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Effects of rainfall pattern and fertilizer nitrogen on nitrogen loss in bypass flow in vertisols at the onset of rain season under tropical environments

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Bypass flow is a major avenue of fertilizer nitrogen (N) loss from Vertisols under environments characterized by alternating dry and wet seasons. The study quantified the effects of rainfall intensity and frequency, and fertilizer N source and rate on N content of bypass flow in a Vertisol. We carried out two experiments. Experiment I comprised of 2 wetting status, 2 rainfall intensities, and 3 N sources. Experiment II involved 3N sources, 3N rates, and 3 levels of rainfall frequencies. In both Experiments, bypass flow was collected, filtered and analyzed for mineral N content. Wetting soil with 30mm of precipitation in 1h before fertilizer application resulted in significantly ($p<0.05$) higher bypass flow and mineral N content than did the no-wetting treatments. Rainfall intensity and frequency, and N rate significantly ($p<0.05$) increased mineral-N recovered in the bypass flow. The 3 N sources used are susceptible to loss in bypass flow.

Key words: Fertilizer nitrogen, nitrogen loss, rainfall patterns, tropical vertisols.

INTRODUCTION

Nitrogen (N) is the most limiting nutrient to crop productivity in the majority of tropical soils (Ahn, 1993). Khalifa and Zidan (1999), and Nyamangara et al. (2003) reported widespread N deficiency in soils and low efficiency of N recovery by cereal crops in the tropics. Nitrogen is the most limiting nutrient element to crop production in Vertisols in Kenya (Ikitoo, 1989). This is attributed to both low soil organic matter and to losses of inorganic N. Most of the N losses from agricultural soils are due to leaching (Nyamangara *et a.,* 2003), bypass flow (Bouma et al*.,* 1981; Sigunga et al*.,* 2008; Smaling and Bouma, 1992), denitrification (Schnabel and Stout, 1994; Sigunga et al., 2002a; Sigunga et al., 2002b) and/or ammonia volatilization (Sigunga et al., 2002c). Increasing concern for the environment and escalating N fertilizer prices (Nyamangara et al*.,* 2003; Pathak et al., 2004) have prompted critical look at N losses from agricultural systems, with a focus on designing strategies for increasing efficiency of N recovery and reducing N losses into the environment.

Moisture content of tropical soils is characterized by temporal variations due to distinct dry and rain seasons. The Vertisols swell during the rain season (Bouma and Loveday, 1988), while during the dry season the soils shrink creating cracks which act as preferential flow paths (Ahmad, 1996; Deckers et al., 2001). The cracks vary in width and depth depending on the type and amount of clay minerals as well as on the magnitude and duration of drying. Infiltration splits into matrix (leaching) and bypass flows (Seiler et al., 2002). Matrix flow involves water movement from saturated upper to unsaturated lower layers of the soil profile (Nielsel et al., 1986). In contrast, bypass flow is a vertical flow of free water along the walls of preferential flow paths down the soil profile (Andreini and Steenhuis, 1990; Smetten et al., 1981). The solute and water circumvent the soil matrix and move down the soil profile before the upper soil layers are saturated (Bouma et al., 1981; Seiler et al., 2002). Bypass flow has

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been shown to facilitate rapid solute transport down the soil profile circumventing biologically active root rhizospheres (Andrieni and Steenhuis, 1990), and flow of microbial populations into underground water masses risking the lives of humans and animals that use the water (Crescimanno et al., 2007).

In rainfed agricultural systems, under tropical conditions, farmers plant at the onset of rains after a long period of drought. At this time cracks in Vertisols are open and applied fertilizer N is susceptible to movement down the soil profile in bypass flow often to depths beyond plant rooting depth, in which case the fertilizer N is considered lost. Fertilizer N loss in bypass flow is influenced by soil's hydrological processes (Booltink and Bouma, 1993), N species (Sigunga et al., 2008), and concentration of preferential flow paths in the soil (Renck and Lehmann, 2004).

Information on fertilizer N losses in bypass flow in Kenyan Vertisols is meager, being limited to the reports by Sigunga et al. (2008) and Smaling and Bouma (1992). Neither of the works investigated the effects of rainfall intensity and frequency on N loss in bypass flow.

The objectives of this study were to quantify the effects of:

(i) rainfall pattern (namely, intensity and frequency) and
(ii) N source and rate on N content of bypass flow from a Vertisol in Kenya.

MATERIALS AND METHODS

Experimental site

Soil columns for the Experiments were excavated from a site in Muhoroni Division, Kenya, located at 00^0 10.06'S, 035^0 13.50'E and used to conduct the experiment on the site. The site had been characterized and classified as Eutric Vertisols and the rainfall pattern of the site is bimodal with more than 2 months of dry periods (Sigunga, 1997; Sigunga et al., 2002a). The site falls under the Lower Midland 2 agro-ecological zone characterized by bimodal rainfall pattern. Monthly rainfall intensity at the site ranges from 22 to 38 mm h^{-1}, with a mean of 30 mm h^{-1}. (Jaetzold and Schmidt,1982). Characteristics of the soils at the site are given in Table 1. The soils are characterized by high clay, cation exchange capacity (CEC), and calcium (Ca) contents and the B horizon showed mottles.

Experiment I

Experimental treatments and design

Experiment I quantified the effects of wetting, rainfall intensity, and fertilizer N source on N content of bypass flow. The treatments comprised of 2 wetting status (i.e., no wetting and wetting soil with 30 mm of water in 1 h before fertilizer application), 2 rainfall intensities (i.e., 20 mm and 40 mm of precipitation in 1 h) and 3 N sources (i.e. urea, ammonium sulphate and calcium nitrate). The no wetting treatment was meant to simulate fertilizer application before the onset of rains in contrast to wetting treatment that simulated fertilizer treatment after the onset of rains. Nitrogen sources were selected to provide different N species, namely NH_2, NH_4^+ and NO_3^-. Nitrogen was applied at an equivalent rate of 100 kg N ha^{-1} just before the application of water. There were 16 treatments in total, including 4 checks. All the checks received no fertilizer. Checks 1 and 2 were not wetted, while checks 3 and 4 were wetted a day before water was applied. The checks 1 and 3 received 20 mm of precipitation in 1 h each, while the checks 2 and 4 received 40 mm of precipitation in 1 h each. Checks 3 and 4 were wetted to bring their moisture condition as close as possible to that of wetted soil columns. The checks were included to provide for calculation of inherent soil N for appropriate wetting status and rainfall intensity. A Completely Randomized Design replicated 3 times was used. The experiment was conducted at the Muhoroni site during dry season when the cracks were wide.

Experimental procedures and data collection

The procedure described by Sigunga et al. (2008) and Smaling and Bouma (1992) was used. In brief, polyvinyl chloride (PVC) cylinders used to excavate soil column were 40.0, 20.0 and 1.5 cm in height, diameter and thickness, respectively, sharpened at the bottom end to facilitate the sliding of the cylinder down the soil. The cylinder was slowly driven into the soil to avoid disturbance of the soil column as much as possible. A liberal amount of Vaseline® was smeared on the inside wall of each PVC cylinder before sampling to prevent water flow along the walls. Soil column depth of 40 cm was chosen to coincide with the effective rooting depth of maize, the principal food crop in the study area (Sigunga, 1997).

The top 15.0 cm of soil was broken down into loose but coarse aggregates to simulate a cultivated field. A head space of 2 cm was left between the soil surface level and the cylinder top to provide a 15 cm deep cultivated top soil on top of 23 cm deep uncultivated subsoil. Rainwater (pH = 7.7; EC = 0.423 mmhos cm^{-1}) was used in simulating rainfall intensity. Simulated rainfall was applied using a rainfall simulator (Figure 1). The water head, h, was kept the same to maintain constant rate of water flow from the irrigation needles (Figure 1a). Each rainfall event of 20 mm in 1 h intensity supplied 628.6 mL of water per column, while that of 40 mm in 1 h supplied 1,257 mL of water per column. The amount of water applied (W) in mL in 1 h per column to simulate required rainfall intensity was calculated as follows (Sigunga et al., 2008):

$$W = \prod r^2 R10^{-3}$$

Where: W is the amount of water applied in mm in 1 hour per column,
R is rainfall intensity (mm h^{-1}), and
r is column radius (mm).

Both fertilizer and simulated precipitation were applied on the surface of the soil column, and the outflow was collected in a beaker below the soil column. The support cylinder provided with a window that facilitated insertion and removal of the beaker (Figure 1b) protected the funnel and the beaker. Precipitation was applied immediately after fertilizer application. The volume of the outflow was measured and a portion stored at -10°C until time of analysis to minimize biochemical transformation of N. Time taken for the outflow to stop following the addition of precipitation was taken.

Mean moisture contents of two soil samples taken at 10 and 30 cm depths along the walls of the pit from which the soil column had just been excavated represented the initial moisture content of the soil column. At the end of the experiment the soil column in the cylinder was gently forced out, and two soil samples were collected at 10 and 30 cm depths of the soil column and their moisture contents determined. Mean moisture contents of the 2 samples represented the final moisture content of the soil column. To determine saturated moisture content of the soil ten lumps (ca. 30g each) of soil were taken at 30 cm depth at the experimental site and placed in a sand bath saturated with water for 2 weeks, and then

Table 1. Soil analysis data of a profile at the research (Muhoroni) site.

	Horizon		
	A	**Bg1**	**Bg2**
Depth (cm)	**0 - 20**	**20 - 42**	**42 – 82**
%Sand	26	22	22
%Silt	14	10	8
%Clay	60	68	70
Texture	Clay	Clay	Clay
pH water (1:2.5)	6.0	6.2	6.6
Organic C (%C)	1.88	1.21	1.0
Total N (%N)	0.17	0.11	0.10
CEC (cmol(+)kg^{-1})	44.4	38.65	34.4
Exch. Na (cmol(+)kg^{-1})	0.62	0.85	1.11
Exch. K (cmol(+)kg^{-1})	0.59	0.62	0.41
Exch. Mg (cmol(+)kg^{-1})	8.4	7.72	8.79
Exch. Ca (cmol(+)kg^{-1})	18.61	25.03	30.21
Soil class	**Eutric Vertisol**		

Source: Sigunga, 1997, pp.26

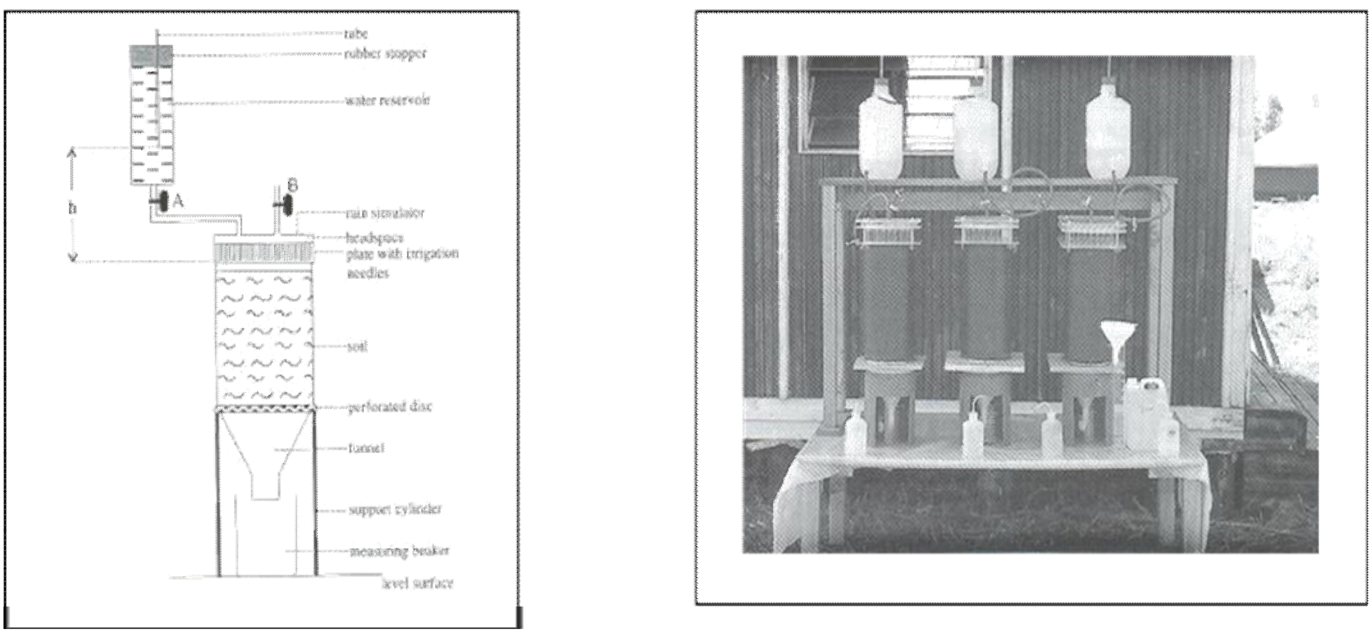

Figure 1. Bypass flow-measuring equipment. **(a)** Vertical section of a single measuring equipment system, and **(b)** three sets of bypass flow measuring equipment system in operation.
(Courtesy of the Department of Water Resources, Wageningen University, the Netherlands.)

the moisture content determined. In order to observe preferential flow paths 50 ml of methylene blue solution (50 g methylene blue in 1000 mL of distilled water) was sprayed on the surface of each soil column before fertilizer application. Water-conducting pores stained dark blue by the dye at the end of the experiment indicate preferential flow paths. The stained spots on the cross section surface of the soil column at 10cm and 40 cm depths were traced on a transparent plastic graph paper to estimate the proportion of the cross section of the soil column occupied by the preferential flow paths (Minh et al., 1997; Sigunga et al., 2008; Smaling and Bouma1992).

Laboratory analysis and calculation procedures

At the time of laboratory analysis the bypass flow stored at -10 ^oC was filtered using whatman no. 42 filter paper before determination of NH_4^+ and NO_3^- concentrations following procedures described by Okalebo et al. (2002). In the determination of NH_4^+ - N 5.0 mL of the reagent N1 (sodium salicylate, sodium citrate, and sodium tartarate) was added to 0.2 mL of the filtered bypass flow in a test tube. The content of the test tube was vortexed after 20 min. Then 5.0 mL of reagent N2 (sodium hydroxide and sodium hypochlorite) was added and vortexed. The test tube content was left to stand for 1h to allow for colour development. The concentration of NH_4^+ - N was read from a spectrometer (Spectronic 21D, Milton Roy Co., Ivyland, Penn. USA) at λ 655 nm. To determine NO_3^- -N 1.0 mL of salicylic acid was added to 0.5 mL of the filtered bypass flow in a test tube, vortexed and left to stand for 30 min. Then 10.0 mL of 4M sodium hydroxide was added and left to stand for 1 h to allow for colour development. The concentration of NO_3^--N was read from the spectrometer at λ 410nm.

The mineral N in the check outflow was deducted from the mineral N in the sample outflow in order to correct for the soil inherent mineral N. The amount of mineral nitrogen recovered in bypass flow was calculated as follows (Sigunga et al., 2008):

$$N_{ha} = V(N_{cs} - N_{cb})3.18 \times 10^{-4}$$

Where;

N_{ha} = mineral N recovered in the outflow (kg N ha^{-1}),
N_{cs} = nitrogen concentration in the treated sample (or control) (mg N L^{-1}),
N_{cb} = nitrogen concentration in the blank (mg N L^{-1}),
V= volume of the outflow from the cylinder (mL)

Total mineral N made up of nitrogen derived from fertilizer (Ndff) and nitrogen derived from soil (Ndfs), whether NH_4^+ - N or NO_3^--N, was calculated from the above relationship where Ncs and Ncb refer to mineral N in sample and in blank, respectively. The Ndff was the difference between the total mineral N and the mineral N recovered from appropriate control. The Ndfs was the total mineral N less Ndff.

Experiment II

Experimental treatments and design

This experiment quantified the effects of N source and rate, and rainfall frequency on N loss in bypass flow. The treatments comprised of 3N sources (urea, ammonium sulphate and calcium nitrate), 3N rates (50, 100 and 200kg Nha^{-1}), and 3 levels of rainfall frequencies (1 rainfall event, 2 and 3 rainfall events). To simulate one rainfall event, water was applied to the soil column at a rate of 40 mm of rainstorm in 1 h once. To simulate 2 and 3 rainfall events 40 mm of precipitation in 1 hour was applied to the columns once each day for 2 and 3 consecutive days, respectively. In all cases, fertilizer was applied just before the first rainfall event. There were 30 treatments including 3 checks (no fertilizer application). One (1) rainfall event was applied to check 1, while 2 and 3 rainfall events were applied to checks 2 and 3, respectively. A Completely Randomized Design replicated three times was used.

Experimental procedures, data collection and laboratory analyses were conducted as described under Experiment I above. Normality of data distribution was confirmed ($P < 0.05$) using Shapiro-Wilks statistic (Sokal and Rohlf, 1981). All data from the two experiments were subjected to analysis of varience (ANOVA) using MSTATC computer software (Michigan State University, 1993), and the means were separated using Duncans Multiple Range Test (DMRT) (Little and Hills, 1978).

RESULTS AND DISCUSSION

Bypass flow and soil moisture changes

The amount of bypass flow (outflow) from the soil columns was affected by wetting status and by rainfall intensity but not by nitrogen (N) source (Table 2).

At a given rainfall intensity pre-wetted soil produced significantly ($p < 0.05$) higher amount of outflow. Within a given wetting status higher rainfall intensity resulted in significantly ($p < 0.05$) higher amount of outflow. Pre-wetting combined with 40 mm precipitation in 1 h resulted in significantly ($p < 0.05$) the highest outflow and also the longest time period taken for the outflow to stop (Table 2). The proportion of precipitation collected as outflow at the end of the experiment varied with wetting and rainfall intensity and ranged from 15 to 70%. The non pre-wetted soils that received 20 mm rainfall event did not produce outflow possibly because the applied amount of water was less than the amount needed to saturate the surface peds of the preferential flow paths. The significantly higher amount of outflow due to pre-wetting and higher rainfall intensity was attributed to very low lateral absorption of water as it flowed down the preferential flow paths (Booltink and Bouma, 1993; Smaling and Bouma, 1992).

The highest final mean soil moisture content of the experimental soil columns was 22% (Table 2), and the mean soil moisture content of saturated experimental soil lumps as determined from saturated sand bath was 65%. The low final mean soil moisture content that was far below the moisture content of the saturated soil and the high proportion of precipitation obtained as outflow indicate the presence of preferential flow paths through which the water passed. In the absence of preferential flow paths, drainage in the soil would commence after complete saturation of the soil column in which case the average soil-moisture content at the end of the experiment would be 65%.

However, the outflow occurred before the equilibrium drainage conditions were met, implying the occurrence of bypass flow phenomenon. Cross sections of the soil columns examined at 10 cm and 40 cm depths after the stop of the outflow revealed that dark-blue stained surfaces at the two depths varied between 15% at 10 cm depth and 10% at 40 cm depth. The low variation in the concentration of the dark-blue stained surfaces indicated that most of the preferential flow paths that originated at the ground level continued to below 40 cm depth. Smaling and Bouma (1992) and Sigunga et al. (2008) also reported on the occurrence of preferential flow paths in these Vertisols.

Mineral nitrogen recovered in bypass flow

Mineral N recovered in the bypass flow varied with wetting status, rainfall intensity, and N source (Table 3). There was no outflow from the no-wetting and the 20 mm precipitation in 1 h treated soil columns (Table 2) and, hence, mineral N content from these soil columns could not be determined (Table 3). Pre-wetting resulted in

Table 2. Effects of wetting status, rainfall intensity, and nitrogen source on amount of outflow, time taken for outflow to stop, and soil moisture increase. Each value is a mean of 3 observations except for soil moisture content where values are means of 9 observations.

Wetting status	[2]Rainfall intensity (mm h^{-1})	Nitrogen source	Mean time (min) taken for outflow to stop	Amount of outflow (mL) collected	Outflow as a % of applied rainstorm	Mean moisture content (%) Initial	Final	Mean increase in soil moisture content (%)
No wetting	20	Urea	0.0^{g}	0.0^{e}	0			
		Ammonium sulfate	0.0^{g}	0.0^{e}	0	14	16	2
		Calcium nitrate	0.0^{g}	0.0^{e}	0			
	40	Urea	54.0^{f}	266.0^{b}	21.2			
		Ammonium sulfate	54.7^{f}	192.0^{bc}	15.3	15	21	6
		Calcium nitrate	56.0^{f}	274.0^{b}	21.8			
[1]Wetting	20	Urea	65.6^{e}	127.0^{d}	20.2			
		Ammonium sulfate	75.7^{d}	172.0^{cd}	27.3	15	22	7
		Calcium nitrate	86.7^{c}	185.0^{cd}	29.4			
	40	Urea	94.6^{b}	815.0a	64.8			
		Ammonium sulfate	97.7^{ab}	830.0^{a}	66.0	13	22	9
		Calcium nitrate	100.7^{a}	880.0^{a}	70.0			

[1]Pre-wetting refers to wetting of the experimental soil with 30 mm of precipitation in 1h before fertilizer application.
[2]Rainfall intensity refers to application of 20 or 40 mm of precipitation in 1h to the experimental soil column.
Means followed by different letters in a column are significantly different at 5% level.

significantly ($p<0.05$) higher total NH_4^+- N and NO_3^- - N in the bypass flow than did the non pre-wetting treatment for a given rainfall intensity and N source. The higher rainfall intensity, 40 mm precipitation in 1h, within a given wetting status resulted in significantly ($p<0.05$) more total NH_4^+- N and NO_3^- - N than did the lower rainfall intensity across the N source (Table 3). However, the amount of total NH_4^+- N recovered in bypass flow was low, ranging from 0.1 to 2.1 kg N ha^{-1}. Calcium nitrate (CN) treatment resulted in significantly ($p<0.05$) higher total and fertilizer NO_3^- - N in the bypass flow than did urea and ammonium sulfate (AS). The total NO_3^- - N recovered in the bypass flow from CN treatment was considerable and ranged from 2.94 to 17.38 kg N ha^{-1}.

The significant effect of pre-wetting and rainfall intensity on the total NH_4^+- N and NO_3^- - N in the outflow indicates that the higher precipitation the more loss of N in the bypass flow. This is applicable as long as the preferential flow paths remain open. Under tropical conditions characterized by distinct wet and dry seasons Vertisols swell and shrink depending on the season (Ahmad, 1996; Deckers et al., 2001). Bypass flow is a common occurrence at the beginning of the rain season before the soil matrix absorbs enough water to cause swelling and consequential closing of the cracks. The low NH_4^+- N recovered (0.79 kg N ha^{-1}) in the bypass flow from AS treatment (Table 3) is attributed to strong ionization of this N source producing NH_4^+ that is electrostatically attracted to the dominantly negatively charged soil colloids. The amount of NH_4^+- N (2.09 kg N ha^{-1}) recovered from urea with pre-wetting and only 1 rainfall event of 40 mm in 1 h is a concern considering that the amount is recovered within the short experimental period of 1 to 1.5 h. Urea is uncharged and remains so longer than the current experimental period, hence, was not electrostatically attracted to the soil colloids; a situation that could have contributed to the relatively high loss compared to the case of AS. The high NO_3^- - N recovered ranging from 2.94 to 17.38kgNha^{-1} (Table 3) and from 12.6 to 45.7kgNha^{-1} (Table 4).

CN treatment is indicative of high potential for NO_3^- - N loss in bypass flow in these Vertisols. These findings are in agreement with that of Smaling and Bouma (1992).

Rainfall frequency, N source, and N rate showed positive interaction with respect to total NH_4^+- N and NO_3^- - N recovered in the bypass flow (Table 4). Rainfall frequency had no effect on total NH_4^+- N and NO_3^- - N in the outflow in respect of urea and AS applied at 50 kg N ha^{-1}. But rainfall frequency 3 had significant ($p < 0.05$) effect on total NH_4^+- N and NO_3^- - N in the bypass flow from the 2 N sources applied at 100 and 200 kg N ha^{-1} (Table 4) indicating rainfall frequency x N source x N rate interaction. Total NH_4^+- N recovered in the bypass flow was low and ranged from 0.45 to 3.84 kg N ha^{-1} for urea,

Table 3. Effects of wetting status, rainfall intensity, and nitrogen source on mineral nitrogen (kg N ha^{-1}) recovered in bypass flow. Nitrogen was applied at an equivalent rate of 100 kg N ha^{-1}. Each value is a mean of 3 observations.

Wetting status	Rainfall intensity (mm h^{-1})	Nitrogen source	Recovered total mineral N (kg N ha^{-1})		Recovered fertilizer N (kg N ha^{-1})		Recovered soil mineral N (kg N ha^{-1})		Recovered proportion (%) of applied N
			NH_4^+	NO_3^-	NH_4^+	NO_3^-	NH_4^+	NO_3^-	
No wetting									
	20	Urea	nd	nd	nd	nd	nd	nd	-
		Ammonium sulphate	nd	nd	nd	nd	nd	nd	-
		Calcium nitrate	nd	nd	nd	nd	nd	nd	-
	40	Urea	0.92^{b}	0.54^{de}	0.69^{b}	0.0^{d}	0.23^{cd}	0.54^{bc}	0.7
		Ammonium sulphate	0.16^{cde}	0.35^{e}	0.04^{d}	0.0^{d}	0.12^{de}	0.35^{c}	0
		Calcium nitrate	0.12^{de}	2.94^{c}	0.0^{d}	2.31^{c}	0.12^{de}	0.63^{abc}	2.3
Wetting									
	20	Urea	0.37^{cd}	0.28^{e}	0.27^{c}	0.03^{d}	0.10^{de}	0.25^{c}	0.3
		Ammonium sulphate	0.11^{de}	0.22^{e}	0.04^{d}	0.04^{d}	0.07^{de}	0.19^{c}	0.1
		Calcium nitrate	0.20^{cde}	8.77^{b}	0.0^{d}	8.16^{b}	0.19^{cd}	0.61^{abc}	8.2
	40	Urea	2.09^{a}	2.77^{cd}	1.47^{a}	1.47^{c}	0.63^{a}	1.29a	2.9
		Ammonium sulphate	0.79^{b}	2.46^{c}	0.38^{c}	1.34^{c}	0.37^{ab}	1.12^{ab}	1.6
		Calcium nitrate	0.37^{c}	17.38^{a}	0.0^{d}	16.22^{a}	0.37^{bc}	1.17^{ab}	16.2

Means followed by different letters in a column are significantly different at 5% level.
nd = not determined

0.30 to 2.87kgNha^{-1} for AS, and 0.29 to 2.49kgNha^{-1} for CN. In the case of CN recovered NO_3^- - N increased with the rate of N application. The sequence of significant differences was in the order 200>100=50 kg N ha^{-1} application at rainfall frequency 1 and 200>100>50 kg N ha^{-1} application at rainfall frequencies 2 and 3, also indicating rainfall frequency x N source x N rate interaction. The amount of NO_3^- - N recovered was considerable, ranging from 0.51 kg to 9.96 kg ha^{-1} for urea, 0.30 to 14.61 $ha^{-1}$for AS, and 0.67 to 45.7 kg ha^{-1} for CN.

The significant effect of rainfall frequency on the amount of fertilizer N in the bypass flow is in agreement with previous reports. Pathak et al. (2004) reported increased NO_3^- - N loss at high soil moisture where macro-pores had formed during dry season, and attributed the phenomenon to higher volume of bypass flow since mineral N moves down the soil column as a solute in percolating water. Nyamangara et al. (2003) and Lehman et al. (2004) also attributed high nitrate concentration in the outflow to high intensity rainfall recorded soon after N fertilizer application. Subject to high rates of fertilizer N application and high rainfall frequency all the 3 N sources used in the current experiment are prone to loss in bypass flow in the order CN > urea > AS (Table 4).

Effect of N rate on total mineral N in the bypass flow increased with rainfall frequency. Total NH_4^+- N and NO_3^- - N in the bypass flow increased significantly ($p< 0.05$) with the N rate at rainfall frequencies 2 and 3 (Table 4). The amount of NO_3^- - N in the outflow has been shown to increase with the rate of fertilizer N application (Barraclough et al., 1983; Shepherd et al., 1993; Sigunga et al., 2008). Sigunga et al. (2008) reported that there was no NH_4^+- N recovered in the outflow; the authors used 2 rainfall events of 30 mm h^{-1} applied 24 h apart.

In the current work various levels of rainfall intensity and rainfall frequency were applied, and it was established that fertilizer NH_4^+- N recovered in the outflow increased with wetting status and rainfall intensity (Table 3) as well as with rainfall frequency (Table 4). Thus, initial soil head and rainfall pattern in addition to soil properties

Table 4. Effects of rainfall frequency, nitrogen source and rate on amount of nitrogen recovered in bypass flow. Each value is a mean of 3 observations.

[1]Rainfall frequency	Nitrogen source	Nitrogen rate (kg N ha^{-1})	[2]Recovered total mineral N (kg N ha^{-1}) NH_4^+	NO_3^-	Recovered fertilizer N (kg N ha^{-1}) NH_4^+	NO_3^-	Recovered soil mineral N (kg N ha^{-1}) NH_4^+	NO_3^-	Recovered proportion (%) of applied N
		50	0.45^{jk}	$0.51k^{l}$	0.00^{f}	0.01^{f}	0.45^{f}	0.50^{f}	0.1
	Urea	100	0.85^{hijk}	2.16^{ghijkl}	0.22^{ef}	0.31^{f}	0.63^{ef}	1.85^{cdef}	0.5
		200	2.09^{bcdef}	4.69^{gh}	0.26^{ef}	0.44^{f}	1.83^{abcd}	4.25^{b}	0.7
1		50	0.40^{jk}	0.30^{l}	0.02^{f}	0.03^{f}	0.38^{f}	0.27^{f}	0.1
	Ammonium sulfate	100	0.86^{hijk}	1.69^{hijkl}	0.20^{ef}	0.05^{f}	0.66^{ef}	1.63^{def}	0.3
		200	1.12^{ghi}	2.06^{ghijkl}	0.52^{ef}	0.06^{f}	0.62^{ef}	2.01^{cdef}	0.3
		50	0.31^{k}	0.67^{kl}	0.00^{f}	0.32^{f}	0.31^{f}	0.35f	0.6
	Calcium nitrate	100	0.49^{ijk}	3.29^{ghijk}	0.00^{f}	2.1^{ef}	0.49^{f}	1.19^{ef}	2.1
		200	1.69^{efg}	16.18^{d}	0.00^{f}	12.62^{cd}	1.69^{bcde}	3.56^{bc}	4.8
		50	0.55^{ijk}	0.52^{kl}	0.04^{f}	0.01^{f}	0.51^{f}	0.51^{f}	0.1
	Urea	100	1.22^{ghi}	1.41^{hijkl}	0.81^{cdef}	0.00^{f}	0.41^{f}	1.41^{def}	0.8
		200	3.33^{ab}	3.64^{ghijk}	1.26^{bcde}	$0.4\ 6^{f}$	2.07^{abc}	3.18^{bcd}	0.9
		50	0.33^{k}	0.34^{l}	0.04^{f}	0.00^{f}	0.29^{f}	0.34^{f}	0.1
2	Ammonium sulfate	100	0.94^{ghi}	0.95^{jkl}	0.66^{def}	0.00^{f}	0.28^{f}	0.95^{f}	0.7
		200	2.87^{bc}	4.86^{gh}	1.67^{abcd}	0.47^{f}	2.12^{ab}	4.39^{b}	1.1
		50	0.40^{jk}	1.02^{ijkl}	0.00^{f}	0.50^{f}	0.40^{f}	0.52^{f}	1.0
	Calcium nitrate	100	0.74^{ijk}	11.99^{ef}	0.00^{f}	10.2^{cde}	0.74^{def}	1.79^{cdef}	7.9
		200	2.49^{bcd}	20.15^{c}	0.03^{f}	15.82^{c}	2.03^{abc}	4.33^{b}	10.2
		50	0.45^{jk}	1.84^{hijkl}	0.05^{f}	1.43^{ef}	0.41^{f}	0.34^{f}	3.0
	Urea	100	1.99^{def}	3.25^{ghijk}	1.76^{abc}	1.84^{ef}	0.23^{f}	1.41^{def}	3.6
		200	3.84^{a}	9.96^{f}	2.53^{a}	8.46^{cdef}	1.31^{bcdef}	1.50^{def}	5.5
		50	0.30^{jk}	1.42^{hijkl}	0.03^{f}	1.24^{ef}	0.28^{f}	0.18^{f}	2.5
3	Ammonium sulfate	100	1.54^{fgh}	6.12^{fg}	0.76^{cdef}	2.28^{ef}	0.78^{def}	3.84^{b}	3.0
		200	2.42^{bcde}	14.61^{e}	2.12^{ab}	8.21^{cde}	2.89^{a}	6.39^{a}	5.2
		50	0.29^{k}	4.84^{gh}	0.05^{f}	4.53^{def}	0.24^{f}	0.31^{f}	9.1
	Calcium nitrate	100	0.72^{ijk}	23.63^{b}	0.00^{f}	20.69^{b}	0.72def	2.94^{bcde}	20.7
		200	1.21^{ghi}	45.70^{a}	0.02^{f}	42.59^{a}	1.19^{cdef}	3.11^{bcd}	21.3

[1]Rainfall frequency 1, 2, and 3 refer to application of 40 mm of precipitation in 1 h once in one day only, once per day for 2 consecutive days, and once per day for 3 consecutive days, respectively. Means followed by different letters in a column are significantly different at 5% level.

influence bypass flow process (Booltink and Bouma, 1993) and, inevitably, fertilizer N carried in the outflow (Pathak et al., 2004).

The fertilizer NO_3^- - N in the outflow from urea and AS (Tables 3 and 4) was attributable to the nitrification of urea and AS in the outflow. McLeod et al. (2008) reported a high potential for microbial bypass flow in structured soils like Vertisols. The outflow was bound to carry in it microorganisms including nitrifying bacteria. During outflow collection, storage, and laboratory analysis – which took about 30 days –some nitrification must have occurred.

The presence of soil N (NH_4^+- N and NO_3^- - N) in the outflow (Tables 3 and 4) is attributed to added nitrogen interaction (ANI) and/or release of organic N that is later nitrified. Mineral N added to the soil is known to either displace what is known as ANI or priming effect (Rao and Parr, 1991; Azam et al., 1994; Norton and Silvertooth, 2007).

Nitrogen application rates influence ANI and/or stimulate mineralization of native N in mineralization of native N (Norton and Silvertooth, 2007). Bregliani (1996), Renck and Lehmann (2004), and Sigunga et al. (2008) reported a release of soil organic N as a result of added mineral N. The released organic N would be nitrified by microorganisms in the outflow.

Proportion of applied nitrogen recovered in the bypass flow

The proportion (%) of the applied fertilizer N recovered in the bypass flow increased with soil moisture content prior to fertilizer application (wetting status) and rainfall intensity (Table 3), and with rainfall frequency (Table 4). In the case of urea with 40 mmh^{-1} rainfall intensity the proportion of applied N in the bypass flow ranged from 0.7% to 2.9% (Table 3), while with rainfall frequency 3 the range was 3.0 to 5.5% (Table 4). This loss could increase to substantial levels if the rainfall intensity and/or frequency as well as N rate were to increase.

Calcium nitrate and AS resulted in the highest and lowest proportions of applied N recovered, respectively at a given wetting status and rainfall intensity (Table 3) and at a given rainfall frequency (Table 4). The proportion of applied N recovered from CN was strongly influenced by wetting status and rainfall intensity, and ranged from 2.3% to 16.2% (Table 3), and at rainfall frequency 3 the range was 9.1 to 21.3% (Table 4). Sigunga et al. (2008) reported similar results using Eutric Vertisol from a different site. Bypass flow process in structured soils is dominated by factors including soil properties and climatic factors (Booltink and Bouma, 1993), and is soil-type and site specific (Deurer et al., 2003).

The effects of N rate on the proportion of applied N recovered in the bypass flow was in the order 200 > 100 >50$kgNha^{-1}$. All the N sources used in the experiment were prone to loss in bypass flow (Table 4), the magnitude of which depends on rainfall patterns, N source, and N rate *inter alia*. Water infiltrating soil splits into bypass and matrix flows (Seiler et al., 2002). In the case of bypass flow mineral N move down the soil column predominantly in the bypass flow and, hence, the factors influencing bypass flow inevitably affect the amount of mineral N in the bypass flow.

Conclusion

The amount of outflow from preferential flow paths depends on soil properties, initial soil moisture content as well as on rainfall intensity and frequency. All of the three N sources used in the current experiments are prone to losing varying amounts of N in the bypass flow in the order calcium nitrate >ammonium sulfate = urea. Rainfall intensity and frequency as well as fertilizer N source and rate, and the time of fertilizer N application vis-à-vis the onset of rains influenced the amount of fertilizer N lost in the bypass.

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