

# Changes in soil organic carbon fractions in a tropical Acrisol as influenced by the addition of different residue materials

Thomas Gaiser · Karl Stahr · Marc Bernard ·  
Biau T. Kang

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**Abstract** Residues of *Leucaena* (*Leucaena leucocephala* (L)), *Senna siamea* (S) and maize stover (M) were tested to evaluate their effect on soil organic matter accumulation and composition under sub-humid tropical conditions. On an *Imperata cylindrica* (I) dominated grass fallow, a total amount of 30 Mg ha<sup>-1</sup> DM were applied within 18 months. Two months after the last application, changes in the light and heavy soil organic carbon fraction (LF and HF) and in the total soil organic carbon content (LF + HF) in the topsoil were observed. All organic materials increased the proportion of the LF fraction in the soil significantly. The increase in HF was 39 to 51% of the increase in total organic carbon, depending on the source of the organic material. The

potential of the tested organic materials to increase total soil organic carbon content (including all soil organic carbon fractions) was in the order L > S > M > I, whereas the order of increase of the HF fraction was L = S > I > M. Cation exchange capacity of the newly formed heavy soil organic carbon was highest with L and lowest with M. Ranking of the transformation efficiency of applied plant residues into the heavy soil organic carbon fraction was I > L = S > M. Transformation efficiency of the residues could neither be explained by lignin nor lignin/N ratio, but rather by extractable polyphenols (Folin–Denis extraction). The results show that accumulation of the HF fraction in tropical soils is feasible through the application of large quantities of plant residues, but depends strongly on the composition of the applied materials.

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Biau T. Kang—deceased.

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T. Gaiser (✉)  
Institute of Crop Science and Resource Conservation,  
University of Bonn, 53115 Bonn, Germany  
e-mail: tgaiser@uni-bonn.de

K. Stahr  
Institute of Soil Science and Land Evaluation,  
University of Hohenheim, 70593 Stuttgart, Germany

M. Bernard  
Federal Agency for Agriculture and Food, 53177 Bonn,  
Germany

B. T. Kang  
Department of Crops and Soil Sciences,  
University of Georgia, Athens, GA, USA

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Soil organic carbon accumulation ·  
Density fractionation · Polyphenols

## Introduction

Soil organic matter is a key factor in the global carbon cycle (Epron et al. 2009). Approximately 30% of global soil organic carbon (SOC) is stored in subtropical and tropical ecosystems, but conversion from native vegetation into cropland causes rapid break down of the carbon stock and emissions of

carbon dioxide (Richards et al. 2007). On the other hand, several studies show the potential of degraded, tropical soils to provide terrestrial sinks of carbon (C) and reduce the rate of enrichment of atmospheric CO<sub>2</sub> (Vagen et al. 2005). In addition, SOC is of great importance for soil productivity, because it influences many other soil properties (Allison 1973). SOC is strongly correlated with soil organic nitrogen and it acts, therefore, directly as main source of nitrogen (Campbell 1989; Stahr et al. 1994). In highly weathered tropical soils, it provides essential soil cation exchange sites (Agboola 1978; Kang 1977; Vagen et al. 2005). Therefore, agricultural research in the tropics has for a long time focussed on measures for maintenance of SOC levels particularly in highly weathered soils (Bayer et al. 2006; Gosai et al. 2009; Nair et al. 2009; Youkhana and Idol 2009, 2011). However, changes in SOC composition may take place in particular with the addition of large quantities of plant residues (Barrios et al. 1996; Bonfils 1963; Seneviratne et al. 2009; Singh et al. 2009a; Youkhana and Idol 2011).

Although in many studies, the mere increase of SOC due to addition of plant residues is considered a reliable indicator of soil improvement (Barthes et al. 2004; Isaac et al. 2005; Lal 2009; Oelbermann et al. 2006a; Oelbermann et al. 2006b; Yamoah et al. 1986), soil functions are also strongly dependent on the composition of the SOC (Gaiser et al. 1998; Llorente and Turrion 2010; Swift and Woomer 1993; Zhang et al. 2007). Therefore, the objective of this study was (1) to measure and compare the quantitative changes in SOC in a tropical Acrisol as impacted by plant residue additions (2) to evaluate the relationship between formation of the heavy SOC fraction and chemical composition of applied organic residues and (3) to characterize the newly formed heavy SOC with respect to its cation exchange capacity.

## Materials and methods

### Location and climate

The experiment was carried out in the southern part of Benin Republic (West Africa) on a Ferrali-Haplic Acrisol (FAO 1988). The climate was classified as sub-humid tropical with a mean annual rainfall of

1200 mm and a bimodal distribution. Mean annual temperature was 26°C with little seasonal variation. The experimental field was located in the outskirts of the city of Allada, an old settlement dating back to the seventeenth century. Mean organic carbon, clay and silt content were 12.3, 87.0 and 50.0 g kg<sup>-1</sup> respectively (Table 1). The capacity of this site to retain a maximum level of soil carbon organic carbon was estimated to be 43.5 g C kg<sup>-1</sup> soil according to (Six et al. 2002). This estimate is based on the concept of protective capacity of a soil with respect to organic carbon and uses the relationship between soil texture and SOC content (Six et al. 2002). Thus, land use history and soil chemical analysis (Table 1) compared to the protective capacity of the soil point to a site with long cropping history and depleted SOC stocks. The field was characterized by a high spatial variability of SOC and other related properties in the surface soil. Therefore, SOC content in each plot was determined at the beginning of the experiment and used as co-variable in the subsequent ANOVA procedure and for the comparison of means (*t*-Test).

### Experimental design

The trial was carried out using a one factorial RCB design with four replications and addition of three organic matter sources and a control as the fourth treatment. The plot size was 48 m<sup>2</sup> per treatment replicate with four plots (replicates) per treatment. The plant residues used included prunings (leaves and small branches with maximum diameter 2 mm) of *Leucaena leucocephala* and *Senna siamea* (S) and maize (*Zea mays*) stover (M). Selection of the organic materials was done according to local availability and

**Table 1** Mean and range estimates of initial surface soil characteristics (0–20 cm) in the experimental site

	Mean	Range
Clay (g kg <sup>-1</sup> )	87	73–108
Silt (g kg <sup>-1</sup> )	50	37–89
Sand (g kg <sup>-1</sup> )	863	796–874
SOC (g kg <sup>-1</sup> )	12.3	7.5–17.6
Soil organic N (g kg <sup>-1</sup> )	0.88	0.51–1.22
C:N ratio	14	13–15
pH (CaCl <sub>2</sub> )	6.2	5.9–6.5

*SOC and soil organic N* Soil analysis based on standard soil sampling and sample preparation

C/N ratios (58, 18 and 13 for maize stover, Senna and Leucaena, respectively, Table 2). The field was under an *Imperata cylindrica* dominated grass fallow, which was slashed twice a year. Following each slashing, the organic materials were applied without chopping on the soil surface at a rate of 15 Mg ha<sup>-1</sup> a<sup>-1</sup> dry matter together with the grass vegetation. High macro-faunal activity decomposed the residues depending on the chemical composition (“Soil sampling and analysis” Section) and mixed the decomposed material into the topsoil. Biomass production and dry matter content of the grass fallow were measured after slashing in each plot and carbon content in the dry matter was assumed to amount to 50%. The carbon input supplied by the grass fallow and the total amount of residue application is shown in Table 3. As a zero control, four additional maize plots adjacent to the experimental field were chosen, which were cultivated continuously without residue input (above ground maize residues and weeds were removed from the field) except below ground root carbon (no OM).

#### Soil sampling and analysis

The surface soil was sampled with a bucket auger (10 cm diameter) at the beginning of the experiment and after 20 months at a depth of 0–20 cm in each plot. The bucket auger allowed inclusion of plant litter and fine roots. Soil samples were fractionated according to the procedure described by Feller et al. (1981) and Anderson and Ingram (1981). This procedure consists in a combination of density and particle size fractionations. At first, soil samples were passed through a 2-mm sieve. The >2 mm-fraction was fractionated by its density into a coarse light fraction (LF >2 mm = **LF1**, density < 1 g cm<sup>-3</sup>) and a coarse heavy fraction (HF > 2 mm, density > 1 g cm<sup>-3</sup>) by flotation in water and decanting the lighter fraction. Then, the < 2 mm-fraction was

**Table 2** Total nitrogen, carbon (g kg<sup>-1</sup>) content and C:N ratio of leaves of Senna, Leucaena, Imperata and of Maize stover

	Leucaena	Senna	Maize stover	Imperata
Nitrogen (g kg <sup>-1</sup> )	38.7	28.1	8.6	14.0
Carbon (g kg <sup>-1</sup> )	520	511	502	519
C:N ratio	13	18	58	37

**Table 3** Timing and amount of residue application (Mg C ha<sup>-1</sup>)

Treatment	Month 1	Month 6	Month 13	Month 18	Total
no OM	0	0	0	0	0
Control ( <i>I. cylindrica</i> )	1.8	2.6	3.9	2.4	10.6
Leucaena	4.1	9.3	9.0	5.0	27.4
Senna	4.4	8.8	9.7	4.8	27.7
Maize stover	4.9	9.0	8.0	3.8	25.6

also fractionated according to density into a light (LF < 2 mm, density < 1 g cm<sup>-3</sup>) and a heavy fraction (HF < 2 mm, density > 1 g cm<sup>-3</sup>). Finally, the LF < 2 mm fraction was separated by a 0.25-mm sieve into a so-called “fine” light fraction (2 mm > LF > 0.25 mm = **LF2**) and a < 0.25 mm fraction (LF < 0.25 mm). The heavy fractions (HF > 2 mm and HF < 2 mm) and the LF < 0.25 mm fraction were then combined into the heavy fraction (HF). In each fraction total nitrogen was determined by the Micro-Kjeldahl method, which includes destruction of samples by concentrated sulphuric acid and determination of ammonia through distillation in a alkaline solution and titration with (0.05 N) HCl. Carbon content of the heavy fraction was determined according to Walkley and Black (IITA 1981), whereas in the light fractions loss of weight by ignition was determined and carbon content estimated (weight loss × 1/1.72). The sum of carbon in all SOC fractions is the total SOC content. Additionally, soil samples from 0 to 20 cm were taken by a Purckhauer auger (diameter 2 cm) for standard sample preparation (dry sieving through a 2 mm sieve and manual sorting out of visible organic debris) and subsequent determination of standard total SOC according to Walkley and Black (IITA 1981). Bulk densities of the different topsoil layers were measured at the beginning and at the end of the experiment by taking undisturbed soil cores (100 cm<sup>3</sup>) and determining the soil mass after drying at 110°C until constant weight. Bulk density of the soil layers was used to calculate the total amount of carbon in the top 20 cm. Carbon transformation efficiency was calculated as the percentage of the carbon input which accumulated in the heavy SOC fraction. Potential cation exchange capacity (CEC) of the soil was determined with NH<sub>4</sub>-acetate at pH 7.0. Total phenolic compounds were determined with the Folin–Denis

reagent (Makkar et al. 1996) and acid detergent lignin according to Van Soest and Robertson (1985).

### Determination of decomposition rates

In each plot approximately 250 g dry matter of *Leucaena* and *Senna* prunings and of maize stover were placed on a fenced area of 60 × 40 cm. The area was open below and above in order to ensure full access of decomposers to the litter. The fence had a mesh size of 1 mm to avoid loss of litter through wind. After 5, 10, 15, 20, 25 and 30 weeks the undecomposed material was gathered from the soil surface, fresh weight was determined and then replaced into the fenced area. Dry matter content at each sampling date was determined from samples taken from the unfenced area of the plot. From the remaining dry matter the accumulated loss in % of the initial weight was determined. Mean decomposition rate was approximated by dividing the percentage loss through the number of days from application to sampling.

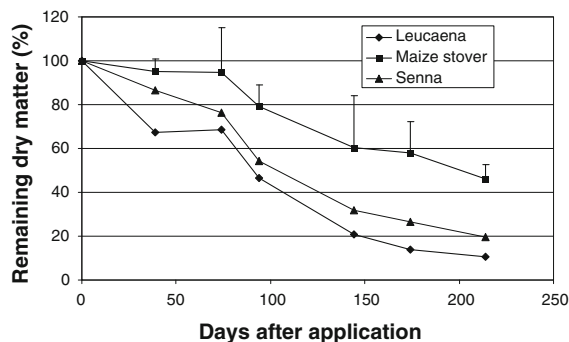
### Statistical analysis

Analysis of variance (ANOVA) and comparison of means (Student's *t*-test) were performed with the SAS software package, Version 9.0 (SAS 2002) using SOC content at the beginning of the experiment as a co-variable in the ANOVA and the separation of means ("Location and climate" section).

## Results

### Litter decomposition

The decomposition process of the three applied organic materials differed significantly in terms of velocity. *Leucaena* mulch showed the fastest initial break down followed by *Senna* mulch, but about 70 days after the application the decomposition process of the two materials went in parallel (Fig. 1). Maize stover showed the slowest decomposition, and after 214 days only 58% of the material was decomposed, whereas more than 80% of *Leucaena* and *Senna* prunings were decomposed at that time. Correlation analysis between decomposition rates of the three materials in the first and second year of application and C/N ratio, lignin content and



**Fig. 1** Break down of contrasting organic materials within 214 days under tropical sub-humid conditions (Bars denote least significant difference at  $P < 0.05$ )

lignin/N ratio indicates that the decomposition rates are most closely linked to the C/N ratio of the applied organic material (Fig. 2).

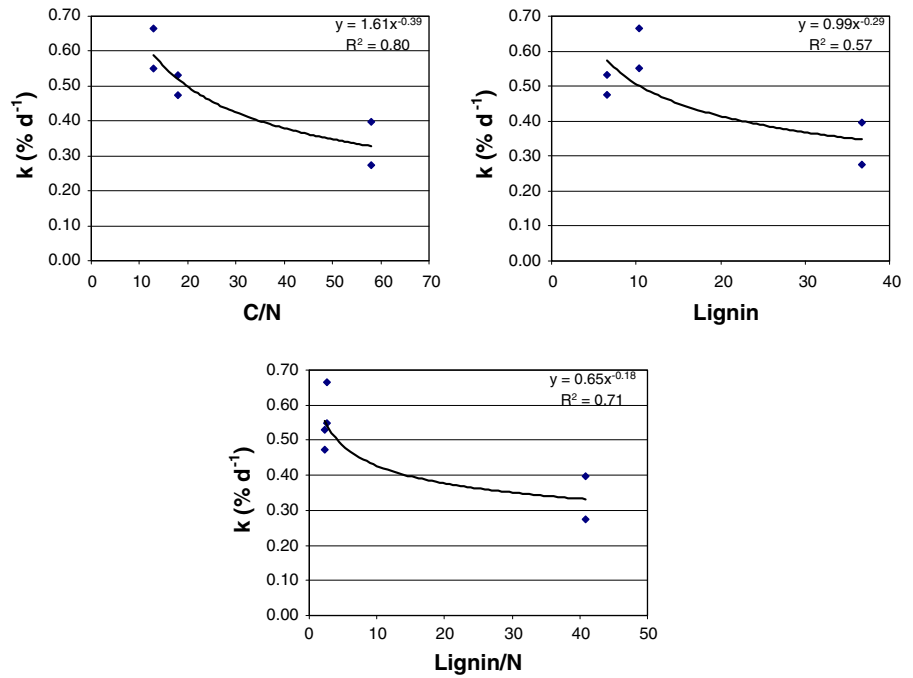
### Changes in soil organic carbon

Standard sample preparation involving dry sieving at 2 mm and careful manual separation of organic debris out of the sample leads to organic carbon contents which reflect mainly the heavy SOC fraction, whereas the total amount of SOC including light fractions is up to 34% higher in the *Leucaena* treatment compared to standard SOC analysis (Table 4).

Application of leaves of *Leucaena* and *Senna* and of maize stover resulted in an increase of the total amount of SOC (including all SOC fractions) of 16.0, 14.6 and 11.3 Mg C ha<sup>-1</sup> respectively after a period of 20 months (Table 5). Although the amount of added organic carbon was slightly higher, the increase in the *Senna* treatment was lower than in the *Leucaena* treatment. In the control plots under *Imperata cylindrica* fallow, which had been regularly slashed, the addition of 10.6 Mg C ha<sup>-1</sup> during the same period increased total organic carbon in the soil by 9.5 Mg C ha<sup>-1</sup>. The ratio of remaining C to input C, which illustrates the ability of the various organic materials in increasing the total SOC content in the soil (including the light fractions), was 89, 58, 53 and 44% for *Imperata*, *Leucaena*, *Senna* and maize stover respectively.

Figure 3 shows that, except in the noOM plots, the undecomposed or partially decomposed organic carbon (LF) constituted a large portion of the total SOC in all treatments. The proportion of the light fraction

**Fig. 2** Mean decomposition rates (% dry matter loss per day) over 144 days as affected by C/N ratio, lignin content and lignin/N ratio



**Table 4** Comparison of organic carbon content in all SOC fractions, in the heavy SOC fraction and total SOC content (0–20 cm soil depth) based on standard soil sample preparation and analysis

Treatment	Standard total SOC <sup>a</sup> (Mg ha <sup>-1</sup> )	Total SOC incl. all fractions (Mg ha <sup>-1</sup> )	% of standard total SOC (%)	Heavy SOC fraction (Mg ha <sup>-1</sup> )	% of standard total SOC (%)
no OM	23.6	25.8	109.0	23.5	99.6
Control (Ic)	30.6	36.1	118.1	30.3	99.1
Leucaena (+Ic)	30.3	40.8	134.5	29.9	98.6
Senna (+Ic)	33.7	42.8	127.0	33.2	98.6
Maize stover (+Ic)	29.4	38.5	130.9	29.2	99.2

<sup>a</sup> Total soil organic C based on standard sample preparation

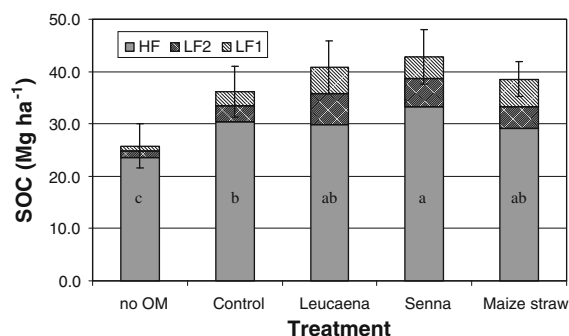
**Table 5** Organic C budget in the surface soil following the application of leaves of Senna, Leucaena, and Maize stover mixed with Imperata (Ic) residues over a period of 20 months

Treatment	Initial soil C	Input C	Soil C at the end of the experiment (Mg ha <sup>-1</sup> )	Remaining C	Remaining C/ input C
no OM	26.3		25.8 c		
Control (Ic)	26.6	10.6	36.1 b	9.5	0.89
Leucaena (+Ic)	24.8	27.4	40.8 ab	16	0.58
Senna (+Ic)	28.1	27.7	42.8 a	14.6	0.53
Maize stover (+Ic)	27.2	25.6	38.5 ab	11.3	0.44
LSD (5%)			4.4	3.8	0.23

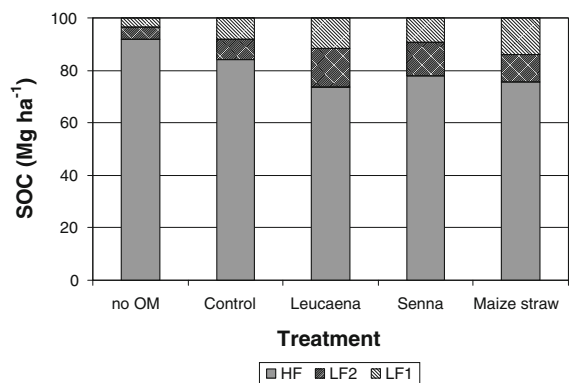
noOM Control without any plant residue input, Control *Imperata cylindrica* grass fallow, HF Heavy SOC fraction, LF2 Light SOC fraction < 2 mm, LF1 Light SOC fraction > 2 mm. (Error bars denote standard error of total carbon content, bars with the same letter are not significantly different at  $P < 0.05$ )

was 26, 25 and 22% of the total SOC in the Leucaena, maize stover and Senna plots respectively (Fig. 4). In the control plots 16% of the SOC belonged to the light fractions. The ratio between coarse (LF1) and fine (LF2) light fraction was approximately 1:1 in all treatments, although in the maize stover plots the ratio tended to be higher.

When changes in SOC content were calculated by excluding either the coarse (LF1) or both the coarse (LF1) and the fine (LF2) light SOC fraction, the amounts and rates of increase were lower (Table 6). For example, total SOC increased in the Leucaena treatment by  $16.0 \text{ Mg C ha}^{-1}$ . However, when the



**Fig. 3** SOC fractions in the 0–20 cm soil depth imposed by different residue materials mixed with *Imperata cylindrica* within a period of 20 months. Error bars denote standard error of total SOC content, bars with the same letter are not significantly different at  $P < 0.05$



**Fig. 4** Relative proportion of different fractions of SOC (HF Heavy SOC fraction, LF1 Light SOC fraction > 2 mm, LF2 Light SOC fraction < 2 mm) in the surface soil (0–20 cm) following application of  $30 \text{ Mg ha}^{-1}$  dry matter of contrasting plant residues mixed with *Imperata cylindrica* within a period of 20 months (Control *Imperata cylindrica* grass fallow, noOM Control without any residue input)

coarse part of the light SOC fraction was omitted, the increase was reduced to  $12.1 \text{ Mg C ha}^{-1}$ . Exclusion of the entire light SOC fraction resulted in an increase of  $7.3 \text{ Mg C ha}^{-1}$  only. Similarly, when the light fraction in the maize stover treatment was excluded and only the increase of the heavy fraction was considered, the increase dropped from  $11.3$  to  $4.3 \text{ Mg C ha}^{-1}$ . Calculated annual increase rates were affected accordingly and dropped to 51% (Senna), 46% (Leucaena) and 39% (Maize stover) of their former values (Table 6). The increase of total SOC was highest with Leucaena followed by Senna, maize stover and control. In contrast, when the increase of heavy SOC was considered, Leucaena and Senna showed similar magnitudes of increase while the control with *Imperata cylindrica* exceeded the maize stover treatment in spite of a much lower organic carbon input in the later.

Assuming that the simultaneous decomposition of the carbon in the heavy fraction was compensated by carbon from root litter and exudates, carbon transformation efficiency of each of the organic materials was calculated as the increase in the heavy fraction divided by the total carbon input. The carbon transformation efficiency decreased in the order Imperata > Leucaena > Senna > maize stover. The highest transformation efficiency was observed to be 57% (control plots with *Imperata cylindrica*) and the lowest was in the order of 17% (maize stover with *Imperata cylindrica*) (Table 7). Table 7 indicates that neither nitrogen nor lignin content or lignin/N ratio explained the differences between the observed transformation efficiencies. On the other hand, carbon transformation efficiency was highest when polyphenol content (Folin–Denis extraction) was highest and lowest when polyphenol content was lowest. Therefore, polyphenol content seemed to be the best indicator for the efficiency of the organic materials to build up stabilised SOC.

Table 8 illustrates that newly formed heavy SOC may differ considerably in its properties with regard to chemical functions like cation exchange capacity. Within the observation period of 20 months, potential cation exchange capacity (CEC<sub>pot</sub>) in the topsoil increased in the Leucaena, Senna and control plots by 17, 8 and 6 mmol (+)  $\text{kg}^{-1}$  soil respectively. Assuming that the increase of the heavy SOC fraction (HF) was entirely responsible for the rise in CEC, calculated CEC per kg of the newly formed heavy

**Table 6** Changes in SOC fractions with addition of leaves of *Leucaena*, *Senna* and of maize stover mixed with *Imperata* (Ic) residues within a period of 20 months and calculated annual carbon transformation rate

Treatment	Increase (+)/decrease (-)				Annual rate	
	HF + LF1 + LF2 (Mg ha <sup>-1</sup> )	HF + LF1 (Mg ha <sup>-1</sup> )	HF (Mg ha <sup>-1</sup> )	HF + LF1 + LF2 (Mg ha <sup>-1</sup> )	HF + LF1 (Mg ha <sup>-1</sup> )	HF (Mg ha <sup>-1</sup> )
No OM	-0.5 d	-0.5 c	-0.5 c	-0.3 d	-0.3 c	-0.3 c
Control (Ic)	+9.5 c	+7.8 b	6.0 ab	+5.3 c	+4.7 b	+3.6 ab
<i>Leucaena</i> (+Ic)	+16.0 a	+12.1 a	7.3 a	+9.6 a	+7.3 a	+4.4 a
<i>Senna</i> (+Ic)	+14.6 ab	+11.7 a	7.5 a	+8.8 ab	+7.0 a	+4.5 a
Maize stover (+Ic)	+11.3 bc	+7.1 b	4.3 b	+6.8 bc	+4.3 b	+2.6 b
LSD (5%)	3.8	3.1	3.8	2.5	1.8	1.7

HF Heavy SOC fraction, LF1 Light SOC fraction > 2 mm, LF2 Light SOC fraction < 2 mm

Treatments in the same column with the *same letter* are not significantly different ( $P < 0.05$ )

**Table 7** Lignin, phenols and nitrogen percentages compared to transformation efficiency of *Imperata* (Ic) mulch and its mixtures with leaves of *Leucaena*, *Senna* and maize stover into the heavy SOC fraction

Treatment	N (g kg <sup>-1</sup> )	Lignin (g kg <sup>-1</sup> )	Lignin/N	Extractable polyphenols (g kg <sup>-1</sup> )	Transformation efficiency <sup>e</sup> (%)
Control (Ic)	1.4	6.0 <sup>a</sup>	4.3	8.4 <sup>d</sup>	57 a
<i>Leucaena</i> (+Ic)	3.9 (2.8)	10.3 <sup>b</sup> (8.6)	2.6 (3.1)	5.0 <sup>b</sup> (6.4)	27 b
<i>Senna</i> (+Ic)	2.8 (2.2)	6.5 <sup>b</sup> (6.3)	2.3 (2.9)	1.6 <sup>b</sup> (4.3)	27 b
Maize stover (+Ic)	0.9 (1.1)	36.7 <sup>c</sup> (24.4)	40.8 (22.2)	0.6 <sup>c</sup> (3.6)	17 c
LSD (5%)					18

<sup>a</sup> Greiling 1985

<sup>b</sup> Tian et al. 1992b

<sup>c</sup> Tian et al. 1992a

<sup>d</sup> Baumann (personal communication)

<sup>e</sup> Treatments with the *same letter* are not significantly different ( $P < 0.05$ )

**Table 8** Estimation of the potential cation exchange capacity (CEC) of the newly formed heavy SOC fraction (HF) with the application of *Imperata* (Ic) and its mixtures with leaves of *Leucaena*, *Senna* and maize stover

Treatment	Increase of HF (g kg <sup>-1</sup> soil)	Increase of CEC (mmol (+) kg <sup>-1</sup> soil)	Estimated CEC of the newly formed HF (mmol (+) kg <sup>-1</sup> HF)	(NxPhenol) content of the applied material (mg kg <sup>-1</sup> )
Control (Ic)	4.03 ab	+6	1490 b	11.8
<i>Leucaena</i> (+Ic)	4.91 a	+17	3470 a	17.9
<i>Senna</i> (+Ic)	5.04 a	+8	1590 b	9.5
Maize stover (+Ic)	2.91 b	0	0 c	4.0
LSD (5%)	1.90		1231	

Treatments in the same column with the *same letter* are not significantly different ( $P < 0.05$ )

organic carbon fraction was 3470 and 1590 mmol (+) in the *Leucaena* and *Senna* treatment and 1490 mmol (+) in the control. In spite of the formation of 4.3 Mg

C ha<sup>-1</sup> of heavy SOC in the maize stover treatment, the newly formed heavy organic carbon provided no additional cation exchange sites. When comparing the

estimated CEC of the newly formed organic carbon in the heavy fraction with the chemical components of the applied residues listed in Table 7, extractable polyphenols together with the nitrogen content seemed to be responsible for the building up of organic compounds with a large number of cation exchange sites.

## Discussion

On cropland, besides quantity and quality of the organic material applied, the rates of transformation of carbon from organic litter to SOC expressed as the increase in SOC per year is regulated by factors like climate, soil properties and cropping system (Scheffer 2002; Stahr et al. 1994). On a comparable site (Ultisol) with sandy surface texture in Benin, an annual increase of  $1.3 \text{ Mg C ha}^{-1} \text{ a}^{-1}$  was observed over a 13 years period in an improved fallow system consisting of *Mucuna puriens* in rotation with maize (Barthes et al. 2004). Although the annual carbon input in the Mucuna–Maize system was  $10 \text{ Mg C ha}^{-1}$ , the observed total SOC (standard analysis) was less than the lowest transformation rate observed in the control plots of our experiment under *Imperata cylindrica* (Table 6). The lower carbon transformation rate in the Maize–Mucuna system may be explained by the slightly lower annual carbon input and by the regular tilling of the soil before the maize cropping, disrupting aggregates which are an effective protection for organic carbon against mineralisation (Singh et al. 2009b; Zotarelli et al. 2007). In 25 years old Cocoa plantations in Ghana without any soil disturbance, Isaac et al. (2005) found a carbon transformation rate of  $3 \text{ Mg C ha}^{-1} \text{ a}^{-1}$  while Youkhana and Idol (2009) reported from coffee plantations an increase of soil carbon of  $5.4 \text{ Mg C ha}^{-1} \text{ a}^{-1}$  when adding between 7.5 and  $11.2 \text{ Mg C ha}^{-1} \text{ a}^{-1}$  of *Leucaena* prunings over two years. This transformation rate is between the observed annual increase in HF + LF1 fractions of the control ( $4.7 \text{ Mg C ha}^{-1} \text{ a}^{-1}$ ) and the Senna ( $7.0 \text{ Mg C ha}^{-1} \text{ a}^{-1}$ ) treatment. However, in the former study no characterisation of the compositional changes of SOC has been carried out, whereas in the latter Youkhana and Idol (2011) found a distinct increase of fine particulate organic carbon (corresponding to the LF1 fraction) and a shift in the proportion of SOC in the

silt + clay fractions (corresponding to the HF fraction), which confirms our observations. Under a two years old *Senna siamea* fallow in Nigeria, which had been cut back and alley cropped for one season, Yamoah et al. (1986) observed an increase of organic carbon in the topsoil (0–15 cm) from 1.62 to 2.21% within 18 months. This corresponded to an annual increase of about  $8 \text{ Mg C ha}^{-1} \text{ a}^{-1}$ . This value is comparable to the annual increase of total organic carbon including the light fractions ( $8.8 \text{ Mg C ha}^{-1}$ , respectively) in the Senna treatment of the present study, but not to the increase observed in the heavy fraction ( $4.5 \text{ Mg C ha}^{-1}$ ). These results illustrate that observed carbon transformation rates in soils should include additional information about the changes in composition of SOC, when cropping systems or management practices are to be evaluated with regard to their transformation potential. SOC composition is important for other soil functions like soil nitrogen mineralisation and subsequent uptake by crops (Gaiser et al. 1998).

In the literature, a wide range of estimates exists for carbon transformation efficiencies of crop residues and organic soil amendments expressed as the proportion of added organic carbon retained in the soil. Lal (2009) report transformation efficiencies of 18–31% for grass fallow residues after three years of fallow in Nigeria, depending on the grass species. Transformation efficiencies in agroforestry systems of 31 and 40% were estimated by Oelbermann et al. (2006b) in Canada and Costa Rica, respectively. At the same site in Costa Rica, the transformation efficiency was found to be higher in alley cropping systems with *Gliricidia sepium* (10%) than with *Elythrina poeppigiana* (58%) (Oelbermann et al. 2006a). However, these studies only monitored the changes in total SOC without taking into account changes in SOC composition. Comparing the efficiency of the organic materials in our study to build up stabilised heavy SOC fractions, *Imperata cylindrica* proved to be most favourable due to higher content of extractable polyphenols (Table 7). Its transformation efficiency (57%) was situated close to the value for *Elythrina poeppigiana* given by Oelbermann et al. (2006a), but above the absolute range which Monnier (1965) gave for different organic materials (8–45%). The transformation efficiency of the Imperata/maize stover mixture (17%) fell within the range that Monnier (1965) established



for cereal stover (8–20%) and was close to the values found for wheat straw (Stewart et al. 2008). The mixture of *Imperata* with leaves of *Senna* or *Leucaena*, which can be considered as green manure, showed surprisingly high transformation efficiencies of 27% (Table 7). De Haan (1977) in his pot experiments assumed that lignin is the principle substrate towards the formation of humus, whereas other authors emphasize the importance of sources of readily available nitrogen (peptides, amino acids, or ammonium) in addition to lignin and phenolic compounds (Mandal et al. 2008; Seneviratne et al. 2009). They assumed that polyphenols inhibit microbial activity and that nitrogenous compounds interact with the reactive groups of the phenolic compounds. The two compounds form polymerized humic products in which organic carbon becomes stabilized. Table 7 shows that neither lignin nor lignin/N ratio could explain the differences in transformation efficiency between the treatments. The results rather suggest that transformation efficiency depended on the extractable polyphenols in the applied organic material. This is in agreement with other authors who observed larger soil carbon accumulation with organic materials with high polyphenol content (Mandal et al. 2008; Seneviratne et al. 2009), although Vityakov et al. (2000) claimed that, transformation efficiency was lowest with two residues with high polyphenol content (>4.5%), because the carbon accumulation occurred mainly in the particulate (>1 mm) SOC fraction. Polyphenols may interfere very effectively in the polymerization and stabilization process of organic carbon in the soil (Northup et al. 1998). Since the decomposition process of organic material depends mainly on lignin/N ratio (Meentemeyer 1978) or C/N ratio and lignin content (Tian et al. 1992a), we conclude that low decomposition rates of organic materials do not necessarily imply high transformation rates and vice versa. This has been shown in the case of *Leucaena* and maize stover. Although the mixture of maize stover with *Imperata* had the highest lignin/N ratio of all organic materials, it had the lowest transformation efficiency (Table 7). In contrast, the mixture of *Leucaena* leaves with *Imperata*, having the highest decomposition rate, turned out to have a considerable efficiency in fixing carbon in the soil. Moreover, when quality of the newly formed organo-mineral compounds was concerned as expressed by the neo-

formation of cation exchange sites, *Leucaena* leaves seemed to surpass all other organic materials tested (Table 8). Obviously, this was due to its high nitrogen content in combination with a moderate level of extractable polyphenols (5 g kg<sup>-1</sup>). Soil organic matter formed by maize stover had very poor quality with respect to the supply of cation exchange sites. Thus, incorporation of residues from maize contributed little to the improvement of cation retention in the sandy topsoil.

## Conclusions

The present investigation illustrates the importance of characterizing SOC fractions when evaluating carbon sequestration effects of green manuring practices with different plant residues. The paper demonstrates the potential of *Imperata cylindrica* pure or in combination with leaves of leguminous shrubs to sequester carbon in stabilised SOC fractions and to produce organo-mineral compounds which increase cation exchange capacity in the soil. Comparing leaves of *Leucaena leucocephala* and maize stover, it has been shown that there is no evidence that high lignin or lignin/N ratio involve high transformation rates of litter carbon to stabilised SOC. We rather conclude, that mixtures of leguminous trees together with grasses which contain high levels of extractable polyphenols and moderate levels of nitrogen may be able to increase the content of heavy SOC fractions within relatively short periods, fixing carbon in the soil and supplying at the same time additional cation exchange sites to improve cation retention in the soil.

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