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Above- and belowground biomass, nutrient and carbon stocks contrasting an open-grown and a shaded coffee plantation

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Abstract Coffee (*Coffea canephora* var *robusta*) is grown in Southwestern Togo under shade of native *Albizia adianthifolia* as a low input cropping system. However, there is no information on carbon and nutrient cycling in these shaded coffee systems. Hence, a study was conducted in a mature coffee plantation in Southwestern Togo to determine carbon and nutrient stocks in shaded versus open-grown coffee systems. Biomass of *Albizia* trees was predicted by allometry, whereas biomass of coffee bushes was estimated through destructive sampling. Above- and belowground biomass estimates were respectively, 140 Mg ha⁻¹ and 32 Mg ha⁻¹ in the coffee–*Albizia* association, and 29.7 Mg ha⁻¹ and 18.7 Mg ha⁻¹ in the open-grown system. *Albizia* trees contributed 87% of total aboveground biomass

and 55% of total root biomass in the shaded coffee system. Individual coffee bushes consistently had higher biomass in the open-grown than in the shaded coffee system. Total C stock was 81 Mg ha⁻¹ in the shaded coffee system and only 22.9 Mg ha⁻¹ for coffee grown in the open. Apart from P and Mg, considerable amounts of major nutrients were stored in the shade tree biomass in non-easily recyclable fractions. Plant tissues in the shaded coffee system had higher N concentration, suggesting possible N fixation. Given the potential for competition between the shade trees and coffee for nutrients, particularly in low soil fertility conditions, it is suggested that the shade trees be periodically pruned in order to increase organic matter addition and nutrient return to the soil.

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Introduction

Coffee (*Coffea canephora* var *robusta*) is a cash crop grown by approximately 40,000 households in Southwestern Togo. The dominant cropping system involves the use of native spontaneous leguminous species as shade trees for coffee, of which *Albizia adianthifolia* (Schum.) W. F. Wight is the most common species. This shading practice provides

some benefit to the coffee but also appears to be a desirable environmental practice as most of the forest vegetation in the coffee zone has been cleared off and reforestation attempts have not been successful. Despite the widespread nature of this shaded coffee system and the fact that farmers use little or no fertilizer in coffee production, there is no published work on carbon (C) and nutrient cycling in shaded coffee plantations in Togo.

Provision of shade in coffee is a common agroforestry practice among farmers in the Tropics. Reasons for shading include timber, fuel wood and fruit production (Peeters et al. 2003; Schaller et al. 2003), sub-canopy microclimate stabilization (Montes 1979) and stability against risk of failure (Beer 1987; Escalente 1995), but also some ecological benefits such as, increased biodiversity (Perfecto et al. 1996; Greenberg et al. 1997), carbon sequestration (De Jong et al. 1997; Peteers et al. 2003), soil conservation and amelioration (Young 1987; Nair 1989). However, shade trees may compete with crops for nutrients, water and light (Beer 1987), the extent of which depends on tree species characteristics, site conditions and management practices.

There is limited information on C and nutrient recycling in coffee agroforestry systems. The few published studies are limited to Central America where *Coffea arabica* has been commonly studied in association with leguminous species such as *Erythrina* sp, *Inga* sp or *Glyricidia* sp, and timber species such as *Cordia* sp (Fassbender et al. 1985; Heuveldop et al. 1985; Glover and Beer 1986; Oelbermann et al. 2005). Very often, these shade trees are periodically lopped or pruned to reduce shading and to transfer nutrients from the tree biomass to the associated coffee crop (Beer 1988). Results from these studies indicate standing aboveground biomass production of 20 Mg ha⁻¹ and 29 Mg ha⁻¹ respectively with *Erythrina* and *Cordia* shade species (Fassbender et al. 1985) and a yearly return of litter ranging from 5 to 20 Mg ha⁻¹ (Beer 1988). Reports of C input to soil from pruning residues amounted 5.2 Mg C ha⁻¹ yr⁻¹ with *Inga* shade species (Nygren 1995) and ranged from 1 to 4 Mg C ha⁻¹ yr⁻¹ with *Erythrina* sp depending on stand age (Oelbermann et al. 2005). In these shaded coffee systems, nutrients as much as those supplied through conventional fertilization were reported to be returned to the system through litter fall and/or pruning residues of the shade trees

(Aranguren et al. 1982; Glover and Beer 1986). Such results reflect essentially tree species, site condition and stand management practice interaction.

Information on biomass production and nutrient partitioning in biomass is important for the selection and management of trees for improved productivity and efficient nutrient and carbon cycling in agroforestry systems. A major attribute of shade trees that facilitates nutrient recycling in agroforestry systems is the production of large quantities of easily recyclable nutrient-rich biomass. Nutrient immobilization in shade tree biomass or nutrient loss through biomass harvesting and export may result in depletion of soil nutrients (Spangenberg et al. 1996), or nutritional disorders for the associated crop (Beer 1988; Young 1989).

Biomass studies in agroforestry systems have largely focused on the aboveground portion relative to the belowground portion of vegetation biomass, owing partly to the difficulty in accessing plant roots (Lafolie et al. 1999; Gill et al. 2002). An accurate evaluation of the role of trees in nutrient recycling in a given cropping system requires that the roots and belowground trunk portion of tree biomass also be measured. Published estimates show that the belowground portion represents approximately 20–30% of total C allocation of a tree (Armson 1977; Young 1989; Oelbermann et al. 2005) and can contribute a considerable portion of the total inputs to soil organic matter (Nye and Greenland 1960; Nye 1961; Nair 1989). Fine roots are found to recycle annually as much N as leaf litter in some tree species (Arthur and Fahey 1992). Given the future potential for small farmers to benefit from the emerging markets on biomass and soil carbon and a tradable value of C based on long term sequestration, it is important to have reliable data on C stocks and dynamics in agroecosystems.

The objectives of this study were: (1) to quantify total vegetation biomass and biomass distribution in a mature coffee plantation with and without shade of *Albizia adianthifolia* in Southwestern Togo, and (2) to determine nutrient and carbon storage in biomass in the two coffee agroecosystems. This study will provide data on the impact of the *Albizia* shade trees on nutrient recycling in shaded coffee systems. The data will serve not only as a basis for appropriate nutrient management recommendations for local coffee systems but will also provide estimates on

the potential for carbon sequestration in coffee agroecosystems.

Materials and methods

Study area

The study was conducted in the Kpélé-Amou districts, which represent a major coffee zone in the Plateau Region located between 6°45 and 8°20N, and 0°40 and 1°50E in Southwestern Togo. The climate is a Sudan-Guinean type characterized by a bimodal rainfall regime with a mean annual rainfall of 1,400 mm distributed from April to July (the main rainy season), and from September to November. Mean annual air temperature is 21–28°C, the highest (34°C) occurs in February and the lowest (19°C) in August (DRDR 1998). Altitude at the site is 300–500 m a.s.l. The soils are Ferralsols (FAO 1991) developed on quartzite and micaschist (Lamouroux 1969), with a sandy-clay texture and pH of about 5.4 in the top 20 cm soil.

The natural vegetation at the site is a combination of Sudan-Guinean type forest species such as *Chlorophora excelsa*, *Antiaris* spp, and bush or tree savanna of *Terminalia* spp, *Butyrospermum* spp, *Andropogon* spp (Lamouroux 1969), but has been greatly encroached due to continuous anthropogenic pressure.

Selection of study site and establishment of study plots

A mature, 13-year-old coffee plantation (10 ha) that is representative of local coffee plantations (open-grown and shaded coffee) was selected for this study. After careful field reconnaissance to evaluate the coffee and shade trees, soils, landscape position and aspect, we selected a representative area (0.8 ha) that had both unshaded and shaded coffee with *Albizia adianthifolia*. For each coffee system (open grown and shaded coffee), a 40 × 40 m² quadrat was marked out (henceforth referred to as shaded coffee plot or open-grown coffee plot) within which four 10 × 10 m² subplots were randomly laid out.

Plot and management history

The coffee plots were established in 1987 by clearing and burning a secondary forest regrowth and planting

Coffea canephora var *robusta* at 3 × 2.5 m² spacing (1,333 coffee plants per hectare). Approximately 400 kg ha⁻¹ of complex NPK fertilizer was applied each year for the first 3 years following coffee establishment. The shade trees regenerated spontaneously prior to- or during the year of coffee establishment. Management of the plantation was then uniform for the two coffee systems and carried out by the same farmer. At the time of sampling, the density of shade trees was 38 *Albizia* trees per ha on the shaded coffee plot. The trees ranged from 18 to 26 m in height and their circumference at breast height varied between 1.35 and 2.36 m.

Estimation of shade tree biomass

Shade tree biomass was estimated using allometric relationships developed based on 12 *Albizia* trees selected to reflect the range of tree size encountered in the area of study. The sample trees were cut at ground level using a chain saw. Before felling each tree, measurement was taken for circumference at 0.40 m height (basal circumference (BC)) and at 1.30 m (circumference at breast height (CBH)) from ground level. Canopy size was measured by averaging the lengths of two perpendicular axes corresponding to the limit of the tree canopy. Tree height was recorded after the tree was felled. The above-ground portion of each tree was separated into stem (main shoot up to the starting point of a secondary ramification), branch, twig (diameter <20 mm) and leaf. Coarse root mass of *Albizia* trees were estimated by digging out the stump from a 1.25-m radius hole around the tree to approximately 0.60 m depth. Fresh weight of each tree compartment was recorded and composite samples of approximately 500 g taken and oven-dried at 70°C to constant weight. Dry mass of the different fractions was calculated based on moisture content of the oven-dried samples.

Stem, branch, twig, leaf and root dry mass of *Albizia* trees were regressed on height, stem circumferences and canopy size using least squares regression. Based on the regression equations developed, tree biomass was computed individually for all *Albizia* trees within the inner 40 × 40 m² shaded coffee plot after measurement of the different predicting variables on each tree. Height used in biomass prediction for these trees were estimated based on a regression relationship derived from the

destructively sampled trees ($n = 12$). Total biomass of *Albizia* trees was obtained by summation of the individual components of tree biomass estimates and extrapolation to a hectare was based on the density of shade trees (38 trees ha^{-1}).

Coffee biomass sampling

In both shaded and unshaded coffee plots, six coffee bushes were randomly selected and cut at ground level. Each coffee bush was separated into stem, twig (fruiting branch) and foliage. Coffee coarse root biomass ($>10 \text{ mm}$ diameter) was estimated by excavating the coffee root from a 0.40 m deep hole stretching up to midpoint between the felled coffee bush and the next one. The roots were separated into woody roots (belowground extension of the stump) and braces (horizontally spreading roots). Fresh weight was recorded and a composite sample taken for each plant component was oven-dried at 70°C to constant weight. Dry weight of very coarse and braces components of the roots were summed up to give total root weight. All masses were extrapolated to a hectare based on the real density of coffee plants ($1,230$ plants per hectare for shaded coffee and $1,267$ plants per hectare for open-grown coffee).

Fine roots biomass

Biomass of fine roots ($\leq 10 \text{ mm}$ diameter) was determined by means of a $20 \times 20 \times 20 \text{ cm}^3$ metal box with cutting edge used to take soil monoliths. For each coffee system, i.e. shaded coffee plot and open-grown coffee plot, soil monoliths were taken from four random locations per subplot (replicate) at $0\text{--}20$ and $20\text{--}40 \text{ cm}$ depths (total of 16 monolith samples for each coffee system per sampling depth). The roots were extracted from soil by soaking the soil monoliths in water in a shallow dish followed by two successive washings of the remaining soil and sieving through a 2 mm screen. The roots were then rinsed in distilled water, separated from organic debris using forceps and classified into two categories: roots $<2 \text{ mm}$ diameter and roots from 2 to 10 mm diameter. No attempt was made to distinguish between live and dead roots. Root samples per subplot were pooled, dried at 70°C to constant weight and root weight per hectare calculated based on the area of the sampling instrument (400 cm^2).

Weed and litter biomass

All herbaceous vegetation (weed) was sampled in July 2000 at four random locations per subplot (16 samples for each coffee ecosystem) using a $50 \times 50 \text{ cm}^2$ wooden frame. All green herbaceous vegetation emerging from within the area delimited by the frame was cut at ground level, weighed, and a composite sample of approximately 500 g was taken for each subplot to be oven-dried at 70°C to constant weight.

Surface litter was sampled using the same method as that for weed biomass, except that the whole sampling per subplot was processed independently to avoid bias in subsampling. To limit soil contamination, fine litter fragments were rapidly soaked in distilled water and all floating material collected. Thereafter, the litter was oven-dried at 70°C to constant weight. Composite litter sample was taken only after litter biomass per subplot had been ground and pooled by plot. Residual soil contamination in fine roots and surface litter tissues was corrected by ashing tissue samples in a furnace at 550°C followed by HNO_3 dissolution of the ash and separation of the residues by filtration on a Whatman 41 filter paper. Nutrient concentration of these tissues was thereafter corrected based on the proportion of soil contamination and mean nutrient concentration of soil of the corresponding horizon ($0\text{--}20 \text{ cm}$ soil for surface litter).

Measurement of nutrients and carbon stocks

Composite samples for the different plant tissues were ground with a Wiley mill through a 2 mm mesh. For *Albizia* trees, composite samples for chemical analysis were restricted to the trees felled from the shaded coffee plot in July 2000. Coarse root samples were made of woody root and lateral root tissues in proportion to their respective contribution to total coarse root mass.

Total C and N content of plant samples were analyzed on a C-N autoanalyzer (Roboprep C & N analyzer) at the Cornell University Crop and Soil Science laboratory. For P, K, Ca and Mg analysis, the plant tissues were digested on a microwave oven with concentrated HNO_3 followed by elemental determination on an inductively coupled argon plasma analyzer (ICP). Nutrient concentrations were determined for each component, and nutrient stocks

computed based on component mass and corresponding nutrient concentration.

Statistical analyses

Models for biomass prediction were derived by least squares regression and standard errors on means obtained by descriptive statistics using the Minitab statistical package (Minitab 1994). Selection of the best model for prediction of each biomass fraction was based on the coefficient of determination (R^2) and graphical examination of the residuals. In addition, a loss function i.e., the unsigned deviation (δ) was used, which expresses the absolute percentage deviation associated with the prediction:

$$\delta = \frac{\sum_{i=1}^n \frac{|\text{Observed} - \text{Predicted}|}{\text{Observed}}}{n} \times 100 \quad (1)$$

where n = sample size.

Bias associated with back transformation of logarithmic models was adjusted by using the approximate correction suggested by Baskerville (1972).

Results and discussion

Allometric equations for *Albizia* biomass prediction

There was a high degree of correlation between the different biomass predictors initially considered for *Albizia* trees (Table 1). This suggests that a single independent variable should be used in the elaboration of biomass prediction models to avoid the issue of multicollinearity. The best models for leaf, stem, branch, twig and coarse root biomass are shown in Table 2. From previous biomass studies circumference at breast height (CBH) has always been referred to as a practical and reliable predictor regardless of tree species and site conditions (Brown et al. 1989; Overman et al. 1994; Nelson et al. 1999). The same conclusion can be drawn from the current study, as CBH best predicts most biomass fractions of *Albizia* tree. For root and branch biomass, however, basal circumference (BC) was preferred because it yielded higher R^2 and normalized residues. All models were of the form:

$$Y = \beta_1 X^{\beta_2} \quad (2)$$

where Y is the dry biomass of a tree component, and X is the predicting variable, and β_1 and β_2 are the scaling coefficients. A logarithmic transformation of these regression equations yielded a linear relationship. A multiplicative model including height was necessary to improve prediction accuracy for stem biomass. The coefficient of determination derived from these models is relatively high (81–98%), except for the model for leaf biomass, and the parameters of the regression equations were significant ($P < 0.001$) with a relatively small standard error, which indicates a good prediction. The absolute percentage of deviation (δ) showed values below 38% for most of the models, except leaf biomass model which produced higher deviations (41%). The models described above could be improved possibly by increasing the sample size; nonetheless, they represent a good tool for the estimation of different components of *Albizia* tree biomass in the present study because of their specificity over recommended mixed-species models (Brown et al. 1989).

Biomass components

Aboveground biomass

Total aboveground biomass and its distribution are presented (Fig. 1) for both shaded and open grown coffee systems. As expected, aboveground biomass production in the shaded coffee system exceeded that in the unshaded one. The bulk of aboveground biomass in the shaded coffee system was contributed by shade trees (87%). The dominant fractions of the shade tree biomass were stem and branch, which represented respectively 47% and 43% of the tree standing biomass. The percentage contributed by twig fraction was only 7% while that of leaves was 3%.

Comparing individual coffee biomass fractions under the two coffee systems, it appears that all biomass fractions showed consistently higher values in the open-grown coffee system. This is likely a consequence of greater light incidence on coffee in full sun, suggesting that light interception by the shade trees in the conditions of this study (approximately 72% of the incident radiation) might be

Table 1 Correlation between different *Albizia* tree parameters^a

	BC	CBH	Canopy size
CBH	$r = 0.988$ $P = 0.000$		
Canopy size	$r = 0.898$ $P = 0.000$	$r = 0.925$ $P = 0.000$	
Height	$r = 0.920$ $P = 0.000$	$r = 0.928$ $P = 0.000$	$r = 0.826$ $P = 0.001$

^a r = Pearson correlation coefficient; P = P -value

suboptimal for coffee development. Previous studies (Lagemman and Heuvelodp 1983; Muschler 1997), have mentioned the negative impact of excessive shade on coffee development. Weed biomass also was higher in the open-grown coffee system (4.1 Mg ha⁻¹) compared to that in shaded coffee (1.8 Mg ha⁻¹). Conversely, surface litter was slightly higher in the shaded coffee system, possibly due to an additional litter deposition by the shade trees. However, these one-time biomass samples do not reflect the dynamics of litterfall in the coffee systems. Although *Albizia* trees continuously shed leaves, a complete leaf shed occurs for the species during the dry season (Edoh 1998). Therefore, greater differences in litter mass can be expected in the shaded coffee system depending on the sampling period.

Data from literature do not allow appropriate comparison with results from this study because of

lack of similarity between site conditions, tree species and management practices (Aranguren et al. 1982; Fassbender et al. 1985; Glover and Beer 1986; Beer 1988). Nevertheless, total aboveground biomass production in the coffee–*Albizia* association in this study (equivalent to 10.8 Mg dry matter ha⁻¹ yr⁻¹) compares well with values reported for various agroforestry systems in humid and subhumid climates (Young 1989) as well as for natural ecosystems (Brown and Lugo 1982; Vitousek and Sanford 1986), but fall below the values reported for mature secondary forests in humid and subhumid tropics (Juo and Manu 1996).

Belowground biomass

Similarly to the pattern observed with aboveground biomass, the shaded coffee system yielded higher belowground mass than the open-grown coffee (Fig. 2). Total root mass was 32 Mg ha⁻¹ in the shaded coffee system, of which 55% was contributed by coarse roots of *Albizia* trees. In the shaded coffee system, coarse roots were the dominant root fraction (66.7%) while they represented only 29.8% of total root mass in the open-grown coffee system. Considering individual coffee bushes under the two growing conditions, both coarse root and fine root biomass were higher for unshaded coffee bushes than for shaded ones. That partitioning was made under the assumption that the *Albizia* trees contribution to fine

Table 2 Best fit equations for estimation of different biomass fractions and height of *Albizia* trees^a

Component	Regression model	Coefficient value	s	r^2	δ (%)	P
Stem	$\text{Ln}Y = \alpha + \beta \ln(\text{CBH}^2 * H)$	$\alpha = -6.16$ $\beta = 0.992$	0.204	0.98	23	<0.0001
Branch	$\text{Ln}Y = \alpha + \beta \ln(\text{BC})$	$\alpha = -10.5$ $\beta = 3.28$	0.592	0.89	30	<0.0001
Twig	$\text{Ln}Y = \alpha + \beta \ln(\text{CBH}^2)$	$\alpha = -5.95$ $\beta = 1.09$	0.435	0.87	31	<0.001
Foliage	$\text{Ln}Y = \alpha + \beta \ln(\text{CBH})$	$\alpha = -4.1$ $\beta = 1.67$	0.488	0.76	41	<0.0001
Root	$\text{Ln}Y = \alpha + \beta \ln(\text{BC})$	$\alpha = -6.34$ $\beta = 2.33$	0.340	0.92	37	<0.0001
Height	$\text{Ln}H = \alpha + \beta \ln(\text{CBH})$	$\alpha = 0.319$ $\beta = 0.540$	0.318	0.81	13	<0.0001

^a s : standard error of regression line; r^2 : coefficient of determination; CBH: circumference at breast height (cm); BC: basal circumference (cm); δ : absolute deviation; H : height (m); Y : biomass (kg)

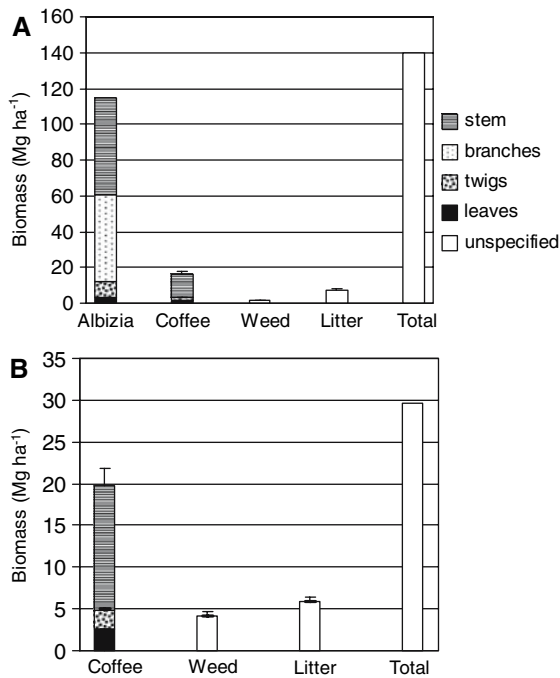


Fig. 1 Total aboveground biomass partitioned by system components in shaded (A) and open-grown (B) coffee systems. Vertical bars represent standard error of means

root biomass was negligible comparatively to fine roots derived from coffee (results of visual inspection). Fine roots density in coffee–shade tree associations has been shown to vary spatially and temporally, the extent of which determines the competitiveness of the associated shading species (van Kanten et al. 2005).

The bulk of coffee fine root biomass concentrated in the top 0–20 cm layer conforms to report of van Kanten et al. (2005) in shaded coffee systems in Costa Rica. This trend is common in agroforestry systems. For example, Dhyani and Tripathi (2000) reported that 70% of root biomass was concentrated in the 0–20 cm layer in alley cropping systems in India. At both depths, there was no apparent difference between the contribution of the 2–10 mm fine root and the <2 mm root fraction. Total fine root mass through the profile (0–40 cm) was 10.7 Mg ha⁻¹ in the coffee–*Albizia* association and represented twice the values reported for *Coffea arabica* shaded with *Cordia* sp or *Erythrina* sp in Costa Rica (Fassbender et al. 1985).

Belowground biomass to total stand biomass ratio was 0.48 in the open-grown coffee system but only

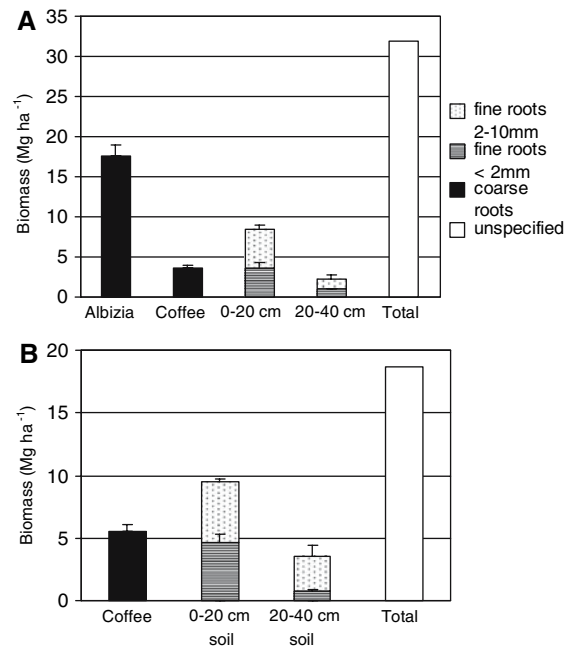


Fig. 2 Total belowground biomass partitioned by root fractions in shaded (A) and open-grown (B) coffee systems. Vertical bars represent standard error of means

0.19 in the shaded coffee system (coffee and shade tree combined). This denotes a proportionally lower contribution of the shade tree to root biomass. Armson (1977) estimated that root biomass might contribute 20–25% of the total living biomass of trees. Thus, the true ratio of root to total standing biomass for the shaded coffee system would expectedly be higher because root biomass estimation in the present study was limited only to the 0–60 cm depth and did not account for the very fine fractions. In our excavation, fewer roots appeared to go below 60 cm.

Nutrient content in plant biomass

Nutrient concentration

Nutrient concentrations differed between the two coffee systems and between the different biomass fractions within each system. The order of nutrient concentration in plant parts was leaves > twigs > fine roots > branch > stem (Table 3). This pattern is of considerable importance for nutrient management, as easily recyclable parts tend to have higher nutrient concentrations. N concentration in *Albizia* leaves was

Table 3 Nutrient concentration in biomass components in shaded and open-grown coffee systems

System and components		Element (%)					
		N	P	K	Ca	Mg	
<i>Shaded coffee</i>							
Coffee (1) + <i>Albizia</i> (2)							
Leaves	(1)		3.22	0.14	1.12	1.41	0.74
	(2)		3.60	0.19	0.80	1.24	0.52
Twigs	(1)		1.19	0.02	0.64	0.76	0.23
	(2)		1.29	0.06	0.50	1.01	0.22
Branch	(2)		0.61	<0.01	0.36	0.36	0.06
Stem	(1)		0.50	nd	0.13	0.25	0.05
	(2)		0.35	nd	0.11	0.18	0.01
Coarse roots	(1)		0.79	nd	0.20	0.28	0.04
	(2)		0.84	0.02	0.28	0.25	0.03
Fine roots 2–10 mm			1.82	0.03	0.29	0.72	0.10
Fine roots <2 mm			2.44	0.08	0.40	0.87	0.30
Weeds			2.85	0.16	1.7	1.55	0.77
Litter			2.50	0.08	0.14	2.28	0.46
<i>Open-grown coffee</i>							
Coffee							
Leaves			2.47	0.15	1.42	1.05	0.62
Twigs			0.93	0.04	0.65	0.68	0.23
Stem			0.40	nd	0.16	0.30	0.07
Coarse root			0.45	nd	0.19	0.46	0.06
Fine roots 2–10 mm			0.88	0.03	0.34	1.00	0.14
Fine roots <2 mm			1.23	0.09	0.41	1.11	0.58
Weeds			1.69	0.14	1.40	1.80	1.03
Litter			2.09	0.09	0.08	2.01	0.65

nd = not detected

3.6%. This value did not account for possible seasonal variations of nutrient concentration in leaves; nevertheless, it represents a relatively high value compared to published values for other leguminous shade species such as *Erythrina* sp (1.52%) or *Inga* sp (1.61%) in Costa Rica (Aranguren et al. 1982). Nutrient concentration in coffee parts was also marked by higher N in shaded coffee tissues. This trend was consistent in all plant parts including weed and litter biomass (Table 3), suggesting that the leguminous *Albizia* trees might be fixing atmospheric N. No *Albizia* root nodule was detected during root excavation in the present study, but data from the literature report nodules for mature trees of *A. adianthifolia* (Wester and Hogberg 1989). Nitrogen concentration in coffee leaves was 3.22% in the shaded coffee system and 2.47% in the unshaded one. The difference in leaf N concentration in the two coffee systems would suggest a better N nutrition of

coffee grown under *Albizia* shade trees and a possible limitation of that element for sun-grown coffee. No particular trend was observed for the other elements, except for Ca and Mg, which tended to be higher in roots and weed biomass in the open-grown coffee system.

Nutrient concentration in roots increased with decreasing root diameter, a possible consequence of a more active nutrient uptake activity in the relatively young root tissues. Such a trend has been previously reported in Ghana for all elements (Greenland and Kowal 1960), but only for N and P in the Amazon (Klinge 1975).

Nutrient stocks in vegetation

There is a remarkable difference in nutrient accumulation between the two coffee systems. Considering the shaded coffee system as a whole, over twice as

much K and Ca accumulated in aboveground biomass as in the sun coffee system (Fig. 3). The main difference came from the shade trees, which contributed 78% of total K and 60% of total Ca in the shaded coffee system. Nutrient stocks in the shade tree compartments decreased in the order: branch > stem > twig > leaf. The total amount of Mg stored in the shaded coffee system was only 142 kg ha⁻¹ versus 112 kg ha⁻¹ in the open-grown coffee, a much smaller difference than with K and Ca. The relatively lower Mg concentration in shade tree biomass and the higher concentration of that element in coffee and weed tissues in the open-grown coffee system helped to reduce the difference. Of all nutrients, N showed the highest accumulation in vegetation biomass. Total N stored in the shaded coffee system exceeded 1,000 kg ha⁻¹ while that in the open-grown coffee system was only 337 kg ha⁻¹. Of that total, 718 kg was found in the shade tree aboveground biomass, which represented an annual increment of 55 kg N ha⁻¹ for that 13-year-old coffee system. As opposed to the other elements, *Albizia* allocated 26% of N stocks to the stem component of its biomass (191 kg out of a total of 718 kg). The general pattern of nutrient accumulation in total biomass was: N > Ca > K > Mg > P, a similar trend to that observed with *Coffea arabica* associated with *Cordia* sp and *Erythrina* sp in Costa Rica (Fassbender et al. 1985), and generally reported with nutrient distribution in mature tropical forest vegetation (Golley et al. 1975).

Belowground accumulation of nutrient (Fig. 4) did not reflect exactly the same trend shown in aboveground accumulation. While N, P and K displayed a pattern similar to that observed with aboveground biomass, Ca and Mg, on the other hand, showed a reverse trend with higher values in open-grown coffee root tissues. This trend may partly be explained by the greater fine root biomass and the relatively higher fine root concentration of Ca and Mg in open-grown coffee system. A notable amount of total plant nutrient stock was found in roots. In the shaded coffee system, 21–36% of plant nutrient stock occurred in roots; the corresponding proportion in the open-grown coffee system was higher (44–65%; data not shown).

The potential for nutrient recycling was evaluated by comparing the amount of nutrients in biomass fractions susceptible to a rapid turnover (leaves, twigs, fine roots) to that in stem, branches and coarse

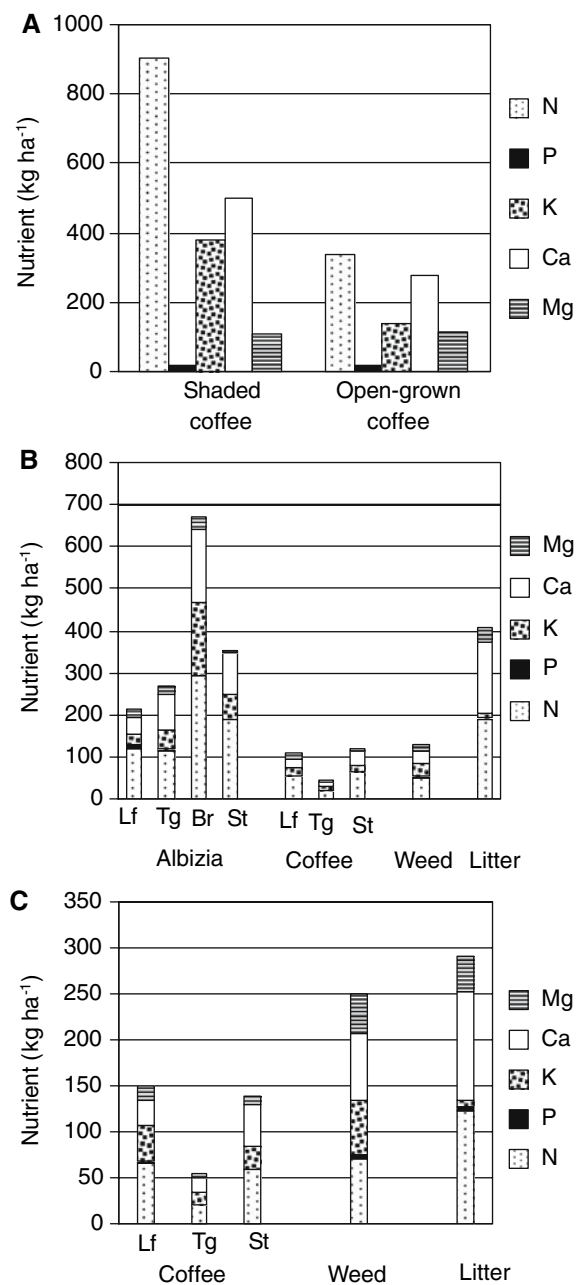


Fig. 3 Total aboveground nutrient stocks (A) and distribution in biomass components in shaded (B) and open-grown (C) coffee systems. Abbreviations: Lf: leaf; Tg: twig; Br: branch; St: stem

roots, which are commonly left unburnt during land preparation, or simply harvested and removed from site. For the 13-year-old coffee system in this study, a considerable amount of K (63%) was retained in tree biomass (Fig. 5). Calcium showed a similar pattern to

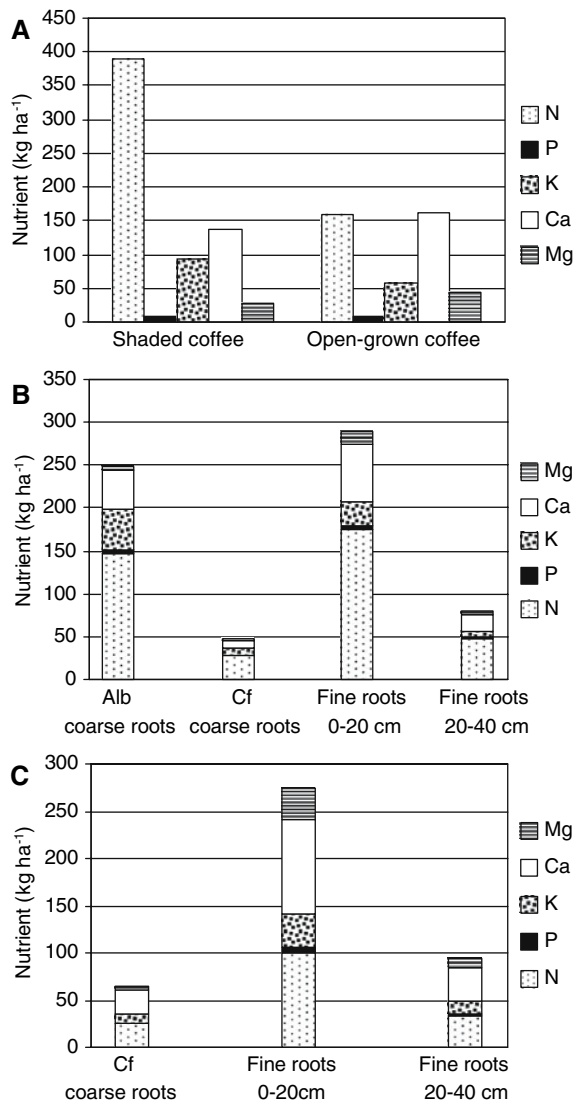


Fig. 4 Total belowground nutrient stocks (A) and distribution by root size in shaded (B) and open-grown (C) coffee systems. Abbreviations: Alb: Albizia; Cf: Coffee

K. On the other hand, most of the Mg in the system is recyclable and so is almost the entire P since only traces of the latter are stored in stem, branch and coarse roots of both coffee and shade trees. Lehmann et al. (2001) also argued about efficient P recycling in P limited soils through organic residues returns from tree crops. Regarding N, although a considerable amount of that element could be recycled through pruning, 51% is still sequestered in the woody biomass fractions of the *Albizia* trees and may impact the N budget in the shaded coffee system. On the

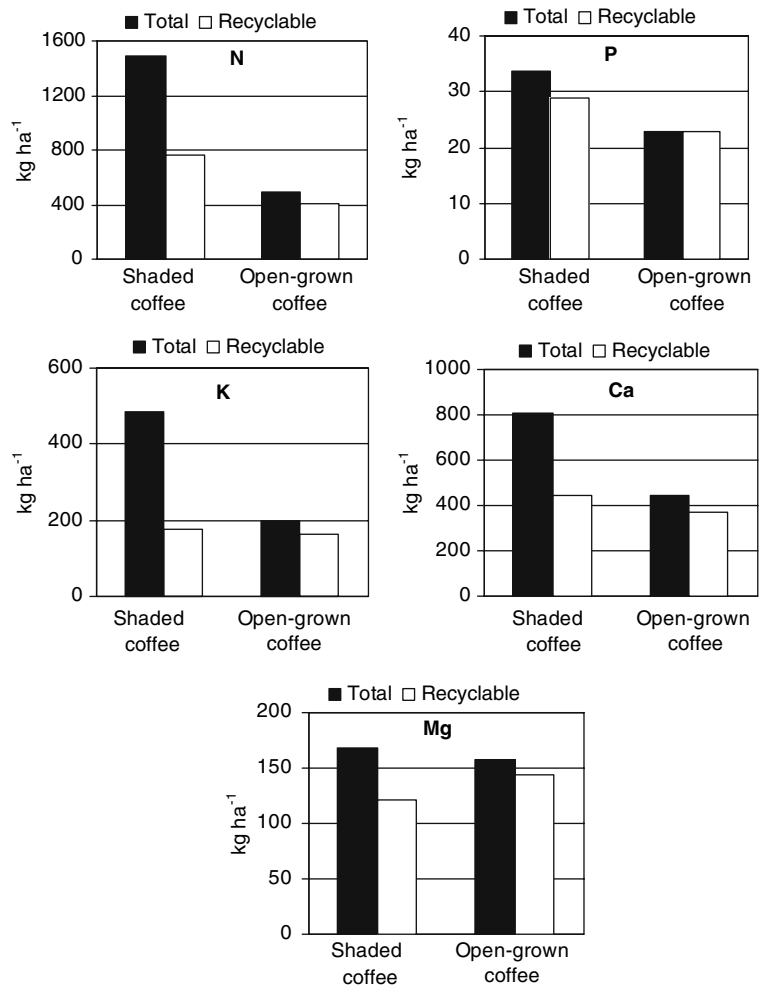
other hand, in the open-grown coffee, assuming that leaves and twigs will be cyclically returned to soil via natural shedding or pruning, most of the nutrients in the vegetation could be efficiently recycled. This approximation of the potential of nutrient recycling may appear as an oversimplification as nutrient retranslocation prior to leaf senescence and abscission have not been accounted for. In addition, throughfall and stemflow pathways have been deliberately omitted as they were outside the scope of this study. Nevertheless, our data provide some useful clues as to possible nutrient limitations in the shaded coffee system.

Carbon stocks

Differences in vegetation carbon stocks in the two coffee systems are shown in Fig. 6. Total plant C stock in the shaded coffee system was 82 Mg ha⁻¹, of which 67 Mg (82%) was found in aboveground fractions. Aboveground C stock in the shaded coffee system was dominated by the *Albizia* trees, which contributed 82% of the total aboveground C. Total vegetation C in the open-grown coffee system was only 23 Mg ha⁻¹, 60% of that amount was allocated to aboveground biomass. The major contributor to aboveground C in the open-grown coffee system was coffee stem, which made up 53% of total aboveground C in that system. Although the belowground C stock in the shaded coffee system was higher than that in the open-grown coffee system, the magnitude of that difference was small compared to the aboveground C difference between the two systems. Apart from shade tree coarse roots, belowground C was essentially contributed by fine roots from the topsoil (0–20 cm).

Our results are comparable to carbon values of 50–75 Mg C ha⁻¹ reported for tropical agroforestry systems (Houghton et al. 1993), but the mean annual C storage of 4.76 Mg C ha⁻¹ yr⁻¹ (values averaged over 13 years) in the current study is higher than C potential of 2.1–3.4 Mg C ha⁻¹ yr⁻¹ estimated for shaded coffee plantations in Mexico (De Jong et al. 1997) and lower than yearly C estimates in *Theobroma cacao-Cordia* sp-*Erythrina* sp agroforestry systems in Costa Rica (Kürsten and Burschel 1993). Fractions of tree C allocated to roots in the current study compares well with data from other studies (Mekonnen et al. 1997; Oelbermann et al. 2005).

Fig. 5 Potential for nutrient recycling in shaded and open-grown coffee systems: nutrients in rapid-turn-over fractions are compared to total biomass nutrient stock



Estimates of C in the upper 40 cm of soil in mature coffee plantations at the site of study showed soil C stock of 97.27 and 95.78 Mg C ha⁻¹ in shaded and open-grown coffee systems, respectively (Dossa et al. 2000, unpublished data). Hence, in the shaded coffee system, vegetation C is as equally important as soil C whereas in the open-grown coffee, total vegetation C would contribute <20% of total system C.

Conclusion and management perspectives

This study showed biomass production comparable to that of other tropical agroforestry systems and secondary forests, and considerable nutrient accumulation in the shade trees. The leguminous *Albizia* trees contributed to an overall higher N budget in the

shaded coffee system presumably as a result of N-fixation. Although high nutrient concentrations in easily recyclable fragments of biomass characterized both coffee systems, large woody biomass fractions in the shaded coffee system still immobilized considerable amounts of nutrients, except P, and to some extent Mg. This suggests that *Albizia* trees may limit nutrient availability for the coffee, particularly in nutrient-limited soil conditions. A minimum management of the shade trees would therefore be necessary to optimize coffee nutrition. This would imply periodic pruning and/or pollarding of the shade trees to increase the cycling of organic inputs to the soil and to limit nutrient storage in the shade tree biomass. Such a practice would also moderate shade intensity, which tends to become excessive and limit coffee production in most traditional small-scale

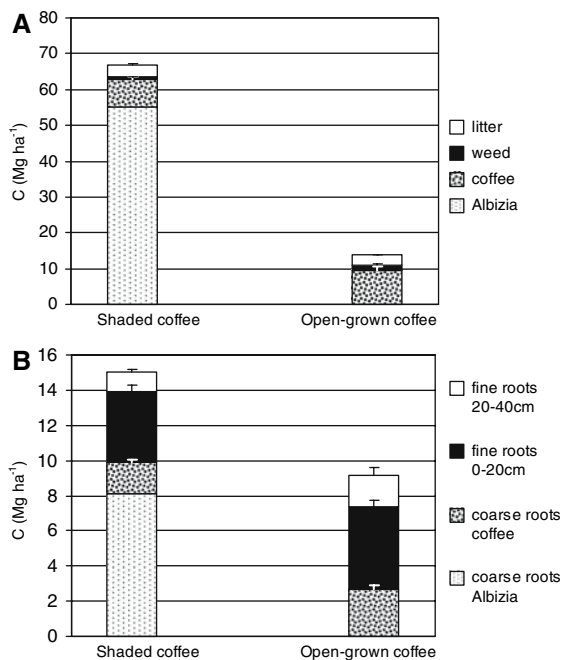


Fig. 6 Aboveground (A) and belowground (B) carbon and distribution in biomass components in shaded and open-grown coffee systems. Vertical bars represent standard error of means

coffee plantations. From an environmental perspective, shading coffee represents a conservation system that would partly compensate for deforestation and mitigate carbon dioxide emission from agricultural practices in the tropics. Furthermore, in Central America, studies of bird diversity in agroecosystems have reported increased diversity in shaded coffee as compared to unshaded coffee (Greenberg et al. 1997). No such data are available for West Africa. Research on optimal management of the shade trees for nutrient recycling, and the impact of such a practice on soil nutrient dynamics and coffee productivity represents an area that warrants further consideration.

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