Monitoring of Nitrogen Leaching from a Tropical Paddy in Thailand

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Abstract

A study on monitoring of nitrogen (N) leaching was conducted in acid- sulfate clayey soil in the central region of Thailand. The objective was to measure the N leaching to shallow groundwater from a tropical paddy field to assess the consequences of agricultural management practices. Mass balance approach was used to estimate the contribution of nitrogen fertilizer to the water environment. The N inputs to and outputs from field were measured by direct method. Inputs of N to the site came from commercial fertilizer, precipitation, irrigation water and soils. Outputs of N from the site were leached to groundwater, harvested crops, in surface runoff, soils and loss from the field. Leaching loss was calculated from daily fluxes of water percolation and soil water N concentrations extracted by vacuum lysimeter. Based on three month observation, average leaching of nitrate nitrogen (NO^-_3-N), ammonium nitrogen (NH_4^+-N) and total Kjeldahl nitrogen (TKN) to groundwater was found 0.04, 0.11 and 0.17 kg $ha^{-1}d^{-1}$ respectively. It was also observed that fertilizer application increased NO^-_3-N concentration at five-fold in groundwater. Although, the measured NO^-_3-N concentration in groundwater was below the threshold value of WHO drinking water standard (10 mg/l), such increment may pose a serious threat during the dry season when the groundwater recharge is very low. Furthermore, nitrogen mass balance result showed that loss of N inputs as outflow to the water and atmosphere were from the 19 % and 13.6% of total applied N respectively which indicates fertilizer input was responsible for water pollution. In this study, minor components such as groundwater input, mineralization and input from the atmosphere through biological fixation were ignored due to lack of available data where it should be considered.

Keywords: Nitrate leaching, Denitrification, Nitrogen fertilizer, vacuum lysimeter

Introduction

Excessive use of fertilizers and pesticides in agriculture is thought to be a major contributor for water pollution (Laegreid et al., 1999). Nitrogen is a vital nutrient for eutrophication in natural water bodies, which has been linked to low dissolved oxygen (DO) concentration that decrease the number of aquatic animal, and then ultimately affects the aquatic ecosystems (Fisher,1989). Contamination of drinking water by nitrate (NO^-_3) is a major problem for municipal water systems and domestic water wells and linked to methemoglobinemia in infants (Ray, 2001) and human birth defects (Fletcher, 1991).

Groundwater pollution by nitrate is a serious problem in many developed countries and has been reviewed in recent years (Wilson et al., 1999).

The sources of nitrate in the soil are from the direct application of nitrate fertilizers, oxidation of ammonium fertilizers, and oxidation of innate soil organic matter. Nitrogen is leached wherever rainfall or water supply exceeds the evapotranspiration, and significant leaching losses have been reported in a number of cropping systems (Katyal et al., 1985). Loss of N by leaching mainly occurs in the form of NO^-_3-N because of the low capacity of most soils to retain anions and quite solubility of nitrate salts in water. However, the movement of waters and solutes through a soil profile is not a simple process. Pore structure in soil is heterogeneous and water moves more rapidly through larger pores than through smaller ones and may be stopped entirely in those that are not continuous. Even within a single pore there is a flow velocity distribution (Hagin and Tucker, 1982).

Furthermore, N leaching is economically and environmentally undesirable. Nitrate that leaches below the crop rooting zone represents the loss of a valuable plant nutrient and hence an economic cost to agriculture. Unless they are managed properly, their positive contribution to agricultural productivity could be negated by their adverse impact on the environment. The understanding the movement of nitrogen through soils is essential for decision making to improve efficiency of nitrogen use and avoiding nitrogen pollution.

Thailand remains as the largest rice exporter in the world (Ministry of Agriculture and Cooperatives, Thailand, 1991) in terms of both by volume and value (FAO, 2000). About one third of Thailand's gross area (51million ha) is arable and 52.8% of arable area is used for rice production while 98.3 % of rice field is occupied by paddy field. In the past, very few studies have been done in nitrate leaching (Asadi, 2002, and Pathak, 2002), however, nitrate leaching phenomenon from paddy field still poorly understood. The objective of this study was to monitor the nitrogen leaching to shallow groundwater to assess the consequences of agricultural management practices.

Materials and Methods

Site description

This study was conducted in an experimental field in 2001 at Asian Institute of Technology, Pathumthani Province, Thailand. The elevation of the experimental site is 2 to 2.5 m above the mean sea level. The region has a humid climate and the mean annual rainfall is 1,300 to 1,400 mm of which more than 80% of precipitation falls in the rainy season. The average monthly temperature ranges from 19 to 35°C and relative humidity fluctuates from 70-80%. Groundwater table is usually high and varied from 0.40 to 1.5 m during the crop period. The area of the experimental field is about 1,600 m^2 with irrigation canal on its three sides (Figure 1) and meteorological station located at about 60 m from the experimental plot.

Experimental field arrangement

To evaluate the quantities of nitrogen input and output in the field, major components of the flow and the storage of water and nitrogen were measured at the experimental field.

Triangular weirs with pressure sensor were installed at the inlet and the outlet of the experimental field to measure the water level and flow rate. Two rain gauges were installed diagonally to the field to fetch the precipitation. Lysimeter was installed inside the plot to measure the evapotranspiration from the field and plants. Eight PVC tube wells having 10 cm inside diameter and 2m length were drilled around the plot at a distance of 4m, while four more PVC wells were drilled at 80m from the field to observe the groundwater level and water quality. Daily groundwater table was measured by the measuring probe. The depth of water in the plot was recorded daily by vernier scale installed at two corner of plot and converted into volume of water stored in the field.

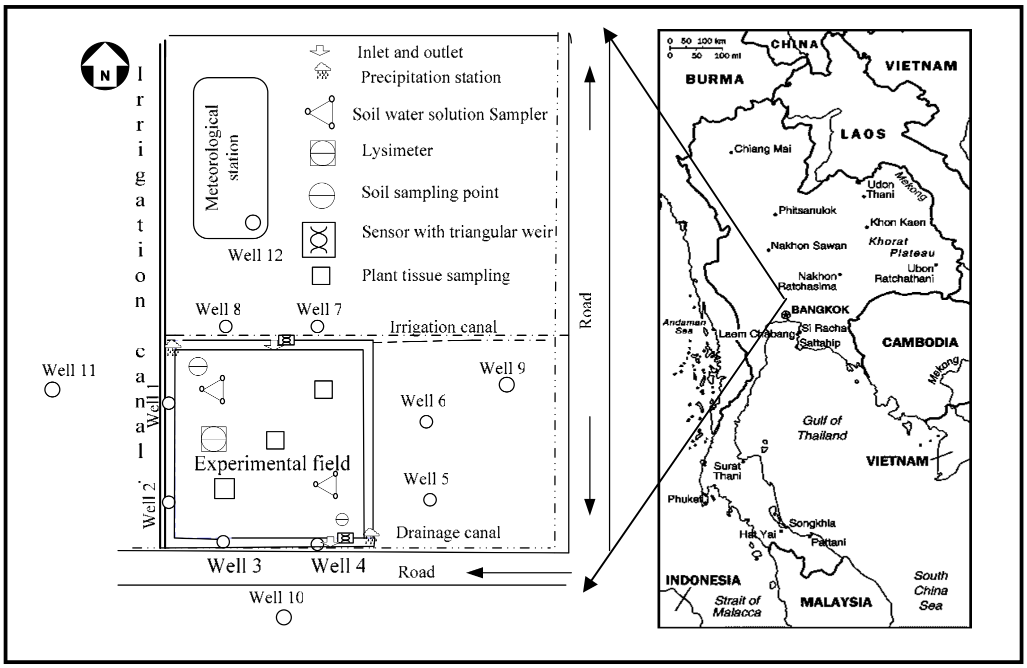

Figure 1 Layout of the study area and experimental management

Soil water existing in the soil pores were collected by soil water samplers having diameter of 4.8cm (Model 1900, Soil moisture Equipment Co.), in order to get more precise estimation of the amount of N leaching into subsurface flow. To avoid possible contamination, ceramic cups of the soil water samplers were washed with dilute acid before inserted into the ground (Litaor, 1988). Vertical holes of 76mm in diameter were dug with a hand auger up to the depths of 20, 40 and 60cm from the soil surface at two points in the experimental field on September 23, just after the emergence. To get good contact between the ceramic cups and the soil, slurry of the soil material was put on the bottom of the hole before inserting the soil water sampler and in the side after inserting the soil water sampler (Grossmann, and Udluft, 1991).

Rice seeds were directly sown on the ground on September 14. Major components of nitrogen flow had been measured until rice was harvested (December 24). The local practice in field management and cropping systems were applied. Three different does of inorganic fertilizer (Table 1) was supplied at the time of seeding and during the cultivation as per local practice in the Thailand. Weeds were controlled manually and pesticide was applied occasionally.

Table 1 Summary of fertilizer application and water sampling date

Date of Fertilizer applied	Fertilizer Dose	Type of Inorganic Fertilizer	Amount of Fertilizer Kg-N/ha	Frequency of water sampling	Sampling depth (cm)
September 14	I	Metrophos	30	*Every weeks after the soil water sampler installed	20
October 13	II	Urea	43		40
November 20	III	Urea	27		60

* Rice seeding was sown on September 14 and the soil water samplers were installed about 2 weeks later.

Soil and water Samples collection and analysis

Irrigation water, drainage water, and precipitation samples were collected at every event in polyethylene bottles. Groundwater samples and ponding water samples were collected twice in a week. Soil-water samples were collected by suction pump once a week from each sampler during whole cultivation period. Vacuum of 30 KPa (1/3 bar) was applied to each sampler about 48 h before the sampling. The extracted sample volume was generally small to minimize the disturbances of the system and sampling period and to avoid alteration of the sample in the sampling system. The first sample was rejected in each case and water samples were analyzed for NO^{-}_{3}-N, NH_4^{+}-N and TKN concentrations by cadmium reduction method and digestion followed by Phenate method respectively (American Public Health Association, 1998).

Soil sampling was carried out at before cultivation and after harvesting from four different layers (mentioned in results and discussions) to identify the physical and chemical properties of soil. Soil samples were taken from four layers with a typical double-cylinder core having 5.6 cm in diameter and 4 cm in height to obtain bulk density of the soil sample. Particle density was measured by pycnometer method. Soil samples to measure saturated hydraulic conductivity were also taken with a typical double-cylinder core having 9.8 cm in diameter and 9.5 cm in height and Falling head method was adopted to measure the saturated hydraulic conductivity.

For chemical analysis, soil samples were also taken to plastic bags from four different depths. Soil-water pH, particle size and organic matter were measured by glass electrode method, hydrometer method and dry ash method respectively. Extraction method (2.0M potassium chloride) was used to measure the NO^{-}_{3}-N in soil. The difference in amount of N in soil samples before cultivation and after harvesting was considered as the amount of N in the soil stored/loss in the soil.

Water balance and nitrogen leaching

Mass balance approach was used to determine the deep percolation of water as follows:

$$DPR = I + P - ET - R \qquad (1)$$

Where DRP is the deep water percolation in mm, I is irrigation water applied during the day in mm, P is precipitation in mm, ET is the evapotranspiration in mm and R is runoff from the plot in mm. In this experimental field, the water loss from the field in terms of lateral seepage was assumed to be zero, as polyethylene sheets were set on the levees to prevent lateral seepage. Leaching at the experimental field was considered above the groundwater surface; therefore, the groundwater outflow was not taken into account.

Total amount of nitrogen in input and out terms were calculated by multiplying the nitrogen concentration in each term mentioned in Equation 2 with the respective volume of water. The nitrogen mass balance in the experimental field can be expressed as

$$N_{loss} = N_{in} - N_{out} - N_{diff\ soil} \qquad (2)$$

Where, $N_{in} = [N_f + N_i + N_p]$, $N_{out} = [N_d + N_l + N_u + N_{loss}]$ and $N_{diff\ soil} = [N_sf - N_{si}]$. The subscripts f, i, p, d, u, l, and loss represent fertilizer, irrigation water, precipitation, drained water, leaching to groundwater, uptake by plants and the loss from the experimental field as denitrification and anammox respectively. N_{si} is the amount of nitrogen stored in pre-cultivation soil and N_{sf} is the amount of nitrogen stored in post-cultivation soil. The amount of nitrogen accumulated in the soil during the cultivation period was estimated by subtracting the amount of nitrogen contained in the soil at pre-cultivation from the post-cultivation. The sphere of one meter depth from the soil surface was assumed to consider the amount of nitrogen stored, and it was calculated by multiplying the weight of dried soil by the average nitrogen content at each layer of soil. The other minor component such as biological nitrogen fixation, mineralization, groundwater contribution, ammonium volatilization and weeds productions were ignored.

Results and Discussions

Properties of the soil

Four different color of soil in the vertical profile was found until total depth of 120 cm. and has been separated into four different soil layer (Table 1). The pore size distribution of the soil profiles was assessed by visual observation and estimated as meso-pores (30 to 100 µm diameter). Average saturated hydraulic conductivity of the soil before cultivation ranged between 2.951E-06 to 4.478E-04 cm/s while the after cultivation was varied from 9.259E-07 to 3.741E-04 cm/s (Table 2a). Saturated hydraulic conductivity at the second layer (20-40 cm) from the soil surface before and after cultivation presented quite different values, suggesting the effect of rice cultivation activities. The criteria set for saturated hydraulic conductivity of clay is generally less than 2.0E-03 m/d (2.31E-06 cm/s) supports that the soil in this experimental field is basically classified as clay (Smedema and Rycroft, 1983). Average bulk density was varied from 1.18 and 1.35 g/cm^3 while average particle density was between 2.65 and 2.71 g/cm^3. The porosity was between 0.47 and 0.62. The bulk density decreased during cultivation by average 18 % and this decrease in bulk density means the increase of pore space in the soil during cultivation which is supported by the increase in porosity (Table 2a).

Table 2a Physical properties of soil in the experimental field

Depth (cm)	Particle size distribution			Saturated hydraulic conductivity (cm/s)		Porosity	
	Clay (%)	Silt (%)	Sand (%)	B	A	B	A
0-20	76.80	11.25	11.95	2.951E-06	9.259E-07	0.47	0.51
20-40	70.55	15.00	14.75	1.742E-05	4.630E-07	0.49	0.57
40-60	80.55	13.75	5.70	1.852E-05	1.470E-05	0.55	0.57
60-120	79.30	16.25	4.45	4.478E-04	3.741E-04	0.55	0.62

Table 2b Physical and chemical properties of soil in the experimental field

Depth (cm)	Bulk density (g/cm^3)		Particle density (g/cm^3)		Organic Carbon (%)		pH	
	B	A	B	A	B	A	B	A
0-20	1.35	1.30	2.65	2.65	4.43	5.24	4.70	3.58
20-40	1.33	1.27	2.70	2.68	4.39	4.16	3.85	3.42
40-60	1.22	1.20	2.71	2.69	4.62	3.61	3.59	3.19
60-120	1.18	1.13	2.69	2.66	3.62	3.27	3.30	3.08

A- after cultivation, B- before cultivation,

The pH value of pre-cultivated soil varied layer by layer and its values ranged from 4.70 to 3.3 (Table 2b). Since the pH in all layers was below five and has high percentage of clay contents, the soil was categorized as acid sulfate. Because of the acid sulfate clayey soil (with pH range from 4.70 to 3.58 on the first layer), NH_3 losses from these soils were less probable (Mountonnet and Fardeau, 1982). Average organic carbon was ranged from 3.45 to 4.84 % and found highest in first the layer.

Water percolation and nitrogen leaching

There were 37 rainfall events during the experimental period and the total depth of precipitation was 541.1 mm. Irrigation water was applied 14 times during the cultivation period and ponding water depth was kept at 10 cm usually. The total volume of irrigation water supplied to the field was 1480.6 m^3 (925.4 mm) and average 79.5 mm irrigation water was taken into the plot by one irrigation event. Drainage occurred 15 times during the cultivation period and the total volume of drainage water from the plot was 550.7 m^3 (344.2 mm). The total amount of evapotranspiration measured by a lysimeter during the cultivation period was 416.75 mm and the average daily evapotranspiration was 4.13 mm. The percolation rates calculated from water balance method during the cultivation period ranged between 0 and 13 mm/d and the average daily percolation was 5.21 mm. At the end of the experiment, the percolation rate was slightly less than that in other periods.

The NO^-_3-N concentration in the precipitation samples ranged between 0.08 and 1.30 mg/l, and total amount of NO^-_3-N from precipitation onto the experimental field for the whole cultivation period was calculated to be 1.14, kg/ha. The NO^-_3-N concentration in the irrigation water samples ranged between 0.01 and 0.20 mg/l and the total amount was 0.64, kg/ha. The NO^-_3-N concentration in the drained water samples ranged between 0.20 and 0.90 mg/l, and the total amounts of NO^-_3-N was 0.52 kg/ha.

The effect of N fertilizer application on NO^-_3-N concentration in the soil water was observed in upper soil layer about the one week after the fertilizer application. However, the effect of first dose of fertilizer could not observe in detail because soil water samplers were installed after the two week of seeding. NO^-_3-N concentrations in soil water solution after application of second dose inorganic fertilizer showed significant increment of NO^-_3-N in different layers and fluctuations in percolation water strongly correlated with groundwater levels and percolation rate (Figure 2a). The greatest concentration of NO^-_3-N in upper layer soil exists one week after the second dose of fertilizer application while at the 40 cm depth the effect was observed after two weeks later. At the depth of 60 cm fertilizer effect was observed after four weeks (on November 14) and delay presumably caused by the low hydraulic conductivity in upper layer. Factors such as planting method, shallow irrigation, formation of macro pore due to alternate soil wetting and dry, and soil disturbance during weeding operation probably buildup the NO^-_3-N concentrations in the soil because these activities encourage better soil aeration for nitrification. Other factors such as shallow rooted crop, primarily uses the nutrients in the surface layer and allow NO^-_3-N to move deeper in the soil, where it is prone to loss via leaching to groundwater.

The effect of third dose of fertilizer also follows almost similar trend with second dose which are not shown in the text, however the values are used while calculating the nitrogen load in the mass balance.

The ground water table during observation period was about 50-70 cm from the ground level and the NO^-_3-N concentration in groundwater was found high after the four weeks of fertilizer application. The amount of NO^-_3-N leached to groundwater was obtained by multiplying the NO^-_3-N concentration in the soil water at the corresponding depth with the percolation rate. The total amount of NO^-_3-N leached to groundwater during whole cultivation period was calculated to be 3.63 kg/ha, implying the average NO^-_3-N leaching was 0.04 kg ha^{-1} d^{-1}. In the beginning of crop period, the rate of nitrate leaching was relatively small and maximum leaching was found after one week of the second and third doses of fertilizer application. It suggests that groundwater is vulnerable to increased level of nitrate right after the fertilizer application. However, the leaching duration and amount varied with soil type, crop type and water availability.

The TKN concentration in soil water solution at different layer of soil shows the direct relation with fertilizer application. Figure 2b trend was generally similar to that of NO^-_3-N leaching at corresponding soil layers. Moreover, NH_4^+-N leached trend was also similar to that of TKN, which is not shown here.

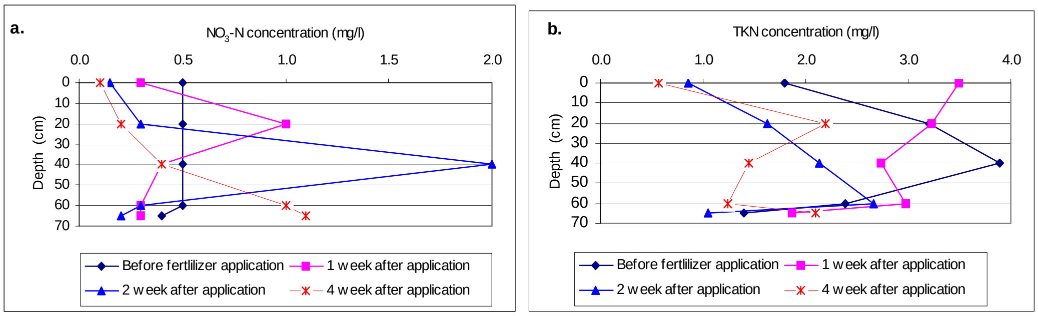

Figure 2 vertical profile of (a) NO^-_3-N and TKN concentration

Nitrogen mass balance

The total amount of nitrogen in pre-cultivation soil was 9,672.3 kg/ha and that in post-cultivation soil was 9,673.5 kg/ha, and the difference was not significant and taken as constant value. However, the calculation of nitrogen amount in soil may contain considerable error due to the spatial variability of soil properties both horizontally and vertically.

Nitrogen contained in the seeds was 3.83 kg/ha. Average nitrogen concentrations in harvested grains, stems, leaves and roots were 1.23, 0.51, 0.75 and 0.63 % of dried matter, respectively. The total amount of nitrogen stored in harvested plant tissues was 84.4 kg/ha and the amount of nitrogen uptake by plants was therefore 80.57 kg/ha.

The NO^-_3-N, NH_4^+-N and TKN concentration in the precipitation ranged from 0.08 to 1.30 mg/l, 0.55 to 15.64 mg/l and 0.11 to 5.03 mg/l, respectively. The total NO^-_3-N, NH_4^+-N and TKN in precipitation were 1.14, 3.68 and 9.72 kg/ha respectively. The total amounts of NO^-_3-N, NH_4^+-N and TKN in irrigation water were 0.64, 1.72 and 8.58 kg/ha, respectively. The amount of NO^-_3-N, NH_4^+-N and TKN in drainage water were 0.52, 1.52 and 4.13 kg/ha respectively. The total amount of N fertilizer applied in three times during the cultivation period was 100 kg/ha.

The total amount of N input from irrigation, precipitation and fertilizer were 9.22, 10.85, 100, kg/ha, while the N output in drainage, percolation and plant uptake were 4.65, 18.20 and 80.57 kg/ha, respectively. Total of amount of N in the soil before and after cultivation was not significant and taken as constant value. Sum of N loss calculated from the nitrogen mass balance model was 16.7 kg/ha (Figure 3) which corresponds to the 13.6% of total N input.

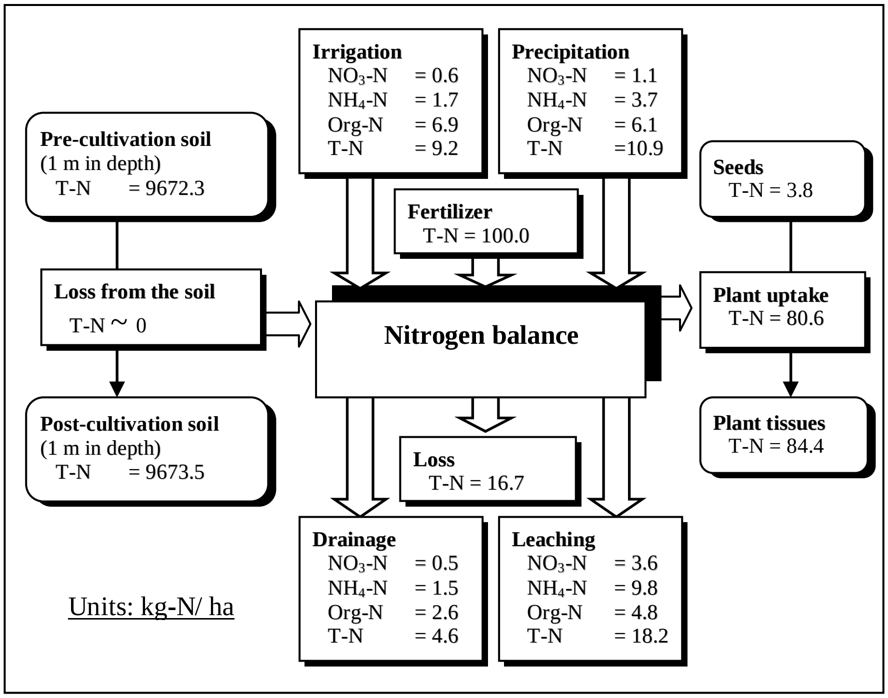

Figure 3 Nitrogen flow in the experimental field for the whole cultivation period

Nitrogen concentration in groundwater

The effect of fertilizer on groundwater was found after one week of the first dose of fertilizer application and NO^-_3-N, NH_4^+-N and TKN concentration increased from 0.6 to 0.70, 0.1 to 0.56 and 1.97 to 2.06 mg/l respectively. Second dose of fertilizer increased NO^-_3-N, NH_4^+-N and TKN concentration from 0.2 to 1.1, 0.58 to 1.77 and 1.05 to 2.10 mg/l which was found after four weeks. The effect of third dose was found after three weeks of application and NO^-_3-N, NH_4^+-N and TKN concentration was increased from 0.4 to 0.7, 0.38 to 2.03 and 1.64 to 4.37 mg/l respectively. It was found that the NO_3-N concentration in shallow groundwater was elevated to five fold after fertilizer application than existing NO_3-N concentration. Though, the NO_3-N concentration in groundwater is below the world health organization (WHO) threshold value (10 mg/l) for the drinking water, such increment in nitrate level pose a serious threat to the water quality and aquatic ecosystems as well.

Since nitrogen loss was determined by the difference of nitrogen components with respect to the total, the quality of the result was influenced by the accuracy of all calculated/ assessed terms. In this study minor components such as groundwater input, mineralization and input from the atmosphere through biological fixation were ignored due to lack of data where it should be included. Under Thai conditions, however these results may be important particularly in finding better management practice on flooded paddy field.

Conclusions

This study aimed to assess the N leaching to groundwater and nitrogen loss from a tropical paddy field. Based on three months observation, total NO^-_3-N leaching and average daily leaching were 3.63 and 0.04 kg/ha respectively. It was also found that the fertilizer application induced five times increment in NO^-_3-N concentration in groundwater. In addition, it was found that NO^-_3-N leaching was high when the soil moisture was high and macro pores was formed during dry field condition. Although, the measured NO^-_3-N concentration in groundwater was below the threshold value of WHO drinking water standard (10 mg/l), such increment may pose a serious threat during the dry season when the groundwater recharge is very low.

Furthermore, the percentage of N outflow to the surface and groundwater was 19.02% of total N input, which indicates the loss of resources and the existence of water pollution as well. The contribution of applied N fertilizer to the atmosphere was found to be 13.6% of total input N, indicating one of the major sources of pollution. Therefore, it is recommended to review the existing cultivation practices to minimize the environmental pollution.

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