

Partial balance of nitrogen in a maize cropping system in humic nitisol of Central Kenya

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Abstract

The application of nitrogen in a soil under agricultural production is subject to several pathways including de-nitrification, leaching and recovery by an annual crop. This is as well greatly influenced by the management practices, nitrogen source and soil conditions. The main objective of this study was to investigate the loss of nitrogen (N) through nitrous oxide (N₂O) emissions and mineral N leaching and uptake by annual crop as influenced by the N source. The study was carried out at Kabete in Central Kenya. Measurements were taken during the second season after two seasons of repeated application of N as urea and *Tithonia diversifolia* (tithonia) leaves. Results obtained indicated that nitrous oxide (N₂O) emissions at 4 weeks after planting were as high as 12.3 $\mu\text{g N m}^{-2} \text{h}^{-1}$ for tithonia treatment and 2.9 $\mu\text{g N m}^{-2} \text{h}^{-1}$ for urea treatment. Tithonia green biomass treatment was found to emit N₂O at relatively higher rate compared to urea treatment. This was only evident during the fourth week after treatment application. Soil mineral N content at the end of the season increased down the profile. This was evident in the three treatments (urea, tithonia and control) investigated in the study. Urea treatment exhibited significantly higher mineral N content down the soil profile (9% of the applied N) compared to tithonia (0.6% of the applied N). This was attributed to the washing down of the nitrate-N from the topsoil accumulating in the lower layers of the soil profile. However, there was no significant difference in N content down the soil profile between tithonia treatment and the control. It could be concluded that there was no nitrate leaching in the tithonia treatment. Nitrogen recovery by the maize crop was higher in the urea treatment (76% of the applied N) as compared to tithonia treatment (55.5% of the applied N). This was also true for the residual mineral N in the soil at the end of the season which was about 7.8% of the applied N in the urea treatment and 5.2% in the tithonia treatment. From this study, it was therefore evident that although there is relatively lower N recovery by maize supplied with tithonia green biomass compared to maize supplied with urea, more nitrogen is being lost (through leaching) from the soil–plant system in the urea applied plots than in tithonia applied plots. However, a greater percentage (37.8%) of the tithonia-applied N could not be

accounted for and might have been entrapped in the soil organic matter unlike urea-applied N whose greater percentage (92%) could be accounted for.

Introduction

In addition to the nitrogen that is either recovered by an annual crop or retained in the soil at the end of a growing season, significant amount of nitrogen (N) is lost directly or indirectly from both organic materials and mineral fertilizers when applied to the soil. Some of the major processes through which N is lost from the plant–soil system include denitrification, leaching, and volatilization. In addition to the prevailing edaphic and climatic conditions, the management systems also influence these processes that govern nitrogen loss from the soil–plant system in both agricultural and agroforestry systems (Dixon 1995). There is little information on the magnitude of N₂O emissions and N leaching in tropical soils under different management regimes and soil types. Due to the high mobility of nitrogen in the soil, these losses in turn influence uptake by annual crops. Therefore, this study was aimed at providing estimates of nitrogen (N) losses through nitrous oxide (N₂O) emissions and mineral N leaching and uptake by annual crop as well as soil N at the end of a growing season as influenced by the N source.

Some of the pathways through which N is lost in different forms include the following:

Denitrification

This refers to nitrate reduction to gaseous nitric oxide (NO), nitrous oxide (N₂O) or dinitrogen gas (N₂) and this mainly takes place under anaerobic conditions (Babbar and Zak 1996) through several bacteria (Loomis and Connor 1992; Singh and Vaje 1998; Brady and Weil 1999) resulting in a net N loss from the system. These N gas losses can be reduced significantly through better soil and fertilizer management. Lehmann et al. (1999) reported that the rate of N loss was lower with mulches compared to inorganic N source and attributed their findings to microclimate amelioration by the organic material. They also observed higher rates of N loss with application of ammonium sulphate [(NH₄)₂SO₄] fertilizer compared to

Acacia saligna mulches in a study in the dry tropical savanna of northern Kenya. Matson et al. (1998), working on wheat in Mexico, found that a reduction of gaseous loss of N from about 14 kg N ha⁻¹ to almost zero could be attained by improved system management. This depicts that organic inputs can be used to minimize gaseous N losses. However, other studies have shown higher denitrification losses with organic as compared to mineral fertilizers (Janzen and Schaalje 1992). More research to ascertain this is needed especially for different agroecological zones and soil types.

Volatilization

Nitrogen loss in the form of ammonia gas and its volatilization is mainly a soil surface phenomenon that is more pronounced in alkaline environments (Glasener and Palm 1995; Palm et al. 1996; Singh and Vaje 1998). Loomis and Connor (1992) noted that at pH 5.0 and below, about 0.004% of the nitrogen is present as free NH₃ but that fraction increases approximately 10-fold with each unit increase in pH. Thus at pH 9.0, about 40% of the total nitrogen available in form of NH₃ is volatilized. When urea fertilizer is applied to the surface of agricultural soils of pH > 7.0 especially in arid and semi-arid regions, NH₄⁺ formed from urea is deprotonized to form NH₃ gas (Terman 1979; Patra et al. 1996). This NH₃ gas readily diffuses into the atmosphere causing reasonable losses of the urea applied nitrogen. Kumar et al. (1994) quoted by Lehmann et al. (1999) noted considerable reduction in NH₃ losses by application of *Sesbania aculeata* leaves as compared to mineral fertilizer application. Glasener and Palm (1995) found a maximum of 11.8% N loss via volatilization on a soil with pH 4.5. This was reduced to zero with incorporation of the organic materials.

Leaching

Nitrogen applied or fixed into the soil is not all taken up by plants; a large amount is incorporated

into the soil organic matter, lost to the atmosphere as discussed earlier or leached into the ground or surface waters (Di and Cameron 2002). Significant amounts of soil organic nitrogen are also mineralized, which are then taken up by plants, lost to the atmosphere or leached down the soil profile (Kimetu 2002). Nitrogen loss through leaching mainly occurs with increased accumulation of nitrates in the soil profile followed by a period of high drainage. Due to the fast conversion of ammonium to nitrate, the concentration of nitrates is higher than ammonium in most soils. Therefore, because soils are mainly negatively charged, nitrates are loosely held in the soil hence can readily be leached down the profile.

Nitrate leaching and water contamination have become a major concern worldwide. This has been due to intensification of agricultural production involving the application of nitrogen fertilizers (Spalding and Exner 1993; Addiscott 1996; Di and Cameron 2002). Although this problem is more pronounced in the developed countries, rising nitrate concentration in groundwater have also been detected in some regions of developing countries where agricultural production has intensified with increased use of both chemical fertilizer and organic fertilizers (Di and Cameron 2002).

Management options to mitigate leaching of nitrates include: reducing N application rates, synchronizing N supply to plant demand, use of cover crops, better timing of ploughing pasture leys, improved stock management and precision farming (Di and Cameron 2002).

The pathways highlighted above and others like crop harvesting and runoff have been noted to be the principal ways through which about 89% of the N applied in the soil is lost (Peoples et al. 1995). Most annual crops are capable of recovering only about 20–50% of the N applied (Paroda et al. 1994) or lower (Mugendi et al. 2000) depending on the form in which the fertilizer is applied (inorganic or organic). More research is needed to establish the amount of N lost through each of the pathways and work on ways and means of minimizing this loss.

The objective of this study was to investigate the loss of nitrogen (N) through nitrous oxide (N_2O) emissions and mineral N leaching and uptake by annual crop as influenced by the N source.

Materials and methods

Site description

The study was carried out at the National Agricultural Research Laboratories (NARLs) station at Kabete, Kenya which is located at $36^{\circ} 46' E$ and $01^{\circ} 15' S$ and an altitude of 1650 m above sea level. The soils are mainly Humic Nitisols (FAO 1990) that are deep and well weathered. The soil pH is 5.4, total N 1.35 g kg^{-1} , extractable P 27 mg kg^{-1} , carbon 1.6%, exchangeable Ca, Mg, and K (cmol kg^{-1}) 5.8, 1.7, and 0.7 respectively, clay 40%, sand 23%, and silt 37%. The mean annual rainfall is about 950 mm received in two distinct rainy seasons; the long rains (LR) received between mid-March and June, and the short rains (SR) received between mid-October and December. The average monthly maximum and minimum temperature is $23.8^{\circ}C$ and $12.6^{\circ}C$, respectively.

Nitrogen (N) recovery, N losses through N_2O emissions and N leaching were compared from application of *Tithonia diversifolia* (tithonia) green manure or urea, both applied at 60 kg N ha^{-1} . Organic materials (freshly collected leaves of tithonia) were applied at the beginning of the season, broadcasted and incorporated by hand in the top 10 cm of soil prior to planting. Urea was applied according to normal practice (split application); a third of the total amount was applied before planting while two-thirds was applied 5 weeks after planting. This was by broadcasting and incorporating up to about 10 cm depth. The calculation of the application amount of organic materials (that would give 60 kg N ha^{-1}) was done on dry matter basis. The maize variety planted was hybrid 512. The experiment, which was designed and established by TSBF in 1999, consisted of 10 treatments replicated four times (Kimetu et al. 2004). The treatments sampled for N_2O , N leaching and N recovery were tithonia treatment, urea treatment and the control.

Sampling and analyses

Measurements were taken during the second season (2000 long rains which occur between March and June) after two seasons of repeated applica-

tion of N as urea and *Tithonia diversifolia* (tithonia) leaves.

Gas sampling

The three treatments (tithonia, urea and control) each replicated four times were sampled for gas analyses. This was done before treatment application, 1 week, and 4 weeks after treatment application. Plastic chambers with internal diameter of 30.5 cm and a height of 10 cm were used for measuring gas fluxes. The top of each chamber had a brass-sampling valve fitted with a teflon septa. A base was constructed using polyvinylchloride (PVC) tubes about 6 cm in height where one end was expanded to enable the chamber to fit tightly. The bases were driven to a depth of 3 cm in the soil 24 h before gas sampling to ensure that disturbed soil had settled (Puget and Drinkwater 2001). At the beginning of each sampling period the chamber was placed into the permanent PVC base. A hole was opened in the chamber's top during placement to avoid creating over-pressure, a rubber bung was placed in the hole once the chamber was situated in the permanent base. Samples were collected from the chamber headspace with 50 ml polypropylene syringes at 0, 10, 20, and 40 min following chamber closure. Thirty milliliters of each sample was injected into 20 ml evacuated glass vials (Labco Exetainer). The vials sampled were properly labeled with plot descriptions and time of sampling and then sent to USDA/ARS laboratory in Fort Collins, CO, USA and analyzed by gas chromatography. Nitrous oxide (N₂O) was analyzed by electron capture detector (ECD) (Matson and Harriss 1995).

0.7. Using the slopes (D_y) of the lines (concentration versus time), the fluxes were calculated as:

$$\text{N}_2\text{O flux} = D_y * 7027.2$$

The above calculations assumed a standard pressure (1 atm.) and standard temperature of 20 °C or 293 K, therefore, corrections for pressure and temperature were made as follows (Source: Matson and Harriss 1995):

$$\text{Flux (corrected)} = \text{Gas flux}$$

$$* \frac{[\text{Pressure (bars)}/1.013]}{[\text{Temperature (K)}/293]}$$

Nitrogen uptake

Nitrogen uptake by the maize crop was determined at the end of the growing season. N uptake was calculated by multiplying the grain, stover and core (husk) yields with the nitrogen concentration in the specific components. Analysis was done on grain and stover samples for total N by Kjeldahl digestion with concentrated sulfuric acid (Anderson and Ingram 1993; ICRAF 1995). The nitrogen concentration in the core was estimated from the values obtained from the stover samples. This is because, earlier research by Gachengo (unpublished data and personal communication) revealed that the nutrient contents in the stover were almost similar to concentrations of the same nutrients in the core. Mugendi (1997) also observed the same in his study in the subhumid highlands of Kenya.

Nitrogen recovery was determined as shown below:

$$\text{Nitrogen recovery (\%)} = \frac{(\text{Nitrogen uptake}_{\text{treatment}} - \text{Nitrogen uptake}_{\text{control}})}{\text{Amount of nitrogen applied}} \times 100$$

Gas analyses

To determine nitrous oxide emission in the different treatments, the following procedure was used:

Gas concentrations in parts per million (ppm) were plotted against time (0, 10, 20, and 40 min) for each chamber. The four replicates were plotted in one graph. The out-liers were eliminated where necessary to obtain an R^2 of the fitted line of above

Soil sampling and analyses

Soil N availability and movement: Soil N dynamics, both in terms of N availability in the topsoil and N movement through the profile were determined by consecutive soil samplings through the cropping season. At the end of the season, control, tithonia and urea treatments were sampled up to 180 cm depth for mineral N (NH₄⁺ and NO₃⁻)

determination at different depths (0–10, 10–30, 30–60, 60–90, 90–120, 120–150 and 150–180 cm). This enabled determination of N dynamics down the soil profile. Soil moisture content was determined and the values used in the calculation of mineral N content in the soil. Soil extraction was done by shaking about 20 g of soil in 125 ml bottles for 1 h in 100 ml of 2 N KCl (ICRAF 1995). The extract was filtered through Whatman paper (no. 5). The filtrates were then analyzed for extractable nitrate by cadmium (Cd) reduction column method (Anderson and Ingram 1993; ICRAF 1995) and for extractable ammonium using colorimetric method (ICRAF 1995).

The effects of treatment on gas fluxes and N leaching were determined separately for each experiment using Genstat 5 for windows (Release 4.1). Treatment means found to be significantly different from each other were separated by least significant differences (LSD) at $p \leq 0.05$.

Results and discussion

Treatment effects on nitrous oxide emissions

Missing out the second split of the urea application might limit any concrete conclusion on the amount of N lost through N₂O emission in the present study. Nevertheless the study reveals some intrinsic facts about N₂O flux with organic input versus synthetic fertilizer inputs as highlighted below.

Nitrous oxide (N₂O) emissions differed significantly with sampling time in tithonia fertilized plots. The range was as low as $-0.3 \mu\text{g N m}^{-2} \text{h}^{-1}$ (before treatment application) and as high as

$12.3 \mu\text{g N m}^{-2} \text{h}^{-1}$ (4 weeks after application) (Table 1). Urea treatment did not show any significant difference between the three sampling periods (before treatment application, 1 week and 4 weeks after application). This was also true with the control.

There was no significant difference in nitrous oxide flux between tithonia and urea treatments before treatment application and one week after application. The amount of N₂O emitted from tithonia treatment one week after treatment application was about $2.4 \mu\text{g m}^{-2} \text{h}^{-1}$ while N₂O emission in urea treatment was $2.9 \mu\text{g m}^{-2} \text{h}^{-1}$.

At four weeks after treatment application, there was significant difference in N₂O emission between tithonia and urea treatments (Table 1). The rate of N₂O emission in tithonia treatment was $12.3 \mu\text{g m}^{-2} \text{h}^{-1}$ as compared to urea treatment which emitted at the rate of $1.3 \mu\text{g m}^{-2} \text{hr}^{-1}$. The relatively lower N₂O emissions in urea treatment could be attributed to split application of the mineral fertilizer. Palm et al. (1997) reported relatively large amounts of N losses from sole application of high quality organic materials as compared to mineral fertilizer alone. Thus, a better option (than the use of either organic or mineral fertilizer alone) could be the use of high quality organics as partial substitution for synthetic fertilizers.

The relatively higher N₂O emissions in the green manure treatment as compared to synthetic fertilizer treatment could be attributed partially to the incorporation of the green manure leaves which promoted high levels of nitrate and available carbon in the soil enhancing denitrification (Janzen and Schaalje 1992). Xu et al. (1993) and Jones et al. (1997) reported

Table 1. Treatment effects on N₂O fluxes at, Kabete, Kenya, 2000.

Treatment	N rate (kg N ha ⁻¹)	Nitrous oxide (N ₂ O) flux ($\mu\text{g m}^{-2} \text{h}^{-1}$)			
		T0	1WAP	4WAP	Lsd _{0.05}
Control	0	1.7	1.2	7.3	11.2
Tithonia	60	-0.3	2.4	12.3	5.4
Urea	20	0.6	2.9	1.3	8.8
Lsd _{0.05}	NA	8.0	3.2	9.4	–

Note. Only 20 kg N ha⁻¹ of urea had been applied at the time of the gas sampling; 40 kg N ha⁻¹ was applied at 5 weeks after planting (1 week later).

Abbreviations. T0, before treatment application; WAP, week(s) after treatment application.

higher losses of N through denitrification when the material is incorporated compared to surface application.

Nitrogen uptake and total %N recovery by maize

Results obtained at the end of the maize growing season revealed that nitrogen concentrations in the grain, stover and core yields differed significantly ($p \leq 0.05$) between the different treatments (Table 2). Nitrogen uptake ranged from 86.3 to 131.9 kg ha⁻¹. Urea treatment gave the highest N uptake while control had the lowest. Total N uptake in the above ground yield from urea sole application was 45.6 kg ha⁻¹ higher than in control plots. This relatively high N uptake from urea treatment could be attributed to the readily available N from the urea. The N uptake by maize that received tithonia green biomass alone as N source was about 119.6 kg ha⁻¹, which was not significantly different from the control.

Nitrogen recovery by the maize crop that received urea was significantly higher compared to nitrogen recovered by maize that received only tithonia green biomass. The apparent percentage N recovery by maize crop that received only tithonia green biomass was 55.5% while urea treatment had 84.7% nitrogen recovery. Other researchers working on different N sources (organic inputs and synthetic inputs) also reported a percentage N recovery ranging from 25% to 111% (Westerman et al. 1972; Kruijs et al. 1988; Christianson et al. 1990; Gachengo et al. 1999; Rees and Castle 2002). The high N recovery by maize crop planted with sole urea was an indication that there

was less N loss from soil–plant system. Therefore, the growing maize crop took up a large percentage of the N supplied by either the synthetic or organic inputs. Nitrogen recovery by annual crops can vary widely depending on biophysical conditions, but is generally thought to be low for organic inputs. Giller and Cadisch (1995) suggest that for most organic inputs, this can be about 20% and in some cases up to 25% when high quality organic materials like tithonia is used as N source (Gachengo et al. 1999). However N recovered from the tithonia-treated plots in the present study was 55.5% which is relatively higher compared to earlier studies by other researchers (Gachengo et al. 1999). This could partially be explained by the residual effect from a previous season which is not discussed in this study or difference in biophysical factors like rainfall and soil type which could influence nutrient uptake by crop and loss from the plant–soil system.

From this study, it was also noted that, grain yield accounted for a greater portion of the recovered N than either stover yield or the core. This was also noted by Mugendi et al. (2000) in their work in the sub-humid highlands of Kenya. N recovery value from the urea applied maize agrees with the findings of Chabrol et al. (1988) in a study in Bedfordshire, England as well as what Mugendi et al. (1999) found out in their studies in the subhumid highlands of Kenya.

Mineral N leaching at the end of the season as influenced by the N source

Soil mineral N movement down the soil profile was also investigated at the end of the season and

Table 2. Nitrogen added, total aboveground nitrogen uptake, and nitrogen recovery by maize crop (2000) at NARL, Kabete, Kenya.

Treatment	N applied (kg N ha ⁻¹)	Nitrogen uptake (kg ha ⁻¹)	%N		Total %N recovery
			Grain	Stover	
Control	0	86.3	1.7	0.63	N/A
Tithonia	60	119.6	1.8	0.8	55.5
Urea	60	131.9	2.0	1.1	76.0
Lsd _{0.05}	N/A	41.0	–	–	N/A

Note. This sampling was done at the end of the season and the second urea spilt urea had been applied giving a rate of 60 kg ha⁻¹. Calculated total %N recovery values obtained in the study were meant to be estimates to the actual recoveries because the material used were unlabeled.

the results revealed significantly higher mineral N content in urea treatment as compared to control and tithonia treatments (Figure 1). This was evident at different layers up to the depth of about 100 cm and could be attributed to leaching of the applied urea N down the soil profile. This was because during this season adequate rainfall was received thus, providing enough water to percolate down the soil profile hence washing down of the soil loosely held nitrate-N to lower layers (Singh and Vaje 1998). At 20 cm depth, soil mineral nitrogen was about 3.6 mg kg^{-1} higher in urea treatment compared to tithonia treatment while at 75 cm depth this difference increased to about 4.5 mg kg^{-1} . This could be as a result of leaching of the nitrate N (Hagedorn et al. 1997).

At depth lower than 100 cm, no significant treatment differences were noted in the mineral N content.

The relatively lower mineral N content in tithonia treatment as compared to urea treatment down the soil profile was an indication of lower rate of N leaching when tithonia green biomass is used as N source as compared to the use of urea. As shown in Table 3, the use of tithonia biomass however is not an assurance of zero N leaching but could help in reducing the rate of N leached. As

noted by Di and Cameron (2002), in organic farming systems, the lack of chemical N fertilizer use would lead to lower N leaching loss. Therefore, farmers could be encouraged to engage in more of organic farming with the use of organic resources like tithonia green biomass to lower N losses through leaching.

Mineral N in the top soil at the end of the season at Kabete, Kenya, 2000

At the end of the season, the mineral nitrogen that remained in the soil at 10 cm depth soil was highly depended on the treatment (Figure 2). Results indicated that the separate application of the different N sources (tithonia or urea) had significantly different levels of influence on mineral N content in the soil. Urea had the highest mineral N content (8.2 mg kg^{-1}) followed by tithonia sole application with 6.7 mg kg^{-1} while control treatment had the lowest mineral N content (3.9 mg kg^{-1}). The relatively higher mineral N content in the urea treatment might be partially explained by the split application of the urea. This could be an indication that all the urea applied in the second split was not full utilized by the maize.

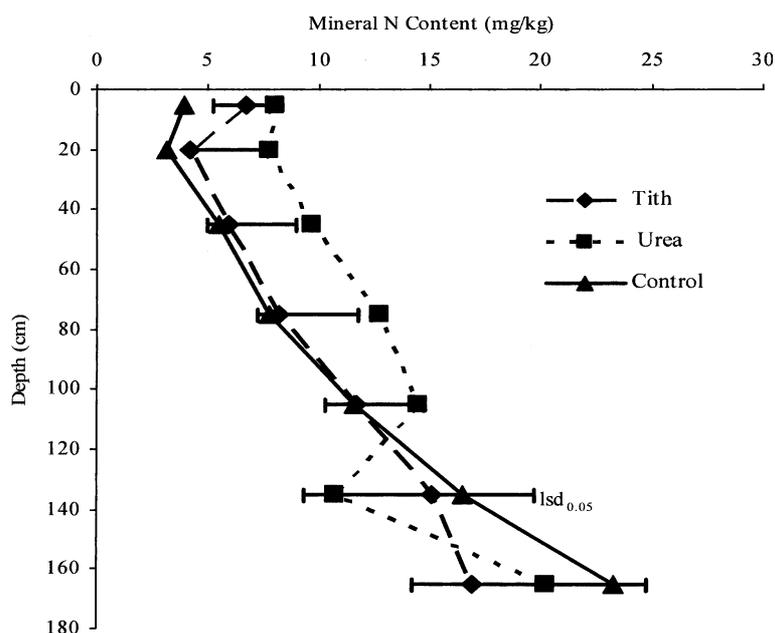


Figure 1. N dynamics down the soil profile – End of 2000 long rain season at NARL, Kabete, Kenya.

Table 3. Nitrogen balance sheet after a maize cropping season at Kabete, Kenya, 2000.

Treatment	Control	Tithonia	Urea	Lsd _{0.05}
N applied (kg ha ⁻¹)	0	60	60	–
Nitrogen lost through leaching (at 70–80 cm depth) (kg ha ⁻¹)	8.6	9.0 (0.4)	14.0 (5.4)	4.6
N lost through nitrous oxide emission at 4WAP (kg ha ⁻¹) per year	0.64	1.10 (0.5)	0.11 (–0.5)	0.8
N recovered by the maize crop (kg ha ⁻¹)	86.3	119.6 (33.3)	131.9 (45.6)	41.0
Mineral N remaining in the top 10 cm soil layer (kg ha ⁻¹)	4.3	7.4 (3.1)	9.0 (4.7)	3.4
N accounted for (kg ha ⁻¹)	99.8	137.1 (37.3)	155.0 (55.2)	–
N not accounted for (kg ha ⁻¹)	–	22.7	4.8	–

Values in parenthesis are net values relative to the control.

Mineral N content available in the soil before the start of the experiment was 17.6 kg ha⁻¹.

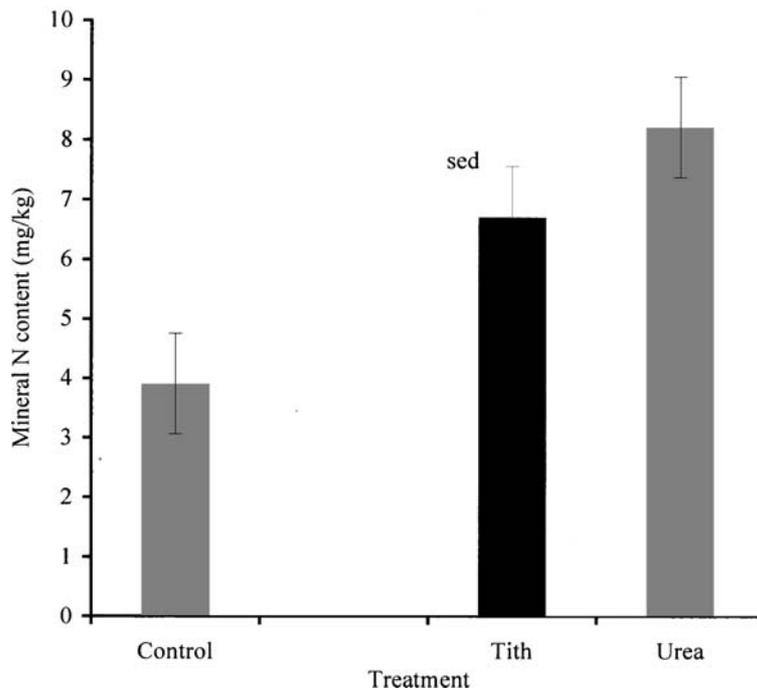


Figure 2. Treatment effect on soil mineral N at the end of 2000 long rains season at 10 cm depth at NARL, Kabete, Kenya.

N budgets at Kabete, Kenya, 2000

Nitrogen lost through leaching in *Tithonia diversifolia* treatment was only 0.4 kg N ha⁻¹ above control treatment which represent 0.7% of the applied N while N loss in urea treatment was 5.4 kg N ha⁻¹ above control representing 9.0% of the applied N (Table 3). This was an indication that more N was being lost through leaching in urea treatment compared to tithonia treatment as already discussed in an earlier section.

Nitrogen loss through nitrous oxide emission was relatively higher with the application of tithonia while urea had relatively lower losses. This could be attributed to the split application of urea. Only 20 kg N ha⁻¹ had been applied at four weeks after planting (4WAP). This was an indication that the use of tithonia green biomass as a source of nitrogen could not be considered as a way for reducing N loss through nitrous oxide (N₂O) emission due to the one-time application practice for the green manure. A possible alternative could

be split application of the green manure but more research is needed to ascertain such a hypothesis. However, missing out the second split of the applied urea in this study limits a concrete conclusion as mentioned earlier.

Maize crop fertilized with tithonia recovered 33.3 kg ha⁻¹ above control which represent 55.5% of the applied N while maize fertilized with urea was able to recover 45.6 kg ha⁻¹ (76% of the applied N). The relatively lower N recovery rate from the tithonia biomass could partially be attributed to the lack of synchrony between N demand by the maize crop and the N released by the decomposing biomass (Mugendi et al. 2000). Urea treatment had the highest amount of mineral N left in the top 10 cm soil (4.7 kg ha⁻¹ above control) while tithonia treatment had 3.1 kg ha⁻¹ above control treatment left in the top 10 cm soil.

Out of this study, we were able to account for 92% of the urea applied N and 62.2% of the tithonia applied N. The decomposition of the tithonia biomass may have led to N retention in soil organic forms that are resistant to rapid mineralization (Haggard et al. 1993; Mugendi et al. 2000) hence relatively lower N accounted for in the tithonia biomass compared to urea treatment. In this study, only the mineral N was determined as remaining in the soil however there was a possibility of some of the applied N being entrapped into the organic N pool. In their studies using *Calliandra calothyrsus* and *Leucaena leucocephala* in the humid highlands of Kenya, Mugendi et al. (2000) found out that close to 60% of N in the applied tree biomass was left in the soil N pool while about 25% could not be accounted for.

Conclusions

In this study, we were able to account for 92% of the urea-applied N and 62.2% of the tithonia-applied N. A greater percentage of the applied N both as tithonia and as urea was recovered by the maize crop. This accounted for 55.5% and 76% of the tithonia-applied N and urea-applied N respectively. Only 0.7% of the tithonia-applied N was leached down the soil profile and 9% from the urea-applied N while about 0.8% of the tithonia-applied N was observed in nitrous oxide emission and virtually no N loss observed in urea-applied plots through nitrous oxide emission. About 5.2%

of the tithonia-applied N was left in the top 0–10 cm soil layer while 7.8% was left in the urea-applied plots. We were not able to account for 37.8% and 8% of the tithonia-applied N and the urea-applied N respectively. More research is needed for long term evaluation on the effect of different nitrogen sources on N losses through N₂O emissions and leaching as well as N recovery by annual crops in the tropical farming systems.

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References

- Addiscott T.M. 1996. Fertilizers and nitrate leaching. In: Hester R.E. and Harrison R.M. (eds), *Agricultural Chemicals and the Environment. Issues in Environmental Science Technology*, Vol. 5, pp. 1–26.
- Anderson J.M. and Ingram J.S.L. 1993. *Tropical Soil Biology and Fertility: A Handbook of Methods*. CAB International, Wallingford, UK.
- Babbar L.I. and Zak D.R. 1996. Nitrogen losses from coffee agroecosystems in Costa Rica: leaching and denitrification in the presence and absence of shade trees. *J. Environ. Qual.* 24: 227–233.
- Brady N.C. and Weil R.R. 1999. *The Nature and Properties of Soils*, 12th ed. Prentice-Hall, Inc., New Jersey.
- Christianson C.B., Bationo A., Henao J. and Vlek P.L.G. 1990. Fate and efficiency of N fertilizers applied to millet in Niger. *Plant Soil* 125: 221–231.
- Di H.J. and Cameron K.C. 2002. Nitrate leaching in temperate agroecosystems: sources, factors and mitigating strategies. *Nutr. Cycl. Agroecosyst.* 46: 237–256.
- Dixon R.K. 1995. Agroforestry systems: sources or sinks of greenhouse gases? *Agroforest. Syst.* 31: 99–116.
- FAO (Food and Agriculture Organization) 1990. *New Environmental Threat: Declining Soil Fertility*. Land and Water Technical Newsletter.
- Gachengo C.N., Palm C.A., Jama B. and Otieno C. 1999. Tithonia and senna green manures and inorganic fertilizers as phosphorus sources for maize in Western Kenya. *Agroforest. Syst.* 44: 21–36.
- Giller K.E. and Cadisch G. 1995. Future benefits from biological nitrogen fixation: an ecological approach to agriculture. *Plant Soil* 174: 255–277.

- Glasener K.M. and Palm C.A. 1995. Ammonia volatilization from tropical legume mulches and green manures on unlimed and limed soils. *Plant Soil* 177: 33–41.
- Hagedorn F., Steiner K.G., Sekayange L. and Zech W. 1997. Effect of rainfall pattern on nitrogen mineralization and leaching in a green manure experiment in South Rwanda. *Plant Soil* 195: 365–375.
- Haggar J.P., Tanner E.V.J., Beer J.W. and Kass D.C.L. 1993. Nitrogen dynamics of tropical agroforestry and annual cropping systems. *Soil Biol. Biochem.* 25: 1363–1378.
- ICRAF 1995. Laboratory Methods for Soil and Plant Analysis: Version 1.1. Nairobi.
- Janzen H.H. and Schaalle G.B. 1992. Barley response to nitrogen and non-nutritional benefits of legume green manure. *Plant Soil* 142: 19–30.
- Jones R.B., Snapp S.S. and Phombeya H.S.K. 1997. Management of leguminous leaf residues to improve nutrient use efficiency in the sub-humid tropics. In: Cadisch G. and Giller K.E. (eds), *Driven by Nature: Plant Litter Quality and Decomposition*. CAB Int., Wallingford, England, pp. 239–250.
- Kimetu J.M. 2002. Nitrogen fertilizer equivalency values for organic materials of contrasting qualities based on maize performance at Kabete, Kenya. M.Env.S Thesis, Kenyatta University, Nairobi, Kenya, 74 p.
- Kimetu J.M., Mugendi D.N., Palm C.A., Mutuo P.K., Gachengo C.N., Bationo A., Nandwa S. and Kungu J.B. 2004. Nitrogen fertilizer equivalencies of organic materials of differing quality and optimum combination with inorganic nitrogen sources in Central Kenya. *Nutr. Cycl. Agroecosyst.* J. 68: 127–135.
- Kruijs A.C.B.M., van Wong M.T.F., Juo A.S.R. and Wild A. 1988. Recovery of ¹⁵N-labelled fertilizer in crops, drainage water and soil using monolith lysimeters in south-east Nigeria. *J. Soil Sci.* 39: 483–492.
- Kumar K.A., Menon P.K.G. and Sivakumar C. 1994. Effect of nitrogen management practices on ammonia volatilization losses in transplanted rice. *J. Trop. Agric.* 32: 54–59.
- Lehmann J., Feilner T., Gebauer G. and Zech W. 1999. Nitrogen uptake of sorghum (*Sorghum bicolor* L.) from tree mulch and mineral fertilizer under high leaching conditions estimated by nitrogen-15 enrichment. *Biol. Fertil. Soils* 30: 90–95.
- Loomis R.S. and Connor D.J. 1992. *Crop Ecology: Productivity and Management in Agricultural systems*. Cambridge University Press, Cambridge.
- Matson P.A. and Harriss R.C. (eds) 1995. *Biogenic Trace Gases: Measuring Emissions from soil and water*. Blackwell Science Ltd, Oxford OX2 OEL.
- Matson P.A., Naylor R. and Ortiz-Monasterio I. 1998. Integration of environmental, agronomic, and economic aspects of fertilizer management. *Science* 280: 112–114.
- Mugendi D.N. 1997. *Tree Biomass decomposition, Nitrogen Dynamics and Maize growth under agroforestry conditions in the sub-humid highlands of Kenya*. PhD Thesis, University of Florida, Gainesville, Florida, USA.
- Mugendi D.N., Nair P.K.R., Mugwe J.N., O'Neill M.K., Swift M.J. and Woome P. 1999. Alley cropping of maize with Calliandra and Leucaena in the Sub-humid highlands of Kenya. Part 2: Biomass decomposition, N mineralization, and N uptake by Maize. *Agroforestry Syst.* 46: 51–64.
- Mugendi D.N., Nair P.K.R., Graetz D.A., Mugwe J.N. and O'Neill M.K. 2000. Nitrogen recovery by alley-cropped maize and trees from ¹⁵N-labeled tree biomass in the sub-humid highlands of Kenya. *Biol. Fertil. Soils* 31: 97–101.
- Palm C.A., Myers R.J.K. and Nandwa S.M. 1997. Combined use of organic and inorganic nutrient sources for soil fertility maintenance and replenishment. In: Buresh R.J. and Sanchez P.A. (eds), *Replenishing Soil Fertility in Africa* SSSA spec. Publ. 51. SSSA, Madison, WI.
- Paroda R.S., Woodhead T. and Singh R.B. (eds) 1994. *Sustainability of Rice–Wheat Production Systems in Asia*. Science Publishers, Lebanon.
- Patra A.K., Burford J.R. and Rego T.J. 1996. Volatilization losses of surface-applied urea nitrogen from Vertisols in the Indian semi-arid tropics. *Biol. Fertil. Soils* 22: 345–349.
- Peoples M.B., Freney J.R. and Mosier A.R. 1995. Minimizing gaseous losses of nitrogen. In: Bacon P.E. (ed.), *Nitrogen Fertilization in the Environment*. Marcel Dekker, Inc., New York.
- Puget P. and Drinkwater L.E. 2001. Short-term dynamics of root- and shoot-derived carbon from a leguminous green manure. *Soil Sci. Soc. Am. J.* 65: 771–779.
- Rees R. and Castle K. 2002. Nitrogen recovery in soils amended with organic manures combined with inorganic fertilizers. *Agronomie* 22: 739–746.
- Singh B.R. and Vaje P.I. 1998. Sustainable management of nitrogen in East Africa. *J. Sustain. Agric.* 13: 59–77.
- Spalding R.F. and Exner M.E. 1993. Occurrence of nitrate in ground water – a review. *J. Environ. Qual.* 22: 392–402.
- Terman G.L. 1979. Volatilization losses of nitrogen as ammonia from surface-applied fertilizers, organic amendments and crop residues. *Adv. Agron.* 41: 189–223.
- Westerman R.L., Kurtz L.T. and Hauck R.D. 1972. Division s-4 – soil fertility and plant nutrition: recovery of ¹⁵N-labeled fertilizers in field experiments. *Soil Sci. Soc. Am. Proc.* 36: 82–86.
- Xu Z.H., Saffigna P.G., Myers R.J.K. and Chapman A.L. 1993. Nitrogen cycling in leucaena (*Leucaena leucocephala*) alley cropping in semi-arid tropics: II. Response of maize growth to addition of nitrogen fertilizer and plant residues. *Plant Soil* 148: 73–82.