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Productivity of *Theobroma cacao* agroforestry systems with timber or legume service shade trees

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Abstract Timber production and cocoa yields were studied (initial 10–11 years) in two experimental plantations: a Cocoa-Legume system (CL, *Erythrina poeppigiana*, *Gliricidia sepium* or *Inga edulis*), and a Cocoa-Timber system (CT, *Cordia alliodora*, *Tabebuia rosea* or *Terminalia ivorensis,* plus *I. edulis* for inter-site comparisons). These trials had two major goals: (1) to evaluate the use of mono-specific timber shade canopies as an alternative to traditional, mono-specific, legume service shade tree canopies; and (2) to determine the production potential of ten cocoa clonal bi-crosses under these shade tree species. Within each site, shade tree species did not influence dry cocoa bean yield nor pod counts (total number of pods produced, number of healthy pods harvested, pod losses due to monilia [*Moniliophthora roreri*], black pod [*Phytophthora palmivora*] or other causes—birds and squirrels in this study-, and total pod losses). Significant differences were found between cocoa bi-crosses for both cocoa bean yield and pod counts. Sites differed only in terms of total pod losses (43% in CL; 54% in CT) and their causal factors (mainly monilia in CL; both monilia, squirrels and birds in CT). At CT, all timber tree species grew rapidly, reaching 30–34 cm dbh, 17–25 m total tree height and 97–172 m^3 ha^{-1} total stem volume (age 10 years). Timber species should be promoted for the shade component of cacao plantations given their potential production and the fact that their presence did not negatively affect cocoa yields.

Keywords *Erythrina poeppigiana* · *Gliricidia sepium* · *Inga edulis* · *Cordia alliodora* · *Tabebuia rosea* · *Terminalia ivorensis* · Cocoa yields · Cocoa bi-crosses · Pod index · *Moniliophthora roreri* · Squirrels · Tree growth · Costa Rica · Panama

Introduction

Cocoa (*Theobroma cacao*) is usually grown under shade, in agroforestry systems with numerous companion trees and other perennial and annual crops. Shade trees: (1) modify the light regime (in both quality and quantity), air temperature, humidity and wind movement within the plantation, directly affecting photosynthesis, growth and yield of cocoa (de Almeida and Valle 2007; Zuidema et al. 2005); (2) favour or hamper the population dynamics and incidence of pests and diseases (and of their natural enemies) that reduce yields of both cocoa and its companion species (Schroth et al. 2000); (3) produce significant quantities of organic matter, recycle

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nutrients and help to maintain the natural fertility of the site (Hartemink 2005), of utmost importance since most cocoa plantations are not fertilized; and (4) produce goods (wood, firewood, fruits, resins, medicinal products, etc.) and services (cultural and aesthetic values; conservation of biodiversity, soil and water; sequestration of atmospheric carbon and mitigation of climate change; etc.) for both households and global society (Bentley et al. 2004; Rice and Greenberg 2000; Ruf and Schroth 2004; Schroth and Harvey 2007). A worldwide bibliographic data base on the relationships between cocoa, shade trees, forests and the environment is available at http://biblioteca.catie.ac.cr/inaforesta.

The diversity, botanical composition and structural complexity of cocoa shade canopies vary widely between cocoa growing regions, between farms within a region, and even between sections within a plantation. Some cocoa shade canopies are species-rich and structurally complex, with several vertical strata and diverse spatial and temporal configurations (Ameyaw-Oduro et al. 2005; Asare 2005; Bentley et al. 2004; Bobo et al. 2006; Hervé and Vidal 2008; Salgado-Mora et al. 2007; Sambuichi 2002; Somarriba and Harvey 2003; Sonwa et al. 2007). However, most cocoa shade canopies are structurally very simple with only one shade strata, usually dominated by one "service" (minimal or no commercial products) tree legume species. Rice and Greenberg (2000) properly named these the "back bone" species of the shade canopy; most backbone species, used in cocoa worldwide, belong to the genus *Inga*, *Gliricidia*, *Erythrina, Albizzia* and *Leucaena*.

The use of mono-specific, timber shade tree canopies is rare in cocoa cultivation. Timber trees in cocoa shade canopies are either remnants of the original forest or recruits from natural regeneration. Timber trees occur at low population densities in cocoa plots (Asare 2005; Beer et al. 1998; Bobo et al. 2006; Chalmers 1971; Duguma et al. 2001; Lim 1978; Orozco et al. 2008; Rolim and Chiarello 2004; Somarriba 2007; Somarriba et al. 2008a, b, Suárez and Somarriba 2002; Suatunce et al. 2003). However, at certain locations, one or a few timber species regenerate profusely, reaching high planting densities and serving as the back-bone species of the cocoa plantation. Notorious examples in Latin America include the complex *Tabebuia neochrysanta—Triplaris cumingiana—Schizolobium parahyba—Cordia alliodora* in coastal Ecuador (Bentley et al. 2004; Mussak and Laarman 1989) and *Cordia alliodora* in Costa Rica and Panamá (Suárez and Somarriba 2002; Somarriba and Harvey 2003). Sometimes a few highly valued timber species (for instance, *Swietenia* spp. or *Cedrela odorata*) are purposely planted to provide both shade to the cocoa and timber for the household (Chalmers 1971; Isaac et al. 2007; Lim 1978; Melo 1999; Méndez 1999; Orozco et al. 2008; Sanchez et al. 2002).

Lumber harvested from cocoa shade canopies help to: (1) satisfy the construction needs of the household and cope with un-expected family needs (timber trees as a saving account, a safenet); (2) generate additional income, crucial at times of low cocoa prices or when new diseases strike cocoa; reduce financial risk; and (3) increase the value of the land (Beer et al. 1998; Navarro and Bermúdez-Cruz 2009; Orozco et al. 2008; Ramírez et al. 2001). In Costa Rica, damage to the cocoa crop due to the felling of *Cordia alliodora* has been shown to be of little economic importance (Ryan et al. 2009). Cocoa is also commonly cultivated in association with other perennial tree crops, such as rubber (*Hevea brasiliensis*), coconuts (*Cocos nucifera*), oil palm (*Elaeis guianeensis*), kola (*Cola nitida*), mango (*Manguifera indica*), cashews (*Anacardium occidentale*), avocado (*Persea americana*), breadfruit (*Artocarpus communis*), arecanut (*Areca catechu*), peach palm (*Bactris gasipaes*), *Citrus* spp. and other valuable species (de Almeida et al. 2006; Cotta et al. 2006; Ekenade and Egbe 1990; Famaye et al. 2005; Herzog 1994; Kolade 1986; Ofori-Frimpong et al. 2005; Oladokun 1990; Oladokun and Egbe 1990; Osei-Bonsu et al. 2002, 2005).

Two basic cocoa shade management models can be identified: (1) cocoa under "service" legume shade trees; and (2) cocoa under "productive" shade tree crops (timber or perennial tree crop species). In model one, the legume trees are spaced, pruned and thinned according to (only) the needs of the cocoa. In model two, both the companion tree crop and the cocoa provide valuable products and plot management must simultaneously satisfy the growth and yield requirements of all productive components of the system. For instance, timber species shall not be pruned or thinned considering only the light regime needed by the cocoa, but also to ensure that: (1) only the best formed and fastest growing trees are kept for future harvest; and (2) a significant number of timber or fruit trees are retained in the plot to reach the output goal for these components set by the land manager, which may result in some over shading and sub-optimal cocoa yields.

In this study, the bean yield and pod counts of hybrid cocoa stands, and the growth of timber (when appropriate), were evaluated at two experimental sites: a Cocoa-Legume (CL) site and a Cocoa-Timber (CT) site. The trials had two major goals: (1) to evaluate the use of mono-specific timber shade canopies as an alternative to the traditional, mono-specific, legume, service shade tree canopies; and (2) to determine the production potential of different cocoa clonal bi-crosses under various shade tree species.

Methods

The CL trial, established in October 1988 on a small, privately owned farm in Margarita, Talamanca, Costa Rica (9° 36′ N, 82° 45′ W) with three main plot treatments (legume shade tree species: *Erythrina poeppigiana*, *Gliricidia sepium* or *Inga edulis*), six sub-treatments (cocoa clonal bi-crosses) and three replicates (blocks), was evaluated until stand age 11 years (first 8 years of cocoa production). The CT trial, established in December 1989 in a small, privately owned farm in Ojo de Agua, Changuinola, Panama (9° 18′ N, 82° 28′ W) with four main plot treatments (three timber shade tree species: *Cordia alliodora*, *Tabebuia rosea* and *Terminalia ivorensis*; and one legume species, *I. edulis*, as the local farmers' control), six sub-treatments (cocoa bi-crosses) and four replicates (blocks), was evaluated until stand age 10 years (first 7 years of cocoa production). Both trials used a split-plot experimental design. *I. edulis* and two cocoa bi-crosses (CatongoxPound12 and UF676xIMC67) were planted at both CL and CT to allow for comparisons between sites. Both sites were managed by researchers in agreement with the farmer and monitored until March 1999. These two sites were the survivors of a larger, 8 ha network of research trials which included two additional CL sites and one more CT site (Somarriba et al. 2001a; Somarriba et al. 1996a). An earthquake, flooding and the sale of one farm destroyed three research sites between 1989 and 1997.

Each shade species was managed differentially (frequency, intensity and timing of thinning and pruning regimes) to satisfy the needs of the cocoa (and timber stands when present). Tree management aimed at creating a micro-environment unfavourable to monilia (*Moniliophthora roreri*, the main disease problem in the region) and to satisfy the light regime needed by a fully stocked (1111 trees/ha), hybrid cocoa stand with good crop husbandry (Somarriba et al. 1996b, 1997). Different sequences of intercropping with annual and other short term crops, planted as temporary shade for cocoa, were used in each site according to local markets and farmer preferences. Detailed descriptions of plot and tree management (both cocoa and shade tree species) and an analysis of the financial performance of these agroforestry systems are presented elsewhere (Beer 1991; Calvo and Somarriba 1998; Somarriba and Beer 1994, 1999; Somarriba et al. 1996a, b, 1997; 2001a; Trejos and von Platen 1995). These documents can be downloaded from http://biblioteca.catie.ac.cr/inaforesta.

Permanent shade tree management involved three phases (establishment, canopy development, canopy maintenance), each with different sets of activities according to the growth habits of each species. For instance, low forking/lateral branches of *I. edulis* had to be pruned regularly for the first 3 years of age, and in order to obtain single stemmed *G. sepium,* obtained from seeds rather than rooted stakes, basal shoots had to be removed quarterly during the first 1.5 years. All legume trees were managed to develop a single stem, clean of branches up to 8 m above the ground, with the crown developed between 8 and 15 m height, thus creating an "empty volume" between the top of the cocoa canopy (4–5 m height) and the base of the shade tree crowns (8 m) to increase aeration inside the plantation and create unfavourable microclimatic conditions for monilia and black pod (*Phythophthora palmivora*). Shade levels were adjusted (pruning and/or thinning) both annually (to compensate for increasing self-shading as the cocoa trees grow older and bigger) and monthly (to cope with local phenological and agronomic rhythms).

Legume trees were thinned systematically seeking spatially homogeneous canopy cover while timber trees were thinned selectively, removing diseased or slow growing trees and providing the growing space of the future harvest trees. Natural mortality rates, foliage characteristics and branching patterns of all tree species were considered; for instance, 50% systematic thinning of *I. edulis* and *E. poeppigiana* at age 5 years compared to 25% thinning of *G. sepium* (sparser crowns) at age 8 years. All timber species were thinned at age 5 years but with different intensities: 14% of the *Terminalia ivorensis* (since it had the highest natural mortality rate,), 24% of *C. alliodora* and 26% of *Tabebuia rosea*. Residual population densities (initial density 278 trees ha^{-1} for all shade tree species) after thinning of *Terminalia ivorensis*, *C. alliodora* and *Tabebuia rosea* were 170 ± 12, 179 ± 6 and 177 ± 8, respectively. These thinning criteria and regimes increase stand quality (for lumber) but may fail to ensure that the cocoa receives spatially homogeneous shade.

Main plots were 36 × 36 m (1296 m^2) in both CL and CT. Each main plot included (initially): (1) 36 shade trees (16 central trees for measurements and 20 border trees) planted at 6 × 6 m (278 trees ha^{-1}); and (2) 100 cocoa trees (36 for measurements and 64 in borders) planted at 3 × 3 m (1111 trees ha^{-1}). Cocoa stands in CL were mixtures of six cocoa clonal bi-crosses: Pound7xUF668, UF613xPound12, UF676xIMC67, UF29xUF613, CatongoxPound12 and UF613xIMC67. Cocoa stands in CT were mixtures of CatongoxPound12, UF12xPound7, UF296xCC18, UF668xPound7, UF613xUF29 and UF676xIMC67. Each bi-cross was represented by six randomly mixed trees per plot. CatongoxPound12 and UF676xIMC67 under *I. edulis* were planted at both sites to enable comparisons between sites in terms of cocoa bean yield and pod counts (total number of pods produced, number of healthy pods harvested, pod losses due to monilia, black pod or other causes –squirrels and birds (S&B), total pod losses). Cocoa bi-crosses used in CT and CL were selected (based on availability from nurseries) from a list of 40 bi-crosses produced and commercially distributed in Central America (crosses between high yielding, Trinitario and Forastero clones) at the time of the experiment.

Cocoa bean yield and pod counts were evaluated fortnightly for most of the harvest seasons, but adjusted to weakly harvests during peak periods and to every 3–4 weeks in periods of low production; data per plot was collected for 8 years (1991–1999) at CL and for 7 years (1992–1999) at CT. Data on a per tree basis (to enable comparisons between cocoa bi-crosses) was collected for the first 4 years of production in CL (1991–1995) and 3 years in CT (1992–1995). At both sites, pod production started at plantation age 2.5 years. Cocoa bean yield (dry cocoa bean weight) was estimated as 40% of fresh bean weight. Pod losses (total and separated by causal factors) were expressed as percentages of the total number of pods produced.

Two data sets (per plant and per main plot) were subjected to ANOVA for all variables measured (cocoa bean yield, pod counts and tree mortality (cumulative tree mortality evaluated at age 5 years); percentage data were arcsin-square root transformed for analysis), using a split-plot, complete randomized block design. Means were compared with the Duncan test. The effects of shade species and experimental blocks on cocoa bean yield and pod counts (per plot data) were analyzed using the following generalized linear model (SAS 1987); the analysis is nested within each site:

$$\mathrm{Y} = \mu + \mathrm{block(site)} + \mathrm{shade(site)} + \varepsilon$$

where Y = dry cocoa bean yield, pod count variables (total pods, healthy pods, losses to monilia, losses to black pod, losses to squirrels and birds (S&B), percent total pod losses) or tree mortality for the whole study period; μ is the general mean of the experiment; and ε is the experimental error.

The effect of bi-crosses on dry bean yield and pod counts was evaluated using per plant data and the generalized linear model below. Means were compared with the Duncan test.

$$\begin{aligned}\mathrm{Y} = \mu &+ \mathrm{bicross(site)} + \mathrm{bicross} * \mathrm{block(site)} \\ &+ \mathrm{bicross} * \mathrm{shade(site)} + \varepsilon\end{aligned}$$

Differences between sites (using cocoa bean yield and pod count data for only UF676xIMC67 and CatongoxPound12 under *I. edulis*) were determined by a one-way ANOVA; means were compared using Tukey. The following generalized linear model was used to evaluate these effects:

$$\mathrm{Y} = \mu + \mathrm{site} + \mathrm{bicross} + \mathrm{bicross} * \mathrm{site} + \varepsilon$$

The frequency distribution of cocoa bean yield per plant at each site (average of 4 years of production data for 324 cocoa trees in CL and average of 3 years of data for 576 trees in CT) was inspected using 500 g yield classes. Differences in the frequency distribution of cocoa trees per yield class between sites and cocoa bi-crosses were compared by chisquare, ANOVA and Duncan. ANOVA was used to determine whether pod losses correlated with yield levels of individual cocoa plants.

Stem diameter at breast height (dbh) and total tree height (h) of timber trees (in CT only) were determined twice per year until age 2 and then annually until age 10 years. Tree dbh and h data for timber trees were used to estimate total over-bark stem volume (V) using the following tree form factors: 0.425 for *C. alliodora* (Somarriba and Beer 1987), 0.375 for *Tabebuia rosea* and 0.475 for *Terminalia ivorensis*. Tree form factors for *Tabebuia rosea* and *Terminalia ivorensis* were derived from trees ($n = 20$ per species) thinned or harvested in the study region (unpublished data).

Results

Cocoa yield and pod counts varied widely between years, with a bumper harvest in 1995–1996 (that affected both sites despite the 1 year difference in plantation age) and a drastic decline after inorganic fertilization was stopped in 1996. Cocoa was harvested throughout the year, with two distinct peaks (major October–January; minor March–June); cocoa production was minimal in August at both sites. Pod index (number of healthy pods needed to produce one kg of dry cocoa beans) was 18.6 in CL and 17.3 in CT.

Within site comparisons

Cocoa bean yield and pod counts (all variables) did not differ between shade tree species treatments at both CL and CT. Significant differences were detected between experimental blocks in terms of nearly all pod count variables; however cocoa bean yield did not differ significantly between blocks (Table 1a, b). Average cocoa bean yield per shade species varied between 802 and 903 kg ha^{-1} y^{-1} in CL and between 669 and 767 kg ha^{-1} y^{-1} in CT. Total pod losses averaged 43% in CL and 54% in CT. Monilia was responsible for 87% of all pod losses in CL whereas in CT losses were due to both monilia (49%) and S&B (42%) (Table 2). Pod losses by causal factor was statistically similar between blocks, but may differ up to 21% as in the case of monilia in CT.

At each site, cocoa bi-crosses differed significantly in bean yield due to differences in the total number of pods produced. Neither shade species nor experimental blocks influenced bean yields or total pod losses of the cocoa bi-crosses, but significant interactions between bi-crosses × blocks were detected for the total number of pods produced (Table 3a). Average annual cocoa yield per bi-cross varied between 698 and 1200 kg ha^{-1} y^{-1} in CL and between 664 and 1048 kg ha^{-1} y^{-1} in CT. The best bi-crosses (>900 kg ha^{-1} y^{-1}) were Pound7xUF668, UF613xPound12 y UF676xIMC67 in CL and UF12xPound7 in CT (Table 3b).

Cocoa yield per plant varied between 0 and 2.97 kg tree^{-1} y^{-1}. On average, 75% of all cocoa trees yielded $\leq$1 kg tree^{-1} y^{-1} of dry cocoa beans, a yield target aimed at by most cocoa agronomists (Table 4). Yield per plant frequency distributions were similar in both sites.

Between site comparisons

Cocoa bean yield, total pods produced, healthy pods harvested and pods lost to black pod for UF676xIMC67 and CatongoxPound12 under *I. edulis* did not differ between sites (Table 5a–c). Significant differences between CL and CT were detected only in terms of total pod losses (between 27–42% in CL and 51–55% in CT) and in the level of losses caused by S&B (between 33–44% in CT and 6–9% in CL). UF676xIMC67 suffered similar total pod losses at both sites (42–55%); for CatongoxPound12, losses varied more widely between sites (27–51%).

Shade trees: mortality and tree growth

Overall shade tree mortality was 17% in CL and 32% in CT (Table 6). At each site, shade species mortality varied widely between blocks and was not homogeneous within some blocks due to small variations in soil drainage (in both CL and CT) or exposure to winds (CT). Natural mortality of *Terminalia ivorensis* was 68% compared to only 9–10% for *E. poeppigiana* and *Tabebuia rosea* (Fig. 1). Mortality of *I. edulis* in CL was nearly double the mortality of this species in CT. However, the means were not statistically different due to the large between-block variability (Table 6). All timber tree species grew very rapidly, reaching 30–34 cm in dbh, 17–25 m in

Table 1 Effect of shade species and experimental blocks ($p > F$) on cocoa (*Theobroma cacao*) yield (dry beans; kg ha^{-1} y^{-1}) and pod counts (pods ha^{-1} y^{-1} for total, healthy ripe harvested and damaged by monilia (*Moniliophthora roreri*), black pod (*Phytophthora palmivora*), squirrels/birds, and total pod losses) in cocoa plantations under the shade of legume (CL) or timber (CT) tree species

(a) Statistics

Variable	Source of variation		
	Model	Block (site)	Species (site)
Bean yield	0.4256	0.1937	0.8597
Total pods	0.0812	0.0741	0.1577
Healthy pods	0.0790	0.0266	0.5765
Monilia loss	0.0020	0.0004	0.4372
Black pod loss	0.0201	0.0061	0.3682
Squirrels/birds loss	0.0002	0.0001	0.3880
Total losses (%)	0.0032	0.0004	0.9319

(b) Means

Site	Species	Variables			
		Bean yield	Total pods	Healthy pods	Total losses (%)
CL	ERYPOE	802 ± 38	26868 ± 4314	15094 ± 1176	0.43 ± 0.06
CL	GLISEP	903 ± 240	30723 ± 1823	17369 ± 2985	0.44 ± 0.06
CL	INGEDU	829 ± 58	25851 ± 3664	14698 ± 1431	0.43 ± 0.05
Mean		845	27814	15720	0.43
CT	CORALL	721 ± 116	27022 ± 3180	12485 ± 2301	0.52 ± 0.10
CT	INGEDU	767 ± 144	27858 ± 4431	12952 ± 2933	0.53 ± 0.09
CT	TABROS	727 ± 163	27453 ± 5030	12047 ± 2471	0.56 ± 0.06
CT	TERIVO	669 ± 135	23415 ± 2333	11115 ± 2157	0.53 ± 0.07
Mean		721	26437	12450	0.54

GLISEP = *Gliricidia sepium*, INGEDU = *Inga edulis*, ERYPOE = *Erythrina poeppigiana*, CORALL = *Cordia alliodora*, TABROS = *Tabebuia rosea*, TERIVO = *Terminalia ivorensis*. (Mean ± SD). Eight years harvest data in CL (1991–1999); seven years in CT (1992–1999)

Table 2 Pod losses due to monilia (*Moniliophthora roreri*), black pod (*Phytophthora palmivora*) and squirrels/birds (S&B) in cocoa (*Theobroma cacao*) plantations under the shade of legume (CL) or timber (CT) tree species

Site	Block	Source of losses (%)		
		Monilia	Black pod	S&B
CL	1	88	5	7
CL	2	89	5	6
CL	3	85	6	9
Means	–	87	5	8
CT	1	39	9	52
CT	2	46	10	44
CT	3	51	8	41
CT	4	60	7	33
Means	–	49	9	42

h and 97–172 m^3 ha^{-1} in V at age 10 years (Table 7). *Terminalia ivorensis* accumulated the highest volume of timber despite its high mortality rate. Mean dbh increment peaked (5–8 cm y^{-1}) at ages 2–3 years; mean h increments were 2–4 m y^{-1} up to age 5, and then 1.5–2.5 m y^{-1} between ages 6–10 years.

Discussion

The management of the cocoa and shade tree species in all treatments was guided by the following goals/rules: (1) to provide good growth and production conditions for the cocoa; (2) retain as many high quality timber trees per plot as possible for lumber

Table 3 (a) Effects of cocoa (*Theobroma cacao*) bi-crosses ($p > F$) on cocoa yields and pod counts (total, healthy, percent loss) at each site. (b) Cocoa (*Theobroma cacao*) yield and pod counts (total, healthy, total losses (%)) by cocoa bi-clonal crosses under the shade of legume (CL) or timber (CT) tree species. CL: harvest data 1991–1995; CT: 1992–1995. Mean ± SD

(a)

Variable	Source of variation			
	Model	Bi-cross(Site)	Bi-cross * Block(Site)	Cross * Shade(Site)
Yield	0.0022	0.0001	0.1171	0.5522
Total pods	0.0001	0.0001	0.0291	0.2240
Healthy pods	0.0176	0.0001	0.0723	0.7378
Total losses (%)	0.0001	0.0001	0.0703	0.8175

(b)

Site	Bi-cross	Bean weight (kg ha^{-1} $año^{-1}$)	Total pods (pods ha^{-1} y^{-1})	Healthy pods (pods ha^{-1} y^{-1})	Total losses (%)
CL	Pound7xUF668	1200 ± 288 b	30829 ± 4541 ab	20953 ± 4110 b	0.32 ± 0.06 a
CL	UF613xPound12	1112 ± 205 ab	35406 ± 10386 b	20912 ± 4691 ab	0.39 ± 0.13 a
CL	UF676xIMC67	917 ± 328 a	26035 ± 7963 a	16489 ± 5149 a	0.37 ± 0.07 a
CL	UF29xUF613	726 ± 383 a	21833 ± 9731 a	14797 ± 7418 a	0.33 ± 0.08 a
CL	CatongoxPound12	723 ± 262 a	22471 ± 7449 a	15409 ± 4939 a	0.30 ± 0.08 a
CL	UF613xIMC67	698 ± 289 a	22013 ± 8490 a	13552 ± 6002 a	0.38 ± 0.09 a
CT	UF12xPound7	1048 ± 275 b	37163 ± 11927 b	17061 ± 4626 b	0.52 ± 0.11 a
CT	UF613xUF29	826 ± 159 ab	48974 ± 8969 c	14739 ± 3126 ab	0.69 ± 0.07 b
CT	UF613xPound7	805 ± 290 a	32630 ± 12155 ab	14076 ± 5234 a	0.56 ± 0.10 a
CT	UF29xCC18	686 ± 230 a	30424 ± 10890 a	13076 ± 4722 a	0.56 ± 0.08 a
CT	CatongoxPound12	665 ± 227 a	27484 ± 6806 a	13408 ± 4460 a	0.52 ± 0.10 a
CT	UF676xIMC67	664 ± 250 a	28094 ± 14642 a	11803 ± 4615 a	0.56 ± 0.11 a

Table 4 Frequency distributions (%) of cocoa (*Theobroma cacao*) dry bean yield per plant (g $tree^{-1}$ y^{-1}) under legume (CL), timber (CT) shade tree species, and pooled data. CL: yield averages of 324 cocoa trees between 1991 and 1995; CT: yield averages of 576 cocoa trees between 1992 and 1995

Yield class (g $tree^{-1}$ y^{-1})	CL		CT		Pooled data	
	Frequency	Cummulative	Frequency	Cummulative	Frequency	Cummulative
0–500	31.17	31.17	34.72	34.72	33.44	33.44
501–1000	37.66	68.83	43.58	78.30	41.45	74.89
1001–1500	20.68	89.51	17.53	95.83	18.67	93.56
1501–2000	7.4	96.91	2.61	98.44	4.33	97.89
2001–2500	2.16	99.07	1.39	99.83	1.67	99.56
2501–3000	0.93	100.00	0.17	100.00	0.44	100.00

production; and (3) differentially manage each shade tree species (in terms of frequency, intensity and timing of thinning and pruning regimes) to satisfy the needs of both the cocoa and timber stands. The principal aim was to determine whether cocoa yields could be maintained under timber shade trees (compared to traditional “service” shade trees). This goal was achieved: cocoa bean yield, pod counts and both

Table 5 Cocoa (*Theobroma cacao*) dry bean yield (kg ha^{-1} y^{-1}), pod counts (pods ha^{-1} y^{-1}) and percent total pod losses for CatongoxPound12 and UF676xIMC67 under *Inga edulis* in Margarita, Talamanca, Costa Rica (CL site; harvests 1991–1995) and Ojo de Agua, Changuinola, Panama (CT site; harvests 1992–1995)

(a) Statistics ($p > F$)

Variables	Source of variation			
	Model	Site	Bi-cross	Bi-cross * Site
Yield	0.2241	0.3930	0.2084	0.6226
Total pods	0.3848	0.1868	0.2378	0.6094
Healthy pods	0.2290	0.4827	0.8400	0.3980
Monilia losses	0.0639	0.9364	0.2019	0.5504
Black pod losses	0.2033	0.0987	0.1380	0.1301
Squirrels/birds losses	0.0310	0.0015	0.1092	0.7866
Total losses (%)	0.0483	0.0093	0.2126	0.2252

(b) Means by site and bi-cross

Variable	Site		Bi-cross	
	CL	CT	CatongoxPound12	UF676xIMC67
Yield	690	611	593	708
Total pods	21338	26771	21871	26276
Healthy pods	13863	12521	13122	13261
Monilia losses	5500	5400	4528	6372
Black pod losses	732	1604	848	1459
Squirrels/birds losses	1280	7243	3371	5153
Total losses (%)	0.34	0.53	0.39	0.48

(c) Means site * bi-cross

Variable	CatongoxPound12		UF676xIMC67	
	CL	CT	CL	CT
Yield	655	531	725	690
Total pods	20135	23607	22619	29933
Healthy pods	14611	11634	13115	13408
Monilia losses	4196	4860	6804	5940
Black pod losses	801	894	603	2314
Squirrels/birds losses	524	6217	2036	8270
Total losses (%)	0.2742	0.5071	0.4178	0.5520

annual and monthly production rhythms were not affected by the shade species, suggesting that timber species are a better option to shade cocoa than the traditional service legume species. Similar recommendations have been given for various cocoa-timber-fruit combinations (Beer et al. 1990; Calvo and Somarriba 1998; Méndez 2005; von Platen 1993; Sanchez et al. 2002; Smiley and Kroschel 2009) and numerous mixed cropping systems with other tree crops (Afolami and Ajobo 1983; de Almeida et al. 2006; Cotta et al. 2006; Ekenade and Egbe 1990; Famaye et al. 2005; Herzog 1994; Kolade 1986; Obiri et al. 2007; Ofori-Frimpong et al. 2005; Oladokun 1990; Oladokun and Egbe 1990; Osei-Bonsu et al. 2002). It remains to be determined, however, whether in the long term a greater contribution of tree legumes to soil fertility would result in better cocoa yields than under non-legume, timber species. In Africa, exhausted soils due to the long term cultivation of cocoa without fertilizer applications must be fallowed

Table 6 Cummulative tree mortality (%) at age 8 years for GLISEP = *Gliricidia sepium*, INGEDU = *Inga edulis*, ERYPOE = *Erythrina poeppigiana*, CORALL = *Cordia alliodora*, TABROS = *Tabebuia rosea*, TERIVO = *Terminalia ivorensis* in Margarita, Talamanca, Costa Rica (CL site) and Ojo de agua, Changuinola, Panamá (CT site)

Block	CL (tree mortality %)				CT (tree mortality %)				
	ERYPOE	INGEDU	GLISEP	Mean	CORALL	INGEDU	TABROS	TERIVO	Mean
1	6	17	42	22	11	0	6	66	21
2	11	17	6	11	57	42	27	61	47
3	11	46	0	19	56	25	6	65	38
4	–	–	–	–	6	6	0	78	23
Mean	9	27	16	17	33	18	10	68	32

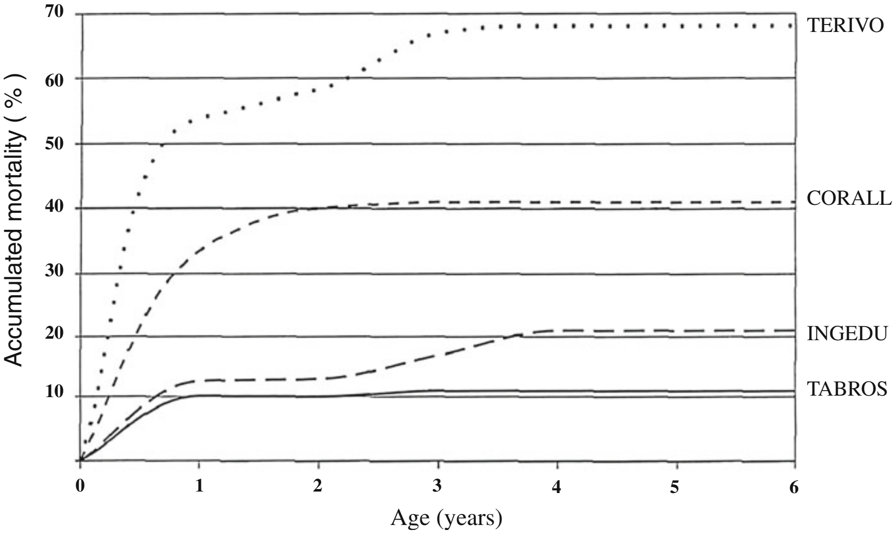

Fig. 1 Cummulative tree mortality (%) for CORALL = *Cordia alliodora*, TABROS = *Tabebuia rosea*, TERIVO = *Terminalia ivorensis*, INDEGU = *Inga edulis* in Ojo de Agua, Changuinola, Panamá (trees planted in1989)

or enriched with planted or volunteer nitrogen fixing tree legumes such as *Albizzia zygia* before they can be cultivated again (Anim-Kwapong 2003; Isaac et al. 2007).

Comparisons of the yields and pod losses recorded in this study with similar data from other sites/countries are limited because the studies differ in: (1) the list of cocoa bi-crosses or other types of cocoa genetic materials used; (2) pest and disease complexes (Adegbola 1981; Chandra-Mohanan and Kaveriappa 1981; Saunders 1981; Suárez-Capello 1981); and (3) site characteristics and crop management. For instance, in Ghana, the national yield average for the traditional Amelonado cocoa is 260 ± 80 kg ha^{-1} y^{-1}, whereas modern hybrids yield 500 ± 107 kg ha^{-1} y^{-1} (Edwin and Masters 2005). In Ivory Coast, the national average is 450 kg ha^{-1} y^{-1} under traditional management, while in Malaysia and Indonesia, well managed hybrid cocoa plantations yield 700–1000 kg ha^{-1} y^{-1} (Ruf 1993). In Cameroon, yields vary between 400 and 900 kg ha^{-1} y^{-1} depending on whether they are from laxly managed traditional plantations or well managed hybrid plantations (Kazianga and Masters 2006). While recognizing the limitations of comparisons, it is noteworthy that yields (669–903 kg ha^{-1} y^{-1}) and pod losses (43–54%) recorded in our study are similar to data from other hybrid cocoa plantations in Latin America (Mejía and Rondón 1981; Quirós 1992; Soberanis et al. 1999). For instance, in Northern Honduras, mixtures of bi-crosses, planted under the shade of *Inga* sp., *Cordia megalantha* or *Nephelium lappaceum* yielded 650–850 kg ha^{-1} y^{-1} (Sánchez et al. 2002). In Bocas del Toro, Panamá, a mixture of bi-crosses and grafted cocoa clones, intercropped with plantain (*Musa* AAB

Table 7 Stem diameter at breast height (dbh, cm), total tree height (h, m) and total overbark stem volume (V, m^3 ha^{-1}) for CORALL = *Cordia alliodora*, TABROS = *Tabebuia rosea*, TERIVO = *Terminalia ivorensis* in Ojo de Agua, Changuinola, Panamá (CT site)

Year	CORALL			TABROS			TERIVO		
	dbh	h	V	dbh	h	V	dbh	h	V
1990	3	2	0	4	4	0	5	2	1
1991	11	6	6	10	6	5	11	7	7
1992	16	10	25	14	8	13	17	10	26
1993	20	14	49	17	10	24	21	14	54
1994	22	17	80	21	12	42	24.5	18	88
1995	23.5/25[a]	19	81/77[a]	22/23[a]	12	43/36[a]	24.7/27[a]	20	101/89[a]
1996	27	21	96	25	14	54	30	20	107
1997	29	22	110	27	15	64	31	22	142
1998	29	23	121	29	16	75	33	24	155
1999	30	24	128	31	17	97	34	25	172

Trees planted in 1989

[a] After thinning

cv. Curraré) and a light shade canopy of 69 trees ha^{-1} of *C. alliodora*, yielded 400–650 kg ha^{-1} y^{-1} (Ramírez et al. 2001). In Turrialba, Costa Rica, cocoa plantations (mixture of two cocoa bi-crosses) under *E. poeppigiana* or *C. alliodora* yielded 700 kg ha^{-1} $año^{-1}$ (Beer et al. 1990), also demonstrating the potential to maintain cocoa yields when a timber species replaces a legume service tree. In Brazil and the Dominican Republic, un-shaded and fertilized (inorganic) hybrid cocoa plantations (mixtures of bi-crosses), without monilia or witches broom (*Moniliophthora perniciosa*), yield 800–1600 kg ha^{-1} y^{-1} (Domínguez 1984). Cocoa bean yields recorded in this study are comparable to other hybrid cocoa plantations worldwide.

Pod losses recorded in this study were strongly influenced by micro-site conditions such as the proximity to forest patches (habitats for squirrels and birds) and minor variations in soil drainage and exposure to winds (influencing tree mortality). Blocking did not evenly spread these effects on all species within the experimental block. Squirrels were an important pest in CT as they are in many other cocoa growing areas worldwide (Emamdie and Warren 1993; Warren and Emamdie 1993). Like other hybrid cocoa plantations worldwide, the bean yield per plant frequency distribution of the hybrid populations in this study, followed a 75:25 rule (i.e., 25% of the trees in the plot produce 75% of the yield (Lotodé and Lachenaud 1988; Paulin 1990). A similar 80:20 rule, known as the "Pareto law" is well known in business management (Reed 2001).

Cocoa producers in Talamanca, Costa Rica and Bocas del Toro, Panama could significantly increase cocoa bean yields by: (1) selecting and propagating the best bi-crosses and elite cocoa trees in their hybrid plantations; and (2) harvesting cocoa all year round and not only during the two annual harvest periods (20% of annual production occurs outside these peak periods). However higher cocoa yields will require more soil nutrients. Whether a particular cocoa farmer will add the extra nutrients needed for higher cocoa yields, is uncertain, but this decision may alter the current balance favouring timber over legume shade. More research on this is needed.

Timber growth was very fast in these experimental cocoa plantations. This was to be expected since the timber trees benefited from the moderate-high quality (agricultural) sites where cocoa is planted, good crop management (weeding, fertilization, etc.) and low tree planting densities. Tree growth recorded in our study is comparable to that recorded for cocoa timber shade trees on other sites (Anim-Kwapong 2003; Beer et al. 1998; Melo 1999; Méndez 1999; Orozco et al. 2008; Ramírez et al. 2001; Sanchez et al. 2002; Somarriba et al. 2001b, 2008a, b; Suárez and Somarriba 2002).

Conclusions

Differential management of shade tree species, aimed at providing good growth and yield conditions (microclimatic) for both cocoa and timber, resulted in similar cocoa yields under all shade tree species within a given site. Cocoa bean yield and pod counts were determined mainly by the genetic composition of the plantation. Farmers can increase cocoa bean yields by selecting the best cocoa bi-crosses and propagating (grafting) high yielding, elite trees from their farms. The best yielding bi-crosses in this study were: Pound7xUF668, UF613xPound12 and UF12xPound7.

The use of timber shade tree species seems preferable over the traditional service legume tree species. Timber trees grow very rapidly and provide farmers with a "saving account" that can be realized at times of low cocoa yields or prices or when unexpected family needs arise. In the study region, *C. alliodora* is recommended as shade for cocoa in sites with fertile, well drained soils. *Tabebuia rosea* is recommended for sites with minor to moderate soil drainage problems. *Terminalia ivorensis,* albeit producing the largest amount of timber in this study, is not recommended for Talamanca, Costa Rica or Bocas del Toro, Panama, due to its high mortality rate.

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