Soil Inorganic N and N Uptake by Maize Following Application of Legume Biomass, Tithonia, Manure and Mineral Fertilizer in Central Kenya

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Abstract In the smallholder farms of central Kenya soils suffer from nitrogen (N) deficiency due to inability to replenish it through application of chemical fertilizers and/or manure. This study evaluated the effect of some organic materials such as *Mucuna pruriens*, *Crotalaria ochroleuca*, *Calliandra calothyrsus*, *Leucaena trichandra*, cattle manure and *Tithonia diversifolia* applied solely or combined with inorganic fertilizer on soil mineral N dynamics and N uptake by maize. Soils and maize samples were taken at 0, 2, 4, 6, 8, 12, 16 and 20 weeks after planting maize (WAP) during 2002 long rain (LR) and 2004 LR seasons and analysed. The study showed that amounts of soil inorganic N and uptake of N by maize varied among the different sampling dates, treatments and between seasons. There was a general increase of mineral N after the start of the season followed by a drastic reduction during 6 and 4 WAP during 2002 and 2004 LR, respectively. This trend was attributed to the decomposition of organic materials at the beginning of the season followed by leaching due to intense rainfall during this period. Treatments that had tithonia, leucaena and calliandra applied recorded the highest amounts of soil inorganic N and also the highest N uptake by maize. Poor rainfall in 2004 LR restricted N uptake and was responsible for lower N uptake by maize in 2002 LR than in 2004 LR. At the end of the growing season, there were high amounts of mineral N at 100–150 cm soil depth that was probably due to leaching. This mineral N is below the rooting zone of most maize plants, consequently not available to maize crop and is therefore of concern.

Keywords Organic materials · Inorganic fertilizer · Soil mineral N · Uptake of N by maize

Introduction

One of the greatest biophysical constraints to increasing agricultural productivity in Africa is low soil fertility (Sanchez et al., 1997). The need to improve soil fertility management has therefore become a very important issue in the development policy agenda because of the strong linkage between soil fertility and food security on the one hand and the implications on the economic well-being of the population on the other. Declining soil fertility in central highlands of Kenya due to intensive cultivation without adequate soil nutrient replenishment has resulted in low returns to agricultural investment, decreased food security and general high food prices (Odera et al., 2000). Though the area has high potential for food production because of favourable seasonal precipitation, many of the soils are deficient in nutrients, particularly nitrogen (N) and phosphorus (P).

Nitrogen is one of the major plant nutrients and in the soil is broadly subdivided into organic and inorganic forms. Inorganic N is available for plant uptake while organic forms slowly become available for plant uptake through microbial decomposition and mineralization. Mineralization involves the microbial conversion of organic N into soil inorganic N or mineral N. The principal forms of inorganic N in soils are ammonium (NH_4^+) and nitrate (NO_3^-) and any nitrogen in

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the soil that is available to the crop is almost always in one of the two forms (Barrios et al., 1998). Both nitrate-N and ammonium-N may be recycled within the soil biota, taken up by the crop, retained within the soil matrix or lost through leaching, volatilization, nitrification and denitrification processes. In central highlands of Kenya the rate of N loss through soil erosion, leaching and crop harvests is higher than the rate of replenishment resulting in negative balances and severe N deficiencies in most of the soils. Farmers usually lack the financial resources to replenish N through mineral fertilizers (Mugwe et al., 2004). The few farmers who use inorganic N fertilizers apply them at very low rates of 15–25 kg N ha^{-1} (Kihanda, 1996).

Options for replenishing N are therefore receiving a lot of attention from scientists and include the use of organic materials such as agroforestry trees, leguminous cover crops and animal manures. The quantity of organic materials is, however, inadequate at the farm level and in the recent past there has been increased interest in devising ways of optimizing nutrient availability by combining the use of organic and inorganic N resources. The use of organic materials and their combinations with fertilizer to optimize nutrient availability to annual crops presents a challenge. This is because mineralization, which is dependent upon the quality of organic materials, environmental factors and proportions (Palm et al., 2001), will have to occur in order to release inorganic N into the soil before plant can utilize. Research in western Kenya showed that organic materials increased soil inorganic N and N mineralization in the plow layer (0–15 cm depth) compared with continuous unfertilized maize (Barrios et al., 1997). These measures of soil N availability were significantly lower following tree legumes with fast decomposing litter than with slow decomposing litter as assessed from the (lignin + polyphenol)/N ratio in their leaves (Barrios et al., 1997). Nitrogen uptake by the crop is also influenced by the quality of organic materials applied to the soil. In the central highlands of Kenya, organic materials being introduced include herbaceous legumes, biomass of leguminous trees and livestock manure, all of which have varying qualities in terms of C:N ratio and the content of polyphenols. An understanding of how these different organic materials will influence soil inorganic N availability and subsequent uptake by the crops would help provide strategic management guidelines for optimizing N utilization in farming systems, in the region and elsewhere, that use organic materials to replenish soil fertility. Such information is scanty, especially in the central highlands of Kenya where only limited studies have been undertaken. This study sought to monitor amounts of soil inorganic N within a growing season and associated N uptake by maize following application of selected organic materials applied solely or combined with inorganic fertilizer.

Research Methodology

The Study Area

The study was conducted in Chuka division of Meru South District of Kenya. Meru South District lies between latitudes 00°03′47•N and 0°27′28•S and longitudes 37°18′24•E and 28°19′12•E. Meru South District covers an area of 1032.9 km^2 and Chuka division covers an area of 169.6 km^2. According to agro-ecological conditions (based on temperature and moisture supply), the area lies in the Upper Midland Zone (UM2-UM3) (Jaetzold et al., 2006) on the eastern slopes of Mt. Kenya at an altitude of 1500 m above sea level with an annual mean temperature of 20°C and a total bimodal rainfall of 1200–1400 mm. The rainfall is in two seasons: the long rains (LR) lasting from March through June and short rains (SR) from October through December. The soils are mainly humic Nitisols (Jaetzold et al., 2006), which are deep, well weathered with moderate to high inherent fertility. The district is a predominantly maize growing zone with small land sizes ranging from 0.1 to 2 ha with an average of 1.2 ha per household.

The area is characterized by rapid population growth, low agricultural productivity, increasing demands on agricultural resources and low soil fertility (GOK, 2001). The main cash crops are coffee (*Coffea arabica* L.) and tea (*Camelina sinensi* (L.) O. Kuntze) while the main staple food crop is maize (*Zea mays* L.), which is cultivated from season to season mostly intercropped with beans (*Phaseolus vulgaris* L.). Other food crops include potatoes (*Ipomea batatas* (L.) Lam), bananas (*Musa* spp. L.) and vegetables that are mainly grown for subsistence consumption. Livestock production is a major enterprise, especially dairy cattle that is of improved breeds. Other livestock in the area include sheep, goats and poultry.

Before planting, soil characterization was carried out. The soil was sampled in March 2000 at 0–15 cm depth and analysed for pH, exchangeable magnesium (Mg), calcium (Ca), potassium (K), available phosphorus (P), total organic carbon (C) and total nitrogen (N). All the analyses were carried out at the International Centre for Research in Agroforestry (ICRAF) laboratories using procedures outlined in the ICRAF laboratory manual (ICRAF, 1995; Anderson and Ingram, 1993). The results showed that pH of the soil was 5.2 while total N and C was 0.21 and 1.8%, respectively. Available P was 7.1 Cmol kg^{-1}, K was 0.3 Cmol kg^{-1}, Ca was 3.4 Cmol kg^{-1} and Mg was Cmol kg^{-1}.

Table 1 Treatments in the experiment at Kirege School, Chuka, Kenya

Treatment	Amount of N supplied (kg ha^{-1}) Organic	Inorganic
Mucuna pruriens alone	[a]	0
Mucuna + 30 kg N ha^{-1}	[a]	30
Crotalaria ochroleuca alone	[a]	0
Crotalaria + 30 kg N ha^{-1}	[a]	30
Cattle manure alone	60	0
Cattle manure + 30 kg N ha^{-1}	30	30
Tithonia diversifolia	60	0
Tithonia + 30 kg N ha^{-1}	30	30
Calliandra calothyrsus	60	0
Calliandra + 30 kg N ha^{-1}	30	30
Leucaena trichandra	60	0
Leucaena + 30 kg N ha^{-1}	30	30
Recommended rate of fertilizer	0	60
Control (no inputs)	0	0

[a] Total N applied varied among seasons and depended on the amount of biomass produced during the previous season

Experiment Establishment and Management

This study was carried out in an experiment that had been established in March 2000 in Chuka division, Meru South District. The experiment had 14 treatments comprising 6 organic resources applied solely or combined with inorganic fertilizer, inorganic fertilizer and a control. The organic resources were two herbaceous legumes *Mucuna pruriens* and *Crotalaria ochroleuca* (intercropped with maize); two leguminous shrubs *Calliandra calothyrsus*, *Leucaena trichandra* (biomass transfer); cattle manure; and *Tithonia diversifolia* (biomass transfer) (Table 1). The experiment was a completely randomized block design with three replications. Plot sizes measured 6 m × 4.5 m and maize was planted at a spacing of 0.75 and 0.5 m inter- and intra-row spacing, respectively. Compound fertilizer (23:23:0) was the source of inorganic N and was applied at sowing during the four seasons. A uniform P application was done in all the plots at the recommended rate (60 kg P ha^{-1}) as triple superphosphate (TSP). Other agronomic procedures for maize production were appropriately followed after planting.

The herbaceous legumes (*Mucuna* and *Crotalaria*) were intercropped between two maize rows 1 week after planting maize. After maize was harvested, legumes were left to grow in the field till land preparation for the subsequent season when they were harvested, weighed, chopped and incorporated into the soil to a depth of 15 cm. The weight of the herbaceous legume biomass applied during the study period varied across the seasons (Table 2). The amount of N contributed into the soil via the incorporated biomass was calculated by multiplying the amount of biomass (kg) with N concentration in the biomass (%).

The other organic materials (calliandra, leucaena, tithonia and cattle manure) were incorporated into the soil to a depth of 15 cm during land preparation. Nitrophosphate fertilizer (23:23:0) was the source of inorganic N and was applied at sowing during the four seasons. A blanket application of P at 60 kg N ha^{-1} was applied to all the plots to prevent P deficiency, which was observed at the start of this experiment. Other agronomic procedures for maize production were appropriately followed after planting. Subsamples of all organic materials were collected uniformly at the beginning of each season and analysed. The samples were first washed with distilled water and oven dried at 65°C for 48 h. Samples were ground, packed in polythene bags and stored under dry conditions before N was determined at ICRAF laboratories (ICRAF, 1995; Anderson and Ingram, 1993). The dry plant samples were analysed for total N, P, K, Ca and Mg by Kjeldahl digestion with concentrated sulphuric acid (Anderson and Ingram, 1993). Nitrogen and phosphorus were determined colorimetrically while potassium was by flame photometry (Okalebo et al., 2002). Magnesium and calcium was by atomic absorption spectrophotometer (Anderson

Table 2 Amount of herbaceous legumes produced and their N contribution in the soil during 2002 LR to 2003 SR at Chuka, Kenya

Treatment	2002 LR	2002 SR	2003 LR	2003 SR	2004 LR	Average	Mean N kg ha^{-1} $season^{-1}$
	……Biomass in t ha^{-1} $season^{-1}$……						
Mucuna	1.7	2.8	0.8	0.2	0.3	1.16	28.6
Mucuna + 30 kg N ha^{-1}	1.9	3.2	0.9	0.3	0.9	1.44	37.7
Crotalaria	2.3	2.3	0.6	0.2	0.6	1.2	33.8
Crotalaria + 30 kg N ha^{-1}	2.8	2.5	0.8	0.3	0.7	1.42	39.1
SED	0.19	0.17	0.11	0.11		0.08	

Table 3 Average nutrient composition (%) of organic materials applied in the soil during the study period

Treatment	N	P	Ca	Mg	K	Ash
Cattle manure	1.3	0.2	1.0	0.4	1.8	45.9
Tithonia	3.2	0.2	2.1	0.6	3.0	13.0
Calliandra	3.3	0.2	1.0	0.4	1.2	5.9
Leucaena	3.6	0.2	1.4	0.4	1.8	8.5
SED	0.4	0.004	0.04	0.01	0.05	0.27

and Ingram, 1993). Table 3 shows the mean nutrient composition of organic materials used during the four seasons under study.

Soil Sampling and Determination of Soil Inorganic Nitrogen

Soil samples were taken in March 2002 and 2004 at the beginning of the season (before planting) at 0–15 cm depth. Subsequent samples were taken at 4, 6, 8, 12, 16 and 20 weeks after planting maize (WAP) at the same depth during the two seasons but in 2004 LR sampling was also done at 2 WAP. Due to the variability of inorganic N in the field 10 soil cores per plot were taken and bulked to give one composite sample. The soil samples were taken using a metal sampling tube, which was driven into the soil and removed. After sampling the soil samples were packed in cooled boxes and delivered to ICRAF laboratory within 24 h. The samples were stored in the fridge at 5°C to restrict mineralization prior to extraction.

During 2002 LR, at harvesting (20 WAP), soil samples were taken at four depths (0–20, 20–50, 50–100 and 100–150 cm) in all plots and samples stored in the fridge at 5°C to restrict mineralization before delivery to ICRAF laboratories. In the laboratory, soil extraction was done using 2 N potassium chloride (ICRAF, 1995; Anderson and Ingram, 1993). The filtrates were then analyzed for extractable nitrate (NO_3^-) by cadmium (Cd) reduction column method (ICRAF, 1995; Anderson and Ingram, 1993) and extractable ammonium determined using colorimetric method (ICRAF, 1995; Anderson and Ingram, 1993).

Determination of Uptake of N by Maize

Destructive random sampling of maize was carried out at 4, 6, 8, 12, 16 and 20 (WAP) for determination of dry matter and N concentration in the plant tissues during 2002 and 2004 LR. At 20 WAP the maize grains and stover were analysed separately. Nitrogen concentration was determined by Kjeldahl acid digestion followed by colorimetry (Okalebo et al., 2002). Nitrogen uptake by maize crop was determined by multiplying the dry matter yields (kg) with the nitrogen concentration (%).

Statistical Analysis

Statistical analysis was performed using Genstat 5 for windows (Release 8.1) computer package (Genstat, 2005). After testing for normality the data were subjected to analyses of variance (ANOVA) that was used to compare treatment means. Significant differences were declared significant at $p \leq 0.05$ and treatment means found to be significantly different were separated by least significant differences (LSD) at $p \leq 0.05$.

Results

Soil Inorganic N at the Plow Layer at Different Sampling Periods

The bulk (almost 90%) of inorganic N found in the soil (0–15 cm) at all sampling periods during 2002

Table 4 Soil nitrate-N and ammonium-N at 0–15 cm soil depth sampled at different periods during 2002 LR at Chuka, Meru South District

	.........Weeks after planting.........						
	0	4	6	8	12	16	20
Treatment	.........Nitrate-N (NO_3^--N) in kg ha^{-1}.........						
Mucuna alone	2.3	11.8	9.2	5.6	16.1	3.4	11.0
Crotalaria alone	6.9	21.8	10.3	6.6	22.3	4.2	10.8
Mucuna + 30 kg N ha^{-1}	10.3	21.2	10.1	5.0	20.6	4.5	11.3
Crotalaria + 30 kg N ha^{-1}	20.6	31.7	11.9	7.0	26.8	5.0	15.0
Manure	3.4	19.3	10.9	8.0	22.6	2.5	19.6
Manure + 30 kg N ha^{-1}	22.8	33.8	10.6	6.9	17.4	4.0	14.8
Tithonia alone	30.7	40.5	13.9	10.1	29.7	7.2	15.5
Calliandra alone	16.0	24.4	11.6	8.0	26.2	9.0	15.0
Leucaena alone	19.1	30.5	11.5	6.7	23.6	4.3	19.4
Tithonia + 30 kg N ha^{-1}	27.5	40.2	13.3	8.5	17.0	2.4	13.4
Calliandra + 30 kg N ha^{-1}	25.3	35.4	12.2	5.9	30.3	6.8	12.6
Leucaena + 30 kg N ha^{-1}	19.4	30.5	10.5	5.4	21.1	3.9	12.5
Fertilizer (60 kg N ha^{-1})	19.1	47.5	6.4	4.2	23.6	4.2	8.8
Control	9.4	20.4	6.3	3.1	12.9	5.3	9.8
p-value	0.001	0.001	<0.001	<0.001	0.005	0.001	<0.001
SED	6.3	6.9	1.4	1.0	4.0	1.3	2.0
	.........Ammonium-N (NH_4^+-N) in kg ha^{-1}.........						
Mucuna	0.7	1.4	2.4	2.4	2.1	3.7	0.6
Crotalaria	1.2	1.8	4.7	3.3	3.2	6.0	1.3
Mucuna + 30 kg N ha^{-1}	1.3	2.0	3.1	3.1	2.5	5.3	3.7
Crotalaria + 30 kg N ha^{-1}	2.1	2.8	2.8	2.8	1.4	5.7	2.0
Manure	0.3	1.0	2.4	2.9	2.1	6.9	2.2
Manure + 30 kg N ha^{-1}	0.4	1.1	2.5	2.5	2.3	5.2	1.3
Tithonia	1.0	1.7	3.7	3.7	2.6	8.3	3.2
Calliandra	0.8	1.3	3.5	4.0	2.0	7.6	3.1
Leucaena	1.3	1.9	3.0	3.0	3.0	7.4	2.2
Tithonia + 30 kg N ha^{-1}	1.2	1.8	3.4	3.4	2.3	6.9	2.5
Calliandra + 30 kg N ha^{-1}	1.6	2.3	3.4	3.4	3.2	6.5	3.0
Leucaena + 30 kg N ha^{-1}	1.3	1.9	3.9	3.9	3.0	6.4	2.3
Fertilizer (60 kg N ha^{-1})	0.9	1.6	3.4	3.4	2.5	3.5	2.1
Control	1.3	1.9	3.2	3.2	2.8	4.3	2.1
p-value	0.23	0.22	0.53	0.84	0.79	0.012	0.17
SED	0.6	0.6	0.9	0.8	0.9	1.2	0.9

LR was in the form of nitrate-N (NO_3^--N) with ammonium-N (NH_4^+-N) contributing less than 10% (Table 4). Nitrate-N was significantly different among the treatments at the different sampling periods while NH_4^+-N was rather uniform across the different treatments at all sampling periods in 2002 LR (Table 3). During this season, there was also a general increase of NO_3^--N from 0 to 4 WAP, followed by a decrease at 6 and 8 WAP and then an increase at 12 WAP followed by a decrease at 16 WAP. In addition, NO_3^--N content was highest at 4 WAP (ranging from 11.8 to 47.5 kg N ha^{-1}) among all the sampling periods with inorganic fertilizer, tithonia, tithonia +30 kg N ha^{-1}, manure + 30 kg N ha^{-1} and calliandra + 30 kg N ha^{-1} recording among the highest amount of inorganic N. The inorganic fertilizer treatment had notably the highest amount of NO_3^--N at 4 WAP. The control treatment and herbaceous legumes alone treatment consistently maintained the lowest amount of NO_3^--N across the season.

During 2004 LR NO_3^--N was also higher than NH_4^+-N at all sampling periods but NH_4^+-N tended to accumulate from 8 WAP (Table 5). During this season NO_3^--N was significantly different among the

Table 5 Soil nitrate-N and ammonium-N nitrogen at 0–15 cm soil depth sampled at different periods during 2004 in Chuka, Meru South District

	.........Weeks after planting.........							
	0	2	4	6	8	12	16	20
Treatment	.........Nitrate-N (NO_3^--N) in kg ha^{-1}.........							
Mucuna	16.2	27.3	5.0	9.5	14.5	22.1	19.7	19.7
Crotalaria	5.6	15.5	4.3	14.7	13.5	19.7	18.3	23.4
Mucuna + 30 kg N ha^{-1}	9.8	20.6	3.9	5.7	15.1	21.5	21.9	21.9
Crotalaria + 30 kg N ha^{-1}	5.4	15.1	3.5	8.5	13.5	16.9	14.1	14.1
Manure	9.5	18.6	3.5	11.6	21.7	19.4	21.1	21.1
Manure + 30 kg N ha^{-1}	7.9	17.0	3.8	9.8	18.1	19.4	20.4	20.4
Tithonia	28.3	44.8	7.2	17.1	16.7	26.6	36.4	36.4
Calliandra	39.8	56.9	5.2	22.7	17.3	28.3	31.8	31.8
Leucaena	31.4	53.8	6.4	16.6	12.7	32.6	38.8	38.8
Tithonia + 30 kg N ha^{-1}	21.4	32.6	4.2	8.3	30.3	16.6	24.5	24.5
Calliandra + 30 kg N ha^{-1}	23.2	32.9	6.7	21.0	21.0	25.5	20.6	20.6
Leucaena + 30 kg N ha^{-1}	17.2	39.2	4.6	18.3	9.9	27.7	29.9	29.9
Fertilizer (60 kg N ha^{-1})	3.8	10.5	2.4	9.6	9.4	14.9	18.0	18.0
Control	3.2	10.9	2.7	11.4	9.0	15.2	17.2	17.2
p-value	0.001	<0.001	0.003	0.013	0.003	0.005	<0.001	0.006
SED	4.5	9.5	0.7	4.4	3.8	4.2	4.4	5.8
	.........Ammonium-N (NH_4^+-N) in kg ha^{-1}.........							
Mucuna	2.5	1.4	0.5	2.0	7.3	1.2	8.5	14.5
Crotalaria	0.4	0.5	0.6	1.9	10.4	6.8	10.6	16.6
Mucuna + 30 kg N ha^{-1}	2.4	1.6	0.4	1.7	13.8	3.2	8.1	14.1
Crotalaria + 30 kg N ha^{-1}	0.4	0.6	0.4	7.0	8.5	6.2	7	13.0
Manure alone	0.4	1.2	0.4	3.1	19.1	4.0	9.6	15.6
Manure + 30 kg N ha^{-1}	0.8	1.7	0.4	1.4	15.1	7.8	10.1	16.1
Tithonia	9.8	3.3	0.9	7.3	13.6	9.8	19.0	25.0
Calliandra	12.8	5.7	0.4	6.3	17.7	5.1	10.8	16.8
Leucaena	16	3.6	0.5	4.9	10.3	7.4	18.0	24.0
Tithonia + 30 kg N ha^{-1}	2.9	1.7	1.2	2.5	14.1	4.1	9.3	15.3
Calliandra + 30 kg N ha^{-1}	2.1	2.4	0.6	3.3	10.1	8.3	10.4	20.2
Leucaena + 30 kg N ha^{-1}	14.5	2.5	0.5	3.5	11.7	8.1	11.2	17.2
Fertilizer	0.2	1.5	0.3	2.6	8.0	6.3	7.4	13.4
Control	0.4	1.3	0.4	2.6	8.2	4.2	10.2	16.2
p-value	0.002	0.007	0.64	0.041	0.083	0.41	0.113	0.115
SED	2.3	1.1	0.4	2.0	3.8	3.3	3.8	3.9

treatments at the different sampling periods while NH_4^+-N was different among the treatments at 2, 6 and 8 WAP (Table 4). Nitrate-N in soils sampled before the season (at 0 weeks) differed significantly among the various treatments with treatments that had sole application of calliandra, leucaena and tithonia recording the highest NO_3^--N with 39.8, 31.4 and 28.3 kg N ha^{-1}, respectively (Table 4). This was followed closely by leucaena + 30 kg N ha^{-1}, calliandra + 30 kg ha^{-1} and tithonia + 30 kg ha^{-1}. During this season NO_3^--N increased in the first 2 WAP, dropped at 4 WAP and then increased gradually to the 16 WAP and remained constant between the 16 and 20 WAP. Overall the highest amount of NO_3^--N among the sampling periods was recorded at 2 WAP, which ranged from 10.5 (control treatment) to 56.9 kg N ha^{-1} (calliandra alone treatment). The lowest amount was recorded at 4 WAP, which ranged from 2.4 (fertilizer treatment) to 7.2 kg N ha^{-1} (tithonia alone treatment). At 20 WAP NO_3^--N was highest in leucaena alone, tithonia alone and calliandra alone treatments with 38.8, 36.4 and 31.8 kg N ha^{-1}, respectively (Table 5).

A difference was observed between the two seasons in relation to the amounts of NH_4^+-N across the seasons. Whereas NH_4^+-N remained almost constant throughout the growing period, during 2002 LR, NH_4^+-N tended to accumulate from the 8 WAP. The accumulation can be explained by the rainfall distribution. Termination of the rains early in the season resulted in NH_4^+-N increasing slowly and to become a significant component of the residual mineral N at 16–20 WAP during 2004 LR (Table 4).

Total soil inorganic N (sum of nitrate-N and ammonium-N) at 0–15 cm was generally lower during 2002 LR than in 2004 LR at all sampling periods (Tables 4 and 5). For example, at 20 WAP, total soil inorganic N in 2002 LR ranged from 10.9 (fertilizer treatment) to 21.8 kg N ha^{-1} (manure alone treatment) while it ranged from 27.1 (crotalaria + 30 kg N ha^{-1}) to 62.8 g N ha^{-1} (leucaena alone treatment) in 2004 LR.

Residual Soil Inorganic N at Different Depths at the End of 2002 LR

Generally, amount of soil inorganic N in all treatments decreased with increase in soil depth from 0–20 to 20–50 cm, after which it increased to 100–150 cm depth (Table 6). At the 0–20 cm soil depth, inorganic N ranged from 27.7 (control treatment) to 63.2 kg N ha^{-1} (tithonia alone treatment). There were significant differences among treatments at this soil depth. At the 20–50 cm soil depth, calliandra + 30 kg N ha^{-1} and crotalaria alone treatments had the highest inorganic N of 57 and 41.7 kg N ha^{-1}, respectively. The lowest inorganic N at this depth was recorded in manure + 30 with 16.2 kg N ha^{-1}, and tithonia + 30 with 16.5 kg N ha^{-1}. There were significant differences ($p = 0.05$) in soil inorganic N among the treatments at the 50–100 cm depth with tithonia alone and leucaena + 30 kg N ha^{-1} having the highest inorganic N of 75 and 69.4 N ha^{-1}, respectively. The lowest amount of inorganic N at this depth was recorded in crotalaria + 30 kg N ha^{-1} (17 kg N ha^{-1}) followed by mucuna alone (20.6 kg N ha^{-1}) and tithonia + 30 kg N ha^{-1} (20.6 kg N ha^{-1}).

At the 100–150 cm depth the highest mineral N was recorded in treatments that had tithonia, calliandra, leucaena applied either alone or in combination with fertilizer. Also, all treatments generally recorded higher amount of mineral N than the control with the exception of the recommended level of inorganic fertilizer.

Nitrogen Uptake by Maize at Different Sampling Periods

Nitrogen uptake by maize was lower during 2004 LR than 2002 LR due to lower rainfall amounts received during 2004 LR than 2002 LR. However, during both seasons, N uptake by maize was slow at 0–4 WAP after which increased up to 12 WAP and decreased from 16 to 20 WAP (Table 7). During 2002 LR, N uptake by maize was highest during 6–8 and 8–12 WAP sampling periods in all treatments. However, during these periods, there were significant differences in

Table 6 Amount of soil inorganic N (kg N ha^{-1}) in soils sampled at different depths at the end of 2002 LR at Chuka, Meru South District, Kenya

	......Soil depth in cm......			
Treatment	0–20	20–50	50–100	100–150
Mucuna	32.9	17.9	20.6	20.4
Crotalaria	55.5	41.7	27.9	52.9
Mucuna + 30 kg N ha^{-1}	32.0	18.7	39.2	40.7
Crotalaria + 30 kg N ha^{-1}	51.8	19.7	17.0	42.2
Manure alone	49.1	17.5	20.5	24.9
Manure + 30 kg N ha^{-1}	39.6	16.2	25.8	43.4
Tithonia	63.2	26.5	75.0	90.2
Calliandra	42.9	19.9	28.1	79.5
Leucaena	50.7	25.3	39.2	85.3
Tithonia + 30 kg N ha^{-1}	39.9	16.5	20.6	95.6
Calliandra + 30 kg N ha^{-1}	43.2	57.0	54.5	197.6
Leucaena + 30 kg N ha^{-1}	40.2	20.9	69.4	166.2
Fertilizer + 60 kg N ha^{-1}	35.9	17.2	24.2	30.1
Control	27.7	21.2	33.7	56.9
p-value	0.076	0.011	0.017	<0.001
$LSD_{(0.05)}$	20.8	25.4	32.8	56.2

Table 7 Nitrogen uptake (kg ha^{-1}) by maize at different sampling periods during 2002 and 2004 LR at Chuka, Kenya

	......Time in weeks......						
	0–4	4–6	6–8	8–12	12–16	16–20	
Treatment	......2002 LR......						Total N uptake
Mucuna	3	10	14	12	9	3	51
Crotalaria	3	18	16	25	8	5	75
Mucuna + 30 kg N ha^{-1}	4	16	17	28	12	7	84
Crotalaria + 30 kg N ha^{-1}	5	19	26	37	10	9	106
Manure	5	12	14	19	13	6	69
Manure + 30 kg N ha^{-1}	4	32	38	58	11	6	149
Tithonia	5	29	34	48	14	8	138
Calliandra	5	23	25	38	10	6	107
Leucaena	5	18	22	39	14	5	103
Tithonia + 30 kg N ha^{-1}	6	29	37	58	15	6	151
Calliandra + 30 kg N ha^{-1}	6	20	28	42	14	6	116
Leucaena + 30 kg N ha^{-1}	5	22	32	46	12	7	124
Fertilizer + 60 kg N ha^{-1}	5	21	23	35	9	5	98
Control	3	12	10	15	12	2	54
p-value	0.05	0.02	0.004	0.001	0.02	0.01	
SED	1.5	4.5	5.9	6.2	3.2	1.6	
	......2004 LR......						
Mucuna	4	5	12	26	4	0.5	52
Crotalaria	3	6	9	10	5	0.5	34
Mucuna + 30 kg N ha^{-1}	4	8	15	25	5	1	58
Crotalaria + 30 kg N ha^{-1}	4	5	14	29	5	1	58
Manure	5	4	6	12	4	0.5	32
Manure + 30 kg N ha^{-1}	4	9	19	30	6	1	69
Tithonia	5	10	23	35	7	2	82
Calliandra	6	6	14	18	8	2	54
Leucaena	5	12	12	17	7	2	55
Tithonia + 30 kg N ha^{-1}	6	14	26	37	6	1	90
Calliandra + 30 kg N ha^{-1}	5	9	13	20	6	1	54
Leucaena + 30 kg N ha^{-1}	3	7	18	22	7	1	58
Fertilizer + 60 kg N ha^{-1}	5	7	22	27	7	0.5	69
Control	3	4	9	12	4	0.2	32
p-value	0.03	0.001	0.02	0.05	0.02	0.03	
SED	1.5	3	3.5	5.6	1.2	0.3	

N uptake among the different treatments. The highest N uptake during these sampling periods was recorded in manure + 30 kg N ha^{-1}, followed by tithonia + 30 kg N ha^{-1} and leucaena + 30 kg N ha^{-1}. At harvest, cumulative N ranged from 51 to 149 for 2002 LR and 24–88 kg N ha^{-1} for 2004 LR. Nitrogen uptake was highest in tithonia + 30 kg N ha^{-1} (151 kg N ha^{-1}), followed closely by manure + 30 kg N ha^{-1} (149 kg N ha^{-1}), calliandra alone (138 kg N ha^{-1}) and leucaena alone (136 kg N ha^{-1}) treatments during 2002 LR. The lowest cumulative N uptake during this season was recorded in mucuna alone treatment (51 kg N ha^{-1}), control treatment (54 kg N ha^{-1}), manure alone (69 kg N ha^{-1}) and crotalaria alone treatment (75 kg N ha^{-1}). During 2004 LR, the highest cumulative N uptake was recorded in tithonia + fertilizer and tithonia treatments.

Discussions

The different pattern observed in the amounts of soil inorganic N among the different sampling periods in the two seasons under study (2002–2004 LR) was attributed to differences in rainfall patterns between the two seasons. During 2002 LR, rainfall was fairly distributed during the growing season, with almost a normal season for the area (Fig. 1) with a peak at around 5 and 6 WAP. On the other hand, rainfall during 2004 LR was very poor as it only rained for the first 3 weeks. The rains started on the 20th of April and rained for the next 3 weeks at 130.5, 84 mm and 131.8 during the first, second and third weeks, respectively and dry conditions prevailed for the rest of the season (Fig. 1). The dry conditions meant that there was low soil moisture content and this could have been the major cause of low N taken up by maize at the different sampling periods, and also the low cumulative amounts of N taken up by maize.

Ammonium-N content was low at all sampling periods because it probably nitrified as fast as mineralization occurred. Nitrification takes place in soils that are well drained, moist and with a pH of 5.5 to about 10 (Tisdale et al., 1990). The soils under this study have these characteristics and thus the bulk of inorganic N as expected was in the nitrate form. Similar low quantities of soil NH_4^+-N compared to NO_3^--N were reported in a kandiudalfic Eutrodox in Western Kenya (Mekonnen et al., 1997; Maroko et al., 1998) and at a humic Nitisol at Embu, central Kenya (Mugendi et al., 2003).

The accumulation of soil NH_4^+-N during 2004 LR from 8 WAP could be attributed to the dry nature of the soil that prevailed during this period. Chikowo et al. (2004) reported a similar accumulation of soil NH_4^+-N towards the end of a growing season during the ninth week when soil moisture was low. Similarly, Barrios et al. (1998) working in an Ustic Rhodustalf in Zambia reported NH_4^+-N content of between 1.1 and 12.3 mg kg^{-1} while NO_3^--N was between 2.1 and 20.1 mg kg^{-1}. This relatively low NH_4^+-N was attributed to rapid nitrification since this process is increased by soil wetting and the soil was sampled 2–3 weeks after the onset of rains. In the following year other soil samples collected on the same place before the onset of the rains (low soil moisture) had higher NH_4^+-N content ranging between 4.9 and 25.2 mg kg^{-1} than NO_3^--N that ranged from 0.7 to 10.2 mg kg^{-1}.

The increase in mineral N from 0 to 4 WAP in 2002 LR and 0–2 WAP in 2004 could be explained by mineralization of organic materials and the flush of nitrogen following rapid mineralization after a dry spell known as the ‘Birch effect’ (Birch, 1964). These corroborate the findings of Mugendi et al. (1999), Chikowo et al. (2004) and Ayuke et al. (2004) who reported nitrogen flush at the start of the rainy season at Embu, Kenya, Zambia and Western Kenya, respectively. The relatively higher amount of NO_3^--N in inorganic fertilizer, tithonia and tithonia + 30 kg N ha^{-1} at 4 WAP compared to all other treatments indicate a higher risk of leaching in these three treatments. While on the other hand it could imply that more N was available in these treatments for crop uptake, but considering the fact that maize roots are not yet developed at 4 WAP, this observation means that high amounts of NO_3^--N might be availed to the crop at a stage it does not require such large amounts of N, implying lack of synchrony. Nitrate-N is vulnerable and is susceptible to losses through leaching (Giller, 2002; Pypers et al., 2005) and the reduction of NO_3^--N at 6–8 WAP during 2002 LR and 4 WAP during 2004 LR was probably

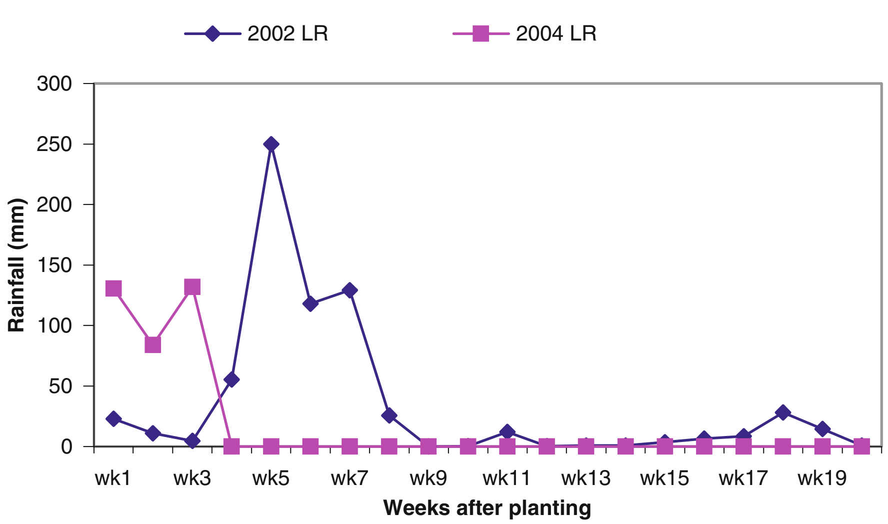

Fig. 1 Comparison of rainfall distribution during 2002 and 2004 LR at Chuka, Meru South District, Kenya

mainly due to plant uptake coupled with leaching. The loss through leaching was more likely at this period due to the high amounts of rainfall received during this period. Such a phenomenon was reported by Thornton et al. (1995) who estimated 40–50% of the mineralized N being lost under high rainfall environments through leaching and Myers et al. (1997) who noted that leaching of mineral N in the soil increased as the rainfall amount increased. The generally higher total inorganic N in the treatments that had organic materials incorporated throughout the cropping season could be explained by the long-term nature of nutrient availability from organic materials. Ayuke et al. (2004) reported similar results in their study in Western Kenya.

The decline in nitrate in the top 20–50 cm depth would suggest that maize roots were able to utilize this nutrient at this depth. Mugendi et al. (2003) reported more than 80% of maize roots to be concentrated in the top 0–60 cm depth and thus could absorb mineral N at 20–50 cm depth. The high mineral N at 100–150 cm soil depth could be attributed to greater N mineralization compared to plant uptake of topsoil immediately after the onset of the rainy season and subsequent nitrate leaching, an observation also reported by Phiri et al. (1998) in Malawi, and Njinue and Wagger (2003) at the Kenyan coast, respectively. This explanation is exemplified by the data on mineral N at different periods, which showed substantial amounts of mineral N at 4 WAP followed by a reduction at 6 WAP. In this region, there is nitrate buildup in the soil early in the season with N (from mineralization) exceeding maize-crop demand during the first 6 weeks of each cropping season (Mugendi et al., 1999; Nyamangara, 2004).

Nitrate leaching followed by adsorption of nitrate on positively charged soil surfaces at the 0.3–1.5 m depth has been reported in Western Kenya (Hartemink et al., 1996; Mekonnen et al., 1997). This mineral N observed in the 100–150 cm depth is below the rooting zone of most maize plants and may not be available to the maize crop (Mugendi et al., 2000; Kibuja et al., 2002). It may also not be readily transformed (denitrified or assimilated) because of the limited microbial population and available C at this depth (Paramasivam et al., 2001).

This high concentration of mineral N at this soil depth is therefore of concern as it is prone to leaching or may percolate to the water table or it could find its way to streams and rivers. Measures to curb downward movement of N like timely application of inputs and split fertilizer application that have been reported to reduce leaching should be encouraged (Randall and Mulla, 2001). In addition trees if well planted and integrated in the farming systems may assist in recovering some of this N that is lost to annual crops as observed by Mugendi et al. (2003) who reported that treatments with tree hedges recorded a lower amount of mineral N in the 100–300 cm depth than treatments without tree hedges. This is mainly because trees root deep into sub-soil layers and way beyond the rooting depth of most annual crop-inaccessible nutrients (Mekonnen et al., 1997; Shepherd et al., 2000) and therefore are capable of taking up nutrients from zones where crop roots do not reach.

During 1–6 WAP, N uptake by maize is low and this is the time when there is substantial amount of mineral N recorded within the plow layer resulting from nitrogen flush at the start of the season and decomposition of the organic materials. There was thus a likelihood of N supply being higher than the demand thus creating asynchrony.

The highest N uptake recorded at 6–8 WAP and 8–12 WAP during 2002 and 2004 LR, respectively, was due to maize growing very fast at these stages therefore taking up a lot of nutrients. In this region, maize grows rapidly from 4 to 12 WAP (silking/grain-filling stage) and this is the phase when maize has the highest demand for N (Karlen et al., 1988; Kihanda, 2003). Increased N uptake in manure, tithonia and leucaena combined with inorganic fertilizer treatments in the 4–6 and 8–12 WAP is an indication of more availability of plant nutrients in these treatments than all the other treatments. This agrees with the findings of Makumba et al. (2005) and Hawara et al. (2006) who reported increased N uptake by maize in treatments that had tree prunings combined with inorganic fertilizers applied. However, this supply and uptake is highly dependent on rainfall, where lack of adequate rainfall restricts maize N uptake consequently causing accumulation of mineral N mainly in form of ammonium-N in the plow layer as observed in this study.

Conclusions and Recommendations

This study showed variation in amounts of soil inorganic N among the treatments, at the different sampling periods (0, 2, 4, 6, 8, 12, 16 and 20 weeks after planting) and between the two seasons under study (2002 and 2004 LR). Generally treatments that had tithonia, leucaena and calliandra incorporated into the soil recorded higher total soil inorganic N than the control, herbaceous legumes and fertilizer treatments in most sampling periods, especially during 2004 LR. The same treatments recorded highest amounts of N taken up by the maize crop that ranged from 120 to 158 kg N ha^{-1}. This is an indication that these organic materials (tithonia, leucaena and calliandra) can be used as sources of N for growing crops.

During 2002 LR, when rainfall was fairly distributed, soil inorganic N increased from 0 to 4 weeks after planting maize and generally reduced from 6 up to 20 WAP. On the other hand, during 2004 LR when the rainfall was poor and rained intensely for the first 3 weeks, inorganic N dropped drastically at 4 weeks after planting maize after which it increased gradually up to 20 WAP. The reduction in soil inorganic was attributed to leaching coupled with plant uptake of N. Indeed, the cumulative N uptake curves showed that the highest uptake of N by maize occurred from 6 to 12 WAP. High rainfall amounts at the start of the season, when the ground is bare, consequently causing leaching is a big challenge in the region and a solution needs to be sought.

During 2004 LR accumulation of both NO_3^--N and NH_4^--N from the 6 WAP was associated with dry conditions that also restricted uptake of N by the maize crop. The dry conditions were also associated with accumulation of NH_4^+-N that occurred from around 8 WAP up to the end of the season. It was evident that the amount of soil inorganic N and N uptake by maize was dependent on organic materials and soil moisture availability where lack of rainfall restricted N uptake by maize and consequently caused accumulation of soil inorganic N.

These results confirmed the nitrogen flush (Birch effect) that occurs at the beginning of the rainy season. Unfortunately most of this N seems to get lost and does not benefit the crop. More investigations are therefore needed on synchrony between N release from decomposing organic materials and plant demand for N to be able to develop a system that maximizes N use.

At the end of the growing season, there was high amounts of mineral N at 100–150 cm soil depth that was probably due to greater N mineralization compared to plant uptake of topsoil immediately after the onset of the rainy season and subsequent nitrate leaching. This mineral N observed in the 100–150 cm depth is below the rooting zone of most maize plants, consequently not available to maize crop and is therefore of concern as it is prone to leaching, or percolation to the water table or many streams and rivers. Measures to curb downward movement of N, such as timely application of inputs and split fertilizer application, need to be investigated. In addition if trees are well integrated in the farming systems, they may assist in recovering some of this N that is lost to annual crops as earlier reported by other studies. This is because trees root deep into sub-soil layers and way beyond the rooting depth of most annual crop-inaccessible nutrients.

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