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Soil nitrogen dynamics in alley cropping and no-till systems on ultisols of the Georgia Piedmont, USA

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Abstract. On highly-weathered Ultisols of the Georgia (USA) Piedmont, a combination of no-till agriculture and alley cropping presents an option for rapidly increasing soil nitrogen availability while restoring long-term soil fertility. Three years after the establishment of *Albizia julibrissin* hedgerows and no-till agriculture trials, we measured inorganic soil nitrogen (NO_3^-–N and NH_4^+–N) and net nitrogen mineralization during a 4-month field study and a 14-day laboratory study . We also measured the influence of tree leaf amendments on grain sorghum production and N uptake. Soil nitrate increased four-fold within two weeks of adding *Albizia* leaf mulch. Soil ammonium did not increase as rapidly nor to the same extent after tree mulch addition. Averaged over the 4-month study, soil nitrate and ammonium were 2.8 and 1.4 times higher in the alley-cropped than in the treeless no-till plots. Net nitrification and mineralization were no higher in the alley cropping plots, during either field or laboratory incubations. Tree mulch additions enhanced crop biomass production and N uptake 2 to 3.5 times under both high and low soil moisture conditions. Our study demonstrates the dramatic short-term impacts of *Albizia* mulch addition on plant available nitrogen. Combined with no-till practices, alley cropping with *Albizia* hedges offers Piedmont farmers an option for reducing reliance upon chemical N fertilizer while improving soil organic matter levels.

Introduction

The soils of the Georgia Piedmont are highly-weathered Ultisols with low organic matter and nutrient reserves. They are highly susceptible to erosion and physical and chemical degradation from tillage. Soil carbon (C) has been shown to decline from 1.33% in undisturbed forest to 0.92% after three years of conventional-till agriculture (Giddens, 1957). Typical agricultural practices in the region rely heavily on inorganic fertilizer inputs.

Concern over the environmental consequences of long-term application of chemical fertilizer has provoked interest in alternative land use practices. No-till techniques plant crops without overturning the soil and protect the soil surface beneath crop residue. On the Piedmont, no-till planting increases crop yields and reduces soil, fertilizer, and chemical loss from agricultural fields (Tyler et al., 1994). This practice has become the most extensively used conservation tillage practice in the region. Conversion from conventional tillage to no-till agriculture on Piedmont Ultisols restores soil organic matter and mineralizable N pools. Cabrera (M. Cabrera, pers. comm., 1996) measured a three-fold increase in both total soil C and N and mineralizable N pools following a decade of no-till farming. The mulch cover and lack of soil disturbance both improve water and physical soil properties (Radcliffe et al., 1988; West et al., 1992) and increase soil biotic activity (Hendrix et al., 1986; Beare et al., 1992).

Combined with no-till practices, alley cropping may offer an effective option to farmers attempting to reduce their reliance on chemical inputs. Nutrients derived from leaf prunings of woody hedge species can substitute for inorganic fertilizer amendments. Hedges of nitrogen-fixing trees can increase the overall nutrient capital and the cycling of plant nutrients. Roots from tree hedges protect against surface runoff and associated soil and chemical loss (Lal, 1989a); they also potentially form a 'safety net' to recycle nutrients from deep within the soil profile back to the surface (van Noordwijk and De Willigen, 1991). In addition to the release of nutrients from decomposing leaf mulch, alley cropping may contribute to soil organic matter buildup and to increased nutrient mineralization from within soil reserves (Haggar et al., 1993). The long-term increase in the SOM pools accrue through the stabilization of above and below-ground inputs and restoration of soil structure.

Tree leaf mulch from hedge species often provides between 100 and 200 kg N ha^{-1} to alley cropping systems (Kang, 1993; Palm, 1995). Nitrogen release from mulch to the soil is controlled by leaf N, lignin and polyphenolic concentrations (Palm and Sanchez, 1989; Constantinides and Fownes, 1994). Leguminous tree species with high leaf N concentrations and low lignin and phenolic compounds, such as *Gliricidia sepium*, *Leucaena leucocephala* and *Sesbania sesban* liberate more than half of their leaf N within two weeks of pruning (Oglesby and Fownes, 1992; Table 1).

While the contribution of leaf mulch to the soil can rapidly increase plant available soil nutrients (Tian et al., 1993; Palm, 1995), the influence of alley cropping on soil organic matter pools requires more time. The degree of long-term soil improvement under alley cropping depends on characteristics of the hedge species (Yamoah et al., 1986; Hauser and Kang, 1993), the soil type (Szott et al., 1991a, 1991b) and the tillage practices (Lal, 1989b). On an Alfisol in Nigeria, Lal (1989b) found that soil C and N reserves declined to a lesser extent with alley cropping and no-till farming than with plow-till. Intercropping with *Gilricidia sepium* hedges was less effective at maintaining soil organic matter than *Leucaena leucocephala* hedges. At the same site, alley cropping with the slowly decomposing species *Senna* (previously named *Cassia*) had a greater positive impact on soil C than *Gliricidia* (Yamoah et al., 1986). Both species generated similar amounts of prunings, but the *Gliricidia* prunings decomposed more rapidly and less C was added to the soil.

The main objectives of this study was to test whether no-tillage with *Albizia*

Table 1. Chemical properties of leaf prunings for *Albizia julibrissin* and other rapidly and slowly decomposing alley cropping species.

Hedge species	N	Lignin	Polyphenol	Lignin:N	Citation
	%				
Albizia julibrissin	3.3	10.1	5.7	3.1	Nissen 1994
Rapid decomposers					
Gliricidia sepium	3.6	11.6	1.6	3.2	Tian et al. 1992
	3.3	7.2	2.3	2.2	Constantinides and Fownes 1994
Leucaena leucocephala	3.6	13.4	5.0	3.8	Tian et al. 1992
Sesbania sesban	3.5	5.6	4.1	1.6	Constantinides and Fownes 1994
Slow decomposers					
Inga edulis	2.5	18.0	9.5	7.3	Constantinides and Fownes 1994
Calliandra calothyrsus	2.6	6.4	20.0	2.5	Constantinides and Fownes 1994
Dactyladenia barteri	1.4	14.9	3.2	10.6	Kachaka et al. 1993

alley cropping can surpass treeless no-till agriculture in terms of nutrient availability and soil restoration. Previous work at this study site (Matta-Machado and Jordan, 1995) indicated an increase in soil P availability in alley-cropped plots. To compare the immediate and long-term benefits of *Albizia* leaf mulch (Table 1) on nutrient reserves and cycling, we quantified inorganic-N and total soil C and N pools as net soil N transformations using field and laboratory mineralization assays and bioassay methods.

Methods

Study site

No-till and alley-cropping research was carried out on previously abandoned farmland near Athens, Georgia, USA (33°57′N, 83°19′W). Annual precipitation and temperature average 1265 mm and 18 °C. The Georgia Piedmont is a humid subtropical region with uniform monthly precipitation (Figure 1). On average, monthly precipitation exceeds 100 mm except between August and November. The frost-free period extends from mid-March through mid-October. The study plots are situated on kaolinitic, thermic Typic Hapludult soils. Surface soils (0–5 cm) have a pH in water of 5.8, 1.65% C, 5–7 mg P kg^{-1} bicarbonate extractable P, and a sandy loam texture.

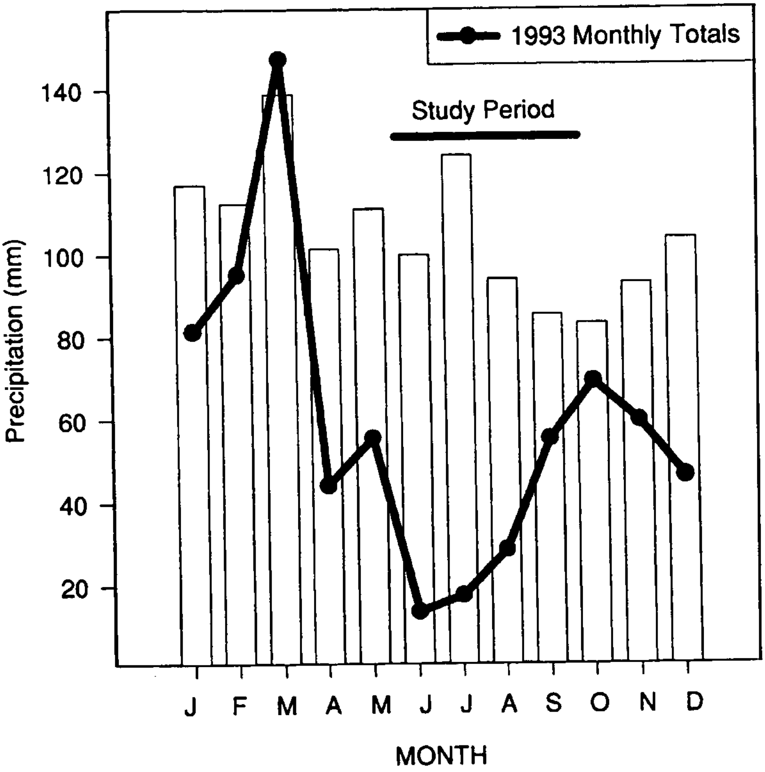

Figure 1. Monthly average precipitation of Athens, Georgia (1961–1990) and monthly total precipitation during the year of the study (NOAA, 1993).

Study design and management

Albizia julibrissin (mimosa) seedlings were planted in 1990 with 50 cm between trees and 4 m spacing between hedgerows. No-till cropping began in 1991 with grain sorghum (*Sorghum bicolor*) during the summer months and winter wheat (*Triticale aestivum*) as a winter cover crop. Paired alley cropping and treeless no-till plots were established in a randomized design with three blocks. Crop and residue management was identical on alley cropping and no-till control plots. Sorghum was planted using a no-till planter with 75 cm spacing between rows. Residues from both summer and winter crops were mowed and left on the plots.

Hedge pruning and mulch additions to the alley cropped plots began in 1991. Trees were hand pruned to 1 m height and leaf material and small branches evenly distributed across alleys. The date of pruning coincided with crop planting in an attempt to synchronize nutrient inputs from leaf biomass with early crop growth. Tree prunings and residual crop mulch were sampled in randomly located, 0.25 m^2 quadrats, immediately after pruning. Prunings were separated into leaf and twig classes and analyzed for biomass and nutrients.

N Cycling

We compared inorganic soil N pools, plant N uptake, net N mineralization and nitrification rates, and total soil N and C reserves in alley cropping and no-till plots. These parameters allow us to differentiate the immediate and long-term benefits of alley cropping with *Albizia.*

During the 1993 summer cropping season, following two years of mulch management, extractable nitrogen and net nitrogen transformations were measured in the 0–5 cm soil layer (Raison et al., 1987; Anderson and Ingram, 1993). In the alley-cropped plots, soil was sampled and incubation chambers were installed along regularly-spaced, perpendicular transects 0, 1, and 2 m from the hedges. Three replicate sample transects were installed per block (3) in alley cropping. Sample locations were selected randomly in no-till plots. Sample and incubation periods were repeated at 7-day intervals for two months, then at 14-day intervals and finally for one 30-day interval. Sampling spanned a 4-month period, beginning at the time of planting and mulch addition (3 June 1993) until crop harvest (23 September 1993).

Soil NO_3^-–N and NH_4^+–N were extracted with 2 *M* KCl from fresh soil within eight hours of sampling (10 g soil : 50 mL extractant). Filtered extracts were frozen until colorimetric analysis on an Alpkem RFA-300 autoanalyzer (Perstorp Inc., Wilsonville, Oregon). Gravimetric soil moisture content was determined by oven drying subsamples at 105 °C for 24 h.

Soil incubation chambers consisted of 10-cm diameter PVC tubes driven through the mulch layer and into mineral soil. Chambers were covered with loose-fitting caps that allowed gas movement and prevented leaching losses. Roots are severed when tubes are installed, so N loss to plant uptake is assumed to be negligible. Within the incubation tubes, changes in inorganic N levels during the sequential incubations represent net nitrogen mineralized from organic sources. Assuming no losses to leaching, plant uptake or gaseous N efflux, net mineralization, nitrification and ammonification were calculated as follows (Hart et al., 1994):

$$\text{Net mineralization} = (NH_4^+\text{–}N + NO_3^-\text{–}N)_{t+1} - (NH_4^+\text{–}N + NO_3^-\text{–}N)_t$$

$$\text{Net nitrification} = (NO_3^-\text{–}N)_{t+1} - (NO_3^-\text{–}N)_t$$

Both the initial and final N concentrations were corrected for the soil moisture content at the time of sampling. Negative net transformation rates indicate that microbial immobilization exceeds gross inorganic N production. Cumulative nitrogen production is the summation of the net nitrogen transformations during the 4-month series of incubations. Total soil N and C for the 0–5 cm and 5–15 soil depths were measured by the Dumas combustion method using a Carol Erba model 1500 CN analyzer (Carlo Erba Instruments, Milano, Italy).

To remove the effects of abiotic in-field variation on N-transformations, we carried out a laboratory incubation under optimal temperature and moisture conditions (Binkley and Hart, 1989). Mulch-free mineral soil from the alley cropping and no-till plots were incubated for 14 days in plastic cups. The gravimetric water content of the incubations was adjusted to field capacity and maintained with deionized water. Samples were maintained at 30 °C. Soil extractions and N transformations were carried out and calculated as above.

During the 1993 summer cropping season, rainfall was only 20 to 30% of the long-term average (Figure 1). The drought withered the sorghum crop and prevented quantification of crop response to alley cropping. To compensate for the drought we carried out a 60-day bioassay with sorghum grown in alley-cropped and no-till soils. Three hundred g of fresh, sieved (< 2 cm) soil was packed into plastic pots to an initial bulk density of 1.2 g cm^{-3}. *Albizia* leaflets and rachises, equivalent to 107 mg N per cup, were added to the surface of half the pots. High and low watering regimes were used to isolate the physical effect of the leaf mulch on soil moisture. Fifty mL of deionized water were added every two or four days to the high and low-moisture regimes. At harvest, above-ground tissue and sorghum roots were dried, ground and analyzed for total N and C.

Results

Pruning biomass

Tree prunings contributed 5.33 tons of dry matter and 118 kg of N per hectare to the alley cropping plots (Table 2). *Albizia* leaf matter comprised 55% of the biomass and 80% of the N inputs. Total tree mulch contributed 2.5 tons of C per hectare.

Table 2. Nitrogen concentration, biomass and nutrient inputs in *Albizia* prunings (n = 36), Georgia, USA.

Pruning component	Tissue N %	Pruning biomass t ha^{-1}	N kg N ha^{-1}	C kg C ha^{-1}
Leaves	3.3	2.9	95	1416
Small twigs (< 1 cm dia.)	1.2	1.0	16	475
Large twigs (> 1 cm dia.)	0.7	1.4	7	618
Total		5.3	118	2509

N cycling

Soil NO_3^-–N increased rapidly following the *Albizia* leaf mulch addition (Figure 2). Within 2 weeks of adding the leaf prunings, NO_3^-–N increased four-fold in the alley cropping plots. Soil NO_3^-–N remained 8 kg N ha^{-1} higher in the alley cropping plots than in the no-till plots for about two months, before declining. Soil ammonium did not respond as rapidly nor as dramatically as nitrate. Averaged over the entire study period, extractable NO_3^-–N and NH_4^+–N were 2.8 and 1.4 times higher in the alley cropping plots (Table 3). Within the alley cropping plots, NO_3^-–N or NH_4^+–N pools were 25 and 22% higher at 1 m compared to 2 m from the *Albizia* hedges (*t*-test, $p = 0.045$ and 0.106).

Net production of soil NO_3^-–N during the field incubations was equal in the alley cropping and no-till treatments (Figure 3). More than 90% of the net N mineralized was also nitrified. In the alley-cropped plots, there was a brief immobilization phase immediately after adding leaf mulch followed by relatively steady production of mineral N. The cumulative gain in nitrate during the 16 week study was equivalent to 25 and 20 kg of NO_3^-–N ha^{-1} in the alley cropping and no-till plots.

Weekly *in situ* mineralization and nitrification rates were not significantly greater in the alley cropping plots (*t*-test, $p = 0.728$ and 0.770) though the trend suggests that N cycling is progressing more rapidly in the alley cropping plots (Table 3). Under optimum moisture and temperature conditions in the laboratory incubation, nitrification rates increased more than six times over the field study.

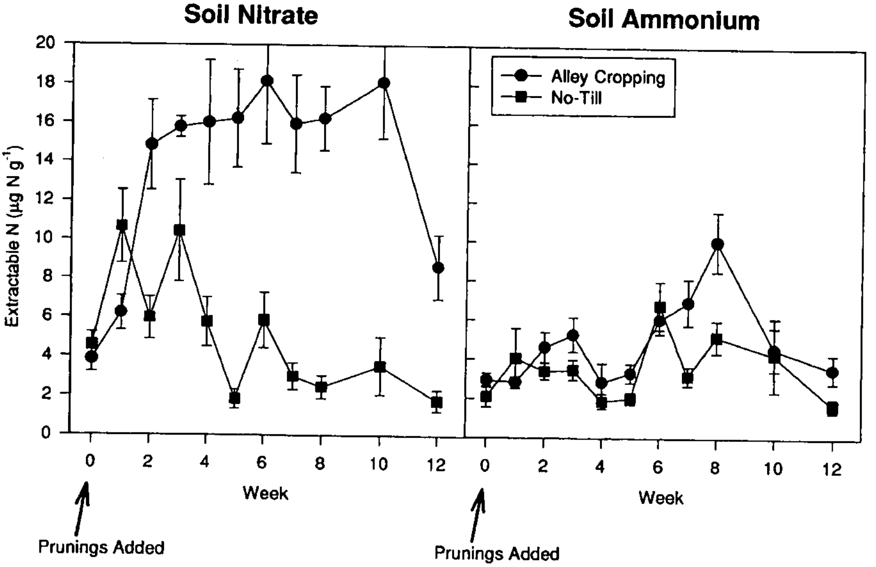

Figure 2. Extractable soil nitrate and ammonium levels in no-till and alley cropping plots during 1993 cropping season, Georgia, USA. Error bars show standard error of the mean.

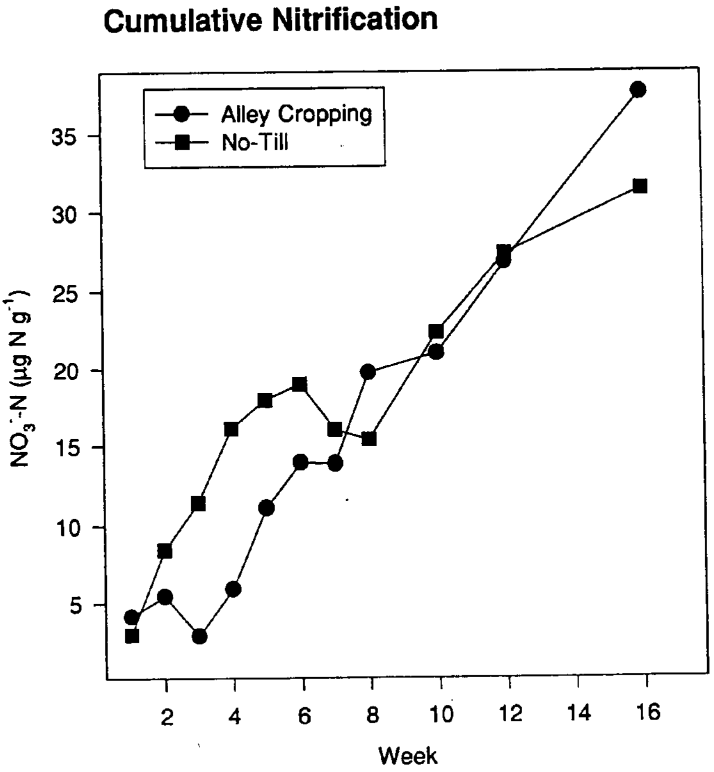

Figure 3. Cumulative net nitrification in alley cropping and no-till plots during the 16 week study period, Georgia, USA. There were no significant difference between the sites at the 0.05 level.

Table 3. Extractable soil N pools and net N transformations during *in situ* (0–5 cm depth) and laboratory incubations. Mean extractable soil pools and *in situ* transformation rates averaged over the 16 week study (SE of mean), Georgia, USA.

	In situ pools		*In situ* rates		Laboratory rates	
	Ammonium	Nitrate	Mineralization	Nitrification	Mineralization	Nitrification
	— (μg N g^{-1}) —		— (μg N g^{-1} wk^{-1}) —		— (μg N g^{-1} wk^{-1}) —	
Alley cropping	4.56 (0.28)	13.56 (0.74)	2.48 (0.80)	2.26 (0.65)	11.51 (0.80)	13.86 (0.79)
No-till	3.33 (0.28)	4.77 (0.45)	2.24 (0.64)	1.98 (0.49)	12..01 (1.98)	13.38 (2.10)
t-test probability =	0.0023	0.00	0.81	0.73	0.82	0.84

Gravimetric soil moisture did not differ significantly between the alley cropping and no-till plots at any time during the study. Averaged over the entire study, the top 5 cm of soil in the alley cropping and no-till plots both had 7.8% moisture content (*t*-test, $p = 0.929$). The drought withered the sorghum plants equally in both treatments.

After a 60-day bioassay under unmulched, dry conditions, sorghum growth and N uptake were similar in the alley-cropped and no-till soils (Figure 4). Addition of leaf prunings increased plant biomass and N uptake 2 to 3.5 times across the soil and moisture treatments. Leaf prunings generated similar increases in plant growth and N uptake as did the increased moisture treatments. Leaf mulch increased soil moisture similarly in both soil types under both soil moisture regimes. Mulching and the increased moisture treatment produced greater plant growth and N uptake responses in the alley cropping than in the no-till soil.

In the alley-cropped soil under moist conditions, the leaf mulch additions increased total plant N uptake two-fold while decreasing soil mineral N (NO_3^-–N + NH_4^+–N) four-fold (Figure 5). Under the drier regime, mulch increased plant N uptake nearly four-fold and doubled soil mineral N. Total plant-soil system N was twice as high under drier conditions (33 vs. 18 mg N pot^{-1}) suggesting leaching or denitrification losses or higher microbial immobilization under the wet regime.

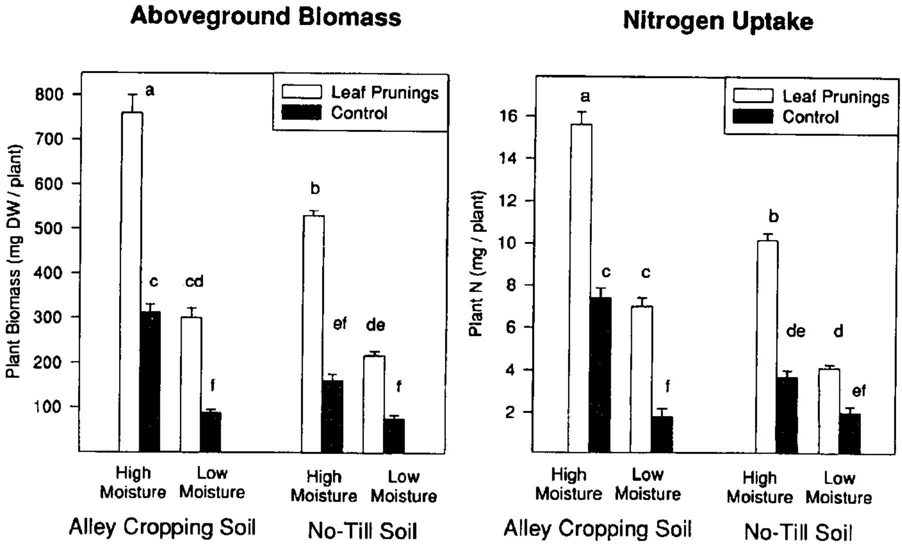

Figure 4. Sorghum aboveground biomass and N uptake during a 60-day bioassay using alley-cropped and no-till soils, Georgia, USA. Error bars show standard error of the mean. Mean values labelled with the same letter are not significantly different for Tukey's means separation test at the 0.05 critical level.

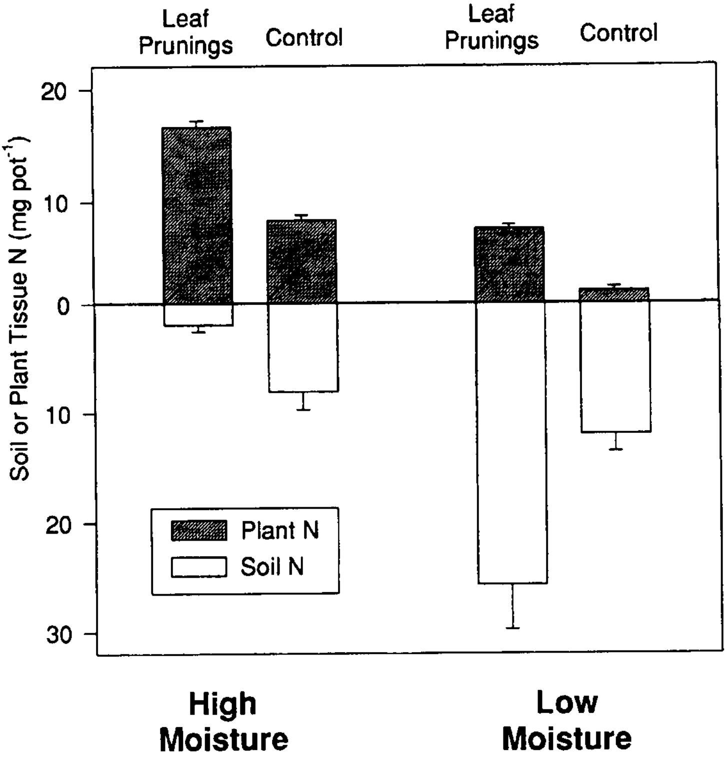

Figure 5. Mulch impact on sorghum biomass (roots + above ground) and soil N in alley cropping soil at completion of 60-day bioassay, Georgia, USA. Soil N values report 2 *M* KCl extractable NO_3^-–N + NH_4^+–N (mg per pot). Error bars show standard error of the mean.

Total soil pools

Total soil C and N pools and bulk density changed little after three years of alley cropping and no-till agriculture (Table 4). Total soil N increased by 9% in the *Albizia* alleys and decreased by 2.5% in the no-till plots. Differences between and 1 and 2 meter plots in the alley cropping sites were not statistically significant. In 1993, total C and N in the alley cropping and no-till plots were not significantly different at either soil depth.

Discussion and conclusions

Short-term effects

Albizia mulch additions directly influenced the plant-available soil nitrate pool. The apparent discrepancy between the soil NO_3^-–N pool and the net nitrifi-

Table 4. Total soil C and N and bulk density in alley cropping and no-till plots, Georgia, USA.

			Total C ($t\ C\ ha^{-1}$)		Total N ($t\ N\ ha^{-1}$)	
	Soil depth (cm)	Bulk density ($g\ cm^{-3}$)	1990	1993	1990	1993
Alley cropping	0–5	1.34	11.52	11.72	0.80	0.88
	5–15	1.40	8.05	8.19	0.56	0.56
No-till	0–5	1.34	10.92	10.45	0.79	0.77
	5–15	1.46	8.47	7.88	0.58	0.52

Source: 1990 data from Matta Machado.

cation rated suggests that the rapid increase in soil NO_3^-–N is generated by N released directly from litter, rather than by a pulse of soil nitrification. The sustained increase in NO_3^-–N may have resulted from the severe drought conditions. Under average rainfall conditions, soil nitrate would have been prone to greater leaching and denitrification losses, as well as higher crop and microbial demand. This was the case during the sorghum bioassay when soil mineral N declined four-fold under wet conditions but doubled under dry conditions for mulched pots.

Albizia leaves decompose and release N rapidly after pruning. Nissen (1994) measured a 40% reduction in *Albizia* leaf mass and 30% N loss after one month in the field. Half of these losses occurred during the first two weeks. This rapid N release is consistent with *Albizia*'s high leaf N and relatively low lignin and polyphenolic contents (Palm and Sanchez, 1989; Constantinides and Fownes, 1993) (Table 1). The *Albizia* prunings contributed about 100 kg N ha^{-1} to the alley cropping plots. Based on *Albizia* litter decomposition studies at our research site (Matta-Machado et al., 1994; Nissen, 1994), about 10 kg of N would have been released from the leaves within two weeks of pruning. During that time period, we measured an 8 kg increase in the extractable soil nitrate pool. Over the course of a 4-month cropping season, *Albizia* mulch would release a total of 40–50 kg N ha^{-1} (Matta-Machado et al., 1994; Nissen, 1994).

Long-term soil changes

We found no evidence that *Albizia* hedgerows generated long-term changes in soil properties beyond levels found in no-till agriculture. On Costa Rican Inceptisols, seven years of alley cropping doubled soil mineralization rates compared to no-till cropping (Haggar et al., 1993). The slight trend towards greater total N and net mineralization on the Georgia Ultisols may continue to aggrade in upcoming years. The degree of soil improvement may be limited by the capacity of the kaolinitic clays to sequester soil C. Substantial SOM accretion may require greater pruning inputs than what is possible due to seasonal and soil fertility constraints of the Piedmont region.

The high-quality *Albizia* litter directly influences inorganic soil N pools, without influencing total SOM pools. Our results agree with research from Nigeria, where rapidly decomposing *Gliricidia* was less effective than slow decomposing *Senna* (Yamoah et al., 1986). In addition to providing refractory organic inputs, slow decomposing litter insulates the soil and conserves soil moisture (Tomar et al., 1992). In our study, crops were not removed from the site, so all residues remained on the alley cropping and no-till plots. Soil moisture was controled more by the low-quality crop residue than by the *Albizia* leaf additions to the alley-cropped plots. This also may explain the relatively stable soil C and N levels compared to other studies where soil C and N declined under alley cropping and no-till agriculture (Lal, 1989b; Tian et al., 1993).

A seen in other sites, alley cropping with leguminous shrubs can satisfy crop requirements for nitrogen (Palm, 1995). *Albizia* alley cropping on the Georgia Piedmont can increase plant available soil N dramatically over levels found in standard no-till farming. Combined with no-till practices, alley cropping with *Albizia* may offer farmers an option for reducing their dependence on inorganic N fertilizers while reducing soil erosion. This production system may appeal to organic farmers producing high value horticultural crops on small acreages.

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