Agroforestry Systems **46**: 51–64, 1999.

Alley cropping of maize with calliandra and leucaena in the subhumid highlands of Kenya
Part 2. Biomass decomposition, N mineralization, and N uptake by maize

D. N. MUGENDI[1, 2, *], P. K. R. NAIR[1], J. N. MUGWE[2], M. K. O'NEILL[3], M. J. SWIFT[4] and P. L. WOOMER[5]
[1] *School of Forest Resources and Conservation, University of Florida, 118 Newins-Ziegler Hall, Gainesville, FL 32611, USA;* [2] *Kenya Forestry Research Institute (KEFRI), P.O. Box 20412, Nairobi, Kenya;* [3] *International Centre for Research in Agroforestry (ICRAF), P.O. Box 30677, Nairobi, Kenya;* [4] *Tropical Soil Biology and Fertility Programme (TSBF), P.O. Box 30592, Nairobi, Kenya;* [5] *Department of Soil Science, University of Nairobi, P.O. Box 30197, Nairobi, Kenya (*Author for correspondence: Present address: Faculty of Environmental Science, Kenyatta University, P.O. Box 43844, Nairobi, Kenya; E-mail: D.Mugendi@cgiar.org)*

Florida Agricultural Experiment Station Journal Series Number R-06876.

Key words: chemical composition, mineral-N, N recovery, rate constants, synchrony

Abstract. A major challenge in developing agroforestry approaches that utilize tree-leaf biomass for provision of N to crops is to ensure synchrony between the N released from decomposing prunings and N demand by crops. A study was conducted in the subhumid highlands of Kenya to assess the rate of decomposition and mineralization of soil-incorporated *Calliandra calothyrsus* Meissner (calliandra) and *Leucaena leucocephala* (Lam.) de Wit (leucaena) tree biomass and maize roots (*Zea mays* L.) both in an alley cropping and a sole cropping system. The amount of mineralized N peaked four weeks after planting (WAP) maize in all the treatments during both seasons of 1995. Cumulative mineralized N at week 20 ranged from 114 to 364 kg N ha^{-1} season^{-1}, the absolute control treatment giving the lowest and the prunings-incorporated treatments giving the highest amounts in the two seasons. Total N uptake by maize, ranging from 42 to 157 kg ha^{-1} season^{-1}, was lowest in the 'alley-cropped, prunings-removed' treatments, and highest in the 'non alley-cropped, prunings-incorporated' treatments. The apparent N recovery rate by maize was highest in the fertilizer applied treatments in the two seasons. Decomposition rate constants (*kD*) ranged from 0.07 to 0.21 week^{-1}, and the rates among the different plant residues were as follows: leucaena > calliandra > maize roots. Nitrogen release rate constants (*kN*), ranging from 0.04 to 0.25 week^{-1}, followed a similar pattern as the rate of decomposition with leucaena releasing the highest amount of N followed by calliandra and lastly by maize roots.

Introduction

In many tropical agricultural systems with limited access to fertilizers, tree biomass is often used to meet the N requirements of annual crops. A major challenge in this approach is to ensure that N in the applied biomass is efficiently utilized by crops. Synchronizing release of N from decomposing biomass with demand (uptake) by crop (Swift, 1987) will lead to increased

N-use efficiency of the incorporated biomass (Becker et al., 1994a), and will in turn minimize the opportunity for N loss (Myers et al., 1994).

Understanding decomposition and nutrient release patterns of plant materials is an important first step to better managing organic inputs that are applied in agroforestry and other related land-use systems (Palm, 1995; Mafongoya et al., 1998). These in turn depend to a large extent on chemical composition of plant tissues (Constantinides and Fownes, 1994). Initial N content of the biomass, C:N ratio, lignin content, lignin:N ratio, and polyphenol and its ratios with N and lignin have been shown to be important chemical qualities affecting the rate of decomposition and mineralization (Palm, 1995; Mafongoya et al., 1998). Other factors that affect the rate of mineralization include climate, soil characteristics, and cultural practices such as the method of application of biomass, application of mineral fertilizers, and methods employed in soil tillage (Becker et al., 1994b; Mugendi and Nair, 1997).

The objectives of this study were to investigate the rate of N mineralization of soil-incorporated tree-leaf biomass (prunings) of *Calliandra calothyrsus* Meissner (calliandra) and *Leucaena leucocephala* (Lam.) de Wit (leucaena) and its subsequent uptake by maize, and to evaluate decomposition and nitrogen release patterns of calliandra and leucaena leafy biomass and maize roots (*Zea mays* L.) both in alley cropping and sole cropping systems. The two leguminous tree species were introduced in the alley cropping trials in the subhumid highlands of central Kenya based on their satisfactory performance in the highlands of western Kenya as described in Part 1 of this study (Mugendi et al., 1999, in press), whereas maize roots are an important organic input into the soil in that they are always left behind in the soil after maize harvest.

Materials methods

The experiment was conducted at Embu Regional Research Centre, Eastern Province, Kenya. The details of the experimental site, layout and treatments, cropping history, lopping of hedges, incorporation of biomass into the soil and other aspects of experiment management are reported in Part 1 (Mugendi et al., 1999, in press). The study was conducted during the long (LR) and short (SR) raining seasons of 1995 (hereafter referred to as season 1 and 2, respectively).

Nitrogen mineralization – sampling and analysis

A modification of the field incubation method for estimating *in situ* nitrogen mineralization, as recommended by the Tropical Soil Biology and Fertility programme (Anderson and Ingram, 1993), was followed in this study. Six pieces of pvc tubes (30 cm long with an internal diameter of 5 cm) were randomly inserted into the soil in each plot (in all the treatments) the same day maize was planted. The tubes were driven into the soil about 25 cm (to prevent root in-growth), leaving 5 cm of the tubes projecting above the soil surface. Three of the six tubes were removed immediately and the soil in them bulked to form a sample which was analyzed to determine the initial mineral-N (NH_4^+ and NO_3^-) concentration in the soil at time-0 (t_0). The remaining three tubes were covered with polyethylene paper to protect the cores from leaching effects by rain. These were removed two weeks later and likewise analyzed for mineral-N concentration (t_1). Net mineralization was calculated as the difference between the two time points ($t_1 - t_0$).

A similar process (i.e., six tubes inserted into the soil, three removed immediately and the remainder removed during the next sampling date) was repeated for all the other sampling dates, i.e., 2, 4, 7, 10, 15, and 20 weeks after maize planting in both season 1 and 2, respectively. For each sampling time, net mineralization was always calculated as the difference in mineral-N between that time of determination and the one preceding it. At each sampling, the bulked soil samples from the respective plots were packed into polyethylene bags, kept in a refrigerator (4 °C) and transported in cooler boxes filled with ice to the laboratory for analysis. On arrival at the laboratory, the samples were again refrigerated before extraction with 2 N KCl, after which the extracts were frozen in a freezer awaiting NH_4^+ and NO_3^- analysis. To avoid contamination, NH_4^+ was always analyzed first followed by NO_3^-. Ammonium was determined by the salicylate-hypochlorite colorimetric method (Anderson and Ingram, 1993) whereas NO_3^- plus nitrite (NO_2) were determined by cadmium reduction method (Dorich and Nelson, 1984).

Soil bulk density (0 cm to 20 cm) was determined to assist in converting the mineralized N into kg ha^{-1} basis. The amounts of NH_4^+-N and NO_3^--N obtained after soil analysis at each sampling period were summed to give the total N mineralized at a given sampling date. The bulk of inorganic N found in the soil at all the sampling periods was in the form of NO_3^--N, with NH_4^+-N contributing less than 10% of the mineralized N.

Crop N uptake and N recovery – sampling and analysis

Destructive random maize sampling was done at 4, 7, 10, 15, and 20 weeks after planting (WAP) maize to determine N concentration in the plant tissue. The last sampling (20 WAP) coincided with maize harvesting. Dry weights (mass) of the harvested plants were determined to assist in assessing N uptake by maize at different stages of crop growth. Except at seedling stage (4 WAP), maize leaves were always separated from the stem and analyzed separately. At harvest, the cob was separated from the grain and stover and the three components analyzed separately. The samples were cleaned with water (where necessary) and oven dried at 65 °C to constant weight (usually 48 hr) after which they were ground to first pass through a 2-mm and finally through a 0.5-mm sieve. The resulting powder was then kept in plastic air tight bottles and stored in a cool dry place awaiting chemical analysis. Nitrogen concentration in the samples was analyzed following the methods outlined by Parkinson and Allan (1975). Apparent N recovery by maize crop was calculated as follows:

$$\%\ N_{\mathrm{REC}} = \frac{\text{N uptake}_{(\text{treatment})} - \text{N uptake}_{(\text{control})}}{\text{Total N applied}} \times 100$$

where, N uptake$_{(\text{treatment})}$ and N uptake$_{(\text{control})}$ are the total N (kg ha^{-1}) in the treatment and control plots, respectively.

Decomposition and N release patterns

Fifty grams (on dry matter basis) of the tree-leafy biomass from all the treatments that received biomass application (Trts 1, 2, 5, 6, 7, and 8) and the previous season's maize roots were put into 1-mm mesh size litter bags and buried into the soil at a depth of about 15 cm (plough-layer) at the time of maize planting (beginning of the season). One bag containing residues from each species was randomly removed from the soil in each block at 2, 4, 7, 10, 15 and 20 weeks after maize planting (WAP). The contents in the bags were cleaned with water, oven dried at 65 °C to constant weight, and dry weights recorded. The dry weights were corrected for ash content, then expressed as percentage of sample remaining undecomposed.

Decomposition rate (kD) and N release (kN) constants were estimated using the Wieder and Lang (1982) first order exponential equation:

$Y = e^{-kt}$, where Y is the percent remaining of initial weight of material at time t in weeks and k is the rate of decomposition/N release per week (rate constant). The k values were estimated using a nonlinear module in SAS (1988).

Nitrogen released (RLS) over time was calculated following the formula by Giashuddin et al. (1993):

$$\%\ \text{N RLS} = 100 - \%\ \text{of original N content remaining } (N_o)$$

where,

$$N_o = \frac{(\%\ \text{N a time } t)}{(\%\ \text{N at time } 0)} \times \%\ \text{of original wt remaining}$$

Samples were analyzed for the initial chemical composition, i.e., N, C, lignin (LG), and polyphenols (PP), by methods outlined by Anderson and Ingram (1993).

Statistical analysis

Data were subjected to analysis of variance (ANOVA) using SAS (1988) program. Means were separated by Tukey’s procedure at the $P < 0.05$ level of significance.

Results

Nitrogen mineralization

Mineral-N content in the 0 to 20 cm soil depth ranged from 15 to 41 kg ha^{-1} and 14 to 66 kg ha^{-1} in seasons 1 and 2, respectively, at the beginning of each season (0 WAP) (Table 1). The amount increased as the season pro-

Table 1. Amounts of N mineralized in the 0 to 20 cm soil depth at different sampling periods during the two growing seasons of 1995 at Embu, Kenya.

Trt	AC/PI/NF[a]	N mineralization (kg N ha^{-1}) at different times (WAP)							
		0[b]	0–2	2–4	4–7	7–10	10–15	15–20	Total
Season 1 – LR 95									
1	C/C/–	23 c	29 c	51 b	28 b	18 b	15 b	15 b	179 c
2	L/L/–	25 c	32 c	54 b	26 b	20 a	18 a	18 b	193 b
3	C/–/–	16 d	21 c	30 c	13 c	16 b	13 b	14 c	123 de
4	L/–/–	16 d	22 c	32 c	15 c	17 b	15 b	18 b	135 de
5	–/C/–	27 bc	43 b	51 b	24 b	22 a	19 a	18 b	204 b
6	–/L/–	41 a	41 b	56 b	36 a	21 a	22 a	19 b	236 ab
7	–/C/25	37 a	67 a	77 a	23 b	23 a	21 a	23 a	271 a
8	–/L/25	32 b	42 b	66 a	25 b	22 a	19 a	18 b	224 ab
9	–/–/50	22 c	24 c	30 c	21 b	12 c	11 c	18 b	138 d
10	–/–/–	15 d	20 c	32 c	14 c	11 c	11 c	11 c	114 e
Season 2 – SR 95									
1	C/C/–	27 de	57 bc	69 a	30 c	19 bc	21 b	30 b	253 b
2	L/L/–	33 cd	63 b	49 b	40 b	23 ab	23 b	28 b	259 b
3	C/–/–	14 f	34 d	27 c	19 d	11 c	12 c	9 d	126 d
4	L/–/–	19 ef	39 cd	28 c	24 cd	14 c	12 c	21 c	157 c
5	–/C/–	45 bc	107 a	76 a	25 cd	17 bc	26 b	36 b	332 ab
6	–/L/–	41 bc	66 b	49 b	26 cd	23 ab	29 a	32 b	266 b
7	–/C/25	57 b	92 a	51 b	56 a	26 a	35 a	47 a	364 a
8	–/L/25	66 a	94 a	70 a	53 a	23 ab	26 b	26 b	358 a
9	–/–/50	35 cd	52 bc	24 c	17 d	14 bc	10 c	28 b	180 c
10	–/–/–	23 ef	44 c	22 c	16 d	22 ab	8 c	13 d	148 cd

Means followed by the same letter within a column are not significantly different at $P < 0.05$.

[a] AC = alley crop tree species (C = calliandra, L = leucaena); PI = type of pruning incorporated (C = calliandra, L = leucaena); NF = nitrogen fertilizer applied (kg N ha-1).

[b] 0 = Amount of mineral N found in the soil at maize planting

Abbreviations: Trt = treatments; LR = long rain; SR = short rain; WAP = weeks after planting.

gressed, peaking approximately 2–4 WAP in all the treatments in both seasons and declining sharply between 4–7 WAP and 7–10 WAP sampling intervals, after which it leveled off until harvest. Treatments where prunings were applied (Trts 1, 2, 5, 6, 7, and 8) mineralized greater amounts of N, whereas the alley-cropped, prunings removed (Trts 3 and 4), and the control treatments (both fertilized and absolute control; Trts 9 and 10) had lower amounts of mineralized N. Total mineralized N over the 20-week period under various treatments ranged from 114 to 271 kg N ha^{-1} for season 1, and 126 to 364 kg N ha^{-1} for season 2. The general pattern observed across the two seasons for the total N mineralized was as follows: prunings applied + fertilizer treatments (Trts 7 and 8) ≥ *ex situ* pruning applied treatments (Trts 5 and 6) ≥ alley-cropped prunings applied treatments (Trts 1 and 2) > fertilizer applied treatment (Trt 9) ≥ alley-cropped prunings removed treatments (Trts 3 and 4) = absolute control (Trt 10).

Nitrogen uptake and recovery by maize

Nitrogen uptake by maize reached its peak during the 4–7 WAP and 7–10 WAP sampling periods in both seasons, and declined progressively thereafter until harvest (Table 2). Just as in the case with soil N mineralization, N uptake by maize was highest in the treatments that received prunings and lowest in the alley-cropped prunings removed treatments. At harvest (20 WAP), total N uptake ranged from 42 to 117 kg ha^{-1} for season 1 and 62 to 157 kg ha^{-1} for season 2. The general pattern of N uptake by maize in the two seasons was somewhat similar to that observed in N mineralization, i.e., prunings applied + fertilizer treatments (Trts 7 and 8) ≥ *ex situ* pruning applied treatments (Trts 5 and 6) ≥ leucaena alley-cropped prunings applied treatment (Trt 2) ≥ fertilizer applied treatment (Trt 9) ≥ absolute control (Trt 10) ≥ calliandra alley-cropped prunings applied treatment (Trt 1) > alley-cropped prunings removed treatments (Trts 3 and 4).

Cumulative apparent N recovery increased progressively until maize harvest during the two growing seasons (Table 3). The fertilizer applied treatment (Trt 10) gave the highest apparent N recovery in the two seasons. Calliandra alley-cropped treatment (Trt 1) recovered less N (starting 10 WAP and 15 WAP in seasons 1 and 2) compared to the absolute control resulting in negative N recovery in both seasons. This was due to severe competition of calliandra hedges with maize, which depressed maize yield in Trt 1 as reported in part 1 of this study.

Differences between soil-mineralized N and uptake by maize

There was substantial amount of excess N (the difference between N mineralized and N taken up by maize) in the top 20 cm soil layer ranging from 15 to 73 and 14 to 107 kg N ha^{-1} per sampling period in season 1 and 2, respectively, in all the treatments in the early part of the two growing seasons (up

Table 2. Nitrogen taken up by maize at different sampling periods in the two growing seasons of 1995 at Embu, Kenya.

Trt	AC/PI/NF[a]	N uptake (kg N ha^{-1}) at different times (WAP)					
		0–4	4–7	7–10	10–15	15–20	Total
Season 1 – LR 95							
1	C/C/–	3 a	26 c	19 c	18 a	7 ab	73 d
2	L/L/–	4 a	40 ab	39 ab	16 a	6 ab	105 ab
3	C/–/–	2 ab	16 d	15 d	5 c	4 bc	42 f
4	L/–/–	3 a	21 cd	23 c	5 c	5 bc	57 e
5	–/C/–	4 a	35 b	50 a	14 ab	5 bc	108 ab
6	–/L/–	4 a	45 ab	46 a	12 b	3 c	110 a
7	–/C/25	4 a	41 b	48 a	14 ab	5 bc	112 a
8	–/L/25	4 a	55 a	41 a	12 b	5 bc	117 a
9	–/–/50	3 a	33 bc	35 ab	15 ab	10 a	96 b
10	–/–/–	3 a	27 c	27 b	20 a	6 ab	83 c
Season 2 – SR 95							
1	C/C/–	4 a	29 c	32 c	7 c	5 c	77 d
2	L/L/–	4 a	44 b	50 ab	7 c	5 c	110 c
3	C/–/–	2 b	32 c	23 d	3 d	2 d	62 e
4	L/–/–	4 a	31 c	24 d	4 d	5 c	68 e
5	–/C/–	4 a	51 b	43 b	22 a	8 b	128 b
6	–/L/–	4 a	53 ab	49 ab	12 b	8 b	126 b
7	–/C/25	4 a	54 ab	63 a	25 a	11 ab	157 a
8	–/L/25	4 a	66 a	50 ab	15 b	8 b	143 a
9	–/–/50	3 ab	47 b	20 d	21 a	14 a	105 c
10	–/–/–	3 ab	26 cd	33 c	15 b	10 b	87 d

Means followed by the same letter within a column are not significantly different at $P < 0.05$.

[a] AC = alley crop tree species (C = calliandra, L = leucaena); PI = type of pruning incorporated (C = calliandra, L = leucaena); NF = nitrogen fertilizer applied (kg N ha^{-1}).

Abbreviations: Trt = treatments; LR = long rain; SR = Short rain; WAP = weeks after planting.

to 2–4 WAP). Treatments that had prunings applied (Trts 1, 2, 5, 6, 7, and 8) registered higher excess amounts of N than the other treatments. Nitrogen deficit started showing during the 4–7 WAP sampling period in almost all the treatments in both seasons. The fertilizer applied treatment (Trt 9) and the absolute control treatment (Trt 10) portrayed a relatively prolonged deficit compared to other treatments (Table 4).

Decomposition and N release patterns

The plant materials showed variations in their chemical compositions during the two seasons of the study (Table 5). The leaves of both leucaena and calliandra contained significantly more N (leading to lower C:N ratio) than maize roots in season 1 and 2, respectively. Leucaena leaves had significantly lower concentration of LG and LG:N, PP:N, and (LG+PP):N ratios compared to calliandra and maize roots. On the other hand, calliandra had the highest

Table 3. Cumulative apparent N recovery by maize for the different treatments at Embu, Kenya during the 1995 growing seasons.

Trt	AC/PI/NF[a]	N recovery (%) at different times (WAP)				
		4	7	10	15	20
Season 1 – LR 95						
1	C/C/–	1 a	0 d	–2 c	–7 d	–18 d
2	L/L/–	1 a	9 b	14 a	15 b	17 bc
5	–/C/–	1 a	6 c	9 b	13 b	15 c
6	–/L/–	1 a	13 a	18 a	19 a	20 b
7	–/C/25	1 a	4 c	7 b	9 c	11 c
8	–/L/25	1 a	14 a	19 a	20 a	21 b
9	–/–/50	0 b	11 b	17 a	23 a	27 a
Season 2 – SR 95						
1	C/C/–	1 a	3 c	2 c	–6 c	–17 d
2	L/L/–	1 a	13 ab	16 ab	18 b	19 bc
5	–/C/–	1 a	16 a	21 a	22 b	24 b
6	–/L/–	1 a	18 a	21 a	21 b	22 b
7	–/C/25	1 a	16 a	19 a	22 b	25 b
8	–/L/25	1 a	14 ab	17 ab	21 b	23 b
9	–/–/50	0 b	13 ab	18 a	30 a	38 a

Means followed by the same letter within a column are not significantly different at $P < 0.05$.

[a] AC = alley crop tree species (C = calliandra, L = leucaena); PI = type of pruning incorporated (C = calliandra, L = leucaena); NF = nitrogen fertilizer applied (kg N ha^{-1}).

Abbreviations: Trt = treatments; WAP = weeks after planting.

concentration of PP and PP:N ratio. Maize roots indicated significantly higher ratios of LG:N and (LG + PP):N compared to the leafy biomass from the two tree species.

The decomposition rate (*kD*) and N release rate (*kN*) constants among leucaena and calliandra leafy biomass and maize roots were significantly different from each other during the two seasons (Table 6). Leucaena biomass had the highest *kD* and *kN* rate constants indicating that it had the most rapid decomposition and N release rates followed by calliandra and lastly by maize roots.

Discussion

The excess mineral-N (excess of plant demand) found in the soil up to 4 WAP, with treatments that had prunings incorporated showing higher amounts, may be susceptible to loss. The N release rate constants observed in this study (Table 6) indicates that leucaena and calliandra soil-incorporated prunings released up to 50% of N into the soil after the first four weeks of application. This helped boost the amount of mineral-N found in the soil in those treatments that received prunings.

Table 4. Differences between N mineralized and N taken up by maize (excess/deficit) at different sampling periods during the two growing seasons of 1995 at Embu, Kenya.

Trt	AC/PI/NF[a]	N excess (+) or deficit (–) in kg N ha^{-1} at different times (WAP)						
		0[b]	0–2	2–4	4–7	7–10	10–15	15–20
Season 1 – LR 95								
1	C/C/–	+23 c	+29 c	+48 b	+2 e	–1 d	–3 c	+8 b
2	L/L/–	+25 c	+32 c	+50 b	–14 b	–19 b	+2 b	+12 a
3	C/–/–	+16 d	+21 c	+28 c	–3 d	–1 d	+8 a	+10 ab
4	L/–/–	+16 d	+22 c	+29 c	–6 c	–6 c	+10 a	+13 a
5	–/C/–	+27 bc	+43 b	+46 b	–11 b	–28 a	+5 b	+13 a
6	–/L/–	+41 a	+41 b	+52 b	–9 bc	–25 a	+10 a	+16 a
7	–/C/25	+37 a	+67 a	+73 a	–18 b	–25 a	+7 a	+18 a
8	–/L/25	+32 b	+42 b	+62 a	–30 a	–19 b	+7 a	+13 a
9	–/–/50	+22 c	+24 c	+27 c	–12 b	–23 a	–4 d	+8 b
10	–/–/–	+15 d	+20 c	+29 c	–13 b	–16 b	–9 e	+5 c
Season 2 – SR 95								
1	C/C/–	+27 de	+57 bc	+65 a	+1 d	–13 c	+14 a	+25 b
2	L/L/–	+33 cd	+63 b	+45 b	–4 c	–27 b	+16 a	+23 b
3	C/–/–	+14 f	+34 d	+25 c	–13 b	–12 c	+9 b	+7 d
4	L/–/–	+19 ef	+39 cd	+24 c	–7 b	–10 c	+8 b	+16 c
5	–/C/–	+45 bc	+107 a	+72 a	–26 a	–26 b	+4 c	+28 b
6	–/L/–	+41 bc	+66 b	+45 b	–27 a	–26 a	+17 a	+24 b
7	–/C/25	+57 b	+92 a	+47 b	+2 d	–37 a	+10 b	+36 a
8	–/L/25	+66 a	+94 a	+66 a	–13 b	–27 a	+11 b	+18 c
9	–/–/50	+35 cd	+52 bc	+21 c	–30 a	–6 d	–11 e	+14 c
10	–/–/–	+23 ef	+44 c	+18 c	–10 b	–11 c	–7 d	+3 e

Means followed by the same letter within a column are not significantly different at $P < 0.05$.

[a] AC = alley crop tree species (C = calliandra, L = leucaena); PI = type of pruning incorporated (C = calliandra, L = leucaena); NF = nitrogen fertilizer applied (kg N ha^{-1}).

[b] 0 = Amount of mineral N found in the soil at maize planting

Abbreviations: Trt = treatments; LR = long rain; SR = short rain; WAP = weeks after planting.

Table 5. Chemical composition of leucaena and calliandra leafy biomass and maize roots in the highlands of Kenya during the two maize-growing seasons of 1995.

Season	Residue	N	C	LG	PP	C:N	LG:N	PP:N	(LG + PP):N
		g kg^{-1}							
1 (LR)	Calliandra	40 a	452 a	128 a	122 a	11.3 a	3.2 b	3.1 a	6.3 b
	Leucaena	42 a	451 a	72 b	31 b	10.7 a	1.7 c	0.7 c	2.5 c
	Maize roots	9 b	469 a	134 a	12 c	52.1 b	14.9 a	1.3 b	16.2 a
2 (SR)	Calliandra	39 a	456 a	104 b	111 a	11.5 a	2.7 b	2.8 a	5.5 b
	Leucaena	37 a	458 a	65 c	35 b	12.4 a	1.8 c	0.9 b	2.7 c
	Maize roots	7 b	470 a	126 a	10 c	67.1 b	18.0 a	1.4 b	19.4 a

Means followed by the same letter within a column in a particular season are not significantly different at $P < 0.05$.

Abbreviations: LG = lignin; PP = polyphenol; LR = long rain; SR = short rain.

Table 6. Decomposition rate (*kD*) and N release (*kN*) constants and their coefficient of determination (R^2) values for the different residues in the highlands of Kenya.

Season	Plant residue	*kD*	R^2	*kN*	R^2
1 (LR)	Calliandra	0.12 b	0.91	0.10 b	0.90
	Leucaena	0.21 a	0.95	0.25 a	0.96
	Maize roots	0.07 c	0.93	0.05 c	0.91
2 (SR)	Calliandra	0.14 b	0.88	0.11 b	0.87
	Leucaena	0.20 a	0.97	0.21 a	0.97
	Maize roots	0.08 c	0.90	0.04 c	0.93

Values followed by same letter within a column in a particular season are not significantly different at $P < 0.05$.
kD and *kN* values are *k*/week.
Abbreviations: LR = long rain; SR = short rain.

In the conditions under which this study was conducted, maize grows rapidly from four to 10 WAP (silking/grain-filling stage). This also is the phase when maize has the highest demand for N (Karlen et al., 1988), as exemplified by the sharp decline in the level of available mineral-N in the soil in all the treatments between 4 and 10 WAP (Table 1). Mafongoya and Nair (1997) reported that a large accumulation of available N in the soil before the peak period of N uptake by maize is needed to achieve synchrony between N supply from prunings and N demand by the maize crop. The question here is what is the optimal time span between the accumulated mineral-N and the peak demand by maize to ensure minimal N loss from the system. The answer is not an easy one for it will depend on many factors, especially climatic and soil conditions. High quality prunings such as those of leucaena, which release over 50% of their N two to three weeks after incorporation into the soil, might be releasing the N too early resulting in asynchrony between N release and critical demand by maize (Rubaduka et al., 1993; Myers et al., 1994; Mafongoya et al., 1997). Such available N in the soil is subject to leaching, volatilization, denitrification, and immobilization. However, despite rapid N release, incorporating high quality prunings close to planting has been shown to give superior yields as opposed to applying them too late (> 4 WAP) after planting (Mafongoya and Nair, 1997). Indeed, Mafongoya and Nair (1997) observed that calliandra and leucaena prunings applied to an alfisol in semiarid Zimbabwe at planting gave the highest maize grain yield and N uptake, though with leucaena, prunings applied at 2 WAP and 4 WAP produced yields that did not differ significantly from the yields of those applied at planting.

The increase of mineralized N in the soil up to 4 WAP was not exclusively observed in the treatments that received prunings only, but also in all the other treatments including the control. As noted earlier, the amount of available mineral-N in the soil was substantial at the beginning of each season, and this seemed to increase in all the treatments (with the highest increase in the prunings-incorporated treatments) with the onset of rains (it is worthwhile noting that the soils of the study site had approximately 2% C). This phenomenon in the tropical soils is commonly referred to as ‘nitrogen flush’ or the ‘Birch effect’ (Birch, 1958). The loss, especially to leaching of the increased amount of mineral-N in the soil, increases as the rainfall increases (Myers et al., 1994). This loss will be more pronounced early in the season (before the crop develops extensive rooting system) if rainfall is too much. Rainfall data (Mugendi and Nair, 1997) indicated that rainfall recorded during the two seasons was mostly received during the early part of the growing season. Some of this N was, therefore, likely lost through leaching (leaching in this study was not assessed because of logistical difficulties). Results using ^{15}N-labeled prunings that were soil-incorporated in the same treatments used in this study (Mugendi et al., pers. comm., 1999) indicated that 20% to 30% of the labeled N could not be accounted for at the end of the growing season. Nitrate-N, which is the principal form of the mineral-N found in these soils, is easily leachable compared to NH_4^+-N. Loses of N through denitrification and volatilization were assumed to be negligible since the soils were well aerated (no loss by denitrification) and also because the prunings were incorporated into the soil whose pH (5.5) was not high enough to facilitate the process of volatilization (Myers et al., 1994).

The differences in decomposition and N release between maize roots and the biomass of the two tree species may be explained by the amount of initial N concentration (and C:N ratios) contained in the tissues of these plant materials. Thus, leucaena and calliandra leafy biomass that had significantly higher N concentration and lower C:N ratio than maize roots decomposed and released N faster than maize roots over the entire 20-week study period, corroborating the results of others that N content and C:N ratio serve as useful preliminary indices of decomposition and N release (Constantinides and Fownes, 1994; Palm, 1995; Mugendi and Nair, 1997). On the other hand, however, the differences in decomposition and N release patterns shown by calliandra and leucaena (though they had similar N concentration and C:N ratio) may be explained by the fact that calliandra contained high levels of polyphenolic compounds, which are known to inhibit microbial activities thereby slowing down the rate of decomposition and N release (Chesson, 1997; Mafongoya et al., 1998). Similar results have been reported by other researchers working in the same area. For example, Handayanto et al. (1994) reported that gliricidia prunings decomposed faster and released more N than calliandra prunings although both had similar C:N ratio, and by Mugendi et al. (1994), who reported 30% higher maize yields with sesbania over calliandra though the two species had similar average leaf N content.

Lignin concentration of calliandra and maize roots were significantly higher than that of leucaena, and this helps to further explain why calliandra and maize roots decomposed and mineralized at a relatively slower pace compared to leucaena. Lignin has for a long time been considered as one of the most important indices determining the rate of decomposition and its role in litter decay and nutrient release is widely reported in literature (Palm, 1995; Jama and Nair, 1996; Mafongoya et al., 1998). Lignin is known to be highly resistant to microbial decomposition and it slows down N mineralization due to binding of N (Chesson, 1997).

Results that are becoming increasingly available from recent studies in decomposition patterns of several agroforestry species reported from a wide variety of situations indicate that the large variations observed in the rates and patterns of decomposition and nutrient release can largely be interpreted based on the chemical quality parameters of the materials; and this information is now being used for making appropriate management decisions (Nair et al., 1999). For example, biomass materials to be used as nutrient sources could be selected to match the nutrient demand pattern of a specified crop depending on their decomposition and nutrient release patterns. This might be achieved by using specific plant materials or mixtures of high and low quality materials which may release nutrients slowly at first, when crop demand is low, and provide an increasing rate of release with time, as the crop grows and demands more (Swift, 1987; Mafongoya and Nair, 1997).

Though this study indicates that decomposition and nutrient release seems to be governed by the chemical composition of the plant materials, there were no detectable differences between calliandra and leucaena *ex-situ* (biomass transfer) prunings applied treatments in terms of N mineralization and N uptake by maize. The differences observed in the alley cropped treatments, especially in terms of N uptake and recovery, seems to be related to the differences in terms of maize yield, which is a consequence of the differences in competition shown by the two tree hedges as was explained in part 1 of this study. However, the fate of the substantial amount of excess mineral-N observed in the top soil layer in all the treatments early in the season before the crop developed extensive rooting system merits further investigations. This mineral-N may be lost to the crop if moved below the crop's rooting depth by percolating water.

Acknowledgements

This research was funded by the Rockefeller Foundation and the Swedish International Development Agency (SIDA). We thank these agencies. We would also like to thank several individuals who collaborated in and supported the study, notably Paul Smithson of ICRAF's analytical laboratory; Cheyrl Palm of TSBF for advice on polyphenol analysis; Jay Harrison of IFAS/University of Florida Statistics; collaborators from KARI and KEFRI in Kenya; and the staff of Kenya's National Agroforestry Research Project at Embu.

References

Anderson JM and Ingram JS (1993) Tropical Soil Biology and Fertility: Handbook of Methods. CAB International, Wallingford, UK

Becker M, Ladha KJ and Ottow JCG (1994a) Nitrogen losses and lowland rice yield as affected by residue nitrogen release. Soil Science Society of America Journal 58: 1660–1665

Becker M, Ladha JK, Simpson IC and Ottow JCG (1994b) Parameters affecting residue nitrogen mineralization in flooded soils. Soil Science Society of America Journal 58: 1666–1671

Birch HF (1958) The effects of soil drying on humus decomposition and nitrogen availability. Plant and Soil 10: 9–31

Chesson A (1997) Plant degradation by ruminants: parallels with litter decomposition in soils. In: Cadisch G and Giller K (eds) Driven by Nature: Plant Litter Quality and Decomposition. CAB International, Wallingford, UK

Constantinides M and Fownes JH (1994) Nitrogen mineralization from leaves and litter of tropical plants relationship to nitrogen, lignin and soluble polyphenol concentrations. Soil Biology and Biochemistry 26: 49–55

Dorich RA and Nelson DW (1984) Evaluation of manual cadmium reduction methods for determination of nitrate in potassium chloride extracts of soil. Soil Sci Soc Am J 48: 72–75

Giashuddin MM, Garrity DP and Aragon ML (1993) Weight loss, nitrogen content changes, and nitrogen release during decomposition of legume tree leaves on and in the soil. Nitrogen Fixing Tree Research Reports 2: 43–50

Handayanto E, Cadisch G and Giller KE (1994) Nitrogen release from prunings of legume hedgerow trees in relation to quality of the prunings and incubation method. Plant and Soil 160: 237–248

Jama BA and Nair PKR (1996) Decomposition- and nitrogen-mineralization patterns of *Leucaena leucocephala* and *Cassia siamea* mulch under tropical semiarid conditions in Kenya. Plant and Soil 179: 275–285

Karlen DL, Flannery RL and Sadler EJ (1988) Aerial accumulation and partitioning of nutrients by corn. Agronomy Journal 80: 232–242

Mafongoya PL and Nair PKR (1997) Multipurpose tree prunings as source of nitrogen to maize under semiarid conditions in Zimbabwe. Part 1. Nitrogen-recovery rates as influenced by pruning quality and method of application. Agrofor Syst 35: 31–46

Mafongoya PL, Nair PKR and Dzowela BH (1997) Multipurpose tree prunings as a source of nitrogen to maize under semiarid conditions in Zimbabwe. 2. Nitrogen-recovery rates and crop growth as influenced by mixtures and prunings. Agrofor Syst 35: 47–56

Mafongoya PL, Giller KE and Palm CA (1998) Decomposition and nutrient release patterns of prunings and litter of agroforestry trees. Agrofor Syst 38: 77–97

Mugendi DN, O'Neill MK and Seward P (1994) Evaluation of potential of leaves of multipurpose tree species as source of nitrogen for maize. African Crop Science Journal 2: 273–278

Mugendi DN and Nair PKR (1997) Predicting decomposition patterns of tree biomass in tropical highland microregions of Kenya. Agrofor Syst 35: 187–201

Mugendi DN, Nair PKR, Mugwe JN, O'Neill MK and Woomer PL (1999) Alley crooping of maize with calliandra and leucaena in the subhumid highlands of Kenya: Part 1: Soil-fertility changes and maize yield. Agrofor Syst (in press)

Myers RJK, Palm CA, Cuevas E, Gunatilleke IUN and Brossard M (1994) The synchronization of nutrient mineralization and plant nutrient demand. In: Woomer PL and Swift MJ (eds) The Biological Management of Soil Fertility, pp 81–116. John Willey & Sons, Chichester, UK

Nair PKR, Buresh R, Mugendi DN and Latt CR (1999) Nutrient cycling in tropical agroforestry systems: Myths and science. In: Buck LE, Lassoie JP and Fernandes ECM (eds) Agroforestry in Sustainable Agricultural Systems, pp 1–31. CRC Press, Boca Raton, FL

Palm CA (1995) Contribution of agroforestry trees to nutrient requirements of intercropped plants. Agrofor Syst 30: 105–124

Parkinson JA and Allen SE (1975) A wet oxidation procedure suitable for the determination of nitrogen and mineral nutrients in biological materials. Commun. Soil Sci Plant Anal. 6: 1–11

Rubaduka EB, Cadisch G and Giller KE (1993) Mineralization of nitrogen in woody legume prunings and recovery by maize. In: Mulongoy K and Merckx R (eds) Soil Organic Matter Dynamics and Sustainability in of Tropical Agriculture. John Willey and Sons, Chichester, UK

SAS (1988) SAS/STAT User’s Guide, Release 6.03. SAS Institute, Cary, NC, USA

Swift MJ (ed) (1987) Tropical Soil Biology and Fertility: Interregional Research Planning Workshop. Special Issue 13, Biology International. Paris France: IUBS

Wieder R and Lang G (1982) A critique of the analytical methods used in examining decomposition data obtained from litter bags. Ecology 63: 1636–1642