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Losses of soil carbon by converting tropical forest to plantations: erosion and decomposition estimated by $\delta^{13}C$

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Abstract

Indonesia lost more tropical forest than all of Brazil in 2012, mainly driven by the rubber, oil palm, and timber industries. Nonetheless, the effects of converting forest to oil palm and rubber plantations on soil organic carbon (SOC) stocks remain unclear. We analyzed SOC losses after lowland rainforest conversion to oil palm, intensive rubber, and extensive rubber plantations in Jambi Province on Sumatra Island. The focus was on two processes: (1) erosion and (2) decomposition of soil organic matter. Carbon contents in the Ah horizon under oil palm and rubber plantations were strongly reduced up to 70% and 62%, respectively. The decrease was lower under extensive rubber plantations (41%). On average, converting forest to plantations led to a loss of 10 Mg C ha^{-1} after about 15 years of conversion. The C content in the subsoil was similar under the forest and the plantations. We therefore assumed that a shift to higher $\delta^{13}C$ values in plantation subsoil corresponds to the losses from the upper soil layer by erosion. Erosion was estimated by comparing the $\delta^{13}C$ profiles in the soils under forest and under plantations. The estimated erosion was the strongest in oil palm (35 ± 8 cm) and rubber (33 ± 10 cm) plantations. The ^{13}C enrichment of SOC used as a proxy of its turnover indicates a decrease of SOC decomposition rate in the Ah horizon under oil palm plantations after forest conversion. Nonetheless, based on the lack of C input from litter, we expect further losses of SOC in oil palm plantations, which are a less sustainable land use compared to rubber plantations. We conclude that $\delta^{13}C$ depth profiles may be a powerful tool to disentangle soil erosion and SOC mineralization after the conversion of natural ecosystems conversion to intensive plantations when soils show gradual increase of $\delta^{13}C$ values with depth.

Keywords: carbon sequestration, deforestation, erosion assessment, land degradation, organic matter decomposition, soil organic matter, subsoil, $\delta^{13}C$ depth profile

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Introduction

Tropical rainforest area is decreasing worldwide through deforestation and transformation into agricultural systems. Between 1985 and 2007, Sumatra Island (Indonesia) lost half of its remaining natural rainforest, which currently covers a mere 30% of the island (Laumonier *et al.*, 2010; Wilcove & Koh, 2010). In 2012, the area of natural rainforest loss was higher in Indonesia than in Brazil (Margono *et al.*, 2014). This deforestation is still ongoing, mainly driven by the oil palm, rubber, mining, timber, and pulp industries (Laumonier *et al.*, 2010; Abood *et al.*, 2015). Land-use changes in tropical ecosystems lead to major modifications of soil properties and processes (Ross, 1993; McGrath *et al.*, 2001; Pabst *et al.*, 2013). Among them, soil organic carbon (SOC) sequestration is a key process mitigating global climate change and ensuring soil fertility and so, the food security (Lal, 2004). The present study is motivated by the need to quantify soil organic carbon (SOC) stocks changes after tropical forest conversion and to elucidate the involved processes.

Loss of SOC is a well-known consequence of converting natural forest to agricultural land (Van Noordwijk *et al.*, 1997; Don *et al.*, 2011). Nevertheless, the magnitude, rates, and even the direction of the changes in SOC depend on the type of conversion and are still unclear (Guo & Gifford, 2002; Don *et al.*, 2011; Ziegler *et al.*, 2012). Conversion of forest to tree plantations is strongly underrepresented in the literature despite the increasing plantation area (Powers *et al.*, 2011). Studies on the conversion of lowland tropical forest to rubber and oil palm plantations showed contrasting results with regard to SOC. Significant decreases of SOC under rubber plantations were reported down to 1 m depth

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(De Blécourt *et al*., 2013; Chiti *et al*., 2014) or only in the topsoil (Schroth *et al*., 2002; Chiti *et al*., 2014). In contrast, Frazão *et al*. (2013) reported no differences or even slightly higher SOC stocks under oil palm plantations than in the surrounding forest.

Two groups of processes explain the possible reduction in SOC after land-use change (Fig. 1): (1) modification of the SOC turnover rate by decreasing the C input or increasing SOC decomposition and (2) erosion of the C-rich surface layer (Lal, 2001; Don *et al*., 2011). Forest conversion to plantation reduces the C input from the above- and belowground litters (Powers, 2004). The decomposition of SOC is enhanced by nutrient release from the dead or burnt biomass and by the labile organic matter released from disturbed soil aggregates during conversion to plantations (Berhe *et al*., 2007). Soil erosion is strongly increased when forest is converted to agricultural land (Islam & Weil, 2000; Sidle *et al*., 2006), especially when the soil protective cover (litter layer and canopy) is removed (Ross & Dykes, 1996).

Decomposition of SOC directly affects its isotopic composition. Firstly, *kinetic fractionation* occurs because reaction rates are slower for heavy isotopes (e.g., ^{13}C) than for lighter isotopes (e.g., ^{12}C), enriching the remaining SOC with heavy isotopes. Isotopic composition is expressed in δ notation:

$$\delta(‰) = (\frac{R_{\text{sample}}}{R_{\text{standard}}} - 1) * 1000 \quad (1)$$

where R is the molar ratio of heavy to light isotope of the sample or the international PDB reference. Accordingly, ^{13}C enrichment leads to less negative $\delta^{13}C$ values.

In natural systems, kinetic fractionation leads to a substrate ^{13}C enrichment. This follows a linear function with the logarithm of the fraction of the remaining initial substrate according to a Rayleigh distillation (Mariotti *et al*., 1981). Secondly, *preferential substrate decomposition* of substances with different isotopic composition might affect the bulk SOC isotopic signature (Werth & Kuzyakov, 2010). Individual substances in a plant can differ up to 9‰ (Hobbie & Werner, 2004). This process, however, should mostly work against a ^{13}C enrichment because easily available substances such as glucose are enriched in ^{13}C compared to more refractory substances such as lignin (Hobbie & Werner, 2004). Despite uncertainties about the mechanisms leading to fractionation during microbial metabolism (Brüggemann *et al*., 2011), a review by Werth & Kuzyakov (2010) shows a mean enrichment of 1.2 ‰ in microbial biomass compared to the bulk SOC. The $\delta^{13}C$ increase during SOC maturation is roughly proportional to the number of cycles in which C is metabolized by microorganisms (Gunina & Kuzyakov, 2014).

In general, the $\delta^{13}C$ increases with soil depth, whereas C content decreases (Natelhoffer & Fry, 1988; Balesdent *et al*., 1993; Garten *et al*., 2000; Wynn *et al*., 2005; Schneckenberger & Kuzyakov, 2007). Various mechanisms were suggested to explain this relative enrichment (Natelhoffer & Fry, 1988; Balesdent *et al*., 1993; Ehleringer *et al*., 2000). The *root-to-shoot ratio* increases with soil depth, which might enrich SOC with ^{13}C because roots are on average enriched in ^{13}C by 1.2‰ compared to shoots (Werth & Kuzyakov, 2010). The other potential mechanisms are related to the increasing average age of SOC with increasing soil depth (Trumbore, 2000). In addition to a more advanced *decomposition* in older SOC, *physical mixing* favors the migration of smaller and more strongly decomposed SOC particles down the soil profile. This leads to a higher proportion of older and more decomposed SOC in deeper horizons. Finally, changes over

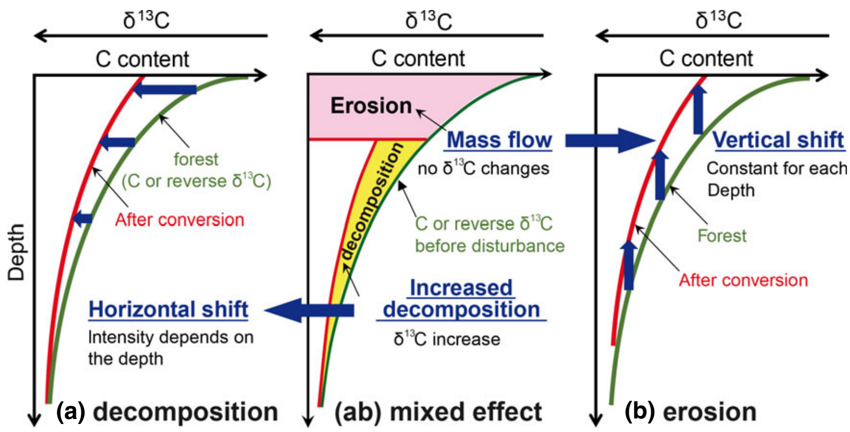

Fig. 1 Impact of forest conversion on the C content and $\delta^{13}C$ distributions in the soil depths (ab) separated by decomposition (a) and erosion (b).

time in the litter $\delta^{13}C$ values would produce a similar trend in the depth profile because SOC is older in deeper soil layers. The *Suess effect* describes the dilution of $^{13}CO_2$ in the atmosphere due to the burning of fossil fuel (depleted in ^{13}C) since the Industrial Revolution (Suess, 1955). The maximal range of the Suess effect in the soil is currently around 2‰ according to the atmospheric ^{13}C depletion since 1840 (Verburg, 2007).

An empirical linear relation was observed between the $\delta^{13}C$ value and the log-transformed C content (log-SOC) in well-drained undisturbed soils (Balesdent *et al*., 1993; Bird & Pousai, 1997). Further studies correlated the slope of the regression, termed β, with SOC turnover (Garten Jr., 2006) or proxies of SOC turnover, for example, mean annual temperature (MAT) (Garten Jr *et al*., 2000; Garten, 2006; Campbell *et al*., 2009; Acton *et al*., 2013), litter C/N ratio (Garten *et al*., 2000; Garten, 2006), and soil texture (Powers & Schlesinger, 2002; Wynn *et al*., 2005; Acton *et al*., 2013). More negative β (steeper slopes) were associated with higher turnover rates. Studies modeled, using the Rayleigh distillation equation, the depth trend of $\delta^{13}C$ values in terms of the remaining SOC fraction instead of the C content (Wynn *et al*., 2005, 2006; Garten, 2006; Diochon & Kellman, 2008). Finally, β values were modeled by isotopic mass balance using the Rayleigh distillation equation and incorporating decomposition rate and physical mixing of SOC (Acton *et al*., 2013). Only few studies have investigated the effect of soil disturbance on the β value (Wynn *et al*., 2005, 2006; Diochon & Kellman, 2008; Campbell *et al*., 2009). Campbell *et al*. (2009), however, pointed to the potential of comparative studies on disturbed and undisturbed soil to investigate the effect of land-use changes on SOC, and Wynn *et al*. (2006) hypothesized the effect of decomposition and erosion on the β value.

Erosion has no direct impact on the $\delta^{13}C$ value because soil particles are mechanically transported without any differentiation between ^{13}C and ^{12}C. Nevertheless, after the loss of the eroded layer, the new surface layer is composed of a mixture of SOC from the subsoil and fresh C from the litter. This leads to a different isotopic composition of the new vs. old surface layer (Häring *et al*., 2013), but without effect on the $\delta^{13}C$ in the subsoil. Furthermore, the $\delta^{13}C$ depth distribution in the soil profile shifts closer to the soil surface after the loss of the upper layer (Fig. 1b). Erosion does not modify the β values because the regression is independent of soil depth (Wynn *et al*., 2006).

We investigated the impact of lowland rainforest conversion to tree plantations on the SOC and its isotopic composition. We compared the vertical distribution of SOC and $\delta^{13}C$ and β values of soils under forest and under plantations to investigate the impact of erosion and SOC decomposition on the decrease of C stocks due to forest conversion. We hypothesized that SOC losses would increase with land-use intensity. Nevertheless, the effects on C content and on $\delta^{13}C$ would be mainly pronounced in the topsoil because of the short period after conversion, leaving the subsoil unaffected. Therefore, we assess erosion by assuming that the C content and its $\delta^{13}C$ values in the plantation subsoil were similar to the values in the forest subsoil prior to conversion. Consequently, when an identical subsoil depth has a higher $\delta^{13}C$ in the plantation than the forest, we suggest that this layer experienced a vertical shift toward the soil surface after erosional loss of the upper layer (Fig. 1b). Following the hypothesis that the subsoil would be unaffected by the land-use change, we assume that the β value in the subsoil of the plantation represents the β value before the conversion to plantation. Consequently, if the SOC turnover in the topsoil would be modified by the land-use change, the $\delta^{13}C$ of the SOC in the plantation topsoil should deviate from the regression line calculated for the plantation subsoil.

In summary, this study was designed (1) to quantify changes of C content and stocks in soil after conversion of lowland rainforest to extensive rubber, intensive rubber, and oil palm plantations, (2) to quantify soil erosion in plantations and (3) to investigate changes in SOC decomposition in plantation topsoils.

Materials and methods

Study sites

The study was conducted in Jambi Province (Sumatra, Indonesia). The climate is tropical humid (27 °C; 2224 mm yr^{-1}; 112–259 mm month^{-1}) with a rainy season lasting from October to April. The experimental design consists of a space-for-time substitution approach to assess the effect of forest conversion to plantations. It includes natural lowland tropical rainforest and three land-use types dominating in Sumatra: (1) jungle rubber, (2) rubber plantation, and (3) oil palm plantation. The design is replicated in 2 regions (called Harapan and Bukit in the manuscript) within the province of Jambi. Soils from both regions were acrisols with sandy loam texture in Harapan and a clay texture in Bukit region. In each region, a large unit of lowland rainforest was used as reference sites: Harapan Rainforest and National Park Bukit Duabelas. The reference sites are old-growth forests that have been subject to minor logging but are still very close to natural state. Jungle rubber is an agroforest in which rubber trees were extensively planted in partially logged forest.

Experimental plots

Four replicate sites for each land use in both regions were selected for a total of 32 field plots. Plot altitudes varied between 50 and 100 m a.s.l and plot slopes between 3 and 12%. On average, oil palm plantations were 14 years old in both regions. Rubber plantations were five years younger in Bukit than the 15-year-old Harapan plantations. The age of jungle rubber ranged from 16 to 42 years. The jungle rubber ages, however, indicate the minimal ages, that is, when the farmer received/bought the land or as far as the farmer could remember. Except for one oil palm site in Bukit (BO1), all rubber and oil palm plantations were smallholding plantations. Usually, rubber and oil palm plantations are established by burning the land after timber extraction. Soils are not tilled, but no measures against erosion are taken by smallholders. The understory vegetation was absent or sparse, leaving the soil mostly bare in oil palm plantations and sparsely covered with leave litter in rubber plantations.

Soil sampling

For each replicate site, one soil pit was dug between October and November 2012. Soils were described and sampled by horizons to a maximum depth of 100 cm. The bottom limit was set at the maximum depth at which soils dry during the dry season. This corresponds to the start of soft iron-clay concretions and/or a gray-red pattern reflecting reallocation of iron due to reduction–oxidation processes. For horizons less than 15 cm thick (mostly Ah and E horizons), the samples were taken from the whole horizon. For horizons thicker than 15 cm, samples were taken in the middle. After collection, soils were air-dried for 2–3 weeks, sieved at 2 mm to remove the root residues and to homogenize the samples, and prepared for total C and N contents and δ^{13}C analyses. If present, 200 g of litter layers (OL: organic horizon with fresh plant residues; OF: organic horizon with fractionated plant residues) was collected beside the soil pit. There was no litter layer in the oil palm plantations. Therefore, we collected litter samples on the top (OL samples) and bottom (OF samples) of frond piles.

Bulk density has been measured by another research project in adjacent pits in each 32 sites at 5, 20, 40, and 75 cm depth. Two hundred and fifty cm^3 cylinders were inserted horizontally from the side of the pit, dried, and weighed.

Sample analysis

Total C and N contents as well as δ^{13}C values (in ‰ of VPDB) were measured on grinded and oven-dried (105 °C overnight) soil and litter samples. Root residues were carefully removed before grinding. Five to forty mg of soil (depending on the C and N content) was weighed in tin capsules. Measurements were taken at the Center for Stable Isotope Research and Analysis (KOSI) of the University of Göttingen with an Elemental Analyser (Eurovector) coupled to an isotope ratio mass spectrometer (Delta plus, Thermo Fisher). Two acetanilide standards were measured every 12 samples. The analytical precision was lower than 0.15 ‰. As no carbonates were present in the soils, total C reflects organic C.

Calculations and statistics

To compare and to present soil profiles with different horizon depths, C and N contents, C/N ratio, and δ^{13}C values were recalculated for fixed depths (20, 35, and 55 cm for all soils and 80 and 100 for the deepest soils). For the calculation, the C and N contents, C/N ratio, and δ^{13}C values in between two adjacent sampling depths were calculated assuming a linear change of the variables in the subsoil between the two sampling depths:

$$v_1 + (v_1 - v_2) * \frac{d_f - d_2}{d_1 - d_2} = v_f \tag{2}$$

where v_1, v_2, and v_f are, respectively, the variable values of the two samples adjacent to the fixed depth and the recalculated value of the fixed depth. d_1, d_2, and d_f are the respective depths of the two samples and the fixed depth. The samples used for the calculation were those directly above and below the fixed depth. When the sample above the fixed depth was the Ah horizon, we chose the two next samples below that fixed depth. Ah horizons were not used for calculations to avoid overestimating the variable due to the strong decrease of all parameters between this organomineral horizon and the mineral horizons. Values of Ah horizons were not recalculated but were the measured values of the samples.

C stocks were calculated by multiplying the C content with the respective bulk density. If a layer could not be sampled (AE horizon or thin horizons), the C content for that layer was calculated by Eqn (2).

Statistics were performed by the open source software R version 2.15.2. Because of differences in plantation ages and small variations of soil textures, we tested land-use effects for each region separately. We assessed the effect of land-use intensity on C and N content, δ^{13}C value, C/N ratio, and C stocks values within a region by using *a priori* comparisons of least squares means. Three contrast comparisons were set to reflect land-use intensity: (1) forest vs. tree plantations (jungle rubber, rubber, and oil palm), (2) extensive (jungle rubber) vs. intensive tree plantations (rubber and oil palm), and (3) rubber vs. oil palm plantations. Tests were performed on Ah horizon and three fixed soil depths (20, 35, and 55 cm) and on stocks from 0 to 10, 0 to 30, and 0 to 50 cm depths. We assessed region effect on C and N contents, δ^{13}C, C/N ratio, and C stocks for (1) forest soils and (2) tree plantations by performing t-tests with region as grouping factor. T-tests were performed on the same four depths as previously and on the 0–30 cm stocks.

The relation between δ^{13}C and the logarithm in base 10 of C content (logSOC) was investigated by linear regression for each soil. The slope of the regression is defined as the β value. The power functions associated with the decrease of C content or to the increase of δ^{13}C value with depth were fitted in Statistica 10 using the following equation:

$$C_d = C_{\mathrm{Ah}} d^k \tag{3}$$

$$\delta^{13}C_d = \delta^{13}C_{\mathrm{Ah}} d^l \tag{4}$$

where C_d, $\delta^{13}C_d$, C_{Ah}, and $\delta^{13}C_{\mathrm{Ah}}$ are the C contents and the δ^{13}C value estimated for the depth d and measured in the Ah horizon, respectively, d is the depth in cm, and k and l are the fitted parameters of the functions. Regressions were fitted using all samples below the Ah horizon. Carbon content and δ^{13}C value were the measured values at the sample collection depth.

Erosion in Harapan region was calculated using the power function describing the distribution of δ^{13}C with soil depth in the forest soils. However, this approach was not possible in Bukit region (see result section). Assuming that the shift in δ^{13}C in the plantation subsoil resulted from shift in the depth due to the erosion after conversion, we calculated the original depth before erosion for all samples under plantations by modifying Eqn (4):

$$d_b = 10^{\frac{\log_{10}(\delta^{13}C_d/\delta^{13}C_{Ah})}{-l}} \quad (5)$$

where d_b is the estimated depth before the conversion to plantation, $\delta^{13}C_d$ is the δ^{13}C value of the samples under plantation at depth d, $\delta^{13}C_{Ah}$ is the mean δ^{13}C value of the Ah horizons under forest, and the parameters l estimated by Eqn (4) for the forest (using the four sites together for the fitting). The difference between the estimated depth before conversion (d_b) and depth at which the sample was collected (d) corresponds to erosion. The erosion for one pit was calculated by averaging the erosion estimated for each sample collected in the pit. We excluded Ah horizons and samples deeper than 77 cm, which corresponds to the deepest sample under forest.

Data are presented as the mean of four replicates ± standard error (SE). If not specified, discussed differences are significant at least at a P-value level of <0.05.

Results

Effect of region and land use on C and N contents

Significant differences in C and N contents between land uses were observed only in the topsoil (Ah horizon). The C content in Ah horizons of soils under plantations was lower than under forest reference sites (Fig. 2). In Harapan region, forest sites had mean C and N contents of 6.8 ± 0.8% and 0.43 ± 0.04%, respectively. Carbon and N contents in intensive land uses (oil palm and rubber plantations) were strongly reduced up to 70% in oil palm and 62% in rubber plantations. The values, however, were not significantly different between oil palm and rubber plantations. The decrease of C and N contents was less strong in jungle rubber than in rubber and oil palm plantations, indicating an effect of land-use intensity on C and N losses in Harapan region (Fig. 2).

Their decrease in Bukit plantations followed a similar trend as in Harapan (forest > jungle rubber > rubber > oil palm) except that the C content was similar under rubber and jungle rubber. Nevertheless, the C content in Bukit region was significantly reduced only between forest sites and the mean C content of all plantations,

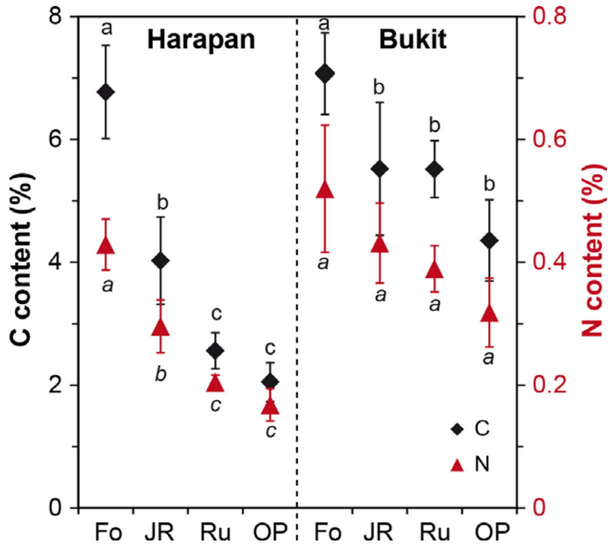

Fig. 2 Carbon and nitrogen contents in the Ah horizons under (Fo) forest, (JR) jungle rubber, (Ru) rubber, and (OP) oil palm plantations in Harapan and Bukit regions. Values represent means ± SE (n = 4). Different letters show statistically significant differences (ANOVA, P < 0.05).

but not between the plantations. There were no differences in N content between land uses.

The C and N contents in Ah horizons under forest were similar in both regions. The mean decrease of C content in the Bukit plantations (27.5%) was much lower than in Harapan (57.5%). The C and N contents in subsoil (under the Ah horizon) of Bukit were similar between land uses but up to 2 times higher than in Harapan subsoils (Fig. 3).

Carbon stocks losses in Harapan in the 0–10 cm layer showed the same decrease pattern as the C content (Table 1). C stocks decreased by 24% under jungle rubber, by 40% under rubber, and by 42% under oil palm plantations compared to the forest. The C stock reduction in plantations was significant down to 30 cm depth, but not when deeper layers were included. The mean decrease was 10.1 ± 2.9 Mg C ha^{-1} of C between plantations and forest in the 0–30 cm depth. In Bukit, however, there were no significant differences in C stocks in the top 10 or 30 cm between land-use types. Plantations had much higher C stocks in the top 30 cm in Bukit (64.0 ± 4.4 Mg C ha^{-1}) than in Harapan (44.2 ± 1.6 Mg C ha^{-1}). This relation reflected both the higher SOC losses after conversion of forest to plantations in Harapan and the higher C content in the Bukit subsoil.

δ^{13}C and C/N ratio in the Ah horizon

In Harapan, the C/N ratio was significantly lower and δ^{13}C value significantly higher in the Ah horizon under

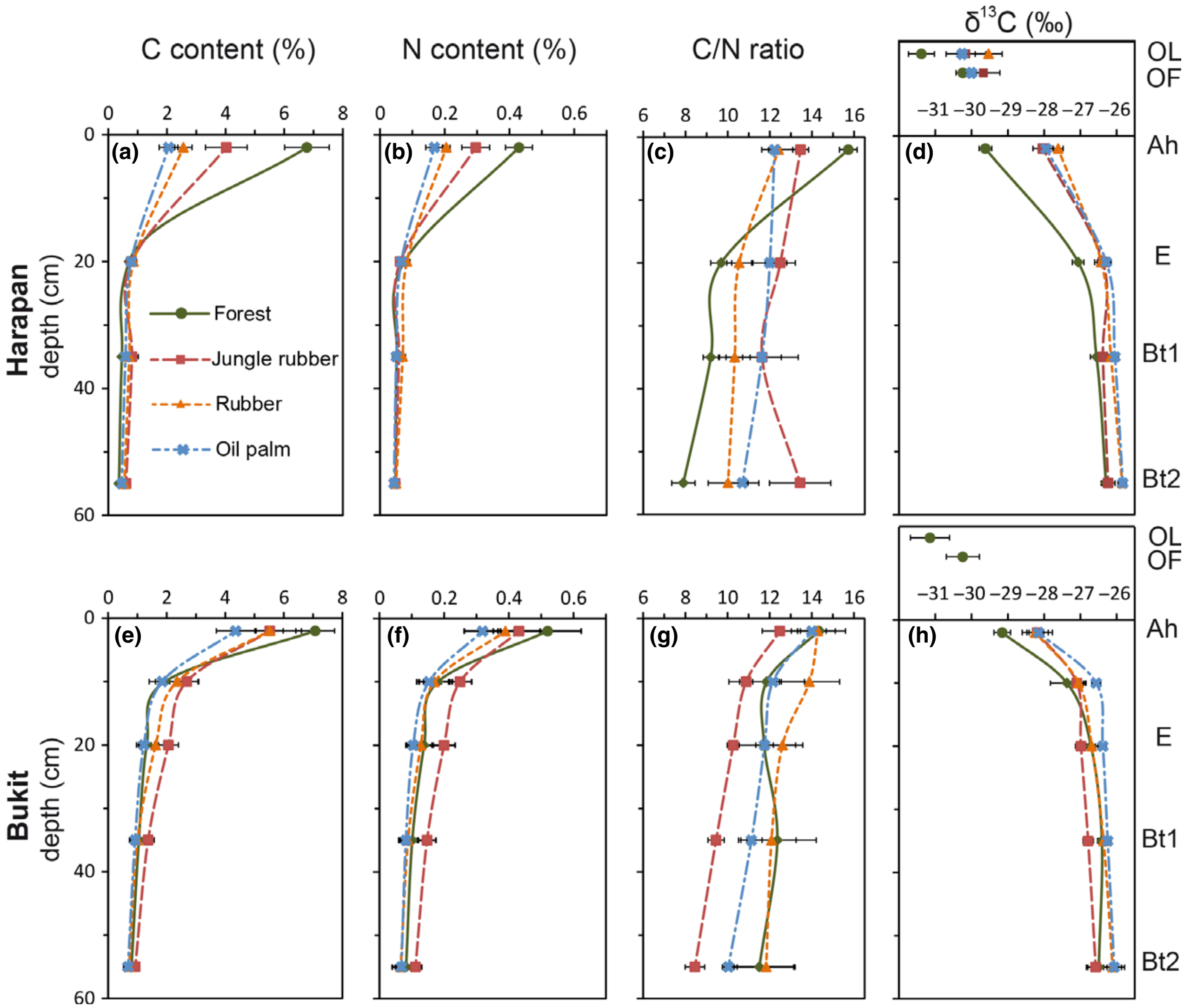

Fig. 3 Soil characteristics distributions with soil depth. (a,e) Carbon content, (b,f) nitrogen content, (c,g) C/N ratio, and (d,h) $\delta^{13}C$ distributions under forest, jungle rubber, rubber, and oil palm plantations in (a–d) Harapan and (e–h) Bukit regions. Values at fixed depths were recalculated from the original sampling points, except for Ah horizons. Ah horizon depth fixed at 1 cm for presentation purpose. Values represent means ± SE (n = 4).

Table 1 Carbon stocks (Mg C ha^{-1}) in four land-use types of Harapan and Bukit regions

	Harapan		Bukit	
Land use	0–10 cm	0–30 cm	0–10 cm	0–30 cm
Jungle rubber	27.1 (3.3)*	47.0 (3.5)	33.2 (7.0)	71.9 (7.0)
Oil palm	20.7 (2.7)	41.3 (3.1)	27.3 (3.6)	53.8 (7.9)
Rubber	21.6 (1.6)	44.4 (1.2)	41.2 (4.9)	81.1 (14.9)
Plantations†	23.1 (1.6)a‡	44.2 (1.6)a	31.5 (2.8)a	64.0 (4.4)a
Forest	35.8 (3.0)b	54.3 (4.3)b	34.0 (4.4)a	62.0 (1.8)a

*Values represent means (SE) (n = 4).
†Means of jungle rubber, rubber, and oil palm plantations.
‡Means followed by different letters within a column differ significantly (t-test at P < 0.05).

the plantations vs. forest, indicating that SOC was more intensively decomposed in the topsoil of the plantations (Fig. 3). Harapan plantations showed higher δ^{13}C values in the Ah horizon compared to forest, up to 2.0 ± 0.2 ‰ in oil palm plantations (Fig. 3d). The maximum difference in δ^{13}C (Δ^{13}C) between the soils under forest and plantations was much higher in Ah horizons than in the litter horizons (0.7 ‰) directly in contact with the Ah horizons (OF for forest, jungle rubber, and oil palm; OL for rubber). In contrast to Harapan, C/N ratios in Bukit region were not significantly different between forest and plantations in the Ah horizon (Fig. 3g).

δ ^{13}C and C/N ratio in the soil profile

The C/N ratios of the plantations in Harapan region were stable with soil depth and slightly higher than those in the forest subsoils (Fig. 3c). Nevertheless, only jungle rubber showed a significant increase of the C/N ratio at 55 cm compared to other land-use types. The δ^{13}C distribution with depth in soils of Harapan plantations showed two patterns depending on land use (Fig. 3d). (1) The δ^{13}C values in the topsoil under jungle rubber were higher than under the forest. The δ^{13}C values, however, were similar in the subsoil below 35 cm depth. (2) The δ^{13}C values below 35 cm depth under rubber and oil palm plantations experienced a constant shift (0.4 to 0.5‰) compared to the forest. Such pattern could not be identified in Bukit region because δ^{13}C values under the forest reached a maximum at 35 cm and decreased at 55 cm depth.

Regression of the C content and δ^{13}C with soil depth

The decrease of C content and the increase in δ^{13}C with soil depth under forest were described by power functions (Eqns 3 and 4). The estimated k parameters were more negative in Harapan than in Bukit, indicating less decrease of C content with depth in Bukit, especially at the forest sites BF1 and BF2 (Table 2). The standard errors on the k parameter were higher, and R^2 of the model were lower in Bukit than in Harapan region.

The parameter l was similar among the four Harapan forest sites, reflecting a low dependency of the δ^{13}C increase in site-specific conditions. The model showed high R^2 (>0.92) and low SE. Furthermore, the regression model including all subsoil samples of the four forest replicates still showed high R^2 (>0.84). Contrastingly, the forest sites in Bukit were separated in two groups. The forest sites BF3 and BF4 showed an increase of the δ^{13}C value with depth similar to that in Harapan, with high R^2 (>0.81). However, the model did not fit the sites BF2 and BF3 (R^2 < 0.46) well. These two sites had lower δ^{13}C value in Ah horizons than the other forest soils, and the δ^{13}C values did not increase in the subsoil after a strong increase from 0 to 10 cm.

Erosion

We applied the power function describing the increase of δ^{13}C value with depth to estimate the erosion (Eqn 4) and used the mean δ^{13}C values of the Ah horizons under the forest and the parameters l fitted with all subsoil samples of the four forest soils in Harapan. Calculation of erosion in Bukit, however, was not possible

Table 2 Parameters of the fitted power functions of C content and δ^{13}C with depth in forest soils of Harapan and Bukit regions

	C content			δ^{13}C		
Sites	C_{Ah}*	k†	R^2	$\delta^{13}C_{Ah}$*	l†	R^2
HF1‡	8.51	−0.81 (0.01)§	0.99	−29.8	−0.032 (0.001)	0.98
HF2	5.30	−0.76 (0.01)	0.99	−29.6	−0.029 (0.001)	0.92
HF3	7.57	−0.78 (0.01)	0.97	−30.0	−0.031 (0.000)	0.98
HF4	5.71	−0.67 (0.01)	0.97	−29.2	−0.029 (0.001)	0.92
BF1	6.39	−0.51 (0.01)	0.96	−28.8	−0.025 (0.001)	0.46
BF2	9.02	−0.52 (0.02)	0.81	−28.7	−0.026 (0.003)	0.00
BF3	6.09	−0.61 (0.02)	0.95	−29.7	−0.031 (0.000)	0.98
BF4	6.79	−0.63 (0.03)	0.95	−29.4	−0.030 (0.003)	0.81
Harapan	6.77 (0.76)	−0.76 (0.01)	0.91	−29.7 (0.2)	−0.031 (0.001)	0.84
Bukit	7.07 (0.66)	−0.57 (0.02)	0.72	−29.2 (0.2)	−0.027 (0.001)	0.68

*C content and δ^{13}C values measured in the Ah horizon of each site and means (SE) of the four forest replicates in Harapan and Bukit regions.
†Estimated parameters of Eqns (3) and (4).
‡H, Harapan; B, Bukit; F, forest; 1, 2, 3, and 4: replicates sites.
§Values represent means (SE).

by this approach because (1) there was no constant shift in $\delta^{13}C$ between the subsoil under any tree plantations and the subsoil under forest in Bukit; and (2) the forest replicate sites were not homogenous in term of $\delta^{13}C$ of Ah and $\delta^{13}C$ increase with soil depth. Finally, two forest sites showed a poor fit of the power function.

The estimated erosion after conversion in Harapan region was higher in oil palm (35 ± 8 cm) and rubber (33 ± 10 cm) plantations than in jungle rubber (14 ± 14 cm) (Fig. 4). The erosion estimates for the land-use type were significantly different from 0 under rubber and oil palm plantations but not under jungle rubber. The standard errors for all soils other than HR1 under intensive land uses were lower than 4 cm, reflecting the good applicability of the $\delta^{13}C$ approach. Based on the $\delta^{13}C$ changes between soils under forest and plantations, significant erosion occurred under the intensive plantations in the Harapan region.

Beta values and SOC turnover

The linear regression of $\delta^{13}C$ with the log-transformed C content showed a similar increase of $\delta^{13}C$ (per tenfold C content decrease) in the four Harapan forest soils. R^2 was high (>0.96) (Fig. 5a). The slopes of the regressions (β values) and the associated R^2 were only minimally modified when the regressions included the Ah horizons (−2.64 ± 0.04) or not (−2.82 ± 0.20) (Table 3). This indicated a constant increase of $\delta^{13}C$ with SOC decrease along the whole soil profile in the Harapan forest sites. In contrast, this relationship was not similar at each Bukit forest site. Although β, calculated on the whole soil profile, varied little among soils

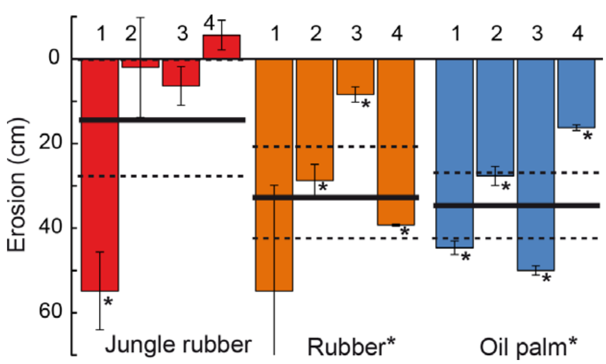

Fig. 4 Soil erosion in the four replicate soils under jungle rubber, rubber, and oil palm plantations in Harapan region. Bars represent means ± SE of the erosion calculated for each samples of one soil (n = 3; except for rubber 1 and 4, n = 2). Horizontal lines represent the mean (solid) ±SE (dashed) in the corresponding land-use type. Asterisks show significant differences to zero for sites (t-test; n = 3, except for rubber 1 and 4: n = 2) and for land uses (t-test; n = 4).

(2.98 ± 0.05), only one forest site showed a constant increase of $\delta^{13}C$ with the C content decrease through the whole soil profile.

In Harapan region, β values were similar under rubber (−2.69 ± 0.31) and under forests, but slightly lower under jungle rubber (−2.29 ± 0.15) and slightly higher under oil palm plantations (−3.12 ± 0.12). Nevertheless, the differences between the four land-use types were not significant. Interestingly, oil palm plantations showed a SOC shift to lower C content in the Ah horizon according to the regression line of their subsoil (Fig. 5d). This shift was not observed in any other land-use type in Harapan but occurred in the four oil palm sites. Therefore, this pattern seemed to be a characteristic of oil palm plantations in Harapan region.

Discussion

SOC losses

Forest conversion to tree plantations leads to decreases of SOC and SON in the topsoil of the studied regions (Fig. 2). The C content decrease in Ah horizons observed under oil palm and rubber plantations of Harapan region are in the same range as the decrease reported in the top 10 cm of soils under similar plantations in Ghana (Chiti *et al.*, 2014). They recorded a decrease of C content from about 5% C in primary forest to about 2% under oil palm and rubber plantations in Oxisols developed on various parent materials. They observed significant C losses also mainly down to 30 cm. The similar C and N contents in the subsoil of forest and plantations support our hypothesis that the subsoil was not affected up to two decades after conversion (Fig. 3).

The magnitude of losses in the topsoil depended on the region. We explain the lower SOC losses in Bukit vs. Harapan by the higher clay content in Bukit soils and the presence of smectite in soils such as BF1 and BF2. Indeed, clays were shown to reduce C losses after forest conversion (Lopez-Ulloa *et al.*, 2005; Powers *et al.*, 2011). The difference in clay content also explains the lesser decrease of C with depth in Bukit subsoil. Indeed, SOC stocks are positively correlated with clay content (Van Noordwijk *et al.*, 1997; McGrath *et al.*, 2001) because clays protect SOM from decomposition by increasing the spatial inaccessibility of SOM within soil aggregates and the interaction with mineral surfaces (Luetzow *et al.*, 2006; Gunina & Kuzyakov, 2014).

The effect of land-use change also depends on the time after conversion. Chiti *et al.* (2014) measured higher mean annual SOC losses in younger vs. older rubber and oil palm plantations. Plantation age cannot

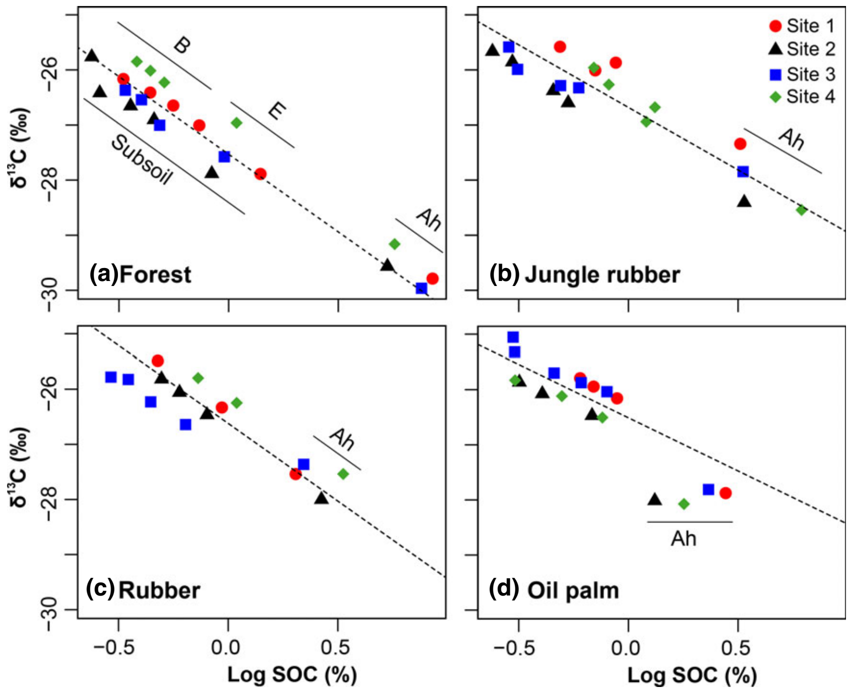

Fig. 5 Relation between δ^{13}C and the logarithm of C content in four replicate sites under (a) forest, (b) jungle rubber, (c) rubber, and (d) oil palm plantations in Harapan region. Dashed lines represent the mean linear regression associated with the subsoil of the four replicate sites of the corresponding land-use type.

Table 3 Average parameters of the linear regression of δ^{13}C with the log-transformed C content per land-use type in Harapan region

	Whole soil*			Subsoil†		
Land use	β	Intercept	R^2	β	Intercept	R^2
Forest	−2.67 (0.04) †	−27.46 (0.18)	>0.97	−2.82 (0.20)	−27.53 (0.15)	>0.94
Jungle rubber	−2.29 (0.15)	−26.67 (0.21)	>0.97	−2.27 (0.37)	−26.68 (0.27)	>0.59
Oil palm	−3.12 (0.12)	−26.89 (0.23)	>0.93	−1.93 (0.11)	−26.51 (0.13)	>0.93
Rubber	−2.69 (0.31)	−26.55 (0.15)	>0.96	−2.82 (0.20)	−26.62 (0.22)‡	>0.97

*Average parameter values and minimum R^2 of the four replicates of each land-use type. Values represent means (SE).
†All samples included except the Ah horizon.
‡Slopes and intercepts of the sites 1 and 4 under rubber were not estimated by regression because only two subsoil samples were collected.

explain the higher C content in the topsoil in Bukit because the oil palm plantations were of about the same age in both regions. Nonetheless, age might be the reason for the more similar C content in the topsoil of rubber plantations and jungle rubber compared to oil palm plantations in Bukit (Fig. 2). The rubber plantations in Bukit were ten years old (four years younger than oil palm plantations). Nevertheless, De Blécourt et al. (2013) showed that 80% of the SOC losses took place within the first 5 years and that a steady state was reached after 20 years in rubber plantations in south China. Therefore, we expect that most of the SOC losses resulting from conversion of forest have already occurred in the rubber plantations. Still, further significant SOC losses by erosion are possible.

Extensive land use such as jungle rubber led to lesser SOC losses than intensive oil palm and rubber plantations. Nonetheless, the magnitude of the decrease and the effect of land-use intensity depend on the region and, most likely, on soil texture. Consequently, the variability of SOC losses after forest conversion should be evaluated at the regional scale and for specific land uses to estimate the ecosystem C fluxes arising from land-use changes.

Processes involved in SOC decrease by land-use changes

The vertical distributions of C content and δ^{13}C followed a power function with soil depth and a linear function with the log-transformed C content in Harapan and, to a lesser extent, in Bukit. Because the effect of land-use type was lower and the variability among soils was higher in Bukit, Harapan region was more appropriate to investigate the mechanisms involved in SOC losses after forest conversion.

Two processes potentially contribute to the decrease of C content and stocks in soil due to land-use change: (1) erosion of the SOC-rich top layer and (2) a stronger decomposition of the SOC after land-use change. Erosion was estimated based on the vertical distribution of δ^{13}C in the soil profile (Fig. 3). SOC decomposition was assessed considering the increase of δ^{13}C as related to the decrease of SOC with depth (Fig. 5).

Erosion

The estimated erosion was very high under intensive plantations, up to 35 ± 8 cm under oil palm for the 15-year period (Fig. 4). The erosion rates for Ferralsols under oil palm and rubber plantations in Malaysia were also high and dependent on plantation age, ranging from 4.7 to 9.9 cm yr^{-1} on newly cleared land and dropping in mature plantations (0.35 to 1.56 cm yr^{-1}) (Gharibreza *et al*., 2013). To evaluate the plausibility of the erosion assessed by δ^{13}C, we calculated the erosion rate on cleared land using the Revised Universal Soil Loss Equation (Renard *et al*., 1996) and parameters taken from the literature. The calculated rates were of the same order of magnitude as reported in Gharibreza *et al*. (2013). The rainfall erosivity in the tropics is very high (Yu *et al*., 2001; Oliveira *et al*., 2013) due to intensive rains, leading to high erosion of unprotected soil. Unlike rubber and oil palm plantations, jungle rubber plantations are usually established without completely clearing the protective layers (canopy and litter horizons). This explains the absence of erosion in three of four jungle rubber plots. The high erosion in the fourth plot might be explained by a different plantation establishment. These results underline the negative role of deforestation and plantation establishment regarding erosion. This calls for strongly improving management practices to reduce erosion rates especially in the first year of plantation establishment. Although canopy cover increases with plantation maturation, erosion continues due to the sparse or absent ground cover. The exposed roots at the base of the oil palm trunks provide additional clear evidence of erosion after plantation establishment.

We rejected the hypothesis that the δ^{13}C shift to higher values in plantation vs. forest subsoils was a consequence of increased mineralization for two reasons. Firstly, increased SOM mineralization is unlikely to enrich δ^{13}C up to 0.5‰ in rubber and oil palm plantation compared to forest during just 15–20 years. For instance, the δ^{13}C increase of 0.4‰ under oil palm at 55 cm corresponds to a decrease of C content by 1/3 according to the linear regression between δ^{13}C and logSOC in forest soils (Table 3). Secondly, erosion and decomposition affect the depth distribution of the δ^{13}C, the C content, and the C/N ratio in two different ways: (1) Stronger decomposition leads to higher δ^{13}C values, lower C contents, and lower C/N ratios. Graphically, this can be represented as a horizontal shift of the profiles of δ^{13}C, C content, and C/N ratio under plantations compared to forest (Fig. 1a). The extent of this shift is not necessarily the same for each depth and for the 3 parameters. (2) Erosion leads to a vertical shift of the same extent of all soil parameters closer to the surface (Fig. 1b). If significant SOM decomposition had occurred in the subsoil after forest conversion, we would have observed a horizontal shift of C content and C/N ratio to lower values in the subsoil under plantations vs. that under forest, which was not the case.

As erosion leads to a vertical shift of the same extent for all soil parameters (Fig. 1b), theoretically the erosion could be estimated using any parameter (e.g., C content, C/N ratio) showing a clear trend with depth. However, except for δ^{13}C, other parameters varied little with depth in Harapan subsoil; that is, the distribution with depth was almost linear and vertical. Consequently, the vertical shift caused by erosion did not significantly affect the distribution of C content and C/N ratio in plantation subsoils.

In conclusion, erosion led to SOC losses in oil palm and rubber plantations but not in jungle rubber. Therefore, SOC losses under jungle rubber are mainly connected with mineralization to CO_2. The δ^{13}C distribution is a time- and cost-efficient way to measure erosion when a reference site is available and when δ^{13}C increases with soil depth. However, the precision of the estimation needs to be assessed by direct measurements of erosion.

Decomposition

The β values of soil under forest fall in the middle range of β values (−3.80 to −1.39) measured in northern Costa Rica (Powers & Schlesinger, 2002). The forest conversion did not significantly modify the β values calculated over the whole depth. This result was expected because decreases in SOC and the C/N ratio after forest conversion were observed only in the Ah horizons of the plantations. As a consequence, forest conversion affects the linearity of the regression between $\delta^{13}C$ and log-transformed C content rather than the slope (β value).

Under jungle rubber and rubber plantations, the SOC decrease in the Ah horizons after forest conversion and the SOC decrease with depth before conversion (reflected in the subsoil) led to a similar ^{13}C enrichment of SOC (Fig. 5b, c). Neither the strong soil erosion in rubber plantations nor the SOC decomposition after forest conversion to jungle rubber plantations modified the ^{13}C enrichment as the SOC decreased. On the one hand, erosion was not expected to modify the β values, but merely to remove the part of the regression line for the soil layer lost by erosion (Wynn *et al.*, 2006). On the other hand, a change in turnover rates in the Ah horizon would modify the ^{13}C enrichment of SOC because β values are correlated with SOC turnover (Garten *et al.*, 2000; Powers & Schlesinger, 2002; Garten, 2006; Wynn *et al.*, 2006; Campbell *et al.*, 2009). The model developed by Acton *et al.* (2013) showed that β values were dependent on SOC decomposition rates. Accordingly, SOC turnover and decomposition rates in the Ah horizon were not modified by the forest conversion to jungle rubber (Fig. 5b). SOC losses due to SOC decomposition should therefore be a consequence of reduced C input from litter. Consequently, C stocks under jungle rubber should reach a new steady state depending on the decrease of C input after forest conversion.

Ah horizons in oil palm plantations unlike rubber and jungle rubber plantations show a shift to lower C content according to the regression in their subsoil (Fig. 5d). This indicates that the turnover and decomposition rates in the Ah horizon decreased after forest conversion to oil palms (Fig. 6). There was no litter input in the oil palm plantations and our samples were taken more than four meters away from the trees, where the belowground C input by roots was low. Therefore, after the decomposition of the labile pools that was not replaced by new C input, the remaining SOC has much slower turnover rates. The old ^{13}C-enriched and refractory SOC that was stabilized in deeper horizons before forest conversion is the only remaining SOC pool after erosion of the topsoil under oil palm plantation. The turnover should continue to decrease in the future because of the strongly reduced C input and the decline in SOC quality.

Soil organic carbon in the Ah horizon under rubber plantations is potentially a mixture of two SOC pools: (1) the old ^{13}C-enriched and refractory SOC stabilized in deeper horizons before forest conversion and (2) the fresh ^{13}C-depleted C from the litter deposition. The mixing of both pools would shift the isotopic composi-

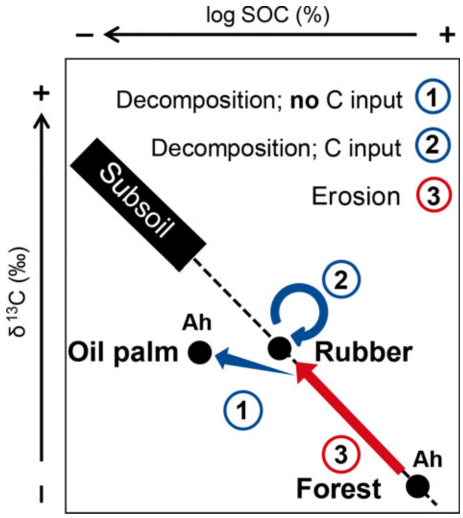

Fig. 6 Effect of erosion and decomposition on the C content and the $\delta^{13}C$ of the Ah horizons under rubber and oil palm plantations depending on the C input from leaf litter.

tion of the Ah horizon to lower $\delta^{13}C$ values (Wynn *et al.*, 2006). Accordingly, the absence of a $\delta^{13}C$ shift in the Ah horizon under rubber plantations (Fig. 5c) implies that the pool of old ^{13}C-enriched SOC was not substituted by ^{13}C-depleted C from the litter deposition. The most likely explanation is that microorganisms use the easily available litter compounds as their main C source rather than the old refractory SOC. As a consequence, the new C from litter is not stabilized in the SOC pool. The SOC in the Ah horizon therefore is mainly composed of the SOC sequestered before the forest conversion and that this pool underwent little modification by decomposition. Nevertheless, the absence of a $\delta^{13}C$ shift does not exclude the possibility that the old SOC is partially substituted with highly decomposed organic compounds from the leaf litter having a similar $\delta^{13}C$.

Oil palm and intensive rubber plantations have similar impacts regarding SOC losses and erosion. Nonetheless, the decomposition of the old remaining SOC pool under oil palm – but not under rubber plantations – could lead to differences in SOC losses in the long term. SOC in rubber plantation reaches a steady state after a phase of intensive SOC losses in the first year (De Blécourt *et al.*, 2013). The steady state of SOC should be reached much later and at a lower C content in oil palm than in rubber plantations because the old remaining SOC pool is decomposed under oil palms. Consequently, oil palm plantations will continue to lose SOC in the future and the losses might increase drastically by the inevitable renewal of old oil palm plantations every 25 years. Such reestablishment has just started in Jambi Province because the older oil palm plantations were established in the early 1990s. We therefore advise (1) to reduce the period without soil protection by planting cover crops at the early stage of the establishment to reduce soil erosion and (2) to leave a maximum of the biomass from the old palm trees on site and/or to keep the land lying fallow for a few years to enable the recovery of SOC pools for the next oil palm generation.

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