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Carbon stocks in shaded *Theobroma cacao* farms and adjacent secondary forests of similar age in Cameroon

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Abstract: Cacao is an important smallholder crop in West Africa, often grown under a forest canopy. Yields from cacao farms are low so farmers consider removing shade trees, however, the impacts on pest and disease dynamics, soil fertility and thus yield in the longer term are not understood. We estimated carbon stocks in shaded cacao systems in Cameroon using equations that took account of wood densities of individual species. The average C stock in cacao trees was 14.4 Mg C ha^{-1}, compared with 121.1 Mg C ha^{-1} in the upper shade tree canopy, 5.8 Mg C ha^{-1} in necromass and 90 Mg ha^{-1} in soil. While total stock was comparable to that in secondary forest, only a small proportion was in the cacao *per-se*. Cutting shade trees would significantly reduce carbon stocks. Impacts of reduced C stock on sustainability are discussed.

Resumen: El cacao es un producto importante entre los pequeños agricultores en África Occidental ycon frecuencia se cultiva bajo el dosel del bosque. Los rendimientos de las fincas de cacao son bajos por loque los agricultores están considerando la eliminación de árboles de sombra;sin embargo, no se conocen los impactos a largo plazo en la dinámica de las plagasy enfermedades, la fertilidaddel suelo ypor lo tanto en los rendimientos. Se estimaron los almacenes de carbonoen sistemas de cacao de sombra en Camerún usando ecuacionesbasadas en las densidades de la madera de las distintas especies. El almacén promedio de C enárboles de cacao fue de 14.4 Mg C ha^{-1}, en comparación con 121.1 Mg C ha^{-1} en el dosel superior de los árboles de sombra, 5.8 Mg C ha^{-1} en la necromasay 90 Mg ha^{-1} en el suelo. Si bien el almacén total fue semejante al estimado en el bosque secundario, sólouna proporciónpequeña estaba en el cacao mismo. Cortar los árboles de sombra reduciría significativamente los almacenes de carbono. Se discuten los impactos de la reducción de los almacenes de C sobre la sostenibilidad.

Resumo: O Cacau é uma cultura importante de pequenos produtores na África Ocidental, muitas vezes cultivado sob sombreamento de floresta. Os rendimentos das fazendas de cacau são baixos pelo que os agricultores consideram remover árvores de sombra, no entanto, os impactos sobre a dinâmica de pragas e doenças, fertilidade do solo e, assim, o rendimento a longo prazo não são compreendidas. Os estoques de carbono em sistemas sombreados de cacau nos Camarões, foram estimados usando equações que tiveram em conta as densidades individuais da madeira das espécies. O estoque médio de C nas árvores de cacau foi de 14,4 Mg C ha^{-1}, em comparação com 121,1 Mg C ha^{-1} na parte superior da copa das árvores de sombreamento, 5,8 Mg C ha^{-1} na biomassa morta e 90 Mg ha^{-1} no solo. Se bem que o estoque total fosse comparável ao da floresta secundária, apenas uma pequena proporção estava no cacaueiro *per-se*. Assim, o abate das árvores de sombra reduzirá significativamente os estoques de carbono. Os impactes da redução dos estoques de C na sustentabilidade são discutidos.

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Key words: Allometrics, carbon stocks, cacao, shade, soil carbon, West Africa.

Introduction

In south Cameroon, the landscape is a mosaic of primary and secondary forest, cacao and other perennial crops, food crop systems and fallows of various ages, often invaded by the exotic weed *Chromolaena odorata* King & Robinson. Cacao systems have been planted traditionally under a thinned secondary forest canopy. Thus systems are heavily shaded and the landscape is a repository of plant, insect and soil faunal biodiversity.

Cacao (*Theobroma cacao* L.) is the most important smallholder cash crop in Cameroon, grown by 69 % of farmers in the Centre, East and South provinces (Sunderlin *et al.* 2000). Sonwa *et al.* (2007) reported that cacao systems in Cameroon are generally multispecies agroforests, have a thinned secondary forest canopy and are thus shaded systems. However, such systems also need to be profitable or provide economic incentives for farmers to maintain them. Research often targets interventions, providing benefits either to farmers or to biodiversity but not to both (Franzen & Borgerhoff Mulder 2007). Typically, many studies citing the global benefits of shaded cacao systems (for example, Bisseleua & Vidal 2008 and Sonwa *et al.* 2007 for plant diversity) have not reported cacao yields and, unfortunately, these can be low in Cameroon, with blackpod fungal disease, caused by *Phytophthora megakarya* Bras. & Griff, destroying a high proportion of pods (Laird *et al.* 2007; Norgrove 2007). From a conservation perspective, it is essential to improve yields; indeed Gockowski & Sonwa (2010) calculated that 21000 km^2 of deforestation could have been avoided if inputs had been applied to cacao systems in West Africa since the 1960s. Norgrove (2007) measured yields in 35-year old shaded cacao farms in southern Cameroon with weekly phytosanitary harvests. In plots not sprayed with fungicide, mean annual bean yield during a four year period was negligible (18.5 kg ha^{-1} yr^{-1}). In contrast, plots sprayed with Ridomil® at 100 % and at 33 % of the manufacturer's recommended rate, produced on average 403 and 173 kg ha^{-1} dry beans per annum, respectively, over a period of four years, clearly demonstrating the production benefits and profitability of increased fungicide use.

The high shade levels found in these cacao farms promote the growth of *P. megakarya*. According to Guest (2007), growth of *P. megakarya* is inhibited by light. Increasing difficulty in controlling *P. megakarya* requires farmers to reconsider the structure of their cacao systems. Short of abandoning their farms, smallholder cocoa farmers have three options: to increase the use of fungicides, to reduce shade by cutting down or pruning shade trees or a combination of both. Farmers often cite that they do not have cash to invest in fungicides, and as pruning upper canopy shade trees is technically difficult, cutting down shade trees might be their only option.

Changing shade levels might impact on ecosystem functions, including soil fertility and carbon stock maintenance. Fertilizer is generally not applied, therefore, plant nutrition depends upon nutrient cycling and decomposition processes. Decreased litter inputs due to reduced tree density might also adversely affect soil faunal activity. Cutting trees will reduce the carbon stocks in the living biomass in the system, at least in the short term.

In this study, we estimate carbon stocks in shaded cacao farms and in adjacent secondary forests, highlighting the distribution of carbon stock between cacao and non-cacao trees and between below- and above-ground components. We also assess the carbon stored in the soil. We then describe the trade-offs between production and conservation objectives and suggest how the farms can remain profitable.

Materials and methods

An experiment was established in Zoatoupsie, approximately 10 km south of Mbalmayo, in southern Cameroon (3° 51' N and 11° 27' E) in February 2001. The land is covered with semi-deciduous mature and young secondary forest. Altitude is 540 m above mean sea level. Sample plots were established in farmers' cacao farms with upper canopy trees and in an adjacent secondary forest. No agrochemical inputs had been applied to the cacao in the previous three years. The land use history was reportedly the same for both cacao and secondary forest (Norgrove *et al.* 2009). All sample areas had been established after a typical slash and burn cycle of secondary forest, whereby smaller trees that are considered not to be valuable and are easily cut with a machete are felled and larger trees or those yielding valuable non timber forest products, such as fruits, nuts or barks, are retained (Hauser & Norgrove 2001). Slash and burn field preparation was followed by a single cropping cycle without the use of agro-chemicals. The land was either converted to cacao or was left fallow since past 35 years. Plots were visually selected for uniformity. Nine plots of 25 m x 25 m were marked out in the cacao and three in the forest. The cacao plots were used subsequently for a fungicide trial with three treatments in three replicates hence the plot number was greater than in the forest. Soil texture in the topsoil (0 - 10, 10 - 20 cm depths) (n = 12) was approximately 67 % sand, 20 % clay and 13 % silt at 0 - 10 cm depth, and 60 % sand, 28 % clay and 12 % silt at 10 - 20 cm depth (recalculated from Norgrove 2007).

Litter mass was sampled from five 0.75 m x 0.75 m areas per sample plot and divided into cacao leaves, other leaves and dead wood. Root biomass was measured using 10 cm long steel cylinders with a radius of 40 mm. Twenty five cores were taken per plot at 0 - 10 cm depth and five cores were taken per plot at 10 - 20 cm depth. Litter, soil and root samples were dried at 40 ºC to constant weight. Litter dry weight was recorded. Roots were manually separated from the soil but were not differentiated by species and root dry weight was recorded.

All cacao trees were counted and mapped. The girth (circumference) at breast height (gbh) (1.3 m) of all non-cacao trees with gbh $\geq$ 10 cm (i.e. equivalent to diameter at breast height $\geq$ 3.2 cm) was measured with a tape to the nearest 0.5 cm. For cacao trees, the following were recorded: the height of the trunk (h1) from the soil to the first major branch, the mean girth of the trunk measured halfway between the soil and h1, the number of primary branches.

Gbh, or trunk girth in the case of cacao, was converted to stem cross sectional area (CSA) assuming a circular cross section, $CSA = (gbh)^2/4\pi$.

Cacao aboveground wood biomass was estimated from regression equations developed by Boyer (1973). Boyer conducted his work in 40 - yr old smallholder cacao systems in southern Cameroon with similar characteristics to the ones evaluated here. Boyer (1973) developed allometric equations based on destructive sampling of eighteen trees: Aboveground wood biomass (Mg) = D * CSA * (L + 2.32B).

where, CSA = mean cross sectional surface area of trunk (m^2), L = trunk length (m), B = number of primary branches, D = average wood density, which Boyer measured as 0.34 Mg m^{-3}.

The standing leaf area at the end of the long dry season is low. According to Boyer (1974), approximately 3 m^2 of leaves per cacao tree are maintained under moderate shade conditions. Here four samples of approximately 75 g of leaves (fresh mass) were weighed, passed through a LICOR LAI 2000 leaf area meter, then dried to constant weight. Specific leaf area (SLA) was calculated as the ratio of leaf area to dry mass leaves. Using SLA the mass of leaves per tree was calculated.

Using a biomass partitioning model developed by Zuidema *et al.* (2005), the total aboveground biomass was assumed to be 87 % of the total plant biomass, with taproot and other roots comprising 5 % and 8 %, respectively. This is slightly lower than the root / shoot ratio of 0.16 used by Brown *et al.* (1989).

For *Terminalia superba* Engl. & Diels, dry mass of trees was estimated using a regression equation developed by Deans *et al.* (1996) for *Terminalia* in the Mbalmayo Forest Reserve: Tree dry mass (Mg) = 0.7631 CSA (m^2), $r^2 = 0.985$, n = 6.

Wood density of *Terminalia* was estimated from the data of Norgrove & Hauser (2002) who destructively sampled 11 *T. ivorensis* trees from a 17 year old plantation near the experimental site. Three to seven cross-sections of bole, approximately 50 mm thick, were sampled at breast height, at the top of the bole and from equidistant points in between. Thickness and fresh weight, to 10^{-1} g resolution, were measured for each cross-section. Cross-sectional area was measured by tracing the shape on paper, cutting it out and passing it through a LICOR leaf area meter. If the section was tapered, the areas of both sides were measured and the mean recorded. The cross-sections were dried for six weeks at 65 ºC. Thickness, weight and cross-sectional area were measured again, as above. A weighted average value of wood density was calculated to be 0.584 Mg m^{-3}.

Total dry weights of all other trees except *Ceiba pentandra* (L.) Gaertn. were estimated by multiplying the equation for *Terminalia* above, with the ratio of the wood density of *T. ivorensis* to the wood density of each of the other tree species (after Deans *et al.* 1996):

$$W_y = 0.7631\ CSA_y \times \delta_y / 0.584$$

where, W_y is the dry weight of tree species Y;

CSA_y is the cross sectional area of tree species Y; δ_y is the wood density of tree species Y. The wood densities of other trees present in the plots were obtained from Lewis *et al.* (2009) and the internet resource “tropix.cirad.fr”. The belowground ratio was assumed to be 0.19 (after Brown *et al.* 1989).

Biomass estimation for *C. pentandra* was conducted separately because of the large size of the trees and low wood density. There were three large individuals in the plantation with the girth at breast height exceeding 800 cm. A tree that had fallen was sawed and four trunk slice samples were taken along its length of varying circumference. Four estimates of slice diameter and eight of slice height (thickness) were made to estimate volume. Samples were weighed fresh then dried for 6 weeks to constant weight. Wood density was calculated for each piece then plotted against the mean diameter. Power and exponential functions were compared for fit. The following function was employed to adjust the wood density to be used depending on the diameter of the tree to be estimated: wood density = 1.105* diameter $^{-0.336}$; $r^2 = 0.92$.

The weights of all non- cacao trees were then summed to obtain the total weight of trees per plot. Carbon stocks in all trees and in litter necromass were estimated by multiplying the dry weights by 0.45 (after Kotto-Same *et al.* 1997).

Soil samples were taken with steel cylinders at five positions per plot, from 0 - 10 cm and 10 - 20 cm depth. Deeper soil layers (20 - 30, 30 - 50, 50 - 70 and 70 - 100 cm) were sampled using a 1 m gouge auger at five points per plot. Samples were dried at 40 °C to constant weight. Bulk density for 0 - 10 cm and 10 - 20 cm depths were calculated as the dry mass of the soil divided by the volume (Norgrove 2007). Deeper layers were assumed to have identical bulk density to those of 10 - 20 cm, as, in Mbalmayo, bulk density does not significantly alter beyond this depth (Nyobe 1998). Soil samples were ground to 0.5 mm for chemical analysis. Organic C was determined by Heanes' improved chromic acid digestion and spectrophotometric procedure (Heanes 1984). Carbon stored in soil was calculated by multiplying C concentrations by soil bulk densities and the increment depth.

Results

Average cacao density was 1362 stems ha^{-1} with trees having a mean diameter at breast height of 10 cm (n = 766 cacao trees). Specific leaf area was 141.4 cm^2 g^{-1}. Assuming 3 m^2 of leaf area per tree (Boyer 1973), the leaf dry biomass per tree was 212 g. The average estimated total biomass of the cacao trees was 31.8 Mg ha^{-1}. This comprised 27.5 Mg ha^{-1} aboveground wood biomass, 0.29 Mg ha^{-1} leaves, 1.59 Mg ha^{-1} fine roots, and 2.55 Mg ha^{-1} taproots.

Shade tree density in cacao plots was 115 stems ha^{-1} and comprised 30 species on an area of 0.56 ha. Fifty-three tree species were found in the forest plots on an area of 0.19 ha. In cacao, the most frequent species was *Terminalia superba* with a density of 11 stems ha^{-1} with total cross sectional area at breast height of 27 m^2 ha^{-1}. The species with the greatest total cross sectional area at breast height was *Ceiba pentandra* (105 m^2 ha^{-1}). In the forest, the most frequent tree encountered was *Isolona hexaloba* with a density of 101 stems ha^{-1}, followed by *T. superba* at 32 stems ha^{-1}. In the forest, *T. superba* had the greatest cross sectional area of 25.2 m^2 ha^{-1}.

In the cacao, total biomass of upper storey trees was estimated at 269.3 Mg dry wt ha^{-1}, subdivided into 218.1 and 51.2 Mg dry wt ha^{-1}, above- and below-ground biomass, respectively. In the forest, total estimated biomass was 423.2 Mg dry wt ha^{-1} (342.8 Mg dry wt ha^{-1} aboveground and 80.4 Mg dry wt ha^{-1} belowground). In the cacao, litter necromass comprised 7.4 Mg dry wt ha^{-1} non-cacao leaf-litter, 1.2 Mg dry wt ha^{-1} cacao litter and 4.2 Mg dry wt ha^{-1} dead wood, thus 12.8 Mg dry wt ha^{-1} was the total necromass. In the forest, litter comprised 7.2 Mg dry wt ha^{-1} leaf litter and 8.3 Mg dry wt ha^{-1} dead wood, thus 15.5 Mg dry wt ha^{-1} total necromass. Measured total root biomass of all species in the 0 - 10 cm layer was 8.6 Mg dry wt ha^{-1} in the cacao and 4.9 Mg dry wt ha^{-1} in the forest. In the 10 - 20 cm layer, root biomass was 8.6 Mg dry wt ha^{-1} in the cacao and 16.2 Mg dry wt ha^{-1} in the forest.

As already reported (Norgrove 2007), average soil organic carbon concentration (mg g^{-1}) in the 0 - 10 cm soil layer was numerically higher in the cacao (15.1 mg g^{-1}) than in the forest (11.6 mg g^{-1}), however, this difference was not significant. In the 10 - 20 cm soil layer, concentrations were lower ($P < 0.01$) in the cacao (6.84 mg g^{-1}) than in the forest (9.66 mg g^{-1}). Differences were not significant at deeper layers with averages across the two systems being 7.17 mg g^{-1} at 20 - 30 cm, 7.41 mg g^{-1} at 30 - 50 cm, 6.31 mg g^{-1} at 50 - 70 cm and 5.89 mg g^{-1} at 70 - 100 cm depths.

Combining C concentrations with bulk density data gave carbon stocks in the soil from 0 to 100

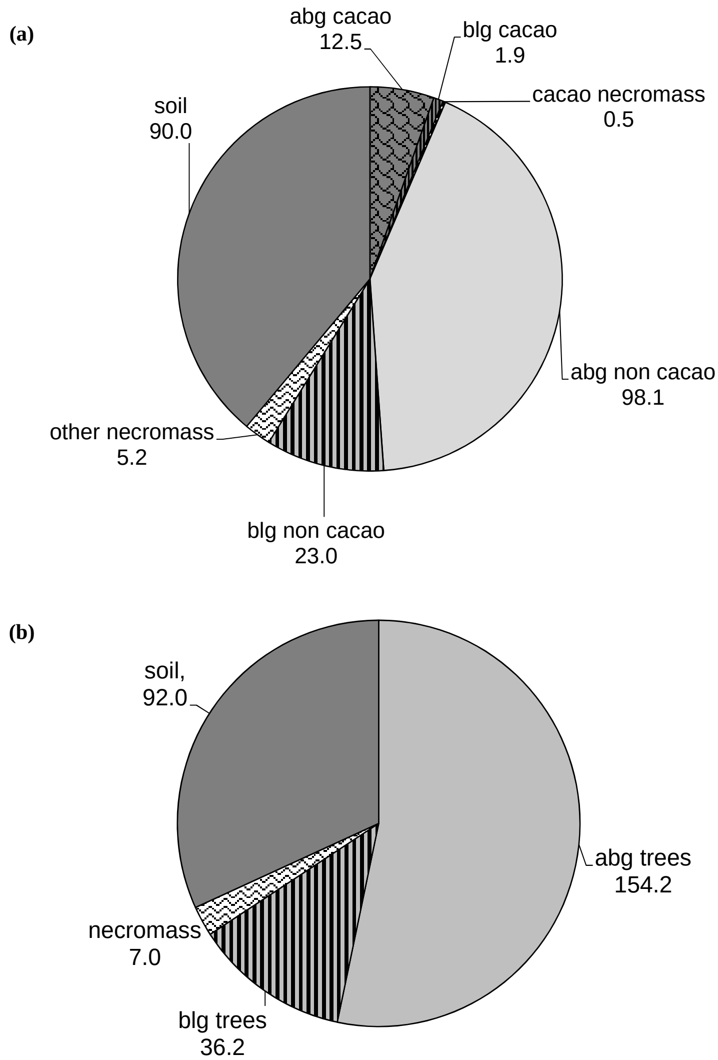

Fig. 1. Carbon stocks (Mg C ha^{-1}) in (a) 35 yr old cacao system with upper-canopy trees and (b) 35 yr old secondary forest (n = 3). abg - aboveground; blg - belowground. All cacao trees were included. For non-cacao trees, only trees with gbh ≥ 10 cm are included.

Table 1. Carbon stocks (Mg ha^{-1}) in the soil in the forest and cacao systems, by depth increment.

Depth (cm)	Forest	Cacao
0 - 10	13.5	16.9
10 - 20	12.2	8.6
20 - 30	9.0	9.0
30 - 50	19.6	17.7
50 - 70	16.2	15.5
70 - 100	21.4	23.1
Sum	92.0	90.9

cm depth of 92 Mg C ha^{-1} in the forest and 90 Mg C ha^{-1} in the cacao (Table 1). The partitioning of carbon into belowground and aboveground cacao and non - cacao trees and also necromass, assuming that none of the dead wood was derived from cacao, are given in Fig. 1. Understorey shrubs in the forest are not included.

Discussion

Mean upperstorey density of trees of gbh ≥ 10 cm was 115 stems ha^{-1} and was thus comparable to that reported by Gockowski *et al.* (2010), who found 131 stems (> 2.5 cm diameter) ha^{-1} in cacao farms in Cameroon.

In the current experiment, only a small proportion of carbon was held in the living cacao *per-se* (14.4 Mg C ha^{-1}). In the sub-humid zone of

Ghana, in 8 yr old cacao systems of densities similar to the present study, aboveground carbon stock in cacao trees was 10.3 Mg C ha^{-1} (recalculated from Isaac *et al.* 2007). Similarly in Ghana, aboveground carbon stocks were 16.8 Mg C ha^{-1} in a 15 yr old cacao stand of 1362 ha^{-1} density and 15.9 Mg C ha^{-1} in a 25 yr old stand of 900 ha^{-1} density (Isaac *et al.* 2005). These figures would give cacao total carbon stocks, (including belowground cacao carbon) of 11.8 Mg C ha^{-1} (recalculated from Isaac *et al.* 2007), 19.3 and 18.3 Mg C ha^{-1} (recalculated from Isaac *et al.* 2005), respectively. Particularly given the age difference, Isaac *et al.*'s figures are much larger than in the current study, however, they applied the multispecies pan tropical equation of Brown *et al.* (1989) to estimate biomass. This equation does not include wood density as a variable and thus would overestimate the biomass and thus carbon stocks of a low wood density species such as cacao. In the current study, although direct measurements of biomass were not made, the allometric equations used were developed locally under similar conditions, for a similar stand age (Boyer 1973, 1974) and a constant aboveground to belowground biomass ratio was applied. Indeed, according to Fearnside (1997), the Brown *et al.* (1989) equation assumes average wood densities of 0.69 Mg m^{-3}, thus its use for cacao, with an average wood density of D 0.34 Mg m^{-3} (Boyer 1973), is inappropriate.

Kotto-Same *et al.* (1997), also quoted and discussed in Gockowski *et al.* (2010), calculated aboveground tree carbon stock in Cameroonian shaded cacao at 88.7 Mg C ha^{-1}, equivalent to 107 Mg total tree C ha^{-1} if aboveground biomass is assumed to be 87 % of total biomass (Zuidema *et al.* 2005). This is less than the estimates of the current study (135.5 Mg C ha^{-1}) and calculations were based on the Brown *et al.* (1989) equation. Incorporating wood densities of separate species, as done in the current study, or developing species specific allometric equations (for example, see Chaturvedi *et al.* 2011) is likely to lead to a more accurate assessment of biomass and thus carbon stocks.

The concentrations of soil organic carbon obtained here in the secondary forests are much lower than those found by Vågen *et al.* (2006) in tropical forest soils in Madagascar (22.8 to 120.8 mg g^{-1}). Nevertheless, in the current study, soil carbon stock to 1 m depth was 90 Mg ha^{-1}. This is low compared with the average soil carbon stock of 150 Mg C ha^{-1} to 1 m depth reported in fifteen year old cacao farms in Indonesia by Smiley & Kroschel (2008) and those of 320 Mg ha^{-1} reported in 30 year old cacao agroforestry systems in Brazil on Oxisol (Gama-Rodrigues *et al.* 2010).

In southern Cameroon, cacao farms are low-input, old, biologically diverse and heavily shaded, having carbon stocks in soil and vegetation similar to those in secondary forest, yet the cacao is susceptible to blackpod and low yield. Management options to improve yields include de-shading by pruning of branches, maintaining shade but developing methods to control blackpod or focusing on new plantings. Reducing tree densities by ring barking or herbicide injections leaves the dead trees standing in the field, which continue to shed branches over the following year causing damage to the cacao trees and posing risk to farmers. Thus only felling is a realistic option but what would be the impact on carbon stocks in living biomass? Clearly given that the majority of carbon is held in the upper canopy trees, felling would initially reduce living carbon stocks although depending on the spatial structure of the farm, other trees might benefit from reduced competition so sequestration rates might subsequently increase.

Older shaded cacao systems can be maintained or replanted but will need suitable methods to control blackpod, so some management changes, including shade reduction are inevitable. In particular, it is important to remove trees that are alternative hosts to *P. megakarya*, such as *Ricinodendron heudelotti* (Euphorbiaceae), a native spice tree present there in forests and being often planted by farmers in association with cacao (Opoku *et al.* 2002). *Ceiba pentandra* is also commonly found in cacao farms in Cameroon as it was in the current experiment. While its wood density is very low, due to its enormous size (up to 3 m diameter) it is a major contributor to carbon stocks in cacao farms. Felling such trees would also cause significant damage to the cacao trees. Yet, *C. pentandra*, along with *Cola* spp., is a host of cocoa swollen shoot virus (CSSV). Although first reported in West Africa in 1936 (Steven 1936) and despite its occurrence in Ghana, Cote d'Ivoire, Nigeria and Togo, where recommendations are to cut down alternative hosts, CSSV has not yet been recorded in Cameroon (Dzahini-Obiatey *et al.* 2010) but might be a threat in the future unless phytosanitary precautions are observed.

Shade reduction by felling upper storey trees will also reduce the amount of litter. The litter layer is the major food source for many soil fauna such as epigeic and anecic earthworms and litter feeding termites. Depending on the degree of shade and consequent litter input reduction, the soil fauna may not find sufficient materials, and the conditions at the soil surface may be altered in such as way (increased moisture and temperature fluctuations) that earthworms and termites begin to avoid it. Thus shade and carbon stock reduction will have cascading effects on other ecosystem services. So, overall, shade tree reduction is likely to lead to a reduction in soil carbon and carbon stocks in living biomass. Furthermore, a reservoir of inoculum of *P. megakarya* is maintained in the soil during the dry season. When rains begin, the spread of zoospores up the trees is greatly enhanced by rain splash (Opoku *et al.* 2007). The litter layer acts as a physical barrier so if shade trees are removed, leaf litter coverage of the soil will be reduced and, ironically, this might increase infection and further yield losses.

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