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Nitrogen transfer between high- and low-quality leaves on a nutrient-poor Oxisol determined by ^{15}N enrichment

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Abstract

It has been proposed that the C/N ratio, or quality, of litter or mulch mixtures affects N release. Although total N release from these mixtures and the effects on soil N are relatively well understood, a mechanistic understanding of the interactions between litter species with respect to their N release is still lacking. This study examines decomposition and N dynamics in mixtures of high-quality leguminous mulch, gliricidia [*Gliricidia sepium* (Jacq.) Kunth. ex Walp.] with a C/N ratio of 13, and low-quality cupuaçu [*Theobroma grandiflorum* (Wild. ex Spring) Schumann] litter with a C/N ratio of 42, which occur in combination in agroforestry systems. Ratios of 100:0, 80:20, 50:50, 20:80, 0:100 of fresh ^{15}N-enriched gliricidia leaves and senescent cupuaçu leaves, totaling the same dry weight of 6.64 t ha^{-1}, were applied to an Oxisol and sampled at 6, 14, 38, and 96 days after application. After more than 40% of the N in the gliricidia leaves had been released and the microbial biomass N reached its peak, a significant increase in available soil N occurred at day 14, which was more pronounced with greater amounts of gliricidia in the leaf mixture. However, relative to the N applied in the leaf mixture, there was no significant difference in available soil N with greater proportions of gliricidia. Total N release from the mixtures corresponded to the total N applied by gliricidia. Until day 38, cupuaçu C mineralization was significantly faster in the presence of the highest proportion of gliricidia compared to lower proportions. This faster C mineralization of more than 0.5% per day, however, did not increase total C loss or N release from cupuaçu leaves after 96 days. The use of ^{15}N tracers identified an N transfer from gliricidia leaves and the soil to cupuaçu leaves and consequently, a lower N release from gliricidia to the soil in the presence of cupuaçu leaves. Though we expected that available N in the soil would also decrease with greater amounts of cupuaçu litter in the mixture, our results indicated an additive effect of the two species on N release and soil mineral N, with gross interactions between them canceling net interactive effects. Therefore, N release of leaf mixtures behaved as predicted from a calculated sum of individual release patterns, in spite of a transfer of N from the high- to the low-quality leaves.

Keywords: Decomposition; *Gliricidia sepium*; Green mulch; ^{15}N; Litter quality; *Theobroma grandiflorum*

1. Introduction

In small-scale tropical agroforestry systems prunings from leguminous trees such as gliricidia (*Gliricidia sepium* (Jacq.) Kunth. ex Walp.) are an accessible N source. An understanding of how different types of leaf materials affect N release and decomposition dynamics can facilitate synchronization with crop demands through appropriate timing of the application of suitable species and quantities of prunings such as green manures or mulches. The term mulch is used in this study to describe applied organic matter from fresh prunings in contrast to naturally fallen litter. Nitrogen release from organic materials such as litter or mulches can vary significantly according to the leaf quality, which can be related to their chemical composition. Some studies were able to correlate the polyphenol/N ratio with N mineralization (Palm and Sanchez, 1990; Oglesby and Fownes, 1992) while others found the initial lignin/N (Handayanto et al., 1997) and (lignin + polyphenol)/N ratios

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(Lehmann et al., 1995; Handayanto et al., 1997; Mafongoya and Nair, 1997) to be better predictors of decomposition and N release. Controls over decomposition and N release can vary according to residue quality. For example, lignin/N ratios (Melillo et al., 1982) and initial N concentrations (Seneviratne, 2000) better explained decomposition for lower quality litters with less than 2% N and high lignin contents, while polyphenol/N ratios controlled decomposition of higher quality green mulches (Palm and Sanchez, 1990; Constantinides and Fownes, 1994; Lehmann et al., 1995; Seneviratne et al., 1998). Additionally, the reactivity of polyphenols, not just the quantity, is important for mineral N accumulation (Mafongoya et al., 1998).

Since it is usually not feasible to considerably change the quality of any given plant material, mulch or litter quality has been manipulated by mixing high- and low-quality organic matter to reduce leaching losses, prolong nutrient availability, and synchronize nutrient release with crop demands (Myers et al., 1994). The intention is to increase N release from low-quality leaves by mixing them with high-quality leaves and vice versa to meet certain requirements such as synchronization between N release and uptake by the crop. In mixtures of leaves with contrasting qualities, N interactions occur and can complicate prediction of N dynamics (Handayanto et al., 1997). Few studies have looked at these interactions in mixtures of leaves from agroforestry species (Handayanto et al., 1997; McGrath et al., 2000), and few have compared N dynamics of fresh leaves to those of senescent litter (Mafongoya and Nair, 1997). Nitrogen tracers are a useful tool for detecting N interactions between mixtures of leaves from different species. Several studies have used ^{15}N-enriched green mulch to trace N uptake from a single species mulch (Haggar et al., 1993; Cadisch et al., 1998) but fewer have applied this technique to trace N recovery from mixed species mulches (Handayanto et al., 1997).

The objective was to investigate interactions between a high-quality leguminous green mulch, gliricidia, and a low-quality litter from cupuaçu trees in terms of decomposition and N release. With ^{15}N tracers, we aimed to quantify the effect of different ratios of gliricidia mulch and cupuaçu litter on N availability in soil. We hypothesized that cupuaçu litter would immobilize N from the higher quality gliricidia mulch and decrease available soil N. We also expected decomposition and nutrient release from cupuaçu litter to increase in the presence of high quantities of gliricidia.

2. Materials and methods

2.1. Site selection and preparation

The study was conducted at the Empresa Brasileira de Pesquisa Agropecuaria—Centro da Pesquisa Agroflorestal (EMBRAPA-CPAA) experimental station located north of Manaus on the BR 174 highway in the central Amazon Basin (2°30′36″–2°30′42″S and 60°01′29″–60°01′46″W). The experimental plot, located in an open grassy field, was selected based on low, homogenous soil C and nutrient contents, minimal prior disturbance, and no previous fertilizer application. The soil was a degraded typic Hapludox with the following soil properties for the upper 0–3 cm: pH in water of 5.05, 1.3 mg N g^{-1}, 18.0 mg C g^{-1} (automatic CN Analyzer, Elementar), 2.05 mg P kg^{-1}, 55.0 mg K kg^{-1} (Mehlich-1 extractable), 11.7 mg Ca kg^{-1}, and 4.6 mg Mg kg^{-1} (KCl extractable).

Treatments were applied to a 5 m×5 m plot 3 weeks after the removal of vegetation in order to allow the soil to stabilize. For each replicate 25×25 cm parcels were marked with 10 cm high aluminum borders in a completely randomized design with four replicates. The entire study area was fenced to prevent large mammals and wind-blown material from entering. To reduce rain splash and excessive drying of the leaves compared to within an agroforestry system, the site was covered with shade cloth, which filtered 50% of the light and reduced rainfall impact without reducing total rainfall volume. The experiment was conducted from July 11, 2002 to October 15, 2002. Total precipitation during the experimental period was 305 mm, and the maximum rainfall in a 24-h period was 43.3 mm.

2.2. Experimental setup

Different ratios of fresh gliricidia leaves without their branches and senescent air-dried cupuaçu leaves were mixed and applied to the soil surface within each 0.25× 0.25 m parcel for each treatment. Fresh gliricidia leaves were mixed with dry cupuaçu leaves to simulate the leaf mixture as it would occur in an agroforestry system following the application of fresh gliricidia mulch to the litter under cupuaçu trees. The objective was to apply the same total dry weight 6.64 t ha^{-1}, equivalent to 41.5 g, of leaves to each treatment in the following ratios of gliricidia to cupuaçu: 100:0, 80:20, 50:50, 20:80, and 0:100. Actual ratios of 100:0, 82:18, 54:46, 22:78, 0:100 and dry weight application rates of 6.44, 6.64, 6.94, 7.24, and 7.44 t ha^{-1}, respectively, deviated slightly from intended ratios due to estimation of leaf moisture contents. Nitrogen ratios, calculated from the dry weights and original N concentrations of the leaves, were as follows: 100:0, 91:9, 71:29, 38:62, 0:100. Table 1 shows initial C/N ratios, N and polyphenol concentrations, and δ^{15}N values of the two leaf species. Senescent cupuaçu leaves about to fall from the tree were collected during 3 weeks prior to application. Fresh ^{15}N-enriched gliricidia leaves were applied within 2 h after pruning. The gliricidia leaves were enriched in ^{15}N by applying 0.57 g ^{15}N, using 10% ^{15}N excess as $(NH_4)_2SO_4$, in solution to the mineral soil in a 1 m radius around the tree 4 1/2 weeks prior to collecting the leaves.

To compare N movement below the 3 cm sampling depth in the parcels, one nylon bag containing 6 g of air-dried

Table 1
Leaf quality parameters of gliricidia (*Gliricidia sepium*) and cupuaçu (*Theobroma grandiflorum*)

Species	C/N	N [g kg^{-1}]	Polyphenol [g kg^{-1}]	δ^{15}N [‰]
Gliricidia sepium	13.4	35.1	23[a]–41[b]	33.8
Theobroma grandiflorum	41.5	12.4	27[c]	2.63

[a] Cadisch et al. (1998).
[b] Lehmann et al. (1995).
[c] Cupuaçu leaves were picked fresh, air-dried, and rewet prior to polyphenol analysis (Seitz, 2003).

Amberlite 150 mixed-bed resin (Rohm and Haas Co., Philadelphia, PA, USA) was buried in each parcel just below 3 cm deep in the soil prior to leaf application. Both NH_4^+ and NO_3^- adhere to mixed-bed resins.

2.3. Sampling

Samples were taken 6, 14, 38, and 96 days after application of the leaf mixtures, except for the resin bags which were collected after 96 days. The leaves were separated by species, cleaned of residual soil with light brushing and dried to a constant weight for 48 h at 65 °C in a drying oven prior to analysis. Resin bags were gently removed from the soil to minimize loss of resin beads, air-dried, and adherent soil removed with gentle brushing prior to mineral N extraction. Soil was collected with a spatula from 0 to 3 cm from most of the parcel area excluding the soil within 5 cm of the parcel edges, mixed, and analyzed for total C, mineral N, total N, δ^{15}N, and microbial biomass C and N.

2.4. Laboratory analyses

Large roots and pieces of organic matter were removed from fresh soil prior to mineral N and microbial analyses. Duplicate 25 g fresh soil samples and the resin bags were extracted with 75 ml of 1 M KCl for 30 min and 1 h, respectively, on a horizontal shaker at 305 rpm (Janke and Kunkel HS 501D). Samples were left overnight to decant and the supernatant was pipetted and analyzed for NH_4^+ and NO_3^- on a continuous flow analyzer (Scan Plus Analyzer, Skalar Analytical B.V., Breda, The Netherlands). Microbial biomass C was determined by glucose-induced respiration (Anderson and Domsch, 1978) and respired CO_2 was measured using a closed chamber Infrared Gas Analyzer (IRGA) Ecotoxicology (ECT)-Soil Respiration Device (ECT—Ecotoxicology GmbH, Flörsheim, Germany) (Förster and Farias, 2000). After collection, soils were stored between 4 and 8 °C. Prior to analysis soils were returned to room temperature of 23 °C and sieved to 2 mm and all visible roots, charcoal and macrofauna were removed. Then 40 g equivalent dry weight was weighed directly into a half cylinder container which was then enclosed and placed in the IRGA ECT-device for a minimum of six readings before a mixture of 6 mg glucose per g soil and 12.5 mg talcum per g soil was added. Respiration measurements following the addition of the glucose substrate continued for at least 10 cycles. Results are reported per dry weight soil, determined by drying at 105 °C for 24 h. Microbial biomass N was determined by the chloroform fumigation–extraction method (Brookes et al., 1985), modified by increasing the incubation time to 72 h.

After oven drying, plant and soil samples were ground with a ball mill to 250 μm. Soil and plant C and N contents and δ^{15}N values were determined by combustion in a CN analyzer (Carlo-Erba model 1110) connected to an isotope mass spectrometer (Thermo Finnigan, San Jose, CA, USA).

2.5. Statistical analyses

Statistical analysis of the data was performed using one-way ANOVA in Minitab 13.1 (Minitab, 2000). Where $P < 0.05$, means were compared using Fishers least significant difference test.

3. Results

3.1. Carbon mineralization and N release from leaf mixtures

After 96 days, 24 and 79% of original C applied with the leaves remained in the 100G:0C and 0G:100C treatments, respectively (Fig. 1a). After 14 days, leaf mixtures with a greater proportion of gliricidia lost significantly more C than all treatments with lower proportions. At 14 days, the cupuaçu litter mixed with the greatest proportion of gliricidia mulch, in a ratio of 80G:20C, had significantly less C remaining than the cupuaçu litter of all other leaf mixtures (Fig. 1b). However, after 96 days, there were no significant differences in C loss of the cupuaçu leaves. Gliricidia C loss was not significantly affected by mixing it with cupuaçu litter after 14 or 96 days (Fig. 1c). At the end of the experimental period, 96 days after application of leaf mixtures, C loss for gliricidia ranged from 67 to 80%, but there was no significant difference among treatments.

After 96 days, N loss from the leaf mixtures as a percent of the N applied with the leaves ranged from 72% in the treatment with only gliricidia added to slight immobilization of less than 1% by the treatment with only cupuaçu added (Fig. 1d). Nitrogen release by the leaf mixtures decreased significantly with decreasing gliricidia and increasing

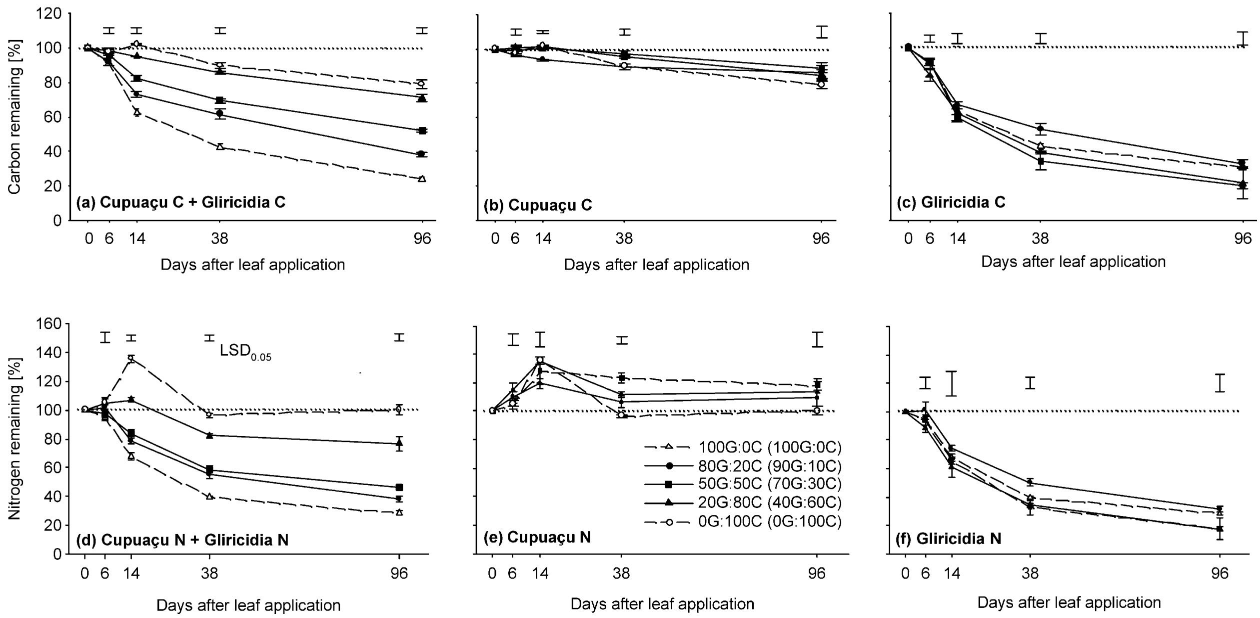

Fig. 1. Percent C and N remaining in gliricidia (*Gliricidia sepium*) and cupuaçu (*Theobroma grandiflorum*) leaves following surface application of different proportions of the two species, expressed as percent gliricidia to cupuaçu by dry weight, on an Oxisol. Each species was analyzed separately and values were combined to graph total C and N loss from leaf mixtures. Ratios of total N applied are in brackets. Bars represent standard errors and Fishers LSD ($P<0.05$; $n=4$).

cupuaçu proportions. In all treatments with gliricidia leaves, gliricidia released N and cupuaçu immobilized N, resulting in a net N release in all treatments except the treatment, where only cupuaçu was added to soil.

In all treatments with cupuaçu in the leaf mixture, immobilization of N by cupuaçu litter increased until 14 days after the start of the experiment and then decreased until 38 days after application, when it remained constant (Fig. 1e). There was no significant difference among treatments in N release from cupuaçu litter after 96 days. Nitrogen release by gliricidia continued during the 96-day experimental period (Fig. 1f). There were no significant differences in percent N release among treatments 14 days after leaf application. By 96 days after application of the leaf mixture, the 100G:0C and 80G:20C treatments had released 72% and 69% of the gliricidia-N applied, respectively, which was significantly less than the 82% of applied gliricidia-N released by the 50G:50C and 20G:80C treatments. The difference in N release between the leaf mixtures with more and less gliricidia could begin to be detected in the C mineralization at 96 days but was not yet significant (Fig. 1c).

3.2. Soil N

Soil mineral N concentrations of all treatments with gliricidia increased significantly until 14 days after application (Fig. 2a). This peak coincided with the largest N immobilization by cupuaçu (Fig. 1e). After 14 days, mineral N concentrations were highest with 100% gliricidia, followed by the 80G:20C treatment and then the 50G:50C and 20G:80C treatments, which were not significantly different. There was no difference in mineral N concentrations between the bare soil and the 0G:100C treatment and no significant change over time in either of these treatments. Total soil N also changed significantly with time and peaked at 38 days in all treatments (Fig. 2b).

Resin-extractable N was significantly higher in all soils, where leaves were applied than the bare soil (Fig. 2b). The highest values occurred in the treatments with the highest proportions of gliricidia in the mixture; the 100G:0C, 80G:20C, and 50G:50C treatments were significantly higher than the 20G:80C and 0G:100C treatments, which were not significantly different. The mulch mixtures did not significantly affect resin-extractable N as a percent of the N applied with the leaves.

3.3. Nitrogen isotope dynamics

Higher proportions of ^{15}N-enriched gliricidia leaves in the mixtures resulted in significantly greater δ^{15}N values in both the soil and the cupuaçu litter. In the cupuaçu leaves the highest δ^{15}N values occurred in the treatments with the highest proportion of gliricidia applied and decreased with decreasing amounts of gliricidia in the mixture (Fig. 3a). δ^{15}N values for gliricidia averaged 38‰ and did not vary significantly among treatments at any given sampling time.

δ^{15}N values of both the soil and cupuaçu leaves with addition of gliricidia were highest at 14 days after mulch application, coinciding with peak soil mineral N concentrations and peak N immobilization by cupuaçu. At this time, δ^{15}N values of cupuaçu leaves were significantly

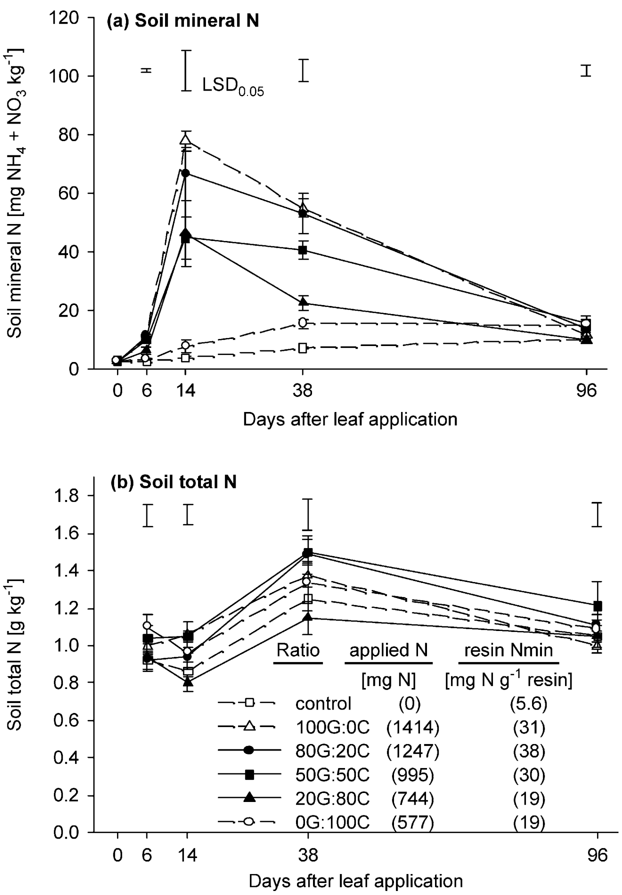

Fig. 2. Mineral N (a) and total soil N (b) concentrations at 0–3 cm soil depth following surface application of different ratios of gliricidia (*Gliricidia sepium*) and cupuaçu (*Theobroma grandiflorum*) leaves, expressed as percent gliricidia to cupuaçu by dry weight, on an Oxisol. The N applied in the leaf mixture and resin-extractable mineral N are indicated in brackets. Bars represent standard errors and Fishers LSD ($P<0.05$; $n=4$).

higher in the 80G:20C and 50G:50C treatments, 13.6 and 11.8‰, respectively, than in the 20G:80C and 0G:100C treatments, 7.5 and 5.4‰, respectively. The soil δ^{15}N values of all treatments with gliricidia in the leaf mixture were higher than the bare soil and than the treatment with only cupuaçu litter (Fig. 3b). The treatment with 100% of the leaf mixture as gliricidia had the highest soil δ^{15}N values. Treatments with mixed applications in ratios of 80G:20C, 50G:50C, and 20G:80C did not differ significantly in soil δ^{15}N values after 14 days. In the treatment with only cupuaçu litter, δ^{15}N values of the cupuaçu leaves peaked at 14 days, but the soil δ^{15}N values did not remain higher over time and were the same as the bare soil at the end of the experiment.

3.4. Soil microbial biomass

Microbial biomass C and N were highest at 14 days after leaf application, ranging from 98 to 247 μg C g^{-1} soil and averaging 31.6 μg N g^{-1} (data for microbial N not shown), coinciding with peak mineral N levels in the soil (Fig. 4).

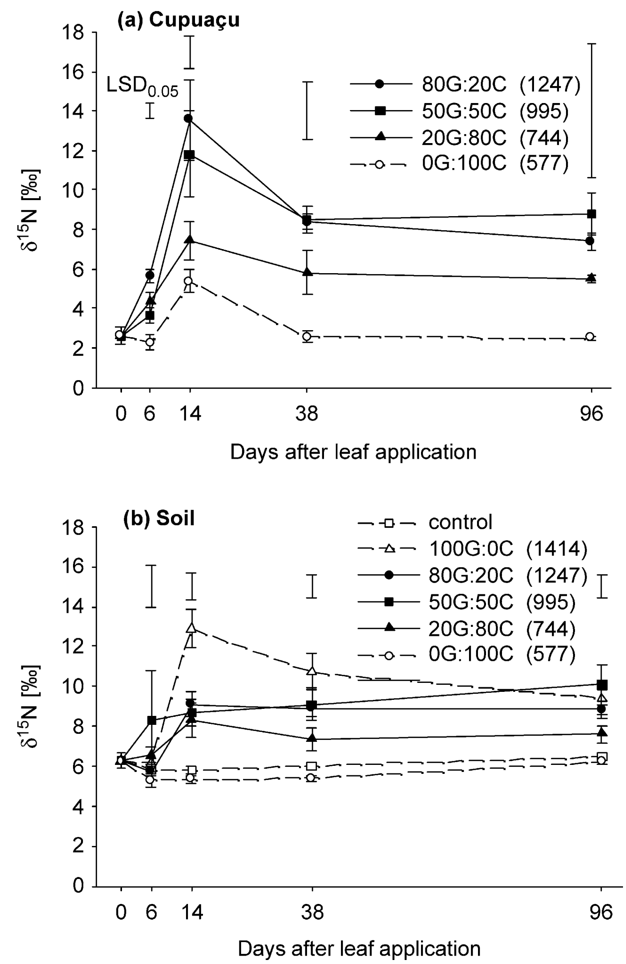

Fig. 3. Mean δ^{15}N values for (a) cupuaçu (*Theobroma grandiflorum*) leaves and (b) soil following surface application of different ratios of senescent cupuaçu and fresh ^{15}N-labeled gliricidia (*Gliricidia sepium*) leaves (average δ^{15}N=38). Ratios are expressed as gliricidia to cupuaçu by dry weight, with total N applied in brackets (mg). Bars represent standard errors and Fishers LSD ($P<0.05$, $n=4$).

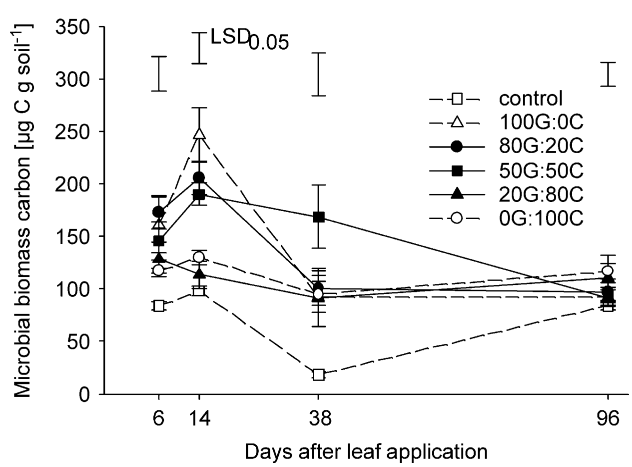

Fig. 4. Soil microbial biomass C from 0 to 3 cm soil depth following surface application of different proportions of gliricidia (*Gliricidia sepium*) and cupuaçu (*Theobroma grandiflorum*) leaves on an Oxisol. Bars represent standard errors and Fishers LSD ($P<0.05$, $n=4$).

After 14 days, the 100G:0C, 80G:20C, and 50G:50C treatments had significantly greater microbial biomass C than the control and remaining treatments. As with soil mineral N concentrations and soil δ^{15}N values, the treatment with 100% of the leaf mixture as gliricidia had the highest microbial biomass C, but not significantly more than the 80G:20C mixture at 14 days. The microbial biomass C of the 0G:100C and 20G:80C treatments was not significantly higher than the bare soil 14 days after leaf application.

4. Discussion

4.1. Nitrogen release dynamics from mulch and litter

Nitrogen released by gliricidia was immobilized by cupuaçu litter and the available soil N pool. Nitrogen transfer from gliricidia to cupuaçu leaves and from gliricidia to the soil was highest 14 days after mulch application, indicated by the increasing δ^{15}N values in cupuaçu (Fig. 3a), and coincided with the fastest N release by gliricidia and peak N immobilization by cupuaçu (Fig. 1). The constant soil δ^{15}N values over time for plots that received no leaves or only cupuaçu leaves indicate that the increase in soil δ^{15}N values of the other treatments was a result of N release from gliricidia mulch and not from cupuaçu litter. Cupuaçu immobilized N from gliricidia mulch and from the soil, as shown by the increase in δ^{15}N at day 14 in the cupuaçu leaves applied in the absence of gliricidia.

Maximum available N in the soil coincided with the highest microbial biomass C, maximum C decomposition, and the fastest N release by gliricidia 14 days after mulch application. Microbial decomposition of the organic material must be held responsible for the N release rather than leaching based on the significant increase in microbial biomass C and a higher microbial respiration than during subsequent sampling periods (data not shown). The effect of N release on total soil N was only detectable after N release by the litter peaked and microbial biomass N decreased.

Nitrogen was cycled among the gliricidia mulch, the cupuaçu litter, and the available soil pool until half of the N had been released by gliricidia and immobilization into microbial biomass had decreased. These results suggest that mixtures of low-quality cupuaçu litter and high-quality gliricidia mulch were able to retain N in the available pool at the soil surface during the first 2–4 weeks after mulch application. However, almost half of the N release by gliricidia occurred between day 14 and 96 when N immobilization in cupuaçu and microbial biomass C contents had decreased. The large amounts of soil mineral N at day 38 suggest that some of that N is susceptible to leaching if it is not taken up by the plants. One month after leaf application appears to be critical for N retention, which should be synchronized with the largest nutrient requirements of the tree crops. Retention of nutrients at the soil surface and reduction of N leaching is especially critical for cupuaçu trees, which have many roots at the interface of the litter and the soil (Haag, 1997). Cupuaçu foliar concentrations of N and other nutrients, such as K and Ca, were found to decrease during the wet season on a Typic Hapludox in central Amazonia (Schroth et al., 2001) which may be a time when mulch additions could increase crop nutrition while they could at the same time reduce potential leaching losses.

4.2. Leaf quality control on decomposition and N release

Increasing amounts of gliricidia in leaf mixtures resulted in more rapid N and C losses and higher available soil N due to the higher litter quality, i.e. higher moisture contents, 76% in gliricidia leaves compared to 21% in cupuaçu leaves, higher N contents and lower C/N ratios. The N release pattern is similar to the N mineralization by mulch mixtures with similar ratios of gliricidia and *Peltophorum dasyrrachis* (Miq.) Kurz under leaching conditions (Handayanto et al., 1997). Mulches composed of more than 50% gliricidia released N immediately, while treatments with little or no gliricidia in the mixture initially immobilized N before releasing it. The rapid C and N loss from gliricidia leaves, which dominated the mixed mulch decomposition and N release, follows that found in other gliricidia prunings (Lehmann et al., 1995; Zaharah and Bah, 1999).

The slow and minimal C loss by cupuaçu litter was consistent with slow decomposition of incubated fresh cupuaçu leaves (Seitz, 2003) and the 2.4 year turnover for cupuaçu leaf litter in a peach-palm (*Bactris gasipaes* Kunth.) and cupuaçu plantation (McGrath et al., 2000). The slow decomposition explains the inability of cupuaçu litter to increase soil mineral N and total N levels above those of the unmulched soil during the 96-day experimental period. The absence of any long-term N release by the cupuaçu litter was also consistent with findings by McGrath et al. (2000). The extremely slow decomposition of cupuaçu can be attributed more to its low moisture content and high lignin content than its low N content (McGrath et al., 2000; Seitz, 2003) and was not increased in the presence of certain diplopod macrofauna species common to agroforestry systems in this region (Seitz, 2003). Such results indicate that N release from a mixture can be regulated by changing the proportions of high- and low-quality leaves, but does not confirm any change in the decomposition and N release of the individual species composing the mixture.

4.3. Leaf quality interactions in leaf mixtures

Total N release patterns indicated an additive effect on soil mineral N in leaf mixtures of high- and low-quality leaves and the absence of net interactions between species for decomposition and N release. Even though increasing proportions of high-quality gliricidia increased total N and C loss from the mixture, the net percent C and N mineralization from cupuaçu leaves was not increased, in contrast to our hypothesis. The net percent N and C release from gliricidia was also not decreased by the presence of cupuaçu in the mixture; conversely, total percent N release from gliricidia increased in the presence of increasing amounts of cupuaçu litter. Total mineral N in the soil per unit soil weight and in the resin bags was higher with greater quantities of gliricidia. However, when the mineral N levels were compared in relation to the amount of N applied in the leaf mixture, there was no difference with increasing amounts of high-quality litter. Therefore, mineral N levels corresponded directly to the amount of gliricidia-N applied.

Even though there were no net interactive effects between the species, we were able to detect gross interactions for C and N mineralization by analyzing each species separately and using N isotope tracing. We found that the C mineralization rate of cupuaçu leaves was initially increased in the presence of the greatest proportion (80%) of gliricidia mulch at day 14, despite no differences in total C loss among the treatments at the end of the observation period of 96 days. The rapid release of N from the high-quality gliricidia may have initially facilitated more rapid mineralization of the C in the cupuaçu leaves by microbes. This faster, but finally not greater C loss, did not increase net N mineralization in cupuaçu litter. However, the N isotope data showed that N from gliricidia moved to cupuaçu leaves, which could help conserve N in the system and might ultimately contribute to greater C loss and release of N from cupuaçu. The movement of gliricidia N to cupuaçu leaves did not vary with the proportion of cupuaçu litter, suggesting that the presence of any cupuaçu litter in the mixture depresses the release of N from gliricidia by N immobilization. It has been shown that immobilization of P by cupuaçu leaves significantly lowers available P in a Typic Kandiustult beneath the litter (McGrath et al., 2000). Though we expected that available N in the soil would also decrease, our results indicated an additive effect of the two species on soil mineral N, with gross interactions canceling any net effect. Therefore, in the presence of larger proportions of cupuaçu litter, gliricidia leaves released a greater percent N to compensate for the larger N sink in cupuaçu leaves.

5. Conclusions

Net release of N was not increased by adding the high-quality mulch material of gliricidia to the low-quality litter under cupuaçu. However, decomposition and N release of cupuaçu was initially faster which was related to a gross N transfer from the high-quality mulch to the low-quality litter detected through isotope enrichment. Despite this significant and persistent N transfer, total N release from cupuaçu leaves or the leaf mixtures did not increase within the experimental period. The additive effects of gliricidia mulch and cupuaçu litter on available soil N suggests that at our site management recommendations for N can be based on gliricidia N dynamics alone. It is possible, however, that with more time gliricidia could increase net cupuaçu decomposition and N release as well as net N release from the mixture. Long-term dynamics of N interactions between organic materials with contrasting qualities should be assessed using stable isotope enrichment. This approach should include soil organic matter studies, which follow the organic N cycles within labile and stable organic matter pools and quantify long-term benefits of leaf mixtures.

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References

Anderson, J.P.E., Domsch, K.H., 1978. A physiological method for the quantitative measurement of microbial biomass in soils. Soil Biology & Biochemistry 10, 215–221.

Brookes, P.C., Landman, A., Pruden, G., Jenkinson, D.S., 1985. Chloroform fumigation and the release of soil nitrogen: a rapid direct extraction method to measure microbial biomass nitrogen in soil. Soil Biology & Biochemistry 17, 837–842.

Cadisch, G., Handayanto, E., Malama, C., Seyni, F., Giller, K.E., 1998. N recovery from legume prunings and priming effects are governed by the residue quality. Plant and Soil 205, 125–134.

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

Förster, B., Farias, M., 2000. Microbial respiration and biomass, in: Höfer, H., Martius, C., Hanagarth, W., Garcia, M., Franklin, E., Römbke, J., Beck, L. (Eds.), Soil Fauna and Litter Decomposition in Primary and Secondary Forests and a Mixed Culture System in Amazonia. Final report of project SHIFT ENV 52 (BMBF No. 0339675), pp. 59–64.

Haag, D., 1997. Root distribution patterns in a polyculture system with local tree crops on an acid upland soil in central Amazonia. MS Thesis, University of Bayreuth, Bayreuth, Germany.

Haggar, J.P., Tanner, E.V.J., Beer, J.W., Kass, D.C.L., 1993. Nitrogen dynamics of tropical agroforestry and annual cropping systems. Soil Biology & Biochemistry 25, 1363–1378.

Handayanto, E., Giller, K.E., Cadisch, G., 1997. Regulating N release from legume tree prunings by mixing residues of different quality. Soil Biology & Biochemistry 29, 1417–1426.

Lehmann, J., Schroth, G., Zech, W., 1995. Decomposition and nutrient release from leaves, twigs, and roots of three alley-cropped tree legumes in Central Togo. Agroforestry Systems 29, 21–36.

Mafongoya, P., Nair, P., 1997. Multipurpose tree prunings as a source of nitrogen to maize under semiarid conditions in Zimbabwe 1. Nitrogen-recovery rates in relation to pruning quality and method of application. Agroforestry Systems 35, 31–46.

Mafongoya, P.L., Nair, P.K.R., Dzowela, B.H., 1998. Mineralization of nitrogen from decomposing leaves of multipurpose trees as affected by their chemical composition. Biology and Fertility of Soils 27, 143–148.

McGrath, D., Comerford, N., Duryea, M., 2000. Litter dynamics and monthly fluctuations in soil phosphorus availability in an Amazonian agroforest. Forest Ecology and Management 131, 167–181.

Melillo, J.M., Aber, J.D., Muratore, J.F., 1982. Nitrogen and lignin control of hardwood leaf litter decomposition dynamics. Ecology 63, 621–626.

Minitab, I., 2000. Minitab Statistical Software vers. 13.1.

Myers, R.J.K., Palm, C.A., Cuevas, E., Gunatilleke, I.U.N., Brossard, M., 1994. The synchronization of nutrient mineralisation and plant nutrient demand, in: Woomer, P.L., Swift, M.J. (Eds.), Biological Management of Tropical Soil Fertility. Wiley, Chichester, UK, pp. 81–116.

Oglesby, K.A., Fownes, J.H., 1992. Effects of chemical composition on nitrogen mineralization from green manures of seven tropical leguminous trees. Plant and Soil 143, 127–132.

Palm, C.A., Sanchez, P.A., 1990. Decomposition and nutrient release patterns of the leaves of three tropical legumes. Biotropica 22, 330–338.

Schroth, G., Elias, M.E.A., Macedo, J.L.V., D'Angelo, S.A., Lieberei, R., 2001. Growth, yields and mineral nutrition of cupuaçu (*Theobroma grandiflorum*) in two multi-strata agroforestry systems on a ferralitic Amazonian upland soil at four fertilization levels. Journal of Applied Botany 75, 67–74.

Seitz, D., 2003. Einfluss der Streuqualität beim Streuabbau und der Nährstofffreisetzung durch Diplopoden in tropischen Agroforst-systemen. MS Thesis, University of Bayreuth, Bayreuth, Germany.

Seneviratne, G., 2000. Litter quality and nitrogen release in tropical agriculture: a synthesis. Biology and Fertility of Soils 31, 60–64.

Seneviratne, G., Van Holm, L.H.J., Kulasooriya, S.A., 1998. Quality of different mulch materials and their decomposition and N release under low moisture regimes. Biology and Fertility of Soils 26, 136–140.

Zaharah, A.R., Bah, A.R., 1999. Patterns of decomposition and nutrient release by fresh gliricidia (*Gliricidia sepium*) leaves in an Ultisol. Nutrient Cycling in Agroecosystems 55, 269–277.