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Quantification of nitrogen leaching losses by paddy cultivation under controlled and continual runoff conditions

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Abstract In Asia, paddy is an important food crop that requires a high level of nitrogen, which is provided by straight chemical fertilizers that contribute a single nutrient, mainly urea. A study was conducted to quantify the leaching loss of nitrogen (as NO_3^--N) under two water management practices: controlled runoff and continual runoff in paddy cultivation at Low Country Intermediate Zone, Sri Lanka from 2015 to 2016 for four consecutive cropping seasons. Urea (N 46%) was applied as a sole source of Nitrogen at the rate of 225 kg ha^{-1}. A randomized complete block design was employed with triplicates by two factors and two levels (cropping seasons; Yala, Maha, gradients; upper, lower). Lysimeters were arranged to collect leached water. The leachate from the study plots was collected weekly throughout the cropping period and the total amount of leached NO_3^--N for each cropping season was quantified. The leaching losses of NO_3^--N accounted under controlled runoff and continual runoff conditions were 8.6 kg ha^{-1} and 3.0 kg ha^{-1} respectively throughout the cropping period. It contributed to 8% and 3% of Nitrogen out of the total amount of applied N fertilizers in the same order. The water management practices and gradient effects were significant with respect to nitrogen leaching losses from paddy fields while cropping season had no effect on nitrogen leaching. A significant amount of nitrogen leaching losses could occur under the root zone, even though a controlled runoff situation posing possible threats of surface and groundwater pollution.

Keywords: Nitrogen leaching, chemical fertilizer, paddy, rice.

1 Introduction

The green revolution was started by the introduction of new technologies, chemical fertilizers, and agrochemicals to fulfill the food demand of the rising population

(Holcomb 2010). Consequently, applications of commercial fertilizers have continuously increased to get a high yield (Anthony 2003). Rice is cultivated more than any other crop world-wide (AQUASTAT 2012). It is the most important food crop in Sri Lanka, taking up approximately 29% of the total agricultural land (CBSL 2020).

Nitrogen fertilizer is a crucial input for intensive rice cultivation and one of the key elements impacting rice production (Spiertz 2010, Zhang *et al*. 2012, Liu *et al.* 2016), since soils are low in nitrogen and typically only recover around half of the applied nitrogen (Fageria 2007). Therefore, nitrogen-based straight fertilizers which supply only one primary plant nutrient such as urea ($CO(NH_2)_2$, 46% N) were widely used in Sri Lanka (Illeperuma 2000) for rice cultivation to increase paddy yield (Iqbal 2011). Only a fraction of applied fertilizer is absorbed by plants (Iqbal 2011) and a fraction of unabsorbed fertilizers is lost from paddy lands through different mechanisms (Choudhury and Kennedy 2005). One of the main pathways for N loss from flooded agriculture is considered as N leaching (Meng *et al*. 2014). Although both ammonia nitrogen and nitrate nitrogen are extremely water soluble, more than 98% of the leached nitrogen is in the form of NO_3^--N as there is a low possibility of binding NO_3^--N with soil colloids (Yan *et al*. 2017). Hence, a significant amount of nitrogen is lost by drainage and runoff from paddy fields polluting the nearby surface waters (Yan *et al*. 2017). Eutrophication, hypoxia, algal blooms, biodiversity reduction and impacting public health, fishing and tourism (Abeygunawardane *et al*. 2011) seemed to be more prominent in the river basins and reservoir catchments that are dense with paddy crops (Piyasiri 2009). Management of fertilizer applications and water supply are important in reducing the nitrogen loss from paddy fields (Alam *et al*. 2023). In this context, the present study attempted to quantify the Nitrogen leaching from paddy lands under two water management systems; controlled runoff and continual runoff conditions. Under the controlled runoff situation, adequate water volume was supplied by supplementary irrigation to the paddy plot to maintain standard water level. However, water runoff from one plot to the other plot is not controlled under a continual runoff situation.

2 Material and Methods

2.1 Study area

The research was carried out in two experimental paddy fields (7.53 N, 80.44 E, 115 m) in Kurunegala District (Sri Lanka) that is part of the Low Country Intermediate Zone (temperature of 26.5-28.5^{0}C, relative humidity of 70-90%, and rainfall of 1750-2500 mm). The soil type is red-yellow podzolic, slightly acidic, with a bulk density of 1.7 Mg m^{-3} (Mapa *et al*. 2005). The study was carried out from 2015 to 2016 during four growing seasons under supplemental irrigation: The Yala season runs from May to the end of August during the Southwest monsoon, and the Maha season runs from September to March during the Northeast monsoon.

2.2 Experimental fields

Two sites (10 x 10 m^2) were selected based on two water management systems employed in the field. Site RS_1 was a well-maintained runoff-controlled paddy field. Rice seedlings that were 14 days old were transplanted with a 15 cm x 20 cm spacing. Urea (46% N), was applied at the rate of 225 kg ha^{-1} (practice by Rice Research and Development Institute) in four split applications at the 2nd, 4th, 6th, and 8th weeks after transplantation which can provide the total nitrogen availability of 103.5 kg N ha^{-1}.

Site FS_2 had the same climatic and soil conditions, while the direct sowing method was followed. For both fields, other agronomic practices were maintained as per the Department of Agriculture recommendations. In both water supply regimes, the water level was maintained similar to that of the surrounding paddy lands. The non-weighable lysimeters were employed for the collection of the leachate from the study plots.

2.3 Construction of leached water collecting device (non-weighable lysimeter)

The leachate from the study plots was collected by non-weighable lysimeters, which are made of 15 cm diameter, 45 cm length, opaque polyvinyl chloride (PVC) tubes (Figure 1).

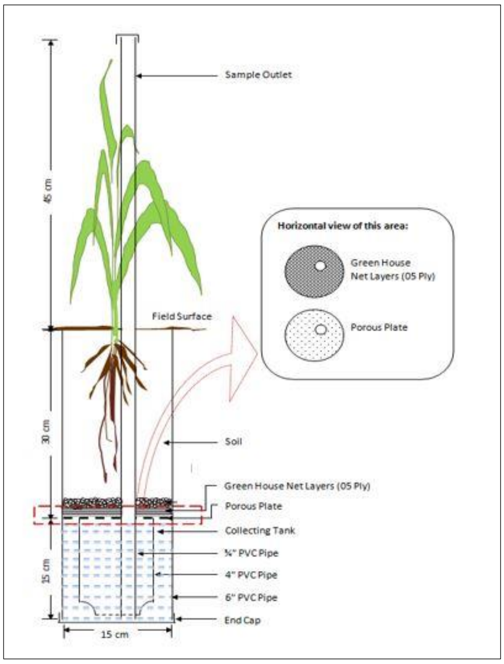

Fig. 1. Non-weighable lysimeter, the device used for collecting leached water from the pore spaces of soil

A tube was separated into two compartments by a porous PVC plate and five piles of greenhouse net to facilitate leaching while preventing the passing of soil particles. The upper part (30 cm) was used for establishing the rice plant and the lower part (15 cm) which was sealed with the end cap, was used as a collecting tank to collect the leached water. A PVC pipe (diameter 3/4") is inserted into the collecting tank, sample outlet is used to suck out the collected water by a suction tube (Figure 1).

2.4 Experimental Design

The lysimeters were arranged as per Randomized Complete Block Design (RCBD) with two levels and two factors (cropping seasons: Yala, Maha, and gradient, slope of the field: upper gradient, lower gradient) with four treatment combinations ($T_{1:}$ Yala, Upper; $T_{2:}$ Yala, Lower; $T_{3:}$ Maha, Upper; $T_{4:}$ Maha, Lower) with triplicates for collecting leached water below the root zone at the depth of 30 cm, during the entire cropping season.

After the preparation of the paddy land, lysimeters were set up with triplicates at the upper and lower end of the gradient of the research plots and filled with the soil of the same paddy field maintaining the same bulk density. At site RS_1, rice seedlings were transplanted in the field as well as in each lysimeter with control. At site FS_2, one rice plant was allowed to develop in each lysimeter after direct sowing. Runoff losses were controlled by providing adequate volume of water and the field's water level was appropriately regulated at site RS_1 but not at site FS_2.

2.5 Sampling and analysis

One day before the fertilization, leached water which filled up into lysimeters was sucked out to estimate the amount of NO_3^--N fertilizer leaching out from the field. During consecutive sampling times after fertilization, water samples were collected throughout the entire cropping season to estimate the leaching NO_3^--N amount. NO_3^--N concentrations were measured in irrigation water, runoff water and nearby water bodies too.

2.6 Determination of Nitrate (NO_3^-) concentration in water

Water samples were analyzed for content of nitrate using the APHA 4500-NO3$^-$-B; ultraviolet spectrophotometric screening method (APHA 2000). The absorbance of Nitrate (NO_3^-) and dissolved organic matter was measured at a wavelength of 220 nm. A measurement at a wavelength of 275 nm was obtained to determine the interference due to dissolved organic matter. Two times the absorbance reading at 275 nm was subtracted from the reading at 220 nm to obtain absorbance due to Nitrate.

2.7 Quantification of lost amount of NO_3^--N by leaching under the root zone

Based on the concentration of nitrate and the volume of leached water, the amount of NO_3^--N lost by leaching below the root zone, 30 cm of soil depth, was calculated. The leaching loss of NO_3^--N (kg ha^{-1}) for an entire growth cycle was quantified by summing up the NO_3^--N content in each sample for each site.

2.8 Estimation of percentage NO_3^--N leaching losses relative to the applied fertilizer amount

The percentage of NO_3^--N leaching losses relative to the applied fertilizer amount (% of pollutant load per applied N amount, kg ha^{-1}) for a given plot was quantified for the study period to understand the magnitude of the pollution load with the applied amount of N fertilizer with the rate of 103.5 kg N ha^{-1}.

2.9 Statistical Analysis

A multiple linear regression model ($Y = \beta_1X_1 + \beta_2X_2 + \ldots. \beta nXn + e$) was applied to assess the impact of three independent categorical variables on the leaching loss amount of NO_3^--N from the research paddy field (Y). The predictors are water management practice (X_1), controlled runoff and continuous runoff, cropping season (X_2), Yala and Maha, and the gradient of the field (X_3), lower gradient, and upper gradient. The effect of the same predictors (X_1, X_2, and X_3) on the leaching loss percentage of N from paddy fields (Y) was evaluated by another multiple linear regression model. Treatment differences were considered statistically significant at $P < 0.05$. Statistical analysis was done by Minitab 17 (Minitab Inc, 2017) statistical and data analysis software package.

3 Results

3.1 Lost amount of Nitrate nitrogen (NO_3^--N) by leaching

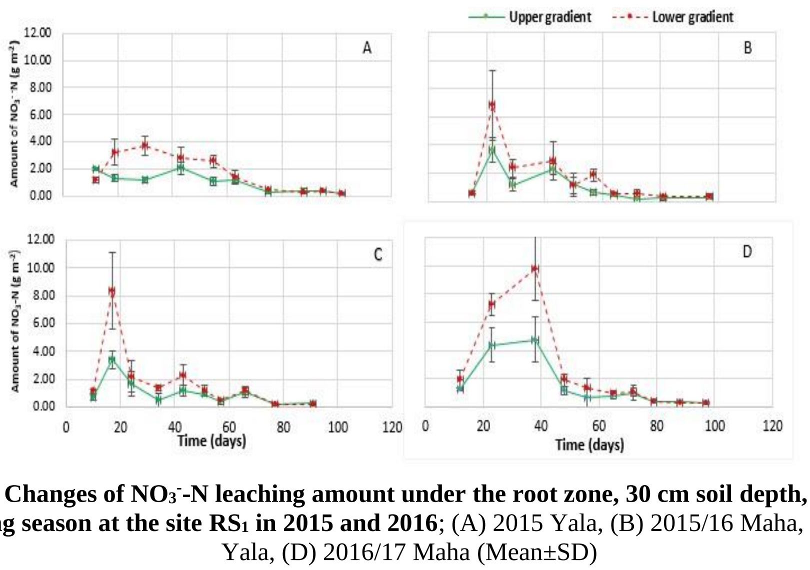

Fig. 2: Changes of NO_3^--N leaching amount under the root zone, 30 cm soil depth, in each cropping season at the site RS_1 in 2015 and 2016; (A) 2015 Yala, (B) 2015/16 Maha, (C) 2016 Yala, (D) 2016/17 Maha (Mean±SD)

In all four cropping seasons, the lower end of the gradient always exhibited a higher NO_3^--N amount than that of the upper end of the gradient (Figure 2). The third week after transplanting recorded the higher NO_3^--N amount which coincided with the 1st fertilizer application. The maximum amount of NO_3^--N in the leachate varied in the range of 1 -10 g m^{-2} in the 3rd week after transplantation in all four growing seasons.

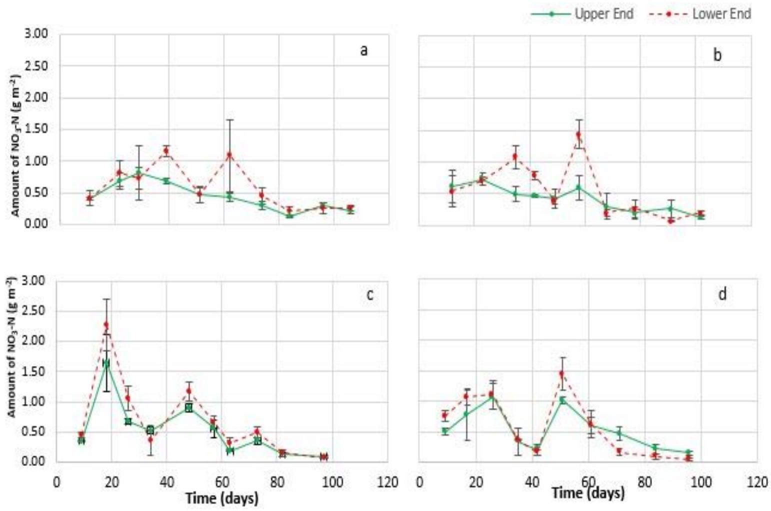

Fig. 3. Changes in mean leaching amount of NO_3^--N under the root zone (30 cm soil depth) within each cropping season at the site FS_2 in 2015 and 2016;
(a) 2015, Yala, (b) 2015/16 Maha, (c)2016 Yala, (d)2016/17 Maha (Mean ±SD)

According to Figure 3, the leached NO_3^--N amount was increased in the early vegetative stage and gradually decreased in the late vegetative stages. The trend was similar to Figure 2. A considerable amount of leached NO_3^--N was noted for all the sampling times recording the highest NO_3^--N lost amount in the 7th week except the 2016 Yala season, which corresponds with the 2nd fertilizer application. The minimum leaching loss was observed in later sampling times (after 60 days of planting) in the late growth stages, which were the observations made at the FS_1 site. Both leaching losses and runoff losses were evident in the FS_2 plot and runoff losses occurred in the range of 2.5 - 3.3 mg L^{-1}. Nitrate content of irrigated water was negligible. However low nitrate concentration (1.8 - 2.2 mg L^{-1}) were observed in nearby water bodies.

3.2 The total lost amounts of NO_3^--N and percentage relative to the applied Nitrogen lost through leaching under the root zone

The total loss amounts of leached NO_3^--N per unit area (kg ha^{-1}) for each growing cycle are given in Table 1. In terms of all the seasons at both sites, site RS_1 reported the highest amount of NO_3^--N loss (11.3 kg ha^{-1}) and it varied between 7 kg ha^{-1} to 11 kg ha^{-1}. The variation of NO_3^--N loss amount in RS_2 site fluctuated from 2.7 kg ha^{-1} to 3.5

kg ha-1. The average of NO_3^--N loss amount was 8.6 ± 1.8 kg ha^{-1} for RS1 while it was 3.0 ± 0.4 kg ha^{-1} for RS_2.

Table 1: Lost amount of NO_3^--N by leaching at controlled run-off (site RS_1) and continuous run-off (site FS_2), for each cropping season in 2015 and 2016.

Cropping season	Plot RS_1	Plot FS_2
	NO_3^- -N (kg ha^{-1})	NO_3^- -N (kg ha^{-1})
2015 Yala	7.1	2.9
2015/16 Maha	8.0	2.7
2016 Yala	8.2	3.5
2016/17 Maha	11.3	2.7
Average	8.6 ± 1.8	3.0 ± 0.4
Avg (Yala)	7.6 ± 0.8	3.2 ± 0.4
Avg (Maha)	9.6 ± 2.4	2.7 ± 0.00

The results obtained by a multiple linear regression model applied to assess the impact of water management practice (X_1), controlled runoff and continuous runoff, cropping season (X_2), Yala and Maha, and the gradient of the field (X_3), lower gradient, and upper gradient on the leaching loss amount of NO_3^--N from paddy fields (Y) (Figure 4).

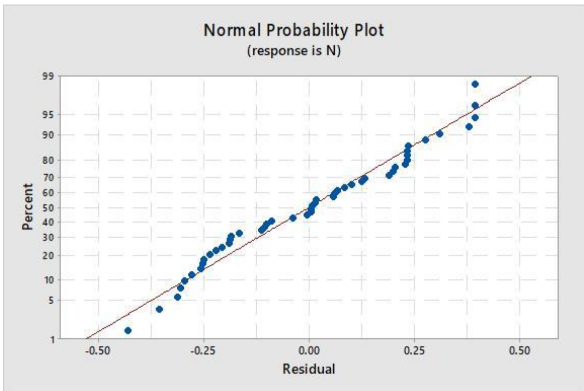

Fig 4. **Normal probability plot of the residual response to leaching loss amount of NO_3^-N**

It was assumed that a sample size of 48 was sufficient to detect significant predictors of NO_3^--N loss from the paddy field, minimizing errors. A linear trend of scatterplots was shown for water management practice, cropping season, and the gradient of the field against the NO_3^--N loss amount. The model explains 82.2% of the variance in NO_3^--N loss amount, with an adjusted R^2 of 81.0%. Water management was a statistically significant predictor of loss of NO_3^--N as indicated by an F statistic of 166.91 with a p value less than 0.000. The gradient of the field was also significant at a 5% level indicating a significant effect on loss of NO_3^--N from paddy fields. Furthermore, cropping season did not have a significant effect on the leaching loss of

NO_3^-N at the significance level of 0.05. The regression equation was Y = 1.1243 - $0.8738X_1 + 0.1024X_2 + 0.3934X_3$. The leaching loss amount of NO_3^--N from the continual runoff water management practice (site FS_2) was significantly lower by 0.8738 compared to the controlled runoff practice (site RS_1). The lower gradient has significantly higher leaching losses of NO_3^--N compared to the upper gradient by 0.3934. The model was fitted well (adjusted $R^2 = 0.8097$) and does not affect external factors on the loss amount of NO_3^--N. The random dispersion of residual plots was observed and confirmed the model assumptions.

According to Figure 5, leaching losses as a proportion of the nitrogen fertilizer applied varied between 7% and 11% at the site RS_1 and 3% to 4% at the site FS_2, where total urea applications were 103.5 kg N ha^{-1}. The average % of NO_3^--N losses was 8.3 ± 1.8 kg ha^{-1} for RS1 while it was 3.3 ± 0.4 kg ha^{-1} for RS_2.

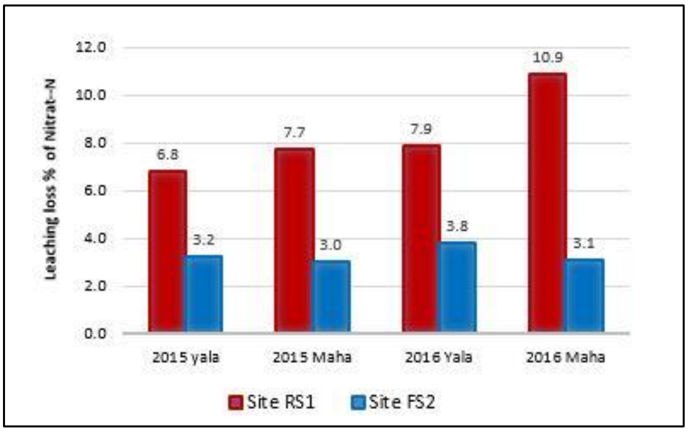

Fig. 5. **Percentage of leaching loss amount relative to the applied fertilizer amount of NO_3^-- N below the root zone,** 30 cm soil depth, at controlled runoff site RS_1 and continual runoff site FS_2 for four consecutive cropping seasons in 2015 and 2016.

Following results achieved by the multiple linear regression analysis that assessed to ascertain the impact of categorical variables such as water management practice (X_1), cropping season (X_2), and the gradient of the field (X_3), on the leaching loss percentage of NO_3^--N from paddy fields (Y). Scatterplots of all predictors against % of the N loss revealed linear tendencies. The model illuminates an adjusted R^2 of 0.7923. Water management practices and gradients illustrate a significant effect on the percentage loss amount of NO_3^--N as indicated by F=144.7, p < 0.000, and F = 35.43, p < 0.000, respectively. There was no significant effect of cropping season on leaching % of NO_3^--N loss amount. The regression equation was $Y = 1.0850 - 0.7847X_1 + 0.0944X_2 + 0.3883X_3$. Under continual runoff water management (site FS_1), loss % of NO_3^--N was significantly lower by 0.7847 compared to controlled runoff water management practice (site RS_1). The lower gradient has a significantly higher percentage NO_3^--N losses compared to the upper gradient by 0.3883. The model was fitted well, indicating adjusted $R^2 = 0.8055$, and external factors were not affected. The random dispersion of residual plots confirms the model assumptions.

4 Discussion

Nitrogen is the most important nutrient impact to the rice yield (Liu *et al*. 2016). Nitrogen fertilizers are applied to paddy lands to enhance the nitrogen level. Since the fraction of applied nitrogen is absorbed by plants and the remaining is lost from paddy lands through different mechanisms, including leaching (Choudhury and Kennedy 2005). These phenomena were well supported by the observations made in this study.

The loss amount of NO_3^--N at the lower gradient was higher than at the upper gradient. This signifies the downward movement of water with the gradient and concentration at the lower ends of the field increasing the leaching of nitrate with water at all times. The flowing water contains dissolved elements including nitrate resulting in comparatively high NO_3^--N amount in the leachate at the lower gradient than the upper gradient (Suprapti *et al*. 2010).

When N-based chemical fertilizer was applied, Nitrate concentration increased over a short period raising the concentration of nitrate in leachate. The same observation was recorded by Iqbal (2011), where he reported that the NO_3^- -N concentration was significantly high at 30 cm soil depth, 7 days after urea application. In the present study, a high NO_3^--N amount was noted in leachate at early growth stages while not in late growth stages. Nitrogen use efficiency was reported to be higher at the late stages of the rice plant and hence, the N losses also declined (Wang *et al*. 2003).

In contrast to the late vegetative stage and reproductive stage, high nitrate losses were seen in the early vegetative stage. The plant absorbed N more effectively and leaching losses were reduced at the late vegetative and reproductive stages most probably due to the well-developed root system and the high demand of the growing stage of the plant. The reproductive stage and ripening stage of BG 358 take 35 and 30 days, respectively (IRRI 2015). During the ripening stage, the plant undergoes grain filling and maturation. At that stage, rice does not absorb N from the soil but utilizes N that is already available in plant tissue (Hashim *et al*. 2015). Plant demand for N was diminishing later as the plant growth rate declined (Glass 2003), and hence N fertilizer was not applied to the field. This results in minimum leaching losses occurring in the late growth stages of the current study as well. Iqbal (2011) and Meng *et al*. (2014) also noted the same observations.

Compared to the leached NO_3^--N amount values of site RS_1, it was low in site FS_2 and the variation pattern was also dissimilar. In the RS_1 plot, of which runoff was controlled, dissolved NO_3^--N was lost mainly through leaching. A high leached NO_3^--N amount was recorded below 30 cm soil depth. Low nitrate concentration was observed in nearby water bodies. However, it was negligible in irrigated water. Only the NO_3^--N amount lost due to leaching was considered in this experiment, and runoff loss was not considered. However, runoff losses were observed under continual runoff conditions at RS_2. Therefore, comparatively a low amount of leached NO_3^--N below 30 cm soil depth was recorded in the FS_2 site. The excessive use of nitrogen fertilizer was especially harmful because a large portion of the N that was not absorbed by plants was converted into nitrate, which was highly water soluble and quickly added into surface waters via runoff. Further, there is a probability to contaminate groundwater (Iqbal 2011).

Nitrate was highly water-soluble (Iqbal 2011) and a significant site difference was observed in the leaching loss of NO_3^--N due to the differences in agronomical and water management practices in the two sites. RS_1 plot was runoff controlled and maintained the standard water level. Therefore, it could be assumed that all excess NO_3^--N amount was lost through leaching. In the farmer's plot (FS_2) which was under continual runoff, excess NO_3^--N loss happened not only by leaching but also as runoff.

Iqbal (2011) observed a loss of NO_3^--N of 1.25 kg/ha (1.38%) when urea was applied at a rate of 196 kg ha^{-1} a (90 kg N ha^{-1}) for the paddy field in the South-east coastal area of China. The same study also reported that the nitrogen losses is increased in parallel to the application rate. For example, when the application was increased up to 784 kg ha^{-1} (360 kg N ha^{-1}), the loss was increased by 0.61% (2.20 kg ha^{-1}). A lysimeter experiment recorded the nitrogen leaching from double-rice grown soil, which reached up to 27.5 kg N ha^{-1} when 200 kg N ha^{-1} was applied (Zhu *et al*. 2000). However, in the same soil, a field experiment showed only 7 kg N ha^{-1} was lost by leaching when 300 kg N ha^{-1} was applied (Zhu *et al*. 2000). A lysimeter experiment, leaching losses of N were approximately 6% when urea was applied with ten identical dosages by total usage of 120 kg N ha^{-1} (Zhu *et al*. 2000). However, one dosage during transplantation led to 13% N leaching loss (Zhu *et al.* 2000). Russian research revealed that the N leaching losses were 3-9%, in China, it was 0.1% to 15% of the applied N fertilizer amount (Zhu *et al*. 2000). The same results were observed in this lysimeter study with recording approximately 8% of NO_3^--N was lost by leaching when urea was applied at rate of 225 kg ha^{-1} (103.5 kg N ha^{-1}) by four split applications in runoff control situation. In continual runoff condition, approximately 3% of N leaching lost amount was recorded.

4 Conclusions

This study revealed nitrogen released from the paddy cultivation as the critical contributory factor for water pollution. The water management practices and gradient effects were significant with respect to nitrogen leaching losses from paddy fields while cropping season did not affect nitrogen leaching. A significant amount of nitrogen leaching losses may still occur under the root zone even in the case of controlled runoff conditions that could potentially be hazardous for contaminating surface and groundwater.

The findings of the current study emphasize the necessity for additional scientific research on the reduction of nitrogen losses from paddy lands and accompanied deterioration of surface water bodies by the usage of chemical fertilizers in paddy agriculture, control measures, as well as the hazardous effects on humans.

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