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SYNCHRONY RELATIONSHIPS OF NITROGEN RELEASE AND PLANT UPTAKE IN A ZIMBABWEAN SANDY SOIL AMENDED WITH MANURE AND FERTILISER NITROGEN

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ABSTRACT

A study was conducted to assess N mineralisation and plant uptake patterns in a sandy soil amended with cattle manure and inorganic N applied at zero or six weeks after planting. Manure was applied at a rate equivalent to 10 t ha^{-1} and the N at 100 kg ha^{-1}. Nitrogen mineralisation, uptake and leaching in the field were estimated by an *in situ* incubation technique. Estimated N uptake was compared with the actual N uptake measured from maize plants. All manure treatments showed an initial immobilisation of N in the first 8 weeks. Early application of N resulted in significantly more N mineralisation in the manure compared to application at 6 weeks after planting. Estimated values of N leaching ranged between 0.67 g m^{-2} and 4.22 g m^{-2} which is 3 % to 42 % of applied N. Greatest amounts were leached from the N treatments. Nitrogen recovery ranged from less than 0% to 69% of applied N.

***Key Words*: Manure, nitrogen release, plant uptake**

RÉSUMÉ

Une étude a été menée en vue d'évaluer la minéralisation de l'azote et son mode d'assimilation par les plantes dans un sol sablonneux amendé avec de la bouse de vache et de l'azote inorganique le jour du semis ou 6 semaines plus tard. La dose utilisée était respectivement de 10 tonnes et 100 kg à l'hectare. La minéralisation de l'azote, l'assimilation et le lessivage sur le terrain ont été estimés *in situ* par incubation. La quantité d'azote estimée après minéralisation a été comparée à celle recouvrée dans les plantes de mais. Toutes les plantes traitées à l'engrais organique, ont montré une immobilisation initiale de l'azote au cours de huit premières semaines. L'application précoce de l'azote a entrancé une minéralisation plus élevée de l'azote comparativement à l'emploi 6 semaines après semis. Les valeurs estimées de l'azote lessivé ont varié entre 0.67 g/m^2 et 4.22 g/m^2 ce qui représente 3 à 42% de l'azote appliqué. Des quantites plus élevées après traitement azoté ont été rapportées. Le taux d'azote recouvré variait de moins de 0% à 69% de l'azote appliqué.

***Mots Clés*: Engrais organique, libération d'azote, assimilation par la plante.**

INTRODUCTION

In natural ecosystems productivity is sustained by a tight integration of nutrient cycling, however, conversion to agricultural systems leads to an increased risk of nutrient loss through leaching (Swift, 1984). The use of organic inputs which slowly release nutrients, can be a way of coupling nutrient release and plant uptake. By manipulating the resource quality and timing of inputs to soil, it is possible to synchronise the transfer of nutrients from the decomposing organic pool to the plants.

In the communal farming systems of Zimbabwe, the main organic input is manure. Crop residues are often removed from the fields for use as cattle feed. It has been observed that the manures have low N contents and need to be supplementd with fertiliser N to avoid deficiencies in the early growth stages (Grant, 1976). Manure is applied during the dry season before planting, while supplementary fertiliser N has generally been found to produce the best response 4-6 weeks after planting (Rodel *et al.*, 1980).

Though not yet well established, nitrogen use efficiency by plants in sandy soils appears to be low which could be due to high $N0_3$-N leaching (Swift *et al.*, 1989). By using an *in situ* incubation technique (Raison *et al.*, 1987), simultaneous measurements of N mineralisation, uptake and leaching from arable soils can be used to determine N use efficiency (Debosz and Vinther, 1989). The aim of this study was to measure nitrogen release and plant uptake patterns in a sandy soil planted with maize, and amended with manure and fertiliser N.

MATERIALS AND METHODS

Field experiments were conducted at the Grasslands Research Station, Marondera, Zimbabwe (18° 11'S and 30°27'E). The experiments were established in October, 1988 and run for three seasons. Only results from the 1990/91 season are presented. It is during this season that equilibrium conditions to the added amendments are likely to have been achieved, and when treatment differences, if any, are more noticeable. The soil is a Kanhaplic Haplustalf (Soil Survey Staff, 1987) having 4% clay and 90% sand (Table 1). The manure used was collected from Seke communal area, aerobically decomposed, dried and sieved to pass a 5 mm sieve. The manure had a total carbon content of 12.04% and a nitrogen content of 0.91%.

A randomised complete block design with six treatments was used. Plot size were 7.6 by 7.6 m. Treatments included: a control, manure only, manure + 100 kg N ha^{-1} (as NH_4N0_3) applied at pre-planting, manure + 100 kg N ha^{-1} applied 6 weeks after planting (WAP), 100 kg N at pre-planting, and 100 kg N ha^{-1} applied 6 WAP. Manure was applied at 10 t ha^{-1} in 1988 and 1990. Basal application of 60 kg K_20 and 37 kg P_20_5 ha^{-1} were made to all plots. After application of the amendments, all plots were planted with maize (local variety R215) at a plant spacing of 63.5 by 63.5 cm and weeded by hand throughout the season.

Three whole plants per plot were taken after 6, 10, 12, 14 and 16 weeks for dry matter yield determination. Roots were sampled by hand in the field to a depth of 75 cm in a 50 cm by 50 cm quadrat. Plant samples were oven dried at 60°C for 48 hr and the dry weight recorded. The dried samples were then analysed for total N (Bremner and Mulvaney, 1982). Grain yield was determined at maturity from 20 plants taken from 5x4 rows at the centre of the plots.

Changes of inorganic N in soil were followed using a method of sequential augering together with the *in situ* incubation of undisturbed soil columns isolated within open ended galvanised metal tubes. The metal tubes, 35 cm long with a diameter of 7.5 cm, were each inserted 30 cm into the ground with 5 cm of the tube left protruding to facilitate removal, the attachment of a plastic sheet and measurement of NH_3 loss. Three pairs of metal tubes, with one of each pair closed with a plastic sheet, were randomly inserted in each plot, but with each pair positioned at the middle of four planting stations. The metal tubes were left in the ground for 2 weeks and opened frequently to allow for aeration. They were subsequently removed and a new set of tubes inserted at different positions. Three seperate auger samples were taken from each plot at the beginning and the end of each incubation. Soil, both from the metal tubes and the auger samples was taken from depths 0–5 cm, 5–15 cm and 15–30 cm to determine N distribution in the plough layer. Soil

TABLE 1. Some chemical and physical characteristics of the experimental soil (Kanhaplic Haplustalf) at the Grasslands Research Station, Marondera, Zimbabwe

Depth (cm)	Texture	pH ($CaCl_2$)	Organic matter			Exchangeable bases (cmol kg^{-1} soil)				
			%C	%N	C/N	Ca	Mg	Na	K	CEC
0–34	coarse sandy	4.5	0.36	0.044	8.18	1.2	0.01	0.01	0.03	1.6
34–71	coarse loamy sand	4.7	0.12	0.031	3.87	1.2	0.01	0.01	0.01	1.4
71–115	coarse sandy loam	4.3	0.12	0.032	3.75	0.3	0.01	0.02	0.05	1.4

moisture content was measured gravimetrically at every sampling time, while rainfall data was obtained from a meteorological station situated 1 km away. A total of 452 mm of rain was received during the 1990/91 rain season.

The N mineralised/immobilised was calculated from the difference between inorganic N in incubated soil (closed tube) and inorganic N in soil from the auger sample taken at the beginning of each incubation. Nitrogen uptake was obtained from the difference between NO_3-N in incubated soil (open tube) and NO_3-N in the auger sample taken at the end of the incubation. Nitrogen leaching was estimated from the difference between NO_3-N in incubated soil (closed tube) and NO_3-N in incubated soil (open tube). Inorganic N was determined by a colorimetric method (Keeney and Nelson, 1982).

Two way analysis of variance and Walter-Duncan's multiple range tests were used to determine treatment differences at the 5 % level of significance.

RESULTS

Nitrogen mineralisation, uptake, and leaching estimated by the *in situ* incubation technique. There were no significant differences ($P \leq 0.05$) in mineral N initially present at different depths within the plough layer (Table 1). Of the interactions between time, treatment, and depth, only time and depth interactions were found to be significant. Even then, it was only evident in the NO_3-N content of auger samples and incubated (open tubes) samples. The NO_3-N in the auger and incubated (open tubes) samples decreased with time. Since the distribution of mineral N within the plough layer was uniform, further calculations of N mineralisation, uptake and leaching were, therefore, made on the basis of the whole plough layer (0–30 cm depth).

Data on N mineralisation, uptake and leaching calculated from the *in situ* incubation technique are shown in Table 2. There was more inorganic N in soils that received N compared to those that did not. Addition of N to manure at pre-planting gave significantly higher inorganic N contents in the soil than when N was added to manure 6 WAP.

There was an initial flush of N mineralisation in the unamended soil during the first 4 weeks,

TABLE 2. Cumulative N mineralisation, uptake and leaching from the plough layer estimated by the *in situ* incubation technique from soil treated with combinations of manure (10 t ha^{-1}) and N (100 kg ha^{-1}) applied at pre-planting (pp) or 6 weeks after planting (WAP)

	N (g m^{-2})								
	Days after planting								
Process and treatment	0	14	28	42	57	73	86	98	112
		N mineralisation							
Control	3.14	12.20	15.47	9.24	9.35	7.45	7.19	6.45	5.88
Manure	3.65	6.10	9.01	8.25	10.60	11.29	11.04	10.80	10.56
Manure+ N (pp)	13.30	3.96	11.54	7.60	10.55	13.72	14.16	13.71	13.72
Manure+ N (6WAP)	7.76	5.61	10.46	6.28	12.33	12.98	11.34	10.98	11.30
N (pp)	5.10	11.74	16.52	9.42	7.58	10.97	11.08	10.49	11.83
N (6 WAP)	4.11	4.92	13.18	4.94	7.08	9.41	10.69	10.20	11.95
		N uptake							
Control		3.07	3.07	3.07	7.25	8.38	8.81	8.81	8.81
Manure		2.09	2.09	2.0g	8.04	8.71	8.71	8.79	8.79
Manure+ N (pp)		4.30	4.30	4.30	8.00	8.90	9.66	9.66	9.66
Manure+ N (6WAP)		2.24	2.24	2.46	8.92	9.70	9.92	9.92	10.03
N (pp)		0.37	0.37	0.37	0.37	0.82	1.16	1.16	1.16
N (6 WAP)		1.50	1.50	1.50	10.36	11.40	11.40	11.40	11.40
		N leaching							
Control		0	1.56	2.07	2.07	2.20	2.20	2.20	2.20
Manure		0	0	0.44	0.44	0.95	1.65	1.89	2.10
Manure+ N (pp)		0	0.29	0.40	0.40	1.21	1.21	1.21	1.51
Manure+ N (6WAP)		0	0	0.17	0.17	0.56	0.56	0.62	0.67
N (pp)		0	2.50	3.16	3.16	3.57	3.97	3.97	4.22
N (6 WAP)		0	0	0.42	0.42	0.42	0.55	0.81	0.87

followed by immobilisation of the released N throughout the remainder of the season. All manure treatments showed an initial immobilisation of N during the first 7 weeks after application as shown by the higher mineral N content in the control relative to the treatments (Table 2). Calculations of the apparent (net) mineralisation from added amendments relative to the control showed that 46% of manure N (equivalent to 4.12 g m^{-2}) was mineralised in the manure treatment after 16 weeks (harvesting time) despite the initial immobilisation.

Nitrogen uptake by crops estimated by the *in situ* technique was greatest in the fertiliser N treatments except when fertiliser N was applied alone at pre-planting. The estimated N uptake of 1.16 g m^{-2} in the treatment where N only was applied at pre-planting, was the lowest compared to all other treatments. The estimated N uptake values from the control and manure amended soil were similar.

Nitrogen leaching was highest when N alone was applied at preplanting (4.22 g m^{-2}), and lowest in treatments that got nitrogen 6 weeks after planting (Table 2). The manure + N (6 WAP), and the N (6 WAP) treatments lost 0.67 g m^{-2} and 0.87 g m^{-2} of N, respectively. The amounts lost as a percentage of applied N in the different treatments were 23% for manure, 7 %, manure + N (pre-planting), 3.5%, manure + N (6 WAP), 42% for N (preplanting), and 8.7% for N (6 WAP). In the control treatment, losses were 2.2 g N m^{-2}, mostly occurring in the first 42 days after planting, and amounting to 29% of the amount mineralised after 42 days.

Dry matter accumulation. The lowest dry matter accumulation of shoots and roots was found in the control and in the treatment which received manure only (Table 3). Shoot dry weights were significantly higher ($P \leq 0.05$) in treatments which received N. Time of N application had no significant effect on root dry matter yield. The only significant increase in shoot dry matter production was found in manure amended soil where N was applied pre-planting. Total dry matter accumulation (shoots + roots) closely followed dry matter yield patterns of the shoots. Total dry weights, and the shoot and root dry weights of all treatments increased with time.

TABLE 3. Dry matter accumulation in maize plants grown in soils treated with combinations of manure (10 t ha^{-1}) and N (100 kg ha^{-1}) applied at pre-planting or 6 weeks after planting (WAP)

Sampling time (weeks after planting) pre-planting	Part of plant	N (g m^{-2}) Control	Manure	Manure + N at	Manure + N 6 wap	N at pre-planting	N 6 wap
6	Shoots	38.77 el	44.99 el	54.14 ej	26.40 ek	30.73 ejk	34.14 ek
	Roots	20.85 ln	14.69 ln	19.51 lm	13.84 lmn	11.83 lm	17.01 lmn
10	Shoots	264.96 dl	337.45 dl	436.21 dj	331.78 dk	431.21 djk	293.06 dk
	Roots	54.02 hn	51.03 hn	73.77 hm	63.71 hmn	53.71 hm	73.34 hmn
12	Shoots	325.99 cl	309.65 cl	629.05 cj	569.48 ck	687.64 cjk	712.20 ck
	Roots	80.66 fgn	68.40 fgn	134.98 fgm	97.42 fgmn	158.27 fgm	100.04 fgmn
14	Shoots	550.65 bl	371.16 bl	931.68 bj	869.99 bk	828.83 bjk	720.13 bk
	Roots	91.45 fn	64.93 fn	139.00 fm	123.46 fmn	160.95 fm	113.40 fmn
16	Shoots	598.75 al	588.32 al	1104.77 aj	899.61 ak	891.44 ajk	766.59 ak
	Roots	59.20 gn	85.78 gn	118.88 gm	84.07 gmn	116.57 gm	82.30 gmn

Means within a plant part followed by the same letter do not differ at the $P = 0.05$ level using Duncan's multiple range test. Normal letters show treatment differences within a sampling date. Bold letters show differences within treatments.

Root dry weight was highest at 12 to 14 weeks after planting. The ratio of roots to shoots at 12–14 weeks ranged between 12–19%, and averaged about 15%. Grain yields per ha were as follows: control-2640 kg, manure-1255 kg, manure+N (pre-planting)-3938 kg, manure+N (6 WAP)-4731 kg, N- (pre-planting)-4394 kg, and N (6WAP)3691 kg. Differences in yields were significant ($P \leq 0.05$).

N uptake by maize. Total crop N uptake per ha (shoots and roots) was as follows: control- 50 kg, manure- 48 kg, manure+N (pre-planting)- 131 kg, manure+N (6 WAP)- 115 kg, N (pre-planting)- 114 kg, and N (6WAP)119 kg. Respective N content per ha in the grain for the different treatments was as follows: 33, 17, 60, 69, 82, and 64 kg. The highest N content in roots ranged between 8–10% of the highest total N for both shoots and roots, while the ratio of N in roots: shoots at 12 WAP was between 8 and 19%. Nitrogen uptake by maize from unamended soil and soil receiving manure only was significantly lower ($P \leq 0.05$) than from the other treatments (Table 4). A combination of N with manure, and time of N application had no significant effect on total N uptake by the maize plants. Nitrogen uptake by shoots and roots increased with time, but root N uptake showed a maximum at 12 to 14 weeks after planting. The relationship between actual and estimated N uptake given in Figure 1 shows a high deviation from unity especially at the lower levels of actual N uptake.

The apparent N recovery by plants as estimated by the difference method, ranged from less than 0% (manure only), 42% (manure + N applied pre-planting), 34% (manure + N applied 6 WAP), 64% (N applied at pre-planting) and, to 69% (N applied 6 WAP).

DISCUSSION

The *in situ* technique gave estimates of N mineralisation, N uptake and N leaching from the plough layer only. Therefore, the method did not provide a total estimate of leaching from the whole rooting zone since utilisation of soil N by maize roots can be up to depths of 150 cm or more (Gass *et al.*, 1971; Broadbent, 1984). In the present study, the roots grew to a depth of 90 cm. Differences in mineral N between different depths in the plough layer were insignificant, probably because of mixing of the soil during application of manure and N, and during weeding.

The estimated N uptake of 1.16 g m^{-2} from soil fertilised with N at pre-planting was low and grossly underestimated the actual uptake by the maize of 11.37 g N m^{-2}. A comparison of N uptake showed that the N uptake figures estimated by the *in situ* incubation technique were very similar to actual N uptake in the manure+N (pre-planting), manure+N (6 WAP), and N (6 WAP) treatments, respectively (Fig. 1). The *in situ* technique overestimated N uptake in the control and in the manure only treatment by about 40–50%, but grossly under-estimated N uptake in the fertiliser N (pre-planting) treatment. The relationship shown in Figure 1 suggests that at lower levels of actual uptake, the *in situ* incubation technique will over-estimate plant uptake. The reason could be that high leaching of N could result in an over-estimate of N uptake as calculations are based on the difference between NO_3-N in incubated soil (open tube) and NO_3-N in the auger sample taken at the end of the incubation.

Nitrogen uptake was closely related to dry weight accumulation and to the seasonal N availability especially in the fertiliser treatments (Table 2). The calculated apparent N recoveries for the treatments receiving manure were low, despite the high mineralisation of 46% calculated after 16 weeks. This was due to the initial N immobilisation in the first 7 weeks after planting,

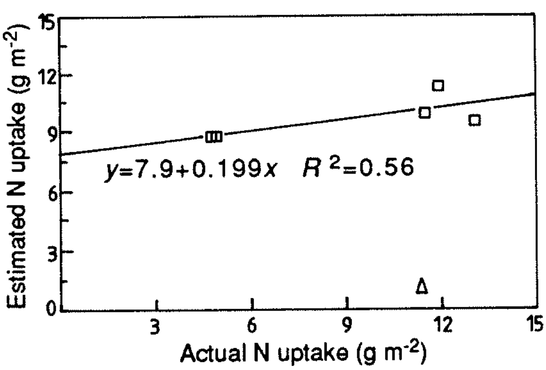

Figure 1. Correlation of actual N uptake by maize plants and estimated N uptake values obtained from the *in situ* incubation technique (Δ outlier)

TABLE 4. N uptake by maize plants grown in soil treated with combinations of manure (10 t ha^{-1}), and N (100 kg ha^{-1}) applied at pre-planting or 6 weeks after planting (WAP)

Sampling time (WAP) pre-planting	Part of plant	N (g m^{-2}) Control	Manure	Manure + N at pre-planting	Manure + N 6 WAP	N at pre-planting	N 6 WAP
6	Shoots	0.988 dg	1.122 dg	1.939 dh	0.695 dh	1.128 dh	0.939 dh
	Roots	0.347 le	0.165 le	0.390 lf	0.183 lf	0.274 lf	0.335 lf
10	Shoots	2.073 cg	2.890 cg	6.493 ch	6.407 ch	6.475 ch	5.859 ch
	Roots	0.250 ke	0.232 ke	0.591 kf	0.628 kf	0.500 kf	0.738 kf
12	Shoots	2.481 bg	2.420 bg	7.072 bh	10.291 bh	7.840 bh	11.754 bh
	Roots	0.451 le	0.329 le	0.975 lf	1.079 lf	1.012 lf	0.982 lf
14	Shoots	4.201 ag	2.591 ag	10.815 ah	12.285 ah	9.163 ah	10.078 ah
	Roots	0.439 je	0.274 je	0.719 jf	0.799 jf	0.957 jf	0.841 jf
16	Shoots	4.707 ag	4.432 ag	12.419 ah	11.065 ah	10.748 ah	11.102 ah
	Roots	0.262 ke	0.323 ke	0.671 kf	0.415 kf	0.622 kf	0.799 kf

Means within a plant part followed by the same letter do not differ at the P = 0.05 level using Duncan's multiple range test. Normal letters show treatment differences within a sampling date. Bold letters show differences within a treatment.

a period which was coincident with high crop growth and N uptake. This shows that crop availability of N in the aerobically decomposed manure used was not in synchrony with plant growth demands, and that it is lower than from fertiliser N because of the slow release of organically bound N (Beauchamp, 1986).

Shoot and root dry weights decreased at the end of the experiment as plants matured, but was particularly noticeable in the roots. The decrease in dry weight at maturity could have been due to respiration losses (Lucas, 1981). The decomposition of fine roots could also be a significant factor for decreased root dry weights. Grain yields and dry weights reflected the N availability in the soil. The lowest yields which were from soil treated with manure only, suggested that N availability was lowest in the manure. Nitrogen mineralisation from this type of manure was found to be very negligible with about 3–6 % N mineralised in the first season (Murwira and Kirchmann, 1992), and consequently the contribution to immediate plant N requirements is minimal (Grant, 1967).

Crop N uptake data from the manure treated soil suggests that there was immobilisation of N since only 48 kg ha^{-1} were taken up in the manure treatment compared to 50 kg ha^{-1} in the control treatment. But it was calculated before that 46 % of manure N was mineralised. Therefore, these results show that there was asynchrony of N mineralisation from manure and N uptake by the crop.

More N was lost through leaching from the control although some could have been caused by denitrification, and from manure only, and in soil receiving late (6WAP) application of N than from the other treatments. This was probably because release of N in the soil was not well synchronised with plant growth. Measurements of N leaching in Zimbabwe using pan lysimeters at 1 m depth gave lower leaching losses amounting to less than 0.3 g m^{-2} under similar conditions namely, the same site, year and fertility management (W.Kamukondiwa, personal communication). These results are in agreement with those of Jokela (1992) who showed that little nitrate was found below 0.9 m, and that most of the nitrate was present in the upper 0.6 m which is where most of the leaching occurred. This may explain why the nitrate leaching values measured by the *in situ* technique at 0.3 m depth were higher than those measured by the pan lysimeter at 1 m depth.

CONCLUSIONS

The *in situ* technique over-estimates N uptake at lower levels of actual plant demand. However, it is sensitive enough to show some treatment differences in N mineralisation patterns and in N uptake and leaching. The technique shows potential for use in sandy soils under arable conditions, but its suitability needs to be tested further for all soil types, and calibrations made to enable estimates of mineralisation, leaching and plant uptake in the whole root zone.

The study also showed that synchrony between N release and plant uptake was best achieved by applying combinations of manure and N, and by late application of N. Late application of N reduced the amount N lost through leaching. If manure only is applied, early application of the manure seems necessary to achieve better synchrony between manure N release and crop uptake, but usually there is little moisture in the soil before the onset of the rains, thus manure decomposition will be negligible.

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