

## Seasonal pattern of nitrogen mineralization and soil moisture beneath *Faidherbia albida* (syn *Acacia albida*) in central Malawi

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**Abstract.** On fertile alluvial soils on the lakeshore plain of Malawi, maize (*Zea mays* L.) yields beneath canopies of large *Faidherbia albida* (syn *Acacia albida*) trees greatly exceed those found beyond tree canopies, yet there is little difference in soil nutrients or organic matter. To investigate the possibility that soil nutrient dynamics contribute to increased maize yields, this study focused on the impact of *Faidherbia albida* on nitrogen mineralization and soil moisture from the time of crop planting until harvest. Both large and small trees were studied to consider whether tree effects change as trees mature.

During the first month of the rainy season, a seven-fold difference in net N mineralization was recorded beneath large tree canopies compared to rates measured in open sites. The initial pulse beneath the trees was  $60 \mu\text{g N g}^{-1}$  in the top 15 cm of soil. During the rest of the cropping cycle, N availability was 1.5 to 3 times higher beneath tree canopies than in open sites. The total production of N for the 4-month study period was  $112 \mu\text{g N g}^{-1}$  below tree canopies compared to  $42 \mu\text{g N g}^{-1}$  beyond the canopies. Soil moisture in the 0–15 cm soil layer was higher under the influence of the tree canopies. The canopy versus open site difference grew from 4% at the beginning of the season to 50% at the end of the cropping season.

Both N mineralization and soil moisture were decreased below young trees. Hence, the impact of *F. albida* on these soil properties changes with tree age and size. While maize yields were not depressed beneath young *F. albida*, it is important to realize that the full benefits of this traditional agroforestry system may require decades to develop.

### Introduction

A goal of agroforestry research is the design of land use management systems that sustain or improve farm productivity. For over a decade, agroforestry research has focused on intensively-managed land use management systems such as alley cropping. As researchers encounter constraints in transferring agroforestry practices from the controlled conditions on experimental stations to rural farmland, researchers have begun to acknowledge and investigate indigenous land use systems. In Malawi for example, the national agroforestry research program has expanded beyond typical on-station and on-farm alley cropping research to identify and study indigenous tree-cropping practices [Maghembe and Seyani, 1991; Bunderson et al., 1995]. Rural surveys identified nearly 150 tree species retained within cropland for a variety of purposes [Maghembe and Seyani, 1991]. More than 25 of these were identified by farmers as important soil improvers.

In Malawi, as in much of semi-arid Africa, *Faidherbia albida* is one of the most highly regarded soil-improving tree species in a variety of cropping systems [Charreau and Vidal, 1965; Radwanski and Wickens, 1967; Felker, 1978; Miede, 1989; Poschen, 1989; Kamara and Haque, 1992]. In Malawi, the tree grows on alluvial soils on the lakeshore plain and on upland sites in the central region [Brown and Young, 1962]. Though farmers maintain and manage tree stocking levels, *F. albida* is rarely planted. Farmers protect naturally regenerating *F. albida* sprouts during tillage operations. Sprouts of other most woody species are removed from croplands, so *F. albida* becomes the dominant species in areas where farming has continued for long periods of time.

Bunderson and coworkers [Bunderson et al., 1995] measured the effect of *F. albida* on maize production over several seasons at a variety of locations in Malawi. They found that maize yields were 100 to 400% higher beneath canopies of large *F. albida* trees, compared to yields in open areas. Results were consistent in 3 different regions, with greatest maize responses occurring on fertile, alluvial soils near Lake Malawi where maize increased from under 1 t ha<sup>-1</sup> to over 2 t ha<sup>-1</sup>. Maximum grain yields occurred 6 to 10 m from the tree trunk. The Malawian results agree with other studies where increased crop yields were measured for millet, groundnuts, and sorghum [Dancette and Poulain, 1969; Poschen, 1989; Depommier et al., 1992].

The positive effect of *F. albida* on crop production is commonly attributed to the tree's combined impact on soil fertility, soil physical conditions, microbial populations and microenvironmental conditions [Jung, 1970; Radwanski and Wickens, 1967; Charreau and Nicou, 1971; Jama and Getahun, 1991]. Increased soil fertility beneath *F. albida* and other parcland tree species derives from both litterfall and accumulations of animal dung [Bernard-Reversat, 1982; Belsky et al., 1989; Kessler and Breman, 1991]. At several sites in Malawi, carbon and total nitrogen range from 3 to 30% and from 5 to 29% higher beneath *F. albida* canopies [Bunderson et al., 1995]. Exchangeable K, Ca, Mg were also higher beneath tree crowns. In an Ethiopian vertisol, Kamara and Haque [1992] found higher N, P, and K beneath *F. albida*, but no differences in exchangeable Ca, Na, Mg or soil pH. In Sudan, organic carbon increased by 3 to 70% and total nitrogen increased by 50 to 90% beneath *F. albida* [Radwanski and Wickens, 1967]. Felker [1978] documented increases of 50 to 100% for soil organic matter beneath *F. albida*. On the lakeshore plain of Malawi, no significant differences in soil nutrient pools were found beneath either large or small trees (Table 1). The high natural fertility of the alluvial soils along with soil mixing during tillage activities may mask nutrient enrichment associated with the trees.

*Faidherbia albida*'s unique canopy phenology influences microenvironmental conditions beneath tree canopies. Leaves are shed at the beginning of the rainy season and maintained during the dry season. Thin shade is cast beneath *F. albida* crowns during the cropping season as compared to dense

Table 1A. Soil properties beneath large tree canopy and in open plots, beyond the canopy (30 m from bole). Values represent mean and (SE) of  $n = 3$  for each size class. Sample depth 0–15 cm.

Large trees: (mean canopy radius = 12 m)

	Canopy <sup>a</sup>	Open	$p^b$
pH <sub>water</sub>	6.3 (0.1)	6.3 (0.1)	0.88
C % <sup>c</sup>	2.5 (0.2)	2.2 (0.2)	0.43
Bray-P mg kg <sup>-1</sup>	21.2 (1.8)	22.7 (2.7)	0.65
Ca mmol <sub>c</sub> kg <sup>-1</sup>	57.1 (4.4)	68.4 (13.7)	0.46
Mg mmol <sub>c</sub> kg <sup>-1</sup>	15.0 (1.2)	17.8 (3.0)	0.41
K mmol <sub>c</sub> kg <sup>-1</sup>	9.8 (0.9)	8.7 (1.0)	0.18
Na mmol <sub>c</sub> kg <sup>-1</sup>	0.87 (0.0)	1.0 (0.0)	0.44

<sup>a</sup> Large tree canopy plots: 6 m from tree.

<sup>b</sup> Two-tailed  $t$ -test.

<sup>c</sup> Walkley-Black C determination.

Table 1B. Soil properties beneath small tree canopy and in open plots, beyond the canopy (15 m from bole). Values represent mean and (SE) of  $n = 3$  for each size class. Sample depth 0–15 cm.

Small trees: (mean canopy radius = 3 m)

	Canopy <sup>a</sup>	Open	$p^b$
pH <sub>water</sub>	6.5 (0.1)	6.4 (0.1)	0.73
C % <sup>c</sup>	2.3 (0.3)	2.7 (0.4)	0.43
Bray-P mg kg <sup>-1</sup>	19.8 (1.9)	22.8 (2.9)	0.40
Ca cmol kg <sup>-1</sup>	6.1 (0.5)	7.1 (0.9)	0.36
Mg cmol kg <sup>-1</sup>	1.6 (1.1)	1.8 (0.2)	0.32
K cmol kg <sup>-1</sup>	0.9 (0.6)	1.0 (0.1)	0.28
Na cmol kg <sup>-1</sup>	0.09 (0.1)	0.1 (0.0)	0.71

<sup>a</sup> Small tree canopy plots: 1–3 m from tree.

<sup>b</sup> Two-tailed  $t$ -test.

<sup>c</sup> Walkley-Black C determination.

shade found beneath crowns of tree species with typical leaf fall dynamics. In West Africa, researchers have documented reduced evapotranspiration and temperature extremes, along with increased relative humidity, and rainfall infiltration beneath *F. albida* [Dancette and Poulain, 1965; Jung, 1966]. The microenvironmental conditions vary with distance and orientation from the tree [Kamara and Haque, 1992]. Farrell [1990] designated regions of tree influence relative to tree canopy and root systems of semi-arid cropland trees. In Malawi, decreased maize yields near the base of *F. albida* correlate with a drastic reduction in photosynthetically active radiation caused by shading from the tree bole and large branches [W.T. Bunderson, unpub.].

During the 1991–1992 cropping season, investigation of traditional tree-cropping systems was expanded to investigate the effect of *F. albida* on seasonal variation in soil moisture and available nitrogen. Past studies of nutrient dynamics beneath trees in semi-arid Africa have documented tree effects on N mineralization and other nutrient pools [Jung, 1970; Bernard-Reversat, 1982; Belsky et al., 1989]. In this study, two tree size classes were differentiated to examine at what age the positive effects of *F. albida* become important. The objective of the study was to identify processes responsible for improved crop production in the indigenous agroforestry system.

## Methods

### *Study site*

The study site was situated on the lakeshore plain of central Malawi (13°47' S, 34°26' E). The elevation is 600 m and average annual rainfall is 900 mm, fluctuating from 500 to 1200 mm. Rainfall occurs during a four-month rainy season (December–March) that provides 85% of the annual moisture. The soil is a sandy loam texture calcimorphic alluvium [Brown and Young, 1962] considered an Ustalf by US soil taxonomy [USDA Soil Survey Staff, 1990]. The natural vegetation is savanna thicket [Brown and Young, 1962] featuring *Acacia* spp., *Adansonia digitata*, *Sterculia africana*, and *Sclerocarya birrea*. Maize is the principal crop in the region, though cotton, groundnuts, and sorghum are also planted. Maize is planted on hand-tilled ridges. Fertilizer use is not widespread; unfertilized maize yields range from 1 to 3 tons dry grain per hectare [Bunderson et al., 1995].

The site was selected because of the high density of *F. albida* growing under traditionally managed, low external input cropping conditions. Maize yields at the site have been monitored since 1988 [Bunderson et al., 1995]. All sample trees were located within a 0.5 km radius. Sample trees were located in the interior of crop plots, at least 50 m from other large trees or *F. albida* stumps.

Tree diameter was measured at 1.5 m above the ground surface. Height was estimated with a Suunto clinometer. The canopy area for each tree was calculated from the average of 4 radii from the tree trunk to the edge of the canopy. The average dimensions of the large tree class ( $n = 3$ ) were the following: diameter = 75 cm, height = 20 m, canopy radius = 11.9 m, canopy area = 455 m<sup>2</sup>. Average dimensions for the small trees ( $n = 3$ ) were: diameter = 38 cm, height = 13.7 m, canopy radius = 3.3 m, canopy area = 34 m<sup>2</sup>. Local farmers estimated the age of the small trees as 10 to 15 years and that of the large trees as 'much older.'

### *Soil sampling and laboratory analysis*

The main interest of the study was to measure changes in production of plant-available soil nitrogen throughout the cropping season. Plant available forms of nitrogen,  $\text{NO}_3^-$ -N and  $\text{NH}_4^+$ -N, are affected by multiple soil and climatic processes that fluctuate rapidly. Measurement of pool size of the different N forms gives only an instantaneous glimpse of soil N conditions and does not provide a reliable index of plant-available nitrogen. Availability is better related by measuring production of inorganic sources of N over discrete periods of time. Mineralization is the transformation of organic forms of N into inorganic, plant-available forms. The microbial processes that enzymatically convert N from organic to inorganic forms are controlled by temperature and soil moisture, as well as by the chemical composition of organic inputs. The chemical properties that define the quality of organic inputs include the C/N ratio and the lignin and polyphenol content [Parton et al., 1987].

To examine the impact of *F. albida* on N availability, a field incubation technique was used to integrate the tree's impact on both soil substrate quality and microenvironmental conditions. The technique measured production of inorganic  $\text{NO}_3^-$ -N and  $\text{NH}_4^+$ -N while controlling losses of inorganic-N due to root uptake, leaching, or denitrification [Eno, 1960; Palm et al., 1989]. Buried-bag, field incubations began in December, at the start of the rainy season and continued at 30-day intervals through the cropping season until harvest in May. Soil sampled from the surface 15 cm was incubated inside low density plastic bags buried in the maize root zone. The buried-bag method allows for gas exchange and maintains soil moisture at fairly constant levels during the incubation period [Binkley and Hart, 1989; Carsky et al., 1990]. Net mineralization was calculated by subtracting the sum of  $\text{NO}_3^-$ -N and  $\text{NH}_4^+$ -N extracted from the soil by a 2 M KCl solution at the start of the incubation period from the amount present after one month. Soil was transported to the laboratory inside sealed plastic bags, and extractions were carried out within 48 h of field sampling. Soil moisture was determined gravimetrically for the 0–15 cm and the 15–30 cm soil, by drying samples for 24 h at 105 °C.

### *Sample design*

Sampling was set up to study distance-dependant variability in soil properties. Sample plots were established along two transects per tree. Transects were oriented to avoid termite mounds and other trees or tree stumps and such that they stayed within one crop field. Plot distances from tree boles were determined by tree and canopy size. For the large tree class (trees > 20 years old), plots were located 2–3, 5–10, 15–20, and 30 m from the base of the tree. For small trees (10–15 years old), plots were 1, 3, 6, and 15 m from tree trunks. The location of the plots allowed comparison of soils taken beneath the canopy with those on the fringe of the canopy and those beyond

the extent of the canopy. The horizontal extent of roots was not sampled, though roots were not observed in soil samples taken from the open sites. Frequent tillage has probably trained the roots to grow below the 30 cm soil sampling depth.

To investigate differences related to orientation about the tree, samples were taken at all 4 cardinal directions, equidistant from the tree bole, beneath the canopy. Plots were located 6 m from the bole of large trees and 3 m from the bole of small trees.

### *Statistical analysis*

Comparisons were made using ANOVA to test for differences between plot means. To control for variations in fertilizer use and soil type, comparison was made after blocking by tree. The data were log-transformed to treat the problem of inequality of variance. Two-tailed *t*-tests were used to compare soil moisture below and beyond tree canopies.

## **Results and discussion**

### *N mineralization*

During the first month of the rainy season, over 60  $\mu\text{g N g}^{-1}$  dry soil was mineralized beneath the large tree crowns (Table 2A). The large flush of net N mineralization was 7 times greater beneath tree canopies compared to open plots. Over 90% of the inorganic N was in the  $\text{NO}_3^-$ -N form. From January until April net mineralization rates below tree canopies were 1.5 to 3 times greater than mineralization in open sites. Only during the first month were plot differences statistically significant ( $p = 0.04$ ). About half the N mineralized during the cropping season became available during the first month of the rainy season. These results compare to seasonal N mineralization patterns measured beneath *F. albida* in Senegal [Jung, 1970], where peak  $\text{NO}_3^-$ -N production occurred at the start of the rain. At that time net  $\text{NO}_3^-$ -N levels near tree trunks were also 3–4 times greater than N levels beyond tree canopies.

Cumulative net mineralization totalled 112  $\mu\text{g N g}^{-1}$  for 4 months beneath large *F. albida* canopies, compared to 42  $\mu\text{g N g}^{-1}$  in open plots. The release of N was 5 and 2% of total soil N (2.4  $\text{g kg}^{-1}$ ) in canopy and open sites, respectively. In semi-arid savanna in northern Senegal, Bernhard-Reversat [1982] found that N turnover below *A. senegal* ranged from 5.1 to 8.2% of total soil N. Small *F. albida* trees did not increase net N mineralization (Table 2B), in fact, during the first two incubation periods N availability was 4 to 5 times less near trees compared to open sites. With the exception of the first month of the rainy season, degree and direction of fluctuation in N mineralization between sample dates was similar for large and small trees. The increase

Table 2. Net N mineralization ( $\mu\text{g N/g/30 days}$ ).A. Large tree class (3 trees; 2 transects per tree;  $n = 3$ )

	Distance from tree (m)				Normal SED	Log SED	ANOVA ( $p$ )
	2-3	5-10	15-20	30			
Dec-Jan	61.2	50.8	13.2	7.5	20.9	0.6	0.04
Jan-Feb	13.8	9.5	1.9	5.5	5.1	1.1	0.26
Feb-Mar	16.7	17.2	11.2	10.3	3.2	0.2	0.12
Mar-Apr	27.3	26.5	15.0	18.5	5.9	0.6	0.22

B. Small tree class (3 trees; 2 transects per tree;  $n = 3$ )

	Distance from tree (m)				Normal SED	Log SED	ANOVA ( $p$ )
	1-2	3-4	6-9	15-20			
Dec-Jan <sup>a</sup>	1.7	2.5	10.8	11.8			
Jan-Feb	5.5	0.8	6.3	12.0	3.8	1.1	0.03
Feb-Mar	12.2	11.7	10.5	7.2	3.4	0.4	0.16
Mar-Apr	26.7	21.7	29.7	24.1	11.0	0.4	1.0

in mineralization at the end of the cropping period records a secondary pulse of microbial activity caused by renewed rainfall after a mid-season dry period.

The initial pulse of N mineralization beneath large *F. albida* canopies occurs when conditions favor activity of soil microorganisms [Birch, 1958; Jung, 1970]. At the onset of the rainy season, decomposers breakdown newly fallen leaf material as well as root tissue, seed pods and livestock manure that have built up below the tree canopies during the dry season. The unique litterfall phenology of *F. albida* provides large amounts of high quality leaf litter during a period of rapid population growth of soil microbes. Though Malawi suffered drought during the 1991-1992 cropping season, the wetting and drying phases were relatively typical. This study documents the N pulse at the onset of the rainy season, followed by the range of fluctuations in mineralization during the cropping season.

Relative to small trees, the increased N dynamics recorded beneath large trees results from both the long-term accumulation of above and below-ground organic inputs and the greater extent of microenvironmental modification. The area covered by the canopy of small trees is less than one tenth that covered by large trees, so organic inputs from litterfall and root turnover are much less. The additional input of dung deposited by animals grazing in the shade of large tree canopies is also absent beneath small trees. The relation between tree size and soil nutrients agrees with patterns measured around Sahelian tree

species, where total soil C and N levels increased with tree diameter [Bernhard-Reversat, 1982].

### *Soil moisture*

Throughout the study, soil moisture in the surface 15 cm was higher beneath tree canopies than in open sites (Table 3A). At the end of the dry season, surface soil moisture was 4% higher ( $p = 0.72$ ) beneath tree canopies; the difference grew to 53% ( $p < 0.001$ ) by the end of the cropping season. Differences in the 15–10 cm depth were less pronounced. These results agree with Farrell [1990] who found soil moisture increases in surface soil beneath the canopies of cropland trees in semi-arid Mexico and no differences in the 15–30 cm depth. In Senegal, however, a study of *F. albida* [Dancette and Poulain, 1969] found improved water conditions to a depth of 120 cm beneath tree crowns. Below 120 cm, soil moisture was lower under the trees. They attributed these findings to reduced evaporation under the trees affecting the upper soil and tree water uptake from the lower depths.

Soil moisture fluctuated widely during the study period. At the end of the dry season subsurface soil moisture was depleted beneath the trees below that of the soil surface. By February, subsoil moisture exceeded the topsoil in both canopy and open sites. Soil moisture change was greater at the soil surface than in the subsoil; tree canopies moderated soil moisture shifts so that canopy sites fluctuated less than open sites.

The impact of tree canopies on rainfall inputs and intensity may have affected soil moisture status. In a savanna ecosystem in Tsavo National Park, Kenya, Belsky et al. [1989] found that soil moisture was higher in grassland surrounding isolated trees at the beginning of the rainy season. Interception losses from tree canopies prevented the first light rains from adding to soil moisture. As rainfall intensified later in the rainy period, soil moisture became greater beneath trees. Researchers in Senegal measured higher precipitation inputs beneath *F. albida* after driving rainstorms [Dancette and Poulain, 1969]; during light showers less rainfall was collected beneath the tree canopies.

Small trees did not increase soil moisture in either the top 15 cm or the subsurface at any point during the study (Table 3B). During the first half of the rainy season, topsoil moisture was 12 to 20% higher in the open than beneath tree canopies. Similar to the area under large trees, subsoil moisture was drawn down through January. The small, leafless canopies do not create enough shade to slow evapotranspiration, and rainfall interception on their branches decreases moisture inputs.

Maize germination and emergence was uniform across the fields; the crops were planted after several hard rains, and germination occurred under uniform moisture conditions. Rainfall in 1991–1992 was 70% of average for the cropping season, and the impact of *F. albida* on soil moisture and the reduced

Table 3. Gravimetric soil moisture (%) in canopy and open plots (Mean and (SE)).

## A. Large trees

	Canopy <sup>a</sup>	Open <sup>b</sup>	<i>p</i> <sup>c</sup>
0–15 cm depth			
December	11.4 (0.8)	11.0 (0.9)	0.715
January	24.0 (1.1)	21.4 (1.2)	0.144
February	12.2 (1.1)	8.8 (0.7)	0.004
March	10.5 (0.8)	7.5 (0.8)	0.010
April	17.8 (1.0)	11.7 (0.8)	0.000
15–30 cm depth			
December	9.3 (0.7)	11.5 (0.7)	0.042
January	19.8 (1.8)	18.8 (0.8)	0.520
February	15.6 (0.7)	14.0 (0.6)	0.114
March	12.4 (0.7)	12.8 (0.7)	0.654
April	18.5 (0.7)	15.1 (0.8)	0.006

<sup>a</sup> Canopy plots 2–10 m from tree.

<sup>b</sup> Open plots 15–30 m from tree.

<sup>c</sup> Two-tailed *t*-test.

## B. Small trees

	Canopy <sup>a</sup>	Open <sup>b</sup>	<i>p</i> <sup>c</sup>
0–15 cm depth			
December	12.4 (1.8)	14.0 (0.5)	0.445
January	21.3 (1.2)	24.6 (1.2)	0.067
February	8.0 (0.9)	9.8 (1.3)	0.295
March	10.1 (0.7)	8.1 (1.2)	0.177
April	11.9 (0.8)	12.0 (1.8)	0.977
15–30 cm depth			
December	8.9 (0.7)	11.4 (1.4)	0.172
January	19.6 (1.2)	19.6 (1.2)	0.979
February	15.2 (1.6)	15.5 (1.8)	0.900
March	13.8 (0.5)	14.0 (1.3)	0.886
April	15.5 (0.6)	18.2 (1.4)	0.128

<sup>a</sup> Canopy plots 1–3 m from tree.

<sup>b</sup> Open plots 6–15 m from tree.

<sup>c</sup> Two-tailed *t*-test.

water stress for crops was visible. Maize growing beneath tree canopies wilted less severely and stayed greener longer than maize growing in the open. Higher maize leaf area below the canopy may have had a positive feedback on surface soil moisture, contributing to the increased disparity between canopy and open plot soil moisture as the crop developed.

### Orientation effects

The effect of orientation on N mineralization was examined beneath tree canopies (Table 4). A pattern emerged for large trees with higher N mineralization on the north and east sides of the canopy compared to the south. The trend was consistent throughout the cropping season, but was greatest during the initial pulse of decomposition when mineralization on the southern side of tree canopies was 8 times less than that occurring on the other sides.

In Malawi, large *F. albida* canopies have a distinct northerly orientation, that is, the canopy volume on the north side of trees is greater than that on the south side. In the dry season when *F. albida* is photosynthesizing, the sun tracks across the northern sky. Canopy architecture reflects the phototropic response of the trees. Similar findings have been reported at 14° N latitude in Sudan, where *F. albida* canopies are oriented towards the south; Ismail [1986] estimated that 3 times more crown biomass is oriented towards the trajectory of the growing season sun.

The orientation effect on soil moisture agrees with the north/south pattern in N mineralization (Table 5). Below the canopies of large trees, soil moisture was 15% higher on the north side than on the south. The trend was similar for small trees. In Mexico, Farrell [1990] did not compare north and south, but found slight differences between east and west sides of *Prunus* and *Juniperus*. As in Malawi, afternoon shade cast east of tree crowns contributed to higher surface soil (0–15 cm) moisture in that zone. Protection from intense afternoon heat may be more crucial to conserving soil moisture than morning shade. These results differ from conditions on an Ethiopian vertisol where soil moisture was higher on the west side of *F. albida* canopies [Kamara and Haque, 1992]. At that site the prevailing wind direction was credited for higher organic matter accumulation towards the west and the improved soil moisture status.

Table 4. Orientation effect on net N mineralization ( $\mu\text{g N/g/30 days}$ ) beneath large tree canopies. Values represent mean and (SE) of  $n = 3$  trees.<sup>a</sup>

	North	East	South	West	$p^b$
Dec–Jan	56.3 (21.0)	46.5 (33.5)	6.4 (2.9)	56.9 (31.6)	0.582
Jan–Feb	20.6 (6.8)	18.3 (0.9)	0 (0)	5.2 (5.2)	0.964
Feb–Mar	23.5 (2.5)	15.0 (3.5)	14.8 (1.6)	14.0 (1.7)	0.041
Mar–Apr	28.7 (5.9)	26.3 (5.3)	21.6 (3.7)	23.4 (5.0)	0.815

<sup>a</sup> Sampled 6 m from tree base.

<sup>b</sup> One-way ANOVA.

Table 5. Orientation effect on soil moisture. Values represent mean and (SE) of  $n = 3$  trees.<sup>a</sup>

	North	East	South	West	$p^b$
Large trees					
0–15 cm	15.5 (1.2)	15.4 (1.6)	13.4 (1.2)	13.8 (1.0)	0.534
15–30 cm	16.8 (0.9)	16.3 (1.2)	14.2 (1.0)	13.7 (0.8)	0.077
Small trees					
0–15 cm	12.3 (1.4)	12.1 (1.2)	10.3 (0.9)	12.4 (1.5)	0.628
15–30 cm	16.7 (1.6)	15.0 (1.0)	13.0 (0.6)	14.6 (0.7)	0.140

<sup>a</sup> 5-month average.

<sup>b</sup> One-way ANOVA.

## Conclusions

The impact of *F. albida* on N mineralization and soil moisture varied seasonally and with tree size. Soil nitrogen and moisture conditions were lower near small trees (10–15 years old) at the beginning of the rainy season, but were similar to open sites during most of the cropping season. Based on local observations that maize yields increase rather than decline near small trees, it is clear that farmers benefit from *F. albida* before trees reach a size to modify soil moisture and N conditions. Large trees had a positive impact on N mineralization that was greatest during the first month of the rainy season when a seven-fold difference existed between sites under the canopy and in the open. The large trees' impact on soil moisture increased steadily during the cropping season and reduced crop wilting during dry periods. While soil C and P (Bray) were similar beneath small and large trees and between canopy and open sites, exchangeable cations around small trees were much lower than those near large trees. Improved crop yields beneath large trees resulted from the combined effect of *F. albida* on sub-canopy microclimate and the long-term and seasonal impact of litter inputs on soil nutrient availability, rather than from preexisting soil patterns [Geiger et al., 1992].

Nitrogen fertilizer trials at this site [Bunderson et al., 1995] indicate that maize is less N limited beneath large tree canopies, so the improved N availability measured beneath tree canopies appears to contribute to increased crop yields. However, the timing of the initial pulse of inorganic N from annual litter inputs and below ground turnover may not be synchronized with crop nutrient requirements. As the period of highest N availability occurs before crop roots have fully developed, a large amount of the N may bypass the crops completely; nearly all the N was in the highly mobile  $\text{NO}_3^-$ -N form that may rapidly leach beyond crop root systems. Further study of this system would clarify the sources of nutrient inputs and the fate of the mineralized N. Investigation of this traditional agroforestry system would detail the impact of *F. albida* on both seasonal nutrient dynamics and long-term changes in soil conditions.

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