for N, P_2O_5, and K_2O, respectively; 150% of the rate was applied to the excessive fertilization (EF) plot, and 70% of the rate was applied to the reduced fertilization (RF) plot. The only difference among the treatments was in the fertilization rate and other treatments were according to standard practice. Examination of the effect on nutrient loading through surface drainage was a main focus of this study. The size of each plot was 100×30 m (Fig. 1).

Soil at the experimental site was slightly acidic and other characteristics were in the range of typical paddy rice fields (Table 2). Fertilization with phosphorus (P) and

Table 3 Agricultural activities during the study period

Date	Agricultural activity	Remark
25 May	Ploughing and basal fertilization	Phosphorus (100%), nitrogen (50%)
29 May	Rice transplanting	15×30 cm, 4 plants/hill
9 June	Tillering fertilization	Nitrogen (30%)
17 July	Panicle fertilization	Nitrogen (20%)
7 October	Harvest	

potassium (K) was carried out at the time of transplanting, but nitrogen (N) was applied at the transplanting, tillering, and panicle initiation stages (Table 3). Month-old rice seedlings (Illpumbyeo, a Korean rice cultivar) were transplanted 15 cm apart in 30-cm-wide rows in ponded water on 29 May and harvested on 7 October 2001. The observation fields had been used for paddy farming with standard practice including fertilization for a long time, and different fertilization treatment was only applied for the study purpose.

Measurements

Ponded water depth in each experimental plot was measured continuously by an automatic water level recorder, and inflow and outflow were measured using weirs installed at the inlet and outlet of each plot, respectively. One water level recorder was installed for each plot; within-plot variation in water level was expected to be small because of the small size and flat bottoms. Four infiltrometers were installed in each plot to measure water loss by deep percolation. Percolation water quality was sampled by two ceramic porous cups embedded to a depth of 0.60 m below the soil surface. Rainfall was recorded using a tipping bucket rain gauge at the site, and evapotranspiration was estimated by the Penman-Monteith equation (Hillel 1998).

Water samples were collected every week during dry days, more frequently during fertilization periods, and several samples were taken per day during wet days to examine the rainfall effect. The samples were analyzed by the standard methods of APHA (1995) for conventional parameters including total N (T-N) and total P (T-P). For each plot, three soil sub-samples were taken from the root zone (3–20 cm below the soil surface), after clearing organic matter from the surface. The samples were analyzed for physical and chemical properties by the methods of soil analysis of ASA and SSSA (1982). Rice plant samples were collected at harvest with three replications, and were analyzed for N and P concentrations using the methods of Allen et al. (1986). Data on rice yield were recorded at harvest based on straw (leaf plus stem), root dry weight, and seed dry weight. The analysis of variance for all data was conducted by the general linear models procedure of SAS. Pooled mean values were separated on the basis of least significant difference (LSD) at the 0.05 probability level.

Mass balance for water and nutrients

Water balance in the paddy fields was estimated by the variation in ponded water depth (W), expressed in the form:

$$W_j = W_{j-1} + IR_{1j} + IR_{2j} + PR_j - (DR_j + ET_j + INF_j) \quad (1)$$

where W_j is ponded water depth; W_{j-1} is ponded water depth on the previous day; IR_{1j} is amount of groundwater irrigation; IR_{2j} is amount of cascade inflow from an upper paddy field; PR_j is rainfall; DR_j is surface drainage through a weir; ET_j is evapotranspiration; and INF_j is deep percolation. The subscript j represents the jth day and all parameters are expressed in millimeters.

The nutrient input to the paddy fields was grouped into natural supply and fertilization, where natural supply included atmospheric deposition and irrigation water, and fertilization included mineral and organic sources. Nutrient output included surface drainage through the weir, deep percolation, and plant uptake. The general mass balance equation for both N and P was approximated in this study as:

$$I_{IR1} + I_{IR2} + I_{PR} + I_{FER} = O_{DR} + O_{INF} + O_{HRV} \quad (2)$$

where I_{IR1} is input from groundwater irrigation; I_{IR2} is input from an upper paddy field; I_{PR} is input from rainfall; I_{FER} is input from fertilization; O_{DR} is output through surface drainage; O_{INF} is output through deep percolation; and O_{HRV} is output through plant harvest.

To examine the impact of paddy rice farming on the water quality, a net output of N or P (O_{Net}) from a paddy field is defined with nutrient terms as shown below excluding fertilization and harvest terms:

$$O_{Net} = O_{DR} + O_{INF} - (I_{IR1} + I_{IR2} + I_{PR}) \quad (3)$$

It can be classified as a “purifying paddy” when O_{Net} is negative, and a “discharging paddy” when O_{Net} is positive.

Results and discussion

Water balance

Initial irrigation with groundwater was applied to the dry paddy field for land preparation, with treatment sites confined by dikes and weir heights adjusted to control water depth. Following the initial irrigation, the ponded water depth varied over time with natural precipitation and irrigation, except during two fertilization periods for tillering (May and June) and at panicle initiation (July). Water was forced to drain through weirs during the fertilization periods. A total of three irrigations with groundwater were applied to all the treatment plots to maintain ponded water depth. Figure 2 shows the variations in water depth and rainfall recorded for the plots. Generally, water inflow was supplied by irrigation for the first month, and thereafter the water level was maintained by rainfall and by drainage water from upper

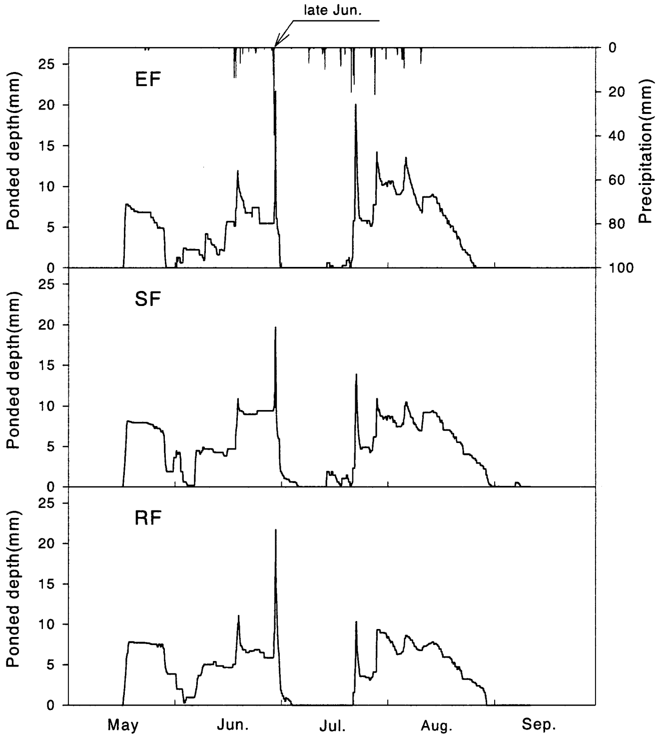

Fig. 2 Hydrograph of ponded water depth and rainfall record

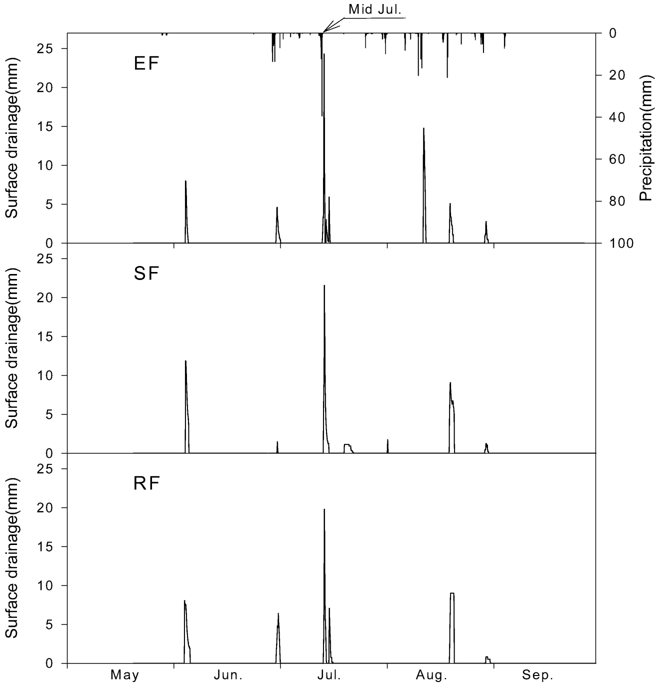

Fig. 3 Surface drainage from treatment plots and rainfall record

paddy fields. The landscape at the experimental site has a gentle slope, and paddy fields are developed in cascade terraces. This allows drainage water from upper paddy fields to flow into the treatment plots and drain to the lower paddy fields successively. Ponded water depth was not recorded after September because there was no significant rainfall or surface drainage. The water outflow pattern was similar among treatments, and surface drainage occurred mainly during times of high rainfall and when there was forced drainage for culturing practices (Fig. 3).

Total water inflow to the treatment plots (Table 4, where numbers in parentheses are percentages) ranged from 1,070–1,232 mm, about 41–48% of which was supplied by rainfall. The remaining inflow was from irrigation and upper paddy fields in about equal amounts. Total water outflow was closely balanced to the total water inflow, where surface drainage and evapotranspiration mainly removed the most water inflow and deep percolation was relatively small. The water balance in paddy fields depended predominantly on rainfall during the growing season; however, the rainfall received was less than that required for paddy rice culture. These results partly explain the importance of timely irrigation for rice production, as well as for total water requirement.

Evapotranspiration rates in all three treatment plots were lower during initial growth stages, higher at the full growth stage, with a maximum of 66.30 mm/10 days in early August, and subsequently declined at crop maturity. Deep percolation loss was relatively high at initial growth stages, with a maximum of 12.32–14.08 mm/10 days, and decreased with time except for a spike in August.

Nutrient balance

When considering the overall mass balance for nutrients (Table 5) among the three treatments, the SF treatment generally had a close balance between inputs and outputs, the EF treatment had a nutrient surplus, and the RF treatment had a deficit. Rice yield was correlated with fertilization rate, implying that within the range of

Table 4 Water balance summary (in mm) in the treatment plots during the study period. *Numbers in parentheses* are percentages

Plot	Inflow				Outflow			
	IR1	IR2	PR	Total	DR	INF	ET	Total
EF	261.87 (24)	296.64 (28)	511.30 (48)	1,069.81 (100)	507.24 (47)	72.88 (7)	488.53 (46)	1,068.65 (100)
SF	312.46 (27)	357.84 (30)	511.30 (43)	1,181.60 (100)	593.21 (51)	77.01 (7)	488.53 (42)	1,159.45 (100)
RF	380.24 (31)	340.14 (28)	511.30 (41)	1,231.68 (100)	648.44 (54)	77.52 (6)	488.53 (40)	1,214.49 (100)

Table 5 Nutrient balance summary (in kg/ha) in the treatment plots during the study period. *Numbers in parentheses* are percentages

Item	Plot	Inflow					Outflow				Difference
		I_{FER}	I_{IR1}	I_{IR2}	I_{PR}	Total	O_{DR}	O_{INF}	O_{HRV}	Total	
T-P	EF	29.46	0.23	0.96	0.01	30.65	1.12	0.00	18.49	19.61	–11.03
		(96)	(1)	(3)	(0)	(100)	(6)	(0)	(94)	(100)	
	SF	19.64	0.27	0.98	0.01	20.89	1.21	0.00	16.34	17.56	–3.34
		(94)	(1)	(5)	(0)	(100)	(7)	(0)	(93)	(100)	
	RF	13.75	0.33	0.89	0.01	14.97	1.20	0.00	15.61	16.81	1.83
		(92)	(2)	(6)	(0)	(100)	(7)	(0)	(93)	(100)	
T-N	EF	165.00	2.72	6.89	7.97	182.58	12.64	1.81	126.27	140.71	–41.87
		(90)	(1)	(4)	(5)	(100)	(9)	(1)	(90)	(100)	
	SF	110.00	3.25	8.09	7.97	129.58	12.73	1.73	115.95	130.40	1.16
		(85)	(3)	(6)	(6)	(100)	(10)	(1)	(89)	(100)	
	RF	77.00	3.95	9.50	7.97	98.42	14.70	1.97	105.63	122.29	23.80
		(78)	(4)	(10)	(8)	(100)	(12)	(2)	(86)	(100)	

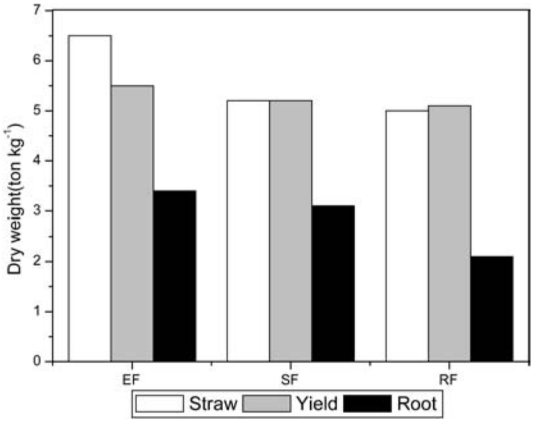

Fig. 4 Total (straw, yield, and root) dry weight of rice plants with treatments

treatments considered, the harvest might be increased by adding fertilizer at rates above the standard practice. The total dry weight per treatment plot in EF was 15.4 ton/ha, followed by 13.5 ton/ha in the SF treatment and 12.2 ton/ha in the RF treatment.

There was an apparent difference in the dry weight of leaf, shoot, and root, according to the change in fertilization rate. However, the dry weight of grain per plot displayed little difference among EF, SF, and RF treatments, with 5.5, 5.2, and 5.1 ton/ha, respectively (Fig. 4). This indicates that a higher fertilization rate does not necessarily assure greater grain production. There were differences between nutrient input vs. output in the treatments (Table 5), with positive values indicating a net loss in the paddy field and negative values indicating accumulation.

Monthly variations of T-P and T-N input and output also occurred (Figs. 5 and 6). Most of the T-P input was supplied by fertilization at transplanting, and a small portion was supplied by irrigation from the upper paddy field and groundwater. The T-N input was mainly supplied by the three applications of fertilizer. In addition, significant amounts of nutrients were supplied by precipitation and from the upper paddy field, comprising 9–18% of the total input, depending on treatment. Groundwater irrigation did not contribute much to the nutrient loading because of its relatively good water quality.

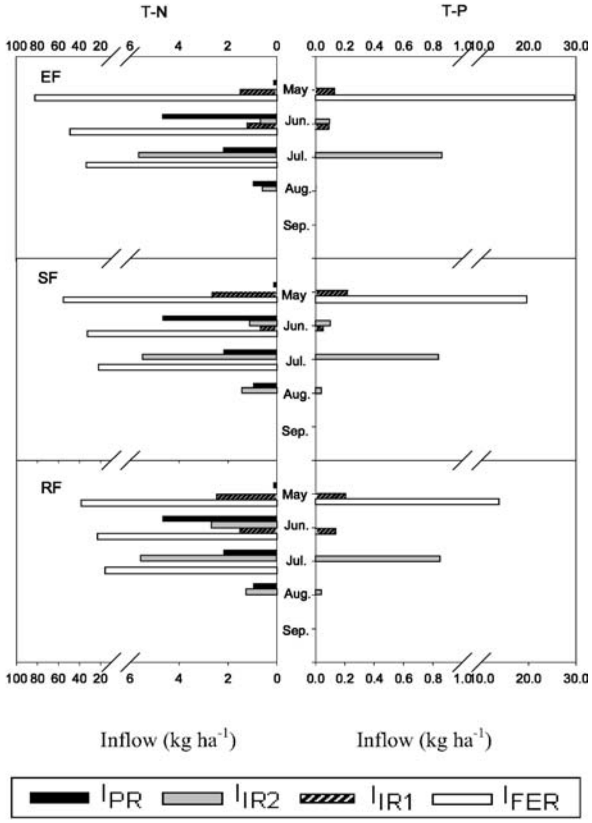

Fig. 5 Monthly nutrient inflow to the treatment plots. I_{IR1} Input from groundwater irrigation; I_{IR2} input from an upper paddy field; I_{PR} input from rainfall; I_{FER} input from fertilization

Although most of the nutrient output was attributed to plant uptake (Fig. 6), nutrient loss by surface drainage was substantial, at about 10% for T-N and 7% for T-P. Nutrient loss by deep percolation was negligible.

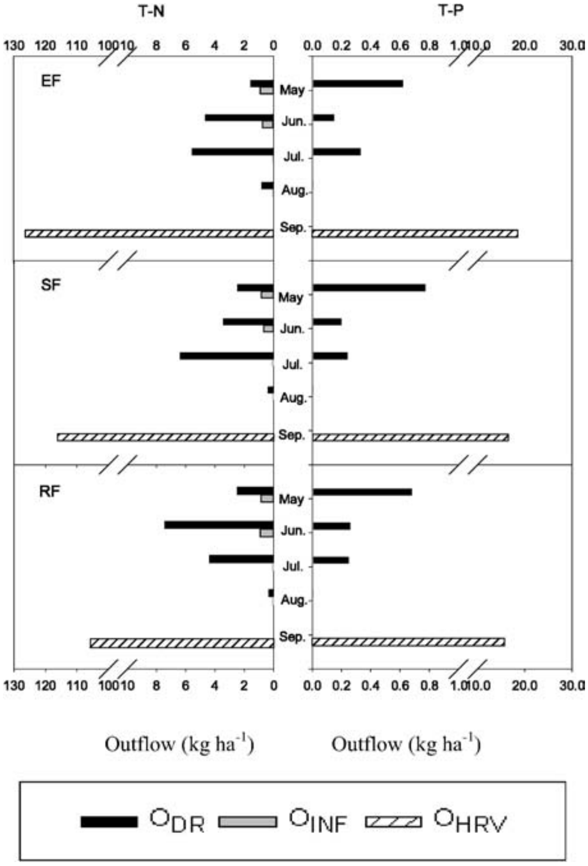

Fig. 6 Monthly nutrient outflow from the treatment plots. O_{DR} Output through surface drainage; O_{INF} output through deep percolation; O_{HRV} output through plant harvest

Nutrient net outflow

Nutrient outputs measured in this study were compared with the results from other studies in Japan (Udo et al. 2000) and Korea (Yoon et al. 2001) in Fig. 7. Although values are scattered, net output of T-N and T-P display general trends of increasing with rainfall amount; this is most apparent for T-N. Except for the Hikone City data, T-N net output tends to be negative when rainfall is less than 800 mm during the growing season, which implies that paddy fields can work as water purifying systems, rather than as pollutant discharging systems, as long as rainfall is relatively low. This is encouraging because annual rainfall is about 1,300 mm in Korea, and amounts below 800 mm during the growing season (May to October) are not unusual. Therefore, Korean paddy field might be classified as a landscape with the potential to purify water, from the perspective of T-N removal. This is contrary to the general idea that paddy rice cultivation always contributes significant amounts of nutrients to receiving water bodies.

The data on T-P net output are within the range of other Korean data; however, Japanese data are more positive, indicating that P is being discharged from the landscape. The discrepancy might be attributed to differences in culturing practices, soil characteristics, and/or rainfall intensity and duration. Overall, nutrient net outflow in Korean paddy fields increases as rainfall increases, and the paddy field could be used in a beneficial manner to retain nutrients, rather than discharging them, as long as rainfall does not exceed 800 mm during a growing period.

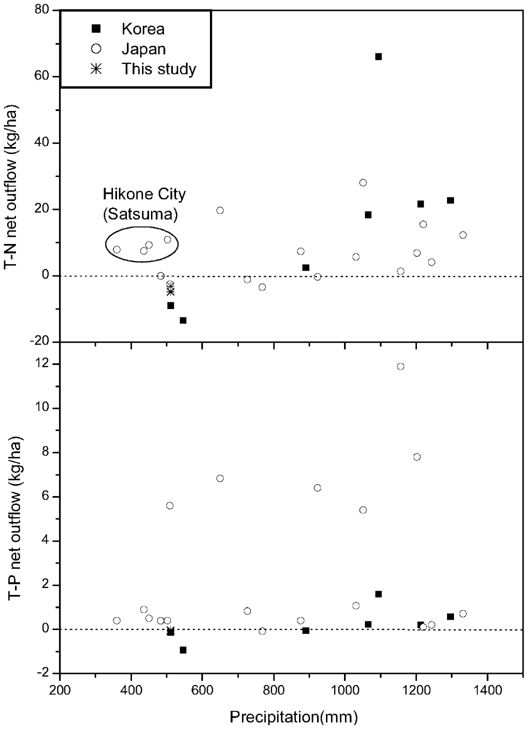

Fig. 7 Comparison of nutrient net outflow with other research results

Discussion

One of the important aspects of this study was to quantify the surface drainage of water, and export of nutrients, from rice fields treated with different fertilization rates. The aim was to suggest practical measures to protect downstream water quality. In all treatments, surface drainage constituted about half the total water loss (Table 4), surpassing evapotranspiration. Saving water by limiting inflow could be a possible strategy to reduce surface drainage, if rice production is not significantly affected. Bouman and Tuong (2001) reported that by reducing ponded water depth from 5–10 cm to the level of soil saturation did not reduce land productivity, and they found that 23% water savings caused only 6% yield reductions. Most Asian farmers on public irrigation systems have little incentive to reduce water inflow to their fields because irrigation is mostly charged on an area basis or not at all. Therefore, shifting to a pay-per-volume system might be considered as a means of saving water. Less water inflow, however, needs careful field management because rainfall does not necessarily meet the water requirements for rice culture, and very accurate and timely water delivery would be required.

Raising the drainage weir height in diked rice fields can increase rainwater storage by reducing excess flow from the field and reducing rainfall excess through surface drainage. A 3-year experimental study (Mishra et al. 1998) in India with weir heights of 6 and 30 cm, at an interval of 4 cm, revealed that about 57 and 100% of the rainfall could be stored in 6- and 30-cm weir height plots, respectively, without significant impact on grain yield. The weir height in this study varied, but was maintained at 10 cm most of the time. It could be raised further to save rainwater and reduce surface overflow if necessary. The other factor to be considered in reducing surface drainage is the irrigation practice for rice culture. Much of the surface drainage during the study period occurred for culturing purposes. Forced midsummer drainage has been practiced mainly for fertilization, and overall surface drainage could be reduced significantly with a minimized forced drain practice.

An important reason for reducing surface drainage water is the reduction of non-point source nutrient loading to receiving water bodies. In many countries, including Korea, water quality problems in rural areas are thought to be attributable largely to excessive fertilization and the resulting agricultural runoff. Nutrient loading from paddy fields occurs where the outflow water carries nutrients. Thus, reducing surface drainage water can reduce nutrient loading proportionally. As shown in Table 5, the fertilization rate itself did not affect nutrient loss by surface drainage. Therefore, paddy fields with even higher fertilization rates may be able to reduce nutrient loading substantially by minimizing surface drainage water outflow, mainly by a higher dike.

Considering the discussion above, water-saving irrigation, raising the drainage weir height in diked rice fields, and minimizing forced surface drainage could be suggested as measures to reduce nutrient loading from paddy fields. The possible benefits might include: (1) reduced irrigation water use and more efficient water resource allocation; (2) increased storage of rainwater with resulting flood prevention and groundwater recharge effects; and (3) reduced nutrient loss, i.e., reduced nutrient loading and fewer water quality problems. This paper describes the result of a 1-year experience with a specific cultivar and irrigation method, and further verification by studies of diverse cultivation conditions over longer periods of time should be sought for more decisive conclusions.

In contrast to the general viewpoint, rice culture in paddy fields may be beneficial from a water quality perspective (Fig. 7). Paddy fields could retain nutrients within the system as well as produce rice unless rainfall is extreme. If dike height is raised to enhance rainwater storage, its capacity to retain nutrients will be increased proportionally. Therefore, raising dike height is recommended for water quality protection as well as rainwater storage, as long as no significant loss of rice production is expected.

Conclusions

In this experimental study, less than half of the total water inflow of about 1,100 mm was contributed by precipitation and the remainder by irrigation. Water outflow generally balanced the inflow, with about half (47–54%) of the total outflow to surface drainage and 40–46% to evapotranspiration. Much of the surface water outflow occurred intermittently due to rainfall excess and forced drainage for rice culturing practices, with the latter being greater than the former.

The nutrient balance for P and N indicated that most (78–96%) of the inputs were supplied by fertilization and most (86–94%) of the outputs occurred as harvested plant material. However, significant amounts (6–12%) of nutrients were lost through surface drainage. Fertilization rate itself had little effect on rice yield or nutrient loss in surface drainage. Reducing nutrient loss by lowering fertilization rate may not work well in the range of normal paddy rice farming practices. Analysis of nutrient net outflow demonstrated that paddy rice culture might become more beneficial to downstream water quality if outflow volumes could be reduced.

Reducing nutrient loss through surface drainage could be achieved by water-saving irrigation, reducing ponded water depth, raised weir heights in diked rice fields, and minimized forced surface drainage. These practices might be suggested to reduce surface drainage outflow, and they could save water and protect downstream water quality. However, deviation from standard practices might affect the rice yield and further investigations on diverse cultivation conditions over longer period are recommended.

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