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Low-Input Cropping Systems and Nitrogen Fertilizer Effects on Crop Production: Soil Nitrogen Dynamics and Efficiency of Nitrogen Use in Maize Crop

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Abstract: Soil N is a major factor limiting crop production in maize-based agriculture in the tropics. In this study, soil N dynamics and efficiency of N use by maize was investigated in five cropping systems (CSs) over two annual cropping phases. The CSs comprised cereal-legume (CS1, CS2, CS3), cereal-cereal (CS4) and cereal-bare fallow (CS5) rotations with three rates of N fertiliser application to maize (0, 60 and 120 kg ha^{-1}). Legumes (cowpea, field pea and lucerne) were either grown in rotation or intercropped with the cereals. All CSs with legumes in the rotation had greater soil total N and soil mineral N at planting of maize. Net and cumulative N mineralization during maize growth in both phases was always highest for CS1, where winter field pea was incorporated as a green manure. Soil total N and mineral N increased with application of inorganic N fertilizer, but the efficiency of N use by maize decreased with increasing N application rate. N use efficiency was highest where N was present in the form of legume residues. The estimated soil N balance after harvest showed significant N gains for CSs that had legumes in the rotation at all N fertilizer rates. In contrast, CSs without legumes had lower soil N gains and addition of N fertilizer at 120 kg N ha^{-1} resulted in a net loss of N from the soil profile. This study shows that the inclusion of legumes, supplemented by inorganic N fertilizer where the legume crop is removed, has the potential to maintain adequate crop production and soil N quality in maize-based cropping systems. Where legumes are absent from rotations and inorganic N fertilizer is the sole N source, soil N quality is likely to deteriorate over time.

Key words: Soil moisture · Soil total N · Soil mineral N · N mineralization · Soil N balance

INTRODUCTION

Soil N quality is a major factor limiting plant production in many agricultural systems and may be improved through the use of legumes and inorganic fertilizer N. To ensure adequate maize production and maintenance of soil N quality in agricultural soils, there is a need to identify best practices for management of N for a range of cropping systems. In a cowpea-maize rotation [1], legume residues provided 60 kg N ha^{-1} and increased maize grain yield by 95% relative to grain yield in a maize-maize rotation. These studies indicated that use of legumes in rotations has the potential to either partially or fully satisfy the N demand of maize crops in farming systems. Legumes provide food for humans and feed for livestock, as well as improving soil N fertility and promoting sustainable crop production [2,3].

To develop best practice for use of legume and inorganic N fertilizers, efficiency of N use by maize must be determined. In crop production, terminologies such as N use efficiency (NUE), N uptake efficiency (NU_pE), N apparent recovery fraction (NRF) and N harvest index (NHI) have been used to assess crop performance following N fertilizer application [4-8]. Increasing NUE of maize through modifications in farming practices would be beneficial in improving the efficiency of fertilizer use and the sustainability of maize-based farming systems [9]. Cropping system, N source and method of fertilizer application have been identified as some of the major factors influencing NUE [10]. Crop rotation also has a

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marked influence on NUE and on the utilization of N sources, as it affects soil mineral N availability and water use and consequently the availability of N for plant growth [11]. There is growing evidence that inorganic fertilizer efficiency is improved by using inorganic and organic fertilizers in combination [12,13]. Large amounts of plant N entering mineralization and immobilization cycles enhance inorganic N availability to growing crops [14,15], as observed in trials with legume leaf residues [16].

The contribution of legume N to the soil will depend upon the net N balance. For example, when legume stover is removed, there will be a significant loss of legume N from the system [17]. For a grain legume that receives no N fertilizer and for which the stover is incorporated into the soil, the N benefit can be assessed by calculating the difference between the amount of N fixed biologically from the atmosphere (P_{fix}) and the N removed in the harvested grain (NHI). Where P_{fix} is not determined, apparent N loss during maize crop growth can be estimated as the difference between N input and output, based on plant N uptake (measured as grain and residue N yields), soil mineral N content and N fertilizer application.

In this study, soil N dynamics and efficiency of N use by maize were investigated in five cropping systems incorporating a range of legume and inorganic fertilizer N treatments. Soils collected over two maize cropping phases were analysed for total N, mineral N and N mineralization. Efficiency of N use by maize was determined by multiple parameters. N balances were estimated following maize crops and were used to compare the performance of the different cropping systems with respect to legume components and rates of N fertilizer application. N balances were based on N yields in grain, stover and forage residues [18].

MATERIALS AND METHODS

This study was conducted during 2001 to 2003 at the Horticulture Field Study Unit of the University of Western Sydney, Richmond (33° 62'S, 150° 75'E, 21 m a.s.l. elevation), NSW, Australia. Soil description and weather conditions during the study period have been provided in Omokanye [18]. A split-plot design was used, with five CSs as main-plots and three inorganic N fertilizer rates as sub-plots (three replications per sub-plot). The CSs comprised cereal-legume (CS1, CS2 and CS3), cereal-cereal (CS4) and cereal-bare fallow (CS5) rotations. The cereals used were maize and barley and the legumes used were cowpea, lucerne and field pea. Details on the establishment and management of these crops are available in Omokanye [18]. CSs included summer and winter cropping seasons within each annual cropping phase (Table 1). Sub-plots in all CSs were fertilized prior to the summer maize crop with 0, 60 and 120 kg N ha^{-1} (N0, N60 and N120) applied as Nitram (NH_4NO_3, 34% N). Sub-plots in CS4 were also fertilized prior to a winter barley crop with 0, 40 and 80 kg N ha^{-1}. The experiment received supplementary (sprinkler) irrigation as outlined in Omokanye [18].

Soil Sampling and Measurement of Soil Moisture, Total N and mineral N: Soil samples were collected to a depth of 60 cm using a 5 cm wide soil auger at least 1 d before maize was planted and harvested in each cropping phase. Three soil cores were taken randomly from each sub-plot and then bulked, mixed and sub-sampled. The sub-sample was divided into two. The first half of the sub-sample, a field moist sample, was placed in a closed plastic bag, stored at 4ºC and used within 2-5 d to determine soil moisture and mineral N contents. The other half of the sub-sample was air-dried, crushed to pass through a 2 mm sieve (plant residues on sieve discarded) and stored for total N determination.

Soil moisture content was determined gravimetrically according to method 2A1 [19]. The determination of soil total N was based on the semi-microKjeldahl automated colour method 7A2 [19]. Mineral N was extracted from 3 g of field moist soil in 2M KCl (1:10 w/v ratio) for 1 h on a rotating shaker, followed by filtering through Whatman #5 filter paper. Filtrates were analysed for NO_3^--N using the Flow Injection Analysis Quikchem Method 10-107-04-1-A [20] and for NH_4^+-N using the Flow Injection Analysis Quikchem Method 10-107-06-1-A [20].

Field N mineralization study: N mineralization was estimated in topsoil by a procedure that involved *in situ* incubation of soil in polyvinyl chloride (PVC) tubes (5 cm x 25 cm) hammered to a depth of 15 cm [21]. The 15 cm depth was chosen because of earlier studies, which showed that the highest net N mineralization occurred within the top 10 or 20 cm of the soil profile [22-24].

Five replicate samples were taken from each sub-plot at 0, 21, 42, 63 and 84 d sampling times under the maize crop in each cropping phase. The 0 d samples were taken at random locations within each sub-plot 3-8 d after the maize crop was sown. On the same day, five tubes were inserted at least 50 cm apart within maize rows (excluding the two rows of maize on the edge of each sub-plot) for the next sampling time (21 d). The tubes were covered with loose-fitting caps to prevent water entry and leaching of nitrate. The tubes also prevented N uptake by plants, because roots were cut when the tubes were hammered into the soil. At 21, 42 and 63 d, five tubes were inserted (as described for the 21 d sample) for the next sampling time. Care was taken at each sampling time to avoid previously sampled locations.

The five replicate samples taken from each sub-plot at each sampling time were pooled, mixed thoroughly, sub-sampled as field moist soils and stored at 4ºC for 2-5 d prior to mineral N extraction (NO_3^--N + NH_4^+-N). Net N mineralization was determined as the difference between mineral N at sampling and mineral N at the previous sampling time, expressed as rate of N mineralization per day.

Nitrogen Efficiency: The following N efficiency parameters were estimated for each phase, using maize crop data from Omokanye [18] and soil N measures presented in this paper. Nitrogen efficiency terminology follows [4-8]:

- N use efficiency (NUE; kg grain kg^{-1} N supply), where N supply (N_s) is the sum of soil NO_3^--N at planting, mineralizable organic N and applied N fertilizer.
- N uptake efficiency (NU_pE; kg N uptake kg^{-1} N supply), where N uptake is based on above-ground plant parts (grain+stover+husk).
- N harvest index (NHI; %), determined as the percentage of N in grain relative to N uptake (grain+stover+husk).
- N apparent recovery fraction (NRF; %), determined as the percentage of N uptake at N_x-N uptake at N_0 relative to applied N at N_x.

Estimation of soil N balance: To compare the five different CSs for their N uptake efficiency and capacity to reduce N loss through leaching, total changes in mineral N content were estimated by calculating N input and output from the 0 to 60 cm soil profile over phase one and phase two using the following equation [25]:

$$N_{l/g} = (N_{up(t2)} + N_{min\,(t2)}) - (N_{fert} + N_{min(t1)}) \qquad (1)$$

Where, $N_{l/g}$ = N balance (i.e. N loss or gain in the system)
$N_{up(t2)}$ = above-ground N uptake at harvest (estimated using data from Omokanye *et al*. undated a and b)
$N_{min\,(t2)}$ = mineral N in the soil profile to a depth of 60 cm measured at harvest in February 2002 and March 2003
N_{fert} = N fertilizer added to the system (0-120 kg N ha^{-1})
$N_{min(t1)}$ = mineral N in the soil profile to a depth of 60 cm measured at planting in November 2001 and December 2002

Soil mineral N was converted from mg N kg^{-1} soil to kg N ha^{-1} using the following formula adapted from the NSW Agriculture Growers Workbook [26]:

$$\text{kg N ha}^{-1} = \text{mg N kg}^{-1} \text{ soil x BD x no. of 10 cm segments in a 0-60 cm soil profile} \qquad (2)$$

where BD is the bulk density (g cm^{-3}), which was determined for all plots using the metal ring procedure [27].

A negative N balance indicates apparent N loss through leaching [28,29] or other N demineralisation processes [30,31].

Statistical Analyses: Data were analysed by ANOVA using the GLM procedure from SAS [32]. Where ANOVA indicated significant CS or N rate effects, means were compared by least significant difference (LSD) using the LSD lines of SAS procedure. Where there was a significant interaction between CS and N rate, LSDs were calculated using the appropriate standard error terms described by Gómez and Gómez [33]. Repeated measures analysis was performed on period of incubation for soil N mineralization measurements to test the significance of changes over time. Significant differences between treatment means in the text refer to P<0.05. The results are presented separately for phases one and two.

RESULTS

Soil Moisture: At planting of maize in both phases, soil moisture was significantly higher for CS1 and CS5 than for other CSs (Table 2). At harvest, soil moisture remained high in CS5 in both phases and was similarly high in CS4 in phase two. Soil moisture in CS2 was significantly lower than in all other CSs at planting and harvest in both phases. Soil moisture ranged from 10.90-23.59% over the study period.

Soil total N and mineral N: In both phases, there were significant differences between CSs in soil total N at planting and harvest of maize (Table 2). Inclusion of legumes in the previous rotation (CS1, CS2 and CS3) significantly increased soil total N at planting and harvest relative to CSs without legumes (CS4 and CS5) in both phases. Soil total N ranged from 0.48 to 1.17 g N kg^{-1} soil over the study period. Soil mineral N reflected soil total N, with the highest mineral N values found in CSs incorporating legumes (CS1, CS2 and CS3) on all sampling occasions (Table 2). Soil mineral N ranged from 1.70-6.80 mg N kg^{-1} soil and was lower at harvest than at planting.

Table 1: Description of cropping systems (CSs) showing crop species, rotations, growing season and specific comments

	Period of planting					
		Cropping phase one		Cropping phase two		
	2000-01	2000	2001-02	2002	2002-03	
	N-F[1]	J-N	N-F	J-N	D-M	
Cropping systems:	Summer	Winter	Summer	Winter	Summer	Specific comments on CSs
Maize/field pea (improved fallow, CS1) early	maize	field pea[2]	maize	field pea	maize	The legume (field pea – *Pisum sativum*) was incorporated as green manure into the soil at flowering, before the subsequent maize crop was planted.
Maize-lucerne/barley-lucerne (legume fodder bank, CS2)	maize	B-L[3]	M-L[4]	B-L	M-L	Lucerne (*Medicago sativa*) was planted in autumn 2000 after the first (baseline) maize crop to represent *Stylosanthes* spp. as a legume fodder bank. The lucerne was intercropped with maize in summer and barley in winter.
Maize-cowpea/field pea (CS3)	maize	field pea[5]	M-C[6]	field pea	M-C	Annual double cropping phases comprising summer maize intercropped with cowpeas and winter field peas grown for grain.
Maize/barley (CS4)	maize	barley	maize	barley	maize	Continuous cereal based double cropping system.
Maize/bare fallow (CS5)	maize	fallow	maize	fallow	maize	Traditional Nigerian maize – winter fallow system.

[1]Months, N-F, November-February; J-N, June-November; D-M, December-March

[2]Field pea used as green manure for subsequent summer maize crop

[3]B-L, barley-lucerne intercrop

[4]M-L, maize-lucerne intercrop

[5]Field pea harvested for grain

[6]M-C, maize-cowpea intercrop

Table 2: Mean soil moisture, total N and mineral N contents (0-60 cm depth) in relation to CS at planting and harvest of maize in two cropping phases

	Soil moisture %				Soil total N g N kg^{-1} soil				Soil mineral N mg N kg^{-1} soil?			
	Phase one		Phase two		Phase one		Phase two		Phase one		Phase two	
Cropping system	Planting	Harvest	Planting	Harvest	Planting	Harvest	Planting	Harvest	Planting	Harvest	Planting	Harvest
CS1	23.16a	17.61b	22.20a	15.62b	1.13a	0.96a	1.17a	1.00a	6.80a	3.15a	6.02a	4.22a
CS2	14.59c	12.19d	15.51c	10.90c	0.95b	0.84b	1.05b	0.90b	5.11b	3.25a	5.03b	3.76b
CS3	21.58b	16.04b	19.44b	14.50b	0.99b	0.83b	0.98b	0.88b	6.20b	2.49b	4.89b	3.24c
CS4	19.74b	17.21b	18.37b	16.95a	0.70c	0.55c	0.59d	0.48d	4.55d	1.80c	4.28c	1.71d
CS5	23.59a	19.24a	23.40a	17.94a	0.78c	0.63c	0.69c	0.59c	4.13e	1.70c	3.85d	1.50d
LSD	1.0	0.6	1.3	1.1	0.07	0.08	0.05	0.04	0.50	0.19	0.42	0.27

Values within a column with different letter(s) are significantly ($P<0.05$) different according to LSD.

Table 3: Mean soil total N and mineral N (0-60 cm depth) in relation to N fertilizer rate at harvest of maize in two cropping phases

	Soil total N		Soil mineral N	
N rate (kg ha^{-1})	Phase one	Phase two	Phase one	Phase two
0	0.59c	0.48c	2.27b	2.60b
60	0.85b	0.70b	2.54ab	2.83ab
120	1.01a	0.86a	2.64a	3.12a
LSD	0.24	0.27	0.35	0.42

Values within a column with different letter(s) are significantly ($P<0.05$) different according to LSD

Table 4: Rate of N mineralization (mg N kg^{-1} soil d^{-1}) in topsoil (15 cm) in five CSs with three N fertilizer rates over two cropping phases

Cropping system	N rate (kg N ha^{-1})	Phase one sampling time (d) 21	42	63	84	Phase two sampling time (d) 21	42	63	84
CS1	0	0.22b	0.27b	0.24b	0.22	0.21	0.30	0.28	0.23
	60	0.30a	0.31a	0.23b	0.23	0.21	0.28	0.24	0.21
	120	0.29a	0.30ab	0.29a	0.21	0.23	0.26	0.28	0.23
	LSD	0.03	0.03	0.03	NS	NS	NS	NS	NS
CS2	0	0.21a	0.15	0.13	0.18b	0.17	0.23	0.16	0.10b
	60	0.20a	0.18	0.15	0.18b	0.18	0.22	0.19	0.11ab
	120	0.14b	0.15	0.13	0.25a	0.20	0.23	0.20	0.13a
	LSD	0.04	NS	NS	0.03	NS	NS	NS	0.02
CS3	0	0.18	0.20	0.23	0.18	0.14	0.19	0.16	0.18ab
	60	0.18	0.21	0.22	0.18	0.09	0.20	0.14	0.16b
	120	0.20	0.16	0.24	0.19	0.16	0.21	0.17	0.20a
	LSD	NS	NS	NS	NS	NS	NS	NS	0.03
CS4	0	0.21	0.19b	0.22	0.19	0.13	0.13	0.10b	0.07b
	60	0.18	0.20ab	0.18	0.12	0.10	0.12	0.15ab	0.11b
	120	0.19	0.23a	0.14	0.15	0.10	0.13	0.18a	0.17a
	LSD	NS	0.03	0.02	NS	NS	NS	0.05	0.04
CS5	0	0.23	0.21a	0.17a	0.17	0.14	0.14	0.13	0.10
	60	0.18	0.15b	0.14b	0.18	0.13	0.13	0.14	0.11
	120	0.19	0.19a	0.15ab	0.17	0.13	0.15	0.15	0.10
	LSD	NS	0.02	0.02	NS	NS	NS	NS	NS

Values within a column with different letter(s) are significantly ($P<0.05$) different according to LSD.NS, indicates not significant.

In both phases, soil total N at harvest increased significantly with N rate up to N120 (Table 3). Soil mineral N at harvest was significantly higher at N120 than at N0 (Table 3).

N Mineralization in Soil During Maize Crop Growth

Rate of N mineralization: In phase one, rate of N mineralization (NO_3^--N + NH_4^+-N) per day was affected by N fertilizer rate for at least one sampling time for CS1, CS2, CS4 and CS5 (Table 4). Where significant differences occurred, rate of N mineralization was increased by at least one N fertilizer rate (N60 and/or N120) relative to N0. In phase two, rate of N mineralization per day was not affected by N fertilizer rate in CS1 and CS5, or in other CSs for the 21 and 42 d samples. However, mineralization rates were higher at N120 in CS4 (63 and 84 d samples) and at N120 in CS2 (84 d sample) relative to N0 (Table 4). Rate of N mineralization ranged from 0.09-0.31 mg N kg^{-1} soil d^{-1} over the study period.

Net N mineralization: In phase one, CS1 had significantly higher net N mineralization than other CSs at all sampling times (Fig. 1). For the other CSs, there was no consistent trend in net N mineralization. Net N mineralization ranged from 8.6-18.5 mg N kg^{-1} soil during phase one. In phase two, net N mineralization was significantly higher in CS1 than in all other CSs (Fig. 2). Net N mineralization was also significantly higher for CS2 than for CS3, CS4 and CS5 over the 0-63 d sampling period. Net N mineralization ranged from 6.5-18.1 mg N kg^{-1} soil during phase two.

Cumulative net N mineralization: Cumulative net N mineralization for the five CSs and three N rates are shown for phases one and two in Figure 3 a and b. In phase one, cumulative net N mineralization for CS1 was significantly higher than for all other CSs at all N rates. Cumulative N mineralization was significantly lower at N0 than at N120 in all CSs. In phase two, inclusion of legumes in the rotation (CS1, CS2 and CS3) resulted in higher cumulative net N mineralization at all N rates relative to CSs without legumes (CS4 and CS5). However, CS1 had significantly higher cumulative net N mineralization than CS2 and CS3 at all N rates. Cumulative net N mineralization was significantly higher at N120 than at N0 in all CSs except CS1.

Nitrogen Efficiency in Maize Crops

N use efficiency (NUE): In general, NUE decreased with increasing N rate, with NUE at N120 being significantly lower than NUE at N0 in all CSs in both phases (Figs. 4 a, b). In phase one, the highest NUE was obtained for CS1 at N0. In phase two, NUE was highest for both CS1 and CS3 at N0. NUE ranged from 38-87 kg grain kg^{-1} N_s in phase one and from 28-77 kg grain kg^{-1} N_s in phase two.

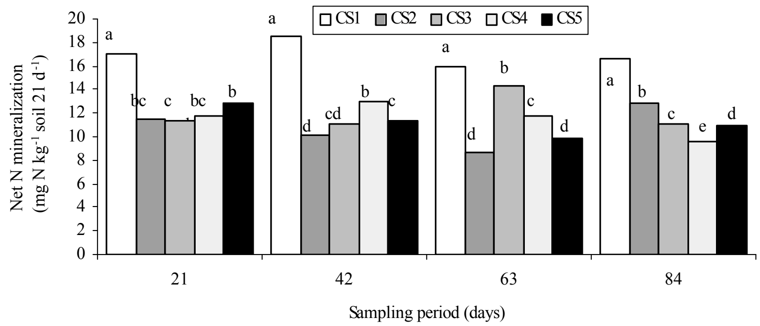

Fig. 1: Net N mineralization of CSs in topsoil (0-15 cm) at four sampling times in phase one (averaged over three N rates). Bars with different letters are significantly ($P<0.05$) different according to LSD within each sampling period (1.01 - 21 d; 1.09 - 42 d; 1.11 - 53 d; 0.79 - 84 d).

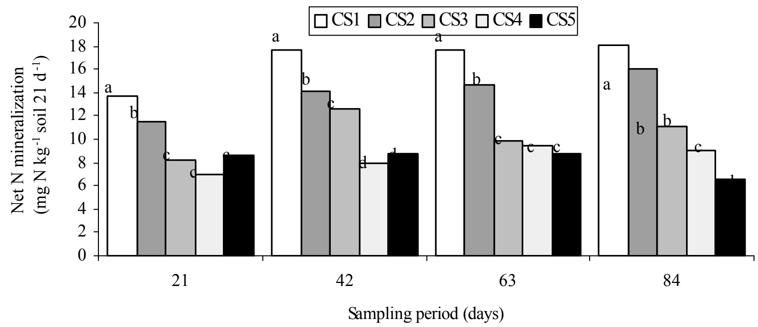

Fig. 2: Net N mineralization of CSs in topsoil (0-15 cm) at four sampling times in phase two (averaged over three N rates). Bars with different letters are significantly ($P<0.05$) different according to LSD within each sampling period (0.83 -21 d; 0.97- 42 d; 0.95 - 53 d; 0.89 - 84d).

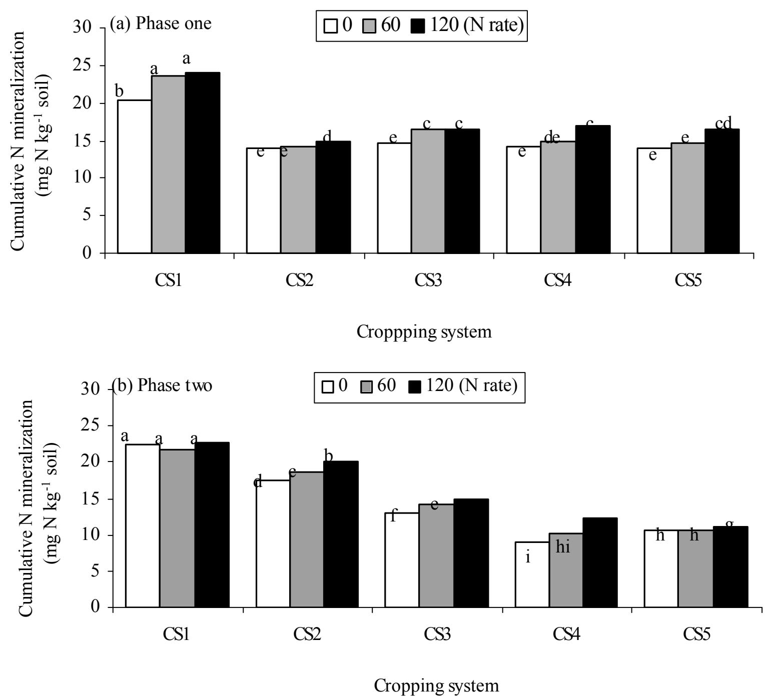

Fig. 3: Effects of CS and N rate on cumulative net N mineralization in topsoil (0-15 cm) in (a) phase one and (b) phase two. Bars with different letters are significantly ($P<0.05$) different according to LSD (1.53 - phase one; 1.1- phase two).

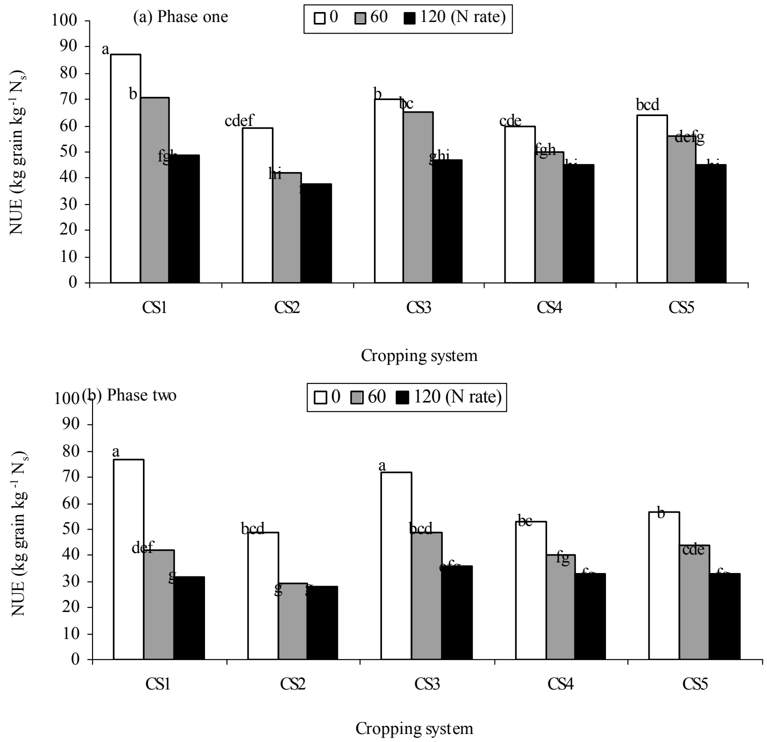

Fig. 4: Effects of CS and N rate on mean NUE of maize in (a) phase one and (b) phase two. Bars with different letters are significantly (P<0.05) different according to LSD (10.0 - phase one; 9.1 - phase two).

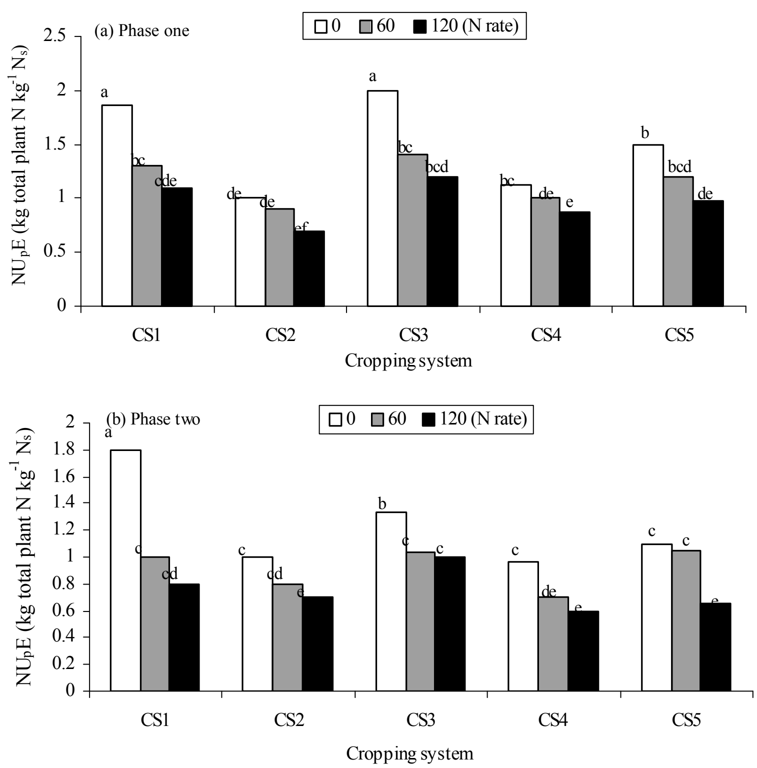

Fig. 5: Effects of CS and N rate on mean NU_pE of maize in (a) phase one and (b) phase two. Bars with different letters are significantly (P<0.05) different according to LSD (0.28 - phase one; 0.24 - phase two).

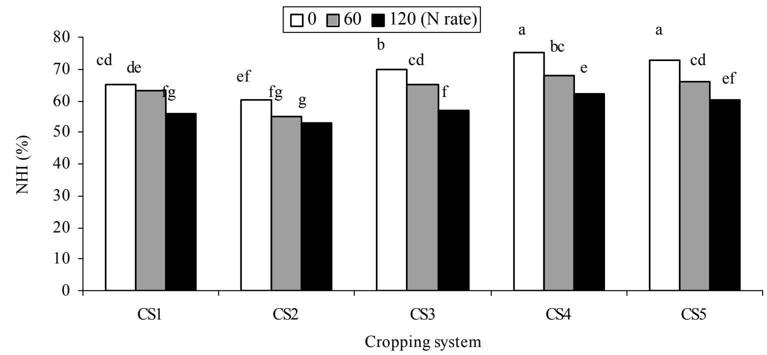

Fig. 6: Effect of CS and N rate on mean NHI of maize in phase two. Bars with different letters are significantly (P<0.05) different according to LSD (14.5).

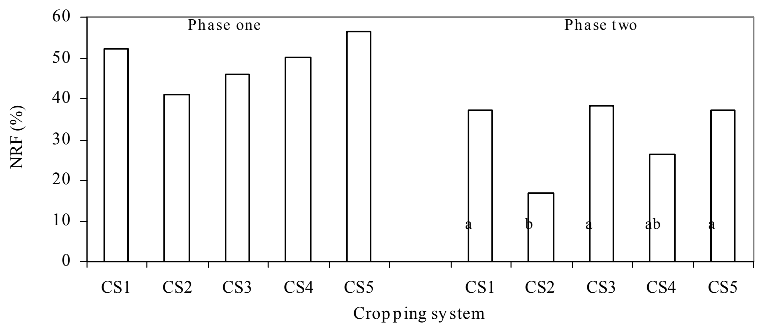

Fig. 7: Mean N apparent recovery fraction (NRF) in relation to CS in phases one and two (averaged over two N rates). Bars with different letters are significantly (P<0.05) different according to LSD (14.7 - phase two).

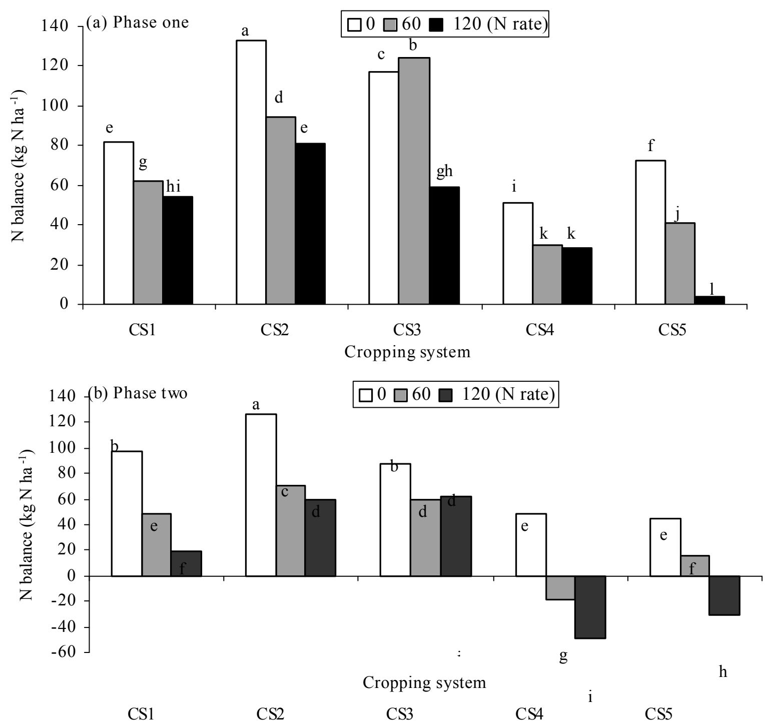

Fig. 8: Effects of CS and N rate on mean N balance (kg N ha^{-1}) in (a) phase one and (b) phase two under maize at harvest. Bars with different letters are significantly (P<0.05) different according to LSD (10.6 - phase one; 8.4 - phase two).

N uptake efficiency (NU_pE): With the exception of CS2, NU_pE of maize at N0 was higher for CSs that had legumes in the rotation (CS1 and CS3) than for CSs without legumes (CS4 and CS5) in both phases (Figure 5 a and b). In most cases, NU_pE at N120 was significantly lower than NU_pE at N0 (except for CS2 in phase one). NU_pE ranged from 0.7 to 1.9 kg total plant N kg^{-1} N_s and from 0.6 to 1.8 kg total plant N kg^{-1} N_s in phases one and two, respectively.

N Harvest Index (NHI): In phase one, NHI was not significantly affected by CS or N rate (data not shown). In phase two, NHI was significantly lower at N120 than at N0 in all CSs (Fig. 6). CSs without legumes in the rotation (CS4 and CS5) had significantly higher NHI at N0 than CSs with legumes (CS1, CS2 and CS3).

N Apparent Recovery Fraction (NRF): In phase one, CS did not significantly influence NRF (Fig. 7). In phase two, NRF was significantly lower for CS2 than for CS1, CS3 and CS5.

Soil N balance: Soil N balances (N loss or gain) were mostly positive (Figs. 8 a, b), indicating soil N gains in most CSs. The only losses in soil N (negative N balance) were obtained for CS4 (at N60 and N120) and CS5 (at N120) in phase two (Fig. 8 b).

At each N rate in both phases, N balance was always significantly more positive for CSs incorporating legumes in the rotation than for CSs without legumes. In phase one, N gain was greatest for CS2 at N0 (133 kg N ha^{-1}) and smallest for CS5 at N120 (4 kg N ha^{-1}). In phase two, N gain was greatest for CS2 at N0 (127 kg N ha^{-1}) and N loss was greatest for CS4 at N120 (-49 kg N ha^{-1}).

DISCUSSION

Soil N quality is a major limiting factor in many maize production systems in tropical environments and is often enhanced through the use of legumes [25]. The N contribution of legumes to subsequent maize crops was quantified in this study by estimating soil total and mineral N, N mineralization, indicators of N use efficiency by maize and N balance at harvest. Choice of legume species and N fertilizer rate in most cases had significant effects on N dynamics and efficiency of N use in the maize crop in both phases. The major findings relating to the measured soil parameters during maize crop growth in both phases are discussed with reference to CS and N rate below.

Cropping Systems

Cropping Systems Incorporating Legumes: Inclusion of legumes in rotations increased soil total N and mineral N at planting of maize, as well as the residual total N and mineral N at harvest. Net and cumulative N mineralization and NUE and Nu_pE at N0, were generally highest for CS1. The estimated soil N balance after harvest was mostly positive (N gain) and was highest for CSs with legumes in the rotation. This confirms earlier reports that integration of legumes into cropping systems has the potential to enhance yields of subsequent crops because of increases in plant-available N in the soil [2,34].

In most cases, the N benefits to maize crop growth in both phases of the current study were greater for winter incorporation of field pea (CS1) than for lucerne-ley (CS2) or removal of winter field pea for grain (CS3), regardless of N fertilizer rate. As noted earlier, the practice of residue incorporation may be better able to sustain N content in arable soils than growing legumes without residue incorporation and represents an important method for managing soil fertility [21]. Incorporation of legume residues improves both the biomass and activity of soil microbial communities through increases in labile soil C and N content [35,36]. This influences the turnover of soil organic matter and consequently the availability of nutrients, including N, for subsequent crop growth (21].

The highest soil mineral N obtained for CS1, CS2 and CS3 in both phases could be attributable to an increase in soil nitrate (data not shown), which, at planting and harvest respectively, was 62 and 73% higher in phase one and 50 and 67% higher in phase two, than in CSs that did not include legumes (CS4 and CS5). Increase soil nitrate is likely to be derived from the mineralization of legume residues, because of the available, high quality organic matter [18]. This is particularly the case for CS1, in which N mineralisation rates were consistently higher than in other CSs.

The highest N mineralization rate following winter incorporation of field pea (CS1) was attributed to the increase amount and higher quality soil organic matter associated with this CS [18]. Groffman *et al*. [37] attributed increased N mineralization and nitrification in part to the decomposition of N rich plant materials. These results are similar to the findings of Barrios *et al*. [38], who reported significant increases in the daily rate of N mineralization in maize in rotation with cowpea and with prunings of gliricidia added as green manure to continuous maize crops.

In most of the CSs, NUE decreased with increasing N fertilizer rate, as reported for maize [10,39,40]. Increase NUE in cereal-based systems where legumes have been incorporated but no N fertilizer added, such as CS1 and CS3 at N0 in this study, has also been [5,41]. In the absence of added fertilizer, N uptake by the maize crop was more efficient in CS1 and CS3 than in CS2, CS4 and CS5 in both phases. NU_pE (N uptake efficiency) declined as N fertilizer rates increased in both phases, which is similar to findings for wheat crops [6,8,41]. N mineralization rates were not always higher in phase one and, where they were, differences were marginal and not tested for significance. In CS2, maize yield (and therefore NUE) was limited by available soil moisture as a result of competition with actively growing lucerne. The NUE values obtained in the present study at all N rates were similar to those reported for wheat and barley [41,42].

In the present study, the lowest soil mineral N loss between planting and harvest of maize crops in both phases from CS1 compared to that of CS2 and CS3 was a reflection of greater NUE by CS1. In CS2 at N0, only a fraction of the N released for growth was utilized by the maize crop, as indicated by the high N gains in the N balance study. The higher mineral N loss in both CS2 and CS3 than in CS1 in both phases reflected the N offtake from the system, where crop residues (total above-ground maize and legumes biomass) were removed. The reduction in soil N loss from CS1 suggests that organic matter input via forage incorporation into the soil may be important in maintaining or stabilizing soil N and reduction in organic matter inputs under CS2 and CS3 may have compromised the soil's ability to store N. Based on these results, it appears that sufficient N fertilizer must be supplied to CS2 and CS3 to compensate for crop N offtake and N losses, if soil N storage is to be sustainable in the longer term. The lowest N recovery fraction of applied N fertilizer obtained from CS2 as a result of lower maize yield could also contribute to higher N loss in the system through leaching and denitrification.

The consistently lower soil moisture measured in the lucerne-ley cropping system (CS2) throughout the experimental period was not unexpected, as earlier reports have shown that lucerne can extract water to a depth of 300 cm [43] and increase soil dryness by 75-175 mm in wet summers [44]. Although lucerne may have contributed to soil total and mineral N through N fixation, higher total and mineral N measured in CS2 relative to CS4 and CS5 may also be partly attributable to lower yields and N uptake by intercropped maize as a result of reduced soil moisture in this system. Soil water shortage has been shown to reduce the ability of grain crops to take up available N from the soil in other cropping systems [45,46]. Other factors could be responsible for the poor performance of CS2 in terms of the poor yields obtained for intercropped cereals, including vigorous lucerne regrowth after cutback [18].

Cropping Systems Without Legumes: Where no legume was incorporated into the cropping system (CS4 and CS5), maize-barley rotations (CS4) had higher soil mineral N than maize fallow rotations (CS5) at planting of maize in both phases. The highest soil mineral N in CS4 at planting is likely to have resulted from a carry-over of N fertilizer (0-80 kg N ha^{-1}) applied to the preceding barley crop in both phases. The similarity in soil mineral N content in CS4 and CS5 at harvest is difficult to explain, as there were no consistent trends in maize yield and N uptake in these CSs [18].

In the present study, CSs which did not incorporate legumes in the rotation gave higher NHI (N harvest index) than CSs which had legumes in the rotation at N0 in phase two, but this was not consistent at N60 and N120. This probably suggests that as N fertilizer rates increased up to N120, the transfer of N to grain ceases to follow N uptake by the maize crop [10].

The lowest soil N balances for CS4 and CS5 suggest that sufficient N fertilizer must be supplied to these systems to replace crop N removal and soil N losses, if the systems are to be sustainable in the longer term. For CS4 at N60 and N120 and CS5 at N120, there were negative N balances, which were mainly attributed to leaching. Leaching may have occurred because a higher proportion of total soil N was present as mineral N in these CSs. Since this was not the case for any of the CSs that had legumes in the rotation, differences may be partly attributable to the lack of other legume benefits such as increased yield in CS4 and CS5. Generally, the figures in the present study suggest that the incorporation of legumes in CSs reduces N loss [47]. However, soil N loss under maize in maize-legume rotations may increase if N levels exceed maize requirements.

N fertilizer application: Application of inorganic N fertilizer at N60 and N120 increased soil total N at harvest in both phases. Soil mineral N rose at N120, with nitrate being the dominant form of N available for maize growth (45-76%) in the majority of plots in both phases (data not shown). Below *et al*. [48,49] reported that nitrate increased production of maize to a much larger extent than ammonium. Berecz and Debreczeni [49] also found that nitrate resulted in 72-88% more grain-N than ammonium. The highest proportion of nitrate N relative to ammonium N in the current study is therefore an added advantage in maize grain production.

Because the interaction between CS and N rate was not significant for grain and stover yield [18] and soil N mineralization rate (in most cases) was similar for all CSs, then the differences in grain yield between CSs must be due to the inclusion of legumes. In contrast to the results obtained in the present study, Kolberg *et al*. [50] obtained significant effects of applied N on soil N mineralization rate within a wheat-maize-fallow rotation. Rasmussen *et al*. [51] reported that the amount of N mineralized, expressed as a fraction of the total N present, increased with increasing N application, reduction in tillage and higher frequency of cropping. However, both Rasmussen *et al*. [51] and Kolberg *et al*. [50] applied up to 180 and 286 kg N ha^{-1} respectively, which is substantially higher than the N fertilizer application rates (60-120 kg N ha^{-1}) used in this study. As in the current study, Delogu *et al*. [8,41], working with wheat, found no significant differences in NRF at various N rates, while Sieling *et al*. [52] reported that NRF in wheat decreased as fertilizer rates increased. NRF of applied N fertilizer by arable crops under average field conditions is generally in the range of 40 to 60%, even if immobilization is taken into account [53], as found for maize in phase one of this study. However, NRF of maize was below 40% in all CSs in phase two, which indicates poor utilisation of applied N.

N losses occur through leaching and other N cycling processes such as nitrate reduction, denitrification and the volatilisation of ammonia]. With the exception of CS4 at N120 in phase one and CS3 at N120 in phase two, estimated N balance decreased significantly with all increases in N rate.

CONCLUSION

This study shows that inclusion of legumes in maize-based cropping systems (CS1 and CS3) can provide an important source of mineral N and improve efficiency of N use by maize crops (as shown by NUE and NU_pE), as long as the legume component does not compete with maize for soil moisture (i.e. lucerne in CS2). Where the legume is incorporated as green manure, there is likely to be sufficient N to maintain maize production and soil N quality on a sustained basis. Where legume N is removed at harvest, maize production and soil N quality may be maintained through addition of inorganic fertilizer N. However, where legumes are absent from maize-based CSs (CS4 and CS5), maintenance of maize production and soil N quality will rely on substantial N fertilizer inputs that may cause excessive nitrate leaching.

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