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REGULAR ARTICLE

Early growth and nutritional response to resource competition in cocoa-shade intercropped systems

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Abstract Intercropping is often promoted for effective mutualism between species, thus compensating for external inputs. However, for optimal farm design resulting in superior production and nutrition, an accurate assessment of plant inter- and intra-specific competition is required. In predominant shade tree-cocoa (*Theobroma cacao*) systems, inconclusive evidence remains on species interactions, limitations to resource availability and subsequent growth and nutritional response, particularly in early growth. We examined cocoa biomass and foliar nutrition as well as nutrient supply through rates of decomposition and N mineralization after 1-year growth. Our approach employed fertilization and mixed planting treatments in an additive design of cocoa in monoculture (control), under artificial shade, and intercropped under two separate shade species (*Terminalia superba* and *Newbouldia laevis*). Intercropping had no effect on cocoa biomass production in comparison to monoculture cocoa. However, artificial shading stimulated foliage and root production both with and without fertilization, suggesting strong effects of light regulation on growth in the absence of belowground competition. Nutritionally, intercropping suppressed K uptake in cocoa foliage as K concentration was reduced by 20–25%, signifying dilution of this nutrient, presumably due to interspecific competition for mobile elements. Foliar N content under *N. laevis* was raised, where N concentration kept up with growth under this intercropped species. Intercropping also delayed decomposition rates, suggesting slower but sustained release of available nutrients into the topsoil. Cocoa under artificial shade, both with and without fertilization, exhibited the greatest nutrient responses as compared to unfertilized monoculture cocoa, where P uptake was stimulated most (175 and 112%), followed by K (69 and 71%), and then N (54 and 42%). Intercropping with shade trees failed to increase cocoa biomass, however, nutrient uptake was sustained for N and P, suggesting low interspecific competition. When fertilizers are undesirable or unavailable, intercropping of appropriately selected shade trees will not competitively suppress early growth of cocoa but will improve light regulation and nutritional status of cocoa saplings.

Keywords Agroforestry · Ghana · Leaf decomposition · Mineralization · *Theobroma cacao* · Vector analysis

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Introduction

Establishment of agroforestry systems is often encouraged to increase farm diversity and food security as well as advance farm nutritional and production sustainability. Interplanting of trees and crops is recommended to promote effective mutualism between species, thus compensating or substituting for external inputs, such as fertilizers and pesticides (Vandermeer 1989; Jose et al. 2004). However, optimal farm design for successful production requires an accurate assessment of plant interspecific (between individuals of different species) and intraspecific (between individuals of the same species) competition and/or facilitation. Employing ecology-based principles such as niche partitioning and species compatibility, investigation on natural plant community interactions (Tilman 1982; Hooper and Vitosek 1998) as well as in both tropical agroforestry (Schroth et al. 2001; Garcıa-Barrios and Ong 2004) and temperate agroforestry (Jose et al. 2004; Thevathesan and Gordon 2004) systems is widely conducted. In theory, if species vary greatly in physiological characteristics and requirements, their interaction may result in utilization of previously limiting resources (Vandermeer 1989; Garcıa-Barrios and Ong 2004), resulting in a synergistic response.

The study of cocoa-shade agroforestry systems is of high priority due to its global cultivation and its integral foundation to small-holder farmer livelihood in many regions of the world (ICCO 1997; Duguma et al. 2001). Studies conducted on-farm and in long-term research trials point to a nutrient and light interplay driving production in these systems (Fassbender et al. 1991; Monteith et al. 1991; Beer et al. 1998). Resource partitioning and synchrony as well as the ability of shade species to capture and cycle nutrients underlie the balance between competition and facilitation between individuals (Beer et al. 1998; Schroth et al. 2001). Such dominant processes may result in improved cocoa crop productivity, however interspecific competition for a particular resource, such as availability of solar radiation or nutrient supply, is also probable. Generally, cocoa biomass production is measured under a variety of shade tree combinations and a range of planting densities, focusing on static pools and subsequent speculation on underlying interactions and growth mechanisms (Beer et al. 1998; Schroth et al. 2001; Hartemink 2005; Isaac et al. 2007). If subsistence farmers are dependent on production, a more precise understanding of mutualisms versus competition within these systems will result in better livelihoods as well as increase farm sustainability and reduce forest conversion.

Cocoa is a shade tolerant species, exhibiting increased production under lowered light levels with optimal cocoa growth ranging from 20 to 30% of full sunlight (Okali and Owusu 1975; Galyuon et al. 1996) usually on soils with high nutrient availability (Hartemink 2005). Although initial hypotheses on cocoa growth suggest that once nutrient requirements are met, understory crop production is primarily dependent on the accessibility of solar radiation (Cunningham and Arnold 1962; Monteith et al. 1991), there remains no conclusive evidence on light and nutrient interactions within cocoa-based agroforestry systems. Research to date has focused primarily on interactions in mature plantations (Beer et al. 1998; Isaac et al. 2007) rather than farm establishment, a sensitive stage in plantation development. Hence, there is a need to assess competition or complementarity between fast growing species and cocoa saplings at early growth for an understanding of improved system design and sustainable practices.

This study examined biomass growth and nutritional response of cocoa after 1 year in experimental research trials with shading treatments provided by shade trees and artificial shade cloth and nutrient additions by fertilization. We employed plantings of cocoa in monoculture (control), cocoa intercropped under two physiologically different shade species (*Terminalia superba* and *Newbouldia laevis*), and cocoa under artificial shade to isolate a potential shading effect. Resultant partitioning and nutritional status of cocoa biomass, as well as sources of nutrient inputs through litter decomposition and N mineralization were used to differentiate interactions and subsequent growth mechanisms. We hypothesized a negative effect from intercropping on cocoa biomass and nutrient uptake due to interspecific competition for nutrients. However, we predicted improved cocoa biomass under artificial shade with fertilization due to removal of interspecific belowground competition (competitive-free state of cocoa under shade). Results will provide useful information for refining agroforestry techniques for successful farm management.

Materials and methods

Experimental site and design

This study was conducted in Kumasi, Ghana (longitude 6 41′N and latitude 01 37″W) located in the semi-deciduous humid zone (elevation of 278 m above sea level). Rainfall is bimodal with peaks in June and October separated by a long dry period from December to February. The mean annual rainfall ranges between 1,300 and 1,600 mm and temperature range is 22° to 31°C with an average of 26.2°C. Soils of the area belong to the Asuansi series (Ghana Classification) and are classified as Ferric Acrisol. These soils are moderately deep, gravely with concretions, moderately well drained with low CEC and base saturation (Soils Survey Division 1969). Site vegetation was an open canopy secondary forest consisting of semi-deciduous tree and shrub species of the *Celtis-Triplochiton* Association. Previous land use was small-scale agriculture with very short fallows or continuous cropping of maize, cassava and plantains. Recently, frequent fires have converted the site into mainly grass vegetation (*Panicum maximum*) with a few shrubs (*Eupatorium* spp.).

The experimental design was a randomized split-plot design with two levels of fertilization, without (−) or with (+) fertilizer application, as the main plot effect, replicated in four blocks. Subplot effects consisted of four randomly assigned treatments of cocoa monoculture (±*C*), cocoa intercropped with *T. superba* (±*T*) and cocoa intercropped with *N. laevis* (±*N*) and cocoa under artificial shade (±*S*). We employed an additive design, where each species had a fixed density, thus overall plant density doubled in intercropped plots (Kelty and Cameron 1995). Plots were established in April of 2005. Three-month-old cocoa seedlings and *T. superba* seedlings, cultured from seed in a local nursery under similar conditions employed by regional farmers, were planted at the site. *N. laevis* seedlings were established as approximately 30 cm shoot cuttings from neighboring mature trees.

Each plot was 2×2 m (with 1 m space separating plots) was arranged in an additive series design. Narrow trenches were dug around each block and plot to minimize belowground inter-plot interference. The fertilizer treatment consisted of a single application of 20-20-20 (N-P_2O_5-K_2O) fertilizer as suggested by the Cocoa Board of Ghana (personal communication). The fertilizer was broadcast on the soil surface at a rate of 375 kg ha^{-1} shortly after planting (75.0 kg N ha^{-1}, 33.0 kg P ha^{-1}, 62.3 kg K ha^{-1}). Artificial shade treatments were constructed from shade cloth (creating 50% shade) covering three sides (in the direction of the sun thus reducing possible direct exposure) of a box frame (2×2×2 m) around the plot.

Species description

T. superba Engl. Et Diels (Combrataceae) is a light demanding dominant tree normally reaching heights of 30 m at maturity. Its form is a narrow, straight bole with a 2–3 m basal buttress at about 8–9 years old. Juvenile trees have lateral branches in whorls, with rapid apical growth (Groulez and Wood 1985), resulting in a large canopy and reduced light infiltration. *N. laevis* (Bignoniaceae), a multi-purpose, native tree, is used mainly for shade 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).

In this study, *T. superba* reached a height (assessed with a measuring tape) of 1.58 (fertilized) and 1.33 m (unfertilized; n=12) and an aboveground dry mass (measured by destructive sampling) of 1.6 kg (n=4) after 1 year's growth. *N. laevis* averaged a height of 0.88 (fertilized) and 0.58 m (unfertilized; n=12) and aboveground dry mass of 0.28 kg dry weight (n=4). Estimates of each species shading ability were based on image analysis taken at 1 year after establishment. A hemispherical lens (180° equiangular fisheye lens) was attached to a digital camera (Nikon Cool Pix 950), mounted onto a mini-tripod, oriented north and leveled for each photo. Random measurements of light transmission through each shade species were collected (n=4). Images were examined by gap light analysis (Gap Light Analyzer, Version 2 1999), providing estimates of percent canopy openness (percent open sky beneath the canopy) for each shade tree species. Shading capabilities of *T. superba* with fertilizer (49.6%) and without fertilizer (45.0%) were significantly greater than shading capabilities of *N. laevis* with fertilizer (24.3%) and without fertilizers (13.8%), but similar to that of the artificial shade treatment.

Plant sampling and analysis

Biomass production was measured from destructively sampled cocoa trees after 1 year growth (n=4 per treatment). Trees were then separated into foliage, shoot and root tissue and weighed. Total foliage samples were oven-dried (70°C for 72 h) and re-weighed. Subsamples of shoot and root tissue were collected in triplicate, weighed, oven-dried (70°C for 72 h) and re-weighed to arrive at a wet/dry ratio for each biomass component and subsequently used to calculate dry weight of each sample. Analysis of fresh foliage was selected as an index of short-term response to environmental changes reflected in allocation to photosynthetic structures (Tilman 1982) and a reported strong correlation between cocoa tree components (Zuidema et al. 2005). Samples (approximately 100 g wet weight) were randomly collected from cocoa trees, oven-dried (70°C for 72 h), and ground in a Wiley Mill (n=12 per treatment). Foliage tissue was wet digested 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). Nutrient concentration was multiplied by foliar dry mass to determine foliage nutrient content.

Soil sampling and analysis

Soil fertility was assessed by collecting a composite soil sample (three subsamples of approximately 100 g per total sample), to a depth of 0–20 cm [the active lateral root zone of cocoa (Kummerow et al. 1982)] at each treatment, repeated at each block. 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, Ca and Mg by leaching air-dried soil samples with ammonium acetate and measured quantitatively by atomic absorption spectrophotometry (Allen 1974).

Soil particle size distribution (sand=68.0; silt=20.0; clay=12.0) was determined by the hydrometer method, soil pH (4.56) by a 1:1 paste of water/soil, percent organic matter (2.53) by oxidation (Allen 1974). Bulk density (0.9 g cm^{-3}±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°C, 48 h) and weighing the soil (Rowell 1994). Percent soil moisture content, measured with collected soil samples at a depth of 15 cm, dried at 105°C for 48 h, weighed and calculated on a dry weight basis, was 34.0% (averaged across blocks and treatments). Soil temperature averaged to 28.3°C (measured with a digital thermometer at all blocks and treatments). All tests were conducted in triplicate.

Decomposition

To measure litter decomposition, three litterbags 15×30 cm with a mesh size of 5 mm, were filled with 20 g of fresh cocoa leaves from each plot, closed with staples, and secured to the ground at random locations within each plot. Wet/dry ratios were calculated for the initial leaf material by drying subsamples at 60°C for 48 h to correct for moisture. Bags were retrieved on a random basis at 14, 28 and 42 days after placement. The material remaining in each collected bag was cleaned, dried, weighed and recorded, as described by Anderson and Ingram (1993). Decomposition was assessed by single exponential decay function: $A_t=A_0e^{-kt}$; where A_t is the amount remaining (g) after time t, A_0 the initial amount (g), t the time (day), and k is the decay rate constant (day^{-1}). The specific decomposition constant, k, was estimated from the slope of the line of the linear regression between $\ln(A_t/A_0)$ and time (Paul and Clark 1996).

Nitrogen mineralization

Nitrogen mineralization rates were determined by isolating soils for incubation in situ within PVC tubing set in pairs to a depth of 20 cm, and covered in plastic to reduce evapotranspiration and over-saturation within the tubes (Isaac and Timmer 2007). To account for moisture variation, all tubes were placed in the ground approximately 24 h after a rainfall event. One tube from each pair was immediately taken to the laboratory for determination of initial nitrate (NO_3^-) and ammonium (NH_4^+) concentrations. The other tubes were retrieved after a 28-day incubation and also analyzed for inorganic nitrogen content. At the beginning (initial) and end (final) of the 28-day test period, incubated soils were subsampled (10 g) and extracted with 60 ml of 2 M KCl, shaken for 1 h and filtered. Filtrate was analyzed for both ammonium–N

and nitrate–N (Keeney and Nelson 1982) using a Technicon Autoanalyzer. Net nitrogen mineralization was calculated, including soil water content to corrected for soil moisture, as the difference between final and initial concentrations of NH_4^+–N plus NO_3^-–N.

Statistical analysis

Cocoa biomass production (foliage, shoot and root) was subjected to split plot analysis of variance with four replications using a mixed model (PROC MIXED) in SAS version 8.0 (SAS Institute Inc. Cary, NC, USA). The main plot consisted of two fertilization levels (±fertilizer) and the subplots consisted of four planting treatments (*C*, *S*, *T* and *N*) designated as fixed effects. Blocks were designated as random effects in the model. In the case of a significant F-test, treatment means were compared to the control, unfertilized monoculture cocoa, using a Dunnett test. Independence, randomness of residuals and a mean error equal to zero were confirmed with a test of residuals for biomass, foliar nutrient concentration and content and soil nutrient data. Normality of residuals was tested using the Shapiro–Wilk test. Inorganic nitrogen production was logtransformed to correct for heteroscedasticity. A type I error rate was set at 0.05 for all statistical tests.

Vector analysis

Dry mass and nutrient status of cocoa foliage was examined by vector analysis to assess nutritional response associated with cocoa grown under inter-

Table 1 Analysis of variance table for cocoa biomass production (foliage, shoot and root) and foliage nutrient concentration and content (N, P, and K) as whole-plot effects of fertilization (Fert) and subplot effects of treatment (Trt) and their interaction (Fert × Trt)

	Source	*F*	P
Biomass			
Foliage	Fert	0.02	0.8995
	Trt	4.54	*0.0375*
	Fert × Trt	1.17	0.3789
Shoot	Fert	0.33	0.5862
	Trt	0.43	0.7344
	Fert × Trt	0.61	0.6232
Root	Fert	0.40	0.5502
	Trt	10.52	*0.0027*
	Fert × Trt	0.76	0.5428
Nutrient Concentration			
N concentration	Fert	0.22	0.6573
	Trt	2.82	0.0998
	Fert × Trt	2.92	0.1002
P concentration	Fert	6.57	*0.0428*
	Trt	4.65	*0.0315*
	Fert × Trt	6.65	*0.0116*
K concentration	Fert	7.93	*0.0305*
	Trt	2.56	0.1204
	Fert × Trt	9.12	*0.0043*
Nutrient content			
N content	Fert	1.51	0.2655
	Trt	27.86	*<0.0001*
	Fert × Trt	12.90	*0.0020*
P content	Fert	17.42	*0.0059*
	Trt	36.35	*<0.0001*
	Fert × Trt	15.50	*0.0011*
K content	Fert	10.37	*0.0181*
	Trt	4.99	*0.0261*
	Fert × Trt	34.76	*<0.0001*

Significant effects are in *italics*.

cropping, artificial shade and in monoculture. Responses were expressed relative to the unfertilized monoculture cocoa control (that was normalized to 100) to facilitate comparisons between various treatments and nutrients. See Timmer (1991), Haase and Rose (1995) and Salifu and Timmer (2003) for a more detailed description.

Results

Allocation of biomass

Analysis of variance revealed no significant fertilization or fertilization-by-treatment effect but did confirm a significant treatment effect on cocoa foliage production after 1 year (foliage: $F=4.54$; $P=0.0375$; Table 1). Neither fertilization nor intercropping with *N. laevis* or *T. superba* significantly affected cocoa biomass (foliage, shoot or root) production as compared to unfertilized monoculture cocoa (Table 2). However, foliage production was greater under artificial shade both with (116.8 g plant^{-1}; Table 2) and without fertilization (128.9 g plant^{-1}), indicating a 56 and 73% increase in mass, respectively, in comparison to cocoa grown in full sun. Root biomass was also significantly larger ($F=10.52$; $P=0.0027$; Table 1) when cocoa was grown under artificial shade (unfertilized=70.5 g plant^{-1} and fertilized=86.4 g plant^{-1}) in comparison to the control (44.9 g plant^{-1}; Table 2).

Foliar nutrition

Nitrogen concentration in cocoa foliage was not significantly affected by treatment, fertilization or fertilization-by-treatment (Table 1). However, P concentration significantly increased in cocoa under fertilized monoculture by 54% and under fertilized artificial shade by 73% in comparison to the control (Tables 1 and 3). Potassium concentration in cocoa leaf tissue declined significantly under both intercropped treatment without fertilization and under *N. laevis* with fertilization, however K concentration increased in cocoa leaves under fertilized monoculture (Tables 1 and 3). Without fertilization, nitrogen content was significantly higher ($P<0.0001$; Table 1) in cocoa foliage under artificial shade and under *N. laevis* than in cocoa under monoculture. However, with fertilization, foliar N content was similar in under both intercropped treatments (+*T*, 1.18 g plant^{-1} and +*N*, 1.17 g plant^{-1}) as compared to the monoculture control (1.25 g plant^{-1}; Table 3). Phosphorus content was higher in cocoa foliage under artificial shade (−*S*, 0.17 g plant^{-1}; +*S*, 0.22 g plant^{-1}) and fertilized monoculture cocoa (0.17 g plant^{-1}) as compared to the control (0.08 g plant^{-1}; Table 3). However, leaf P content was lower in cocoa under *T. superba* in contrast to significantly greater P content in cocoa under *N. laevis* without fertilization (Table 3). With fertilization, K content in cocoa foliage was significantly higher under artificial shade (0.76 g plant^{-1}) and monoculture cocoa (0.84 g plant^{-1}).

Table 2 Dry weight (±standard error) of partitioned cocoa biomass into foliage, shoot and root components after 1 year growth in monoculture cocoa (*C*), intercropped with *T. superba* (*T*) or *N. laevis* (*N*) or under artificial shade (*S*) for both unfertilized and fertilized plots

Treatment	Partitioned biomass (g plant^{-1})		
	Foliage	Shoot	Root
Unfertilized (−)			
C	74.7±16.73	97.2±30.07	44.9±11.62
T	74.0±32.02	68.8±24.60	32.9±10.08
N	95.5±21.73	98.9±28.70	40.2±6.90
S	128.9±29.17*	98.5±26.75	70.5±14.80*
Fertilized (+)			
C	98.0±7.35	125.3±44.02	46.4±15.07
T	78.8±17.80	93.9±45.32	37.9±11.53
N	80.1±30.27	98.5±40.40	45.1±13.59
S	116.8±6.29*	117.1±5.11	86.4±10.01*

*$P<0.05$; denotes significantly different than the control *C* (unfertilized monoculture cocoa) using the Dunnett test

Table 3 Nutrient concentration (%) and nutrient content [concentration × foliar biomass (see Table 2)] of cocoa foliage (g plant^{-1}) after 1 year in cocoa grown in monoculture (*C*), intercropped with *T. superba* (*T*) or *N. laevis* (*N*) or under artificial shade (*S*) for both unfertilized and fertilized plots

Treatment	Nutrient concentration (%)			Nutrient content (g plant^{-1})		
	N	P	K	N	P	K
Unfertilized (−)						
C	1.67	0.11	0.60	1.25	0.08	0.45
T	1.61	0.12	0.45*	1.19	0.09	0.34
N	1.62	0.15	0.48*	1.55*	0.15*	0.46
S	1.38	0.13	0.60	1.78*	0.17*	0.77*
Fertilized (+)						
C	1.80	0.17*	0.86*	1.76*	0.17*	0.84*
T	1.50	0.13	0.71	1.18	0.10	0.56
N	1.46	0.15	0.43*	1.17	0.11	0.34
S	1.65	0.19*	0.65	1.93*	0.22*	0.76*

*$P<0.05$; denotes significantly different than the control *C* (unfertilized monoculture cocoa) using the Dunnett test

Nutrient supply

Decomposition

Intercropping with *T. superba* and *N. laevis* significantly reduced cocoa leaf decomposition (k=0.016 and 0.009, respectively) compared to decay under monoculture cocoa. In unfertilized monoculture cocoa, leaf material remaining after 42 days of decomposition was significantly lower (F=7.23; P=0.0288) with a higher decay constant (k=0.048). With fertilization, rates of cocoa leaf decomposition were similar under all treatments (Fig. 1).

Soil pools

Production of soil inorganic N in the effective rooting zone of cocoa significantly varied between treatments

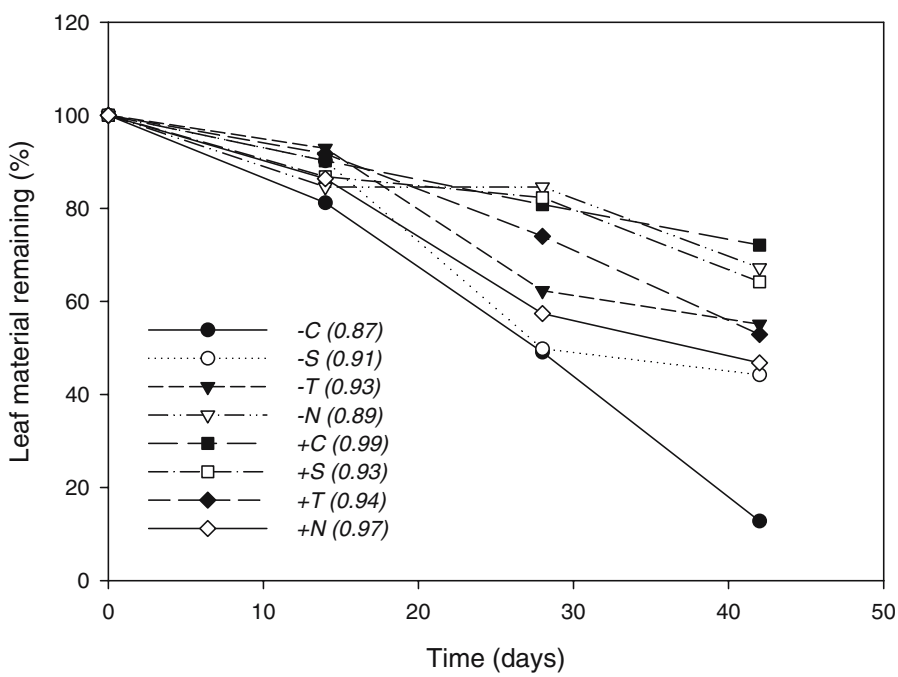

Fig. 1 Decay curves (% initial dry weight remaining) of *T. cacao* leaves measured in decomposition bags under monoculture cocoa (*C*), cocoa intercropped with *T. superba* (*T*) or *N. laevis* (*N*) or cocoa under artificial shade (*S*) for both unfertilized (−) and fertilized (+) plots. Four weighing times were used: days 0, 14, 28, and 42. R^2 value for each decay curve is *in parentheses*

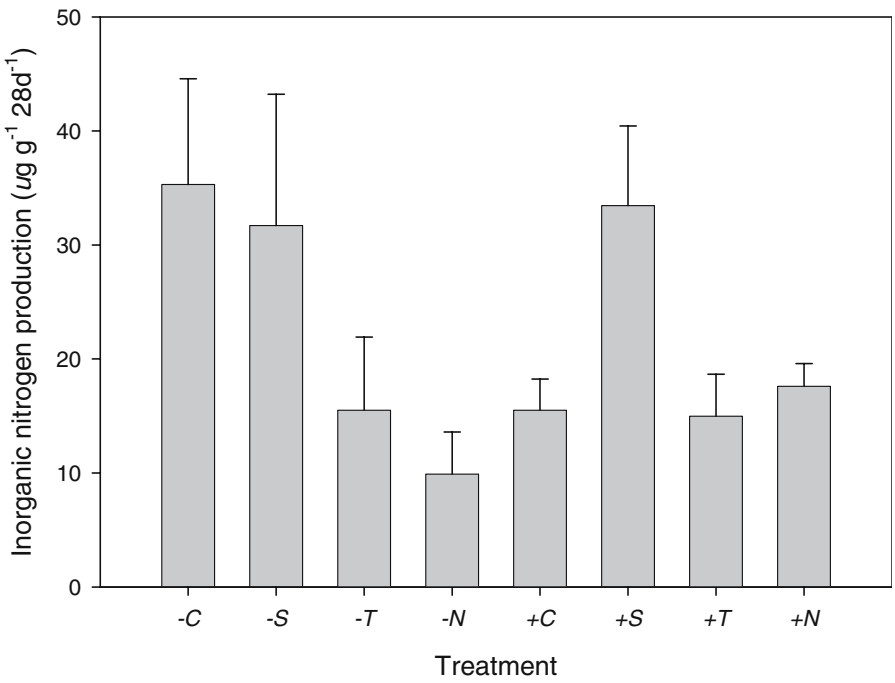

Fig. 2 Inorganic (NO_3^-–N plus NH_4^+–N) nitrogen production (μg N g^{-1} 28 day^{-1}) derived from in-situ soil incubations under monoculture cocoa (*C*), cocoa intercropped with *T. superba* (*T*) or *N. laevis* (*N*) or cocoa under artificial shade (*S*) for both unfertilized (−) and fertilized (+) plots. *Bars* represent standard error of the mean (n=4)

(F=3.25; P=0.0299; Fig. 2). Incubated soils under cocoa-shade exhibited no fertilizer effect and produced significantly lower levels of inorganic N as compared to the control (35.3±9.27 μg g^{-1} 28 day^{-1}). In contrast, soils under artificial shade (−*S*=31.7± 11.52 μg g^{-1} 28 day^{-1} and +*S*=33.5±6.98 μg g^{-1} 28 day^{-1}) exhibited similar rates of mineralization as the control. Soils under monoculture cocoa with fertilizer application showed suppressed production of inorganic N (15.5±2.75 μg g^{-1} 28 day^{-1}).

Detailed results on soil pools (total N, available P, and exchangeable K, Ca, Mg) 1 year after treatment establishment (means of two fertilization levels) are shown in Table 4. Note no significant difference was found between treatments or soil pools, which probably reflects site nutrient sufficiency, large soil variability and/or excessive leaching of nutrients.

Discussion

Intercropping effect on cocoa

The addition of intercropped shade trees showed no effect on cocoa biomass production after 1 year growth (Table 2), although shade tree-cocoa inter-

Table 4 Soil nutrient pools (±standard error) to a depth of 20 cm 1 year after establishment of cocoa and fertilizer application under monoculture cocoa (*C*), cocoa intercropped with *T. superba* (*T*) or *N. laevis (N*) or under artificial shade (*S*)

Parameter	*C*	*S*	*T*	*N*
Total N (mg g^{-1})	1.40±0.039	1.35±0.073	1.32±0.061	1.42±0.083
Available P (mg kg^{-1})	16.50±1.133	15.99±1.067	15.36±2.295	15.03±1.057
Exch. K (cmol kg^{-1})	0.24±0.041	0.14±0.023	0.19±0.028	0.21±0.091
Exch. Mg (cmol kg^{-1})	0.83±0.139	0.65±0.122	1.07±0.094	0.91±0.196
Exch. Ca (cmol kg^{-1})	2.92±0.458	2.30±0.693	3.45±0.397	2.72±0.555

Unfertilized (−) and fertilized (+) data sets were pooled due to lack of significant fertilization effect

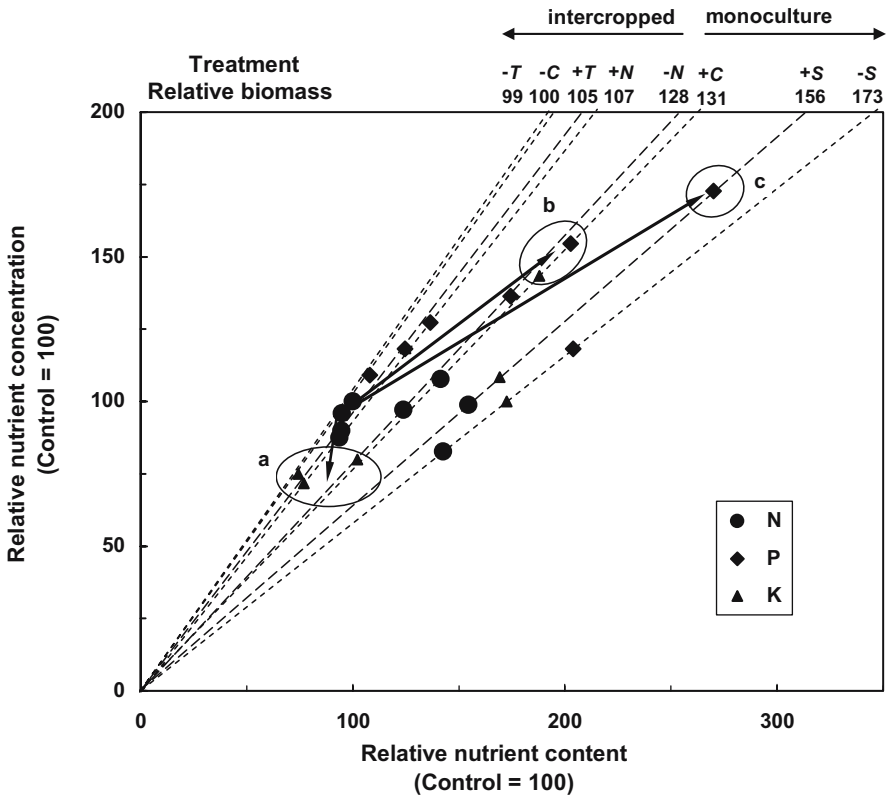

Fig. 3 Nomogram of relative response in dry mass and nutrient content (N, P and K) of cocoa foliage in monoculture cocoa (*C*), cocoa intercropped with *T. superba* (*T*) or *N. laevis* (*N*) or cocoa under artificial shade (*S*) for both unfertilized (−) and fertilized (+) plots. Responses are relative to the control: the unfertilized monoculture cocoa was normalized to 100. *Vectors to circles* depict statistically significant responses of dilution of K under intercropping (decrease in nutrient concentration without biomass change: *a*), luxury consumption of P and K under monoculture with fertilization (increase in concentration without biomass change: *b*), and deficiency of P under artificial shade (increase in concentration and content as well as biomass: *c*). All other points reflect sufficiency (no change in concentration or biomass). See Salifu and Timmer (2003) for further details on nutrient status interpretation of vector shifts

actions did exhibit a significant nutritional response (Table 3). Intercropping suppressed foliar K concentration (−*T*, −25%; −*N*, −20%), signifying dilution of this nutrient with increasing growth presumably due to strong competition for this mobile element (Table 3; Fig. 3). For instance, structurally, *T. superba* is characterized by a large crown architecture and shallow rooting zone (Groulez and Wood 1985), reaching an average height of 1.65 m and an average aboveground dry mass of 1.6 kg after only 1 year growth. Consequently, the larger root structure of this shade tree species may have out-competed cocoa seedlings for resources such as topsoil nutrients (Schroth 1999).

No changes in foliar N concentration under *T. superba* or *N. laevis* were measured. However, N uptake (content) was significantly greater under *N. laevis* in the absence of external inputs, suggesting that N uptake kept up with growth (Table 3; Fig. 3). Often, improved N uptake is reported in agroforestry systems due to higher nitrogen supply from larger litter inputs and enhanced nitrogen cycling from stratified rooting zones (Haggar et al. 1993; Hartemink 2005; Isaac et al. 2007). Although our results revealed reduced N supply from N mineralization under intercropping (Fig. 2), the cocoa saplings maintained nutrient sufficiency in foliage under *N. laevis* without fertilization illustrating a closed, efficient cycling of N. Species co-existence may be due to differing spatial and temporal resource requirements, resulting in facilitation (Jose et al. 2004). This suggests that, although lacking in biomass response, nutrient enrichment of cocoa was presumably contingent on shade tree species selection in terms of tree characteristics.

Enrichment effect on cocoa

Fertilization did not affect cocoa biomass growth in monoculture, although foliar nutrient uptake (content) was increased as compared to the unfertilized control (N, 41%; P, 112%; K, 87%; Table 3; Fig. 3). Both leaf P and K concentration were significantly increased in fertilized monoculture with no associated biomass change, signifying luxury consumption of these nutrients. Higher tissue nutrient content presumably reflects sufficient nutrient availability and low intraspecific competition. Furthermore, the site may be nutrient sufficient since fertilizer addition did not result in detectable accumulation in soil nutrient pools 1 year after application (Table 4). However, the dose rate was modest, and further research with augmented fertilizer application is recommended. Again, even though cocoa nutrient requirements were met with enrichment, no biomass response ensued. This absent response may be a result of non-optimal light regulation in monoculture, where excessive exposure to solar radiation may inhibit cocoa growth (Okali and Owusu 1975; Galyuon et al. 1996).

Shading effect on cocoa

The addition of artificial shade in the absence of shade trees induced the most positive growth and nutritional response in cocoa, indicating that with minimal below ground competition, light regulation is an important mechanism in cocoa growth (Table 2). Without fertilization, P uptake in foliage was stimulated most (112%) followed by K (71%), and then N (42%; Table 3; Fig. 3). Concentration levels of N, P and K in foliage remained relatively constant with increasing growth, indicating sufficiency of these nutrients (Table 3). Soil nutrient pools were unchanged, also reflecting sufficiency.

Cocoa biomass was not enhanced under *N. laevis* shade despite optimal light conditions, approximately 20% shade (Okali and Owusu 1975; Galyuon et al. 1996) which suggests that lack of growth response is associated with interspecific competition for belowground resources (Vandermeer 1989). Under *T. superba*, light availability was low (approximately 50%), similar to light levels created under artificial shade. However biomass production was not increased, reflecting strong interspecific competition for other resources, such as nutrients.

Shade and nutrient interaction

Our results are consistent with previous hypothesis that once nutrient demands are met, light is the next most important resource, particularly, regulation of light. Artificial shade and fertilization revealed stimulated P uptake in foliage (175%), followed by K (69%), and then N (54%) with fertilization (Table 3; Fig. 3) as compared to unfertilized monoculture cocoa. Phosphorus concentration in fertilized cocoa under artificial shade was significantly increased with the extra growth, indicating an enrichment response to limitations of this nutrient (Table 3; Fig. 3). In general, artificial shade stimulated growth and nutrient uptake, both with and without external enrichment. Apparently, possible nutrient demands from accelerated growth were compensated for by greater allocation to root production (Tables 1 and 2), expanding the soil nutrient acquisition zone (Vandermeer 1989; Schroth et al. 2001). Evidently, cocoa growth under regulated light conditions and minimal competition resulted in an efficient allocation of resources.

Fertilization did not affect nutrient content in cocoa under intercropping, suggesting two possible explanations: (1) the site was nutrient sufficient hence the effect of nutrient addition was minimal and/or (2) fertilization augmented growth of shade trees thus increasing potential of interspecific nutrient competition. Nutrient addition stimulated shade tree growth, increasing *N. laevis* height by 37% and *T. superba* height by 10%. Apparently, this response augmented shade tree competition with cocoa saplings, suppressing nutrient uptake even with nutrient addition. Fertilization also suppressed K uptake in cocoa under *N. laevis*, presumably due to dilution of this nutrient, which was not compensated by addition of K (Table 3; Fig. 3).

It was expected to find higher decomposition rates under fertilization due to superior litter quality (Vanlauwe et al. 1996), however in our study, little difference was measured in cocoa foliar N concentration (Table 3) signifying comparable tissue attributes such as C/N. This suggests minimal contribution from varying litter quality to overall decomposition rates. Interestingly, decomposition rates under intercropped cocoa in comparison to rates under the unfertilized monoculture were slower (Fig. 1). Presumably, well-developed shade tree crowns (Groulez and Wood 1985; Amanor 1994) reduced light infiltration to the cocoa stratum, altering both temperature and moisture

conditions at the soil surface. Furthermore, the addition of mixed litter (cocoa and shade leaves) on the soil surface influenced soil microbial populations (Anderson and Swift 1983; Seneviratne 2000). Slower decay rates under intercropping in the long term may provide a source of sustained nutrient supply to the cocoa saplings (Seneviratne 2000).

Supply of N via mineralization was also suppressed under intercropping (Fig. 2). Similar to decay conditions, shade trees contribute a supplementary source of leaf litter. Consequently, litter from *T. superba* and *N. laevis* may have induced short-term immobilization of N in the topsoil due to high demands for N sources (Montagnini et al. 2000). Although net production of inorganic N is important as a source of plant useable N, there is a high probability that this mobile nutrient will be leached down the soil profile, rendering it inaccessible for crop uptake (Schroth et al. 2001; van Noordwijk and Cadisch 2002). In the long-term, however, it is expected that under intercropping, slower decomposition and subsequent accumulation of organic material may in fact result in a greater supply of readily mineralizable material later.

Conclusions

Although intercropping with shade trees failed to increase cocoa biomass, nutrient uptake was increased by the presence of shade trees, suggesting minimal interspecific competition for resources. Our study revealed augmented N and P nutritional status of the cocoa sapling under *N. laevis* where complementarity between species resulted in enhanced nutrition of the desired crop (Jose et al. 2004). In early growth, cocoa requires optimal levels of shading to promote increased biomass, and therefore, high probability of increased pod production. Although our study exhibited enhanced biomass and nutrition under artificial shade, on-farm shade construction is economically prohibitive and labor intensive for most cocoa farmers. However, appropriate shading can be provided by intercropped shade trees. Species selection appears critical during this early stage of cocoa establishment: large, fast growing species, although economically valuable, are ecologically undesirable as cocoa does not have a competitive advantage. When fertilizers are undesirable or unavailable, the presence of appropriately selected shade trees will not competitively suppress cocoa biomass production but will provide light regulation and improved nutritional status of cocoa saplings.

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