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FULL-LENGTH RESEARCH ARTICLE

Effect of Inorganic and Organic Fertilizer Application on Nitrate Leaching in Wetland Soil Under Field Tomato (*Lycopersicon esculentum*) and Leaf Rape (*Brassica napus*)

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Abstract The implications of increased application of N inputs to agricultural systems in Africa for nitrate leaching are still only partially understood in Africa. A lysimeter experiment was carried out on a loamy sandy soil in central Zimbabwe in order to determine the effect of cattle manure and mineral N application on nitrate leaching. A cluster of zero-tension (free flowing) lysimeters was established, and leachates and soil samples were analyzed for nitrate N concentration and mineral N content, respectively. Increasing the application rates from 100 kg N fertilizer + 15 Mg manure to 200 kg N fertilizer + 30 Mg manure ha^{-1} increased NO_3–N leaching by 60 %. Applied N lost in leachate increased by 6 and 19 % for the tomato and rape crops, respectively, when N fertilizer and manure application rate was doubled. Higher mineral N fertilizer and cattle manure applications increase total N lost in leachate. The pollution of groundwater with nitrate in leaf rape cropping in Zimbabwe is potentially higher than that found in the production of tomato for the crop rotation in the current study.

Keywords Wetland · Soil · Tomato · Rape · Nitrate leaching

Introduction

Sustainable fertilizer application should provide sufficient nutrients for growth of crops while simultaneously avoiding the risk of water and air pollution due to nutrient surpluses [3]. In the African sub-tropical regions, water is one of the most critical factors that limit smallholder food crop production. The integrated resource management concept, which has become a dominant paradigm in sustainable rural development in developing countries, has encouraged the tapping of local wetland water resources by smallholder farmers in order to improve food security systems [22]. Smallholder farmers grow vegetable crops in small gardens along wetlands and river courses [9]. The high commercial value of the vegetable crops has encouraged wetland vegetable producers to over-fertilize in order to minimize any risk of yield reduction due to nutrient stress [27]. However, vegetable cropping systems that include tomato and leaf rape have a low N recovery compared with cereal crops (70 % N recovery) and consequently, about 50 % of N applied as mineral fertilizer or N mineralized from added animal manures remains unused in the soil and is subject to leaching [10, 15, 17]. The relatively early harvest of vegetable crops compared to other field crops creates a high nutrient leaching potential for both native and previous crop

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residue N during growing period. The fertilizer N use efficiency for tomato crop is generally considered to be low with values lower than 50 % [8].

Manures play an important role in soil fertility management through their short-term effects on nutrient supply and long-term contribution to the soil organic matter [19, 29, 30]. The low efficiency of manures from most smallholder areas as sources of N has prompted farmers to supplement manures with inorganic N fertilizer [19, 24]. Before manure N is available to plants, nitrogenous organic compounds must undergo decomposition and N mineralization. The mineralization and immobilization of N from applied manure depend on its total N content, C:N ratio, and polyphenol content [16]. Polyphenols in applied manure affect the release of N from decomposing organic material by forming stable complexes with proteins, thereby stabilizing the organic material [16, 29, 30].

The concentration of nitrate in ground water, rivers, and lakes has been increasing steadily over the past 30 years in large parts of the world [2, 3, 10, 15]. Regulatory agencies in most countries limit the amount of nitrate permissible in drinking water to less than half the concentration known to cause toxicity. In the USA, the limit on nitrate is 45 mg L^{-1} nitrate (or 10 mg L^{-1} N in nitrate form). In Europe, the standard is 50 mg L^{-1} nitrate [2, 28]. Key drivers of nitrate leaching from cropping systems were described extensively in a related study by Mishima et al. [17]. About 19 % of applied N fertilizer is lost as NO_3–N leaching from soil at global level [17].

In Zimbabwe, about 66 % of soils on potential arable land are coarse-grained granitic sands [13] characterized by high infiltration rates normally associated with high nitrate leaching [18]. Wetlands in Zimbabwe cover approximately 1.28 million hectares, of which 25 % are found in the smallholder areas where rape and tomato crops are grown [9]. The main objective of the current study was to determine the effects of N fertilizer and cattle manure application on NO_3–N leaching under field tomato and rape crops grown on wetland. In this study, it was hypothesized that NO_3–N leaching increases with increasing rates of application of N fertilizer and cattle manure.

Materials and Methods

Site Description

The study was conducted between 2007 and 2008 in a wetland garden at Dufuya (19°17′S; 29°21′E) wetland in Lower Gweru smallholder area in central Zimbabwe. The experimental site is located in Agro-ecological Region III characterized by mean annual rainfall ranging from 650 to 800 mm and a mean annual temperature of 21 °C [18]. The soil is deeply weathered and is coarse-textured loamy sand in top-soils over lying sandy loam sub-soils derived from granite and classified as Udic Kandiustalf (USDA) and Gleyic Luvisol (FAO) [11, 23, 25]. Tomato and rape are high-value vegetable crops grown under informal irrigation by smallholder farmers at Dufuya. Generally, the vegetable crops have a low applied N recovery rate [8, 27] and in an effort to avoid yield depression of the high-value crops, smallholder farmers apply manures and mineral fertilizers at rates far in excess of those employed in commercial agriculture [9]. Because of lack of availability and higher cost of fertilizers, smallholder farmers have resorted to the use of cattle manure which are readily available. However, wetland farmers with financial resources from vegetable sales apply cattle manure in combination with mineral fertilizers in order to increase nutrient availability and vegetable production. Usually, 15 Mg ha^{-1} of cattle manure is applied by wetland farmers with limited number of cattle (less than 6). On average, 30 Mg of cattle manure ha^{-1} is applied by wetland farmers with larger cattle herds (more than 6). Mineral N fertilizer applications in combination with cattle manure are applied in rates of 100–200 kg N ha^{-1} depending on the financial resources of the farmer. The fertilizer rates were used as treatments in the experiments in order to capture the common farmer practice. Under wetland cropping conditions, N is readily lost by leaching and denitrification [17, 22], with nitrate concentrations in shallow ground water reaching hazardous levels.

Meteorological Data Collection

Rainfall data were collected daily at 10.00 h from a rain gage at the study site. Maximum and minimum daily temperature data at the study site were obtained from the department of Agricultural Technical and Extension Services (AGRITEX) meteorological information at Sogwala (19°17′S; 29°21′E) rural service centre located 2 km west of the study site. The meteorological station records daily weather data.

Treatment Details

The following hypothesis was tested: Increasing the application rates of smallholder cattle manure and N fertilizer increases NO_3–N leaching and N_2O fluxes in soil. The specific objective of this study was to determine the effects of application rates of smallholder cattle manure and N fertilizer on NO_3–N leaching. The following treatments were used in the lysimeter experiment:

(i) Control
(ii) 100 kg N fertilizer ha^{-1} + 15 Mg cattle manure ha^{-1} (low rate)

(iii) 200 kg N fertilizer ha^{-1} + 30 Mg cattle manure ha^{-1} (high rate)

A randomized complete block design with four replications was used in the experiment. A basal application rate of 1,000 kg ha^{-1} compound S (5 % N, 7.9 % P, 16.6 % K, 8 % S) [9] was used in all treatments before planting each crop, in order to capture farmer practice. Cattle manure was applied only once in the study period before planting of the first tomato crop. The manure was evenly broadcast in the respective lysimeters and then incorporated into the topsoil a few days before transplanting the first crop. Ammonium nitrate fertilizer (100 and 200 kg ha^{-1} N, 34.5 % N) was applied to each crop in two equal applications (50 and 100 kg N ha^{-1}). The first application was banded into the planting furrows and covered with soil a day before planting. The second application was done by banding fertilizer on the side of the planted rows a month after transplanting.

Soil Sampling and Analysis

Twenty soil cores (5 cm diameter, 5 cm height) for soil characterization were randomly collected from the experimental site. Organic carbon in soil was determined using the Walkley and Black method [20]. Soil texture was determined by the Bouyoucos hydrometer method [5]. The soil cores were used to determine soil bulk density and porosity.

The soil cores were oven-dried at 105 °C (to constant weight) for determination of mean gravimetric water content. Total porosity was calculated by considering particle density of soil as 2.65 g cm^{-3} [4]. Total N in soil was measured by the Kjeldahl method using concentrated H_2SO_4, K_2SO_4, and HgO to digest the sample [6].

Total carbon and N in cattle manure were determined using the procedure described by Nelson and Sommers [21] and Bremner and Mulvaney [7, 26], respectively. Total C and N constituted 22.82 and 1.36 % of manure on dry matter basis, respectively. The C:N in manure was 17:1 with a soil + ash content of 77.18 %. The contents of organic C and total N in manure on a soil- and ash-free basis were 61.3 and 6.4 %, respectively.

Field Lysimeter Experiment

Figure 1 shows an aerial view of the lysimeter set-up in the field experiment. A cluster of zero-tension (free drainage) 40 × 40 × 50 cm lysimeters was established in November 2006, about 10 months before commencement of the experiment in September 2007. The lysimeter boxes were fabricated from 1.6-mm-thick galvanized steel sheets, which do not easily rust [1]. Repacking of the lysimeters closely followed the sequence of the soil horizons identified during soil excavation. Four holes were drilled into soil 15 cm from the lysimeters using a soil auger to weathered material limiting effective depth. Perforated rigid polyvinyl chloride pipes (RPVC) that allow free movement of soil water were placed into the auger-drilled holes for measurement of water table depth. The first tomato, first rape, second tomato, and second rape crops were grown in sequence in the same lysimeters subjected to various N fertilizer and cattle manure treatments. Four rape and two tomato seedlings were planted in each lysimeter. About 35 mm of irrigation water was applied using the bucket system once a week to maintain plant growth at field capacity moisture level during the dry season and midsummer season dry periods for both test crops. This is a common practice by farmers based on extension advice. Wetland vegetable farmers at Dufuya do not vary the amounts of irrigation water from crop to crop.

Leachate and Soil Sampling

Cumulative leachate volumes were computed and recorded every fortnight during the vegetative period of each crop (six for rape and seven for tomato). Leachate samples were collected and immediately analyzed for nitrate N concentration by calorimetric method [14]. Nitrogen loads were calculated as follows:

$$NO_3 - N_{leach} = [NO_3{-}N] \times Vol \times 0.002 \times T_{days}, \qquad (1)$$

where NO_3–N_{leach} is the total NO_3–N leached from soil in kg N ha^{-1}, (NO_3–N) is the concentration of NO_3–N in leachate, Vol is the mean daily leachate volume in liters for the period, 0.002 is the conversion ratio after resolving mg (NO_3–N) to kg N ha^{-1} and converting NO_3^- molar mass to N content (14/62), and T_{days} is the number of days of approximately similar leachate volumes.

At the same time that leachate samples were collected, soil samples collected from each lysimeter were analyzed for NH_4–N and NO_3–N using colorimetric techniques [14].

Dry Matter Yield

Rape leaves and tomato fruits that reached horticultural maturity were harvested from the randomly selected plant in each lysimeter at every harvesting event and taken to the laboratory (98 and 84 days of harvesting for tomato and rape crops, respectively). The samples were rinsed, oven-dried at 65 °C, weighed, and kept in a dry place. At the end of the growing season, the aboveground biomass of the selected plants was summed up. The composite samples were analyzed for N concentration using the semi-micro Kjeldahl method [7]. Total N uptake was determined by multiplying the N concentration with dry matter yield.

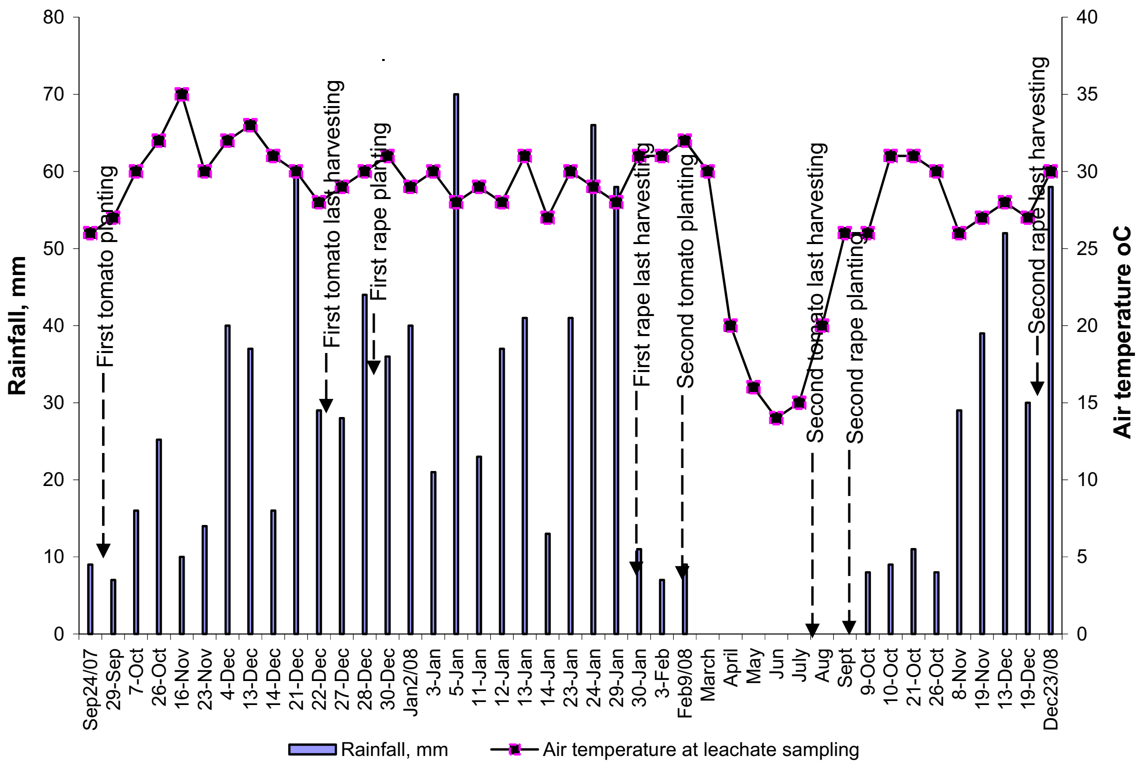

Fig. 1 Daily rainfall and air temperature at the study site

Statistical Analysis

Treatment effects on the measured variables were analyzed using repeated measurements analysis of variance to determine the significance of variance between treatments on the data recorded over time and Two-Way ANOVA of final recording of data in GenStat 14 software [12]. Differences between treatment means were judged significant at $p \leq 0.05$ as determined by Fisher's protected least significant difference test.

Results

Weather Conditions

The 2007–2008 summer rainy season started at the end of September. Long-term data analysis has shown that the rainy season starts generally at the beginning of November for the area. About 98 % (792 mm) of the total rainfall (808.2 mm) was received in the first half of the season (September–January; Fig. 1). The 2007–2008 dry (winter) season was generally frost free and had maximum and minimum temperatures of 20 and 15 °C, respectively. The mean maximum and minimum temperatures for the area are 20 and 15 °C, respectively. The 2007–2008 rain (summer) season had the mean maximum and minimum temperatures of 31.5 and 24.5 °C, respectively. The 2008–2009 rain (summer) season started at the beginning of October when 36 mm of rainfall was recorded. The summer season was characterized by hot and humid weather with the maximum and minimum air temperatures of 30.5 and 26.5 °C, respectively.

Volumes of Leachate Collected from Lysimeters

The pattern of leachate volumes collected from lysimeters was largely similar for all treatments for specific periods clearly showing that treatment effects on volumes of leachate were not significant ($p > 0.05$). Cumulative volumes of leachate recorded during the growing periods of the second tomato and rape crops exceeded cumulative incident precipitation by 5 and 26 %, respectively. Overall, total leachate volumes over two seasons of the study exceeded cumulative precipitation by 188.1 mm (16 %) (Fig. 2). The upward capillary rise and lateral movement of soil water did not enter the lysimeters because of the impervious fabricating material of the lysimeters. The net volumes of leachate collected from lysimeters were not affected by the upward capillary rise of soil water.

Mineral N Concentrations in Soil

In the current study, NH_4–N was regularly recorded in soil samples collected every 14 days of the growing period of

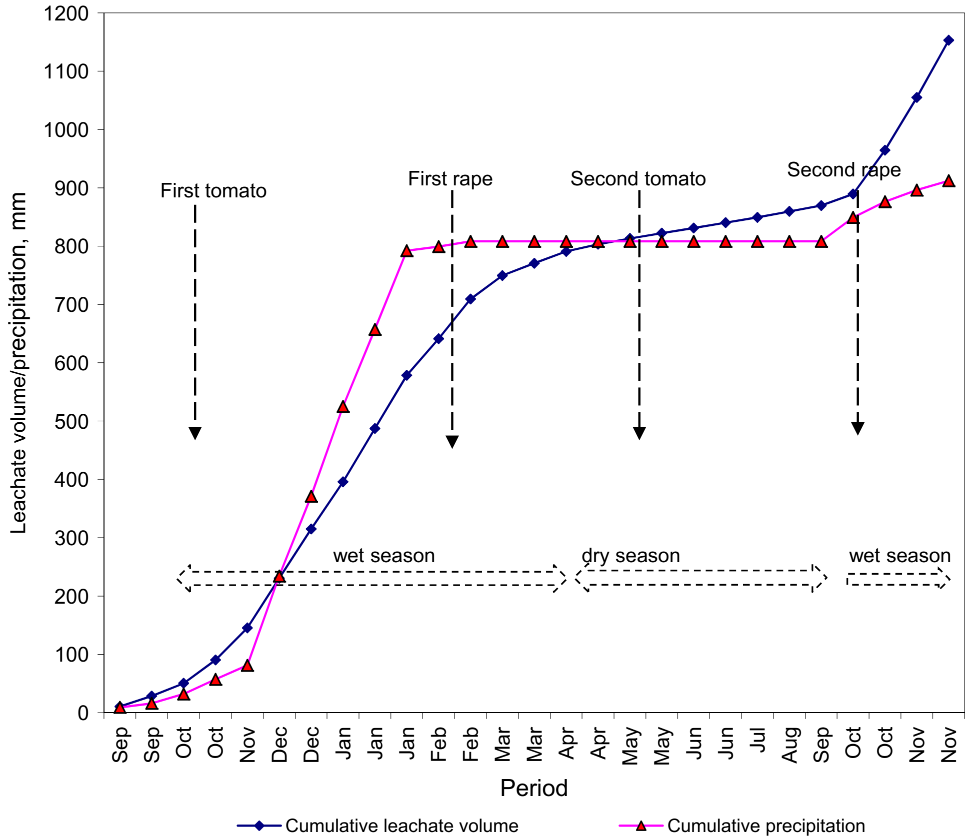

Fig. 2 Cumulative precipitation and leachate volumes following various application rates of ammonium nitrate fertilizer and cattle manure in 2007 and 2008

tomato and rape crops (Fig. 3). There were significant ($p < 0.05$) differences in the concentrations of mineral N (NH_4–N + NO_3–N) in lysimeter soil as the application rates of cattle manure and mineral N fertilizer varied (Figs. 3, 4). The concentration of mineral N in soil subjected to application of 100 kg N + 15 Mg manure (low rate) and 200 kg N + 30 Mg manure ha^{-1} (high rate) consistently exceeded that recorded in control lysimeters by 136 and 223 %, respectively.

Increasing the rate of application of mineral N fertilizer and manure from low to high was accompanied by an increase in the concentration mineral N in soil of 38 %. Over the course of the growing seasons, concentrations of NH_4–N and NO_3–N in the 0–20-cm soil layer gradually decreased toward the end of the growing period of tomato and rape crops (Figs. 3a, c, d and 4a, c, d) with expected increase in N uptake and the gradual decrease in organic N decomposition processes. This, however, was not the case for the first rape crop where the concentrations appeared to increase toward the end of the growing season (Figs. 3b, 4b).

Nitrate N Concentration in Leachate

Application rate of mineral N fertilizer and cattle manure had a significant effect ($p < 0.05$) on the concentration of nitrate N in the leachate throughout the study period (Fig. 5). The concentrations of NO_3–N in leachate samples collected from lysimeters that received 100 kg N + 15 Mg manure and 200 kg N + 30 Mg ha^{-1} were 119 % (3.8–9 mg L^{-1}) and 266 % (6.5–21.9 mg L^{-1}) more than those recorded in leachate samples from the control lysimeters, respectively. The concentration of NO_3–N in leachate from lysimeters subjected to 100 kg N + 15 Mg and 200 kg N + 30 Mg ha^{-1} exceeded the recommended 10 mg L^{-1} for safe drinking water by 1.3–2 and 2.2–3 times, respectively. Control lysimeter concentrations of NO_3–N exceeded the safe drinking water standard by 0.4–0.5 times for the first rape and the second tomato and rape crops (Fig. 5b, c).

Estimated Loss of N Through Leaching

Significant differences in the total amounts of N lost in leachate NO_3–N ($p < 0.05$) were recorded between treatments (Tables 1, 2). Losses of N through leaching were substantially higher in the period of December 2007–January 2008 in lysimeters that received 200 kg N mineral fertilizer + 30 Mg manure ha^{-1} (28.1 kg N leached ha^{-1}) under the first tomato and rape crops when highest rainfall totals were registered (Table 2; Fig. 6). Generally, the proportion of applied N lost in leachate was lower in the

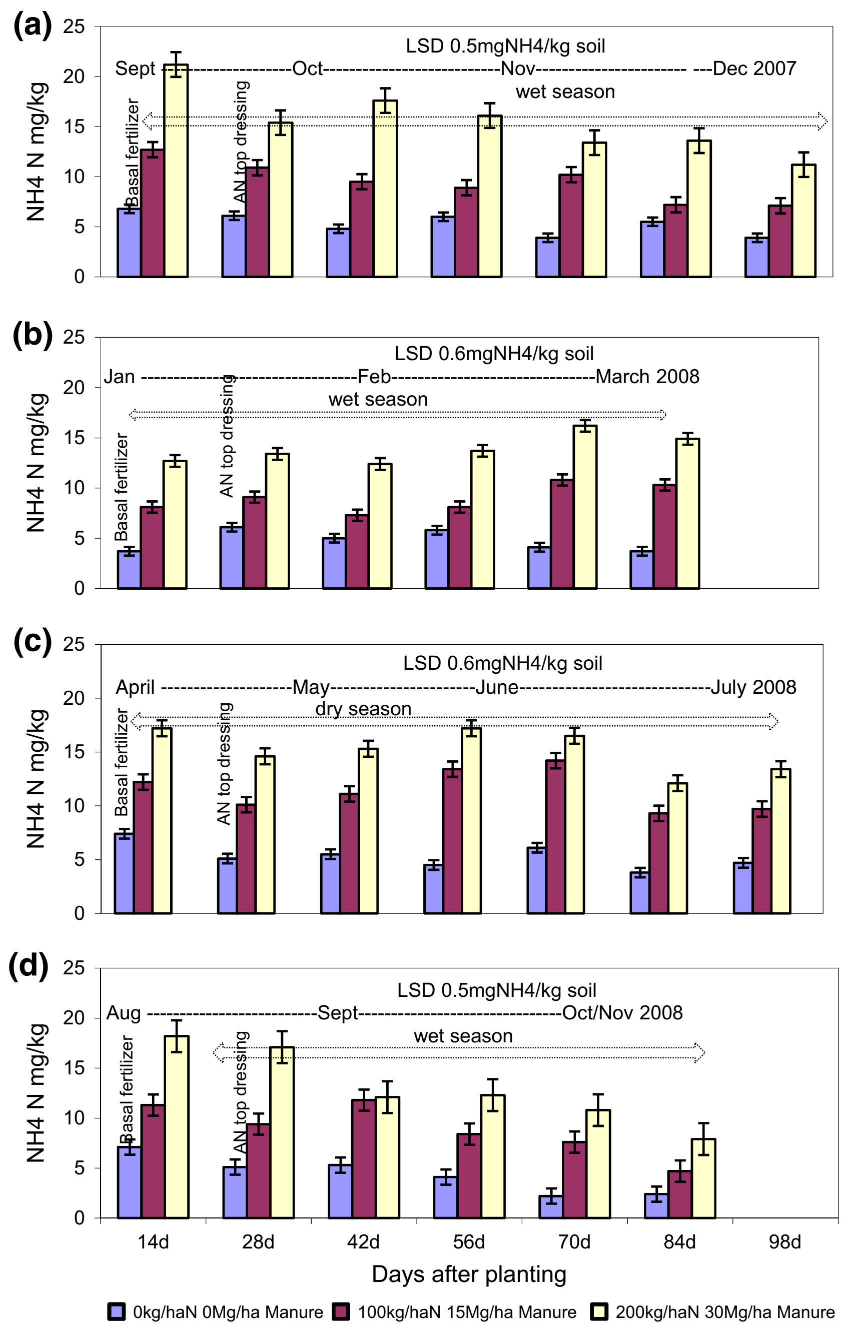

Fig. 3 Ammonium N concentration in soil under first tomato (**a**), first rape (**b**), second tomato (**c**), and second rape (**d**) crops. AN topdressing—2nd application of ammonium nitrate fertilizer as top dressing a month after planting each crop

crop that grew under dry weather conditions (3 % for the second tomato) and higher in the crops that experienced wet weather conditions (15 % for the first and second rape crops).

Nitrogen losses through leaching were by 64 and 32 % when N fertilizer and cattle manure application rates were increased from low to high for the tomato and rape crops, respectively. Lysimeters amended with low and high fertilizer applications recorded 1.5–3 and 2.3–3.7 times higher losses of N as NO_3–N in leachate, respectively, when compared with those on control lysimeters. Higher total N losses were observed for manure in combination with inorganic fertilizer treatments in the first tomato (33.9 kg N ha^{-1}) and rape crops (35.3 kg N ha^{-1}).

Mean total N losses in leachate gradually increased with increasing volumes of leachate and NO_3–N concentrations in leachate for both crops. The proportion of applied N lost in leachate was higher in the tomato crop than in the rape crop. When 100 kg N + 15 Mg manure and 200 kg N + 30 Mg manure ha^{-1} were applied to the tomato and rape crops, 6 and 19 % of applied N was lost as NO_3–N in leachate, respectively (Table 2).

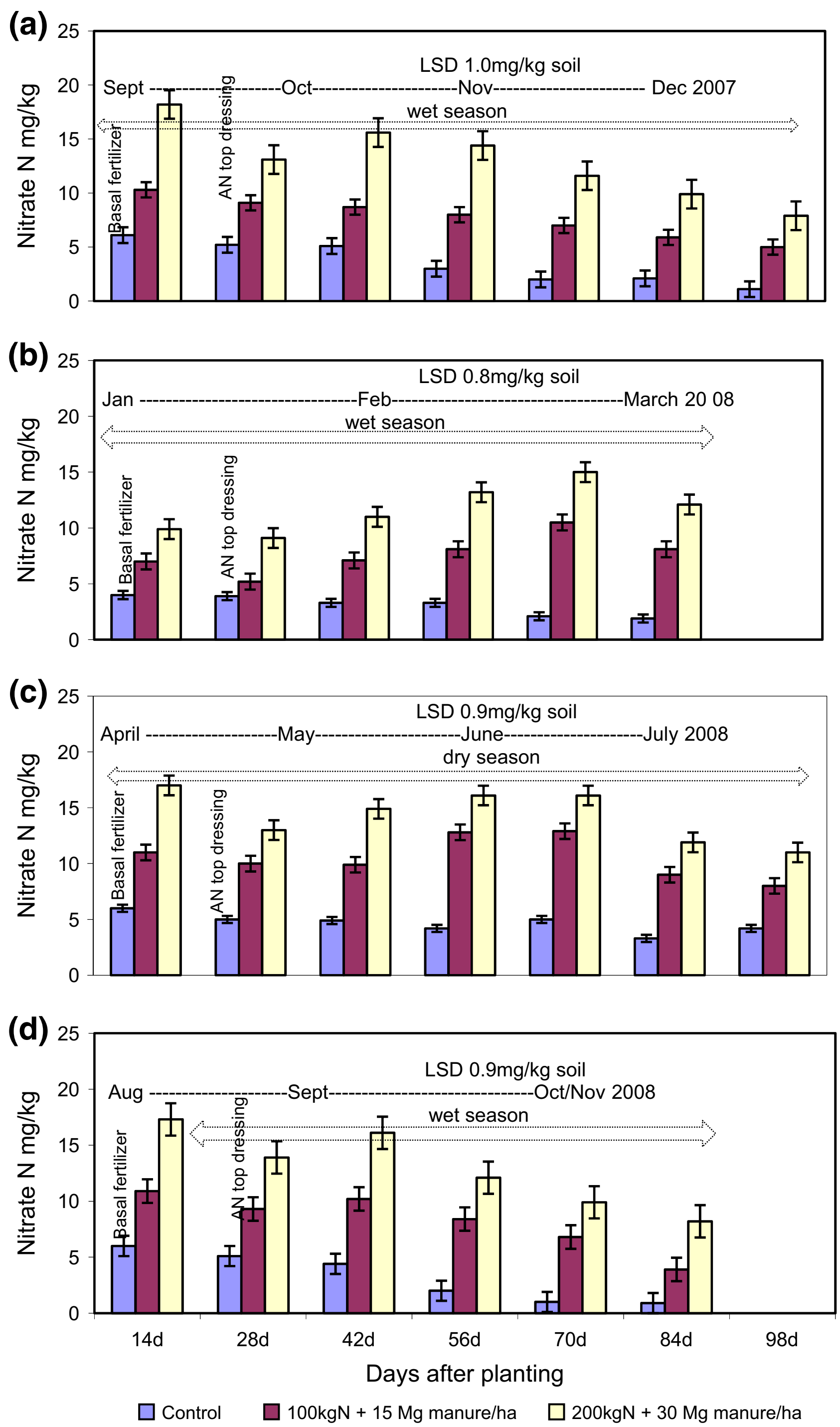

Fig. 4 Nitrate N concentration in soil under first tomato (**a**), first rape (**b**), second tomato (**c**), and second rape (**d**) crops. AN topdressing—2nd application of ammonium nitrate fertilizer as top dressing a month after planting each crop

Dry Matter Yield and Nitrogen Uptake

The different application rates of ammonium nitrate fertilizer and cattle manure had significant effect ($p < 0.05$) on N uptake and dry matter yield of the vegetable crops (Table 3). Doubling N fertilizer and manure application rates from 100 kg N + 15 Mg to 200 kg N + 30 Mg ha^{-1} for the first tomato and rape crops and the second tomato and rape crops increased N recovery in the above ground vegetable biomass by 146, 83, 423, and 80 %, respectively. Nitrogen use efficiency (NUE) was 65 and 91 % in lysimeters that received 100 kg N + 15 Mg manure and 200 kg N + 30 Mg manure ha^{-1} under the first tomato crop, respectively. Likewise, NUE for the first rape crop

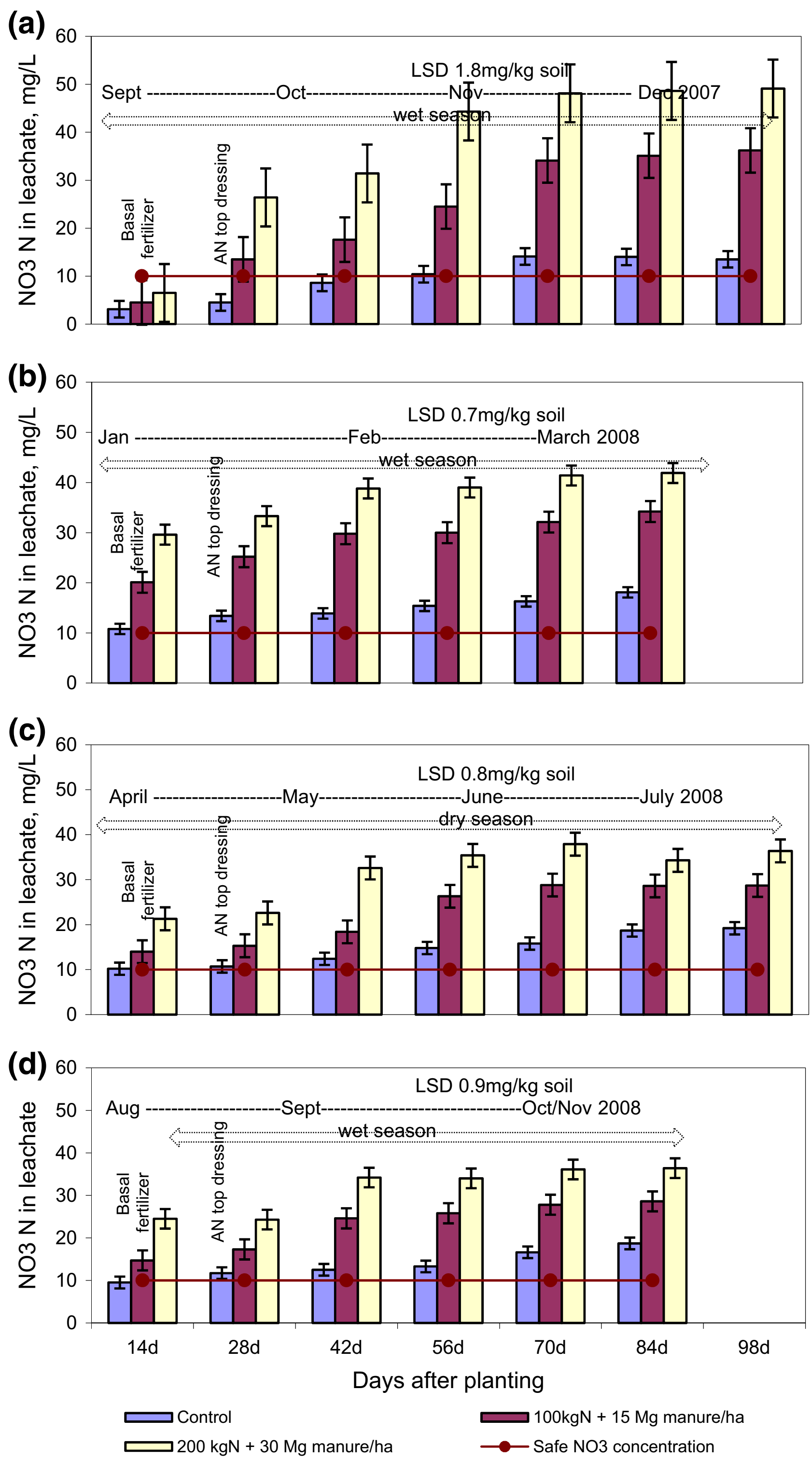

Fig. 5 Nitrate N concentration in leachate under first tomato (**a**), first rape (**b**), second tomato (**c**), and second rape (**d**) crops. AN topdressing—2nd application of ammonium nitrate fertilizer as top dressing a month after planting each crop

was 50 and 53 % in 100 kg N + 15 Mg manure and 200 kg N + 30 Mg manure ha^{-1} lysimeters, respectively. When 100 kg N + 15 Mg manure and 200 kg N + 30 Mg ha^{-1} manure were applied, NUE was 31 and 33 % of the applied N, respectively. Nitrogen uptake by the second rape crop accounted for 83 and 87 % of applied N in lysimeters that received applications of 100 kg N + 15 Mg manure and 200 kg N + 30 Mg manure ha^{-1}, respectively.

Table 1 Chemical and physical properties of the experimental soil

Soil depth (cm)	Soil pH (H_2O)	Org-C (%)	Total N mg kg^{-1}	Sand (%)	Clay (%)	Silt (%)	Total porosity (g cm^{-3})	Bulk density (g cm^{-3})	Saturation gravimetric water (g g^{-1})
0–20	5.5	0.4	24	85	10	5	0.45	1.37	0.31
20–60	5.8	0.2	20	80	15	5	0.45	1.36	0.33
60–100	5.7	0.2	20	78	17	5	0.44	1.35	0.33

Table 2 Estimated total N lost through leaching

Trts	First tomato crop						First rape crop					
	Temporal interval (days after planting)	Mean leachate (NO_3N) (mg L^{-1})	Mean daily leachate volume (L)	N leached (kg ha^{-1})	Total N applied (kg ha^{-1})	% leached N of applied N	Temporal interval (days after planting)	Mean leachate (NO_3N) (mg L^{-1})	Mean daily leachate volume (L)	N leached (kg ha^{-1})	Total N applied (kg ha^{-1})	% leached N of applied N
T1	0–21	3.1	0.7	0.1	–	–	0–35	12.1	5.6	4.7	–	–
	22–49	7.8	3.7	1.6	–	–	36–84	15.9	5.8	9.0	–	–
	50–98	13.9	5.4	7.4	–	–	–	–	–	–	–	–
Total	–	–	–	9.1	0	–	–	–	–	13.7	0	–
T2	0–21	4.5	0.9	0.2	–	–	0–35	22.7	5.9	9.4	–	–
	22–49	18.5	3.9	4.0	–	–	36–84	31.5	5.8	17.9	–	–
	50–98	35.1	5.9	20.3	–	–	–	–	–	–	–	–
Total				24.5	304	8	–	–	–	27.3	100	27
T3	0–21	6.5	0.8	0.2	–	–	0–35	31.2	5.9	12.9	–	–
	22–49	25.2	4.0	5.6	–	–	36–84	38.8	5.9	22.4	–	–
	50–98	48.6	5.9	28.1	–		–	–	–	–	–	–
Total	–	–	–	33.9	608	6	–	–	–	35.3	200	18
Fpr			NS		–	–	–		NS		–	–
Lsd	–	0.9	0.3	0.1	–	–	–	1.4	1.0	0.3	–	–
CV	–	9.4	1.4	1.6	–	–	–	0.9	1.8	1.4	–	–
	Second tomato crop						Second rape crop					
T1	0–35	10.7	1.4	1.0	–	–	0–35	10.6	1.1	0.8	–	–
	36–98	16.2	0.6	0.9	–	–	36–98	15.3	5.7	8.5	–	–
Total	–	–	–	1.9	0	–	–	–	–	9.3	0	–
T2	0–35	14.7	1.6	0.8	–	–	0–35	16.0	1.1	1.2	–	–
	36–98	26.2	0.8	2.1	–	–	36–98	26.7	5.7	14.9	–	–
Total	–	–	–	2.9	100	3	–	–	–	16.1	100	16
T3	0–35	24.4	1.8	3.1	–	–	0–35	24.4	1.1	1.9	–	–
	36–98	35.1	0.7	2.4	–	–	36–98	35.2	5.7	19.7	–	–
Total	–	–	–	5.5	200	3	–	–	–	21.6	200	11
Fpr	–		NS		–	–	–		NS		–	–
Lsd	–	1.1	0.3	0.2	–	–	–	0.3	0.3	0.3	–	–
CV	–	8.2	4.6	4.9	–	–		1.7	1.2	1.7	–	–

Treatments T1 Control, *T2* 100 kg N + 15 Mg manure ha^{-1}, *T2* 200 kg N + 30 Mg manure ha^{-1}, *NS* not statistically significant, *Fpr* F ratio

Correlations Between Selected Variables

A large proportion of the concentration of NO_3–N in leachate (r^2 values between 0.98 and 0.99, $p < 0.05$) could be predicted by variations in the concentration of NO_3–N in soil (Fig. 7a–d). Soil nitrate N was also an important predictor of the estimated loss of N through leaching with r^2 values ranging between 0.30 and 0.89 ($p < 0.05$, Fig. 8a–d).

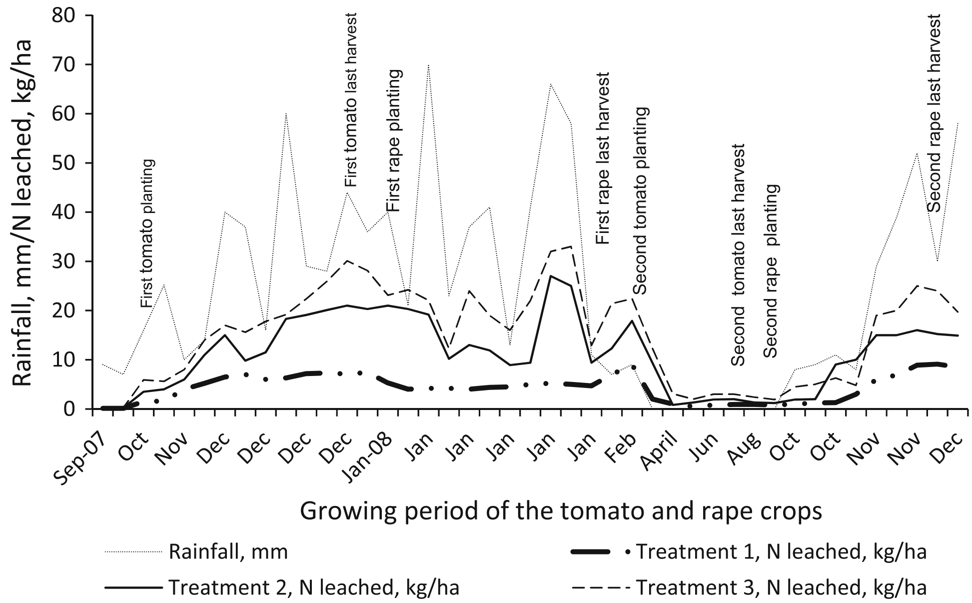

Fig. 6 Effect of rainfall on estimated N leached from soil under tomato and rape crops. Treatment—1–0 kg N + 0 Mg manure ha^{-1} (Control), Treatment 2—100 kg N + 15 Mg manure ha^{-1}, and Treatment 3—200 kg N + 30 Mg manure ha^{-1}

Table 3 Dry matter yield and N uptake by aboveground plant biomass

Trts	First tomato (2007–2008)			First rape (2008–2009)			Second tomato (2008–2009)			Second rape (2008–2009)		
	DM yield (T ha^{-1})	Mg N (g^{-1}) DM	N uptake (Kg ha^{-1})	DM yield (T ha^{-1})	Mg N (g^{-1}) DM	N uptake (Kg ha^{-1})	DM yield (T ha^{-1})	Mg N (g^{-1}) DM	N uptake (Kg ha^{-1})	DM yield (T ha^{-1})	Mg N (g^{-1}) DM	N uptake (Kg ha^{-1})
T1	2.9	9.8	28.4	9.9	1.0	9.9	2.9	12.3	35.7	14.8	2.2	33.1
T2	7.8	16.6	129.5	16.3	5.3	86.4	7.9	9.7	76.6	21.1	4.0	84.9
T3	9.6	32.9	315.8	18.9	8.0	151.2	9.7	17.3	167.8	25.1	7.0	175.7
Fpr	*	*	*	*	*	*	*	*	*	*	*	*
Lsd (5 %)	0.1	0.3	2.3	0.9	0.8	0.7	0.1	0.7	1.3	0.2	1.0	1.3
CV %	0.5	0.8	9.1	3.1	5.6	4.8	0.9	2.5	11.1	0.6	7.9	11.0

T1 Control, *T2* 100 kg N + 15 Mg manure ha^{-1}, *T3* 200 kg N + 30 Mg manure ha^{-1}, *DM* dry matter

* Fpr is less than 0.05 as determined by Fisher's least protected difference

Discussion

Dry Matter Yield and Nitrogen Uptake

Despite the low N recovery rate by vegetable crops, the uptake of N and subsequent assimilation into plant biomass represent an important bio-sink of mineral N that would otherwise be exposed to leaching. Although N uptake by vegetable crops is poor for most conditions, the uptake levels are sufficiently significant enough to reduce the nitrate leaching losses. The comparatively high losses of N by nitrate leaching (Table 2) are indicative of very low efficiency of conversion of N taken into dry matter production.

Mineral N Concentrations in Soil and Nitrate N in Leachate

Nitrogen in applied N fertilizer and cattle manure continuously changes from one form to another because of the activities of plants and microorganisms [15, 29]. In the process of N mineralization in applied manure, heterotrophic soil microorganisms simplify and hydrolyze the organic N compounds, ultimately producing the NH_4^+ and NO_3^- ions [16]. The mineralization of organic N in added manure initially yielding NH_4–N form of mineral N and its subsequent nitrification to NO_3–N is suspected to have significantly contributed to the higher concentrations of leachable N in lysimeter soil recorded in the current study.

The decline in NH_4–N and NO_3–N concentrations in soil appeared to coincide with particularly wet weather conditions especially for the first tomato crop and second rape crop (Figs. 1, 3a, d and 4a, d). This was attributable to the fact that wet weather conditions are associated with a decline in the concentration of mineral N in soil. Flooding of soil decreases atmospheric oxygen diffusion to the soil by a factor of 10^5 [22] and sets in motion a series of unique physical, chemical, and biological processes in the transformation of N derived from applied N fertilizer and

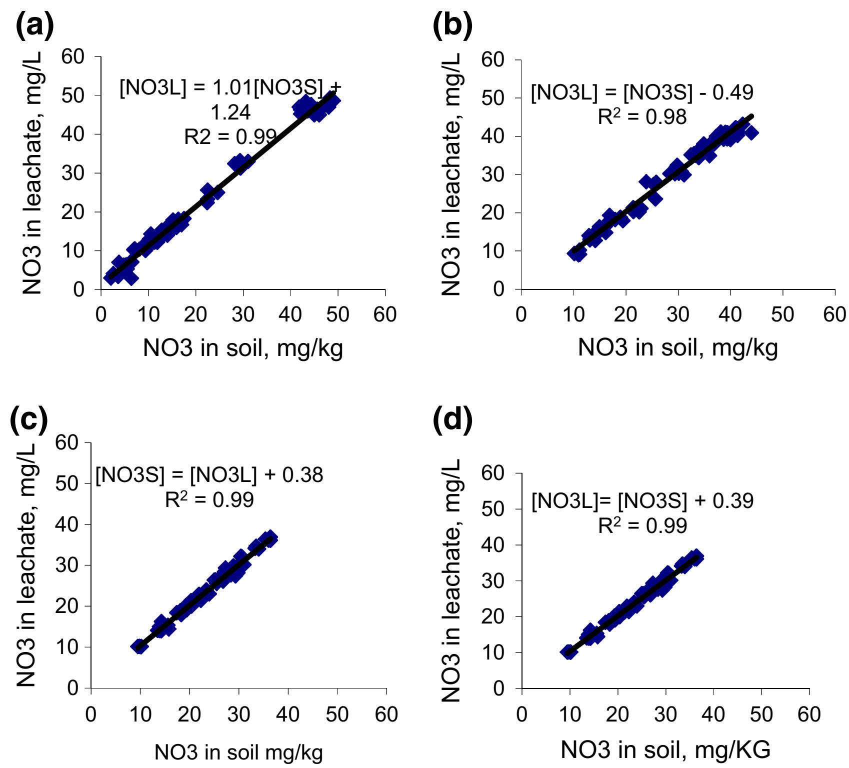

Fig. 7 Regression analysis showing effect of soil NO_3–N on NO_3–N concentration in leachate under first tomato (**a**), first rape (**b**), second tomato (**c**), and second rape (**d**) crops

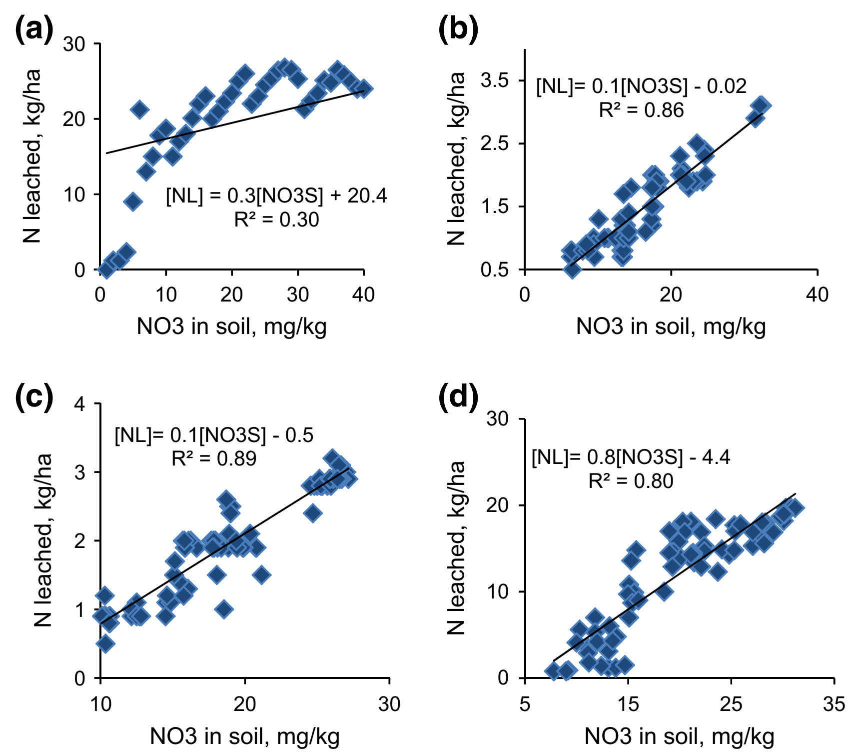

Fig. 8 Regression analyses showing the effect of soil NO_3–N concentration on NO_3–N leached from soil under first tomato (**a**), first rape (**b**), second tomato (**c**), and second rape (**d**) crops

manure not found in dry land soils. The limited quantities of NO_3–N had a higher susceptibility to leaching due to lack of nitrate adsorption by colloidal particles of the soil [3]. This effectively reduced the concentration of mineral N in soil during wet weather conditions recorded in the current study.

Nitrate N Loss in Leachate

While soil conditions are regarded as generally anoxic, significant pockets of the soil profile are well aerated. The aerated portions of the soil profile encourage active oxidative decomposition of nitrogenous matter in manure leading to elevated release of mineral N observed during the vegetative period of the second crop in this study. Applications of 100 kg and 200 kg ha^{-1} of mineral N are suspected to have narrowed the C:N ratio in manure [19, 29, 30], thereby creating conducive conditions for net mineralization of N-containing organic compounds in manure by microbial action [16]. The result was the generation of a net positive balance of nitrate N in leachate from lysimeters that received N fertilizer and cattle manure applications observed in this study.

Although the total amounts of N lost through leaching appear small in this study, they can represent a substantial loss from the available N pool in systems that are inherently poor in N content [10, 27]. The loss of N in leachate was shown to constitute an important nutrient flux, and the variability in the losses was determined by varying application rates of mineral N fertilizer and manure.

Although the application of mineral N fertilizer as a supplement to cattle manure application is a recommended practice in wetland vegetable production by resource-poor smallholder farmers in the sub-tropics of Africa [8], the practice substantially increases the potential of the wetland vegetable production system to release NO_3–N into the soil water where it is susceptible to leaching [15]. In a related study on the effect of N source on the growth and yield of tomato, Cavero et al. [8] concluded that the content of N in applied organic materials considerably influences the direction (mineralization or immobilization) of microbial decomposition of nitrogenous organic substance (in manure crude protein) in soil. The application of mineral N fertilizer in combination with cattle manure narrowed the C: N ratio from 18:1 to 11:1.

Generally, the proportion of applied N lost in leachate was higher in the rape crop than in the tomato crop. When 100 kg N + 15 Mg manure and 200 kg N + 30 Mg manure ha^{-1} were applied to the tomato and rape crops, 3–8 % and 11–27 % of applied N was lost as NO_3–N in leachate, respectively. This implies that the production of rape in wetlands is potentially more damaging to groundwater pollution than the production of tomato crop at least for the current crop rotation system and soil fertility management at Dufuya wetland. This was attributed to the shorter growing period of 84 days for the rape crop compared with 98 days for the tomato crop. The tomato crop had a longer growing period for the uptake and sequestration of leachable N from the soil than that of the rape crop.

The current vegetable cultivation practices at the study site that employs high fertilizer application rates have the potential to overload the leachate with nitrates. Irrigated vegetable production systems represent one of the most intensively fertilized and cultivated production systems. The conditions of high N inputs (in forms of fertilizer and manure), frequent cultivation, relatively short periods of plant growth, and low nutrient use efficiency by many vegetable crops make the vegetable production system highly vulnerable to nitrate leaching [8, 10, 27]. Wetland smallholder farmers often sink shallow wells for the supply of drinking water at household level [9]. When soil becomes excessively wet, the soil will reach a point where it cannot hold any more water. This happens because the air spaces between soil particles become filled with water. As these air spaces fill, gravity will cause water to move down through the soil profile [10]. An important factor that can affect the degree of leaching is how much water a soil can hold. For example, by their nature, sandy soils cannot hold as much water as clay soils. This means that leaching of nitrates will take place much more easily in a sandy soil compared to a clay soil [10]. Other factors that can affect nitrate leaching include amount of rainfall (Fig. 1), amount of water use by plants, and how much nitrate is present in the soil system. The magnitude of N loss is proportional to the concentration of nitrates in soil solution and the volume of leaching water [10, 15]. Based the results of the current study, the loss of NO_3–N in leachate was determined by the varying application rates of mineral N fertilizer and cattle manure. Considering that nitrate overloads in leachate may be translocated to ground water vertically with percolating soil water and laterally by gravitation, the nitrate contamination has a potential to cause detrimental impacts down slope.

Conclusion

Results from the current study demonstrate that the loss of N via leaching constitutes an important nutrient flux, and the magnitude of the losses depended upon application rates of mineral N fertilizer and manure. Higher concentrations of nitrate N in leachate beyond the USEPA limits recommended for portable water suggest that the practice of combining manure applications with mineral N at high rates will increase groundwater contamination. The proportion of applied N lost in leachate was higher in rape crop than in the tomato crop.

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Conflict of interest None.

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