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Soil degradation in oil palm and rubber plantations under land resource scarcity

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ABSTRACT

Tropical regions, such as Sumatra, experiencing extensive transformation of natural ecosystems, are close to complete exhaustion of available land. Agroecosystems strongly modify water and nutrient cycles, leading to losses of soil fertility, C sequestration and biodiversity. Although large companies are the main drivers of deforestation and plantation establishment, smallholders account for 40% of the oil palm and the majority of the rubber production in Indonesia. Here, we assess the extent and mechanisms of soil degradation under smallholder oil palm and rubber plantations in a context of land scarcity. The topsoil properties (C and N contents, C stocks, C/N ratio, bulk density) in 207 oil palm and rubber plantations in the Jambi province of Sumatra were determined beside trees, inside rows and interrows. Soils under oil palms were on average more degraded than under rubber, showing lower C content and stocks, lower N and higher bulk density. While soil properties were homogenous under rubber, two opposite trends were observed under oil palm plantations: the majority of soils had C content <2.2%, but about one fifth of the plantations had >9% C. This resulted from the establishment of oil palms under conditions of land scarcity. Because the oil palm boom started when rubber was already well-established, oil palms were frequently planted in marginal areas, such as peatlands or riparian areas (high C) or soils degraded by previous use (low C). The management of oil palms led to subsequent soil degradation, especially in interrows: C content decreased and bulk density increased in older oil palm plantations. This was not observed in rubber plantations because of a C input from leaf litter spread homogeneously all over the plantation, higher ground cover and a limited use of motorized vehicles. Considering that 10% of soils under oil palms had very low C content (<1%), we conclude that intensive cultivation can lead to intensive soil degradation and expect future degradation of soils under young oil palms. This challenges the sustainability of agricultural intensification in Sumatra. Because Sumatra is a pioneer of tropical land-use change, this should be regarded as potential threats that other tropical regions may face in future.

1. Introduction

Agricultural intensification in response to an increasing demand for food, feed, timber and biofuel has led to extensive conversion of natural ecosystems to agroecosystems (Lambin and Meyfroidt, 2011; Tilman et al., 2001). In tropical regions, new agricultural lands were gained mostly at the expense of forested land (Gibbs et al., 2010), resulting in a strong decrease of tropical forest area worldwide (Hansen et al., 2013). Driven by the pulp, timber, mining, rubber and oil palm industries, Indonesia became the main hotspot of land-use change by 2012; experiencing higher deforestation rate than Brazil (Abood et al., 2015; Margono et al., 2014). However, deforestation is not a new trend in Indonesia.

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Sumatra Island had already lost almost half of its forest cover by 1985 (Laumonier et al., 2010). Out of the three biggest Indonesian islands (Sumatra, Kalimantan and Papua), Sumatra is the one where deforestation is most advanced, with only 9% of lowland forest cover left in 2012 (Margono et al., 2014). Because most of the easily accessible forest on Sumatra had already been transformed before 2000, new agricultural land was mainly established in marginal areas, such as wetlands or hilly landscapes (Margono et al., 2014; Miettinen et al., 2012a). The exhaustion of easily accessible forest on Sumatra is also indicated by forested area under new industrial concession five times lower compared to Kalimantan, or Papua where deforestation is at a nascent stage (Abood et al., 2015).

Smallholder farmers play an important in role land-use changes by accounting for almost the entire rubber production and 40% of the palm oil production in Indonesia (Euler et al., 2015b). While rubber and oil palm cultivation has a positive impact on smallholder farmers' livelihoods (Euler et al., 2015a), they are associated with extensive ecosystem degradation (Barnes et al., 2014; Wilcove and Koh, 2010). A reduced net primary production (Kotowska et al., 2015), very high soil erosion (Guillaume et al., 2015) and soil compaction are threats to soil fertility. In fact, various studies have reported a strong decrease of soil organic carbon (SOC) after forest conversion to plantations, with most of the losses in the topsoil (de Blécourt et al., 2013; Guillaume et al., 2015; van Straaten et al., 2015). Even though SOC losses tended to be slightly higher under oil palm plantations, differences were small and not significant between these intensive plantation types. Aside from its role in C sequestration, SOC is an important indicator of soil fertility in the heavily-weathered soils common in the tropics. Because of nutrient leaching in the tropics, nutrient recycling between the vegetation and the organic matter in the topsoil is the main source of nutrients to sustain plant growth (Vitousek, 1984). Large SOC losses after forest conversion to plantations, therefore, raise major concerns about the sustainability of such land-use types in the tropics (Lal, 2010).

Studies investigating soil degradation under oil palm and rubber plantations are mainly limited to observations from plantations established directly after deforestation on well-drained mineral soil or peat soils. This land-use history was the most frequent in tropical regions, when large forested area were still available (Gibbs et al., 2010). Nonetheless, more complex land-use histories with successive uses are expected in regions, like Sumatra, experiencing high deforestation and suffering from scarcity of available agricultural land (Gatto et al., 2015). Moreover, the proportion of plantations established on less accessible lands such as wetlands increases with land scarcity (Margono et al., 2014). Therefore, we hypothesized that the negative environmental impacts of agricultural intensification would not only depend on the crop itself and the management practice associated with its cultivation, but also on the land scarcity at the time of the crop expansion. Accordingly, even though the differences in the soil degradation under rubber and oil palm plantations are small when all factors, except the land-use type, are controlled, the recent expansion of oil palm cultivation is associated with stronger environmental impacts. Sumatra island is a pioneer region for tropical land-use changes. Therefore, it is a relevant model to assess the impacts of agricultural intensification on soil degradation in the tropics. Consequently, the experiences from this region could be of relevance for tropical regions, such as Kalimantan, Papua, Central Africa or Latin America in order to mitigate the environmental cost of tropical agriculture intensification. The objectives of this study were 1) to assess the soil quality under smallholders' rubber and oil palm plantations in the Jambi province, a province in Sumatra with one of the most advanced transformations of natural ecosystems, 2) to assess differences in the degradation of soils between plantation types and 3) to assess the soil heterogeneity within plantations resulting from small-scale management practices within plantations.

2. Materials and methods

2.1. Study area

The study was conducted in the lowland (peneplain) of Jambi province, located in central Sumatra, Indonesia. The elevation of the lowland does not exceed 100 m a.s.l. except in the west of Bungo regency; the foothill of the Barsian Mountains. The entire region has a tropical humid climate (27 °C; 2200 mm yr^{-1}; 110–260 mm $month^{-1}$) with a rainy season lasting from October to April. Acrisols are the dominant soil type in the lowland of Jambi province, but peats (Histosols) are frequent in landscape depressions and in the vicinity of the east coast (Hooijer et al., 2010; Ishizuka et al., 2005). Jambi province is the 5th largest producer of oil palm and the 3rd largest for rubber in Indonesia (Schwarze et al., 2015). Oil palm cultivation by smallholders in Jambi Province started in the late 1980s, when rubber was already a well-established cash crop, occupying 510,000 ha in 1996 (Gatto et al., 2015). While the area under rubber increased by 27% from 1996 to 2011, the area under oil palm almost quadrupled during that time, reaching 580,000 ha. During the 1980s and 1990s, the Indonesian government favored the establishment of oil palms by smallholder farmers through various so-called "transmigration programs" and collaboration with private companies (McCarthy and Cramb, 2009). Nowadays, however, smallholder adoption mainly occurs independently. While the area under oil palm is still increasing, the adoption rate by farmers reached a peak in 2007 and has declined since then (Euler et al., 2015b). Oil palm cultivation is not spread evenly across the province (Fig. 1). Because the harvested fresh fruit bunches have to be processed within 1–2 days to maintain good product quality, the cultivation of oil palm is constrained by the location of the palm oil mills and the quality of infrastructure such as roads. The regency of Muaro Jambi, the closest to the province's capital, has the largest area under oil palm and the largest number of mills (Euler et al., 2015a,b).

2.2. Plantation selection

Five major lowland regencies (Bungo, Batanghari, Muaro Jambi, Sarolangun and Tebo) covering half of the 53,000 km^2 of the Province were purposely selected, because they include most of the smallholder oil palm producers in the province (Euler et al., 2015b). To capture the plantation diversity of the province, a random sampling approach was used to select four districts per regency and two villages per district, for a total of 40 villages (Faust et al., 2013). In each village, one third of the farmers were selected randomly for a total of 207 plantations sampled, including 16 extensive rubber, 146 intensive rubber and 45 oil palm plantations (Table S1). The lower number of sampled oil palm compared to sampled rubber plantations (30%) corresponded to the difference in the surface area allotted to each plantation type (36%), as observed in a larger survey of 100 villages of the Jambi Province (Schwarze et al., 2015). 82% of the sampled oil palm plantations were located in the regencies of Batanghari and Muaro Jambi. This reflected the high oil palm adoption rates observed in these two regencies (Euler et al., 2015b). The oil palm plantations of Sarolangun, however, might have been slightly under-represented, because the oil palm

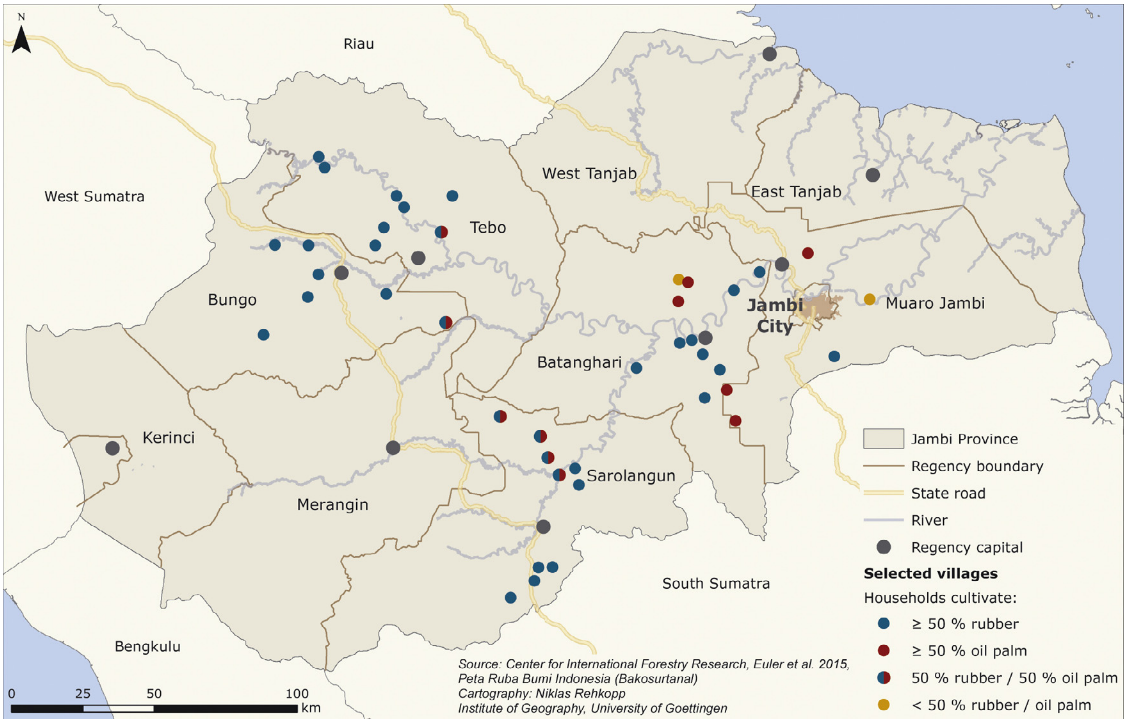

Fig. 1. Map of the Jambi province with the proportion of rubber and oil palm adoption by farmers in the selected villages. Map is reproduced from Faust et al. (2013). Adoption data from household survey conducted by (Euler et al., 2015b).

adoption rate was found to be intermediate between those in Muaro Jambi and Batanghari.

2.3. Plantation characteristics

All plantations were smallholder plantations. According to a larger survey, the average area cultivated per farm was 3.6 ha for oil palm and 2.9 ha for rubber (Schwarze et al., 2015). With an average age of 11 years, oil palm plantations were younger than rubber plantations (17 years). Management was more intense in oil palm plantations. Fertilizers and herbicide were applied in 78 and 81%, respectively, of the oil palm plantations, while they were used in only 28 and 49% of the rubber plantations. Moreover, when used, farmers invest three times more for application of fertilizers and herbicides per ha of oil palm than per ha of rubber (Schwarze et al., 2015). The amount of labor per ha is lower for oil palm than for rubber plantations (which are commonly tapped every two days), but the labor requirements are much less evenly distributed over time, and peak at the harvesting dates, usually twice a month. Generally, dead oil palm fronds are collected and piled every 2–3 interrows, and residues from oil palm bunches or fruit are not spread on the plantations.

We made a distinction between two rubber production types: intensive and extensive by three main characteristics. First, the plot establishment varies. While intensive rubber fields are completely cleared prior to the establishment and seeds are sowed in regular spacing, seeds are sowed in an existing forest with irregular spacing for extensive production. This seeds sowing, common in the early days of rubber development, results in an irregular alignment of the productive trees in extensive plantations; opposed to the line-structured intensive plantations. Second, extensive producers did not use fertilizers at all. Third, the average density of trees was significantly higher in intensive production (508 trees ha^{-1}) than in extensive production (412 trees ha^{-1}).

2.4. Soil sampling and analysis

Soil samples were collected in representative areas away from the edges of the plantations, i.e. roads, harvesting paths, etc. were avoided. To assess the effects of the structure of oil palm plantations on the soil, samples were collected in four operational zones of each plantation (Fig. 2): beside a tree (within 30 cm); directly between two trees of the same row (the maximum distance from tree effects inside a row); in the interrow between two trees; and at the midpoint between four trees (the maximum distance from tree effects in the interrow). Because of the absence of structure in extensive rubber plantations, and to keep the same sampling design, samples from extensive rubber plantations were

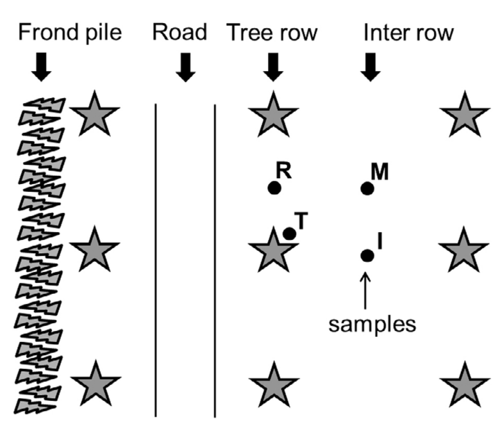

Fig. 2. Soil sampling design. In oil palm plantations, frond piles, roads and other disturbed locations were avoided to ensure sampling representativeness. In each rubber and oil palm plantation, samples were collected close trees (T), in the rows between two trees (R), in the interrows between two trees (I) or at the midpoint between four trees (M). This sampling design allowed investigation of the small scale spatial distribution of soil properties within the plantations.

collected at each corner of a 5-by-5 meter square, where one corner was located at the base of a rubber tree. Soil samples were collected with a 3.8 cm diameter ring from 0 to 5 cm depth, because most of the C losses are located in the topsoil (Guillaume et al., 2015). The collected soil was air-dried, sieved at 2 mm to remove coarse-root residues, oven-dried at 105 °C and weighed to calculate bulk density. Carbon and N contents of ground soil were measured at the Georg-August University of Göttingen using an elemental analyser (Eurovector).

2.5. Statistics

All statistical analyses were performed using the open source software R version 3.2.2. Differences in the C and N contents and C stocks, C/N ratio and bulk density of mineral soils (<14%) between plantation types or between regencies were tested by the Kruskal–Wallis test because of unequal samples sizes and non-normal distributions. Due to missing values for bulk density, three rubber and four oil palm plantations were not included when testing bulk density and stocks. The difference in soil properties between plantation types (the median of all possible differences between a sample from one plantation type and a sample from a second plantation type) and their confidence intervals were estimated by Mann–Whitney U tests (function *wilcox.test* in R). Kolmogorov-Smirnov tests (function *Ks.test* in R) were used to assess the similarity of the soil properties under rubber and oil palm plantations of Muaro Jambi. The heterogeneity of soil properties (C and N content, C stocks, C/N ratio and bulk density) within each plantation was tested separately for each plantation type by a linear mixed effects model (function *lme* in R) including the four operational zones as fixed factors and the plantation as a random effect. Except for bulk density, all values were log-transformed to reach variance homogeneity and normality for residuals and for the random effect. Five plantations under intensive rubber and one under extensive rubber, having extreme values in one or more locations of one or more soil properties, were not included. Seven oil palm plantations with high variability of one or more soil properties were analyzed separately. The regression between oil palm plantation age and properties of mineral soils were performed using the mean of the four sampling locations. The age of four plantations (from 38) could not be determined, therefore, 34 plantations were used for the analysis. Because of non-normal distributions of soil properties within land-use types, medians instead of means are presented. If not specified, discussed differences are significant at least at a p-value <0.05.

3. Results

3.1. Soil characteristics under plantations

The 828 soil samples covered the full range of C content in soil: from purely mineral (<0.1% C) to purely organic (60% C) soils (Fig. 3). The lowest mean C content of a plantation, however, was 0.59% in the top 5 cm of the soil. Despite the fact that the plantations were located mostly on mineral soil with low C content (median: 3.7%, Table S1), organic soils, as defined by the World Reference Base (≥20% C), were found under five out of the 45 oil palm plantations and three out of 146 rubber plantations. The distribution of C content in mineral soils had a gap with a distinct group of 12 mineral soil samples from two oil palm and five rubber plantations having a high C content (from 14 to 18%). The maximum C content did not exceed 6.3% under extensive rubber plantations.

The distribution of C content in mineral soils (<14% C) was different between plantation types. The C content and bulk density were normally distributed among extensive rubber plantations

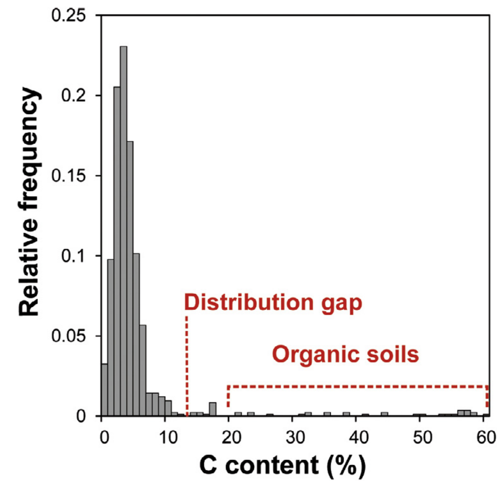

Fig. 3. C content distribution of the 207 plantations. The soils above 20% C content were considered as organic soils (IUSS Working Group WRB, 2014). Because of a distribution gap between 13 and 14% C content, the soils above this threshold were not included when comparing land-use types. Soils above 14% C content were found only under intensive rubber (3% of soils) and oil palm (13% of soils).

(Fig. 4) with similar median (3.5% C; 0.89 g cm^{-3}) and mean (Table S1). Intensive and extensive rubber plantations did not differ in their C and N contents, but intensive rubber plantations had higher bulk densities, resulting in higher C stocks in the top 5 cm of

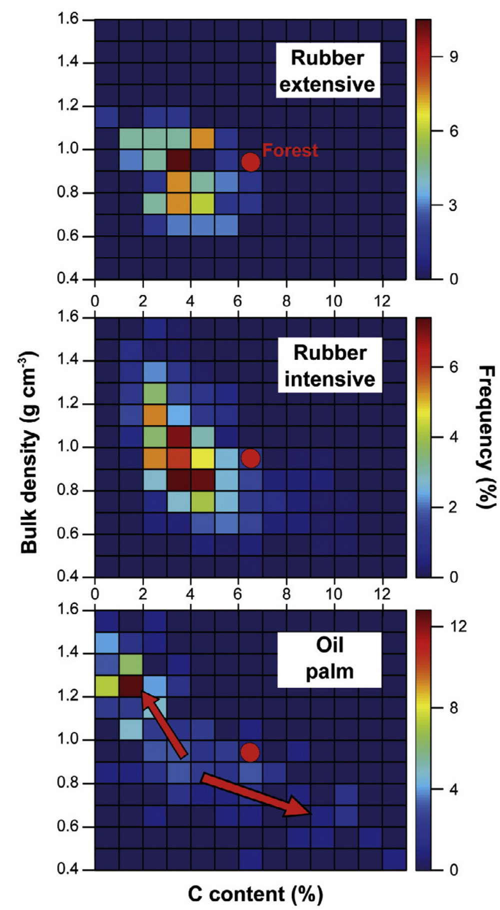

Fig. 4. Distributions of C content and bulk density in mineral soils under three land-use types: extensive and intensive rubber, and oil palm plantations. The dots correspond to the mean C content (Ah horizons) and bulk density (0–10 cm) in 8 well-drained forest sites from two forest units in Jambi province (Guillaume et al., 2015).

soils (Table S1). Furthermore, soils under intensive rubber showed a larger variation in C content and bulk density distributions. The C content was not normally distributed; values were slightly skewed to low C content with a median (3.7% C) lower than the mean (4.0% C). The variation and the skewness of the C content and bulk density distribution were much stronger under oil palm (Fig. 4). Soils having either low C content (<2% C) and high bulk density (>1.2 g cm^{-3}) or high C content (>9% C) and low bulk density (<0.8 g cm^{-3}) were much more frequent under oil palm than under rubber plantations. Consequently, the C content under oil palms was significantly lower than under intensive rubber (−1.3%; CI: −1.6, −1%) and under extensive rubber (−1.1%; CI: −1.5, −0.6); only 10% of the intensive rubber plantations had a lower C content than the median C content under oil palm. Oil palm also had lower N content and C stocks, but higher bulk density compared to rubber plantations (Table S1).

Intensive rubber plantations were distributed fairly uniformly across the five regencies (Table S1). The strongest differences between median soil parameters of the regencies did not exceed 0.9% C content, 0.05% N content and 0.11 g cm^{-3}, indicating limited variability in C, N and bulk density under intensive rubber plantations between regencies (Table S1). 82% of oil palm plantations were located in two regencies: Muaro Jambi (23 plantations) and Batanghari (14 plantations). Although the soil properties under rubber plantations in the regencies of Batanghari and Muaro Jambi were homogenous, the soils under oil palm plantations in Batanghari showed on average lower C content (−2.2% C) and stocks (−1.0 kg C m^{-2}), and higher bulk density (+0.26 g cm^{-3}) compared to Muaro Jambi (Fig. 5). The median soil properties were similar in both plantation types in Muaro Jambi. However, this was not because the soils were similar, but rather because of the presence under oil palms of either degraded soils or soils with high C contents and low bulk densities. In contrast, soils with high C contents were rare under the oil palm plantations in Batanghari, and the degraded soils had even lower C contents and higher bulk densities than in Muaro Jambi, indicating great variability of soil conditions under oil palms at the regency level.

In summary, soils under extensive and intensive rubber plantations were similar and did not differ strongly between the regencies of Jambi province. The main differences consisted in wider distributions of soil properties under intensive rubber plantations. Further, higher bulk density resulted in higher C stocks in the upper 5 cm under intensive compared to extensive plantations. In contrast, soils under oil palm plantations were more heterogeneous with a higher frequency of soils with either low or high C content and bulk density. In conclusion, soils under oil palm plantations were on average more degraded (lower C content and stocks, and higher bulk density) than under rubber plantations.

3.2. Spatial heterogeneity within plantations

Only oil palm plantations showed differences in the soil properties depending on the sampling location i.e. beside trees, in rows, in interrows between trees or at the midpoint between four trees (Fig. 6). The soil properties under intensive and extensive rubber plantations were homogenous. According to the standard deviation of the C content between sampling locations (SD: 1.4%), the probability (power) to detect a difference in C content of 0.3% between two locations in the intensive rubber plantations was 80%. While the C contents beside trees and at the midpoint between four trees under rubber did not differ more than $0.2 \pm 0.1\%$, this difference under oil palm plantations reached $0.6 \pm 0.2\%$. Under oil palm plantations, the soil beside trees had higher C and N contents, higher C stocks, higher C/N ratio and lower bulk density than in interrows (Fig. 6). The soil properties of the two locations in interrows (between trees or at the midpoint between four trees) were similar. The soil in oil palm rows tended to be less degraded than in the interrows, but these differences were not significant. The seven oil palm plantations with high soil

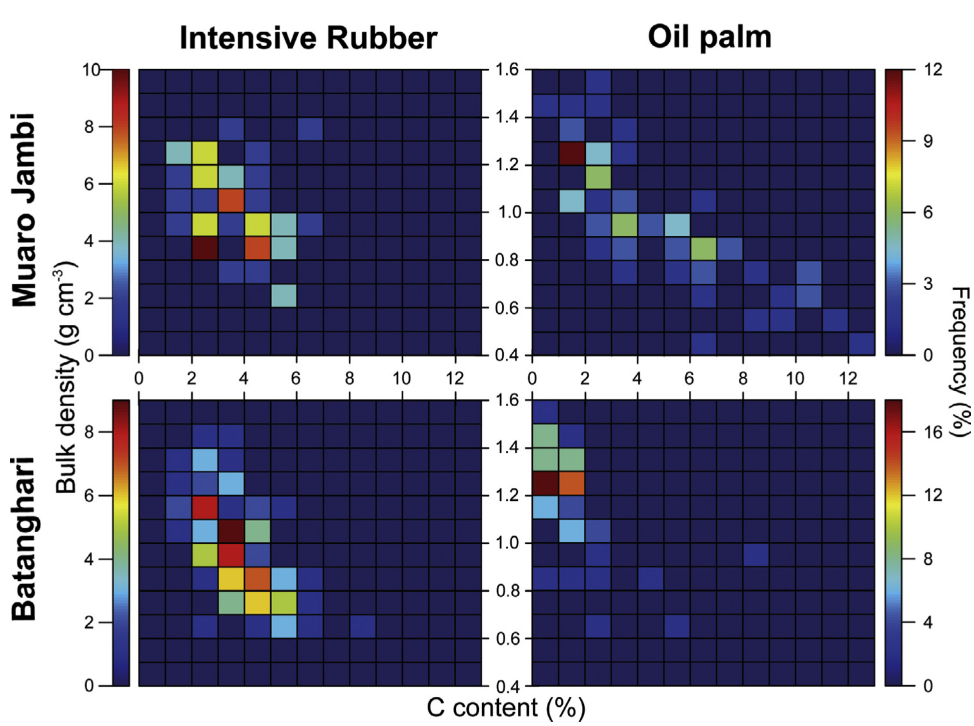

Fig. 5. Distributions of C content and bulk density in mineral soils under intensive rubber and oil palm plantations in regencies of Muaro Jambi and Batanghari. The soil properties under oil palm exhibit a wider range than under intensive rubber. However, oil palm plantations in Batanghari showed almost exclusively highly degraded soils with low C content and high bulk density.

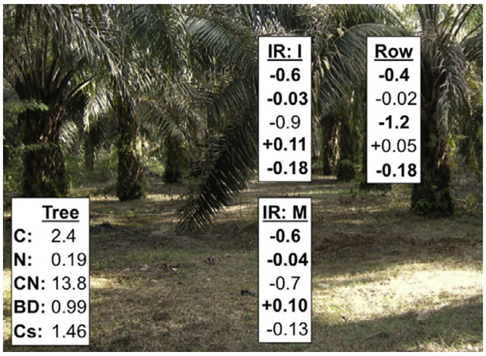

Fig. 6. Heterogeneity of soil properties within oil palm plantations. The C content (C:%), N content (N:%), C/N ratio (C/N), bulk density (BD: g cm^{-3}) and SOC stocks (Cs: kg m^{-2}) at 0–5 cm depth beside the trees are presented against the difference of the soil properties in rows and interrows between two trees (IR:I) and between four trees (IR:M). Bold values indicate significant differences ($p < 0.05$, linear mixed effect model) between the soil beside trees and the other locations.

variability did not show any trends relating to plantation structure. Thus, the oil palm plantations showed a high heterogeneity of soil conditions not only between plantations, but also within a single plantation.

3.3. Effects of plantation age

The C content and the bulk density of soil under rubber were independent on the plantation age (data not shown). In contrast, the C content in soil under oil palm plantations decreased and the bulk density increased significantly with the age (Fig. 7). The variance explained by the regression models was low (C content: $R^2 = 0.28$, $p < 0.001$; bulk density: $R^2 = 0.12$, $p < 0.05$) indicating effects of other factors on the large area of the survey. The C content data had to be log-transformed to meet the assumption of normality. A non-linear relationship between C content and age would indicate that 1) SOC losses are higher in the first years after the plantation establishment than later during the plantation maturation and 2) that the C content is more variable in younger than in older plantations. Extrapolation of the regression models

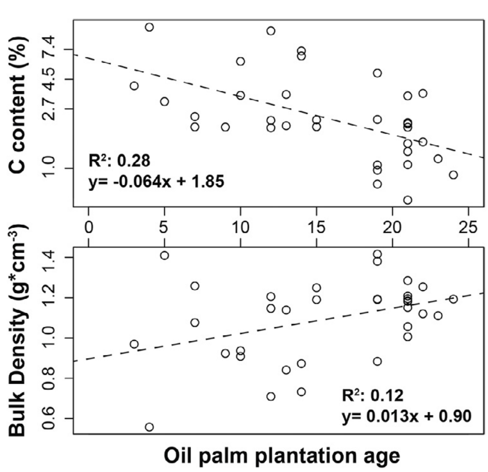

Fig. 7. Carbon content and bulk density under oil palm plantations with mineral soils depending on the plantations' age. For the C content, the linear regression was performed on log-transformed data ($n = 34$). For clarity, the C content is presented on a logarithmic scale with non-transformed values. R^2 correspond to adjusted R^2. Despite low R^2, the effect of age was significant for C content ($p < 0.001$) and bulk density ($p < 0.03$).

let conclude that soils under rainforest (age = 0) should have C content of 6.3 ± 1.3% and a bulk density of 0.90 ± 0.10 g cm^{-3}.

4. Discussion

The C content in the top 5 cm (Ah horizon) of well-drained clay or loam Acrisols from eight plots in two tropical forest units in Jambi province ranged from 5.3 to 9% (Guillaume et al., 2015). The majority of plantations had about half or less of the topsoil C content under these well-drained forest (3.7% for intensive rubber, 3.5% for extensive rubber and 2.2% for oil palm). On the other hand, 19% of oil palm plantations and 3% of intensive rubber plantations had a C content higher than the range found under well-drained forest.

4.1. High C content under plantations

The plantations with high soil C content were most likely established on peats or on soils experiencing regular waterlogging thereby having higher initial SOC than the typical forests growing on well-drained soils. Since the late 90s, peatland deforestation driven by smallholders in Sumatra and Jambi province in particular has been observed by satellite imagery (Lee et al., 2014; Miettinen et al., 2012b). While none of the extensive rubber plantations were established on such soils, it was a common practice for oil palm and a rare practice for intensive rubber plantations. Extensive rubber was the initial type of plantation to be developed in the province and nowadays new plantations are rarely established (Feintrenie et al., 2010). Prior to land scarcity, farmers most likely selected well-drained sites with high C content and fertility, resulting in a narrow range of C content under extensive rubber. In contrast, oil palm cultivation by smallholders started when rubber was already a well-established cash crop, and unutilized land was scarce. Indeed, the intensification of rubber cultivation had already reached its peak before the oil palm boom. Since 1996, the area under rubber has increased by only a quarter, while the area under oil palm quadrupled (Euler et al., 2015b). Therefore, the scarcity of unutilized land pushed farmers to establish oil palm plantations in marginal areas, such as peat or riparian zones, more frequently than in the past. Indeed, nearly all industrial plantations on peatlands were established in the last 20 years (Miettinen et al., 2012a). Large wetland clearing on Sumatra was attributed to an expansion by private companies from lowland to wetland regions (Margono et al., 2014). Our study shows that a similar trend operates at the smallholder level. Furthermore, this expansion is not only into wetland regions, but also into marginal riparian sites within landscapes dominated by well-drained soils, which has not been taken into account by studies using satellite imagery.

4.2. Low C content under plantations

Despite the fact that oil palm cultivation was not necessarily associated with higher soil degradation than rubber cultivation, highly degraded soils with low C content and high bulk density were an exception under rubber, but frequent under oil palms. In contrast to oil palms, the introduction of rubber cultivation resulted in similar soil degradation all over Jambi province, including Batanghari and Muaro Jambi regencies, which account for 82% of the sampled oil palm plantations. The impact of the land-use type (rubber and oil palm) on the SOC was compared in Indonesia, Cameroon and Peru, on plantations with similar soils and land-use history, and compared with forest sites as references (Allen et al., 2015; Guillaume et al., 2015; van Straaten et al., 2015). While the SOC losses were high and tended to be higher under oil palm plantations, the difference between plantation types was small and generally not significant. Therefore, a high frequency of oil palm soils in an advanced degraded stage is explained by their frequent establishment on soils already degraded by previous use. Indeed, while smallholders' oil palm plantations are not substituting for intensive rubber plantations because of the income loss during the conversion period (Euler et al., 2015b), they are frequently established on extensive rubber or fallow land (Gatto et al., 2015). Therefore, the scarcity of unutilized land resources during the oil palm boom not only led farmers in the Jambi province to establish new plantations on soils with high C content but also on previously degraded soils.

4.3. Impact of land-use type

The land-use intensity in rubber plantations had no effect on the SOC quantity and quality, but only on the soil compaction. Higher bulk densities under intensive rubber in Jambi Province were previously reported (Allen et al., 2015). They are explained by greater soil erosion due to reduced groundcover (Guillaume et al., 2015) and by increased soil compaction by more intense trampling due to the higher rubber tree density and harvesting frequency.

The high variability of the initial soil conditions of oil palm plantations hides the effect of the plantation type. Nevertheless, independently of the initial soil conditions, the specific structure and management of oil palm plantations resulted in additional C losses and soil compaction in the interrows and, to a lesser extent, within rows. Various mechanisms explain a more negative impact and a higher soil heterogeneity under oil palm than under rubber plantations: i) despite similar net primary production remaining in both plantation types (Kotowska et al., 2015), the concentration of leaf litter C in frond piles slightly increases the SOC stocks in this location (Carron et al., 2015; Haron et al., 1998), but leaves the majority of the plantation area with only the root-derived C. Thus, ii) the increasing distance from the trees results in a decrease of root-derived C input, and hence of SOC (Frazão et al., 2013). Additionally, iii) soil erosion is the a common mechanism of SOC loss in oil palm plantations (Gharibreza et al., 2013; Guillaume et al., 2015). Erosion is more intense in interrows because of reduced canopy cover and higher runoff intensity after strong rainfall events. Furthermore, in the oil palm plantations, farmers use trucks or pickups for collecting the fresh fruit bunches, increasing the soil compaction in interrows. In contrast, no heavy vehicles are used in rubber plantations.

The relationships between the age of oil palm plantations and C content or bulk density have to be taken with caution because younger plantation had a higher probability to be established in marginal or degraded areas due to increasing land scarcity. Indeed, as indicated by the log-transformation of the C content data, the variability of soil conditions was higher in younger plantations. The C content under plantations not older than 5 years (n = 3) ranged from 10.8 to 3.1% and the bulk density from 0.6 to 1.4 g cm^{-3}, suggesting that young plantations were established on riparian area or degraded soils. Nevertheless, there is a clear C content decrease and bulk density increase in older plantations. The C content and bulk density of the initial conditions prior to plantation establishment and estimated from model extrapolations; i.e. plantation age equals zero, falls in the middle of the range measured in well-drained forest soils. The increased soil degradation in older plantations might results from the cumulative impact over time of erosion, soil compaction and the absence of aboveground C input during plantation ageing. In contrast, there were no trends under rubber plantations, suggesting that the C content and bulk density under rubber plantation were not affected by plantation ageing. In contrast to oil palm plantations, the soil under rubber plantations receive a continuous and homogenous C input from leaf litter all over the plantation area that also increases ground cover. The leaf litter and a reduced activity of motorized vehicles might mitigate soil degradation during the ageing of rubber plantations. The majority of SOC losses occurs within the first five years after the plantation establishment (de Blécourt et al., 2013). Therefore, other factors resulting from the very broad sampling area that included various plantation managements explain more of the variance of SOC and bulk density in rubber plantations than the plantation age.

Further studies focusing on the site history, establishment and management practices of the plantations are necessary to disentangle the influential factors and their relative impacts on soil quality under oil palm plantations, as well as their variability between regencies. The trend towards agricultural intensification on peatland, riparian zones or degraded soils confirms the land scarcity already observed in 1) an increasing proportion of wetland forest loss, as revealed by satellite images (Margono et al., 2014), 2) a decrease of forest area under concessions (Abood et al., 2015) and 3) a decrease of oil palm adoption rate by farmers (Euler et al., 2015b).

4.4. Environmental impacts

The Jambi province illustrates a new stage of agricultural intensification in the tropics, in which agricultural intensification is achieved mostly by land-use intensification, rather than by conversion of natural ecosystems to agroecosystems (Gibbs et al., 2010). Converting the remaining forests in marginal areas such as peatlands or riparian areas is a regression in terms of agricultural resource-use efficiency. Because of the large amount of C stored in such soils (Hooijer et al., 2010), the greenhouse gas emissions per area are much higher than for the conversion of well-drained mineral soils (Carlson et al., 2012). The increasing area of tropical peatland converted to plantations and the related concerns about greenhouse gas emissions have been underlined by numerous studies (Hergoualc'h and Verchot, 2011; Hirano et al., 2012; Melling et al., 2013; Miettinen et al., 2012a; Nurulita et al., 2014). The increasing conversion of mineral soils with high C content in riparian areas, however, is a new trend underlined by this study that exacerbates the challenges of mitigating greenhouse gas emissions from land-use change.

The C content and compaction in the majority of oil palm plantations is a source of concern. The effects of the three land-use types on microbial activity was investigated in well-drained soils in the regency of Batanghari (Guillaume et al., 2016). Microbial biomass and respiration were resistant to SOC losses down to 2.7% C, but strongly decreased below this threshold. Although this threshold might change depending on soil type, the majority of soil under oil palm was far below this limit. Furthermore, a bulk density of 1.3 g cm^{-3} is close to that in Bt horizons, i.e. horizons of clay accumulation in the subsoil (Allen et al., 2015), where water percolation is strongly reduced, further increasing the risk of erosion through runoff and decreasing groundwater recharge (Bruijnzeel, 2004). Thus, we observed a strong loss of ecosystem services (C sequestration, water storage and infiltration, nutrient cycling) in soils under oil palm. After the disturbance induced by land-use change, the C content should stabilize to reach a new equilibrium corresponding to the new biophysical conditions in the plantations (de Blécourt et al., 2013; Smith et al., 2012; van Straaten et al., 2015). Considering the high frequency of soils having less than 1% C content and a bulk density higher than 1.3 g cm^{-3}, the potential stabilization level of soil degradation seems incompatible with a sustainable soil use. The erosion observed in mature plantations (Gharibreza et al., 2013) and the re-establishment of new plantations on previously degraded soils might be the mechanisms preventing a replenishment of SOC stocks. This raises major concerns about the sustainability of agricultural intensification in Sumatra and the success of the 2nd oil palm generation that is now starting after some 30 years of oil palm cultivation in the region.

In conclusion, the intensification of agriculture in a province that was subjected to land scarcity exacerbated not only the global negative impacts associated with losses of C sequestration in soil and high greenhouse gas emissions, but also the local negative impacts associated with the loss of soil fertility. Land scarcity decreased the natural resource-use efficiency of agricultural production in the region, independently of the type of intensive plantation. Because Sumatra island and especially the Jambi province are pioneers of land-use changes in Indonesia, with high land scarcity, the results are relevant not only regionally, but should be regarded as potential threats that the islands of Kalimantan, as well as many other tropical regions experiencing rapid conversion of natural ecosystems, may face in the near future.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agee.2016.07.002.

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