Agroforest Syst (2010) 78:97–114
DOI 10.1007/s10457-009-9259-1

Yield development and nutrient dynamics in cocoa-gliricidia agroforests of Central Sulawesi, Indonesia

G. L. Smiley · J. Kroschel

Received: 12 August 2008 / Accepted: 10 November 2009 / Published online: 11 December 2009

Abstract In the Napu and Palolo Valleys of Central Sulawesi, Indonesia, a chronosequence sought to identify the relationship between tree age, nutrient dynamics and cocoa (*Theobroma cacao* L.) yield in association with gliricidia (*Gliricidia sepium* (Jacq.) Steud.). The chronosequence surveyed cocoa-gliricidia plantations with a maximum age of 8 and 15 years, respectively, in Napu and Palolo. The characteristics of the valleys were also quite different, with an altitude of 1,139–1,166 m a.s.l. in Napu and 592–651 m a.s.l. in Palolo. Annual rainfall was 1,543 mm in Napu and 1,811 mm in Palolo. The yield of cocoa increased fairly steadily, with growth rates higher in Palolo than in Napu. Whereas a higher level of bean P led to a higher single bean weight (g d.w.) in Napu, a higher level of bean K led to a lower single bean weight in Palolo. The relatively high level of K appeared to have coincided with immature growth stages of cocoa. As trees matured, their increased rate of C assimilation was seen in the form of higher single bean weight. We found no statistically significant change in the soil's carbon-nutrient levels when viewed over the entire timeframe of 8 and 15 years in the 2 valleys. In addition, there was no correlation between the soil's carbon-nutrient levels and the single bean weight. Nor did we find any correlation between the soil's carbon-nutrient levels impacting the bean's carbon-nutrient levels. Of regression lines, P had the steepest slope and was considered the most limited nutrient relative to the other nutrients although its correlation was insignificant. The farmers' estimation of cocoa yield was about 68% less than our measured bean weight per area per year (kg d.w. ha^{-1} $year^{-1}$), implying a more refined definition of ripeness. In a cocoa agroforest, income could be supplemented by durable tree crops instead of growing gliricidia which is removed after several years of growth. This removal and the shallow rooting of cocoa indicate that the cocoa production would be sustainable only in the immediate future.

Keywords Export crops · Forest conversion · *Gliricidia sepium* · Plant–soil interactions · Resource transfer · *Theobroma cacao*

Introduction

Sustainability of a farming system is reflected by its appropriateness in the given economic and environmental circumstances. In the case of cocoa (*Theobroma cacao* L.), an important tree crop in

G. L. Smiley
Institute of Plant Production in the Tropics and
Subtropics, University of Hohenheim, 70593 Stuttgart,
Germany

J. Kroschel (✉)
Integrated Crop Management Division, Apartado 1558,
La Molina 12, Lima, Peru
e-mail: j.kroschel@cgiar.org

humid-moist zones, most (ca. 80%) is cultivated on farms having less than 5 hectare. Cocoa has not fared well in large-scale production under current macroeconomic conditions and incidence of diseases such as witches' broom (*Crinipellis perniciosa* (Stahel) Singer) (Lass 1999). With its origin as an understory shrub in lowland Amazonia, cocoa is a true shade loving species in its juvenile stages and in most areas it is virtually impossible to begin its cultivation without shade in the first 2–3 years (de Alvim 1977). Shade modifies the cocoa tree's microclimate and the reduced air movement allows less moisture loss or stress to the tree (de Alvim and Cabala-Rosand 1974). Shade can also stimulate foliage and root production (Isaac et al. 2007). Mature cocoa trees, provided that the nutrient and moisture levels are adequate, may not need shade. Although higher yields may be achieved without shade, a tree's productive life span can be shortened and/or the incidence of insect attacks may increase (Lass 1999).

Shade trees may provide substantial inputs of litterfall to the system. In associations of cocoa with shade trees in Costa Rica, 5,000–21,000 kg d.w. ha^{-1} $year^{-1}$ may be added to the system as litter (including pruning residues) but commonly this falls between 5,000 and 10,000 kg d.w. ha^{-1} $year^{-1}$ (Beer 1988). A key benefit of litter contributed by shade trees is that the soil organic matter (SOM) may increase as well as the cation exchange capacity and the soil carbon–nitrogen (C:N) ratio, which has been positively correlated to cocoa production (Beer 1988). In addition to the SOM, soil microorganisms decompose litter and roots transform these into CO_2 or CH_4. Shade trees may be N_2-fixing leguminous species that contribute to increase N availability in the cocoa plantations through litterfall, pruned biomass and roots decay and exudation (Beer 1988).

A key benefit of litterfall contributed by shade trees is that the SOM concentrations are positively correlated with the cation exchange capacity (CEC). A higher CEC may reduce the rate of nutrient leaching. Furthermore, high carbon–nitrogen (C:N) ratios (9.5–11.1) are positively related to cocoa production. Even where leguminous shade trees are used, N_2-fixation does not exceed 60 kg N ha^{-1} $year^{-1}$ (Beer 1988).

Due to its origin in the lowland rainforests of Amazonia, the cultivation of cocoa is generally constrained to a narrow belt 15°N and 15°S of the equator. Nearer the equator, the cultivation of cocoa is possible at higher elevations, such as in Columbia (1,000–1,200 m a.s.l.), Venezuela (900 m a.s.l.) and Uganda (1,100–1,300 m a.s.l.). The mean annual temperature of cocoa growing areas varies from 22.4°C in Pariquera-Acu, Brazil (24°45″S) to 26.7°C in Manaus, Brazil (3°08″S) (de Alvim 1977). In general, the mean maximum temperature varies between 30 and 32°C and the mean minimum temperature between 18 and 21°C, with an absolute minimum of 10°C (Lass 1999). The annual rainfall varies between 1,400 and 2,000 mm in most regions (de Alvim 1977) to 1,250–3,000 mm with a dry season lasting less than 3 months (Lass 1999). In the formation of yield, cocoa pods require about 5 months from pollination until ripeness, with favorable temperatures ranging from 18–21 to 30–32°C and rainfall around 1,250–3,000 mm $year^{-1}$ (Lass 1999). In traditional systems, the yield of cocoa without the application of fertilizers varied from 300–500 kg d.w. ha^{-1} $year^{-1}$ to a fertilized yield of 2,000–3,000 kg d.w. ha^{-1} $year^{-1}$ (de Alvim 1977). A fertilized and high yielding cultivar, without shade, obtained a record yield of 3,700 kg d.w. ha^{-1} $year^{-1}$ (Ahenkorah et al. 1974; cited in de Alvim 1977, pp 296). In Ghana, the yield of cocoa under coconut (*Cocos nucifera* L.) was 1,771–2,337 kg d.w. ha^{-1}; grown with gliricidia (*Gliricidia sepium* (Jacq.) Steud.), the yield of cocoa was only 614–807 kg d.w. ha^{-1} (Osei-Bonsu et al. 2002).

In Indonesia, the cultivation of cocoa commenced in 1560 and was concentrated in Java and parts of Sumatra. Around 1975, an expansion program greatly increased the area planted to cocoa with millions of hybrid seedlings distributed to farmers. The Upper Amazon Interclonal Hybrid was chosen for this endeavour. The output of cocoa in Indonesia rose from 16,000 t (1981–1982), 320,000 t (1996–1997) and 440,000 t (2002–2003) (ICCO 2003). Sulawesi in particular led Indonesia in becoming the third main cocoa producer after Côte d'Ivoire and Ghana (ICCO 2003).

The association of cocoa with the N_2-fixing leguminous species gliricidia is widespread along the forest margin of Lore Lindu National Park, Central Sulawesi, Indonesia. However, the process of resource transfer within this agroforestry arrangement has not been previously elicited in great detail in the literature and at best no determination of the system's sustainability has been made. This study sought to identify the general trends in cocoa production using a chronosequence and relate such performance to cocoa bean weight and the soil's carbon-nutrient levels. We wanted to know the status of nutrients in cocoa production, the conditions that enable the greatest yields and changes in plant–soil nutrients over time with and without gliricidia. In this study, a chronosequence is a comparison of cocoa-gliricidia agroforests of similar agroecological conditions though varying in age. Two valleys, Napu and Palolo, were the focus of study and contrast in elevation, rainfall and history of cocoa production. For example, the village of Sintuwu in Palolo Valley had ca. 72% of its paddy rice (*Oryza sativa* L.) fields converted to cocoa during 1992–1993. More than 60% of Sintuwu's land area was used for the production of cocoa (Sitorus 2002). Meanwhile, the village of Watumaeta in Napu Valley (about 3 km north of the village of Wuasa) began cocoa production in 1995 and had only 14% of land area planted to cocoa (Burkard 2002). While the average age of cocoa in Sintuwu was 10.8 years (with some cocoa trees 25 years old), the average age in Watumaeta was 2.9 years old. Another feature of the study was to survey cocoa production on soils with varying properties such as texture, density and nutrients levels. The objective was to quantify the development of cocoa yield and the related tree-soil carbon and nutrient levels with time in order to identify the resource most limiting to a sustained or increased cocoa yield. The study aimed at finding relationships between the age of an agroforest, nutrient levels and cocoa yield. However, although the 2 valleys are distinct in elevation and rainfall, we treated the 2 valleys as case studies and did not aim at a statistical comparison of the valleys. The hypothesis maintains that the existing cocoa production practice is sustainable from a nutrient-based perspective.

Materials and methods

Site location

From November to December 2002, 14 cocoa agroforests were selected along the eastern (Napu Valley) and northern (Palolo Valley) perimeter of Lore Lindu National Park, Central Sulawesi, Indonesia. Our study assumed that the cocoa grown in Central Sulawesi was the Upper Amazon Interclonal Hybrid variety. The agroforests had a constant density of 1,111 cocoa trees ha^{-1} or 3 × 3 m spacing, with the density of gliricidia reduced with time. Gliricidia were periodically trimmed or pollarded to reduce its competitiveness with cocoa for sunlight. No verifiable information was collected regarding the previous land use as the subject was contentious. Instead, a standard response in both valleys was that the land was secondary rainforest (and not National Park). After felling trees and burning the plant residue, farmers cleared the land and planted maize (*Zea mays* L.) and cocoa-gliricidia a few years later. Most of the cocoa-gliricidia plantations had all rainforest tree species removed as this action helped to claim land. We surveyed only cocoa-gliricidia and avoided sections that had mixed canopies with other tree species.

In Napu, 6 agroforests were surveyed in the villages of Wuasa and Kaduwaa (Table 1). The elevation of agroforests was 1,139–1,166 m a.s.l. During 2002, 1,543 mm rainfall was recorded in Wuasa with an average temperature of 21.1°C. In Wuasa, soils were sandy loams (1-year-old agroforest) or silty loams (3-year-old agroforest). In Kaduwaa, the soil in the 1.5-year-old agroforest was clay rich (0–15 cm layer), sandy clay (15–30 cm layer) and silty loam (>30 cm layer). The 4-year-old agroforest in Kaduwaa had a predominately silty soil. In Kaduwaa, the 5- and 8-year-old agroforests had either sandy or sandy loamy soils, respectively.

In Palolo Valley, the cocoa agroforests were aged 2–15 years after forest conversion. Two agroforests were located in Makmur, 3 in Nopu and 3 in Pangana (Table 2). The elevation of the agroforests was 592–651 m a.s.l. The village of Nopu received 1,811 mm during 2002 and had an average temperature of 24.5°C. The density of cocoa and gliricidia was an initial 1,111 trees ha^{-1}. In Palolo, the soils surveyed were loams or sandy loams.

Cocoa yield and carbon-nutrient levels

To assure randomization, a marked stick was thrown into the agroforest and from the point where it landed, the 4 closest cocoa trees in a square pattern (3 × 3 m

Table 1 Elevation, location, tree density and soil texture of agroforests in the Napu Valley, Central Sulawesi, Indonesia

Site	Elevation (m a.s.l.)	Location		Cocoa density	Gliricidia density	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	BD[a]
		South	East							
Wuasa 1 year	1,166	01 23.995	120 19.908	1,111	1,111	0–15	64	17	18	1.4
						15–30	64	20	16	1.6
						30–60	65	17	18	1.6[b]
						60–100	70	15	15	1.6[b]
Kaduwaa 1.5 years	1,144	01 27.400	120 18.430	1,111	1,111	0–15	18	13	69	–[c]
						15–30	57	2	41	–[c]
						30–60	32	52	16	–[c]
						60–100	35	52	13	–[c]
Wuasa 3 years	1,160	01 25.380	120 19.670	1,111	555	0–15	9	61	30	1.1
						15–30	9	64	27	1.2
						30–60	3	70	27	1.3[b]
						60–100	10	69	22	1.5[b]
Kaduwaa 4 years	1,139	01 27.400	120 18.430	1,111	555	0–15	21	63	16	1.4
						15–30	28	59	14	1.2
						30–60	32	51	17	1.2[b]
						60–100	14	41	45	1.3[b]
Kaduwaa 5 years	1,163	01 26.230	120 18.273	1,111	555	0–15	53	26	21	1.4
						15–30	58	26	16	1.5
						30–60	76	16	8	1.7[b]
						60–100	70	21	9	1.7[b]
Kaduwaa 8 years	1,163	01 26.230	120 18.273	1,111	370	0–15	53	24	22	1.2
						15–30	60	21	19	1.3
						30–60	70	18	11	1.5[b]
						60–100	82	12	6	1.7[b]

[a] Soil bulk density or g cm^{-3}

[b] Soil bulk density was sampled at increments of 0–15, 15–30, 30–45 and 45–60 cm

[c] No data available as large rocks prohibited the estimation of soil bulk density. Further calculations for the 1.5-year-old agroforest, Kaduwaa, assumed the bulk density values of its counterpart (4-year-old agroforest, Kaduwaa)

spacing) were chosen. From the 4 trees, 4 ripe cocoa pods were collected either from the same tree or any combination of the 4 trees. This was repeated three times for a total of 12 pods per agroforest. The beans were separated from the pericarp (husk), dried at 70°C for 72 h and weighed (bean weight per pod or g d.w. pod^{-1}). From each dried sample, 10 random beans were weighed (single bean weight or g d.w.) and the number of beans per pod (no. beans pod^{-1}) was determined. Beans were milled and analyzed for carbon-nutrient contents (C, N, P, K, Ca and Mg) by Inductively Coupled Plasma Spectroscopy (ICP-OES) after digestion of the samples with HNO_3 and H_2O_2 in a closed microwave digestion system (MLS 1200 Mega, MLS GmbH, Germany) at the Institute of Agricultural Chemistry, University of Hohenheim, Germany.

For a ‘present stand’ estimation of bean weight per area (kg d.w. ha^{-1}) and the number of pods per area (no. pods ha^{-1}), another marked stick was thrown into the agroforest and from that point, proceeding from row to row, the number of ripe pods (a pod with a husk that had already begun to change from green to yellow–orange) was counted on 45 cocoa trees. This procedure avoided tedious measurements of bean weight per area over a longer span of time such as 1 year. We also compared the bean weight per area measurement by querying farmers on the amount and

Table 2 Elevation, location, tree density and soil texture of agroforests in the Palolo Valley, Central Sulawesi, Indonesia

Site	Elevation (m a.s.l.)	Location		Cocoa density	Gliricidia density	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	BD[a]
		South	East							
Makmur 2 years	592	01 03.723	120 03.709	1,111	1,111	0–15	54	31	15	1.4
						15–30	57	24	18	1.4
						30–60	69	20	10	1.5[b]
						60–100	52	34	14	1.5[b]
Makmur 4 years	592	01 08.625	120 03.776	1,111	555	0–15	50	32	17	1.4
						15–30	50	30	19	1.4
						30–60	53	32	15	1.4[b]
						60–100	59	23	18	1.5[b]
Nopu 3 years	651	01 11.124	120 05.541	1,111	555	0–15	46	32	22	1.2
						15–30	42	39	19	1.2
						30–60	44	36	20	1.4[b]
						60–100	59	23	18	1.4[b]
Nopu 5 years	637	01 11.042	120 05.540	1,111	370	0–15	53	26	21	1.4
						15–30	48	29	23	1.1
						30–60	48	29	23	1.2[b]
						60–100	57	32	11	1.2[b]
Nopu 12 years	603	01 10.319	120 05.419	1,111	0	0–15	59	28	13	1.4
						15–30	57	26	17	1.4
						30–60	57	29	14	1.4[b]
						60–100	68	21	10	1.3[b]
Pangana 2.5 years	624	01 09.663	120 07.896	1,111	1,111	0–15	63	24	14	1.5
						15–30	62	23	15	1.4
						30–60	65	22	13	1.4[b]
						60–100	78	12	10	1.5[b]
Pangana 9 years	635	01 09.714	120 08.061	1,111	0	0–15	68	15	17	1.5
						15–30	67	17	16	1.4
						30–60	66	18	15	1.4[b]
						60–100	71	18	11	1.7[b]
Pangana 15 years	635	01 09.714	120 08.061	1,111	0	0–15	45	36	19	1.1
						15–30	44	33	23	1.3
						30–60	45	35	21	1.4[b]
						60–100	47	31	23	1.5[b]

[a] Soil bulk density or g cm^{-3}

[b] Soil bulk density was sampled at increments of 0–15, 15–30, 30–45 and 45–60 cm

frequency of cocoa harvests. The amount of carbon-nutrients exported was estimated by taking the farmers' estimation of bean weight per area (kg d.w. ha^{-1}) and multiplying this by the respective percentage of carbon or nutrient. The farmers' estimation of bean yield, harvested weekly, was multiplied by 36 weeks for a yearly value (kg d.w. ha^{-1} year^{-1}). The value of 36 weeks was preferred as 48 weeks yielded ca. 5,000 kg d.w. ha^{-1} year^{-1}. Moreover, 36 weeks allowed for some fluctuations in cocoa harvesting due to wet or dry seasons, labor peaks or holidays. An estimation of the number of days a farmers works was 230 days per year and the average labor usage of a farmer was 3.37 ha per year (ICCO 2003). Our measured yield was calculated by multiplying the bean weight per area (kg d.w. ha^{-1}) by 36 weeks for an estimate of bean weight per area per year (kg d.w. ha^{-1} year^{-1}).

Soil carbon-nutrient levels

A Pürckhauer soil corer of 2 cm diameter was hammered with a mallet 6–8 times per agroforest to the depths of 0–15, 15–30, 30–60 and 60–100 cm. Soil samples were homogenized per stratum and air dried. Part of the soil sample was sent to the Institut Pertanian Bogor, Indonesia, for the determination of texture. The soil bulk density was estimated with an 8 cm diameter root corer (Eijelkamp, the Netherlands) at increments of 0–15, 15–30, 30–45 and 45–60 cm. A root corer was used as the project did not have a proper tool for the measurement of bulk density of the deeper soil strata. From the core's interior, an intact section was separated and the rough upper and lower parts of the core were smoothed with a knife after which the length of the intact sample was measured. The weight of the core was measured in the field with an electronic scale, then oven-dried at 105°C for 72 h and weighed. From the radius, length and weight of each sample, the soil bulk density was calculated.

The chemical analysis of soils was conducted at the University of Hohenheim with the following methods: pH was measured with $CaCl_2$, C and N were determined by IR-absorption after combustion of the samples in a stream of oxygen (Vario EL, manufactured by Elementar, Germany). Soil P was measured with the P-Bray procedure. Mg was determined after extraction with 0.01 M $CaCl_2$ solution and measured by atomic absorption spectroscopy (AAS). Exchangeable cations were extracted with 1 M NH_4Cl solution and measured by ICP-OES (PerkinElmer Inc., USA). All farmers included in this survey used external inputs in the form of urea (N) and sometimes NPK though the amount and frequency of dressings were not accurately measured. Farmers did not know the amount of fertilizer used although they generally applied fertilizers twice a year. We did not assess the effect of gliricidia and the fixation of N, measure rates of pruning, or the production of organic matter on the status of cocoa-gliricidia agroforests.

Statistical analysis

Using SigmaStat ver. 3.0, data were subjected to Analysis of Variance (ANOVA) or Kruskal–Wallis ANOVA on Ranks with $P \leq 0.05$ values if normality or equal variance tests failed. Significant means were separated with the Tukey-Test. Linear regression tested the correlation of bean weight versus bean carbon-nutrient levels, bean weight versus soil carbon-nutrient levels and the carbon-nutrient levels in beans versus carbon-nutrient levels in soils. For the ANOVA, the 0–15, 15–30, 30–60 and 60–100 cm depths were treated as a 0–100 cm sample. Levels of significance were as follows: NS = not significant: *, ** = significant at $P \leq 0.05$, 0.01.

Results

Cocoa yield

Napu

In Napu, the first cocoa yield of 43.71 kg d.w. ha^{-1} was recorded in the 3-year-old agroforest (Table 3). By year 8, the yield (kg d.w. ha^{-1}) and the number of pods per area were significantly greater than year 3.

Palolo

The single bean weight (g d.w.) and bean weight per pod (g d.w. pod^{-1}) significantly differed between years 2 and 15 (Table 4). The bean weight per area and the number of pods per area increased in roughly three stages: years 1–4, 5–9 and 10–15. We found no significant change over time in the number of beans per pod.

Cocoa yield and bean carbon-nutrient levels

Napu

The level of bean N, K, Ca and Mg did not significantly change over time (Table 5). The 3-year-old agroforest had significantly higher bean C and P levels than the other age groups. In addition, the 3-year-old agroforest had the highest single bean weight. There was a significant correlation of bean C and P to the single bean weight. A comparison not shown (and not significant) was bean weight per area relative to bean carbon-nutrient levels.

Table 3 Temporal development of cocoa yield, Napu Valley

Age	Single bean weight (g d.w.)	Bean weight per pod (g d.w. pod^{-1})	Bean weight per area (kg d.w. ha^{-1})	No of beans per pod (no beans pod^{-1})	No of pods per area (no pods ha^{-1})
1	0[a] a	0 a	0 a	0 a	0 a
1.5	0 a	0 a	0 a	0 a	0 a
3	0.87 d	15.61 b	43.71 b	18.00 b	2,802.19 b
4	0.61 b	14.37 b	95.79 bc	23.62 b	6,666.00 bc
5	0.70 bc	16.13 b	137.79 c	22.67 b	8,542.36 cd
8	0.79 cd	20.83 b	230.39 d	26.31 b	11,060.62 d
	$y = 0.114x + 0.068$[b]	$y = 3.059x - 0.316$	$y = 34.755x - 45.717$	$y = 4.032x - 0.020$	$y = 1{,}741.500x - 1{,}685.30$
	$r = 0.74$ NS	$r = 0.88$*	$r = 0.99$*	$r = 0.86$*	$r = 0.97$**

[a] Means are presented. Different letters represent statistically significant subsets

[b] The age of the agroforest represents the x-axis and the single bean weight, bean weight per pod, bean weight per area, number of beans per pod and number of pods per area represent the y-axis

*, ** Significant at $P \leq 0.05, 0.01$

Table 4 Temporal development of cocoa yield, Palolo Valley

Age	Single bean weight (g d.w.)	Bean weight per pod (g d.w. pod^{-1})	Bean weight per area (kg d.w. ha^{-1})	No of beans per pod (no beans pod^{-1})	No of pods per area (no pods ha^{-1})
2	0.62[a] a	13.56 a	31.80 a	18.98 a	2,345.44 a
2.5	1.21 ab	19.00 ab	37.05 a	15.83 a	1,950.42 a
3	0.98 ab	24.47 ab	91.84 a	24.86 a	3,752.71 ab
4	0.93 ab	29.33 ab	89.80 a	33.09 a	3,061.42 a
5	1.07 ab	35.73 b	244.34 b	33.40 a	6,838.82 c
9	1.22 ab	38.58 b	220.98 b	31.42 a	5,727.82 bc
12	0.87 ab	22.09 ab	490.84 bc	24.40 a	22,220.00 d
15	1.36 b	40.44 b	636.36 c	30.00 a	15,751.51 d
	$y = 0.024x + 0.878$[b]	$y = 1.196x + 20.053$	$y = 44.305x - 60.376$	$y = 0.519x + 23.093$	$y = 1{,}310.00x - 893.640$
	$r = 0.49$ NS	$r = 0.60$ NS	$r = 0.97$**	$r = 0.38$ NS	$r = 0.87$**

[a] Means are presented. Different letters represent statistically significant subsets

[b] The age of the agroforest represents the x-axis and the single bean weight, bean weight per pod, bean weight per area, number of beans per pod and number of pods per area represent the y-axis

** Significant at $P \leq 0.01$

Palolo

Over time, there was no significant change in the bean carbon-nutrient levels (Table 6). A gradual increase in the single bean weight occurred between years 2 and 15 and correlated with higher assimilation of C in the bean. However, an increased single bean weight had a lower level of K. We found significant correlation for higher bean C, K and Mg ($P \leq 0.05$) and higher bean weight per pod but no significance by comparing bean weight per area and bean carbon-nutrient levels (data not shown).

Temporal change in soil carbon-nutrient levels

Napu

Of soil carbon-nutrient levels, we found that years 1.5, 3 and 4 had higher levels of pH, Ca, Mg and CEC than the younger age groups (Table 7).

Table 5 Relationship of single bean weight (g d.w.) relative to bean carbon-nutrient levels, Napu Valley

Age	Single bean weight (g d.w.)	Bean C (%)	Bean N (%)	Bean P (%)	Bean K (%)	Bean Ca (%)	Bean Mg (%)
3	0.87[a] c	57.30 b	2.12 a	0.53 b	1.53 a	0.13 ab	0.34 a
4	0.61 a	53.93 a	2.16 a	0.42 a	1.27 a	0.15 b	0.32 a
5	0.70 ab	54.13 a	2.06 a	0.47 ab	1.44 a	0.14 ab	0.31 a
8	0.79 bc	55.83 ab	2.17 a	0.50 ab	1.36 a	0.08 a	0.33 a
		$y = 0.068x - 3.015$[b]	$y = -0.050x + 0.849$	$y = 2.379x - 0.399$	$y = 0.816x - 0.400$	$y = -1.879x + 0.977$	$y = 6.900x - 1.500$
		$r = 0.96$*	$r = 0.02$ NS	$r = 0.99$**	$r = 0.81$ NS	$r = 0.52$ NS	$r = 0.79$ NS

[a] Means are presented. Different letters represent statistically significant subsets. The statistical subsets for single bean weight were amended versus those shown in Table 3 as there was no bean data from the 1-year-old and 1.5-year-old agroforests. The regression equation for the single bean weight was shown in Table 3

[b] The bean carbon-nutrient level represents the x-axis and the single bean weight represents the y-axis

*, ** Significant at $P \leq 0.05$, 0.01

Table 6 Relationship of single bean weight (g d.w.) relative to bean carbon-nutrient levels, Palolo Valley

Age	Single bean weight (g d.w.)	Bean C (%)	Bean N (%)	Bean P (%)	Bean K (%)	Bean Ca (%)	Bean Mg (%)
2	0.62[a] a	52.67 a	2.23 a	0.45 ab	1.59 b	0.17 ab	0.36 ab
2.5	1.21 ab	57.60 ab	1.96 a	0.27 a	1.15 a	0.35 b	0.39 b
3	0.98 ab	55.57 ab	2.06 a	0.42 ab	1.34 ab	0.15 ab	0.30 ab
4	0.93 ab	56.50 ab	2.04 a	0.40 ab	1.13 a	0.12 ab	0.31 ab
5	1.07 ab	57.37 ab	2.17 a	0.42 ab	1.25 ab	0.10 ab	0.30 ab
9	1.22 ab	58.03 ab	2.06 a	0.43 ab	1.12 a	0.12 ab	0.30 ab
12	0.87 ab	53.77 a	2.16 a	0.49 b	1.36 ab	0.18 ab	0.35 ab
15	1.36 b	59.53 b	2.18 a	0.47 b	0.98 a	0.09 a	0.31 ab
		$y = 0.098x - 4.518$	$y = -1.016x + 3.173$	$y = -0.961x + 1.435$	$y = -1.128x + 2.431$	$y = -0.035x + 1.038$	$y = -1.755x + 1.607$
		$r = 0.97$*	$r = 0.39$ NS	$r = 0.27$ NS	$r = 0.91$*	$r = 0.01$ NS	$r = 0.26$ NS

[a] Means are presented. Different letters represent statistically significant subsets. The regression equation for the single bean weight was shown in Table 2

[b] The bean carbon-nutrient level represents the x-axis and the single bean weight represents the y-axis

* Significant at $P \leq 0.05$

However, the increase subsided in the subsequent years.

Palolo

In Palolo, some of the agroforests had extremely high P values (e.g. 61.88 mg P kg^{-1} at year 3) but later the values diminished (Table 8). Only soil Al was found to significantly increase in the older agroforests.

Cocoa yield and soil carbon-nutrient levels

Napu

In Napu, we found no correlation between the soil's carbon-nutrient level and single bean weight (Table 9). Relative to the other nutrients, P had the steepest slope and highest correlation coefficient. In addition, a comparison of bean weight per pod and bean weight per area was insignificant (data not shown).

Palolo

As in Napu, the soil carbon-nutrient levels in Palolo were not significantly correlated with the single bean weight (Table 10). However, soil C and N were positively correlated to the single bean weight whereas the other nutrients were negatively correlated. Of the nutrients in question, soil P had the steepest negative slope. In comparing the bean weight per area versus the soil's carbon-nutrients, soil C correlated ($P \leq 0.05$) with the higher bean weight per area (data not shown). The soil nutrients had no such effect on the higher bean weight per area.

Bean and soil carbon-nutrient levels

Napu

In Napu, none of the relationships between the levels of soil and bean carbon-nutrients were significant (Table 11). Of nutrients, however, the steepest slope was found in the case of soil and bean P. In a comparison of the 0–15 cm layer, we found no significance in the relation of soil and bean carbon-nutrients (data not shown).

Table 7 Temporal change in soil carbon-nutrient levels from the 0–100 cm layer, Napu Valley

Age	pH ($CaCl_2$)	C (%)	N (%)	C:N	P (mg kg^{-1})	K (CEC_{eff} $cmol_c\ kg^{-1}$)	Ca (CEC_{eff} $cmol_c\ kg^{-1}$)	Mg (CEC_{eff} $cmol_c\ kg^{-1}$)	Na (CEC_{eff} $cmol_c\ kg^{-1}$)	Al (CEC_{eff} $cmol_c\ kg^{-1}$)	CEC (CEC_{eff} $cmol_c\ kg^{-1}$)
1	5.11[a] ab	1.14 a	0.14 a	8.1 a	5.18 a	0.30 a	7.55 ab	1.73 ab	0.10 a	0.14 a	9.73 ab
1.5	6.13 b	1.47 a	0.16 a	9.2 a	10.88 a	0.47 a	12.98 ab	4.00 ab	0.10 a	0.01 a	17.48 bc
3	5.96 b	2.03 a	0.22 a	9.2 a	11.98 a	0.27 a	17.55 b	4.10 b	0.12 a	0.01 a	22.03 c
4	5.42 ab	1.58 a	0.17 a	9.3 a	6.78 a	0.11 a	10.15 ab	5.35 b	0.22 a	0.02 a	15.90 b
5	4.95 ab	0.99 a	0.11 a	9.0 a	6.68 a	0.16 a	6.65 a	0.73 a	0.10 a	0.07 a	7.66 ab
8	4.58 a	1.01 a	0.11 a	9.2 a	5.85 a	0.16 a	5.40 a	0.90 ab	0.10 a	0.25 a	6.79 a
	$y = -0.161x + 5.964$[b]	$y = -0.062x + 1.603$	$y = -0.008x + 0.182$	$y = 0.852x + 8.681$	$y = -0.389x + 9.352$	$y = -0.036x + 0.379$	$y = -0.892x + 13.392$	$y = -0.327x + 4.029$	$y = 0.0009x + 0.122$	$y = 0.023x - 0.001$	$y = -1.223x + 17.851$
	$r = 0.69$ NS	$r = 0.39$ NS	$r = 0.49$ NS	$r = 0.48$ NS	$r = 0.35$ NS	$r = 0.70$ NS	$r = 0.50$ NS	$r = 0.43$ NS	$r = 0.02$ NS	$r = 0.60$ NS	$r = 0.51$ NS

[a] Means are presented. Different letters represent statistically significant subsets

[b] The age of the agroforest represents the x-axis and the soil carbon-nutrient represents the y-axis

Table 8 Temporal change in soil carbon-nutrient levels from the 0–100 cm layer, Palolo Valley

Age	pH ($CaCl_2$)	C (%)	N (%)	C:N	P (mg kg^{-1})	K (CEC_{eff} $cmol_c$ kg^{-1})	Ca (CEC_{eff} $cmol_c$ kg^{-1})	Mg (CEC_{eff} $cmol_c$ kg^{-1})	Na (CEC_{eff} $cmol_c$ kg^{-1})	Al (CEC_{eff} $cmol_c$ kg^{-1})	CEC (CEC_{eff} $cmol_c$ kg^{-1})
2	4.81[a] ab	1.12 a	0.13 a	8.6 a	13.83 ab	0.13 ab	4.83 ab	1.83 ab	0.10 a	0.15 a	7.00 ab
2.5	4.80 ab	1.05 a	0.12 a	8.8 a	9.73 a	0.11 a	4.38 ab	0.64 a	0.10 a	0.20 a	5.38 a
3	5.37 b	1.26 a	0.16 a	7.9 a	61.88 b	0.71 b	9.75 b	3.95 b	0.10 a	0.09 a	14.58 b
4	4.82 ab	0.96 a	0.11 a	8.7 a	9.95 a	0.09 a	5.00 ab	1.93 ab	0.11 a	0.17 a	7.25 ab
5	4.99 ab	1.21 a	0.16 a	7.6 a	25.15 ab	0.26 ab	10.15 b	3.28 b	0.10 a	0.13 a	13.88 b
9	4.61 a	0.98 a	0.12 a	8.2 a	10.40 a	0.12 ab	3.03 a	0.44 a	0.10 a	0.43 a	4.08 a
12	5.14 ab	1.30 a	0.15 a	8.7 a	42.03 ab	0.27 ab	8.18 ab	0.98 ab	0.10 a	0.14 a	9.60 ab
15	4.65 a	1.50 a	0.16 a	9.4 a	10.55 ab	1.28 b	4.35 ab	1.26 ab	0.10 a	0.79 a	7.70 ab
	$y = -0.014x + 4.99$	$y = 0.024x + 1.018$	$y = 0.002x + 0.128$	$y = 0.056x + 8.119$	$y = -0.271x + 24.721$	$y = 0.050x + 0.040$	$y = -0.089x + 6.790$	$y = -0.109x + 2.504$	$y = -0.0002x + 0.102$	$y = 0.036x + 0.024$	$y = -0.114x + 9.432$
	$r = 0.26$ NS	$r = 0.63$ NS	$r = 0.39$ NS	$r = 0.48$ NS	$r = 0.07$ NS	$r = 0.58$ NS	$r = 0.16$ NS	$r = 0.42$ NS	$r = 0.21$ NS	$r = 0.75$*	$r = 0.15$ NS

[a] Means are presented. Different letters represent statistically significant subsets

* Significant at $P \leq 0.05$

Table 9 Relationship of single bean weight (g d.w.) relative to soil carbon-nutrient levels from the 0–15 cm layer, Napu Valley

Age	Single bean weight (g d.w.)	Soil C (%)	Soil N (%)	Soil P[c] (%)	Soil K[d] (%)	Soil Ca (%)	Soil Mg (%)
3	0.87[a] c	4.63	0.45	0.0039	0.86	0.62	0.37
4	0.61 a	3.37	0.34	0.0013	0.76	0.39	0.23
5	0.70 ab	2.17	0.25	0.0010	0.46	0.24	0.14
8	0.79 bc	2.27	0.23	0.0009	0.42	0.21	0.13
		$y = 0.040x + 0.618$[b]	$y = 0.417x + 0.610$	$y = 54.242x + 0.646$	$y = 0.067x + 0.701$	$y = 0.264x + 0.646$	$y = 0.441x + 0.646$
		$r = 0.41$ NS	$r = 0.37$ NS	$r = 0.67$ NS	$r = 0.13$ NS	$r = 0.44$ NS	$r = 0.44$ NS

[a] Means are presented. No statistical subsets are shown as the values for soil carbon-nutrients are based solely on one value, that of the 0–15 cm layer. The regression equation for the single bean weight was shown in Table 1

[b] The soil carbon-nutrient level represents the x-axis and the single bean weight represents the y-axis

[c] Soil P was converted from mg kg^{-1} to a percent

[d] Soil K, Ca and Mg were converted from CEC_{eff} $cmol_c$ kg^{-1} to a percent

Table 10 Relationship of single bean weight (g d.w.) relative to soil carbon-nutrients from the 0–15 cm layer, Palolo Valley

Age	Single bean weight (g d.w.)	Soil C (%)	Soil N (%)	Soil P[c] (%)	Soil K[d] (%)	Soil Ca (%)	Soil Mg (%)
2	0.62[a] a	1.63	0.18	0.0027	0.27	0.14	0.08
2.5	1.21 ab	1.50	0.16	0.0010	0.28	0.14	0.09
3	0.98 ab	1.94	0.21	0.0071	0.56	0.29	0.17
4	0.93 ab	1.35	0.16	0.0016	0.29	0.15	0.09
5	1.07 ab	1.93	0.23	0.0035	0.57	0.29	0.17
9	1.22 ab	1.26	0.15	0.0009	0.20	0.10	0.06
12	0.87 ab	1.91	0.21	0.0029	0.46	0.24	0.14
15	1.36 b	2.76	0.25	0.0018	0.42	0.22	0.13
		$y = 0.162x + 0.744$[b]	$y = 1.196x + 0.801$	$y = -37.076x + 1.132$	$y = -0.005x + 1.034$	$y = -0.004x + 1.033$	$y = -0.021x + 1.035$
		$r = 0.33$ NS	$r = 0.19$ NS	$r = 0.32$ NS	$r = 0$ NS	$r = 0$ NS	$r = 0$ NS

[a] Means are presented. No statistical subsets are shown as the values for soil carbon-nutrients are based solely on one value, that of the 0–15 cm layer. The regression equation for the bean weight per area was shown in Table 2

[b] The soil carbon-nutrient level represents the *x*-axis and the single bean weight represents the *y*-axis

[c] Soil P was converted from mg kg^{-1} to a percent

[d] Soil K, Ca and Mg were converted from CEC$_{\text{eff}}$ cmol$_c$ kg^{-1} to a percent

Palolo

The relationship of bean and soil carbon-nutrients levels was insignificant (Table 12). As was the case in Napu, P had the steepest slope. Of the 0–15 cm layer, the correlation coefficients improved for C and N, decreased for P and K but did not greatly change for Ca and Mg (data not shown).

Farmers' estimation versus own measured cocoa yield

All farmers harvested on a weekly basis (weekly yield) but acknowledged that the harvest schedule was not abided by too rigorously over the year. However, we could not establish a typical seasonality (e.g. flowering in March and harvesting in October) in the development of cocoa pods. Based on the farmers' estimation, the cocoa yield was around 1,188 kg d.w. ha^{-1} year^{-1} at year 3 (Table 13). During years 5–15, an average yield of 2,655 kg d.w. ha^{-1} year^{-1} was estimated in which the peak production level of 3,600 kg d.w. ha^{-1} year^{-1} was reached at year 12. One vital distinction in our methodology was that the farmers' estimation of yield was a sun-dried estimate and we used an oven-dried estimate. Thus, the farmers' estimate was about 68% less than our measured yield (bean weight per area per year), meaning that at the time of the survey, about a third of the cocoa yield (bean weight per area per year) was actually ripe enough to fulfill the harvest criteria of farmers.

Carbon-nutrients removed in cocoa yield

Napu

In accordance with the increasing yield, the amount of C removed from the agroforests in Napu gradually increased with time (Table 14). Of nutrients, the highest magnitude of nutrient removal was for N and was closely followed by K. The level of P removed relative to the other macronutrients was low at 2.7–10.2 kg P ha^{-1} year^{-1}. The level of Ca removed was the lowest of the nutrients, and Mg was removed at a level almost as high as that of P.

Palolo

C was removed at a comparatively large level relative to the nutrients (Table 15). Of nutrients, N followed by K was exported in the greatest quantity. Using years 3–15, about 10 kg P ha^{-1} year^{-1} was exported in the harvest of cocoa. As in Napu, the amount of Mg removed was just below that of P removed. Ca was removed in the smallest amount relative to the other nutrients.

Table 11 Relationship of bean carbon-nutrient levels relative to soil carbon-nutrient levels from the 0–100 cm layer, Napu Valley

Age	Soil C (%)	Bean C (%)	Soil N (%)	Bean N (%)	Soil P (%)	Bean P (%)
3	2.03[a]	57.30	0.22	2.12	0.0012	0.53
4	1.58	53.93	0.17	2.16	0.0007	0.42
5	0.99	54.13	0.11	2.06	0.0007	0.47
8	1.01	55.83	0.11	2.17	0.0006	0.50
		$y = 1.702x + 52.913$[b]		$y = 0.092x + 2.113$		$y = 102.550x + 0.400$
		$r = 0.54$ NS		$r = 0.10$ NS		$r = 0.61$ NS
Age	**Soil K (%)**	**Bean K (%)**	**Soil Ca (%)**	**Bean Ca (%)**	**Soil Mg (%)**	**Bean Mg (%)**
3	0.86	1.53	0.44	0.13	0.26	0.34
4	0.62	1.27	0.32	0.15	0.19	0.32
5	0.30	1.44	0.15	0.14	0.09	0.31
8	0.27	1.36	0.14	0.08	0.08	0.33
		$y = 0.136x + 1.331$		$y = 0.101x + 0.099$		$y = 0.090x + 0.311$
		$r = 0.35$ NS		$r = 0.47$ NS		$r = 0.61$ NS

[a] Means are presented. The statistical subsets were presented in earlier tables

[b] The soil carbon-nutrient level represents the x-axis and the bean carbon-nutrient level represents the y-axis

Table 12 Relationship of bean carbon-nutrient levels relative to soil carbon-nutrient levels from the 0–100 cm layer, Palolo Valley

Age	Soil C (%)	Bean C (%)	Soil N (%)	Bean N (%)	Soil P (%)	Bean P (%)
2	1.12[a]	52.67	0.13	2.23	0.0014	0.45
2.5	1.05	57.60	0.12	1.96	0.0010	0.27
3	1.26	55.57	0.16	2.06	0.0062	0.42
4	0.96	56.50	0.11	2.04	0.0010	0.40
5	1.21	57.37	0.16	2.17	0.0025	0.42
9	0.98	58.03	0.12	2.06	0.0010	0.43
12	1.30	53.77	0.15	2.16	0.0042	0.49
15	1.50	59.53	0.16	2.18	0.0011	0.47
		$y = 1.579x + 54.528$[b]		$y = 2.259x + 1.794$		$y = 9.754x + 0.396$
		$r = 0.13$ NS		$r = 0.52$ NS		$r = 0.28$ NS

Age	Soil K (%)	Bean K (%)	Soil Ca (%)	Bean Ca (%)	Soil Mg (%)	Bean Mg (%)
2	0.27	1.59	0.14	0.17	0.08	0.36
2.5	0.21	1.15	0.11	0.35	0.06	0.39
3	0.57	1.34	0.29	0.15	0.18	0.3
4	0.28	1.13	0.15	0.12	0.09	0.31
5	0.54	1.25	0.28	0.10	0.17	0.30
9	0.16	1.12	0.08	0.12	0.05	0.30
12	0.37	1.36	0.19	0.18	0.12	0.35
15	0.30	0.98	0.15	0.09	0.09	0.31
		$y = 0.364x + 1.117$		$y = -0.341x + 0.219$		$y = -0.313x + 0.360$
		$r = 0.28$ NS		$r = 0.31$ NS		$r = 0.41$ NS

[a] Means are presented. The statistical subsets were presented in earlier tables

[b] The soil carbon-nutrient level represents the *x*-axis and the bean carbon-nutrient level represents the *y*-axis

Table 13 Farmers' estimation versus own cocoa yield estimates per area per year (kg d.w. ha^{-1} $year^{-1}$), Napu and Palolo Valley

Age	Farmers' estimation (kg d.w. ha^{-1} $year^{-1}$)	Bean weight per area per year (kg d.w. ha^{-1} $year^{-1}$)	Differences between farmers and own yield estimates (%)	Weekly yield (kg d.w. ha^{-1})
2	366	1,145	68	10[a]
2.5	427	1,334	68	12[a]
3[b]	1,080	1,584	32	30
3	1,188	3,306	64	33
4[b]	648	3,448	81	18
4	1,440	3,232	55	40
5[b]	2,160	4,932	56	60
5	2,160	8,796	75	60
8[b]	1,980	8,294	76	55
9	2,700	7,955	66	75
12	3,600	17,670	80	100
15	2,160	22,909	91	60

[a] Two farmers did not respond and the average (68%) of other estimates was substituted

[b] Agroforests located in Napu Valley, all others were in Palolo Valley

Table 14 Farmers' estimation of cocoa yield and carbon-nutrient export estimates (kg d.w. ha^{-1} year^{-1}), Napu Valley

Age	Farmers' estimation (kg d.w. ha^{-1} year^{-1})	C (kg d.w. ha^{-1} year^{-1})	N (kg d.w. ha^{-1} year^{-1})	P (kg d.w. ha^{-1} year^{-1})	K (kg d.w. ha^{-1} year^{-1})	Ca (kg d.w. ha^{-1} year^{-1})	Mg (kg d.w. ha^{-1} year^{-1})
3	1,080	618.8	22.9	5.7	16.6	1.4	3.7
4	640	345.2	13.9	2.7	8.2	1.0	2.0
5	2,160	1,169.3	44.4	10.2	31.0	2.9	6.8
8	1,980	1,105.5	43.0	9.8	26.9	1.7	6.6

Table 15 Farmers' estimation of cocoa yield and carbon-nutrient export estimates (kg d.w. ha^{-1} year^{-1}), Palolo Valley

Age	Farmers' estimation (kg d.w. ha^{-1} year^{-1})	C (kg d.w. ha^{-1} year^{-1})	N (kg d.w. ha^{-1} year^{-1})	P (kg d.w. ha^{-1} year^{-1})	K (kg d.w. ha^{-1} year^{-1})	Ca (kg d.w. ha^{-1} year^{-1})	Mg (kg d.w. ha^{-1} year^{-1})
2	366	192.8	8.2	1.7	5.8	0.6	1.3
2.5	427	246.0	8.4	1.1	4.9	1.5	1.7
3	1,188	660.1	24.4	5.0	15.9	1.8	3.5
4	1,440	813.6	29.4	5.7	16.3	1.7	4.4
5	2,160	1,239.1	46.9	9.1	26.9	2.2	6.5
9	2,700	1,566.9	55.7	11.6	30.3	3.3	8.2
12	3,600	1,935.6	77.9	17.5	48.8	6.5	12.7
15	2,160	1,285.9	47.0	10.1	21.3	2.0	6.7

Discussion

Cocoa yield

The single bean weight values (0.61–0.87 g d.w. in Napu; 0.62–1.22 g d.w. in Palolo) were similar to the 94 or 85 g d.w. per 100 beans for *Forestero* and *Criollo*, respectively, measured by Lass (1999). In Palolo, the single bean weight attained its highest levels around years 12–15 yet the highest single bean weight in Napu was from the 3-year-old agroforest. The 18.00–26.31 beans pod^{-1} (Napu) and 15.83–33.40 beans pod^{-1} (Palolo) were not vastly different from the 30 or more beans pod^{-1} for *Forestero* cocoa and 20–30 beans pod^{-1} for *Criollo* cocoa (Lass 1999). There was also a moderate increase in the number of beans per pod in Napu and Palolo (contrary to the single bean weight). Our results of bean weight per pod (15.61–20.83 and 13.56–40.44 g d.w. pod^{-1} in Napu and Palolo, respectively) were similar to the 35 g d.w. pod^{-1} of cocoa planted at a density of 1,000 trees ha^{-1} in Cameroon (Boyer 1973). In Napu, the range of bean weight per pod was not very large. Palolo had a much larger increase in bean weight per pod (and single bean weight) at year 15. We assume, therefore, that the bean weight per pod at year 15 did not represent the maximum yield.

Elevation-rainfall effect on cocoa yield

In general, the higher temperature and rainfall of Palolo were more favorable for the production of cocoa (though other variables such as soil properties could have impacted the growth of cocoa) than in Napu. For example, the 20.83 g d.w. pod^{-1} at year 8 in Napu was already attained at years 2.5–3 in Palolo. Of the same age groups, the single bean weight was always higher in Palolo, such as 0.87 vs. 0.98 g d.w. (year 3), 0.61 vs. 0.93 g d.w. (year 4) and 0.70 vs. 1.07 g d.w. (year 5) for Napu and Palolo, respectively. A similar trend was found for the number of beans per pod: 18.00 vs. 24.86 beans pod^{-1} (year 3), 23.62 vs. 33.09 beans pod^{-1} (year 4) and 22.67 vs. 33.40 beans pod^{-1} (year 5) for Napu and Palolo, respectively. Hence, the chronosequence was able to describe the general magnitude in which the elevation and rainfall affected the cocoa yield.

Effect of carbon-nutrient levels on cocoa yield

In Napu and Palolo, we detected no significant change in the status of soil C over time under cocoa-gliricidia agroforestry. This contrasts with the findings of Beer et al. (1990) in Costa Rica who found that the soil organic matter of the 0–45 cm layer increased after 10 years of cocoa, poro (*Erythrina poeppigiana* (Walper) O. F. Cook) and laurel (*Cordia alliodora* (R + P) Oken). We also did not find that a higher level of soil C led to a higher single bean weight, contradicting Beer (1988) in which the higher soil C:N ratio led to a higher cocoa yield. Our measured C:N ratio did not greatly change over time. Moreover, our research found no relationship between the level of soil C and bean C. We found that the maturity of trees was essential as the tree size increased the ability to assimilate C and develop a higher single bean weight ($P \leq 0.05$ in Napu and $P \leq 0.01$ in Palolo).

Soil N levels did not significantly change over time, nor was there a significant response to the level of bean or soil N in the way of a higher single bean weight. The inclusion of gliricidia was not found to drastically change the level of bean N or soil N nor did it improve the cocoa yield. In a 2, 15- and 25-year-old cocoa agroforest in Ghana, the nitrification rates (and litter fall) increased over time but caused no significant change in the total soil N of the 0–15 cm layer (Isaac et al. 2005). On the other hand, a study in Napu and Palolo found that N was added in the form of rainfall at the level of roughly 2.7 kg N ha^{-1} year^{-1} (Dechert et al. 2005) but that amount was very small compared with the total N-stock. Their study also found that soil ammonium (NH_4^+) cycling rates were higher in a cocoa-coffee agroforest than in the rainforest. The higher N cycling could have been caused by the N-rich root exudates and plant residues of leguminous shade trees *Gliricidia sepium*, *Erythrina fusca* Lour. and *Erythrina subumbrans* Merr. (Corre et al. 2006). Thus, we surmise that the level of soil N was sufficient for the formation of cocoa yield. The amount of N in the cocoa yield could be satisfied by fertilizer or a mixture of leguminous shade trees, estimated to fix up to 60 kg N ha^{-1} year^{-1} (Beer 1988).

The level of higher bean P in Napu significantly ($P \leq 0.01$) affected a higher single bean weight. Yet none of the other comparisons of P was significant in relation to single bean weight or the level of bean P. We found an abnormally high P value at year 3 and attributed this to fertilization rather than the native soil P or a function of age. However, the steepest slopes were indicated for P, suggesting that this nutrient was the most readily uptaken. The soils in Napu and Palolo had low pH and this could have been a factor in a P deficiency as P can become fixed as forms unavailable to plants. In Costa Rica, Alpízar et al. (1986) found that only a fraction of the soil P was transferred to the vegetation. Some nutrients, especially P, can be localized at a higher level in trees (and litter) than in soils (Hartemink 2005). Compared to annual or alley cropping systems, however, a multi-storied agroforest in Costa Rica composed of 15-year-old cocoa and laurel in a non-fertilized treatment stored more plant available P (Szott and Melendez 2001). Others have reported that specific agroforestry shade trees (*Terminalia superba* Engl. and Diels, and *Newbouldia laevis* (P. Beauv.) Seem. ex Bureau) strongly compete with cocoa for resources, notably K (Isaac et al. 2007). This underscores the need to determine the amount of P being exported with the yield and to apply a higher application rate of P than the amount removed by the yield (Smithson and Giller 2002).

Our research found some significantly higher soil K values (e.g. year 2 in Palolo) but the values tended to diminish in a later age group. We surmise that K fertilization was the cause and that the reduction was not a function of agroforest age. Where K was significantly correlated ($P \leq 0.01$) to single bean weight in Palolo, it was negatively correlated (the higher level of bean K led to a lower single bean weight), suggesting that K was not a limited nutrient. This appeared to be caused by a high level of K relative to a juvenile growth stage of cocoa. We also did not find that Ca and Mg significantly affected the status of cocoa yield nor did they significantly change over time. Although we observed that the CEC improved during the intermediate years, by year 8 (Napu) and year 15 (Palolo), the CEC was no longer significant. In addition, soil Na and Al did not significantly change over time.

Farmers' estimation versus own measured cocoa yield

A main difficulty in the estimation of farmers' yield versus our measured cocoa yield was that farmers periodically harvested pods over the year. Based on the farmers' estimation, the average cocoa yield was 1,467 kg d.w. ha^{-1} year^{-1} in Napu and 1,755 kg d.w. ha^{-1} year^{-1} in Palolo. However, our methodology (kg d.w. ha^{-1} multiplied by 36 weeks) gave a yearly sum that well exceeded any value of the literature. We concluded that farmers had a more refined definition of the ripeness of cocoa pods than we used to determine cocoa yield. Nonetheless, the farmers' estimation was also higher than most values of the literature. For example, in Ghana, the yield of cocoa grown with gliricidia was 29.6–810.1 kg d.w. ha^{-1} year^{-1} for years 3 and 7, respectively. At year 9, the yield fell to 223.5 kg d.w. ha^{-1} year^{-1} (Osei-Bonsu et al. 2002). A fertilization rate of 300 kg NPK ha^{-1} year^{-1} for monocropped cocoa in Nigeria produced a 10 year average of 718 kg d.w. ha^{-1} year^{-1} (Oladokun and Egbe 1990). In Costa Rica, during years 1–5, the cocoa yield was 306–377 kg d.w. ha^{-1} year^{-1} with *C. alliodora* and *E. poeppigiana*, respectively (Beer et al. 1990). Yields increased to 626 and 712 kg d.w. ha^{-1} year^{-1} with *C. alliodora* and *E. poeppigiana*, respectively, during a 7 year time frame (Heuveldop et al. 1988) and 1,036–1,057 kg d.w. ha^{-1} year^{-1} with *C. alliodora* and *E. poeppigiana*, respectively, during years 6–10 (Beer et al. 1990). A 30-year-old cocoa-mixed shade agroforest in Venezuela yielded 636 kg d.w. ha^{-1} year^{-1} (Aranguren et al. 1982). On alluvial soils of coastal Sulawesi, the cocoa yield ranged from 250 kg ha^{-1} year^{-1} after 2 years of growth to 1,500 kg ha^{-1} year^{-1} after 5 years of growth, fairly similar to the farmers' estimate of our study. With adequate fertilization and pruning, a cocoa yield of 3,000 kg ha^{-1} year^{-1} can be attained (Ruf et al. 1995). The average yield of smallholder cocoa producers in Sulawesi was 400–800 kg ha^{-1} year^{-1} (Panlibuton and Lusby 2006).

Transfer of nutrients in farmers' estimation of cocoa yield

In a study by Bénach and Dejardin (1970), the level of cocoa yield ranged 10–30 pods per tree year^{-1} or 20 pods per tree year^{-1} (corresponding to 10,000–30,000 pods ha^{-1} year^{-1}) according to Boyer (1973). The value of 10,000–30,000 pods ha^{-1} year^{-1} was much higher than results of our study (8,542.36–11,060.62 pods ha^{-1} for years 5–8 in Napu and 22,220.00 pods ha^{-1} for year 12 in Palolo). If about 32% of the bean weight per area (kg d.w. ha^{-1}) was ripe enough to fulfill the harvest criteria of farmers, then our estimated number of pods ha^{-1} year^{-1} was much lower than those of Bénach and Dejardin (1970). At a bean weight of 350–1,050 kg d.w. ha^{-1}, 36.0 kg N, 6.6 kg P, 76.4 kg K, 8.6 kg Ca and 7.2 kg Mg ha^{-1} year^{-1} was removed (Boyer 1973). These nutrient export figures are similar to our results (if a similar cocoa yield is assumed) except for K, Mg and Ca in which our estimates of nutrient removal were much less. At CATIE in Costa Rica, during the first 7 years, 12.0–15.2 kg N, 2.9–3.0 kg P, 6.8–7.5 kg K, 0.8–0.9 kg Ca and 1.8–2.1 kg Mg ha^{-1} year^{-1} were transferred in the cocoa yield, which also concurred with our results. At CATIE, the removal of N in the cocoa yield was relatively low. In the case of P, its removal was low for the system but high for the cocoa tree (Heuveldop et al. 1988; Fassbender et al. 1988). We also found a similar magnitude of nutrient export in cocoa yield, with N as the nutrient removed in the greatest quantity, as reported by Santana and Cabala-Rosand (1982). Dechert and Veldkamp (2003) found that 57.0 kg N ha^{-1} year^{-1} was transferred in the combined cocoa-coffee yield, a value which concurred with our results (about 46.9–77.9 kg N ha^{-1} during years 5–15) using mature cocoa trees. The same authors determined that the largest loss of system P (9.1 kg P ha^{-1} year^{-1}) was in the cocoa-coffee yield, which concurred with our results of 9.1–17.5 kg P ha^{-1} during years 5–15. Cocoa ecosystems lose most nutrients in the harvest of cocoa, and the loss of nutrients is greater when the husks are removed from the agroforest (Hartemink 2005). The 21.3–48.8 kg K ha^{-1} removed during years 5–15 (at 2,160–3,600 kg d.w. ha^{-1} year^{-1}) was similar if not somewhat higher than the 10 kg K ha^{-1} per 1,000 kg as reported by Hartemink (2005). Therefore, to counterbalance the removed nutrients, notably P, the use of fertilizers (or leguminous species for N_2-fixation) appeared to be necessary for prolonged cocoa production. Hartemink (2005) found negative N, P and K balances in cocoa ecosystems, which was especially pronounced for K due to rainwash. The magnitude of nutrient removal in our calculations generally concurred with values of the literature.

Conclusion

In a chronosequence conducted in Napu and Palolo Valleys, the present study sought to increase knowledge on some of the biophysical relationships in cocoa-gliricidia agroforestry systems. From the perspective of sustained or increased cocoa production, the development of cocoa yield versus nutrient dynamics is a topic not well described in the literature. We also set out to find the relationships between the age of an agroforest, nutrient dynamics and cocoa yield.

In Napu and Palolo, the soils surveyed had relatively good properties for agricultural use. At the same time, cocoa has not been cultivated in these valleys as long as in other parts of Central Sulawesi or Indonesia. Therefore, the oldest agroforests were aged 8 years in Napu and 15 years in Palolo. The span of time studied did not appear to have been long enough to observe large changes in the soil nutrient status or cocoa yield. We found, instead, that the age of cocoa trees played the greater role. For example, older cocoa trees greatly increased the root length density (RLD) along a horizontal plane and can presumably capture more growth resources (Smiley 2006).

Of the nutrients, P had the steepest slope and we determined that it was the most limited nutrient for the formation of cocoa yield. In addition to P fertilizer, lime could raise the soil pH and increase the availability of P. The shade tree gliricidia appeared to spread its roots in much of the same vertical and horizontal soil strata as cocoa and we recommend testing other species of shade that do not share the same above- and below-ground strata (Smiley 2006). As gliricidia had no direct economic benefit to farmers, and farmers were not using gliricidia for N_2-fixation or the improvement of soil organic matter, such trees could include those related to the marketing of cocoa such as cashew nuts (*Anacardium occidentale* L.) or macadamia nuts (*Macadamia integrifolia* Maiden et Betche).

As a research tool, one of the strengths of a chronosequence was its ability to rapidly gather data on the relationships between the age of an agroforest, the status of nutrients and cocoa yield. However, the rapid approach also had inherent weaknesses, such as a need to verify the age of agroforests, fertilizer application and actual harvesting practices. We view the chronosequence as a first step in research, with subsequent research investigating an area of inquiry in greater detail.

Acknowledgments We thank the German Research Council (DFG) in its providing of financial support for the Stability of Rainforest Margins (STORMA) project that was executed by the Georg-August-University of Göttingen and the University of Kassel, Germany. We thank Dr. J. Breuer at the University of Hohenheim and Dr. I. Anas at the Institut Pertanian Bogor. We also appreciate the helpful comments of two anonymous reviewers on an earlier version of the manuscript.

References

Alpízar L, Fassbender HW, Heuveldop J, Fölster H, Enríquez G (1986) Modelling agroforestry systems of cacao (*Theobroma cacao*) with laurel (*Cordia alliodora*) or poro (*Erythrina poeppigiana*) in Costa Rica. Agrofor Syst 4:175–189

Aranguren J, Escalente G, Herrera R (1982) Nitrogen cycle of tropical perennial crops under shade trees II Cacao. Plant Soil 67:259–269

Beer J (1988) Litter production and nutrient cycling in coffee (*Coffea arabica*) or cacao (*Theobroma cacao*) plantations with shade trees. Agrofor Syst 7:103–114

Beer J, Bonnemann A, Chavez W, Fassbender HW, Imbach AC, Martel I (1990) Modelling agroforestry systems of cacao (*Theobroma cacao*) with laurel (*Cordia alliodora*) or poro (*Erythrina poeppigiana*) in Costa Rica. Agrofor Syst 12:229–249

Bénach R, Dejardin J (1970) Essai d'engrais sur cacaoyers au Cameroon (région de Yaoundé). Café Cacao Thé (Paris) 14(1):13–27

Boyer J (1973) Cycles de la matière organique et des éléments minéraux dans une cacaoyère camerounaise. Café Cacao Thé (Paris) 17(1):3–23

Burkard G (2002) Stability or sustainability? Dimensions of socio-economic security in a rainforest margin. Research Project on Stability of Rain Forest Margins (STORMA), Georg-August-Universität Göttingen, Germany. STORMA Discussion Paper Series, No. 7, pp 1–39

Corre MD, Dechert G, Veldkamp E (2006) Soil nitrogen cycling following montane forest conversion in Central Sulawesi, Indonesia. Soil Sci Soc Am J 70:359–366

de Alvim PT (1977) Cacao. In: de Alvim PT, Kozlowski TT (eds) Ecophysiology of tropical crops. Academic Press, New York, pp 279–313

de Alvim PT, Cabala-Rosand FP (1974) Um novo sistema de representacao grafica da fertilidade dos solos para cacau. Cacao Atual (Brasil) 11(2):2–6

Dechert G, Veldkamp E (2003) Changes of soil properties and input-output balance of nutrients in land-use systems following rainforest conversion in Central Sulawesi, Indonesia. In: Wollny C, Deininger A, Bhandari N, Maass B, Manig W, Muuss U, Brodbeck F, Howe I (eds) Technological and Institutional Innovations for Sustainable Rural Development: International Research on Food

Security, Natural Resource Management and Rural Development. Deutscher Tropentag 2003. Book of Abstracts. Georg-August-Universität Göttingen, Germany, p 336

Dechert G, Veldkamp E, Brumme R (2005) Are partial nutrient balances suitable to evaluate nutrient sustainability of land use systems? Results from a case study in Central Sulawesi, Indonesia. Nutr Cycling Agroecosyst 72:201–212

Fassbender HW, Alpízar L, Heuveldop J, Fölster H, Enríquez G (1988) Modelling agroforestry systems of cacao (*Theobroma cacao*) with Laurel (*Cordia alliodora*) and poro (*Erythrina peoppigiana*) in Costa Rica. III Cycles of organic matter and nutrients. Agrofor Syst 6:49–62

Hartemink AE (2005) Nutrient stocks, nutrient cycling, and soil changes in cocoa ecosystems: a review. Adv Agron 86:227–253

Heuveldop J, Fassbender HW, Alpízar L, Enríquez G, Fölster H (1988) Modelling agroforestry systems of cacao (*Theobroma cacao*) with laurel (*Cordia alliodora*) and poro (*Erythrina poeppigiana*) in Costa Rica. II Cacao and wood production, litter production and decomposition. Agrofor Syst 6:37–48

ICCO (2003) International Cocoa Organization, London. http://www.icco.org/questions/indonesia.htm. Cited 26 Feb 2004

Isaac ME, Gordon AM, Thevathasan N, Oppong SK, Quashi-Sam J (2005) Temporal changes in soil carbon and nitrogen in west African multistrata agroforestry systems: a chronosequence of pools and fluxes. Agrofor Syst 65:23–31

Isaac ME, Ulzen-Appiah F, Timmer VR, Quashi-Sam SJ (2007) Early growth and nutritional response to resource competition in cocoa-shade intercropped systems. Plant Soil 298:243–254

Lass RA (1999) Cacao growing and harvesting practices. In: Knight I (ed) Chocolate and cocoa. Blackwell, Oxford, pp 11–42

Oladokun MAO, Egbe NE (1990) Yields of cocoa/kola intercrops in Nigeria. Agrofor Syst 10:153–160

Osei-Bonsu K, Opuku-Ameyaw K, Amoah FM, Oppong FK (2002) Cacao-coconut intercropping in Ghana: agronomic and economic perspectives. Agrofor Syst 55:1–8

Panlibuton H, Lusby F (2006) Indonesia cocoa bean value chain: case study. MicroReport #65, USAID, USA

Ruf F, Jamaluddin Y, Waris A (1995) The 'spectacular' efficiency of cocoa smallholders in Sulawesi: Why? Until when? In: Ruf F, Siswoputranto S (eds) Cocoa cycles: the economics of cocoa supply, Woodhead, Cambridge, pp 339–376, http://books.google.com. Cited 9 Jan 2009

Santana MBM, Cabala-Rosand P (1982) Dynamics of nitrogen in a shaded cacao plantation. Plant Soil 67:271–281

Sitorus F (2002) Revolusi cokelat: social formation, agrarian structure and forest margins in upland Sulawesi. STORMA discussion paper series, No. 9, pp 1–19

Smiley GL (2006) Biophysical resource use and productivity in cocoa-gliricidia agroforests of Central Sulawesi. In: Kroschel J (ed) Tropical Agriculture (19)—Advances in Crop Research (9). Margraf, Weikersheim, Germany

Smithson PC, Giller KE (2002) Appropriate farm management practices for alleviating N and P deficiencies in low-nutrient soils of the tropics. Plant Soil 245:169–180

Szott LT, Melendez G (2001) Phosphorus availability under annual cropping, alley cropping, and multistrata agroforestry systems. Agrofor Syst 53:125–132