

## Original Paper

# Shade tree effects in an 8-year-old cocoa agroforestry system: biomass and nutrient diagnosis of *Theobroma cacao* by vector analysis

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**Abstract** Farm product diversification, shade provision and low access to fertilizers often result in the purposeful integration of upper canopy trees in cocoa (*Theobroma cacao*) plantations. Subsequent modification to light and soil conditions presumably affects nutrient availability and cocoa tree nutrition. However, the level of complementarity between species requires investigation to minimize interspecific competition and improve resource availability. We hypothesized beneficial effects of upper canopy trees on cocoa biomass, light regulation, soil fertility and nutrient uptake. We measured cocoa standing biomass and soil nutrient stocks under no shade (monoculture) and under three structurally and functionally distinct shade trees: *Albizia zygia* (D.C.) Macbr, a nitrogen fixer; *Milicia excelsa* (Welw.), a native timber species; and *Newbouldia laevis* (Seem.), a native small stature species. Vector analysis was employed to diagnosis tree nutrition. Cocoa biomass was higher under shade (22.8 for sole cocoa versus 41.1 Mg ha<sup>-1</sup> for cocoa under *Milicia*), and declined along a spatial gradient from the shade tree ( $P < 0.05$ ). Percent canopy openness differed between the three shade species ( $P = 0.0136$ ), although light infiltration was within the optimal range for cocoa production under all three species. Soil exchangeable K was increased under *Newbouldia*, while available P decreased and total N status was unaffected under all shade treatments. Nutrient uptake by cocoa increased under shade (43–80% and 22–45% for N and P, respectively), with K (96–140%) as the most responsive nutrient in these multistrata systems. Addition of low-density shade trees positively affected cocoa biomass close to the shade tree, however proper management of upper stratum trees is required for optimum cocoa productivity and sustainability.

**Keywords** Ghana - Light availability - Multistrata system - Nutrient uptake - On-farm research - Soil fertility

## Introduction

Multistrata planting schemes integrating both upper canopy trees and cocoa (*Theobroma cacao* L.) are purposefully developed by farmers to diversify farm products, secure land tenure, provide shade for cocoa seedlings and increase biophysical advantages for production. Specifically in regions with low access to inorganic fertilizers, multistrata plantations are established to maintain soil fertility and subsequently increase nutrient availability for cocoa. Presumably, enhanced production in these systems result from improved resource status associated with common agroforestry processes; efficient nutrient cycling, improved soil characteristics, modified light infiltration, enhanced moisture availability and reduced weed competition (Ahenkorah et al. [1987](#); Beer et al. [1998](#); Schroth et al. [2001](#); Hartemink [2005](#)). Often, multiple species in an agroforestry system contribute functions not found in monocultures, such as the partitioning of resources, synchrony of resource use, and the ability of each species to capture and cycle nutrients (Ewel and Bigelow [1996](#); Schroth et al. [2001](#)). However, facilitative interactions that enhance cocoa productivity may be offset by interspecific competition for particular resources. Presumably, both antagonistic and facilitative interactions may occur between species in a multistrata system. Therefore, knowledge of species complementarity in multistrata systems for maximizing resource availability is important for increasing crop productivity.

To date, several studies have focused on species interactions and subsequent growth in both natural communities and agroecosystems (Alpizar et al. [1986](#); Fassbender et al. [1991](#); Ewel and Bigelow [1996](#); Tilman [1999](#)), where productivity is often found to be dependent on a functional attribute of a species (Silver et al. [1996](#); Hooper [1998](#)) such as nitrogen fixation, or structural aspects such as canopy architecture and subsequent light availability (Ewel and Bigelow [1996](#)). For cocoa plantation systems, it is hypothesized that once nutrient requirements are met, understory crop production is primarily dependent on the accessibility of solar radiation (Cunningham and Arnold [1962](#)). The effect of upper canopy shade species on light infiltration is presumably dependent on species specific crown structure and subsequent modifications to light availability for the cocoa crop.

Although some work has been conducted in cocoa-shade tree systems (Alpizar et al. [1986](#); Ahenkorah et al. [1987](#); Fassbender et al. [1991](#)), little research has examined species-specific modifications to light availability and soil nutrient pools as well as indirect effects on cocoa nutrient uptake. As cocoa nutrition is a critical factor for farm sustainability, we employed vector analysis, a comprehensive diagnostic tool to assess tree nutrient responses (Hasse and Rose [1995](#); Imo and Timmer [1997](#)), to speculate on long-term maintenance of cocoa nutrition.

Our approach was to examine the effects of three structurally and functionally distinct upper canopy trees in farmer-designed multistrata agroforestry systems in Ghana. The upper canopy species were: *Albizia zygia* (D.C.) Macbr, a nitrogen fixer; *Milicia excelsa* (Welw.), a native timber species; and *Newbouldia laevis* (Seem.), a native small stature multi-purpose species. The objectives of our study were to 1) compare cocoa tree biomass under no shade and under three different shade species, 2) measure light availability, soil nutrient stocks and cocoa nutrient content under no shade and three shade trees, and 3) employ vector analysis to diagnosis nutrient uptake and relate cocoa biomass and nutrient status with possible causal factors.

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## Materials and methods

### Study site and experimental design

Field work, conducted over one month during the pre-rainy season (2005) with additional data collection during the pre-rainy season in 2006, was in the moist semi-deciduous tropical zone in the Western Region (06°12' N and 02° 29' W) of Ghana, West Africa. The soils of the study region are dominated by ochrosol-oxisol intergrades (Rhodic Ferralsol) that have developed from granite parent material. These highly leached soils are relatively low in fertility

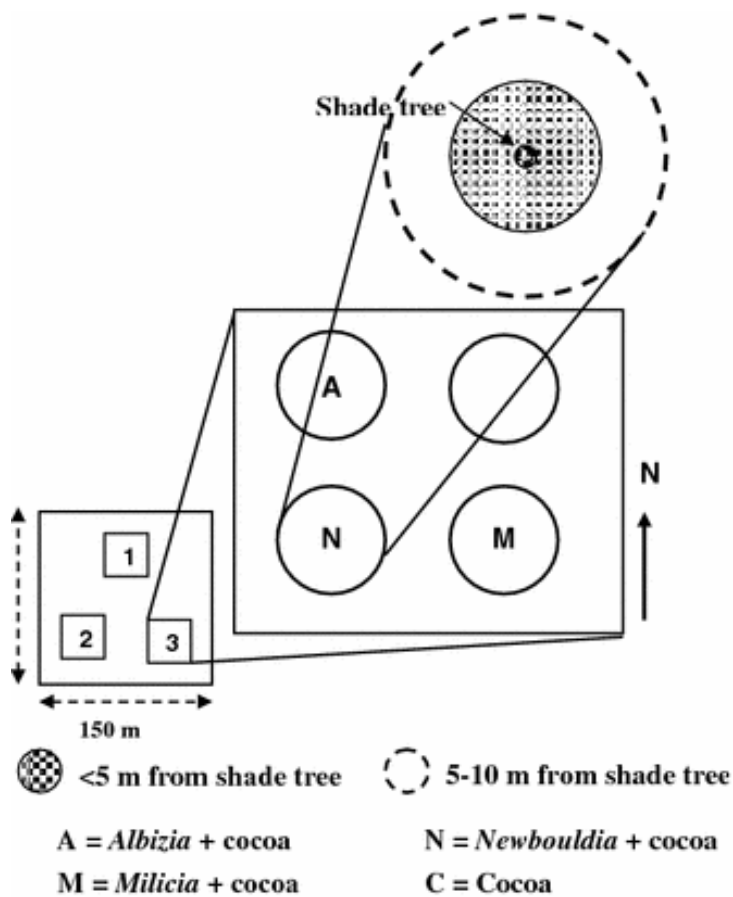
and highly acidic (Soils Survey Division [1969](#)). This region typically has a mean annual precipitation of 1100 mm in bi-modal rainy seasons (April to July and September to November) with an average aboveground temperature of 26.0 °C. The study site, an 8 year-old cocoa (or cacao) plantation (approximately 2 ha in size), was selected due to its history of sole landownership of cocoa production since forest conversion, consisting of bi-monthly weeding without burning and fertilizer use. Stand structure was comprised of two strata: a cocoa stratum at a height of approximately 5 m and a shade stratum as described in Table [1](#). Although these two strata were found throughout most of the plantation, some areas contained only monoculture cocoa. The three shade species were replanted or naturally regenerated at the time of conversion from secondary forest to cocoa plantation. The plantation had a uniform cocoa planting density of approximately 1100 trees ha<sup>-1</sup> interspersed with sparsely distributed upper canopy test species at a density of approximately 30 trees ha<sup>-1</sup>.

**Table 1** Diameter at breast height (DBH), height, crown radius, leaf biomass nutrient concentration (mean ± SE) and canopy openness (%) of *Albizia*, *Milicia* and *Newbouldia* planted as shade trees on a 2 ha cocoa farm in the Western Region, Ghana ( $n = 3$ )

Characteristic	Treatment (shade tree)		
	<i>Albizia</i>	<i>Milicia</i>	<i>Newbouldia</i>
DBH (cm)	17.4 ± 0.23	34.3 ± 5.87	19.7 ± 1.47
Height (m)	11.0 ± 0.49	13.7 ± 1.15	9.4 ± 1.16
Crown radius (m)	4.13 ± 0.521	5.50 ± 0.861	2.80 ± 0.557
Nitrogen (%)	0.91 ± 0.039	0.64 ± 0.019	0.65 ± 0.024
Phosphorous (%)	0.12 ± 0.018	0.12 ± 0.002	0.14 ± 0.003
Potassium (%)	1.47 ± 0.134	1.39 ± 0.003	1.26 ± 0.073
Canopy openness (%) <sup>a</sup>	69.6 ± 1.72	68.1 ± 2.25	80.1 ± 1.41

<sup>a</sup> Canopy openness was based on image analysis using hemispherical canopy photos ( $n = 12$ )

The on-farm experimental design, a randomized complete block design, consisted of three multistrata treatments: cocoa with *Albizia zygia* (*Albizia* + cocoa), cocoa with *Milicia excelsa* (*Milicia* + cocoa) and cocoa with *Newbouldia laevis* (*Newbouldia* + cocoa), and a monoculture control (cocoa). Each multistrata treatment consisted of one shade tree in combination with a cocoa tree stratum. By on-site inspection, 12 random 10 m radius circular plots centered around the upper canopy shade tree were selected with approximately 25 cocoa trees in each plot. Plots were then blocked into three, with each block consisting of the three multistrata treatments and a control as shown in Fig. [1](#). Shade trees on site were established, either by natural regeneration or planting, during cocoa tree establishment, therefore are the same ages as the cocoa trees. It was confirmed in advance by the landowner that shade tree location, hence treatment application, was on a random basis. Two sampling distances representing a radial spatial gradient were selected 1) within 5 m from the shade tree (<5 m) and 2) 5 to 10 m away from the shade tree (5–10 m). Although the latter is further away from the shade tree, this is not to be confused with sole cocoa (monoculture control), where no shade trees were located. The 5–10 m radial distance is simply a greater distance from the shade tree.



**Fig. 1** Schematic of on-farm experimental design. Twelve random 10 m radius circular plots centered on the upper canopy shade tree were selected by on-site inspection. Plots were then blocked into three, each block consisting of the three multistrata treatments [*Albizia* + cocoa (A), *Milicia* + cocoa (M) and *Newbouldia* + cocoa (N)] as well as a randomly selected area of monoculture cocoa (C). Biomass and soil sampling was conducted within two radial distances (<5 m and 5–10 m away from shade tree). Cocoa density was relatively uniform (1100 trees ha<sup>-1</sup>) with approximately 25 trees per 10 m radius plot

## Species description

Detailed shade species dimensions and nutrient characteristics are presented in Table 1. *Albizia zygia* (Fabaceae), a nitrogen fixing species, has a spreading crown architecture and an average height of 11 m at the study site. This genus is recommended as a shade tree for cocoa plantations in Ghana (Anim-Kwapong 2003). *Milicia excelsa* (Moraceae), a fast growing tall timber species, can reach 50 m in height and has branches only on the upper half of the trunk. It has been identified as a desirable species for cocoa production due to its structural nature (low crown/stem ratio) and ability to provide income as timber (Manu and Tetteh 1987). *Newbouldia laevis* (Bignoniaceae), a multi-purpose, native tree, is used mainly for shade and live yam stakes as well as for medicinal purposes. It is commonly small in stature with a narrow crown and is easily reproduced from cuttings of lead shoots or lateral roots (Amanor 1994). Minimal research has been conducted on this species.

## Soil conditions

Soil particle size distribution (sand =  $68.0 \pm 3.53$ ; silt =  $14.0 \pm 1.45$ ; clay =  $18.0 \pm 1.64$ ) was determined by the hydrometer method, soil pH ( $5.9 \pm 0.07$ ) by a 1:1 paste of water:soil, percent organic matter ( $3.4 \pm 0.09$ ) by

oxidation and cation exchange capacity ( $17.5 \text{ cmol kg}^{-1} \pm 0.71$ ) by leaching and subsequent atomic absorption spectrophotometry (Allen [1974](#)). Bulk density ( $0.9 \text{ g cm}^{-3} \pm 0.02$ ) was determined for each treatment by collecting a known volume of soil with a metal core placed into the top 20 cm of soil, drying ( $105 \text{ }^\circ\text{C}$ , 48 h) and weighing the soil. All tests were conducted in triplicate.

## Soil sampling

Soil fertility was assessed by collecting three composite soil samples (approximately 100 g per sample), to a depth of 0–20 cm [the active lateral root zone of cocoa (Kummerow et al. [1982](#))] in each plot at the two locations (<5 m and 5–10 m) from the shade tree. At the sole cocoa treatment, six random composite soil samples were collected. Soil samples were air-dried and sieved to pass 2 mm. Samples were wet-digested and analyzed for total N (Kjeldahl method), available P by Bray's method and measured colorimetrically using molybdate method, and exchangeable K by leaching air-dried soil samples with ammonium acetate and measured quantitatively by atomic absorption spectrophotometry (Allen [1974](#)). Estimates of soil nutrient stocks ( $\text{kg ha}^{-1}$ ) were based on measured bulk density and a 20 cm sampling depth.

## Plant sampling

Aboveground biomass for the upper shade stratum and the cocoa stratum were estimated from diameter at breast height (DBH) measures ( $n = 15$  per distance). Since no species-specific biomass equation was available in the literature, we used a generalized tree biomass equation developed for this specific precipitation zone (Brown 1997):

$$y = \exp[-2.134 + 2.530 \ln(\text{DBH})] \quad (R^2 = 0.97)$$

where  $y$  = dry aboveground biomass (kg) and DBH = diameter at breast height (cm). This equation is considered suitable for estimating total aboveground tree biomass of individuals with <150 cm DBH in relatively dense stands (Brown [1989](#), 1997), and is recommended for aboveground biomass estimation where destructive sampling can not be conducted (Anderson and Ingram [1993](#)), as in our case due to farmer set restrictions. Although cocoa pod yield is the focal issue in farm production, our dependent variable was cocoa biomass that functions as an indicator of long-term farm sustainability. There is usually a strong correlation between cocoa tree components, biomass and pod yield under low shade intensity (Zuidema et al. [2005](#)). Height (m), DBH (cm) and crown radius (m) of the three upper canopy trees were measured and listed in Table [1](#). Cocoa and shade tree densities were calculated from the number of trees per 20-m<sup>2</sup> subplot extrapolated to a per hectare basis.

Samples of foliage, branch (approximately 100-g wet weight for each component type) and stem (approximately 40-g wet weight) tissue were collected from three randomly selected cocoa trees for all treatments and both locations (<5 m and 5–10 m). Foliage sampling was consistent for all individuals as recent and fully mature leaves from current season's growth around the basal perimeter of the crown (shaded leaves). Newer branches were sampled from the lower perimeter of the crown, and stem tissue was collected with a sampling corer at DBH. Samples were oven-dried ( $70 \text{ }^\circ\text{C}$ ) for 72 h and ground in a Wiley Mill ( $n = 9$  per distance). Foliage and bulked woody tissue (composite branch and stem) were wet digested separately with hydrogen peroxide and sulfuric acid and analyzed for total N by auto-analysis, P by molybdate method and K by atomic absorption spectrophotometry (Allen [1974](#)). Subsequently, woody tissue and foliage concentrations were averaged for each individual and multiplied by total aboveground dry weight to derive plant nutrient content. Similarly, foliage material (approximately 100-g wet weight for each species) was randomly collected from the three upper canopy species and analyzed by similar

methods.

## Light transmission measurements

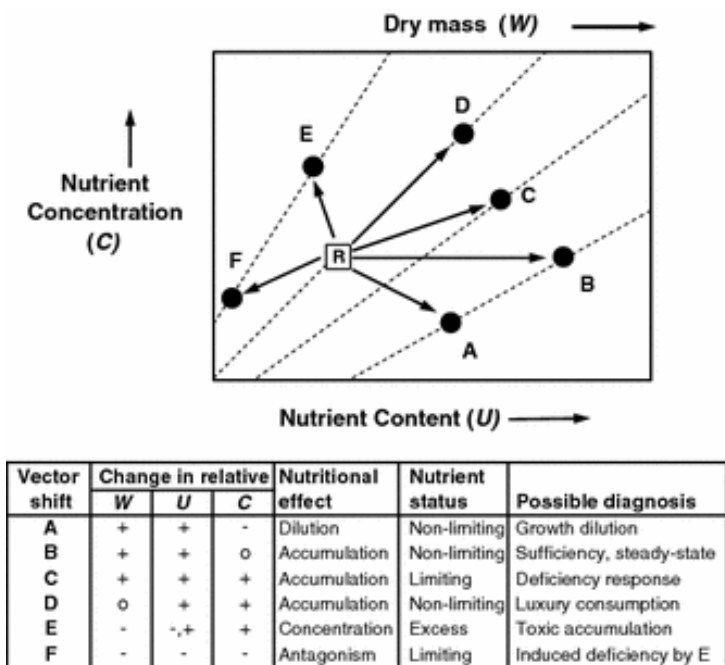
Estimates for light transmission both above and below the cocoa strata were based on image analysis. A hemispherical lens (180-degree equidistant fisheye lens) was attached to a digital camera (Nikon Cool Pix 950), mounted onto a tripod, oriented north and leveled for each photo. Light transmission through the shade tree was measured on four transects at a 1 m radial distance from the shade tree above the cocoa stratum for each shade tree (approximately at a 5 m height) ( $n = 12$ ). Images were examined by gap light analysis (Gap Light Analyzer, Version 2 [1999](#)), providing estimates of transmission indices, specifically percent canopy openness (% open sky beneath the canopy) for each shade tree species.

## Statistical analysis

Data were analyzed as one-way analysis of variance (ANOVA) using the Proc GLM in SAS version 8.0 (SAS Institute Inc. Cary, NC, USA). Significant ANOVA's were subsequently assessed by a Tukey's test (HSD) and a Type I error rate was set at 0.05 for all statistical tests. Nutrient concentration and nutrient content were compared to monoculture cocoa using the Dunnett test. *T*-tests were applied to assess parameter differences close (<5 m) and far (5–10 m) from shade trees. Independence, randomness of residuals and a mean error equal to zero were confirmed with a test of residuals for biomass, biomass nutrient concentration and soil nutrient data. Normality of residuals was tested using the Shapiro–Wilk test.

## Vector analysis

Dry mass and nutrient status of the plants was examined by vector analysis to assess nutritional response associated with the three agroforestry treatments (Haase and Rose [1995](#); Imo and Timmer [1997](#)). The vector diagrams (Fig. [2](#)) reflect the function that nutrient content (or amount) in a plant (bottom horizontal axis) is the product of its nutrient concentration (vertical axis) multiplied by its biomass (top horizontal axis). Changes in these parameters relate to two key processes driving plant growth: nutrient uptake and dry matter production that characterize differing treatment responses. Responses are expressed relative to the control (that is normalized to 100) to facilitate comparisons between various treatments and nutrients. Individual responses are depicted by vectors (arrows) that may differ in length and direction. Vector length represents response magnitude, and vector direction identifies specific nutritional responses. Thus a treatment induced increase in both nutrient uptake and dry mass with decreased nutrient concentration (Shift A) would reflect a dilution of this nutrient due to accelerated growth. A similar response without change in concentration (Shift B) signifies sufficiency of this nutrient since concentration was stable and kept up with increased growth and nutrient uptake. Increased biomass, nutrient concentration, and nutrient content (Shift C) would reflect an enrichment response to a deficiency because both growth and nutrient uptake improved. A similar response without biomass change (Shift D) would suggest luxury consumption because nutrient uptake was enhanced without growth increase. Other vector shifts depicting toxicity (Shift E, increased concentration with reduced growth and nutrient uptake) and antagonistic (Shift F, declines in the three parameters) responses were not evident in our study, but are described in more detail by Haase and Rose ([1995](#)) and Imo and Timmer ([1997](#)). The cocoa monoculture treatment was designated as the control, or reference(R), in our analysis.



**Fig. 2** Interpretation of directional changes in relative dry mass and nutrient status of plants depicted in a vector diagram. The reference condition (R) is normalized to 100. Diagnosis (A to F) is based on shifts (increase [+], decrease [-] or no change [0]) of individual nutrients characterized in response curves relating plant growth, nutrient concentration, and nutrient content to treatment (modified from Imo and Timmer [1997](#))

## Results and discussion

### Cocoa biomass

Biomass of cocoa trees was significantly higher for trees grown under shade than with no shade ( $P = 0.004$ ; Table [2](#)). Aboveground biomass was almost doubled under *Milicia* and *Albizia* canopies as compared to sole crop culture (41.0, 39.6 vs 22.8 Mg ha<sup>-1</sup> for *Milicia* + cocoa, *Albizia* + cocoa and sole cocoa, respectively). Cocoa trees closer to the shade tree (<5 m) were significantly larger than those further away (5–10 m). Only the *Milicia* + cocoa treatment exhibited more cocoa biomass (21.97 kg per tree) at a greater distance as compared to monoculture cocoa (Table [2](#)). Biomass estimates were within the range of other reported measures (Fassbender et al. [1991](#)) and specifically for this region (Isaac et al. [2005](#)). Our results support earlier studies that indicate cocoa biomass benefits from shade (Alpizar et al. [1986](#); Fassbender et al. [1991](#); Beer et al. [1998](#); Isaac et al. [2005](#)).

**Table 2** Aboveground biomass (kg tree<sup>-1</sup>) for monoculture cocoa (Cocoa) and for cocoa under three individual shade trees (*Albizia*, *Milicia* or *Newbouldia*) at two radial distances from the shade tree

Treatment	Aboveground biomass of cocoa (kg tree <sup>-1</sup> )

	<5 m <sup>a</sup>	5–10 m <sup>b</sup>	<i>P</i> value <sup>c</sup>
Cocoa	20.75a	20.75a	
<i>Albizia</i> + cocoa	36.00b	20.07a	0.0059
<i>Milicia</i> + cocoa	37.28b	21.97a	0.0046
<i>Newbouldia</i> + cocoa	27.99ab	19.71a	0.0052

Means within a column followed by the same letter are not significantly different at  $P < 0.05$ , according to Tukey's test ( $n = 15$ )

<sup>a</sup><5 m radius from shade tree

<sup>b</sup>5–10 m radius from shade tree

<sup>c</sup> *P* value for location effect within a row

## Light availability

Percent open canopy between the cocoa and the shade strata was significantly different ( $P = 0.0136$ ; Table 1). Canopy openness was similar for *Albizia* and *Milicia* (69.6 and 68.1%, respectively), but higher for *Newbouldia* (80.1%). However, light infiltration under all three species was within the optimal range for cocoa growth and pod yield, where growth is generally maximized at low shade levels as photosynthetic rates of cocoa decrease at high light intensities (Galyuon et al. 1996; Zuidema et al. 2005). Thus here, higher cocoa biomass was found under low levels of shade, as previously suggested in model simulations of biomass and pod yield under shade (Zuidema et al. 2005). However, crown architecture of individual species may affect light infiltration. *Milicia* and *Albizia* are characterized by a large, sparse and spreading crown, where light infiltration may be regulated over distance and, in particular for *Albizia*, allows for more evenly distributed sun flecks to reach the cocoa stratum (Manu and Tetteh 1987; Anim-Kwapong 2003). *Newbouldia*, with a narrow and dense canopy (Amanor 1994) presumably provides higher shade close to the upper canopy tree.

## Soil nutrient stocks

Soil fertility status at both distances from the shade trees are given in Table 3. Available P pools in the top soil were smaller ( $P < 0.001$ ) under *Milicia* + cocoa (19.7 kg ha<sup>-1</sup>) and *Newbouldia* + cocoa (19.5 kg ha<sup>-1</sup>) compared to monoculture pools (22.2 kg ha<sup>-1</sup>; Table 3), inferring depletion of this nutrient close to shade trees. Accelerated growth in agroforestry systems may increase demands on soil P supply (Ofori-Frimpong and Rowel 1999). This may result in enlarged P depletion zones, possibly inducing interspecific competition for soil P resources (Vandermeer 1989). However, P availability under *Albizia* + cocoa (22.7 kg ha<sup>-1</sup>) was comparable to the monoculture cocoa, indicating a lack of competition for P resources under *Albizia*. Nutrient transfer is often higher under N-fixing species in comparison to a non-N fixing timber species (Fassbender et al. 1991) possibly due to improved litter quality, which may accelerate nutrient cycling processes in the 5 m zone around the shade trees.

**Table 3** Soil nutrient stocks (kg ha<sup>-1</sup>) to a depth of 20 cm under monoculture cocoa (Cocoa) and under cocoa in combination with three individual shade trees (*Albizia*, *Milicia*, or *Newbouldia*) at two radial distances from the shade tree

Soil parameter	Cocoa	<i>Albizia</i> + cocoa	<i>Milicia</i> + cocoa	<i>Newbouldia</i> + cocoa
<5 m <sup>a</sup>				
Total N (kg ha <sup>-1</sup> )	1232.3a	1290.0az	1389.0az	1288.3az
Available P (kg ha <sup>-1</sup> )	22.2a	22.7az	19.7bz	19.5bz
Exchangeable K (kg ha <sup>-1</sup> )	141.4a	113.5az	129.3az	214.5bz
5–10 m <sup>b</sup>				
Total N (kg ha <sup>-1</sup> )	1232.3a	1355.9az	1254.1az	1138.0az
Available P (kg ha <sup>-1</sup> )	22.2ab	23.2cz	19.6bz	23.0acy
Exchangeable K (kg ha <sup>-1</sup> )	141.4a	107.5az	100.3az	133.2ay

Means within a row followed by the same letter (a-b) are not significantly different at  $P < 0.05$ , according to Tukey's test ( $n = 9$ )

Means within a column at each location followed by the same letter (y-z) are not significantly different at  $P < 0.05$ , according to Tukey's test ( $n = 9$ )

<sup>a</sup><5 m radius from shade tree

<sup>b</sup>5–10 m radius from shade tree

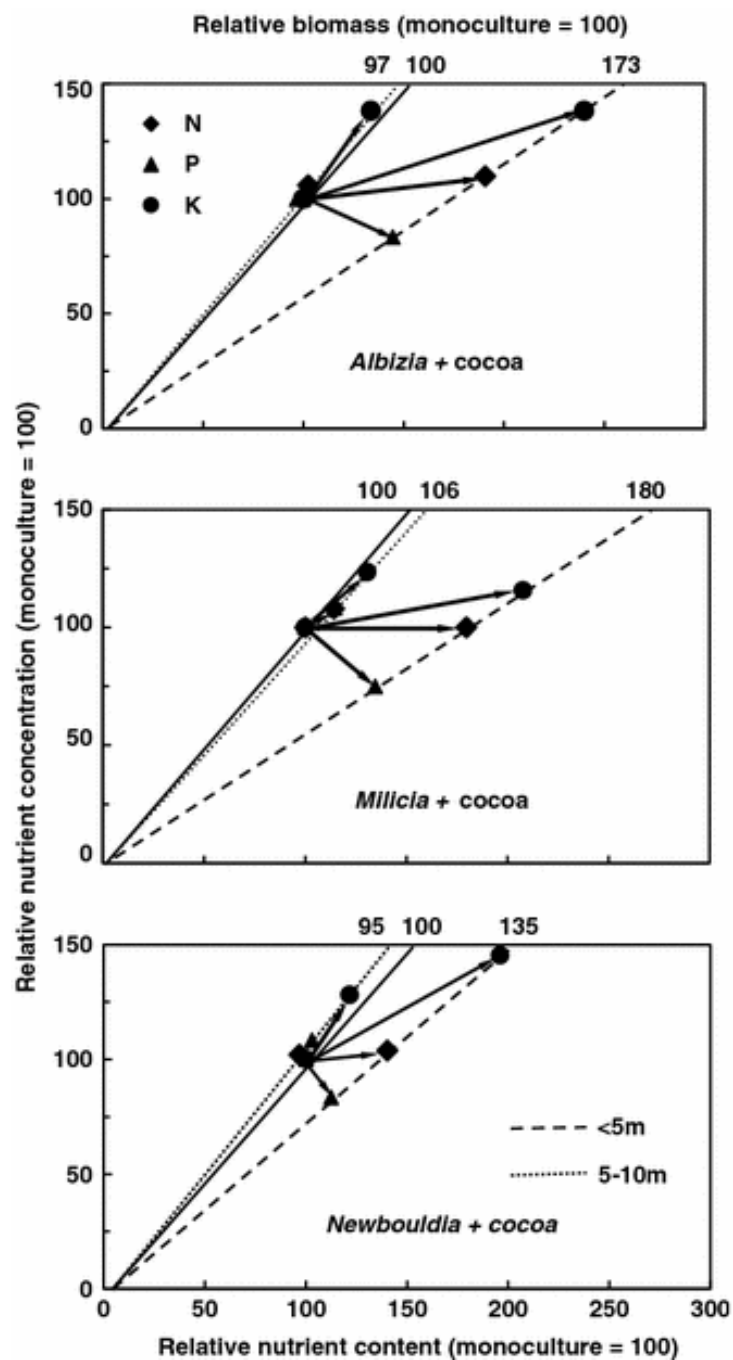
Total soil N was similar under shade for all three shade + cocoa treatments and monoculture cocoa, but decreased with distance under *Newbouldia* + cocoa, presumably due to *Newbouldia*'s narrow crown and lower structure thus impacting a smaller area. The expectation was to find elevated soil nitrogen under the N-fixing species *Albizia*, although no increases were detected. This result is not uncommon, as limited contribution from N-fixation in mature agroforestry systems has previously been reported (Nygren and Ramirez [1995](#); Beer et al. [1998](#)). As there was no marked difference in soil nitrogen pools, improved cocoa biomass was likely associated with rapid nutrient cycling rather than N-fixation (Beer [1988](#)).

Exchangeable K in the top soil pool was higher under *Newbouldia* + cocoa (214.5 kg ha<sup>-1</sup>) as compared to the monoculture (141.4 kg ha<sup>-1</sup>) and the other shade treatments (Table [3](#)). Generally, low re-absorption of K before cocoa litterfall and the high K transfer via rainwash (Boyer [1973](#); Hartemink [2005](#)), combined with *Newbouldia*'s particularly narrow and dense canopy may result in increased accumulation under this species. Soil exchangeable K also decreased with distance from *Newbouldia*, supporting our suggestion of a zone of concentrated K under *Newbouldia* (Table [3](#)). As found in previous studies, larger K soil pools lead to higher concentrations of K in cocoa biomass (Boyer [1973](#)), suggesting considerable plant uptake of potassium, and a possibility of luxury consumption.

## Plant nutrition

Nutrient interactions of the cocoa plants under the different species and distances from shade trees are illustrated in Fig. [3](#), where the relative biomass, nutrient concentrations and nutrient content of the cocoa plant were compared in a single nomogram with monoculture cocoa normalized to 100. At <5 m distance, cocoa trees achieved the highest biomass response (35–80%) compared to a lower response (–5% to 6%) further away (5–10 m from shade tree).

Concentration levels declined with P, but remained unchanged with N, and increased with K (Table 4). These changes (Fig. 3) reflect vector shifts A, B and C that signify, respectively, dilution of P, sufficiency of N, and deficiency of K in cocoa growth (Fig. 2). Under shade K uptake was stimulated most (96–140%), followed by N (43–88%), and then P (22–45%). With increasing distance from the shade tree, K uptake was enhanced most (22–34%), followed by P (9–21%), and then N (–3% to 13%).



**Fig. 3** Nomograms of relative response in dry mass and nutrient content (N, P and K) of cocoa trees under *Albizia*, *Milicia* or *Newbouldia*. Monoculture cocoa was normalized to 100. Both radial distances are shown on the nomogram: <5 m and 5–10 m away from the shade tree

**Table 4** Nutrient concentrations (mean  $\pm$  S.E.) and nutrient contents (concentration  $\times$  biomass) (mean  $\pm$  S.E.) for nitrogen (N), phosphorous (P) and potassium (K) of cocoa biomass (foliage and aboveground woody tissue) in monoculture (Cocoa) and under shade trees (*Albizia*, *Milicia*, or *Newbouldia*) at two radial distances (<5 m and 5–10 m) from the shade tree

Treatments	Nutrient concentration (% of dry weight)			Nutrient content (g tree <sup>-1</sup> )		
	N	P	K	N	P	K
Cocoa	1.54 $\pm$ 0.042	0.12 $\pm$ 0.006	1.28 $\pm$ 0.155	320.2 $\pm$ 8.72	24.0 $\pm$ 1.26	265.4 $\pm$ 32.13
<5 m						
<i>Albizia</i> + cocoa	1.68 $\pm$ 0.052	0.10 $\pm$ 0.004 <sup>a</sup>	1.77 $\pm$ 0.177*	603.0 $\pm$ 18.67*	34.9 $\pm$ 1.57*	637.0 $\pm$ 63.62*
<i>Milicia</i> + cocoa	1.50 $\pm$ 0.060	0.09 $\pm$ 0.003*	1.48 $\pm$ 0.096	558.5 $\pm$ 22.40*	34.8 $\pm$ 1.18*	553.4 $\pm$ 34.51*
<i>Newbouldia</i> + cocoa	1.64 $\pm$ 0.046	0.10 $\pm$ 0.006*	1.86 $\pm$ 0.122*	459.3 $\pm$ 12.96*	29.3 $\pm$ 1.74*	520.0 $\pm$ 34.09*
5–10 m						
<i>Albizia</i> + cocoa	1.63 $\pm$ 0.078	0.12 $\pm$ 0.006	1.77 $\pm$ 0.053*	327.1 $\pm$ 15.61	24.2 $\pm$ 1.14	355.6 $\pm$ 10.58*
<i>Milicia</i> + cocoa	1.65 $\pm$ 0.075	0.13 $\pm$ 0.004	1.58 $\pm$ 0.112	361.7 $\pm$ 16.43*	29.0 $\pm$ 0.89*	346.0 $\pm$ 24.67*
<i>Newbouldia</i> + cocoa	1.57 $\pm$ 0.052	0.13 $\pm$ 0.004	1.64 $\pm$ 0.067	309.0 $\pm$ 10.20	26.1 $\pm$ 0.76	323.0 $\pm$ 13.17*

<sup>a</sup> indicates means that are significantly different from monoculture cocoa at  $P < 0.05$ , according to Dunnetts test ( $n = 9$ )

A consistent trend of P dilution (Shift A; Fig. 2) in cocoa under each species would suggest that the next limiting nutrient on this farm would be phosphorus (Fig. 3). Near the shade tree, P uptake was least (22–45%) in comparison to the other nutrients (N = 43–88%; K = 96–140%), reflecting relatively slower cycling of this element (Fassbender et al. 1991). Phosphorous status in soils (Table 3) and in cocoa biomass (Table 4) was lower under shade trees than in monoculture. Low phosphorous status is common in tropical agricultural systems, because of widespread P deficiency in highly weathered acid tropical soils and is usually most limiting within tropical agroforestry systems (Alpizar et al. 1986). Similar to here, cocoa-shade agroforestry systems in Costa Rica reported low P accumulation in crops, attributed to relatively low phosphorus mobility within these systems (Fassbender et al. 1991; Table 4). In our case, soil P may become limiting if concentrations cannot be maintained with accelerated cocoa growth under shade.

There was no significant difference in total N concentration in cocoa under all three species (Table 4; Fig. 3), suggesting little contribution from our shade species towards N transfer. Despite higher tree foliar N levels (Table 1), N-fixing *Albizia* failed to raise soil N or cocoa N status compared to the other species. Although N concentration was stable with enhanced growth under shade trees, N content increased across all treatments in comparison to the monoculture cocoa. Apparently, N uptake kept pace with growth, a common sufficiency response (Table 4; Fig. 3). Overall, nitrogen content values were comparable to a 9 year-old cocoa agroforestry system with *Cordia alliodora* and *Erythrina poeppigiana* in Costa Rica (Alpizar et al. 1986).

Potassium concentration was significantly higher in cocoa under *Albizia* and *Newbouldia* close to the shade tree, presumably due to corresponding higher K levels in soils under this tree (Table 3). However, potassium uptake by cocoa near the shade tree (<5 m) was enhanced in all multistrata treatments, especially under *Albizia* (140%) where

K concentration rose 40%, hence signifying a typical deficiency response (Shift C; Fig. 2). On the other hand, with increasing distance from the shade tree, K contents (*Albizia* + cocoa = 355.6 g tree<sup>-1</sup>; sole cocoa = 265.4 g tree<sup>-1</sup>) were increased without substantially increasing N, P and biomass status (Table 4; Fig. 3). These vector patterns reflect luxury consumption (Shift D; Fig. 2) of potassium, since K accumulation occurred without increased biomass. Vector length comparisons showed that K was the most responsive element within this system, exhibiting enhanced uptake even with distance from shade tree. As noted in Table 3, the multistrata systems resulted in either a neutral or positive effect on soil exchangeable K pools, probably because of high K inputs from litter and elevated K transfer via rainwash (Boyer 1973; Hartemink 2005). Cycling of subsoil K to the surface through shade tree uptake may also occur, because after N, potassium is usually considered more readily mobile as compared to other macronutrients (Barber 1984). Specifically for K, our results illustrate a possible facilitating effect of nutrient pumping under shade trees, likely because of enhanced nutrient transfer by upper canopy trees.

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## Conclusions and implications

The inclusion of low-density shade trees in this 8-year-old cocoa plantation positively affected biomass of neighboring cocoa trees through nutrient and/or light manipulation. Aboveground dry matter of cocoa increased with shade, and declined along a spatial gradient away from shade trees. Light availability under all three shade tree species was within the optimal range for cocoa production. Although soil exchangeable K was increased under *Newbouldia* + cocoa, in general, available P decreased and total N stocks were unaffected in the soils under all shade treatments. Vector analysis showed that nutrient uptake of cocoa was highest near shade trees, and that K was the most responsive nutrient in these systems. Research trials that incorporate fertilizers (in particular K) and shade manipulation are recommended to further elucidate the specific mechanisms involved in these responses.

Our study illustrates a beneficial relationship between shade trees and enhanced cocoa biomass presumably due to provision of optimal shade and overall improved nutrient cycling capabilities near the shade trees. Nutrient uptake was maintained with accelerated cocoa growth under shade suggesting a potential for sustained productivity. We found minimal variation in the level of complementarity of each upper canopy species, however, appropriate management of upper canopy trees may vary over time. Either one of these factors may emerge more important at different points in the life of the plantation. Presumably, young cocoa trees are more sensitive to high light and require shading, however in mature plantations, the main role of upper canopy trees may shift from providing shade to enhancing nutrient stability in both soils and biomass. Therefore, farmer management of the upper canopy is critical for optimal levels of cocoa productivity and sustainability.

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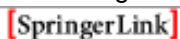
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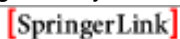
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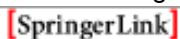
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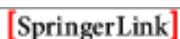
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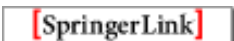
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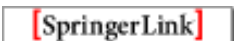
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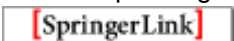
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