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CONTENTS

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Effects of organic and inorganic nitrogen fertilizer on maize (*Zea mays L.*) nitrogen uptake and nitrate leaching measured in field lysimeters

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Maize (*Zea mays L.*) production in the smallholder farming areas of Zimbabwe is based on both organic and inorganic nutrient sources. A study was conducted to determine the effect of cattle manure, N fertiliser, and their combinations on nitrate concentration in leachate leaving the root zone and to establish N fertilisation levels which minimise N leaching. Maize was grown for two seasons (1996/97 and 1997/98) in field lysimeters repacked with a coarse-grained sandy soil. Average leachate volumes over the two seasons were similar between different treatments, and ranged from 388 to 418 mm yr^{-1}. Nitrogen fertiliser, especially the high rate (120 kg N ha^{-1}), and manure plus N fertiliser combinations resulted in high nitrate leachate concentrations (up to 37 mg N L^{-1}) and nitrate losses (up to 56 kg N ha^{-1} yr^{-1}) which represent both environmental and economic concerns. Nitrate leaching from manure only treatments was relatively low (average less than 23 kg N ha^{-1} yr^{-1}), and plant availability in these treatments tended to be higher in the second season. It was concluded that N leaching at high inorganic N fertiliser rates posed a serious economic and environmental risk when all the fertiliser was applied at planting. It was also concluded that the risk of N leaching from aerobically composted cattle manure was low in the short term.

Keywords: Nitrate leaching, lysimeter, manure, mineral N.

Introduction

The smallholder cropping systems in Zimbabwe are based on maize, the staple food crop, which accounts for about 50 percent of the calories consumed. Cattle manure remains the major source of nutrients for plant growth in the smallholder farming sector although some inorganic fertiliser is also used. The Alvord system, recommended for the smallholder farming sector of Zimbabwe, has widely been adopted by the farmers and is based on the application of 30 to 40 t ha^{-1} of manure to a four-course rotation of two maize crops, followed by a legume and finally a small grain crop (Grant, 1976). However, the low efficiency of smallholder manures as sources of nitrogen (Murwira and Kirchmann, 1993; Nyamangara, *et al.*, 1999) has prompted farmers to supplement the manures with inorganic N fertiliser. There is need to improve synchrony between N release and plant uptake in order to optimise yield and minimise N leaching losses which may occur when organic and inorganic fertilisers are used in combination.

Nitrogen leaching from agricultural soil represents both an economic loss to farmers and environmental pollutant to natural water systems. The concentration of nitrate in ground water, rivers and lakes has been increasing steadily for the past 30 years in large parts of the developed world, and agriculture is considered to be the major contributor (Addiscott, *et al.*, 1991; Beckwith, *et al.*, 1998). However, the situation is quite different for most smallholder farmers in developing countries in Africa and elsewhere, for whom inorganic fertilisers are often unaffordable (Kamukondiwa and Bergström, 1994a), and hence their efficient use is of both agronomic and socio-economic importance.

Most studies on N leaching from soils amended with manure and / or inorganic fertilisers have focussed on humid temperate regions (Beckwith, *et al.*, 1998; Thomsen, *et al.*, 1993; Unwin, 1986), and overall, very few quantitative measurements of N leaching have been made in tropical and subtropical regions of Africa (Arora and Juo, 1982; Omoti, *et al.*, 1983; Wong, *et al.*, 1987). In Zimbabwe, N leaching losses of up to 39 kg N ha^{-1} yr^{-1} have been reported on a sandy soil (Kamukondiwa and Bergström, 1994b). However, the above study was carried out during a sequence of very dry years, which limits the representativeness of the results. Other studies, also on sandy soils in Zimbabwe (Hagmann, 1994; Vogel, *et al.*, 1994), indicated that most of the fertiliser (up to 54 percent of applied N) was leached out of the plough layer (0-0.5 m) when heavy rains followed N fertiliser application. However, some of the leached nitrogen can probably be recovered by roots later in the season.

In addition to being a potential environmental threat, large leaching losses of N may also cause nitrate-related health problems. The World Health Organisation (WHO) of the United Nations, the European Community (EC) and the US Environmental Protection Agency (USEPA) limit concentrations for nitrate in potable water at 22 (Killham, 1994), 11.3 (Addiscott, *et al.*, 1991) and 10 (Spalding and Exner, 1993) mg NO_3-N L^{-1}, respectively. However, Addiscott and Benjamin (2000) recently reported that nitrate is important in the control of gastro enteritis in humans. Although concentrations greater than 10 mg NO_3-N L^{-1} have been reported in some districts in Zimbabwe (Interconsult A/S - NORAD, 1985) their link to agricultural activities is unclear.

Although the rainfall is seasonal, highly variable and generally insufficient in most smallholder farming areas of Zimbabwe (Piha, 1993), its intensity is often very high and this may trigger N leaching in the predominantly coarse-textured soils used for agriculture (Twomlow, 1994). This led us to design a study in which the objective was to measure nitrate in water leaving the root zone in agricultural fields typical of smallholder cropping systems of Zimbabwe, and to establish fertilisation levels which minimise N leaching losses, but maintain crop yields.

Materials and Methods

Experimental location and soil properties (Table 1)

The 2 year study was conducted at Domboshawa Training Centre (17^{0}35′S, 31^{0}10′E), about 35 km north of Harare, Zimbabwe, where average rainfall is 900 mm *per annum* (Agroecological Region IIa), mostly restricted to the summer season (November to April). The soil was a well drained, loamy sand (Typic Kandiustalf in the USDA soil classification system, or Haplic Lixisol in the FAO system) (Nyamapfene, 1991) with a low water holding capacity (AWC = 9 percent vol.) (Vogel, *et al.*, 1994).

Table 1: Chemical and physical properties of the experimental soil.

Soil depth Cm	pH ($CaCl_2$)	org-C %	N[1] $mg\ kg^{-1}$	Clay %	Silt %	Fine sand %	Med. sand %	C.sand %	Bulk density $Mg\ m^{-3}$
0-20	4.7	0.4	23	6	3	23	51	17	1 625
20-60	4.6	0.2	21	10	3	20	52	15	1 620

[1] Soil brought to field capacity using monocalcium phosphate and incubated for 14 days at 35° C before KCl-extraction (Saunder, *et al.* 1957).

Lysimeter installations

A lysimeter station consisting of 27 repacked lysimeters was established in the autumn of 1995 at the field site. A trench at the centre of the lysimeter station contained 27 buckets to collect leachate. The lysimeters, square-shaped (1 m^2) and 1.1 m deep, were constructed from 1.6 mm thick galvanized steel sheets. The lysimeter walls were painted to provide a rough surface that would prevent water from channelling between the soil and the tank walls. The lysimeter boxes were surrounded by field soil to prevent excessive heating of the lysimeter soil.

A 1 mm wire mesh was fixed at the lysimeter outlet and covered with a 10-cm layer of gravel before the soil was placed, reducing the effective depth of the lysimeters to 1 m. The gravel improved drainage (Stevens, *et al.*, 1992) and also prevented the fine soil material from washing into the 10 mm steel outflow pipes. The pipes were laid at a slope of ca 2 percent to ensure rapid water flow to the collecting vessels.

The topsoil was a coarse loamy sand (0 to 0.3 m) overlying a sandy loam subsoil (0.3 to 1.0 m). The layers were repacked to original density following the sequence of the soil profiles identified during site characterisation. Repacking the soil was considered appropriate because it only introduces small changes in water transport and nitrogen behaviour in course textured soils (Bergström, 1990). The lysimeters were water saturated from the bottom end and thereafter allowed to drain freely, and left to settle for 14 months before the experiment was started in the summer of 1996.

Experimental design and layouts
The treatments were manure (0, 12.5, and 37.5 t ha^{-1}, which contained 0, 116 and 348 kg N ha^{-1}) and N fertiliser (0, 60 and 120 kg N ha^{-1} as NH_4N0_3) replicated three times in a 2 factor randomised complete block design. The manure rates were based on current recommendations for maize in smallholder farming areas of Zimbabwe where about 37 t ha^{-1} is applied every fourth year, or annually at about 12 t ha^{-1} (Mugwira and Murwira, 1998). The 12.5 t ha^{-1} manure and N fertiliser treatments were applied in both years but the larger manure treatment was applied only in the first year.

The manure was aerobically composted and contained 0.93 percent N, 8.37 percent C (C:N = 9) and 73.7 percent soil. The low N and high soil contents of the manure is typical of manures from smallholder farming areas in Zimbabwe (Mugwira and Murwira, 1998). The manure and fertiliser, all applied before planting, were incorporated into the top 0.1 m of the soil at planting. Two maize plants were grown in each lysimeter during both summer seasons, which were seeded on 3 December 1996 and 24 November 1997, respectively. The above-ground maize parts were harvested after 12 weeks each year (milk dough stage) and the fresh weight, dry weight and N content determined.

Leachate sampling and measurement of nitrate concentrations
Leachate volume was recorded following each rain event when break-through of leachate was expected. Representative samples were taken 1 to 3 times each week depending on volume of leachate for nitrate-N determination by colorimetric analysis (Keeney and Nelson, 1982). It was assumed that the concentration of ammonium-N in leachate was negligible.

Statistical analysis
The analysis of variance (ANOVA-2) procedure (MSTAT, 1988) was carried out to compare the effect of manure and mineral N fertiliser on cumulative leachate volume, total above ground N uptake by maize plants and N leaching losses over the two cropping seasons.

Results

Soil, weather and drainage conditions
The 1996/97 growing season was wetter (1 395 mm) than the long-term seasonal average for the area, whereas in 1997/98 seasonal rainfall was close to average (840 mm). Rainfall recorded between planting and harvesting in 1996/97 was 685 mm compared 603 mm in 1997/98 (Figure 1). Compared to 1997/98, most of the rainfall received in 1996/97 was in the form of high intensity storms (up to 120 mm day^{-1}) (Figure 1), which contributed to the larger total leachate volumes recorded in 1996/97

(average 496 mm) compared to 1997/98 (average 311) (Table 2). In both seasons leachate volumes accounted for about a third of the total seasonal rainfall. The possible effect of repacking on leachate volume was not estimated.

Above-ground N uptake

Total above-ground N uptake by maize from lysimeters which received manure or N fertiliser was significantly ($P<0.001$) greater than that from the control in both seasons (Table 3). There was a positive manure x N fertiliser interaction which was more significant in the first growing season (1996/97) ($P>0.001$) than in the second growing season (1997/98) ($P=0.0004$). Nitrogen uptake from the manure only rates (12.5 and 37.5 t ha^{-1}) was greater (60 and 36 percent, respectively) in the second season compared to the first season.

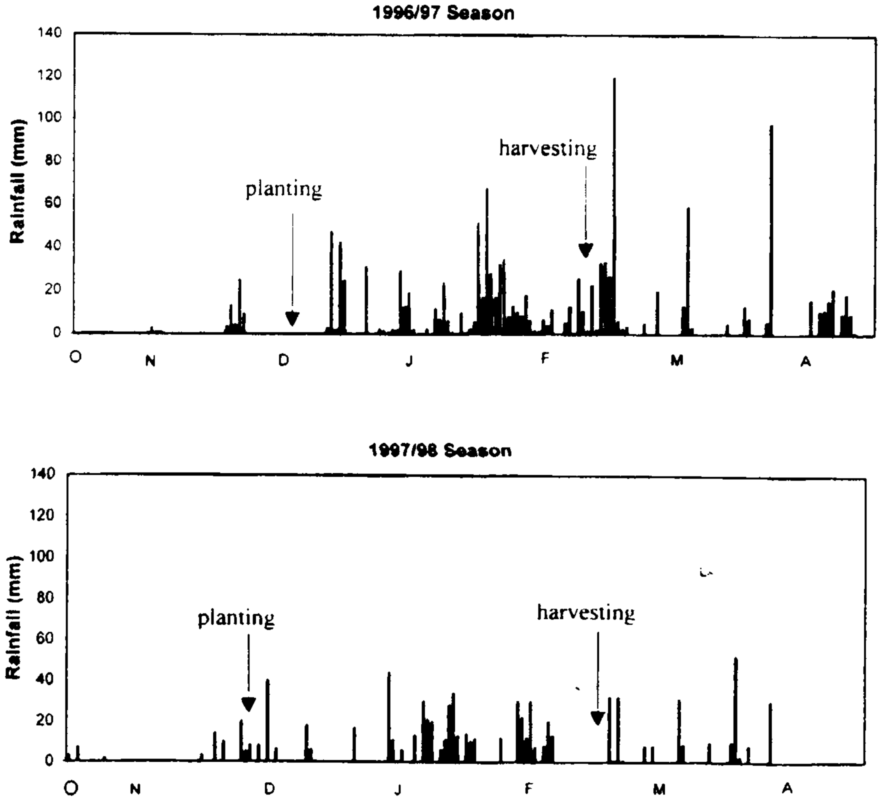

Figure 1: Daily rainfall distribution for 1996/97 and 1997/98 cropping seasons at the Domboshawa Training Centre.

Table 2: Cumulative leachate volumes for the study period.

Treatment		Leachate (mm) 1996/97	1997/98	Average
Control	NO	509	325	418
60 kg N ha^{-1}	N60	480	296	388
120 kg N ha^{-1}	N120	495	294	395
12.5 t ha^{-1} Manure	ML	493	300	398
37.5 t ha^{-1} Manure	MH	494	335	415
12.5 t ha^{-1} Manure + 60 kg N ha^{-1}	N60ML	496	319	408
12.5 t ha^{-1} Manure + 120 kg N ha^{-1}	N120ML	489	317	412
37.5 t ha^{-1} Manure + 60 kg N ha^{-1}	N60MH	508	310	409
37.5 t ha^{-1} Manure + 120 kg N ha^{-1}	N120MH	501	303	402
Significance		NS	NS	NS
CV (percent)		9.8	11.9	7.8
LSD (P<0.05)		86.1	64.6	53.6

[1]The high rate of manure in the zero fertiliser treatment was only applied in the first season.

Table 3: Total N uptake in above-ground plant parts during 1996/97 and 1997/98 growing seasons

Treatment	N uptake (kg N ha^{-1}) 1996/97	1997/98
N0	25.5	22.5
N60	45.4	56.3
N120	95.2	63.4
ML	48.7	78.1
MH	70.8	96.6
N60ML	77.9	105.0
N120ML	153.6	133.6
N60MH	90.2	116.0
N120MH	189.1	144.7
Significance	***	***
Interaction (MxF)	***	***
CV	17.8	17.4
LSD (P<0.05)	23.4	25.9

M – Manure, F – Fertiliser.

Nitrate concentration in leachate

Nitrate concentrations in the leachate of treatments during the experimental period are shown in Figure 2. Concentrations from lysimeters amended with manure were comparable to the control (< 15 mg N L^{-1}) during the two growing seasons.

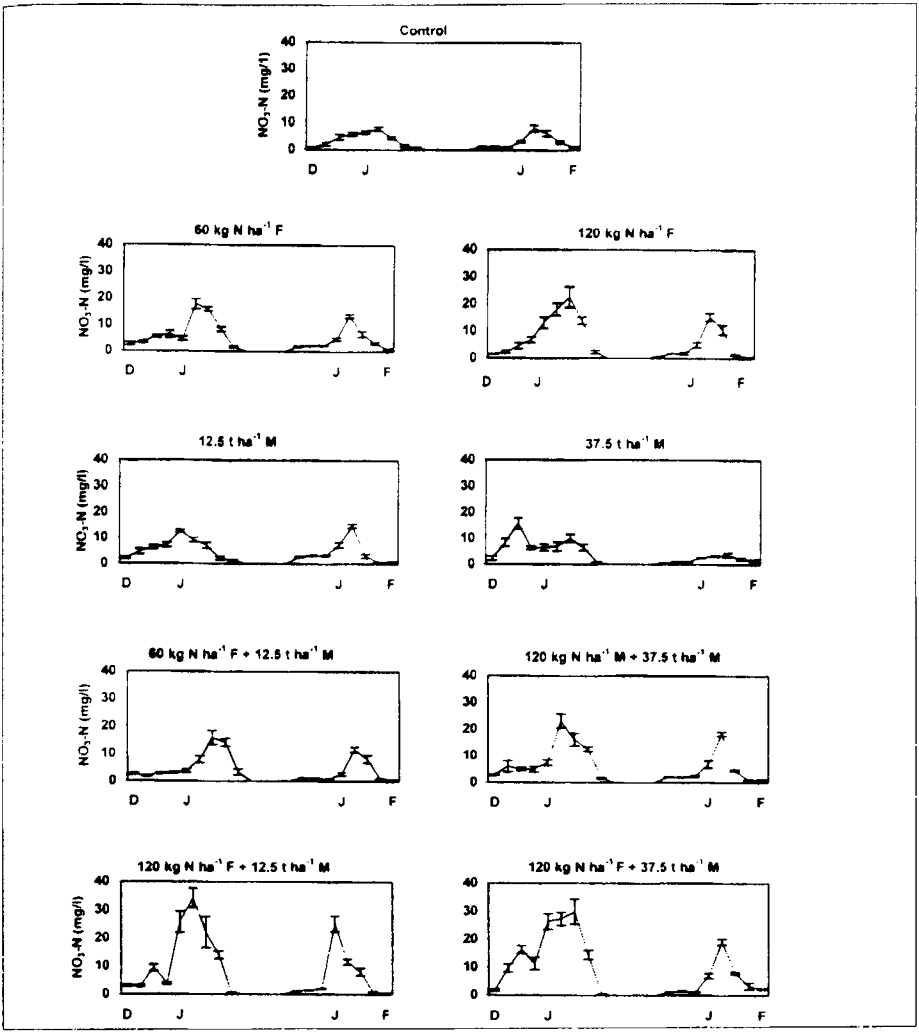

Figure 2: Average nitrate concentration in leachate collected from relicate lysimeters during the study period. Bars represent standard errors.

Concentration from lysimeters amended with N fertiliser were higher than the control in both growing seasons.

Manure and N fertiliser treatment combinations resulted in nitrate concentrations in leachate reaching 37 mg N L^{-1} when the high N fertiliser rate (N120) was used. The depressed nitrate concentration in the high manure plus high N fertiliser (N120MH) treatment during the second season was not expected.

Nitrate leaching losses

The annual nitrate leaching losses ranged from 18.9 to 56.3 kg N ha^{-1} in the first year and from 11.8 kg to 24.2 kg N ha^{-1} in the second season (Table 4). The addition of N fertiliser only, or in combination with manure, significantly ($P<0.01$) increased nitrate leaching in the first (1996/97) growing season, while the addition of manure only had no significant effect on N leaching compared to the control. In the second season, only combinations of N fertiliser with the high (MH) manure rate significantly increased nitrate leaching compared to the control. There was a positive manure x N fertiliser interaction which was only significant in the first growing season ($P<0.001$).

Table 4: Nitrate leaching losses during 1996/97 and 1997/98 growing seasons.

Treatments	N leached (kg N ha^{-1})	
	1996/97	1997/98
NO	18.9	11.8
N60	41.9	14.3
N120	56.3	15.8
ML	24.2	14.0
MH	27.5	16.7
N60ML	48.0	16.7
N120ML	53.6	16.9
N60MH	47.5	22.1
N120MH	56.1	24.2
Significance	**	*
Interaction (MxF)	***	NS
LSD (P<0.05)	19.7	5.8
CV (%)	13.5	22.9

Overall, N uptake in all treatments was weakly correlated to N losses for both growing seasons ($R^2<0.20$). For manure only treatments, correlation was only strong in the first season ($R^2= 0.97$), whereas for N fertiliser treatments the correlation was relatively strong for both seasons (1996/97, $R^2 = 0.80$; 1997/98, $R^2 = 0.94$).

Discussion

Lack of synchrony between N release from soil organic matter and plant uptake implies that N leaching also occurs in uncultivated soils. Addiscott (1988) reported high nitrate leaching losses (up to 45 kg ha^{-1} yr^{-1}) over 7 years from uncultivated and bare soil and attributed the losses to N mineralisation from soil organic matter. Therefore the pollution of ground water by nitrate can not be controlled by limiting the use of fertilizer only, especially in high organic matter soils.

Greater N uptake from manure treatments implied that manure N became more available (through mineralisation) for plant uptake in the second year compared to the first year (Table 3). The lower N uptake from the higher N fertilizer rate in the second year compared to the first year (Table 3) was not expected and could be attributed to gaseous N losses. Kamukondiwa, *et al.* (1996) also reported lower N concentration in leachates from lysimeters receiving similar manure as used in this study, compared to corresponding lysimeters receiving equal amounts of N in inorganic fertiliser. However, there are examples showing the opposite situation. For example, in a study performed under cold climate conditions, N concentrations in drainage water was higher in poultry manured soils than in soils receiving equal amounts of N with inorganic fertiliser (Bergström and Kirchmann, 1999). However, it is important to keep in mind that the manure used in that study and our study were quite different, which precludes a direct comparison of the results. The manure and fertiliser interaction which was strongest in the first season when rainfall was highest suggested that improved root growth (manure effects on soil physical and chemical environment) may have increased the ability of the crop to capture fertiliser N that would have been lost through leaching.

The higher nitrate leaching in the fertiliser treatments can be attributed to the large amounts of readily available N early in the season, whereas most of the N derived from manure had to undergo mineralisation before it became available for uptake and leaching. The high intensity rainfall recorded after application of the N fertiliser (Figure 1) may have leached the soluble N resulting in high nitrate concentrations in N fertiliser treatments, although much less than one pore volume of water had leached through the profile between fertilisation and this break through of water. For example in 1996/97 when nitrate leaching was highest, 118 mm of rainfall was recorded within 2 weeks after planting, a period when plant demand for N is very low. Therefore, there is reason to believe that some of the fertiliser-N was displaced by preferential flow induced by an unstable wetting front (Steenhuis and Parlange, 1991). This flow behaviour was likely enhanced by the high rainfall intensity (Figure1). However, most smallholder farmers can not afford high N fertiliser rates of (up to 120 kg ha^{-1}) and the fertiliser is applied in two split applications. Under such conditions, N leaching is expected to be relatively lower.

Conclusion

Due to the high intensity nature of rainfall experienced at the study site and the low water holding capacity of the soil, the effects of differences in plant growth on evapo-transpiration were not significant. The rainfall pattern (distribution and intensity) determined the partitioning between N plant uptake and leaching. The increased N uptake at higher N fertiliser rates means that high fertiliser addition within reasonable limits does not necessarily result in more N leaching. The application of aerobically composted manure from the smallholder farming areas of Zimbabwe to soil does not pose any economic and environmental concern due to nitrate leaching in the short-term. The application of inorganic N fertiliser to sandy soils can result in high nitrate leaching losses when all the fertiliser is applied at planting. However, in practice smallholder farmers split-apply the fertiliser at planting and 4 to 6 weeks after planting. The low manure (12.5 t ha^{-1}) plus 60 kg N ha^{-1} fertiliser treatment was the best treatment in terms of maintaining dry matter yield and minimising N leaching losses. Further studies are required to determine the effect of manure quality and split application of N fertiliser on plant uptake and leaching losses, and also the effect of soil type.

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