

# Temporal change in carbon stocks of cocoa–gliricidia agroforests in Central Sulawesi, Indonesia

G. L. Smiley · J. Kroschel

Received: 10 October 2006 / Accepted: 28 April 2008 / Published online: 13 May 2008  
© Springer Science+Business Media B.V. 2008

**Abstract** In a false-time series, the temporal development of cocoa–gliricidia carbon (C) stocks and soil organic carbon (SOC) were investigated in Napu and Palolo Valleys of Central Sulawesi, Indonesia. As a first step, the Functional Branch Analysis (FBA) method was used to develop allometric equations for the above- and below-ground growth of cocoa and gliricidia. FBA resulted in shoot–root ratios of 2.54 and 2.05 for cocoa and gliricidia, respectively. In Napu and Palolo, the trunk diameter and carbon levels per gliricidia tree were always much greater than that of cocoa. The highest aerial carbon levels were attained at year four in Napu (aerial cocoa–gliricidia = 20,745.2 kg C ha<sup>-1</sup>) and at year five in Palolo (aerial cocoa–gliricidia = 38,857.0 kg C ha<sup>-1</sup>). After years four or five, however, the reduced stocking density of gliricidia attributed to a loss of aerial C. During the time spans in question, SOC remained fairly stable though slightly decreasing in Napu and slightly increasing in Palolo. The SOC harbored a vastly greater amount of system C (one-half and one-third of SOC in the 0–15 cm stratum in Napu and

Palolo, respectively) relative to tree components. Eight years (Napu) or 15 years (Palolo) after conversion of a rainforest to cocoa–gliricidia agroforestry caused an 88% and 87% reduction of aerial C-stocks in Napu and Palolo, respectively.

**Keywords** Export crops · *Theobroma cacao* · *Gliricidia sepium* · Forest conversion · Carbon sequestration · Global climate change

## Introduction

Tropical rainforests are among the foremost in ecological productivity and one of the main sources of terrestrial carbon storage. A measure of photosynthetic productivity is generally considered in g of carbon (C) fixed m<sup>2</sup> year<sup>-1</sup> and calculated from tree growth rates and biomass density (kg biomass ha<sup>-1</sup>) (Smith 1996). Above-ground, undisturbed tropical rainforests may produce an estimated 219.6 t C kg ha<sup>-1</sup> with a system total, including below-ground C, of 305 t C ha<sup>-1</sup> (Woomer et al. 2000). In a moist zone of Sarawak, Malaysia, the above-ground biomass of dipterocarps ranged from 280 to 385 t ha<sup>-1</sup> (Government of Malaysia 1987; cited in Brown 1997).

In the upper one m of global soils, the soil organic carbon (SOC) was estimated at 1,220 Gt C or one and a half times more than the aerial biomass. Below one meter, tropical soils may contribute an extra 50 Gt C, excluding root, charcoal and soil fauna C

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

J. Kroschel (✉)  
International Potato Center, Apartado 1558, La Molina,  
Lima 12, Peru  
e-mail: j.kroschel@cgiar.org

(Soembroek et al. 1993). High precipitation and temperature of tropical rainforests continually allow the replenishment of SOC by litter and root turnover along with high decomposition rates of microbes and fungal oxidation (Kürsten and Burschel 1993). The emission of CO<sub>2</sub> during the decomposition of organic matter is a main pathway of C loss (Trumbore 1997) though estimates of CO<sub>2</sub> emissions from soils are highly variable (Veldkamp 1994). The activities of clear cutting, burning and cultivation displace CO<sub>2</sub> to the atmosphere which has been suggested as a driver of global warming (Smith 1996). In Asia, an estimated 4.7 million ha or 1.4% per annum was deforested from 1980 to 1990 (Lal et al. 1997). Once the cycle is disturbed by deforestation and cultivation, there is normally a rapid mineralization of SOC and nutrients, which become available for plant growth (Robert 2001). With less detritus produced, the reduced soil cover not only enables higher rates of erosion but also accelerates the oxidation rates of soil organic matter (Soembroek et al. 1993). By wind and water erosion, some 500 Mt C ha<sup>-1</sup> are lost yearly from agricultural soils (Lal 2000). In the first 10 years of cultivation, up to 50% of the original SOC pool may leave the agroecosystem (Lal 1996). An estimated 12% of the world's terrestrial soil C is found in agroecosystems (Dixon 1995).

Soil C has been referred to as a total, organic C pool (Sommer et al. 2000; Szott and Palm 1996) though the term total C may be of limited use as an indicator of soil fertility (Szott et al. 1991). Other studies divide the soil C pool into different fractions according to the length of time that it takes for C to decompose (Robert 2001; Szott et al. 1991) though there is no standardized method for the separation of C into pools of different turnover times (Trumbore 1997). One conceptualization of soil organic matter (OM) and soil C is of a pool with different turnover rates or the active, intermediate and passive fractions. The rate of decomposition of organic matter depends on the biogeochemical composition, for example, the physical protection through the encapsulation of organic matter with clay particles. Chemical protection refers to the bonds of organic matter with colloids or clays (Robert 2001). In terms of size, the active or labile fraction is small (roughly 5%), a source of microbial decomposition and nutrient availability, and turns over in less than a year or

several years. The intermediate fraction is relatively large (60–85%) and has a turnover rate of 10–100 years. The passive fraction is 10–40% of the total pool size, composed of humified, inert intra-micro-aggregate material and decomposes at rates spanning thousands of years (Robert 2001; Townsend et al. 1997; Trumbore 1997; Veldkamp 1994; Szott et al. 1991; Parton et al. 1987).

Most of the C entering soils as decomposed biomass becomes part of the active fraction, with only a fraction becoming part of the less dynamic, inorganic carbonate carbon pool (Robert 2001; Powell and Delaney 1998; Soembroek et al. 1993). However, the active fraction is not necessarily limited to the topsoil as tree roots can drive C cycling to greater depths (Trumbore 1997). One feature of tropical rainforests is the low level of carbonate carbon due to the high rates of solubilization and leaching of carbonates from the weathered parent material (Soembroek et al. 1993). Changes in land use, however, mostly affect the organic matter layer and not the inorganic carbonate (Powell and Delaney 1998).

In order to attain the initial carbon values of a natural forest, decades may be needed for natural regeneration or afforestation. For example, while the mean above-ground biomass of three remnant-secondary (age unspecified) forests was 175.5 t C ha<sup>-1</sup> or 390 t C ha<sup>-1</sup> in Lampung, Indonesia, a 20-year-old fallow had 76.5 t C ha<sup>-1</sup>. In contrast, a one-year-old fallow had only 4.1 t C ha<sup>-1</sup> (van Noordwijk et al. 2002). In Katu, an enclave in Lore Lindu National Park, Central Sulawesi, the fallow biomass started with 2.3 t C ha<sup>-1</sup> at year one and reached 5.9 t C ha<sup>-1</sup> (excluding trees >5 m height) at year six. Including trees >5 m height, a total of 24.23 t C ha<sup>-1</sup> was attained (Schmohl 2002).

Agroforestry systems such as silviculture, agro-silviculture, tree fences or plantation crops possess an above-ground C sequestration potential of 3–25 and up to 60 t C ha<sup>-1</sup> (Kürsten and Burschel 1993). One study showed the above-ground biomass of a generic, simple five-year-old agroforest at 18.2 t C ha<sup>-1</sup> (equivalent to 65 t biomass ha<sup>-1</sup>). At 23.1 years, the agroforest amassed 75 t C ha<sup>-1</sup> (equivalent to 130 t ha<sup>-1</sup>) (Woomer et al. 2000).

The biomass levels of agroforestry systems have been estimated by destructive and non-destructive methods. To circumvent large-scale destructive

sampling, models using allometry have been developed for a number of tropical agroforestry tree species. In Costa Rica, models of leafy and woody components accurately estimated ( $r = 0.90\text{--}0.96$ ) the biomass of cocoa (*Theobroma cacao* L.) trees five and 10-years old. The basal area of all branches ( $>5$  cm diameter at one m intervals) was converted to mass and summed per tree (Beer et al. 1990). Alpízar et al. (1986) measured the height and diameter of cocoa trunks and branches, specific weight of wood as well as the number of leaves and related these to biomass.

In Kenya, grevillea (*Grevillea robusta* A. Cunn.) biomass was accurately estimated by allometry which required measuring the diameters of all branches. An alternative method based on the trunk's cross-sectional area (csa) substantially reduced time and highly correlated ( $r = 0.99$ ) to actual total canopy mass (Lott et al. 2000). A linear equation for gliricidia (*Gliricidia sepium* (Jacq.) Steud.) biomass was developed by Stewart et al. (1992) in which tree height and summed total diameter<sup>2</sup> of all branches were highly correlated to biomass ( $r = 0.82\text{--}0.99$ ). Below-ground, gliricidia and coffee (*Coffea* spp.) roots followed fractal branching rules in Guadeloupe (Ozier-Lafontaine et al. 1999) and Indonesia (van Noordwijk et al. 2002). Another approach for the estimation of biomass is known as Functional Branch Analysis (FBA). The premise of FBA is that trees follow fractal (self-repeating) branching rules (van Noordwijk 2002; van Noordwijk and Mulia 2002; Mulia 2001; Spek and van Noordwijk 1994; van Noordwijk et al. 1994). An advantage of FBA over other models is that once parameterized, the biomass of subsequent trees can easily be estimated by the measurement of the trunk diameter at a specified height.

Along the forest margin of Lore Lindu National Park, Central Sulawesi, Indonesia, large forested areas continue to be illegally clear cut and planted to cocoa and the shade tree gliricidia. The expansion of cocoa cultivation into protected areas of Central Sulawesi has been supported by a favorable world market price and lax law enforcement. It is imperative to understand, given the current circumstances, the contribution of cocoa–gliricidia agroforestry systems within local, regional or global carbon cycles. Where carbon losses, especially SOC, are great the question of the system's sustainability increases in relevance.

In a false-time series (a comparison of sites of similar agroecological conditions though varying in age) conducted in Napu and Palolo Valleys of Central Sulawesi, the investigation set out to quantify the temporal changes in tree carbon density and SOC in cocoa–gliricidia agroforests. In this study, FBA was the method by which tree growth was estimated. The overall hypothesis maintains that cocoa–gliricidia agroforestry, compared to the benchmark C-stock of a natural forest, is a sustainable land use system.

## Materials and methods

### Site location and climate

During November–December 2002, agroforests aged 1–15 years after forest conversion were located near the perimeter of Lore Lindu National Park, Central Sulawesi. In Napu Valley, six agroforests were used in the survey and aged one, one and a half, three, four, five and eight-years old. The agroforests were located near the villages of Wuasa and Kaduwaa at an elevation of 1,139–1,166 m a.s.l. In Palolo Valley, eight agroforests were surveyed in the villages of Makmur, Nopu and Pangana. The elevation of the agroforests in Palolo Valley ranged from 592 to 651 m a.s.l. The age of the agroforests in Palolo Valley was two, two and a half, three, four, five, nine, 12 and 15-years old.

Rainfall was collected by STORMA-managed climatic stations in Wuasa (Napu Valley) and Nopu (Palolo Valley) from 1 January 2002 to 31 December 2002. During 2002, 1,543 mm year<sup>-1</sup> rainfall and a mean temperature of 21.1°C were recorded in Wuasa. During the same time span, Nopu received more rainfall (1,811 mm year<sup>-1</sup>) and had a slightly higher mean temperature of 24.5°C.

### Biomass and carbon

Trees were randomly selected by throwing a marked stick into the agroforest. From this point, the first tree was chosen and its trunk diameter was measured twice (to account for non-cylindrical trunks) at 50 cm height. The next tree was selected along the same row until the row ended or an obstacle impeded further measurements. If a tree branched below 50 cm height, the next tree in the row was measured

instead. In total, 45 cocoa and 45 gliricidia species were measured per agroforest.

Tree diameter was averaged (two diameter measurements per tree) and related to an allometric equation in the form of  $y = aD^b$  as derived by FBA (Smiley 2006). The allometric formulae were calculated for the cocoa shoot and for the proximal cocoa root (Table 1). The root equation was applied to the diameters of 17 proximal roots. The relationship between above- and below-ground dry weight (DW) of the three-year-old cocoa tree resulted in a shoot–root (S–R) ratio of 2.54. Therefore, in every agroforest in the false-time series, the below-ground cocoa biomass was determined using this ratio. Allometric formulae were calculated for gliricidia, also measured at 50 cm height. In the three-year-old agroforest, the gliricidia tree had 13 proximal roots which, after summation of root values, resulted in a shoot–root ratio of 2.05.

For the conversion of above- and below-ground tree biomass to C, the factor 0.45 was used. Conversion factors vary from 0.40 to 0.50 C (Snowdon et al. 2000; Brown 1997). The conversion factor of 0.45 C was used for coffee in Indonesia (van Noordwijk et al. 2002).

### Soil organic carbon

With a Pürckhauer soil corer (two cm diameter) and 6–8 replications per site, soil samples were collected at 0–15, 15–30, 30–60 and 60–100 cm depths. Per stratum, soil was homogenized and air dried. To relate soil C to a  $\text{kg ha}^{-1}$  basis, bulk density results from 30 to 45 cm were related to the soil C results of 30–60 cm; bulk density results from 45 to 60 cm were assumed to be valid for 60–100 cm. Carbon (C) was analyzed at the Institute of Agricultural Chemistry, University of Hohenheim. In this article, only soil C is discussed and treated as a total C pool.

**Table 1** Allometric formula for cocoa and gliricidia components (DW)

Component	Formula
Cocoa shoot	$0.202 \text{ kg} \times \text{Dia}^{2.112}$
Cocoa root	$0.142 \text{ kg} \times \text{Dia}_{\text{prox}}^{2.064}$
Gliricidia shoot	$0.294 \text{ kg} \times \text{Dia}^{2.269}$
Gliricidia root	$0.064 \text{ kg} \times \text{Dia}_{\text{prox}}^{2.152}$

Bulk density was determined at 0–15, 15–30, 30–45 and 45–60 cm depths using an Eijkelkamp root corer of eight cm diameter as the proper bulk density instrument was not available. The height and fresh weight of samples were measured immediately in the field, oven-dried at 105°C for >3 days and weighed again. Bulk density was calculated based on the volume of each sample divided by its DW. To determine the weight of soil per stratum, the equation of Arias Sánchez et al. (2001) was applied:

$$\text{DW}(\text{t ha}^{-1}) = \text{area of one ha}(10,000 \text{ m}^2) \\ \times \text{depth of stratum(m)} \\ \times \text{bulk density}(\text{gm}^{-3}).$$

SOC was estimated by multiplying the weight of each stratum by percentage C.

### Statistical analysis

Using SigmaStat ver. 3.0, data were subjected to the Analysis of Variance (ANOVA). If data did not adhere to normal distribution or equal variance tests, the Kruskal–Wallis ANOVA on Ranks was used instead. Significant means ( $P < 0.05$ ) were separated with the Tukey-Test. In comparisons where gliricidia was removed from the agroforest and thus its diameter equaled zero, these cases were excluded from statistical analysis. However, these cases were considered statistically different subsets in order to fulfill the requirements of the standard ANOVA procedure. Figures were produced with SigmaPlot ver. 8.0.

## Results

### Tree density

In both valleys, the surveyed cocoa agroforests had a spacing of  $3 \times 3 \text{ m}$  ( $1,111 \text{ trees ha}^{-1}$ ). While the spacing of cocoa remained constant over time, gliricidia was reduced from  $3 \times 3 \text{ m}$  to  $3 \times 6 \text{ m}$  ( $555 \text{ trees ha}^{-1}$ ) and  $3 \times 9 \text{ m}$  ( $370 \text{ trees ha}^{-1}$ ) during years five and eight (Table 2). In the eight-year-old agroforest sampled in Napu Valley, gliricidia was still present. In contrast, gliricidia was removed after year five in Palolo Valley. However, the present study does not rule out the possibility of remnant gliricidia in older cocoa agroforests although this would be an exception to the rule.

**Table 2** Age of agroforest and gliricidia density in Napu and Palolo

Age	Density in Napu	Age	Density in Palolo
1	1,111	2	1,111
1.5	1,111	2.5	1,111
3	555	3	555
4	555	4	555
5	555	5	370
8	370	9	0
		12	0
		15	0

### Formation of trunk diameter

#### Napu

In Napu, trunk diameter was measured on 270 cocoa and 270 gliricidia trees ( $n = 45$  per species and site). Starting at one cm diameter, the trunk diameter of cocoa increased 1.20 cm annually until year eight (based on 9.57 cm at year eight divided by number of years). At year eight, the trunk diameter of cocoa exceeded that of gliricidia (Table 3). At year three, the diameter of the sampled cocoa trees returned a large value of 8.31 cm. This high value may have been due to a farmer misstating the tree's actual age and/or the site having more favorable soil properties. In contrast, gliricidia was propagated from stakes and therefore started with a large girth of 6.04 cm diameter at year one. Its trunk diameter increased to 10.42 cm at year four or a yearly increment of

**Table 3** Cocoa–gliricidia trunk diameters at 50 cm height, Napu.

Age	Cocoa diameter (cm)	Gliricidia diameter (cm)
1	1.00 a (0.04 <sup>a</sup> )	6.04 a (0.14 <sup>a</sup> )
1.5	1.58 a (0.08)	7.76 b (0.19)
3	8.31 c (0.22)	7.27 b (0.23)
4	5.80 b (0.17)	10.42 c (0.42)
5	5.29 b (0.20)	9.81 c (0.29)
8	9.57 c (0.20)	7.27 b (0.32)
	$y = 1.101x + 1.129$ , $r = 0.82^*$	$y = 0.190x + 7.383$ , $r = 0.29$ ns

<sup>a</sup> Means and standard error. Different letters represent statistically significant subsets

\* Significant at  $P < 0.05$

1.10 cm diameter over 4 years. However, as gliricidia was propagated from stakes of varying diameter, there was no clear connection between age of agroforest and trunk diameter of gliricidia. When deemed too competitive to the growth of cocoa, a gliricidia tree may also be removed and replaced by a new gliricidia tree.

#### Palolo

In Palolo Valley, 360 cocoa trees and 225 gliricidia trees were measured in eight agroforests ( $n = 45$  per species and site). The exceptions were years nine, 12 and 15 where no gliricidia was present. At year two, the diameter of cocoa was a relatively large 3.88 cm (Table 4). At year 15, the diameter of cocoa reached 12.88 cm or an annual increment of 0.86 cm. Conversely, gliricidia started at 5.50 cm and reached 14.89 cm at year five or an annual increment of 1.88 cm. While initially lower than gliricidia, the trunk diameter of cocoa did not surpass that of gliricidia until year nine. The removal of gliricidia after year five simplified the structure of agroforests. Due to the removal of gliricidia after year five, and assuming a trunk diameter of zero, the regression equation becomes negative.

**Table 4** Cocoa–gliricidia trunk diameters at 50 cm height, Palolo

Age	Cocoa diameter (cm)	Gliricidia diameter (cm)
2	3.88 a (0.22 <sup>a</sup> )	5.50 b (0.74 <sup>a</sup> )
2.5	7.75 b (0.25)	11.64 c (0.34)
3	6.92 b (0.27)	12.10 c (0.40)
4	5.84 ab (0.22)	11.02 c (0.33)
5	10.33 c (0.30)	14.89 d (0.54)
9	12.27 cd (0.35)	0 a <sup>b</sup> (0)
12	11.81 cd (0.26)	0 a (0)
15	12.88 d (0.19)	0 a (0)
	$y = 0.590x + 5.085$ , $r = 0.86^{**}$	$y = -1.008x + 13.507$ , $r = 0.78^*$

<sup>a</sup> Means and standard error. Different letters represent statistically significant subsets. \*\*\* Significant at  $P < 0.05$ , 0.01

<sup>b</sup> As no gliricidia was present in years 9–15 these age groups were not included in ANOVA (as they result in abnormal distribution) but considered a statistically significant subset

## Carbon stocks

*Napu*

As the relationship of trunk diameter to aerial C was based on constants, the statistically significant subsets were the same as in the case of the trunk diameter of cocoa. However, this did not pertain to gliricidia due to its lower stocking density after year three (Smiley 2006). For example, on a per tree basis ( $\text{kg tree}^{-1}$ ), gliricidia weighed much more than cocoa. Even the root biomass of gliricidia exceeded that of the aerial cocoa biomass. At year eight, the aerial cocoa biomass (or carbon) reached a level similar to that found in gliricidia.

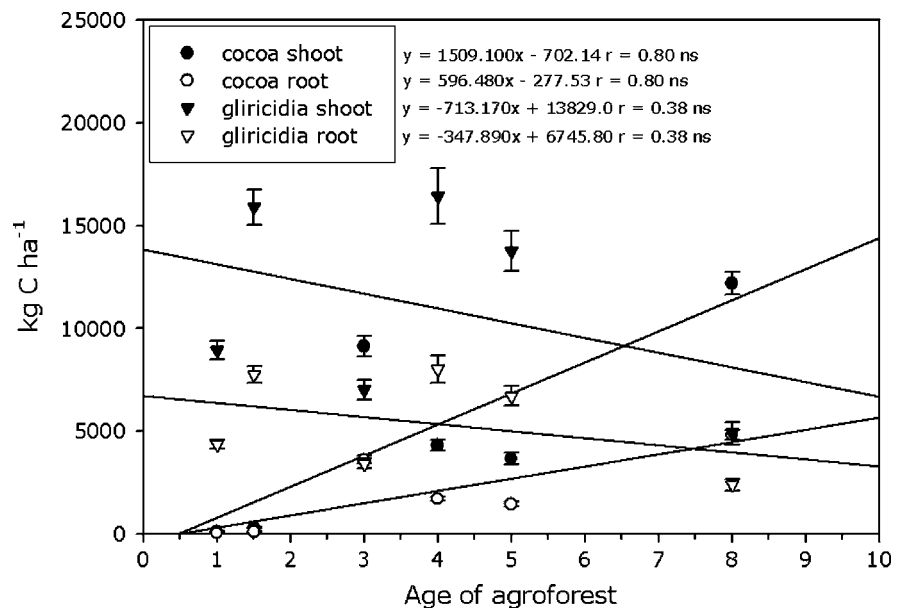
On a per hectare basis, the statistical subsets were the same for cocoa, yet changed for gliricidia due to its reduced stocking density. The much lower stocking density and the smaller trunk diameter of gliricidia at year eight led to its C value being much lower than that of its five-year-old counterpart. At year eight, the C value of gliricidia was even lower than its year one value. Still, the C value of aerial gliricidia was greater than that of aerial cocoa on a per  $\text{kg tree}^{-1}$  and per  $\text{kg ha}^{-1}$  basis, except during the latter stage (with the exception of year three).

At year one, the aerial contribution of cocoa was  $111.7 \text{ kg C ha}^{-1}$  (Fig. 1). At year eight, it reached  $12,185.8 \text{ kg C ha}^{-1}$  or  $1,523.2 \text{ kg C ha}^{-1} \text{ year}^{-1}$

fixed annually. Also at year one, the aerial contribution of gliricidia was  $8,942.4 \text{ kg C ha}^{-1}$  and reached its highest value of  $16,423.6 \text{ kg C ha}^{-1}$  at year four. At year eight, however, it was reduced to  $4,903.6 \text{ kg C ha}^{-1}$ . From years 1–4, there was an increase of  $4,105.9 \text{ kg C ha}^{-1} \text{ year}^{-1}$ . After year four, due to its reduced stocking density, a loss of  $2,880.0 \text{ kg C ha}^{-1} \text{ year}^{-1}$  occurred (based on years 5–8). By only considering the aerial components of cocoa–gliricidia, year four was the highest at  $20,745.2 \text{ kg C ha}^{-1}$ . At year eight, this decreased to  $17,089.4 \text{ kg C ha}^{-1}$  or a decrease of  $914.0 \text{ kg C ha}^{-1} \text{ year}^{-1}$  over 4 years. The percentage of gliricidia's contribution to the total C-stock was highest (98%) during years 1–1.5 but fell to 45% at year three, to 80% at years 4–5 and finally to 30% at year eight.

While the total shoot–root system increased during years 1–8, or  $7,616.2 \text{ kg C ha}^{-1} \text{ year}^{-1}$ , there was a loss of  $6,166.9 \text{ kg C ha}^{-1}$  (or  $1,541.7 \text{ kg C ha}^{-1} \text{ year}^{-1}$  based on years 4–8) after year four. Year four had the highest system C due to the presence of gliricidia. However, at year eight the total shoot–root system of both species was 80% of the year four value. Therefore, in the relatively short (1–8 year) time span under consideration, the system remained stable as gliricidia was not completely removed and cocoa continued to grow.

**Fig. 1** Carbon density of the cocoa–gliricidia shoot and root, Napu. ns = not significant





## Palolo

As in Napu, the biomass ( $\text{kg tree}^{-1}$ ) of gliricidia in Palolo was much greater than that of cocoa. For example, at year five, the magnitude was about 18 times more than that of cocoa. In all age classes (until its removal at year nine), the shoot–root biomass of gliricidia exceeded that of the shoot–root biomass of cocoa. However, the removal of gliricidia at or around year five led to a negative regression curve.

While the subsets of cocoa remained the same on a per hectare basis, the lower stocking density of gliricidia formed new subsets. On a  $\text{kg ha}^{-1}$  basis, the highest DW was attained at year two and a half and decreased at year five. At year two, gliricidia biomass was 5.1 times greater than cocoa biomass. At year five, this was reduced to only 1.7 times greater than cocoa biomass.

In Palolo, the aerial C-stocks of cocoa rose fairly steadily from years 2 to 15. An annual  $1,502.7 \text{ kg C ha}^{-1} \text{ year}^{-1}$  was added by aerial components of cocoa (Fig. 2). Of all age classes, year two and a half had the highest gliricidia density which either meant that it was planted well in advance of cocoa and/or it was propagated from stakes of large girth. With such uncertainty, year five was considered the end stage of gliricidia's development. Therefore, until year five, gliricidia fixed  $4,853.4 \text{ kg C ha}^{-1} \text{ year}^{-1}$ . While gliricidia contributed 80–82% of the

total C stocks from years 2 to 2.5, its contribution declined to 64% at year five.

The total, cocoa–gliricidia shoot C had its highest value of  $38,857.0 \text{ kg C ha}^{-1}$  at year five, or a yearly increment of  $7,771.4 \text{ kg C ha}^{-1} \text{ year}^{-1}$ . The removal of gliricidia meant a loss of  $16,316.2 \text{ kg C ha}^{-1}$  over 10 years, ending at  $22,540.8 \text{ kg C ha}^{-1}$  at year 15. Including roots, the highest C-stock was  $56,461.3 \text{ kg C ha}^{-1}$  at year five or an annual fixation of  $11,292.3 \text{ kg C ha}^{-1} \text{ year}^{-1}$ . In terms of C-stocks, an older, monocropped cocoa plantation had a reduced level of C. At year 15, it was determined that 56% of year five's C-stock remained.

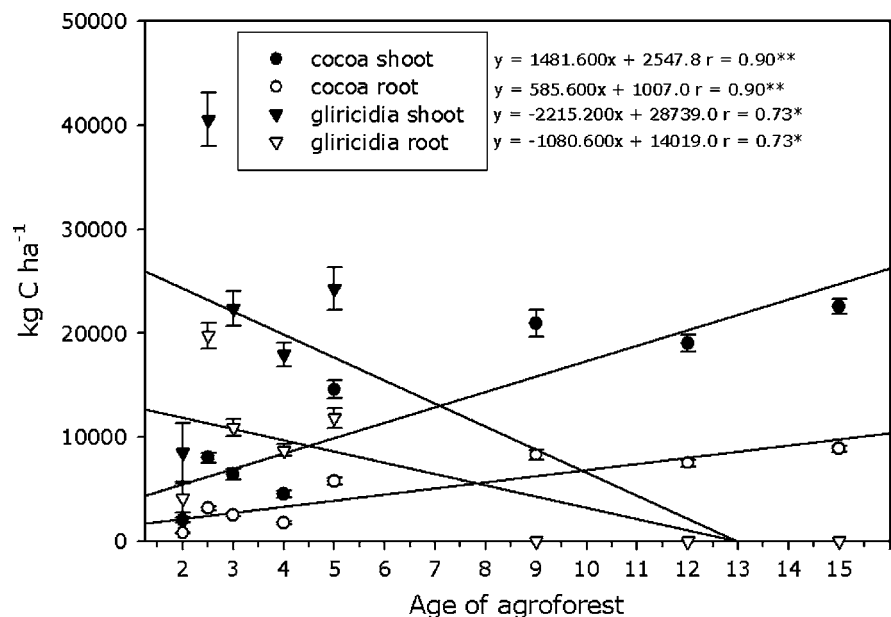
In comparing the results of Napu and Palolo, the annual fixation of C was similar for the cocoa shoot ( $1,523.2$  and  $1,502.7 \text{ kg C ha}^{-1} \text{ year}^{-1}$  for Napu and Palolo, respectively) and for the gliricidia shoot ( $4,105.9$  and  $4,853.4 \text{ kg C ha}^{-1} \text{ year}^{-1}$  for Napu and Palolo, respectively). However, the total shoot and shoot–root values were much higher in Palolo.

## Vertical-temporal development of SOC

### Napu

In Napu, more than half of the SOC was stored in the 0–15 cm stratum (Table 5). Temporally, there was no great change in SOC (based on a mean of 0–100 cm).

**Fig. 2** Carbon density of the cocoa–gliricidia shoot and root, Palolo.  
\*\*\* Significant at  $P < 0.05, 0.01$



**Table 5** The vertical-temporal distribution of SOC (%), Napu

Age	0–15 cm	15–30 cm	30–60 cm	60–100 cm	Mean 0–100 cm	% 0–15 cm
1	2.95	0.94	0.44	0.21	1.14 a (0.62 <sup>a</sup> )	65
1.5	3.01	2.11	0.38	0.38	1.47 a (0.88)	51
3	4.63	1.39	1.40	0.69	2.03 a (0.66)	57
4	3.37	1.34	1.50	0.12	1.58 a (0.67)	53
5	2.17	1.07	0.50	0.20	0.99 a (0.43)	55
8	2.27	1.13	0.44	0.19	1.01 a (0.47)	56

<sup>a</sup> Means and standard error. Different letters represent statistically significant subsets

**Table 6** The vertical-temporal distribution of SOC (kg C ha<sup>-1</sup>), Napu

Age	0–15 cm	15–30 cm	30–60 cm	60–100 cm	0–100 cm
1	61,950 [1.4 <sup>a</sup> ]	22,560 [1.6]	21,120 [1.6]	13,440 [1.6]	119,070 a (10,912.64 <sup>b</sup> )
1.5	63,210 [1.4]	37,980 [1.6]	13,680 [1.6]	19,760 [1.6]	134,630 a (11,121.58)
3	76,395 [1.1]	25,020 [1.2]	54,600 [1.3]	41,400 [1.5]	197,415 a (10,855.67)
4	70,770 [1.4]	24,120 [1.2]	54,000 [1.2]	6,240 [1.3]	155,130 a (14,516.59)
5	45,570 [1.4]	24,075 [1.5]	25,500 [1.7]	13,600 [1.7]	108,745 a (6,677.52)
8	40,860 [1.2]	22,035 [1.3]	19,800 [1.5]	12,920 [1.7]	95,615 a (5,975.58)

<sup>a</sup> Soil bulk density or g cm<sup>-3</sup> was sampled at increments of 0–15, 15–30, 30–45 and 45–60 cm and is given within brackets

<sup>b</sup> Sum and standard error. Different letters represent statistically significant subsets

<sup>c</sup> No data available

Per hectare in Napu, the SOC increased during years 1–4 (Table 6). After year four, SOC values dropped. This reduction was likely due to site-specific heterogeneity rather than land use. In Napu, as there were no older agroforests in the false-time series, it was not possible to assess long-term changes in SOC.

### Palolo

Compared to Napu, in Palolo the SOC was more equally distributed amongst strata with about a third of SOC found in the 0–15 stratum (Table 7). This may have been due to the higher annual rainfall and temperature in Palolo that led to greater root activity

**Table 7** The vertical-temporal distribution of SOC (%), Palolo

Age	0–15 cm	15–30 cm	30–60 cm	60–100 cm	Mean 0–100 cm	% 0–15 cm
2	1.63	1.36	1.04	0.46	1.12 a (0.25 <sup>a</sup> )	36
2.5	1.50	1.16	1.16	0.37	1.05 a (0.19)	36
3	1.94	1.53	1.14	0.41	1.26 a (0.33)	39
4	1.35	1.15	0.86	0.47	0.96 a (0.28)	35
5	1.93	1.23	1.11	0.56	1.21 a (0.36)	40
9	1.26	1.10	1.07	0.48	0.98 a (0.24)	32
12	1.91	1.80	1.14	0.35	1.30 a (0.17)	37
15	2.76	1.41	1.26	0.58	1.50 a (0.46)	46

<sup>a</sup> Means and standard error. Different letters represent statistically significant subsets



**Table 8** The vertical-temporal distribution of SOC ( $\text{kg C ha}^{-1}$ ), Palolo

Age	0–15 cm	15–30 cm	30–60 cm	60–100 cm	0–100 cm
2	34,230 [1.4 <sup>a</sup> ]	28,560 [1.4]	46,800 [1.5]	27,600 [1.5]	137,190 a (4,416.75 <sup>b</sup> )
2.5	33,750 [1.5]	24,360 [1.4]	48,720 [1.4]	22,200 [1.5]	129,030 a (6,033.00)
3	34,920 [1.2]	27,540 [1.2]	47,880 [1.4]	22,960 [1.4]	133,300 a (5,441.29)
4	28,350 [1.4]	24,150 [1.4]	36,120 [1.4]	28,200 [1.5]	116,820 a (2,501.85)
5	40,530 [1.4]	20,295 [1.1]	39,960 [1.2]	26,880 [1.2]	127,665 a (4,994.30)
9	28,350 [1.5]	23,100 [1.4]	44,940 [1.4]	32,640 [1.7]	129,030 a (4,655.83)
12	40,110 [1.4]	37,800 [1.4]	47,880 [1.4]	18,200 [1.3]	143,990 a (6,312.07)
15	45,540 [1.1]	27,495 [1.3]	52,920 [1.4]	34,800 [1.5]	160,755 a (5,633.90)

<sup>a</sup> Soil bulk density or  $\text{g cm}^{-3}$  was sampled at increments of 0–15, 15–30, 30–45 and 45–60 cm and is given within brackets

<sup>b</sup> Sum and standard error. Different letters represent statistically significant subsets

and rates of weathering, forcing more C turnover, decomposition and leaching to the lower strata. Temporally, there was no large difference in SOC (based on a mean of 0–100 cm) although years 12 or 15 indicated a slight increase.

Per hectare, the SOC remained relatively stable and even increased during years 12–15 (Table 8).

#### Total system carbon

#### Napu

In Napu, the bulk of the total system C was in the soil (Table 9). The highest system C levels were during years 1.5–4 but these values were due to the higher SOC rather than to the shoot–root C. The decrease in system C following year four appeared to be caused by heterogeneous soil conditions rather than the soil bulk density.

**Table 9** The temporal development of cocoa–gliricidia biomass and soil to system carbon ( $\text{kg C ha}^{-1}$ ), Napu

Age	Shoot–root C	SOC [0–100 cm]	System total C
1	13,460.3 <sup>a</sup>	119,070	132,530.3
1.5	24,058.5	134,630	158,688.5
3	23,191.7	197,415	220,606.7
4	30,464.9	155,130	185,594.9
5	25,597.4	108,745	134,342.4
8	24,298.0	95,615	119,913.0

<sup>a</sup> Summation of cocoa–gliricidia shoot–root biomass

**Table 10** The temporal development of cocoa–gliricidia biomass and soil to system carbon ( $\text{kg C ha}^{-1}$ ), Palolo

Age	Shoot–root C	SOC [0–100 cm]	System total C
2	15,551.5	137,190	152,741.5
2.5	71,453.8	129,030	200,483.8
3	42,329.9	133,300	175,629.9
4	32,944.9	116,820	149,764.9
5	56,461.3	127,665	184,126.3
9	29,258.2	129,030	158,288.2
12	26,557.6	143,990	170,547.6
15	31,450.1	160,755	192,205.1

#### Palolo

As in Napu Valley, the above- and below-ground tree biomass in Palolo usually contributed a smaller proportion to the total system C. Thus, a large amount of a system's C was located in the soil. Temporally, it appeared that the total system C remained fairly stable (Table 10).

## Discussion

In the assessment of the carbon sequestration potential of cocoa-based agroforestry, a main problem in comparing results is the wide variation in tree spacing, the growing of gliricidia for shade or other uses such as providing fuelwood, or the type of shade tree used. For instance, Beer et al. (1990) found significant differences in cocoa growth depending on species of shade tree, either *Cordia alliodora* (R + P)

Oken or *Erythrina poeppigiana* (Walper) O.F. Cook. While cocoa biomass at year five was similar under both shade trees (9.8 and 8.3 t ha<sup>-1</sup> with *C. alliodora* or *E. poeppigiana*, respectively), at year 10 cocoa grown with *C. alliodora* had much higher biomass. At year five, a large proportion (31–34%) of biomass was tied up in leafy material. However, at year 10 the proportion fell to 10% and 13% with *C. alliodora* or *E. poeppigiana*, respectively, as the proportion of wood increased.

Beer et al. (1990) reviewed data of Aranguren et al. (1982) for 30-year-old cocoa (950 trees ha<sup>-1</sup>) grown under shade. The total above- and below-ground biomass of cocoa was 17.1 t ha<sup>-1</sup>. Fine root (FR) biomass ( $\leq 2$  mm) of the five-year-old cocoa was 4.2 and 1.8 t ha<sup>-1</sup> with *C. alliodora* and *E. poeppigiana*, respectively (Beer et al. 1990). At year 10, the values increased to 9.8 and 5.7 t ha<sup>-1</sup>, respectively. For 30-year-old cocoa under shade, Aranguren et al. (1982) estimated root biomass of 7.3 t ha<sup>-1</sup>.

To date, however, no comparable study of cocoa–gliricidia agroforestry has been undertaken. Various studies have looked at the potential of gliricidia for its biomass production. In the tropical, premontane wet forest of Central America, for example, a 30-year-old stand of gliricidia at 330 trees ha<sup>-1</sup> resulted in 312.7 kg tree<sup>-1</sup> or 51.6 t C ha<sup>-1</sup> (Salazar 1984; cited in Kürsten and Burschel 1993, p. 535). However, no below-ground data on gliricidia were found in the literature. Dixon (1995) estimated the potential C storage (above- and below-ground C) for agrosilvicultural and silvopastoral agroforestry systems in the humid tropical lowlands and highlands. For the humid tropical lowlands, the range was 39–102 t C ha<sup>-1</sup> in Brazil and 92–228 t C ha<sup>-1</sup> in India. For the humid tropical highlands, agrosilvicultural systems ranged from 29 t C ha<sup>-1</sup> in Congo, 53 t C ha<sup>-1</sup> in Zaire, to 133–154 t C ha<sup>-1</sup> in a silvopastoral system in Mexico. Agrosilvicultural systems in the dry lowlands of Brazil yielded between 88 and 195 t C ha<sup>-1</sup>; in India the range was 68–81 t C ha<sup>-1</sup> (Dixon 1995). Schroeder (1994) found that the above-ground biomass of a sub-humid forest contained 21 t C ha<sup>-1</sup> while a humid forest stored 50 t C ha<sup>-1</sup>. In Guatemala, the combined above-ground woody biomass of coffee and shade trees (e.g. *Inga* spp., *Grevillea robusta*, *Alnus* spp.) was determined to be 27.3 t C ha<sup>-1</sup> (Powell and Delaney 1998). In coffee grown with shade in Indonesia, van Noordwijk et al. (2002) recorded an average, above-

ground biomass of coffee at 18.4 t C ha<sup>-1</sup>. During the establishment phase, the magnitude was one, almost two or 3.5 t C ha<sup>-1</sup> year<sup>-1</sup> for sun coffee, shade coffee and fallow growth, respectively.

In Zambia, at 2,500 gliricidia ha<sup>-1</sup>, Kwesiga (1994; cited in Stewart 1996, p. 34) reported a total (wood only) weight of 2.5–10.8 kg tree<sup>-1</sup> for gliricidia at 2.25 years and 2.9–11.5 kg tree<sup>-1</sup> for 3.25-year-old gliricidia. Per hectare, this amounted to 2.9–12.6 and 3.3–12.9 t C ha<sup>-1</sup> for years 2.25 and 3.25, respectively. In Napu, the present study found that the aerial biomass of gliricidia ranged from 8.9 to 16.4 t C ha<sup>-1</sup> for years one and four, respectively. At year eight, the aerial biomass of gliricidia fell to 4.9 t C ha<sup>-1</sup>. In Palolo, the aerial values of gliricidia ranged from 8.5 to 24.3 t C ha<sup>-1</sup> for years one and five, respectively.

In the present study, the figure of 12.2 t C ha<sup>-1</sup> for the aerial biomass of cocoa grown with gliricidia (year eight in Napu Valley) coincided with the 12.2 t C ha<sup>-1</sup> for cocoa grown with *E. poeppigiana* in Costa Rica. With *C. alliodora*, however, the 10-year-old cocoa in Costa Rica generated more carbon (16.2 t C ha<sup>-1</sup>) (Beer et al. 1990). In comparison, the aerial biomass of cocoa (year nine in Palolo Valley) in the present study produced 21.0 t C ha<sup>-1</sup>. In 30-year-old cocoa at 950 trees ha<sup>-1</sup> grown under shade, Beer et al. (1990), citing research by Aranguren et al. (1982), calculated a total of 7.7 t C ha<sup>-1</sup> (17.1 t ha<sup>-1</sup>). A study in Ghana by Isaac et al. (2005) estimated the above-ground C stocks of cocoa at 2.4, 16.8 and 15.9 t C ha<sup>-1</sup> for 2, 15 and 30-year-old cocoa, respectively. A direct comparison of the Ghanaian study with the present study is difficult as their stocking densities ranged from 3,125, 1,362 and 900 trees ha<sup>-1</sup> for the 2, 15 and 30-year-old cocoa, respectively.

Using the initial, above-ground biomass of a natural forest as a reference value, the impact of forest conversion and the establishment of cocoa–gliricidia agroforestry was inferred. Before forest conversion, an average of 173.2 t C ha<sup>-1</sup> was estimated from four values referenced in the literature: 219.6 t C ha<sup>-1</sup> for tropical rainforests (Woomer et al. 2000); an aerial biomass of 126–173.3 t C ha<sup>-1</sup> in Sarawak, Malaysia, derived by multiplying the original figures of 280–385 t ha<sup>-1</sup> (Government of Malaysia 1987; cited in Brown 1997) by the conversion factor of 0.45; and a remnant-secondary forest at

175.5 t C ha<sup>-1</sup> in Lampung, Indonesia (van Noordwijk et al. 2002). In Napu, the combined above-ground output of cocoa–gliricidia C-stocks reached a maximum 12% (year four) and ended at 10% (year eight) of the initial forest C-stock. In Palolo, the distinct role of gliricidia to overall system productivity was evident. Above-ground C-stocks first peaked at 28% of the natural forest value at year two and a half and again at 22% at year five. This was due to the temporary storage of C in gliricidia but the compensation was later lost by the removal of gliricidia. At year 15, the system productivity fell to 13% of the natural forest value. Due to the slower growth rates of mature trees, it is probable that at later stages the proportion remains around 13%. After forest conversion and the establishment of agroforestry, C was degraded by 88% in Napu (year eight) and 87% in Palolo (year 15). In any particular year, the higher biomass values of Palolo were likely due to the lower elevation and higher rainfall.

The present study found SOC to be relatively stable considering the time spans in question. In the cocoa-based trial conducted in Costa Rica, after 10 years the SOM reserves of the 0–45 cm stratum increased from 198 to 240 t ha<sup>-1</sup> (with *E. poeppigiana*) and 168 to 184 t ha<sup>-1</sup> (with *C. alliodora*). As the SOM increased compared to the initial SOM, the system was deemed sustainable for at least 10 years or even longer in the case of *E. poeppigiana* (Beer et al. 1990). In comparison, a 25 year chronosequence of cocoa in Ghana reported that 22% of the soil C (from the 0 to 15 cm stratum) was lost in the first 2–15 years. However, by 25 years, 3.3% of the soil C was replenished in the agroecosystem (Isaac et al. 2005). When assessing the impact of forest conversion to agroforestry, a drawback of the false-time series is that young agroforests may have higher remnant SOC values from the previous tropical rainforest vegetation and thus give an initially high SOC value. Further studies that include agroforests older than eight or 15 years may elicit when changes in SOC occur and provide a better prognosis of long-term sustainability.

The present study found that aerial C gains due to increased tree productivity were nullified by the removal of gliricidia ca. 5–8 years after establishment. Without this additional source of litterfall or root turnover, and assuming that cocoa does not greatly surpass the size attained at year 15 due to its

growth habit, the typical monocropped cocoa agroforest could be a stable form of SOC storage. The inclusion of a shade or fruit tree with cocoa could increase the SOC. By allowing a companion tree to remain with cocoa, the farmer would benefit from the additive properties of tree growth rather than the economic loss incurred in the planting, controlling and removal of gliricidia. Alternatively, a permanently associated tree species such as a high-value timber or fruit species could enhance the C-stock as well as increase a farmer's income. But where the nutrient export or crop damage associated with timber production is large, such as in the case of *C. alliodora*, this may not lead to an economic advantage (Beer et al. 1990). In Sumatra, coffee integrated into forests without the cutting of the shade tree was more profitable than coffee grown without shade. Moreover, the total, time-averaged C-stocks were 30 t C ha<sup>-1</sup> higher for shade than sun coffee (van Noordwijk et al. 2002).

## Conclusion

In the initial years after the establishment of a cocoa-based agroforest, the system biomass and C-fixation were dominated by gliricidia as it was planted from stakes of large girth. In the interim, gliricidia was gradually controlled as it was deemed too competitive for the growth resources designated for cocoa. Furthermore, with the elapse of time, cocoa was no longer as dependent on the benefits of shade. Thus, the system experienced a loss of C when gliricidia was ultimately removed around years 5–8. Fifteen years after the clear cutting of a tropical rainforest, it is estimated that the aerial monocropped cocoa agroforestry attained about 13% of the original aerial C-stock. This low value would probably not greatly increase after 25–30 years given the growth habit of cocoa. In addition, SOC appeared to be relatively stable over time but the false-time series could have been influenced by remnant SOC, giving the younger agroforests relatively high SOC values. In terms of C-stocks, it therefore appeared that the cocoa–gliricidia system is sustainable but also harbors the potential to sequester more C, as well as being a better economic investment, if high-value companion trees are integrated into the system on a long-term basis.

**Acknowledgements** We are grateful to 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.

## References

- Alpízar L, Fassbender HW, Heuvelod 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
- Arias Sánchez K, Ruiz-Silvera C, Milla M, Fabio Messa H, Escobar A (2001) Almacenamiento de carbono por *Gliricidia sepium* en sistemas agroforestales de Yaracuy, Venezuela. *Livestock Research for Rural Development* (13) 5. <http://www.cipav.org.co/lrrd/lrrd13/5/ruiz135.htm>. Cited 27 June 2003
- 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
- Brown S (1997) Estimating biomass and biomass change of tropical forests. FAO, Rome, pp 1–55
- Dixon R (1995) Agroforestry systems: sources or sinks of greenhouse gases? *Agrofor Syst* 31:99–116
- Government of Malaysia (1987) Inventori hutan nasional II semenanjung Malaysia 1981–1982 Unit Pengurusan Hutan. Ibu Pejabat Perhutan, Semanananjung Malaysia, Kuala Lumpur
- Isaac ME, Gordon AM, Thevathasan N, Oppong SK, Quashie-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
- Kürsten E, Burschel P (1993) CO<sub>2</sub> mitigation by agroforestry. *Water, Air Soil Pollut* 70:533–544
- Kwesiga F (1994) Performance of fifteen provinces of *Gliricidia sepium* in eastern Zambia. *For Ecol Manage* 64(2/3):1616–1617
- Lal R (1996) Deforestation and landuse effects on soil degradation and rehabilitation in western Nigeria. II. Soil chemical properties. *Land Degrad Dev* 7:87–98
- Lal R (2000) Restorative effects of *Mucuna utilis* on soil organic C pool of a severely degraded Alfisol in Western Nigeria. In: Lal R, Kimble JM, Stewart BA (eds) *Global climate change and tropical ecosystems*. CRC Press LLC, Boca Raton, pp 147–156
- Lal R, Kimble J, Adilson Serrao E, Eswaran H (1997) Carbon pools and dynamics in tropical ecosystems. Recommendations and conclusions. In: *An international workshop* 1–5 Dec. 1997, Belem
- Lott JE, Howard SB, Black CR, Ong CK (2000) Allometric estimation of above-ground biomass and leaf area in managed *Grevillea robusta* agroforestry systems. *Agrofor Syst* 49:1–15
- Mulia R (2001) Brief explanation for WanFBA: a program for estimating shoot and root biomass. ICRAF, Bogor
- Ozier-Lafontaine H, Lecompte F, Sillon JF (1999) Fractal analysis of the root architecture of *Gliricidia sepium* for the spatial prediction of root branching, size and mass: model development and evaluation in agroforestry. *Plant Soil* 209:167–180
- Parton WJ, Schimel DS, Cole CV, Ojima DS (1987) Analysis of factors controlling soil organic matter levels in the Great Plains grasslands. *Soil Sci Soc Am J* 51:1173–1179
- Powell M, Delaney M (1998) Carbon sequestration and sustainable coffee in Guatemala. Final report. Winrock International. <http://www.winrock.org/fact/facts.cfm?BU=9058&CC=5146>. Cited 28 July 2003
- Robert M (2001) Soil carbon sequestration for improved land management. World soil resources reports 96, FAO, Rome
- Salazar R (1984) Produccion de lena en arboles de *Gliricidia sepium* usado como sombra en cafetales en Costa Rica. *Silvoenergia* No. 2, CATIE, Turrialba
- Schmohl S (2002) Sukzession, Biomasseentwicklung und Nährstoffdynamik auf Brachen traditioneller Brandrodungssysteme Zentral-Sulawesis. Master thesis, Institute of Plant Production in the Tropics and Subtropics, University of Hohenheim, Germany
- Schroeder P (1994) Carbon storage benefits of agroforestry systems. *Agrofor Syst* 27:89–97
- Smiley GL (2006) Biophysical resource use and productivity in cocoa–gliricidia agroforests of Central Sulawesi. In: Kroschel J (ed) *Tropical agriculture—advances in crop research*, vol 19(9). Margraf Publisher, Weikersheim
- Smith RL (1996) *Ecology and field biology*, Fifth edn. Harper Collins, New York
- Snowdon P, Eamus D, Gibbons P, Khanna P, Keith H, Raison J, Kirschbaum M (2000) Synthesis of allometrics, review of root biomass and design of future woody biomass sampling strategies. National carbon accounting system technical report no. 17. Australian Greenhouse Office, pp 1–113
- Soembroek W, Nachtergaele F, Hebel A (1993) Amounts, dynamics and sequestering of carbon in tropical and subtropical soils. *Ambio* 22(7):417–426
- Sommer R, Denich M, Vlek PLG (2000) Carbon storage and root penetration in deep soils under small-farmer land-use systems in the Eastern Amazon region, Brazil. *Plant Soil* 219:231–241
- Spek LY, van Noordwijk M (1994) Proximal root diameters as predictors of total root system size for fractal branching models. II. Numerical model. *Plant Soil* 164:119–128
- Stewart JL, Dunsdon AJ, Hellin JJ, Hughes CE (1992) Wood biomass estimation of Central American dry zone species. *Tropical forestry papers* no. 26. Oxford Forestry Institute, Oxford
- Stewart JL, Allison GE, Simons AJ (eds) (1996) *Gliricidia sepium* genetic resource for farmers. *Tropical forestry papers* no. 33. Oxford Forestry Institute, Oxford
- Szott LT, Palm CA (1996) Nutrient stocks in managed and natural humid tropic fallows. *Plant Soil* 186:293–309
- Szott LT, Fernandes ECM, Sanchez PA (1991) Soil–plant interactions in agroforestry systems. *For Ecol Manage* 45:127–152

- Townsend AR, Vitousek PM, Desmarais DJ, Tharpe A (1997) Soil carbon pool structure and temperature sensitivity inferred using CO<sub>2</sub> and <sup>13</sup>CO<sub>2</sub> incubation fluxes from five Hawaiian soils. *Biogeochemistry* 38:1–17
- Trumbore SE (1997) Potential responses of soil organic carbon to global environmental change. *Proc Natl Acad Sci* 94:8284–8291
- van Noordwijk M (2002) Scaling trade-offs between crop productivity, carbon stocks and biodiversity in shifting cultivation landscape mosaics: the FALLOW model. *Ecol Model* 149:113–126
- van Noordwijk M, Mulia R (2002) Functional branch analysis as tool for fractal scaling above- and belowground trees for their additive and non-additive properties. *Ecol Model* 149:41–51
- van Noordwijk M, Spek LY, de Willigen P (1994) Proximal root diameter as predictor of total root size for fractal branching models. *Plant Soil* 164:107–117
- van Noordwijk M, Rahayu S, Hairiah K, Wulan YC, Farida A, Verbist B (2002) Carbon stock assessment for a forest-to-coffee conversion landscape in Sumber-Jaya (Lampung, Indonesia): from allometric equations to land use change analysis. *J Sci China. Special issue on impacts of land use change on the terrestrial carbon cycle in the Asian Pacific region*, pp 1–12
- Veldkamp E (1994) Organic turnover in three tropical soils under pasture after deforestation. *Soil Sci Soc Am J* 58:175–180
- Woomer PL, Palm CA, Alegre J, Castilla C, Cordeiro DG, Hairiah K, Kotto-Same J, Moukam A, Riese A, Rodrigues V, van Noordwijk M (2000) Slash-and-burn effects on carbon stocks in the humid tropics. In: Lal R, Kimble JM, Stewart BA (eds) *Global climate change and tropical ecosystems*. CRC Press, Boca Raton, pp 99–115