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ORIGINAL ARTICLE

Effect of manure quality on nitrate leaching and groundwater pollution in wetland soil under field tomato (*Lycopersicon esculentum*, Mill *var. Heinz*) rape (*Brassica napus*, L *var. Giant*)

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Abstract Recent decades have seen an increase in groundwater pollution thought to be a consequence of increasing intensity of land use, primarily through greater use of high N analysis materials as fertilizers. A two-season lysimeter experiment was carried out in a wetland in central Zimbabwe in order to determine the effect of cattle manure quality on (1) NO_3–N concentration in leachate and nitrate leaching (2) dry matter accumulation and uptake of N by tomato and rape crops grown in wetland conditions. Two cattle manure quality types based on N content were used in the experiment. The manure collected from a kraal of the smallholder wetland community was classified as high quality manure (high N, 1.36 % N) while that collected from the adjacent commercial farming area was classified as low quality manure (low N, 0.51 % N). The two manure types were applied in rates of 0, 15, 30 Mg ha^{-1}. The treatments were arranged in a randomized complete block design with four replicates. When 15 and 30 Mg high and low N manure ha^{-1} were applied, the concentration of NO_3–N in leachate exceeded the recommended 10 mg L^{-1} concentration in portable water by 15–104 and 53–174 % respectively. The substitution of 15 and 30 Mg of high N manure with 15 and 30 Mg ha^{-1} of low N manure reduced total N lost through leaching by 10–43 and 22–69 % respectively. Ground water contamination by nitrate overload can be considerably reduced by application of low N manure to vegetable crops.

Keywords Manure · Quality · Nitrate · Leaching · Wetland

Introduction

In developing countries, the increasing prices of inorganic fertilizers coupled with growing concerns for sustaining soil productivity has led to renewed interest in the recycling of organic waste as soil fertility-restorer inputs (Sankaram 1996; Reddy et al.

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2000). Animal manures play an important role in soil fertility management for resource-poor smallholder farmers in the tropics through their short-term effects on nutrient supply and long-term contribution to the soil organic matter (Lekasi et al. 2002; Ondersteijn et al. 2002; Groot et al. 2006). However, the manure incorporated to a soil in excess of the crop requirements may contribute to ground water pollution by nitrates (Kirchmann and Bergström 2001; Vogeler et al. 2007). 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 (Salo and Turtola 2006).

Recent decades have seen an increase in the attention paid to pollution by fertilizer applications in intensive agricultural practices. In particular, much research has focused on nitrate leaching because of increasing concentrations in ground and drinking waters (Hansen et al. 2001; Follett and Delgado 2002; Akinsanmi and Perry 2002). Nitrate leaching as a result of agricultural practices is responsible for much of the environmental damage caused to terrestrial and aquatic ecosystems, which is generally attributed to the excessive application of nitrogen fertilizers. However, the organic matter incorporated to a soil may also contribute to ground water pollution by nitrates (Reuter 2000; Scholberg et al. 2000; Venterea and Rolston 2000; Kirchmann and Bergström 2001; Ajdary et al. 2007). If the groundwater is used as drinking water, nitrate has the potential to cause toxic effects on human health. A much more widespread water quality problem associated with nitrate is the degradation of aquatic ecosystems. Once it arrives in surface waters, nitrate contributes to the problem of eutrophication (Addiscott and Benjamin 2000). In the USA, the limit on nitrate concentration in portable water is 10 mg L^{-1} N in nitrate form. In Europe, the standard is 50 mg L^{-1} nitrate (European Environmental Agency 2001a; Silva et al. 2005).

Wetlands are important in crop production in the smallholder semi-arid areas of southern Africa, because they have enough water for a longer period to allow crops to be grown throughout the year. Wetland cropping in southern Africa usually involves the production of leafy vegetables. Vegetables are high value crops and smallholder farmers apply high manure rates in order to eliminate the risk of yield depression due to lack of plant available N (Campbell et al. 1998). The relatively low recovery rate of applied N by vegetable crops means that there are risks of significant N losses to the environment. Usually, only about 70 % of applied fertilizer nitrogen is recovered in the harvested biomass of vegetable crops (Lowrance and Smittle 1988; Reuter 2000; Venterea and Rolston 2000).

Organic matter decomposition dynamics largely determines the rate of release of mineralized N, which may be subjected to loss by leaching in a wetland soil system. Although there is a general trend relating net mineralization/immobilization to the C: N ratio, there is no critical precise value, which marks the reversal from immobilization to mineralization. Other aspects such as substrate quality, which include lignin and polyphenol contents, have a major impact on rate and direction of decomposition (Vitten and Smith 1993; Mtambanengwe et al. 1998). Taylor et al. (1989) and Silva et al. (2005) concluded that the C: N ratio is a better predictor of decay rate for substrates low in lignin when comparing substrates with a wide range of lignin contents. Organic materials rich in N-free lignins and low-N residual substances of soils are poor energy sources for most microorganisms (Yates et al. 2006). Polyphenols affect the release of N from decomposing organic material by forming stable complexes with proteins thereby stabilizing the organic material (Mafongoya et al. 1998a; Yates et al. 2006). Thus, application of poor quality cattle manure (low N, high C) might be a way to reduce the risk of NO_3^-–N leaching from soil due to immobilization of N by heterotrophic microorganisms. Jarvis et al. (1989) and Nicholson et al. (1997) reported that incorporation of carbon-rich organic materials to a soil significantly decreased NO_3–N leaching. The lignin content of smallholder manures in sub-tropical Africa is variable depending on the type of grazing and degree of composting. Lignin content is expected to be relatively high in areas where browsing forms a significant part of cattle diet (Mafongoya et al. 1998a). Cattle manures from smallholder farming areas in Zimbabwe are generally regarded to be of lower quality than manures from commercial farming areas due to scarce and low quality grazing, and poor handling methods (Mugwira and Mukurumbira 1984; Khombe et al. 1992; Murwira 1995; Mugwira and Murwira 1997; Mafongoya et al. 1998a).

About 66 % of soils in Zimbabwe on potential arable land are coarse-grained granitic sands characterized by high infiltration rates (Vogel 1992) normally associated with high nitrate leaching. Nitrate N concentration in drainage water ranged from 16 to 69 mg L^{-1}. In a study on soil moisture conservation under maize at Domboshava Training Centre in Zimbabwe, Vogel (1992) reported that water draining out of the plough layer accounted for 18 and 36 % of total rainfall recorded under conventional and tied ridging, respectively, on a sandy soil.

Both conservationists and agriculturalists have recognised the potential vulnerability of wetland environments to the effects of increasing wetland soil fertility, but there is little scientific information about the effects of elevated manure derived N on losses of N through nitrate leaching in Zimbabwe. In addition to that, cattle manures vary widely in their content of nitrogen due to varying cattle grazing quality. There has been limited research on the effect of manure quality on nitrate leaching under wetland vegetable cropping systems. A two-season lysimeter experiment was established in order to determine the effect of aerobically composted cattle manure quality on nitrate leaching in wetland under field tomato and rape crops.

Materials and methods

Site description

Fieldwork was conducted between 2007 and 2008 in a wetland garden at Dufuya (19°17′ S; 29°21′ E) wetland in Lower Gweru Communal Lands 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 (Vincent and Thomas 1960). The soil is deeply weathered and is course textured loamy sand in topsoil over lying sandy loam subsoils derived from granite and classified as Udic Kandiustalf (USDA) and Gleyic Luvisol (FAO) (FAO 1988; Nyamapfene 1991; Soil Survey Staff 1992). They are perennially moist and smallholder farmers have established vegetable gardens along the wetland. Vegetable production is all year round and high rates of organic fertilizers are applied to soils to ensure high yields. Smallholder farmers usually apply 10–35 T of cattle manure to rape and tomato crop production systems.

Wetland hydrology of the study site

The Dufuya watershed (724 ha) is largely covered by Kalahari sands gently sloping southwards at an almost homogeneous slope of 4 %. Long narrow fields (300 × 40 m) under rain-fed maize cropping cover the greater part of the watershed. The fields are bordered with trees or small shrubs with contour ridges separating the narrow fields. There are no significant signs of surface runoff problems. The area has several wetlands on streams running down slope. The wetlands, which are seasonal, are covered almost entirely by a dense growth of bulrushes. One of these wetlands is the Dufuya. Below the wetland, an intermittent stream meanders downstream into a system of dotted small gardens located on perennially damp and marshy strip, which bisects the system.

Major cropping system of the study site

The smallholder farmers at Dufuya wetlands practice intensive vegetable production in small gardens under informal irrigation. In wetland systems, water is not conveyed by large engineered channels nor pumped from deep wells. It arrives as groundwater and is usually lifted by hand buckets from less than 2 m deep. The wetland gardens are usually placed immediately adjacent to one another often sharing common fences. The gardens near the central drainage area are wetter and their soils contain more organic matter. The gardens further from the system's central axis are drier and their soils are sandier.

Tomato is a high-value vegetable crop grown under informal irrigation by smallholder farmers at Dufuya. The crop is grown typically using high rates of N fertilizers and cattle manure in order to avoid yield depression. Commercial tomato growers in the wetland community apply nitrogen fertilizers and cattle manures in amounts of 300–400 kg N and 10–35 Mg ha^{-1}, respectively. Because of lack of availability and higher cost, smallholder farmers have resorted to use of cattle manure which are readily available without chemical fertilizers. The application rates of 15 and 30 Mg cattle manure ha^{-1} were used in the lysimeter experiments in order to capture the common farmer practice. For field tomato production, the use of transplants is common. Transplants are typically 5 week old, having 3–5 leaf-bearing nodes, an initial leaf area of 15–40 cm^2, and a dry weight of 0.2–0.30 g $plant^{-1}$. Under wetland cropping conditions, N is readily lost by leaching and denitrification, with nitrate concentrations in shallow ground water reaching hazardous levels. High levels of nitrate leaching are suspected to have caused the smallholder farmers in the wetland community to abandon their homestead boreholes as sources of domestic water supply.

Rape or canola has been an important arable crop for a couple of decades for its addible leaves in Africa and Asia. In Zimbabwe and other southern African countries, rape is commonly grown under irrigation. Smallholder farmers often apply about 10–30 Mg ha^{-1} of cattle manure for the production of rape under small-scale informal irrigation to achieve yields levels of 25–30 Mg of leaf mass ha^{-1}. In the current experiment two rates of 15 and 30 Mg manure ha^{-1} were used to test the influence of these rates on nitrate leaching in wetland soil under rape. The Dufuya wetland community (communal land) shares a boundary with the Vungu commercial farming area (private commercial land) where cattle production is the main enterprise. The wetland smallholder farmers commonly use manure from this commercial farming area as well as manure from within the wetland community for tomato and rape production in the community gardens. The two adjacent communities have grazing areas with different forage values and therefore the qualities of the cattle manure from the two communities were expected to be considerably different. Nitrate leaching potential of manure fertilized wetland soil is variably dependent on the content of N in manure. For this reason, it was necessary to test the effect of these two types of cattle manure on nitrate leaching in wetland soil under tomato and rape production.

Soil sampling and analysis

Initial soil characterization was done by collecting twenty soil samples from randomly selected points of the field experimental site at a depth of 0–20 cm using a soil auger. The soil samples were mixed thoroughly in a clean plastic bucket to obtain a composite sample. The soil composite sample was taken to a laboratory, air-dried, sieved (<2 mm) and characterized (Table 1). A 0.5 g air dried soil sample was ground to pass through a 0.05 mm sieve prior to determination of organic carbon by the Walkely and Black method (Nelson and Sommers 1986). Soil texture was determined by the Bouyocous hydrometer method (Bouyocous 1965). Soil pH was determined by weighing a 15 g soil sample in a 200 ml honey jar to which 75 ml 0.1 M CaCl_2 were added. The mixture was shaken mechanically for 30 min and pH was determined using a digital pH meter (Model: Orion 701). Soil bulk density was determined by the core method (Black and Hartge 1986). Twenty soil cores for bulk density determination were randomly collected from the experimental site. Bulk density (*Db*) was calculated using the following equation:

$$Db = Ms/Vt \tag{1}$$

where *Ms* is mass of oven dry solids and *Vt* is total soil volume. The soil cores were oven-dried at 105 °C (to constant weight) for determination of mean gravimetric water content. Taking particle density (Pd) of soil to be 2.65 g cm^{-3} total porosity was calculated as:

$$1 - Db/Pd \tag{2}$$

Total N in soil was measured by the Kjeldahl method using concentrated H_2SO_4, K_2SO_4 and HgO to digest the sample (Bremner 1996).

Main objective and hypothesis of the study

The main objective of this study was to determine the effects of aerobically composted cattle manure application rate and manure quality (N content in manure) on NO_3–N leaching and N uptake by tomato and rape crops grown on wetland. The hypotheses that NO_3–N leaching and N uptake by aboveground biomass of field tomato and rape crops increased with increasing application rate and quality (N content) of aerobically composted cattle manure were tested in the lysimeter experiments.

Experimental manure

Two types of manure were used in the study. Manure quality was determined by the concentration of N. The manure collected from a kraal of a homestead was classified as high quality (high N, 1.36 % N) manure while that collected from the adjacent commercial farming area was classified as low quality (low N, 0.51 % N) manure. Manure application rates were determined on a moisture free basis. Manure samples were analyzed for organic C (Nelson and Sommers 1982), total N using the Kjeidahl procedure

Table 1 Chemical and physical properties of the experimental soil

Soil depth, cm	Soil pH (H_2O)	Organic C (%)	[1]N (mg kg$^{-1)}$	Sand (%)	Clay (%)	Silt (%)	Total porosity (g cm^{-3})	Bulk density (g cm^{-3})	Saturation gravimetric water (gg^{-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 Selected chemical properties of cattle manure from communal and commercial farming areas

Manure type	Organic C (%)	Total N (%)	C: N ratio	Soil + ash content (%)	Soil and ash-free basis (%)	
					Organic C	Total N
High N manure	22.82	1.36	16.8: 1	77.18	61.3	6.4
Low N manure	9.13	0.51	17.9: 1	90.87	23.0	2.3

(Stevenson 1982; Bremner and Mulvaney 1982), soil and ash content (Table 2).

The smallholder farmers in the community have been advised by extension agencies that the manure from the commercial farming area is of better quality because the assumed better grazing quality. Quite a few farmers in the community have the transport means in the form of ox-drawn carts. Some smallholder farmers do not have the transport to haul the manure from the commercial farming area. For this reason, both manure types are used by the wetland vegetable farmers for soil fertility improvement.

Field lysimeter experiment

The field lysimeter study comprised two experiments, where high N and low N cattle manures were used in the first and second experiments respectively. In each 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 experiments in September 2007 (Fig. 1). The lysimeter boxes were fabricated from 1.6 mm thick galvanized steel sheets, which does not easily rust. The choice of galvanized steel as material for lysimeter box fabrication was made after considering the fact that it is light, easy to handle, relatively cheap, has good thermal conductivity and inert. The depth of the lysimeters was chosen after considering the rooting depth of the test crops (rape and tomato), which rarely exceed 40 cm (Aboukhaled et al. 1982). To avoid sidewall flow, the lysimeters were coated with asphalt-based waterproofing paint, which provided a rough surface. A 1 mm wire mesh was fixed at the lysimeter outlet and covered with a 10 cm layer of gravel before the soil was emplaced, thereby reducing the effective depth of the lysimeters to 40 cm. The gravel enhanced drainage and prevented the soil from washing into the lysimeter outlet, which effectively stopped blockage. Each lysimeter outlet was connected to a flexible plastic pipe laid at a slope of 1 % to ensure rapid leachate flow into collecting buckets. Repacking of the lysimeters closely followed the sequence of the soil horizons identified during soil excavation.

Tomato and rape crops were used as test crops in the study. The seedbeds for seedlings were prepared on experimental site. The first tomato crop was transplanted on 9 September 2007 while the first rape crop was planted from 6 to 8 January 2008. The second tomato crop was established in April 2008 while the second rape crop was planted in September 2008. The crops were grown in the same lysimeters in a rotation. The growing lengths of the tomato and rape crops were 98 and 84 days respectively. Two tomato and six rape plants were planted in each lysimeter. Weed control was done by hand pulling. Manure application rates were determined on a moisture free basis. The seedbeds were prepared and planted to tomato and rape seeds on the study site.

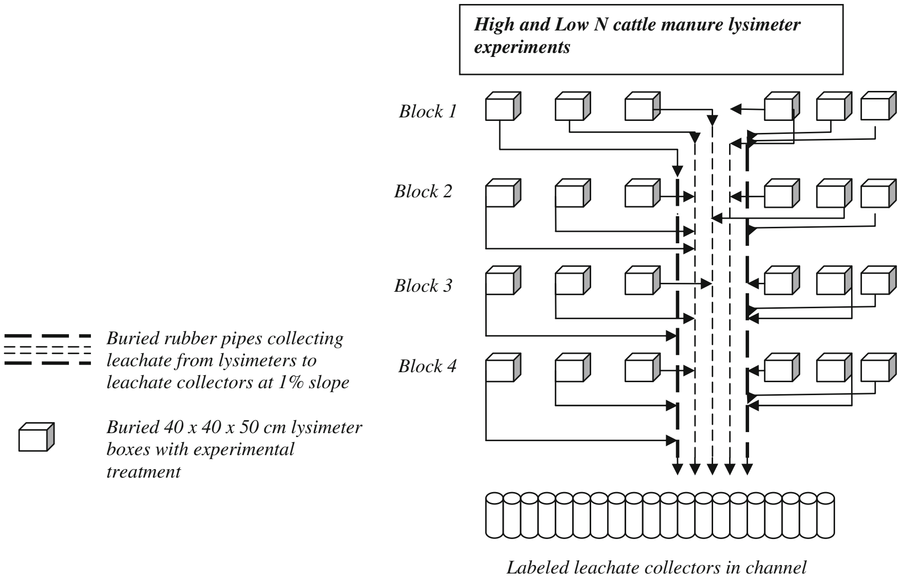


Fig. 1 Aerial view of the lysimeter station for the experiments

Experimental treatments and design

The field lysimeter study comprised two experiments. High and low N manures were used in the first and second experiment, respectively. The following treatments were used in the lysimeter experiments:

Experiment 1:

1. 0 Mg cattle manure ha^{-1} (Control);
2. 15 Mg high N (1.36 % N) manure ha^{-1};
3. 30 Mg high N (1.36 % N) manure ha^{-1}.

Experiment 2:

1. 0 Mg cattle manure ha^{-1} (Control);
2. 15 Mg low N (0.51 % N) manure ha^{-1};
3. 30 Mg low N (0.51 % N) manure ha^{-1}.

A randomized complete block design with four replications was used in the experiments. A basal application rate of 1,000 kg ha^{-1} compound L (5 % N, 7.9 % P, 16.6 % K, 8 % S) was used in all treatments, including the control, before planting each crop in order to capture a common practice by the smallholder farmers. The compound fertilizer was spread on the surface of each lysimeter and incorporated. Cattle manure was applied only once in the study period before planting of the first tomato crop. The manure was evenly broadcasted in the respective lysimeters and then incorporated into the topsoil a few days before transplanting the first crop.

Sampling and analysis

Volumes of leachate were recorded whenever there was a leachate break-through. Cumulative leachate volumes were computed and recorded every fortnight during the vegetative period of each crop. Representative 100 ml samples of composite leachate were collected for nitrate N concentration analysis by calorimetric method (Keeney et al. 1982). A Cecil spectrometer (model CE2010) was used to measure absorbance. Nitrogen loads were calculated as follows:

$$NO3Nleach = [NO3N] \times Vol \times 0.002 \times Tdays \tag{3}$$

where *NO3 Nleach* is total NO_3–N leached from soil in kg N ha^{-1}, *[NO3N]* is concentration of NO_3–N in leachate, *Vol* is mean daily leachate volume in litres for the period, 0.002 conversion ratio after resolving mg [NO_3–N] to kg N ha^{-1} and converting NO_3^- molar mass to N content (14/62); *Tdays* is the number of days of approximately similar leachate volumes.

At the same time that leachate samples were collected, soil samples were analyzed for NH_4–N and NO_3–N using colorimetric techniques (Robertson et al. 1999). A randomly selected plant was chosen and labelled in each lysimeter for crop biomass sampling. Rape leaves and tomato fruits that reached horticultural maturity were harvested from the selected plants at every harvesting event and taken to the laboratory and analyzed for N concentration using the semi-micro Kjeldahl procedure (Bremner and Mulvaney 1982). Total uptake of N was calculated as follows:

$$Nut = DM \times [N] \qquad (4)$$

where *Nut* is *N* uptake in kg ha^{-1}, *DM* is dry matter yield in T ha^{-1}; *[N]* is nitrogen content in $mgNg^{-1}DM$.

Statistical data analysis

Treatment effects on measured variables were analyzed using One Way ANOVA (GenStat Discovery Edition 3 2003). Differences between treatment means were judged significant at $p \leq 0.05$ as determined by Fisher's protected least significant difference test. Mean separation was performed using the LSD since there were not more than three treatments in each set of experiment. Statistical significance of the differences between measured variables in lysimeters subjected to high N and low N manure applications was established by performing *t* test for unpaired samples using the GenStat package. The Pearson correlation coefficients between measured variables and their coefficients of determination values were calculated and the significance of the correlations between selected variables was established using GenStat statistical package.

Results and discussion

Weather conditions

The 2007–2008 rain season at the end of September. About 98 % (792 mm) of the total rainfall (808.2 mm) was received in the first half of the season (September–January; Fig. 2). The first tomato and first rape crops were cultivated during the first half of the 2007–2008. Loss of NO_3–N in leachate was considerably higher under these crops. The 2007–2008 winter season was generally frost-free and had maximum and minimum temperatures of 20 and 15 °C, respectively. The summer season was characterized by hot and humid weather conditions with maximum and minimum temperatures of 30.5 and 26.5 °C respectively (Fig. 1). The 2008–2009 rainy season started at the beginning of October (36 mm). The last quarter of the study period occupied about half of the 2008–2009 summer season (October–December 2009) during which the last rape crop was grown. The first 3 months of the summer season accumulated 156 mm of rainfall. The summer season was characterized by hot and humid weather with a maximum and minimum air temperature of 30.5 and 26.5 °C respectively.

Volumes of leachate

The pattern of leachate volumes collected from lysimeters was largely similar for all treatments for specific periods clearly implying that treatment effects on volumes of leachate were not significant (Fig. 3, $p > 0.05$). Leachate quantity collected from a unit area contributes substantially to the groundwater budget of the area. The volume of leachate collecting under a specific area for a constant concentration of NO_3–N determines considerably the total quantity of N in nitrate form lost through leaching. The experimental soil is coarse-grained granitic sands characterized by high infiltration rates (Vogel 1992) normally associated with high nitrate leaching. As a result, small external additions of water from rain tended to swiftly shift soil moisture levels from field capacity to saturation. The volumes of leachate therefore followed daily rainfall events in the periods preceding leachate collection and measurements. A water saturated soil normally sheds off excess soil water together with its dissolved salts into ground water reserve where they may cause contamination. In the USA, the limit on nitrate concentration in portable water is 10 mg L^{-1} N in nitrate form. In Europe, the standard is 50 mg L^{-1} nitrate (USEPA 1990; European Environmental Agency 2001a; Silva et al. 2005).

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. Total leachate volumes over two seasons of the study exceeded cumulative precipitation by 188.1 mm (16 %).

Manure quality

The concentrations of N in the two types of cattle manure differed considerably (Table 2). Various studies by Khombe et al. (1992) and Mugwira and Murwira (1997) reported low N content of smallholder cattle manures due to inadequate and low quality grazing and inappropriate handling of the manure in

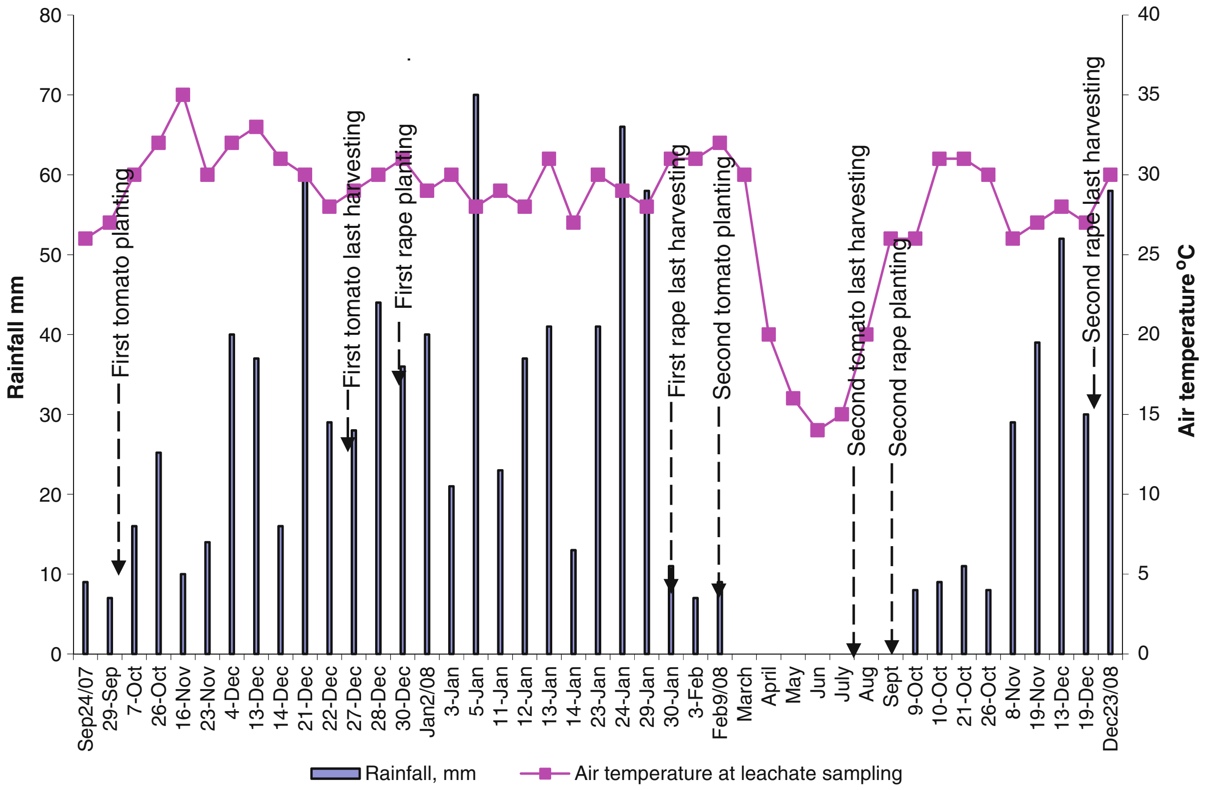


Fig. 2 Daily rainfall and air temperature at the study site

kraals in sub-tropical Africa. In this study, two manure types were used to test the effect of their quality and application rates on nitrate N leaching under wetland vegetable production. Results of the chemical analysis of the two types of cattle manures showed quite the opposite of these previous findings (Table 2). The content of organic C and total N in high N manure (smallholder manure) were 2.5 and 2.7 times higher than that found in low N manure (commercial farm manure). This was due in greater part to the perennially green grazing of high forage value around the wetland area, which acted as an effective supplement for the poor grazing in the dry land portions of the smallholder community. The quality of animal manure largely depends on dietary condition of the grazing area, manure handling and storage; nature and amount of litter added (Mafongoya et al. 1998a).

The considerable differences found in the content of organic C and total N in the high N and low N manure were however narrowed in the C: N ratios of 17:1 and 18:1, respectively. The quality of cattle manure, specifically N content, C to N ratio and presence of lignified materials, are important determinants of organic N mineralization dynamics after incorporation (Silva et al. 2005). Since NO_3–N, the major contaminant of ground and terrestrial water resource by nitrate overload, is generated in the mineralization of organic N, the potential of applied manure to pollute the environment is influenced substantially by its quality (Jarvis et al. 1989; Nicholson et al. 1997). Thus, application of poor quality cattle manure (low N, high C) might be a way to reduce the risk of NO_3–N leaching from wetland soil due to immobilization of N by heterotrophic microorganisms.

Mineralized N concentrations in soil

In the current study, cattle manure quality (N content) and rates of application had a significant effect ($p < 0.05$) on the concentration mineralized N (NH_4–N and NO_3–N) in soils coarsely estimated over 98 days for the tomato and 84 days for the rape crops (Figs. 4, 5). Differences in the concentrations of

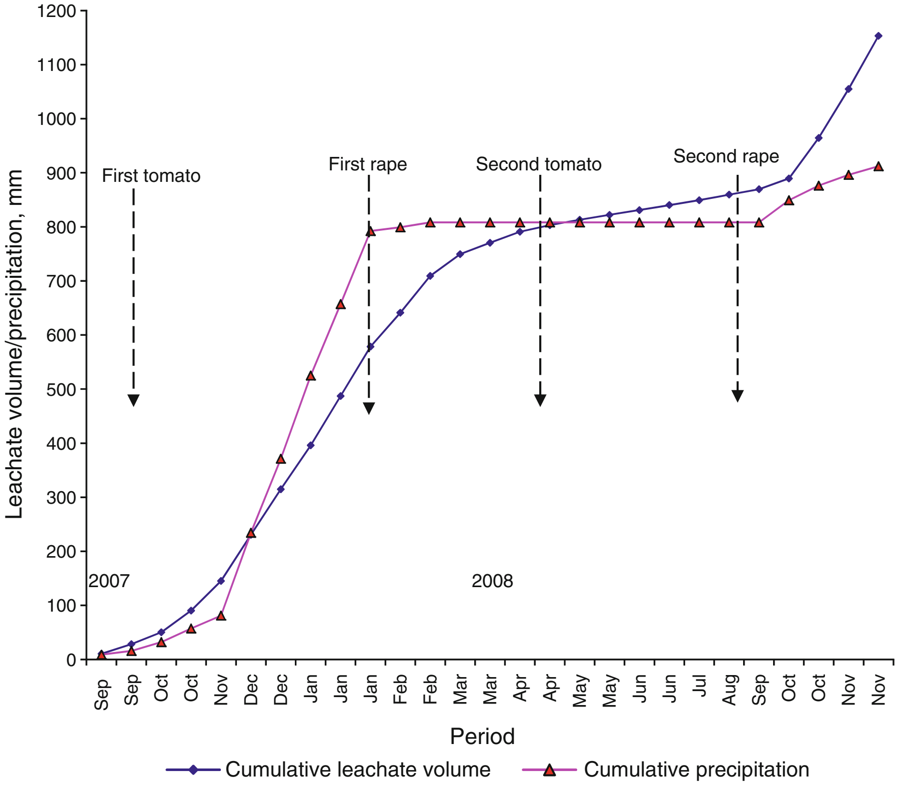


Fig. 3 Cumulative precipitation and leachate volumes

mineralized N in soil between lysimeters amended with high and low N manure became apparent in this study at 42 days after application. The lowest concentrations of mineralized N in soil were recorded in the control lysimeters.

Soil N is continuously changing from one form to another because of the activities of plants and microorganisms. The decomposition of organic matter converts organic N in applied manure into mineral N in a process termed mineralization in which ammonium (NH_4^+), nitrite (NO_2^-) and nitrate (NO_3^-) are generated (Sankaram 1996, Reddy et al. 2000). In the process of N mineralization, heterotrophic soil microorganisms simplify and hydrolyse the organic N compounds, ultimately producing the NH_4^+ and NO_3^- ions (Lekasi et al. 2002, Ondersteijn et al. 2002). While the decomposition and N mineralization processes are beneficial as organically-bound N is converted to plant available mineralized forms (Ondersteijn et al. 2002), the nitrification of NH_4–N to NO_3–N by primary and secondary nitrifiers essentially marks the onset of terrestrial and aquatic ecosystems pollution through nitrate leaching under water saturated soil conditions (Vogeler et al. 2007).

In wetland conditions, the oxygenated soil air is gradually displaced by soil water thereby creating environments that do not encourage rapid nitrification of ammonium N. Higher concentrations of NH_4–N in soil were therefore recorded in the current study (Fig. 4). The nitrate supplying potential of applied manure under decomposition and mineralization is dependent on the content of N in the manure (Taylor et al. 1989; Lovett et al. 2002; Yates et al. 2006).

Except for the first tomato crop, mineralized N concentration differences between control lysimeters and those that received low and high N manure were generally small (Figs. 4, 5). This was due to the case that, the application of aerobically composted manure with a high content of lignified C (Mafongoya et al. 1998a) may cause active immobilization of mineralized N by heterotrophic micro flora (Taylor et al. 1989; Lovett et al. 2002; Yates et al. 2006). Under such conditions, the small reserve of mineralized N in soil recorded in this study is a net balance after higher

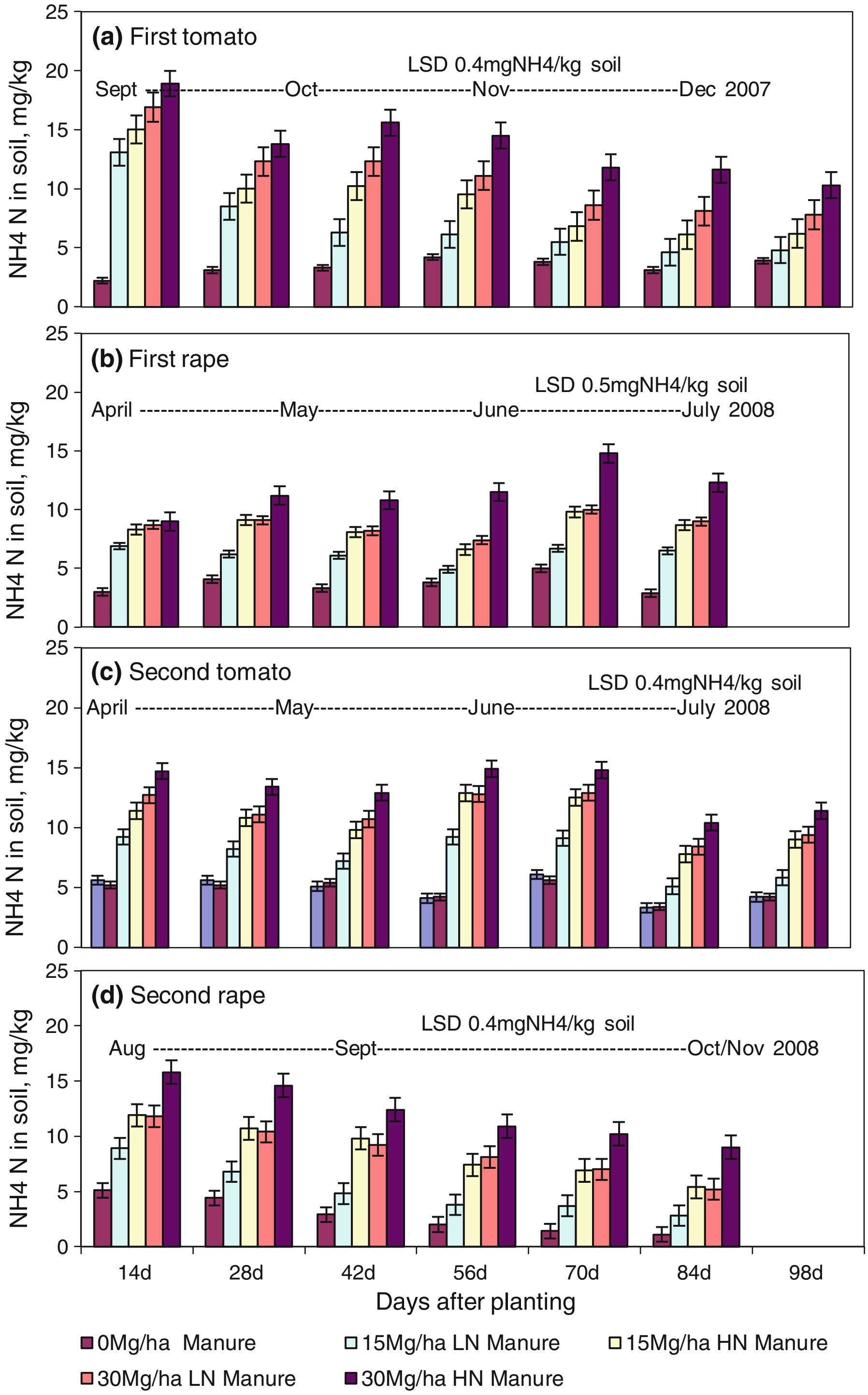


Fig. 4 Ammonium concentration in soil. *HN* High N manure, *LN* Low N manure

reductions associated with N precipitated in the reaction between reactive phenols and amino acids from manure decomposition, assimilation into microbial cell substance, nitrate leaching, denitrification and N crop uptake (Yates et al. 2006). The low availability of N to microbes ensured that immobilization of mineralized N

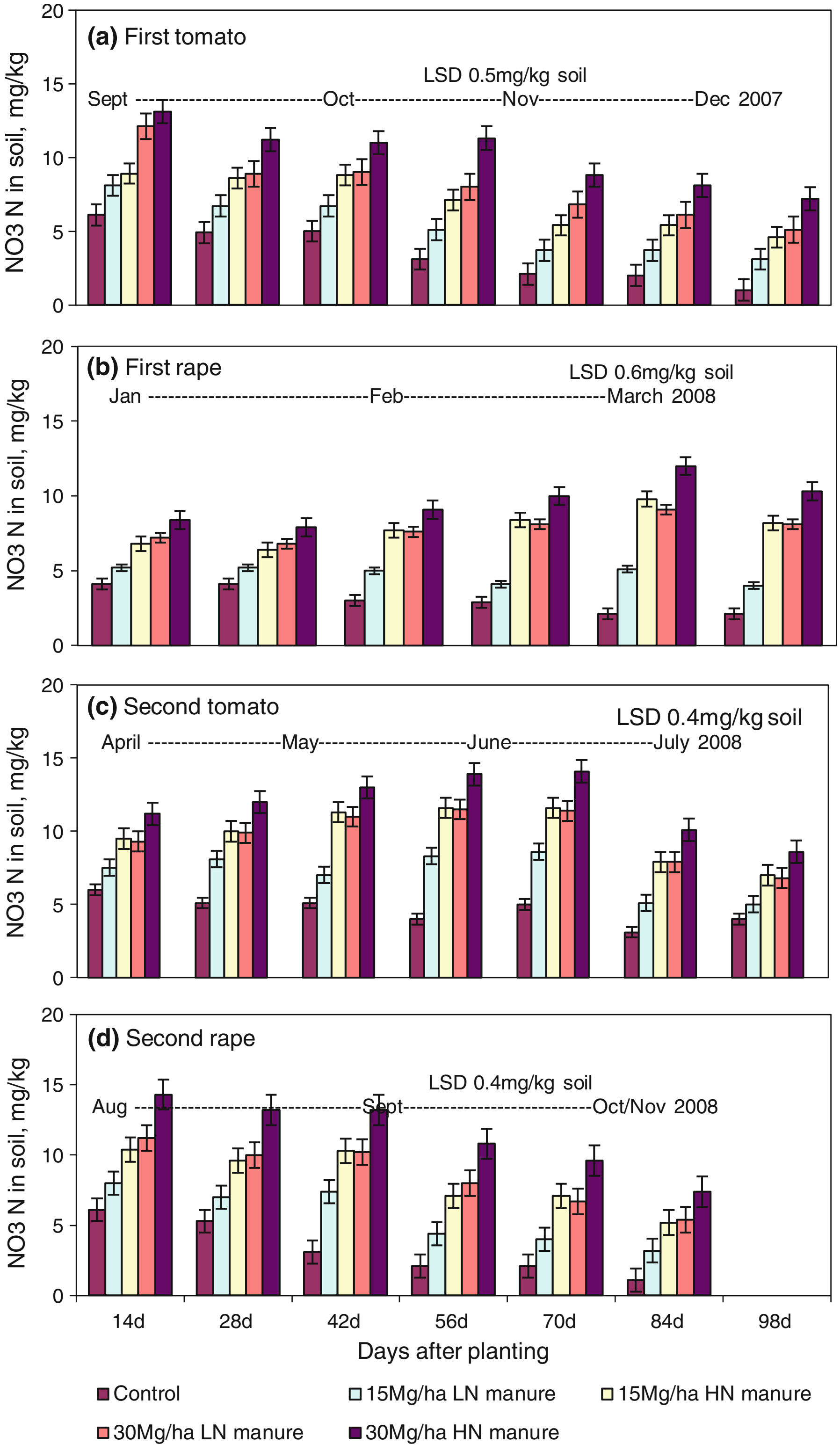


Fig. 5 Nitrate N concentration in soil. *HN* High N manure, *LN* Low N manure

was kept high (Vogeler et al. 2007). The net result was a smaller difference in the concentrations of mineralized N in control lysimeters against that in manure fertilized lysimeters.

Increasing the high and low N manure application rates from 15 to 30 Mg ha^{-1} increased the concentration of NH_4–N and NO_3–N in soil by 8–88 and 18–97 %, respectively. This clearly implies that the potential for groundwater pollution by NO_3–N overload from manure fertilized vegetable production system increases substantially with increasing rates of application. In a related study on organic farming and nitrate leaching, Kirchmann and Bergström (2001) concluded that incorporated manure applied in excess of the crop requirements may contribute to ground water pollution by nitrates. In the current study, higher mineralized N concentrations in wetland soil were recorded in lysimeters that received 30 Mg of high and lower N manure (Figs. 4, 5). The decomposition of N-containing organic matter in applied manure initially yields ammonium N (NH_4–N) which is gradually oxidized to generate the nitrate N (NO_3–N) by primary and secondary nitrifiers (Yates et al. 2006). As NH_4–N acts as a substrate for nitrification, elevated concentrations of NH_4–N in soil were followed by an increase in the content of NO_3–N in soil. Applications of irrigation water and incident rain in amounts beyond field capacity of the wetland soil caused a net translocation of dissolved nitrate N in leachate to groundwater reserve where it posed a potential hazard of contamination. The concentrations of mineralized N increased with increasing high and low N manure application rate. Increased use of animal manures has accentuated nitrate–N contamination (Vogeler et al. 2007), because nitrate leaching in the ground water is related to N fertilization rate (Kirchmann and Bergström 2001). A wetland soil environment by its very nature has such permanent soil wetness that the water table rarely falls beyond 15 cm from the surface during the rainy season (Brinkman and Blokhuis 1986) and under such conditions the margins between field capacity and gravitational soil moisture levels are very narrow indeed. This means that wetland soil conditions are highly susceptible to leaching processes.

In a study on indicators of nitrate leaching loss under different land uses in southern Oklahoma Silva et al. (2005) recorded significant influence of manure quality, specifically N content, on the dynamics of release of mineralized N, which may be subjected to loss by leaching. In the current study, the substitution of 15 Mg of low N with 15 Mg ha^{-1} of high N cattle manure (manure quality) significantly increased mineral N content in soil by 13–52 %. At 30 Mg ha^{-1} manure application rates, the substitution increased mineral N content in soil by 18–35 %. This may be attributed to high total N content (1.36 % N) in the high N manure. The higher content of N in the high N manure increased the soluble N release capacity of this type of cattle manure upon microbial decomposition. Wetland vegetable farmers in the study site commonly use both types of cattle manure. The manure collected from kraals around and within the wetland poses greater danger of the ground water contamination with nitrates from vegetable production systems. The use of manures collected from adjacent commercial farming area poses a reduced hazard of wetland ground water contamination by nitrates. Higher NO_3–N concentrations in soil were recorded during the drier periods of the growing season when nitrate leaching was least expected (Fig. 5c). Nitrification of ammoniacal N to NO_3–N proceeds rapidly in well aerated soil conditions where nitrate is minimal.

Mean differences in the concentrations of mineralized N in lysimeters subjected to high and low N manure applications were comparatively small one month after planting the first tomato crop (Figs. 4a, 5a). The two types of cattle manure had C: N ratios below the threshold (24: 1) of net immobilization of mineralized N (Silva et al. 2005). The narrow C: N ratios of high and low N manures may not necessarily mean that they readily release mineralized N upon microbial degradation soon after application (Mafongoya et al. 1998a). Other manure quality parameters such as condensed tannins; soluble C and fibre-bound N have also been highlighted as important modifiers of N release patterns (Mafongoya et al. 1998a; Yates et al. 2006). The materials constituting aerobically composted manure commonly contain high levels of reactive phenols and tannins, which polymerize with a range of amino acids (containing N) from decomposing crude proteins in manures to generate complexes, which are resistant to enzymatic decomposition by micro-organisms in soil (Yates et al. 2006). This results in slow release of mineralized N into the soil solution. The first season after application of high and low N manures may have encouraged a rapid growth of heterotrophic microbial biomass due to an abundance of organic substrate which placed a heavy demand for N on the limited amounts of mineralized N from slowly decomposing manure. The active uptake and assimilation of the limited reserves of mineralized N by the microbiotica is suspected to have entirely obliterated the superior potential of the high N manure over low N manure to supply mineralized N observed before 42 days after application of manure. This implied that the potential for ground water pollution by nitrate overloads and accumulations from manure fertilized wetland vegetable production was reduced at the beginning of the first season after manure application.

The three crops planted after application of manure recorded significant differences in the concentrations of mineralized N between high and low N manured lysimeters ($p < 0.05$) as early as 14 days after planting. This is attributed to the longer period of exposure of manure to decomposition in which mineralized N accumulation was in surplus of the uptake by crops and microbial biomass. The higher content of N in the high N manure with narrow C: N ratio generated an increased potential of the high N manure over low N manure to supply more NO_3–N into the soil solution as the post manure application period increased.

Nitrate N concentration in leachate

In the current study, nitrate concentration in leachate differed significantly ($p < 0.05$) in the treatments between 42 and 98 days after planting the vegetable crops (Fig. 6). The concentration of NO_3–N in leachate from lysimeters that were subjected to high and low N manure applications significantly exceeded ($p < 0.05$) that from the control lysimeters by 41–224 and 60–457 %, respectively. When 15 Mg of low N manure was substituted with 15 Mg ha^{-1} of high N manure the concentration of NO_3–N in leachate increased by 22–74 %. The substitution of 30 Mg of low N manure with 30 Mg ha^{-1} of high N manure increased the concentration of NO_3–N in leachate by 21–60 %. When 15 and 30 Mg high and low N manure ha^{-1} were applied, the concentration of NO_3–N in leachate exceeded the recommended 10 mg L^{-1} concentration in portable water by 15–104 and 53–174 % respectively.

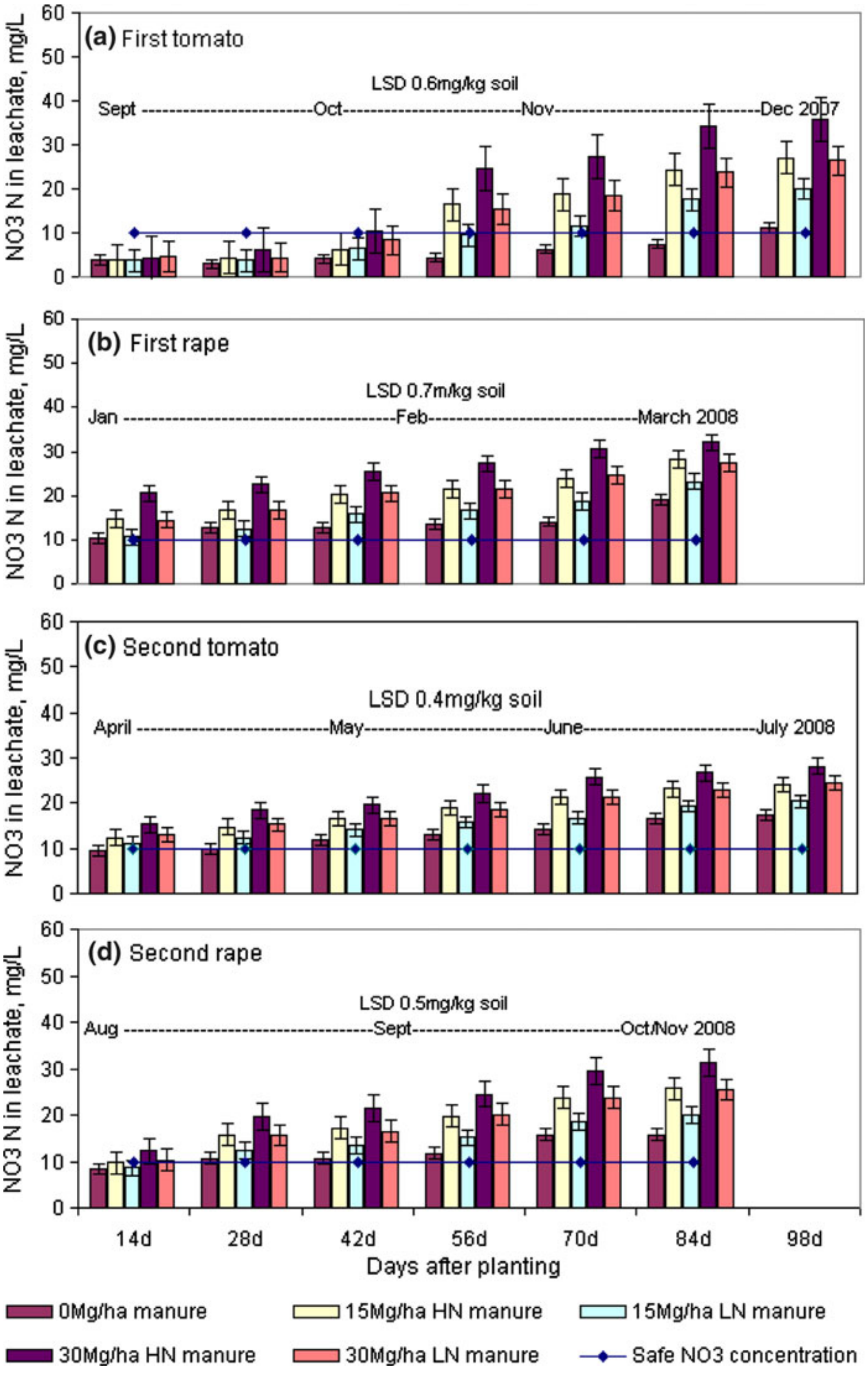
Leachate nitrate concentrations on agricultural land may be major contributors of ground water contamination. In a related study on nitrogen balance as an indicator of nitrogen leaching in Finland, Salo and Turtola (2006) reported accentuated NO_3–N accumulation in soil profile and increased nitrate leaching with increasing manure application rates. High inputs of nitrogenous fertilizers are a major potential source of nitrate contamination of groundwater (Kirchmann and Bergström 2001; Vogeler et al. 2007).

Presently, smallholder farmers in the wetland rely on boreholes for domestic water supply. Some of the ground water recharge of the boreholes originates from the cultivated wetland. Nitrate N concentrations in leachate represent the concentration of NO_3–N in portable borehole water for the villagers. High nitrate concentrations in potable water cause nitrate-related health problems. In addition, high nitrate concentrations in surface water pose the risk for eutrophication of terrestrial water bodies (Addiscott and Benjamin 2000). Generally, leachate NO_3–N concentrations from all lysimeters were above the USEPA recommended 10 mg L^{-1}.

The concentration of NO_3–N in leachate from lysimeters subjected to the application of 15 and 30 Mg high N manure ha^{-1} was 65–158 and 145–214 % above the USEPA recommended concentration for safe drinking water. In this study we reported insignificant ($p > 0.05$) percolate volume responses to rates and manure quality treatments for all four crops. This implied that under equal weather conditions leachate discharges from lysimeters subjected to the three application rates of the two types of manure would be constant for the same soil conditions. It was, therefore, leachate nitrate N concentration responses to treatments that introduced changes in the quantities of N lost through leaching to ground water resource where it caused concentrations of nitrate N to reach levels beyond the maximum permissible limit of 10 mg L^{-1} for safe drinking water (USEPA 1990).

Variations in the volumes of leachate between seasons determined the quantities of N lost by leaching for each crop. As a result, test crops grown during the wet summer season had higher losses of N in the manure-applied treatments. In response to excessive wetting of wetland soil during the rainy summer season N losses typically increased. The controlling influence of rainfall on losses N in leachate has been previously reported (Vogel 1992; Ajdary et al. 2007) and is thought to be consequence of nitrate-ladden downward movement of soil moisture beyond field capacity.

Fig. 6 Nitrate N concentration in leachate. *HN* High N manure, *LN* Low N manure



Dufuya wetland soils are characterized by poor water holding capacity and increased hydraulic transmittance due to high sand content and poor soil aggregation (Table 1). The transmission of soluble pollutants in such soils is rapid. Small external additions of water through incident rain tended to swiftly shift soil moisture levels from field capacity to saturation water, which was discharged from lysimeters as leachate. The volumes of leachate therefore tended to follow daily rainfall events in the periods preceding leachate collection. Incident rainfall totals received determined the loss of N through leaching quantitatively and the nitrate N concentrations determined the loss of N by leaching qualitatively.

In this study, the substitution of high N with low N manure reduced loss of nitrate N to groundwater. This may be attributed to high total N content (1.36 % N) in the high N manure. The higher content of N in the high N manure increased the soluble N release potential of this type of cattle manure upon microbial decomposition. Wetland vegetable farmers in the study site commonly use both types of cattle manure. The manure collected from kraals around and within the wetland poses greater danger of the ground water contamination with nitrates from vegetable production systems. The use of manures collected from adjacent commercial farming (low N) area poses a reduced hazard of wetland ground water contamination by nitrates. Previous studies by Silva et al. (2005) have indicated that the use of low N containing manure as sources of plant N substantially reduces groundwater pollution. Increased use of N fertilizer and animal manures has accentuated nitrate–N contamination, because nitrate leaching in the ground water is related to N fertilization rate (Ajdary et al. 2007). A wetland soil environment by its very nature has such permanent soil wetness that the water table rarely falls beyond 15 cm from the surface during the rainy season and under such conditions the margins between field capacity and gravitational soil moisture levels are very narrow indeed. This means that wetland soil conditions are highly susceptible to leaching processes.

Estimated total N lost in leachate

Significant ($p < 0.05$) nitrate N leaching responses to treatments were recorded (Tables 3, 4). Studies by Hansen et al. (2001), Akinsanmi and Perry (2002) and Follett and Delgado (2002) concluded that nitrate leaching as a result of agricultural practices is responsible for much of the environmental damage caused to terrestrial and aquatic ecosystems, which is generally attributed to the excessive application of nitrogenous fertilizers including manures beyond crop requirements. Lowest amounts of total N lost in leachate were regularly observed in the control lysimeters (1.3–9.6 kg N ha^{-1}). However, loss of N under the second tomato crop was generally low for the three treatments when no rainfall event was recorded during the April–July 2008 winter season and substantial nitrate N leaching was least expected. Higher total N losses were recorded when 30 Mg high N manure ha^{-1} was applied just before planting the first tomato crop in September 2007 (27.7 kgN ha^{-1}) and in the first (24.4 kg N ha^{-1}). Both crops experienced exceptionally wet summer seasons (Fig. 2). Substituting 15 and 30 Mg ha^{-1} of high N manure with 15 and 30 Mg ha^{-1} of low N manure reduced N losses by an average of 10–43 and 22–69 % respectively.

The results obtained from this study imply that application of poor quality cattle manure (low N, high C) might be a way to reduce the risk of NO_3–N leaching from cultivated wetland soil. In related studies Jarvis et al. (1989) and Nicholson et al. (1997) concluded that incorporation of carbon-rich and N-poor manure to a soil significantly decreased NO_3–N leaching. Apparently, lysimeters that received low N manure recorded substantially lower nitrate N leached clearly implying that wetland vegetable production fertilized with low N manure can potentially reduce ground water pollution.

Correlations between selected variables

A large proportion (r^2 values between 0.50 and 0.75, $p < 0.05$; Tables 5, 6) of the NO_3–N concentrations in soil could be consistently predicted by variations in soil moisture under first tomato and second rape crops only. Nitrate N concentrations in soil decreased with the expected increase in NO_3–N leaching from soil as soil moisture increased. Nitrate N concentrations in soil and soil moisture were also significant predictors of variations in the concentrations of NO_3–N in leachate for the first tomato and second rape crops only. However, the influence of NO_3–N concentrations in soil on NO_3–N in leachate was stronger (r^2 values between 0.75 and 0.99, $p < 0.05$) than that of soil moisture (r^2 values between 0.51 and 0.71, $p < 0.05$).

The manure organic matter decomposition process is essentially oxidative and proceeds only in the presence of water at least up to field capacity moisture content. The growing periods of the first tomato and second rape crops ran through both dry (winter) (September 2007 and 2008) and rain seasons (after October 2007 and 2008, Fig. 2). The dry spring periods

Table 3 Estimated total nitrogen lost in leachate following application of high N manure

Trts	Temporal interval (days after planting)	Mean leachate [NO$_3$N] mgL^{-1}	Mean daily leachate volume, L	N leached kgha^{-1}	Total N applied kg/ha	% Leached N of applied N	Temporal interval (days after planting)	Mean leachate [NO$_3$N] mgL^{-1}	Mean daily leachate volume, L	N leached kgha^{-1}	Total N applied kg/ha	% Leached N of applied N
	First tomato crop						First rape crop					
T1a	0–49	3.3	4.1	1.3	–	–	0–35	11.0	5.3	4.1	–	–
	50–77	8.6	6.6	3.2	–	–	36–63	12.1	5.6	3.8	–	–
	78–98	16.4	6.7	4.6	–	–	64–84	14.6	5.8	3.6	–	–
Total	–	–	–	9.1	0	0	–	–	–	11.5	0	0
T2a	0–49	5.0	4.4	2.2	–	–	0–35	15.7	5.3	5.8	–	–
	50–77	10.5	6.7	4.0	–	–	36–63	20.1	5.6	6.3	–	–
	78–98	19.8	6.8	5.7	–	–	64–84	26.0	5.8	6.3	–	–
Total				11.9	204	6	–	–	–	18.4	0	0
T3a	0–49	6.5	4.7	4.0	–	–	0–35	21.6	5.5	8.3	–	–
	50–77	25.2	6.8	9.6	–	–	36–63	26.4	5.8	8.6	–	–
	78–98	48.6	6.9	14.1	–		64–84	31.4	5.7	7.5	–	–
Total	–	–	–	27.7	408	7	–	–	–	24.4	200	0
Fpr	–	*	NS	*	–	–	–	*	NS	*	–	–
Lsd	–	1.1	0.4	1.4	–	–	–	2.1	1.3	2.1	–	–
CV	–	7.8	3.1	2.2	–	–	–	2.7	1.9	1.9	–	–
	Second tomato crop						Second rape crop					
T1a	0–63	10.7	0.5	0.7	–	–	0–21	8.4	0.8	0.3	–	–
	64–98	16.0	0.5	0.6	–	–	22–63	11.1	5.1	4.7	–	–
	–	–	–	–	–	–	64–84	21.1	5.2	4.6		
Total	–	–	–	1.3	0	0	–	–	–	9.6	0	0
T2a	0–63	14.3	0.5	0.9	–	–	0–21	12.8	0.8	0.4	–	–
	64–98	21.2	0.5	1.2	–	–	22–63	18.5	5.1	7.9	–	–
							64–84	24.8	5.2	5.4		
Total	–	–	–	2.0	0	0	–	–	–	13.7	0	0
T3a	0–63	18.5	1.4	3.2	–	–	0–21	16.0	0.7	0.4	–	–
	64–98	24.2	0.7	1.2	–	–	22–63	23.0	5.2	10.0	–	–
							64–84	30.5	5.3	6.8		
Total	–	–	–	4.4	0	0	–	–	–	17.2	0	0
Fpr	–	*	NS	*	–	–	–	*	NS	*	–	–
Lsd	–	1.6	0.6	0.3	–	–	–	1.6	0.3	1.2	–	–
CV	–	9.1	5.1	4.4	–	–		1.9	1.0	1.9	–	–

Treatments: T1a—(Control), T2a—(15 Mg high N manure ha^{-1}), T3a—(30 Mg high N manure ha^{-1})

Table 4 Estimated total nitrogen lost in leachate following application of low N manure

Trts	Temporal interval (days after planting)	Mean leachate [NO_3N] mgL^{-1}	Mean daily leachate volume, L	N leached $kgha^{-1}$	Total N applied kg/ha	% Leached N of applied N	Temporal interval (days after planting)	Average leachate [NO_3N] mgL^{-1}	Mean daily leachate volume, L	N leached $kgha^{-1}$	Total N applied kg/ha	% Leached N of applied N
	First tomato crop						First rape crop					
T1b	0–49	3.1	4.0	1.2	–	–	0–35	11.2	5.3	4.2	–	–
	50–77	8.7	6.5	3.2	–	–	36–63	12.4	5.6	3.9	–	–
	78–98	16.4	6.6	4.6	–	–	64–84	14.1	5.8	3.4	–	–
Total	–	–	–	9.1	0	0	–	–	–	11.5	0	0
T2b	0–49	5.0	4.1	2.0	–	–	0–35	11.6	4.2	3.4	–	–
	50–77	10.5	6.3	3.7	–	–	36–63	16.2	5.7	5.2	–	–
	78–98	18.8	6.5	5.1	–	–	64–84	20.9	5.5	4.8	–	–
Total				10.8	76.5	5	–	–	–	13.4	0	0
T3b	0–49	5.8	4.7	2.7	–	–	0–35	15.7	5.5	6.0	–	–
	50–77	16.9	6.8	6.4	–	–	36–63	21.0	5.8	6.8	–	–
	78–98	25.1	6.9	7.3	–		64–84	26.0	5.3	5.8	–	–
Total	–	–	–	16.4	153	4	–	–	–	18.6	0	0
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					
T1b	0–63	10.7	0.4	0.5	–	–	0–21	8.2	0.7	0.2	–	–
	64–98	16.2	0.6	0.7	–	–	22–63	11.0	5.3	4.8	–	–
	–	–	–	–	–	–	64–84	21.2	5.0	4.5		
Total	–	–	–	1.2	0	0	–	–	–	9.5	0	0
T2b	0–63	13.4	0.6	1.0	–	–	0–21	10.5	0.7	0.3	–	–
	64–98	18.8	0.6	0.8	–	–	22–63	14.3	5.2	6.2	–	–
	–	–	–	–			64–84	19.3	5.0	4.0		
Total	–	–	–	1.8	0	0	–	–	–	10.5	0	0
T3b	0–63	15.9	0.6	1.2	–	–	0–21	13.0	0.7	0.4	–	–
	64–98	22.9	0.7	1.1	–	–	22–63	18.3	5.3	8.1	–	–
							64–84	24.6	5.4	5.6		
Total	–	–	–	2.3	0	0	–	–	–	14.1	0	0
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—(15 Mg low N manure ha^{-1}), T3—(30 Mg low N manure ha^{-1})

Table 5 Pearson correlation coefficients between physical and chemical characteristics

	High N manure			Low N manure		
		NO_{3L}	NO_{3S}		NO_{3L}	NO_{3S}
First tomato crop	NO_{3L}		0.91*	NO_{3L}		0.99*
	SM	0.72*	−0.62*	SM	0.71*	−0.71*
	ST	0.62 NS	0.50 NS	ST	0.63 NS	0.61
First rape crop	NO_{3L}		0.87*	NO_{3L}		0.23*
	SM	0.06 NS	−0.06 NS	SM	0.12 NS	−0.10 NS
	ST	0.08 NS	0.08 NS	ST	0.04 NS	0.09 NS
Second tomato crop	NO_{3L}		0.99*	NO_{3L}		0.99*
	SM	0.02 NS	−0.48 NS	SM	0.03 NS	−0.73 NS
	ST	0.48 NS	0.51 NS	ST	0.53 NS	0.51 NS
Second tomato crop	NO_{3L}		0.78*	NO_{3L}		0.99*
	SM	0.77*	−0.78*	SM	0.84*	−0.87*
	ST	0.16 NS	0.16 NS	ST	0.12 NS	0.13 NS

Asterisks denote two-tailed 5 % level significances (*$p < 0.05$)

NS not statistically significant, *NO_{3L}* nitrate N in leachate, *NO_{3S}* nitrate N in soil, *V_L* volume of leachate, *SM* soil moisture, *ST* soil temperature

Table 6 Regression analyses showing the direct and the indirect effects of soil factors on selected variables following application of high and low N manure

Test crop	High N manure treatments		Low N manure treatments	
	r^2 values	Regression equations	r^2 values	Regression equations
First tomato	0.50	$[NO3S] = -0.4[SM] + 32$	0.51	$[NO3L] = 0.5[SM] + 22$
First tomato	0.51	$[NO3L] = 0.4[SM] + 22$	0.50	$[NO3S] = -0.5[SM] + 21$
First tomato	0.99	$[NO3L] = [NO3S] - 1$	0.99	$[NO3L] = [NO3S] - 1$
First rape	0.75	$[NO3L] = [NO3S] + 5$	0.77	$[NO3L] = [NO35] + 1$
Second tomato	0.99	$[NO3L] = [NO3S] + 0.3$	0.95	$[NO3L] = [NO35] - 0.1$
Second rape	0.51	$[NO3S] = -0.4[SM] + 32$	0.95	$[NO3L] = [NH4S] + 1$
Second rape	0.61	$[NO3L] = 0.8[SM] + 14$	0.71	$[NO3L] = [SM] + 13$
Second rape	0.86	$[NO3L] = 0.7[NO3S] + 7$	0.75	$[NO3S] = -[SM] + 32$

[NO3S]—Concentration of nitrate N in soil, [NO3L]—Concentration of nitrate N in leachate, [SM]—Content of soil moisture, [NH4S]—Concentration of ammonium N in soil

were characterized by soil moisture contents within field capacity ranges, which allowed aerated soil profile for the rapid oxidative manure organic matter decomposition with enhanced production of mineralized N. At field capacity moisture content, NO_3–N leaching processes are minimized. The onset of wet summer season in the vegetative period of the crop introduced saturated wetland soil conditions with reduced soil profile aeration and the associated reduction in organic matter decomposition and mineralization processes. Under such conditions, production of mineralized N is scaled down and NO_3–N leaching is enhanced. The significant dependence of NO_3–N concentrations on soil moisture content was observed when the moisture levels in soil varied considerably within the vegetative period of the vegetable crop such as that recorded under the first tomato and second rape crops. Where substantial variabilities in soil moisture content within the growing period of a vegetable crop (first rape and second tomato crops) were not recorded, soil moisture

Table 7 Dry matter yield and N uptake by aboveground plant biomass following application of high N manure

Trts	First tomato			First rape			Second tomato			Second rape		
	DM yield T/ha	MgN/ g DM	N uptake Kg/ha	DM yield T/ha	MgN/ g DM	N uptake Kg/ha	DM yield T/ha	MgN/ g DM	N uptake Kg/ha	DM yield T/ha	MgN/ g DM	N uptake Kg/ha
T1a	3.0	9.6	27.9	9.7	1.2	9.8	3.1	12.1	35.2	14.7	2.2	32.3
T2a	6.8	11.7	79.6	12.5	4.6	57.5	7.8	7.1	55.7	18.5	3.2	59.2
T3a	8.5	17.2	146.2	16.0	8.5	136.2	8.6	16.1	138.2	21.0	5.8	121.8
Fpr	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Lsd (5 %)	0.1	0.8	0.7	1.4	1.3	0.5	0.5	1.6	1.2	1.0	1.2	0.6
CV %	1.0	4.1	5.3	6.2	15.4	5.4	4.2	6.6	7.4	3.8	12.4	6.8

T1a—Control (0 Mg manure ha^{-1}), T2a—15 Mg high N manure ha^{-1}, T3a—30 Mg high N manure ha^{-1}, DM—dry matter yield, mgN/g DM—milligrams of N per gram dry matter

Table 8 Dry matter yield and N uptake by aboveground plant biomass following application of low N manure

Trts	First tomato			First rape			Second tomato			Second rape		
	DM yield T/ha	MgN/ g DM	N uptake Kg/ha	DM yield T/ha	MgN/ g DM	N uptake Kg/ha	DM yield T/ha	MgN/ g DM	N uptake Kg/ha	DM yield T/ha	MgN/ gDM	N uptake Kg/ha
T1b	3.0	9.7	27.6	10.3	1.5	10.2	3.0	12.3	35.8	14.4	2.4	32.4
T2b	6.6	11.3	74.8	10.4	4.5	46.5	6.4	6.1	44.2	13.4	2.9	51.0
T3b	8.1	16.1	130.2	13.4	7.1	95.4	8.1	15.1	136.9	14.5	5.1	118.8
Fpr	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Lsd (5 %)	0.1	2.4	0.7	0.7	1.5	0.3	0.2	2.6	0.6	0.4	2.2	0.2
CV %	0.9	12.1	5.2	3.5	19.8	3.7	2.0	12.0	4.5	1.9	21.0	4.4

T1b—Control (0 Mg manure ha^{-1}), T2b—15 Mg low N manure ha^{-1}, T3b—30 Mg low N manure ha^{-1}, DM—dry matter yield, mgN/g DM—milligrams of N per gram dry matter

content was a weak predictor of soil NO_3–N concentrations.

Nitrogen uptake and aboveground dry matter yield

Nitrogen uptake was monitored for all the treatments throughout the growing seasons of the four vegetable crops. Statistical significance of the differences between N uptake and dry matter yield in lysimeters subjected to high N and low N manure applications was established by performing t-test for unpaired samples using the GenStat package. There were significant treatment effects on N uptake and dry matter yield ($p < 0.05$; Tables 7, 8).

The uptake of N by crops is an effective biological sequestration of N that can otherwise be exposed to leaching especially under wetland conditions. In the current study, risks of significant N losses to the environment were generally high because vegetable crops have a low recovery rate of applied N. In a related study on nitrogen cycling in a multiple crop-vegetable production system Lowrance and Smittle (1988) reported N recovery rate of about 70 % of applied N. In a conference paper presented to the Industry Federation of Australia, Reuter (2000) reported significantly low N use efficiency by vegetable crops and the associated risk of environmental pollution.

The substitution of 15 and 30 Mg ha^{-1} high N manure with low N manure reduced N uptake by 4.4–38.6 and 1.4–40.8 kg ha^{-1} respectively. This indicates that while the application of low N manure to vegetable crops may be used to reduce nitrate overloads in wetland soil, the positive effects of this ameliorative measure are over-shadowed by the fact that the same practice reduced the N uptake by all test crops. Application of low N manure reduced considerably the positive effects of biological N sequestration from nitrate leaching process and the associated pollution of ground water. This was attributed to the fact that the content of N in the high N manure was more than double the content of N in low N manure (Table 2). The elevated content of N in the high N manure increased its capacity to supply mineralized N for crop biomass accumulation, which in turn increased uptake of N from the wetland soil system.

When rates of high N manure were increased from 15 to 30 Mg ha^{-1}, aboveground dry matter yield of tomato and rape crops increased by (25–26 %) and 0.2–4 Mg ha^{-1} (1–32 %), respectively. The same practice in wetland vegetable production elevated aboveground dry matter yield by 1.3–1.6 Mg ha^{-1} (19–25 %) and 1.0–2.8 Mg ha^{-1} (8–26 %) when low N manure was applied on tomato and rape crops respectively. Substituting 15 and 30 Mg high N manure ha^{-1} by the same rates of low N manure considerably decreased aboveground dry matter yield by 0.2–3.4 Mg ha^{-1} (3–21 %) and 0.3–3.1 Mg ha^{-1} (4–19 %) respectively. Practically, the use of low N containing manures reduces the risk of shallow groundwater pollution by nitrate overload while compromising the farmers' ability to produce higher yield per unit area. In this context, the use of low N as a fertility restorer in vegetable production systems reduces the risk of groundwater contamination while simultaneously trading off this risk reduction with lower vegetable productivity.

Conclusion

Many smallholder farmers in sub-tropical Zimbabwe are unable to access adequate quantities of inorganic fertilizer to maintain food production and soil fertility. The smallholder farmers usually rely on use of cattle manure to increase productivity in wetland vegetable production. High cattle manure rates are applied to vegetables in order to eliminate the risk of yield depression due to lack of plant available N. The relatively low recovery rate of applied N by vegetable crops means that there are risks of significant N losses to the environment through nitrate leaching under wetland soil conditions. The groundwater contamination potential of manure fertilized wetland vegetable by nitrate overload depends on the content of N in the applied manure. When low N manures are applied to a soil as an ameliorative measure for reducing the potential of NO_3–N contamination of ground water the possibility of a yield reduction increases considerably. The groundwater risk of contamination by applying high N manure for increased yield responses is weighed against the benefit of reduced risk of groundwater contamination and increased possibility of yield reduction when low N manure is applied. The results of this study have shown that a trade-off between these two competing objectives of smallholder farmers is established by applying higher rate of low N manure (30 Mg ha^{-1}) for increased yield coupled with reduced risk of ground water contamination.

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