Tree pruning mulch increases soil C and N in a shaded coffee agroecosystem in Hawaii

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A B S T R A C T

Agroforestry can increase the sequestration of carbon (C) in soils of tropical agroecosystems through increased litter and tree pruning inputs. Decomposition of these inputs is a key process in the formation of soil organic matter and in nutrient cycling. Our objectives were to study decay of tree pruning mulch and effects on soil C and N in a shaded coffee agroecosystem in Hawaii. Chipped tree pruning residues (mulch) were added to coffee plots shaded with the Leucaena hybrid KX2 over three years. We measured mulch decomposition and nitrogen loss over one year and changes in soil carbon and nitrogen (N) over two years. Mass loss of mulch was 80% over one year and followed first-order decay dynamics. There was significant loss from all major biochemical components. Net N loss from the mulch was positive throughout the entire period. The C:N and lignin:N ratios of the mulch declined significantly over the decomposition period. Mulch additions significantly increased soil C and N in the top 20 cm by 10.8 and 2.12 Mg ha⁻¹, respectively. In the no-mulch treatment, there was no significant change in soil C or N concentration, but a decline in soil bulk density led to a significant decline in total soil C. Leucaena mulch can provide an important source of organic C and N to coffee agroecosystems and can help sequester C lost as plant biomass during shade tree management.

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1. Introduction

Agroecosystems play a central role in the global carbon cycle and contain approximately 12% of the world’s terrestrial carbon (Dixon, 1995). In most terrestrial ecosystems, the majority of the net primary production (NPP) is shed as plant litter and subsequently enters the decomposition pathway. Decomposition of litter is a key process in organic matter and nutrient cycling (Peng and Liu, 2002). It is a complex ecological process conducted largely by a community of microorganisms whose collective activity is controlled by litter chemistry, nutrient availability, environmental conditions, and biotic interactions (Berg and McLaugherty, 2003; Sariyildiz and Anderson, 2003a; Sariyildiz et al., 2005). Air temperature and moisture were the strongest factors influencing mass loss of litter in tropical forests (Vitousek et al., 1994). The amount of C, N, lignin and polyphenols in litter are the most common chemical criteria used to define litter quality (Palm and Rowland, 1997). Ratios of these constituents, such as C-to-N, lignin-to-N, and (lignin + polyphenol)-to-N have been used to predict decomposition and nutrient release. Rapid decomposition and nutrient release are associated with high quality litter, and conversely, immobilization or slow release of N and other nutrients is associated with low quality litter (Swift et al., 1979).

The biochemical fractions that are degraded during litter decomposition are commonly thought to proceed from more soluble and easily degraded components to those that are more recalcitrant, especially lignin and lignin-like substances. However, this may have as much to do with the succession of the decomposer community colonizing the litter than any inherent characteristics of the litter itself. It has been shown that high quality litters containing an abundance of available N and C tend to be readily colonized by generalist bacteria and fungi, which can competitively exclude lignolytic basidiomycetes (Cox et al., 2001). However, exceptions do occur in which dominant lignolytic fungi colonize litter and preferentially degrade lignin and/or cellulose (Cox et al., 2001). Thus, litter quality may define the potential rates of decomposition, but actual decay rates and the biochemical fractions degraded are significantly influenced by colonization and succession of the decomposer community (Sariyildiz et al., 2005). Agroforestry provides a realistic option for increasing the C sequestration of agroecosystems in plant biomass and soil organic matter (Albrecht and Kandji, 2003). First, agroforestry systems generally have a higher input of organic material to the soil...
compared to sole crop systems. They also increase recycling of nutrients within the system (Oelbermann et al., 2006). Second, trees help stabilize soils against erosion and reduce soil disturbance through modified management practices (Ataroff and Monasterio, 1997). In addition, the use of N-fixing trees can increase litter decomposition, soil organic matter and N availability (Mafongoya and Nair, 1997).

Crop residue management has been shown to significantly affect the decomposition process of plant debris in soil (Coppens et al., 2007). In agroforestry systems, trees may be pruned regularly to moderate shade levels and maintain adequate understory crop productivity. The trade-off is that pruning of trees removes C sequestered as woody biomass. Stabilization of pruning residues as soil organic matter may help conserve some of the C lost as woody biomass while improving the soil’s physical, chemical, and organic properties. Studies have reported that soil C, N, phosphorus (P) and sulfur (S) status were improved in plots with additions of mulch from the multi-purpose N-fixing tree *Leucaena leucocephala* (Wendt et al., 1996; Heineman et al., 1997). Mulching of tree pruning residues has also contributed to increased soil water infiltration and retention, improved soil physical properties, reduced weed infestation and increased soil microbial and faunal activities (Kang, 1997).

In addition mulching has the capacity to reduce evaporation from the soil surface and thus to conserve soil water over a long period (Sands et al., 1999). Mulumba and Lai (2008) found that wheat straw mulch significantly increased available water capacity and soil moisture content at field capacity. Mahboubi et al. (1993) reported higher available water capacity under no-till which is usually associated with higher coverage of crop residues. Similar observations were made by Duiker and Lai (1999).

The objectives of this study were to measure decomposition, N loss from litter, and changes in soil C and N from additions of chipped tree pruning residues (mulch) of a fast-growing *Leucaena* hybrid managed as a shade tree in a coffee agroecosystem in Hawaii.

2. Materials and methods

2.1. Study site

The study was carried out at the University of Hawaii, College of Tropical Agriculture and Human Resources, Waimanalo Research Station on the windward side of the island of Oahu. The site is 20 m above sea level and is classified as a humid tropical environment (Giambelluca et al., 1986). Mean annual rainfall is 1080 mm (National Climatic Data Center, 2002) with distinct wet and dry seasons (Fig. 1). The soils are generally unconsolidated colluvium from the volcanic Koolau Mountains, mixed with coral from the nearby oceanic shoreline. They are classified mainly as Vertic Haplustolls, dominated by the Waimanalo series. These soils are typically base-rich, high in organic matter, and relatively fertile with pH 6.0–6.5.

In the field that was selected for this experiment, *Leucaena* variety KX2 was planted on 30 August 2002 as a seed orchard in 8 rows of 20 trees, each on a 2 × 2 m spacing. Variety KX2 is a hybrid from two species-*L. leucocephala* “K8” × *Leucaena palida* “376”– developed for psyllid resistance and rapid growth (Brewbaker, 2008). Sixteen plots were established, each 4 × 6 m in size, encompassing 6 *Leucaena* trees in a 3 × 2 tree arrangement. The inner 6 rows and 18 trees per row were included in the plots, leaving a border row of trees around the entire orchard. Drip irrigation was applied to all plots during dry periods to maintain plant survival and growth.

On 20 September 2005, all trees in the plots were pollarded at 1 m above ground level. The harvested biomass was chipped in a mechanical tree chipper and distributed uniformly back to the

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**Fig. 1.** Mean monthly air temperature and relative humidity and cumulative rainfall at the study site during 2006.

*Leucaena* plots as mulch. On 20 March 2006, two seedlings of coffee (*Coffea arabica* var. ‘Kona Typica’) were planted in eight randomly selected plots, each 2 m apart between the tree rows so that each plant was surrounded by 4 trees. The remaining *Leucaena* plots were left as controls as part of a larger experiment investigating the effects of shade tree pruning frequency on coffee productivity and C sequestration. We trenched to a depth of 1 m between all plots and lined the trench with plastic sheeting to prevent overlap of root systems between adjacent plots. The eight coffee plots were randomly assigned to either a mulch or no-mulch-addition treatment (*n* = 4).

On 20 August 2006 all trees were pollarded as before. The chipped tree mulch was distributed uniformly back to the mulch-addition plots only. Tree pollarding and mulch addition were repeated on 20 August 2007. Dry mass, C, and N content of mulch additions are listed in Table 1.

To monitor the decomposition dynamics of the tree mulch, we created decay microplots in all measurement plots. A 50 × 50 cm area of ground was cleared of any plant litter and debris. A 1-mm mesh nylon screen was placed over this surface. The screen was separated into 4 quadrants using a rigid aluminum mesh screen barrier placed down the center parallel to the 4 sides of the screen. A 10-cm diameter hole was cut out of the screen in each quadrant. A 10-cm diameter ABS plastic cylinder was driven 1–3 cm in the soil surface inside each hole and allowed to protrude 2–3 cm above the surface. The mesh screen cut out of the hole was placed inside the cylinder on the soil surface. In the mulch-addition plots, we estimated the average initial mulch wet weight to be ~ 550 g per unit area covered by the screen. Approximately 50 g of fresh mulch was weighed in the field to the nearest 0.1 g and placed inside each cylinder; the remainder of the 550 g was spread evenly over the rest of the screen surface. Subsamples of mulch were taken back to the lab and oven-dried at 70 °C to constant weight to determine water content and initial dry mass, as well as tissue C and N

<table>
<thead>
<tr>
<th>Year</th>
<th>Dry Mass</th>
<th>Carbon</th>
<th>Nitrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mg ha⁻¹</td>
<td>g kg⁻¹</td>
<td>Mg ha⁻¹</td>
</tr>
<tr>
<td>2005†</td>
<td>17.60</td>
<td>423</td>
<td>7.45</td>
</tr>
<tr>
<td>2006</td>
<td>24.33</td>
<td>414</td>
<td>9.97</td>
</tr>
<tr>
<td>2007</td>
<td>26.77</td>
<td>421</td>
<td>11.24</td>
</tr>
</tbody>
</table>

† Mulch added to all plots in the *Leucaena* stand.
concentrations and biochemical composition. The decay microplots in the no-mulch treatment were established as in the mulch-addition treatment, but the cores remained empty. Natural litterfall was excluded from the decay microplots by placing a plastic mesh tray over the top of the microplot for the duration of the decomposition experiment.

At 3-month intervals, the mulch from one cylinder was removed in order to estimate mass loss, change in C and N concentration, and change in biochemical composition. The samples were oven-dried to determine remaining litter mass. We corrected for mineral soil contamination via loss on ignition in a muffle furnace to digest the lignin fraction. The remaining organic material was hemicellulose. The residue was digested in potassium permanganate to acidify. Soils were then dried for 3 days and analyzed for total C by an inductively coupled plasma emission spectrometer. Soil samples from 0 to 20 cm were collected randomly within the plots at 6-month intervals from May 2006 until May 2008 to monitor changes in soil C and N concentration. To correct for inorganic carbonate in the soil, 8 soil samples (4 g each) were placed in glass crucibles inside a glass desiccator alongside a beaker of 250 ml of concentrated hydrochloric acid (12 M HCl). The desiccator was sealed, and the samples were left overnight to acidify. Soils were then dried for 3 days and analyzed for total C by ADSC. Inorganic C averaged 5% of total soil C, so results were corrected to reflect soil organic C only. Bulk density was determined from core samples (Anderson and Ingram, 1990) from 0 to 20 cm depth once a year from 2005 until 2008 in order to scale soil C and N concentrations to a mass per area basis.

### Table 2
Initial soil characteristics (2005) in a shade coffee agroecosystem.

<table>
<thead>
<tr>
<th>Soil depth (cm)</th>
<th>0–20</th>
<th>20–40</th>
<th>40–60</th>
<th>60–100</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH</td>
<td>6.03</td>
<td>6.03</td>
<td>4.86</td>
<td>4.80</td>
</tr>
<tr>
<td>B.D. (Mg m⁻³)</td>
<td>1.08</td>
<td>1.10</td>
<td>1.12</td>
<td>1.13</td>
</tr>
<tr>
<td>C (g kg⁻¹)</td>
<td>36.90</td>
<td>21.80</td>
<td>11.70</td>
<td>6.00</td>
</tr>
<tr>
<td>N (g kg⁻¹)</td>
<td>2.20</td>
<td>1.70</td>
<td>1.20</td>
<td>ND</td>
</tr>
<tr>
<td>Ca (g kg⁻¹)</td>
<td>17.1</td>
<td>13.1</td>
<td>10.1</td>
<td>ND</td>
</tr>
<tr>
<td>Mg (g kg⁻¹)</td>
<td>198</td>
<td>181</td>
<td>8.33</td>
<td>8.47</td>
</tr>
<tr>
<td>P (mg kg⁻¹)</td>
<td>1034</td>
<td>929</td>
<td>252</td>
<td>126</td>
</tr>
<tr>
<td>K (mg kg⁻¹)</td>
<td>4371</td>
<td>3810</td>
<td>610</td>
<td>332</td>
</tr>
<tr>
<td>Mg (mg kg⁻¹)</td>
<td>5551</td>
<td>1450</td>
<td>1250</td>
<td>1100</td>
</tr>
</tbody>
</table>

* B.D.: Bulk Density.

### 2.2. Statistical analysis

Mulch decomposition rates were fitted to a negative exponential decay model:

\[ L_t = L_0 e^{-kt} \]  

where \( L_t \) is the proportion of litter mass remaining at time \( t \), \( L_0 \) is the proportion of litter mass at time zero, and \( k \) is an exponent that characterizes the decomposition rate over the measured time interval (Chapin et al., 2002). The fit of data to the equation was assessed using Pearson’s coefficient of determination \( (R^2) \). Because \( L_0 \) by definition equals 100% of initial litter mass, the equation was modified to eliminate \( L_0 \) as a distinct variable. SigmaPlot software, V. 8.02 (Systat Software, Inc., San Jose, CA) was used to determine the least-squares regression coefficient \( (k) \) and determine the \( R^2 \) value.

Changes in litter N content and biochemical composition over time were compared via repeated-measures analysis of variance using the MIXED procedure in SAS, V. 9.1.3 (SAS Institute Inc., 1990). Where a significant overall time effect was indicated, specific contrasts were made between months 0–3, 3–6, and 6–12. To protect the critical \( \alpha \) value of 0.05, a Bonferroni \( \alpha \) adjustment of 0.017 was used to test the means of each contrast. For biochemical composition, both the mass of each component remaining and its proportion of total remaining mass were analyzed.

Changes in soil C and N concentration (g kg⁻¹) and total content (Mg ha⁻¹) were analyzed via repeated-measures multivariate analysis of variance (MANOVA), using the GLM procedure in SAS (von Ende, 1993; Maxwell and Delaney, 2004) to test both treatment and time effects. To test the within-subject effects of time in the MANOVA, the following were used: Wilks’ lambda, Pillai’s trace, Hotelling-Lawley trace, and Roy’s greatest root (Scheiner, 1993). Although each test examines the eigenvectors in different ways, there was no difference in \( P \)-values for each test conducted; thus only one value is shown for each within-subject effect. Where the treatment effect was significant, a specific contrast was made between treatments at year 2 (2008). Where there was a significant treatment \( \times \) time interaction, specific contrasts of differences between year 0 and 2 (2006 and 2008) were tested for each treatment individually.

### 3. Results

#### 3.1. Litter mass and N loss

Mass remaining after 3, 6, 9 and 12 months was 52, 39, 28 and 20%, respectively, of initial mass. Mass loss fit a first-order decay curve (Fig. 2). Nitrogen remaining from initial tissue content was 78.5, 70.4, 64.8 and 58.6% after 3, 6, 9 and 12 months, respectively (Fig. 3). Net N loss was significant between months 0–3 and 6–12 \( (P < 0.017) \) and equaled 41% of the initial content.

#### 3.2. Biochemical composition

Mass loss varied among the major biochemical components in the Leucaena mulch over time (Fig. 4). Mass loss as a percentage of the initial was 78, 83, 86, and 89% for the soluble, hemicellulose, cellulose, and lignin fractions, respectively. There was significant loss of all components from months 0–3 and 6–12 \( (P < 0.017, \text{Table 3}) \). There were also shifts in the proportion of each component in the mass remaining (Fig. 5). The initial percentage of mass as soluble, hemicellulose, cellulose, and lignin was 33, 29, 21, and 13%, respectively. The proportion of mulch as cellulose and lignin declined significantly over time to 15 and 7.34%, respectively (Table 3).
3.3. Indicators of litter quality

The C, N, and lignin concentrations of the mulch all significantly declined over the one-year study period (Table 4). The C concentration declined from 51.22 to 30.02% over one year. Half of this decline occurred in the first 3 months. The N concentration decreased linearly over time from 1.03 to 0.78%. The large decline in the C concentration resulted in a significant decline in the C:N ratio, from 50:1 to 38:1. The lignin concentration decreased dramatically from 13.23 to 7.34%. As with C, half of this decline occurred in the first 3 months. As a result, the lignin:N ratio of the mulch declined significantly over one year from 13:1 to a final value of 9:1.

3.4. Soil C and N

Mulch additions from 2006 to 2008 in this system significantly increased soil C and N in the top 20 cm by 10.8 and 2.12 Mg ha\(^{-1}\), respectively (\(P < 0.05\) for C and N, Table 5). In the no-mulch treatment, there was little change in soil C concentration, but a decline in soil bulk density from 0.95 to 0.83 Mg m\(^{-3}\) from 2006 to 2008 led to a significant decline in total soil C by 4.8 Mg ha\(^{-1}\) (\(P < 0.05\)). There was a non-significant increase in soil N (0.40 Mg ha\(^{-1}\)) in the no-mulch treatment (\(P = 0.25\)). Soil C and N in 2008 were significantly higher in the mulch than the no-mulch treatment.

4. Discussion

4.1. Mass loss

Mass loss of the *Leucaena* mulch was rapid in this system. The rate of mass loss fit a first-order exponential decay curve, similar to other studies of fine litter decomposition (Kumar and Deepu, 1992; Jama and Nair, 1996; Pereira et al., 1998), including *L. leucocephala* (Budelman, 1988; Jamaludheen and Kumar, 1999). The initial rapid decay phase typically lasts two to four months. The second phase is characterized by the gradual loss of litter mass and can take many months for complete decay. Although this pattern has generally been identified for leaves and other fine litter, we found a similar pattern for the chipped tree pruning residues of the *Leucaena* hybrid, KX2, which included a mixture of leaves, seed pods, branches and orthotropic shoots from the main stem.

Decomposition rates are strongly influenced by climatic conditions and initial chemical composition of the litter (Couteaux et al., 1995). Vanlauwe et al. (1995) found a positive correlation between rainfall and evapotranspiration and dry matter loss from decomposing leaves of *L. leucocephala* and *Senna siamea* under sub-humid tropical conditions. In the current study, air temperature and relative humidity remained favorable for decomposition throughout the year, and drip irrigation may have partially offset the reduction in rainfall during the dry season.

![Fig. 2. Mulch decomposition in shade coffee system.](image)

![Fig. 3. Nitrogen loss from litter in shade coffee system. Error bars represent ±1 S.E. *Indicates significant N loss between months 0 and 3. †Indicates significant N loss between months 6 and 12.]()

![Fig. 4. Mass loss from mulch biochemical components in shade coffee system.](image)


**Table 3**

<table>
<thead>
<tr>
<th>Component</th>
<th>Time (mo)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0–3</td>
</tr>
<tr>
<td>Mass loss</td>
<td></td>
</tr>
<tr>
<td>CHO</td>
<td>*</td>
</tr>
<tr>
<td>HEM</td>
<td>*</td>
</tr>
<tr>
<td>CEL</td>
<td>*</td>
</tr>
<tr>
<td>LIG</td>
<td>*</td>
</tr>
<tr>
<td>Proportion of mass</td>
<td></td>
</tr>
<tr>
<td>CHO</td>
<td>*</td>
</tr>
<tr>
<td>HEM</td>
<td>*</td>
</tr>
<tr>
<td>CEL</td>
<td>*</td>
</tr>
<tr>
<td>LIG</td>
<td>*</td>
</tr>
</tbody>
</table>

*Significant at \(P < 0.017\); ns, not significant.

CHO = soluble carbohydrates; HEM = hemicellulose; CEL = cellulose; LIG = lignin.
The influence of litter quality on decomposition has been extensively studied, and various indices that relate quality to decomposition and to N loss from litter have been proposed. The litter C:N ratio has been considered as an important factor influencing the degradability of organic residues added to the soil (Melillo et al., 1981). This also influences the pattern of N gains and losses in decaying litter. A C:N ratio of 25:1 has generally been considered the threshold for net loss of N from agronomic residues (Paul and Clark, 1996). A more recent review of a global dataset of decomposition from varied litter sources suggests this threshold is closer to 50:1 (Manzoni et al., 2008). In the humid tropics, nitrogen, lignin, and the lignin:N ratio have been reported to have a better control over the litter decay rate than the C:N ratio (Swift et al., 1979). In general, if the lignin concentration is below 20% then most of litter mass comprises structural polysaccharides that are readily degraded by microorganisms, and the decomposition rates can be predicted from the initial C:N ratios or simply N concentrations (McClaugherty and Berg, 1987). Because of their intimate physical association and covalent bonding in the cell wall (Monties, 1994), higher concentrations of lignin increasingly dominate the processes of litter decomposition, and mass loss can be related to initial concentrations of lignin (Fogel and Cronack, 1977; Sariyildiz and Anderson, 2003a,b, 2005) or lignin:N ratios (Aerts, 1977; Sariyildiz, 2008). Lignin is considered to be an interfering factor in the enzymatic degradation of cellulose and other carbohydrates as well as proteins (Alexander, 1977). It decomposes slowly and physically protects cell wall constituents from degradation (Chesson, 1997).

Because we had only one litter type and one set of environmental conditions, it is not possible to apply these empirical models to predict litter decay. Based on studies of other litter types (Palm, 1995; Young, 1997), the initial C:N and lignin:N ratios of the Leucaena mulch in our study were moderate; thus, our rapid decay rates were somewhat unexpected. The initial C:N ratio of the Leucaena mulch was 50:1, near the threshold for net N loss. Although we saw a significant decline in the C:N ratio over time, the lignin:N ratio decreased to a much greater extent over the 12-month decomposition period. This should support rapid litter decay and net N loss throughout the decay process. Similar patterns of mass and N loss during decay of pruning residues from N-fixing trees have been observed in previous studies (Wilson et al., 1986; Oglesby and Fownes, 1992; Constantinides and Fownes, 1994). Specifically, Van der Meersch et al. (1993) found that N loss from L. leucocephala mulch (37 g N kg$^{-1}$) was 90% after one year.

For N-rich substrates, rapid initial mass loss may be due to leaching and preferential utilization of soluble components (Yadav et al., 2008). In our study, there was loss of all major biochemical components in the first 3 months. There was significant loss of the more recalcitrant components—lignin and cellulose—throughout the entire 12-month period and even a decrease over time in the proportion of these components. This suggests that decomposition was not dominated by leaching or preferential utilization of more soluble or easily degraded components.

The preferential loss of lignin and cellulose was unexpected. The sequential digestion procedure we employed was not developed for woody mulch; however, the results from the digestion are supported by the decline in litter C concentration. Lignin in particular is comprised of more C-rich compounds than cellulose, proteins, sugars, and structural polysaccharides, which affects the C concentration of plant materials (Lamlov and Savidge, 2003). Preferential loss of lignin, therefore, would be expected to result in a decline in the C concentration of the remaining organic matter.

The preferential loss of lignin and cellulose may reflect early colonization by lignolytic fungi. The mulch was isolated from the mineral soil by the mesh screen, which may have limited early colonization by generalist bacteria. The greater mobility of filamentous fungi allows them to colonize surface residues and import nutrients from the mineral soil (Fisher and Binkley, 2000). The warm, humid conditions of the site would support rapid decay, and in the case of fungal colonization, there would be preferential loss of cellulose and lignin.

Nitrogen in surface-applied residues may be subject to volatilization, thus reducing the overall input to plant-available soil N (Palm, 1995). Loss of N via volatilization from green manures measured in laboratory incubations ranges from 5 to 50% but is usually less than 20% of the added N (Costa et al., 1990; Glasener, 1991; Janzen and McGinn, 1991). Higher quality materials that release N...
rapidly tends to lose more N via volatilization (Glasener, 1991). Assuming volatilization losses of 20% in our study, 33% of initial mulch N was added to soil pools after one year.

4.3. Soil C and N

The importance of organic matter input from tree pruning and litterfall to help maintain or increase soil organic C and N has been demonstrated by several studies in tropical and temperate agroforestry systems. For example, Dulormne et al. (2003) reported a 15% increase in soil C to a 20 cm depth after 10 years of silvopasture with Gliricidia sepium in the French Antilles. Carbon sequestration averaged 1.9 Mg C ha\(^{-1}\) yr\(^{-1}\), while soil organic N increased at rate of 166 kg N ha\(^{-1}\) yr\(^{-1}\). In Nigeria, Kang et al. (1999) studied a 12-yr-old alley cropping system that used either Gliricidia or Leucaena as the hedgerow species. They found higher organic C concentrations (10.4 and 10.2 g kg\(^{-1}\)) and litterfall additions in tropical agroforestry systems have shown a clay soil in Kenya led to a 15% increase in soil C concentration after 3M yr a\(^{-1}\). This by itself led to a small but significant increase in total soil C and N (Mg ha\(^{-1}\) yr\(^{-1}\)). One complicating factor for calculating changes in the levels of soil C can be detected.

Our results showed a significant increase in soil C and N after only 2 years of mulch addition. Final soil C and N in the mulch-addition treatment was also significantly greater than in the no-mulch treatment. One complicating factor for calculating changes in total soil C and N (Mg ha\(^{-1}\)) over time was that there was an approx. 15% decrease in soil bulk density in the top 20 cm over the 2-year study period. This by itself led to a small but significant decline in total soil C in the no-mulch treatment (4.8 Mg ha\(^{-1}\)), despite virtually no change in soil C concentration. Numerous studies in tropical and subtropical regions have shown that incorporation of trees and additions of mulch in agroecosystems can decrease soil bulk density, generally in the range of 15–25% (Gunasea et al., 1991; Rosecrance et al., 1992; Otu and Agboola, 1994; Arachchi and Liyanage, 1998; Kimemia et al., 2001; Youkhana and Idol, 2008). For example, Kimemia et al. (2001) measured decreases in bulk density from 19 to 25% after 3 years of adding mulch of 7 leguminous tree species in a clay soil in Kenya at a rate of 3 Mg ha\(^{-1}\) yr\(^{-1}\). This is usually associated with higher levels of soil organic matter and greater formation and stabilization of soil macroaggregates and macropore space. This effect of trees and mulch on bulk density, however, can lead to counter-intuitive effects on calculations of total soil C and N. Because of a decline in bulk density, increasing soil C and N concentrations may not lead to significant increases in total soil C and N calculated on a volumetric or area basis. It is unlikely that the additional soil organic matter is displacing soil minerals, so the net result should be greater total soil mass and volume. Calculations of total soil C and N on a per-depth increment in newly established agroforestry systems, however, will reflect this decline in bulk density. In our system, the trees were planted in 2002, three years prior to the beginning of the study. A longer study period may be required for soil bulk density to reach equilibrium with current management practices so that effects of mulch additions can be more fully assessed.

An additional complicating factor for comparison of soil C and N in the mulch and no-mulch treatments is that tree growth after pollarding in 2006 and 2007 was approx. 3 times greater in the mulch-addition plots (data not shown). This was not the case for growth after pollarding in 2005, when mulch was returned to all of the plots uniformly. Most likely, the leaching and mineralization of nutrients from the tree pruning residues stimulated tree regrowth in the mulch-addition plots. The overall effect of mulch additions on soil C and N likely include increased inputs of litterfall and fine root turnover as well as direct mulch inputs. It is impossible to separate the effects of these various litter sources in our study, but the net effects of returning tree pruning residues back to the soil surface are clear.

Finally, some studies have reported that as much as 70–90% of the C in surface mulch may be respired back to atmosphere as CO\(_2\) (Batjes and Somboek, 1997; Flesa et al., 2002). Therefore, some of the increased soil organic matter in our study may be from other sources, such as increased root activity, rather than mulch transformation into soil organic matter. Increased soil water content and soil nutrient availability in mulch-addition plots may stimulate fine root growth and activity (Batjes and Somboek, 1997; Rathore et al., 1998), which would result in increased organic matter inputs from root exudation and turnover. However, increased soil water and nutrients would also stimulate microbial degradation of organic matter, so the net effect on soil C is unclear. To our knowledge, these indirect effects of mulch addition on soil organic matter and C have not been explicitly investigated.

Pruning of shade trees reduces C sequestration in plant biomass. Thus, increases in soil C are important not only for soil quality but also as a means of conserving C lost due to management of shade levels. Although this has not been explicitly quantified in most studies, our results suggest it can be important. The average increase in soil C in the mulch-addition plots was 10.8 Mg ha\(^{-1}\), even with the mitigating effect of lower bulk density. This represents 50% of the C added as mulch over the same 2 years and 38% of the mulch added from the start of the experiment (3 years total). Ultimately, the soil’s capacity to store C under prevailing environmental conditions will limit total sequestration from mulch additions; however, soil organic matter increases can continue for at least the first 10 years (Fassbender, 1998). Future research will determine the relative proportions of the additional soil C that is being stored in labile vs stable and recalcitrant fractions in order to evaluate the relative stability of the added organic matter.

Total soil N increased in both treatments; this was significant in the mulch-addition plots. As with soil C, this increase is likely due to a combination of increased soil organic matter from mulch and inputs from tree litterfall and turnover of roots and N-fixing nodules. In both treatments, pollarding should result in a pulse of fine root turnover. As other studies have shown, incorporation of N-fixing trees in coffee agroforestry systems can support the move toward low-input and organic production through enrichment of soil organic matter and N. For surface-applied residues, volatilization losses need to be accounted for when calculating the ability to meet plant N demands or replace fertilizer inputs.

5. Conclusions

Leucaena mulch added to a shaded coffee agroecosystem decayed rapidly and lost significant amounts of N over a one-year period. The combination of a humid tropical climate and moderate to high litter quality likely accounted for these patterns. Mass loss occurred in all major biochemical components, but especially in lignin and cellulose. This may have been due to early colonization by wood-decay fungi. Decay of this material also resulted in significant increases in soil C and N. Carbon sequestration in soil organic matter was half of the C added as mulch over the same two years. Thus, application of mulch can partially offset losses of C as
plant biomass and promote increased N availability in agroforestry systems where shade is managed to maintain high coffee yields.

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FIRST-YEAR BIOMASS PRODUCTION AND SOIL IMPROVEMENT IN LEUCAENA AND ROBINIA STANDS UNDER DIFFERENT POLLARDING SYSTEMS

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YOUKHANA, A. & IDOL, T. 2008. First-year biomass production and soil improvement in Leucaena and Robinia stands under different pollarding systems. The study of biomass production and soil improvement of two fast growing and multipurpose trees, Leucaena leucocephala and Robinia pseudoacacia, was carried out in Mosul Forest, northern Iraq, to examine the impact of pollarding height (0, 15, 30 and 45 cm) and frequency (no pollarding, pollarding every three or six months) on growth responses and soil properties. These species are being studied as part of a larger research programme to develop novel agroforestry systems in Iraq. Leucaena leucocephala showed the greatest response in terms of branching, shoot basal diameter, height, biomass and nitrogen and phosphorus contents of leaves and stems with pollarding every three months at 15 cm. For R. pseudoacacia, pollarding once after six months at 45 cm resulted in the greatest growth response of leaves and stems. Physical soil properties such as bulk density, infiltration rate and chemical properties such as pH, total soil organic matter and nitrogen, available potassium and phosphorus were all improved under L. leucocephala and R. pseudoacacia. Management of these trees in Iraq for soil improvement or in agroforestry systems with different crops such as wheat, barley, corn and cotton should take into consideration optimal pollarding frequency and height as well as planting density to produce the desired levels of shade, soil cover and green manure, as well as animal fodder or wood products.

Keywords: Leucaena leucocephala, Robinia pseudoacacia, agroforestry system, soil properties, tree management

YOUKHANA, A. & IDOL, T. 2008. Penghasilan biojisim dan penambahbaikan tanah pada tahun pertama pertumbuhan dirian Leucaena dan Robinia di bawah sistem cantasan yang berbeza. Kajian tentang penghasilan biojisim dan penambahbaikan tanah dijalankan terhadap dua pokok pelbagai guna yang cepat tumbuh iaitu Leucaena leucocephala dan Robinia pseudoacacia di Hutan Mosul, utara Iraq. Ini bertujuan untuk mengkaji kesan ketinggian mencantas (0 cm, 15 cm, 30 cm dan 45 cm) serta frekuensinya (tiada cantasan, cantasan setiap tiga bulan atau enam bulan) terhadap gerak balas pertumbuhan dan ciri tanah. Kajian kedua-dua spesies ini merupakan sebahagian daripada satu kajian yang lebih besar untuk membangunkan sistem perhutanan tani di Iraq. Leucaena leucocephala menunjukkan gerak balas yang paling besar dari segi pencabangan, diameter pangkal pucuk, tinggi, biojisim dan kandungan nitrogen serta fosforus daun dan batang setelah dicantas setiap tiga bulan pada ketinggian 15 cm. Bagi R. pseudoacacia cantasan sekali selepas enam bulan pada 45 cm menghasilkan gerak balas pertumbuhan daun dan batang yang terbanyak. Ciri fizikal tanah seperti ketumpatan pukal, kadar penyusupan dan ciri kimia seperti nilai pH, jumlah kandungan jirim organik tanah serta kandungan nitrogen, kalium tersedia dan fosforus semuanya didapati bertambah baik di bawah L. leucocephala dan R. pseudoacacia. Pengurusan kedua-dua pokok ini di Iraq untuk menambahbaik tanah atau untuk sistem perhutanan tani dengan tanaman lain seperti gandum, barli, jagung dan kapas harus mengambil kira frekuensi cantasan dan ketinggian optimum dan juga ketumpatan tanaman. Ini dapat memastikan agar aras naungan, penutup tanah dan baja hijau yang dikehendaki dapat dicapai selain daripada menghasilkan makanan ternakan dan keluaran kayu.

INTRODUCTION

The maintenance of soil fertility, and therefore of crop productivity, is crucial to the development of sustainable agriculture. Modern agricultural systems depend heavily on large inputs of chemical fertilizers for maintenance of crop productivity. On a global scale, the cultivation of nitrogen-fixing trees is of increasing importance in agroforestry systems to improve soil nitrogen...
availability and promote soil conservation (Russo & Budowski 1986). This reduces the need for fertilizer and supports organic production. Many nitrogen-fixing trees are suitable as animal fodder or may produce seeds and pods that are edible for human consumption. Most species can be used as fuelwood, and some produce valuable timber. If pruned, they provide green manure that improves soil cover, suppresses weeds and increases organic matter and nutrient return to the soil.

Robinia pseudoacacia (black locust) is native to the south-eastern North America, yet worldwide the land area covered by black locust stands has enlarged dramatically to about 3 million ha, an area only exceeded by that of Eucalyptus and Populus species (Hanover et al. 1991). Black locust is a multipurpose tree that is used in erosion control and reclamation of disturbed areas (Chang-Seok et al. 2003). It is tolerant against drought, has excellent wood properties (DeGomez & Wagner 2001), is easy to regenerate from root suckers, grows efficiently on poor sites and improves nitrogen supply and element recycling (Ntayombya & Gorden 1995). Depending on stand age and density as well as on climatic conditions, R. pseudoacacia fixes 35–150 kg N ha\(^{-1}\) year\(^{-1}\), indicating a high capacity for N\(_2\) fixation (Danso et al. 1995).

Leucaena leucocephala is a fast growing, ubiquitous tropical legume which has found use in agroforestry, soil improvement (Lalljee et al. 1998), land reclamation, wood and forage production due to its exceptional capacity to produce biomass (Danso et al. 1992). Leucaena yields of > 15 Mg ha\(^{-1}\) year\(^{-1}\) have been reported in South-East Asia and Hawaii, with plants spaced 0.5–1.0 m apart in rows 1–3 m apart (Brewbaker 1987). It has been shown to improve soil fertility due to high biomass production, high nitrogen fixation rate (100–500 kg N ha\(^{-1}\) year\(^{-1}\)), and high foliar concentration of N, P, K and Ca (Young 1991).

Some of the plant management issues to be considered in agroforestry and soil improvement systems using these trees include planting density, pollarding frequency and pollarding height. Although some studies have been conducted on pollarding height and frequency, there are still gaps in the available knowledge. Burner et al. (2006) studied the effects of harvest date and pollarding height on foliar and shoot allometry of black locust trees; they found that there was a large increase in basal shoot diameter and foliar and shoot mass for pollarded trees. Depending on row configuration, black locust yielded 900–5000 kg dry matter ha\(^{-1}\) year\(^{-1}\) of pruning (foliage plus shoot) biomass in Oregon, USA (Seiter et al. 1999).

For Iraq, L. leucocephala and R. pseudoacacia show promise for green manure production and decreasing the demand for mineral fertilizers that have been used in huge quantities recently. This could reduce soil erosion and nutrient leaching and reduce the need for expensive external inputs to farming systems. The objectives of this study were to address the following questions: (1) What are the effects of pollarding frequency and height on the growth performance of L. leucocephala and R. pseudoacacia trees? (2) Do these trees improve soil organic matter and nutrient status? (3) What is the optimal pollarding height and frequency to maximize biomass production and nutrient concentration of pruned shoots and leaves?

MATERIALS AND METHODS

The experiment was carried out in Mosul Forest, a part of Mosul city located along the Tigris River in northern Iraq (36° 35’ N, 43° 3’ E and 222 m asl). Mean annual rainfall ranges from 300 to 600 mm (mean 400 mm), and the mean monthly temperature ranges from 17.2 °C in January to 32.0 °C in July. The soil in this area is derived from alluvial deposits from the Tigris River and has a sandy loam texture.

Three adjacent fields normally used for propagation of tree seedlings were used for this experiment beginning September 2003. Each field was 34 × 40 m. Each field was split into four blocks, each 10 × 13 m. There was a 5-m buffer between the outside edge of each block and the edge of the field and a 4-m buffer between adjacent blocks (Figure 1).

The first field was left unplanted as a control for comparison of soil properties at the beginning and end of the experiment. The second field was planted with one-year-old seedlings of Leucaena leucocephala, and the third field was planted with one-year-old seedlings of Robinia pseudoacacia. Seedlings were planted in September 2003 in rows at 1 × 1 m spacing. Each block contained 13 rows of seedlings with 10 plants per row. Individual pollarding treatments were randomly assigned to an entire row within each block.
In January 2004, all the tree seedlings were clipped at a uniform height of 0.5 m above ground level. In March 2004 four pollarding height treatments were applied by clipping seedlings at ground level, 15, 30 or 45 cm. Within each height treatment, trees were assigned to one of three pollarding frequencies: no pollarding, pollarding once after 6 months or twice at 3-month intervals. One row in each block was left as a control without any pollarding after January 2004.

Shoots of individual trees were sampled at the time of pollarding (June and September 2004) and at the end of the experiment (December 2004). Biomass growth was calculated as the total biomass accumulated from the beginning of the growing season (March 2004). The number of shoots per plant was counted and shoot basal diameter was measured with a caliper 5 cm from the distal end. Shoot height was measured with a haga altimeter. Samples of leaves and stems were collected for each species to determine N and P contents. Samples were oven-dried at 70 °C and milled to 0.5 mm. Samples were digested with 18 M sulphuric acid (Anderson & Ingram 1993). Digests were analyzed for total organic N by a micro-Kjeldahl method (Bremner & Mulvaney 1982). Phosphorous was measured colorimetrically by the molybdate blue method (Olsen & Dean 1965).

Soil physical properties bulk density (kg m⁻³), particle density (kg m⁻³), percent porosity, infiltration rate (kg cm⁻²), particle size distribution (percent sand, silt and clay) and soil nutrient status under both species and the open field were analyzed at the beginning and end of the study. Analyses were conducted following the techniques of Anderson & Ingram (1993). Available P and K were measured by atomic adsorption spectroscopy while total soil nitrogen was analyzed by digestion as described above. Extractable ammonium and nitrate were determined using selective ion electrodes.

The experimental design was a randomized complete block with two factors (pollarding height and frequency), four replicates of each treatment, and 10 plants in each replicate. For analysis of tree growth response and nutrient concentration, species were analyzed separately. For analysis of soil properties, treatments were combined within blocks and comparisons were made between the two species and the control. The data were log-transformed to achieve a normal distribution. Analysis of variance was used to analyze the log-transformed data (SAS Institute 1998). Duncan’s multiple range test was used to compare treatment means, with a significance level of p < 0.05. Back-transformed data are reported in the results.

Figure 1  Layout of the experiment
RESULTS

Both pollarding height and frequency had significant effects on the biomass production and nutrient concentration of *L. leucocephala* and *R. pseudoacacia*, but their interactions were not significant. For *L. leucocephala*, pollarding twice (every 3 months) at 15 cm yielded the greatest growth response and tissue N and P contents. For *R. pseudoacacia*, pollarding once after 6 months at a height of 45 cm yielded the highest biomass production and tissue N and P contents (Figures 2 and 3).

The physical properties of the soil were also significantly different under *L. leucocephala* and *R. pseudoacacia* (Table 1). Soil bulk densities were lower under both species (810 and 816 kg m\(^{-3}\) for *L. leucocephala* and *R. pseudoacacia* respectively) at the end of the experiment compared with the value prior to planting (901 kg m\(^{-3}\)). Soil porosity was slightly higher under *L. leucocephala* and *R. pseudoacacia*, and infiltration rates were significantly greater than at the beginning of the experiment. Results of soil particle size distribution (texture) showed no differences in all fields. Soil chemical and nutrient properties were also significantly improved in the presence of the tree species (Table 2). Soil pH increased significantly under *L. leucocephala* and *R. pseudoacacia* (5.58 and 6.20 respectively compared with 4.92 prior to planting). Total soil organic matter and nitrogen under the tree species also increased significantly over the course of the experiment. Available potassium in the soil increased from an average of 212 ppm at the beginning of the experiment to 375 ppm respectively.

![Figure 2](image)

Figure 2  Effects of pollarding height on *Leucaena leucocephala* and *Robinia pseudoacacia* growth responses. Bars with the same letter do not differ significantly (p < 0.05).
Table 1  Effects of *Leucaena leucocephala* and *Robinia pseudoacacia* on soil physical properties

<table>
<thead>
<tr>
<th>Site</th>
<th>Bulk density (kg m(^{-3}))</th>
<th>Particle density (kg m(^{-3}))</th>
<th>Porosity (%)</th>
<th>Infiltration rate (cm min(^{-1}))</th>
<th>Particle size (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All field before planting</td>
<td>901 a</td>
<td>2220 b</td>
<td>64.22 b</td>
<td>0.43 c</td>
<td>41.20</td>
</tr>
<tr>
<td><em>L. leucocephala</em></td>
<td>810 b</td>
<td>2680 a</td>
<td>69.20 a</td>
<td>1.66 a</td>
<td>42.90</td>
</tr>
<tr>
<td><em>R. pseudoacacia</em></td>
<td>816 b</td>
<td>2605 a</td>
<td>67.45 ab</td>
<td>0.88 b</td>
<td>40.90</td>
</tr>
<tr>
<td>Open field at the end of the experiment</td>
<td>906</td>
<td>2225</td>
<td>63.40</td>
<td>0.56</td>
<td>41.00</td>
</tr>
</tbody>
</table>

Values within a column followed by the same letter do not differ significantly (p < 0.05).

Figure 3  Effects of pollarding frequency on *L. leucocephala* and *R. pseudoacacia* growth responses. Bars with the same letter do not differ significantly (p < 0.05).
under *L. leucocephala* and 304 ppm under *R. pseudoacacia*. Available phosphorus, however, was not significantly different between the various treatments. Surprisingly, available ammonium and nitrate did not differ significantly between the soils although nitrogen availability in all soils was quite high, especially for ammonium.

**DISCUSSION**

It is clear from the results that the two legume trees showed a significant ability to recover rapidly following pruning. Some tree species with resprouting capacity recover slowly following pruning while others recover rapidly by shifting carbohydrate reserves from basal tissues to resprouting stems (Garcia *et al.* 2001, Oppong *et al.* 2002, Wildy & Pate 2002). It has been reported that coppiced stumps of *L. leucocephala* and *Vitex negundo* showed an increasing trend in biomass production in the second harvest, and the yield per plant and on a per unit area basis were higher in coppiced stands (Tewari *et al.* 2004). In another report, black locust yielded more foliar biomass when pollarded at 50 or 100 cm than at 5 cm, with or without P fertilization (Burner *et al.* 2005). This is presumably due to a reduction in total storage carbohydrates available for regrowth (Magel *et al.* 1994, Larbi *et al.* 2005). Conversely, Duguma *et al.* (1988) found that increasing pruning frequency and decreasing pruning height increased the biomass, dry wood and nitrogen yield of *L. leucocephala*, *Gliricidia* and *Sesbania*. A lower pollarding height in *L. leucocephala* seedlings may stimulate greater growth response because of a greater concentration of storage carbohydrates in the basal portion of the stems which can be readily mobilized for regrowth. Similarly, *Gliricidia* cuttings planted in the field tend to resprout at the base of the stem rather than at the distal end (personal observation). More work needs to be done to understand these contrasting growth responses.

Soil bulk densities were lower under both species compared with the fields prior to planting. This difference was probably due to the increase in soil organic matter under both species. The porosities of the soils were slightly higher under *L. leucocephala* and *R. pseudoacacia*, and infiltration rates were significantly greater than at the beginning of the experiment because of higher soil organic matter. Greater rooting activity of these tree species likely increased aggregate structure and macropore space (Young 1991).

The substantial increase in total nitrogen and available potassium is likely due to the inputs of nutrient-rich organic matter from these nitrogen-fixing species. On the other hand, nitrogen-fixing plants are known to reduce available soil P to the point where it can limit growth rates. Also, soils in this region are known to fix P (Wilkinson 1989). This may have masked organic P returns from the tree litter and pollarded biomass. The soils in this experiment had very high available nitrogen, especially ammonium, which may be a consequence of past fertilization as these soils had previously been used for tree seedling propagation. This may explain why the growth of these nitrogen-fixing trees failed to increase available soil nitrogen.

**CONCLUSIONS**

Results indicate that both *L. leucocephala* and *R. pseudoacacia* are highly suitable for agroforestry and soil improvement in Iraq. Pollarding
frequency and height both significantly affected the growth rate and nutrient concentrations of respouting stems of these species. For  *L. leucocephala*, the optimal pollarding was every 3 months at 15 cm height. For  *R. pseudocacia*, the optimal pollarding was after 6 months at 45 cm height. Both species improved soil physical and chemical properties, organic matter and nutrient status. Management of these trees for soil improvement or in agroforestry systems should also take into consideration planting density to produce the desired levels of shade, soil cover and green manure, animal fodder, or wood products. They can also reduce the need for N and K fertilizers and pH adjustment.

**REFERENCES**


Managing Shade Trees for Coffee Can Benefit the Soil

By Travis Idol and Adel Youkhana

Many small coffee farms in Hawaii and around the world incorporate trees as part of the production system (e.g. fruit and nut trees), as windbreaks, for landscaping around the home, or even to protect the coffee plants from excessive sun and high temperatures. Actively managing shade trees to maintain optimal shade levels (around 40-50%) can be a lot of work, and dealing with the pruning waste also becomes an issue.

Chipping and mulching the tree pruning residues is one option to recycle and make good use of this material. Mulch is a good soil cover. It can suppress weed growth, reduce water runoff and erosion, insulate the soil from extremes of heat, reduce surface evaporation, and stimulate soil biological activity. Most tree mulch makes a poor nutrient source, though, since wood generally has a low nutrient concentration. That may not be the case with mulch from nitrogen (N) fixing trees, since they generally have a higher N concentration than other tree species. Past studies have shown that leaf and fine root litter from N-fixing trees can add over 100 kg of N per hectare (100 lb per acre), but this was without pruning or otherwise managing the shade levels.

An ongoing study at the University of Hawaii-Manoa is showing that chipping and mulching the pruning residues from an N-fixing tree can have positive benefits for the soil. We are using the Leucaena hybrid KX2 developed at UH-Manoa as a fast-growing and multipurpose shade tree for coffee. Because the tree fixes its own N, mulching of the pruning residues acts like a slow-release fertilizer to the soil. This may also help to build up the soil organic matter level.

Results from this study have shown exactly what we had hoped. Pruning every 6-12 months adds approx. 25 Mg per ha (25 tons per ac) of mulch to the soil every year, including over 150 kg per ha (150 lb per ac) of N! Decay of this mulch results in a release of N beginning in the first 3 months and continuing for at least one year. After only two years, soil C in the top 20 cm (8 in) also increased significantly by over 10 Mg per ha (10 tons per ac). This obviously has benefits
for improving soil quality and can support organic farming practices.

This system could be altered so that the trees are grown separately from the coffee, adding the mulch from tree pruning to open-grown coffee plants. Although this eliminates competition for resources among the trees and coffee plants, our results suggest that the trees suffer due to the loss of nutrients exported in the mulch. It is unclear how long this system could be maintained before tree growth slows to the point where there isn’t enough mulch to satisfy the coffee plants.

In short, tree pruning residues are a valuable source of organic matter and potentially nutrients that can be put to good use in an agroforestry system, such as shade-grown coffee. Integrating N-fixing trees within these systems ensures the trees are able to maintain growth rates, providing a long-term source of N and organic matter to the soil.

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