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Research article

The effects of management practices on soil organic carbon stocks of oil palm plantations in Sumatra, Indonesia

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ABSTRACT

The rapid increase in global production of and demand for palm oil has resulted in large-scale expansion of oil palm monoculture in the world's tropical regions, particularly in Indonesia. This expansion has led to the conversion of carbon-rich land-use types to oil palm plantations with a range of negative environmental impacts, including loss of carbon from aboveground biomass and soil. Sequestration of soil organic carbon (SOC) in existing oil palm plantations is an important strategy to limit carbon losses. The aim of this study was to investigate SOC stocks of oil palm plantations under different management systems. Soil samples were collected from three different management systems (best management practices (BMP), current management practices typical of large plantations (CMP) and smallholder management practices (SHMP)) in north Sumatra, Indonesia. Plantations were divided into four management zones that were sampled separately with four replicate profiles in the weeded circle, frond stack, harvesting path and interrow zones. All the soil samples were collected from five (0–5, 5–15, 15–30, 30–50 and 50–70 cm) soil depths. Soil samples were analysed for concentration of SOC, soil texture, soil bulk density and pH. Calculations of SOC stocks in the soils were undertaken according to the fixed-depth and equivalent soil mass approaches. Results showed that SOC stocks of plantations under BMP (68 t ha^{-1}) were 31% and 18% higher than under CMP (57 t ha^{-1}) and SHMP (46 t ha^{-1}) respectively. In the BMP system, soils under the interrow zone that received enriched mulch and frond stack positions stored significantly more SOC than the harvesting path of the BMP system (77, 73 and 57 t ha^{-1} respectively). BMP also had a 33% higher fresh fruit bunch yield compared to the SHMP system. This study shows that residue incorporation or retention as a part of BMP could be an effective strategy for increasing SOC stocks of oil palm plantations and confirms that these management practices could improve yields from SHMP systems.

1. Introduction

Oil palm (*Elaeis guineensis* Jacq.) is the most important tropical crop both in terms of production volume and trade. Currently, oil palms provide 30% of the world's vegetable oil (FAO, 2019). The world's leading producer and exporter (>30%) of palm oil is Indonesia, that has a total harvested oil palm area around 11.3 M ha (BPS, 2017), an area that is projected to grow to 17 M ha by 2025 (Sung, 2016). In the past couple of decades, crude palm oil production in Indonesia has increased from 0.84 M t in 2001 to almost 27 M t in 2017 (FAO, 2019). This increase is explained almost entirely by the expansion of the area on which oil palm is cultivated, which is increasing at a rate of 11.7% per year (Petrenko et al., 2016). Although the expansion of the area under oil palm is often linked to deforestation, there is some debate as to the exact percentage of forest conversion to oil palm. While some studies report that oil palm expansion accounts for around 50% of deforestation (Koh and Wilcove, 2008), others report this percentage to be much lower, varying between 7.6% and 16% (Fitzherbert et al., 2008; Fairhurst and Härdter, 2003). While some of the expansion has taken place in the areas used for shifting cultivation, rubber, grassland or other crops (Rhebergen et al., 2019; Wicke et al., 2011; Fairhurst and Härdter, 2003), it is certain that rapid expansion is occurring to meet the increasing demand

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for palm oil, and that available non-forest land is becoming increasingly scarce. Thus, there is a considerable risk that further expansion will contribute to future deforestation (Fitzherbert et al., 2008).

However, there is scope for increasing oil palm production through sustainable intensification of existing plantations rather than continuing the ongoing area expansion (Rhebergen, 2019; Hoffmann et al., 2015; Rhebergen et al., 2014; Oberthür et al., 2012; Donough et al., 2010). Intensification through best management practices (BMP) has shown promising results in large-scale plantations of Indonesia where BMP have increased yields by 6 t ha^{-1} (Donough et al., 2010; Fairhurst and Griffiths, 2014).

Although large-scale plantations are responsible for 60% of the current palm oil production, they cover only half of the area under oil palm in Indonesia (RSPO, 2018). Smallholders produce the remaining 40% and play an increasingly prominent role, yet they are typically seen as inefficient and only manage to achieve around 50% of the attainable yield (Woittiez et al., 2017; Euler, 2016). There is thus room for large increases in the palm oil production from smallholder plantations through intensification practices, such as BMP.

BMP involve more frequent harvest cycles and improved access to fields, leading to more complete crop recovery (harvesting all the suitable crop, including the complete collection of loose fruits) than is currently the case on smallholder sites. This accounts for an immediate increase in yield in such systems (Rhebergen et al., 2018). Other differences between BMP and smallholders' practices concern nutrient management, including the recycling of organic residues. There are three different management schemes in BMP that focus on reducing yield gaps in oil palm plantations through the efficient use of production-related inputs and resources (Donough et al., 2009). One of these is a soil moisture and nutrient management scheme, which – among other things – involves the application of more organic residues such as pruned fronds, empty fruit bunches (EFB) and palm oil mill effluent (POME). Residue management plays a role in conserving soil moisture as well as adding plant nutrients and contributing to the SOC pool. A study from Central Sumatra, Indonesia found that application of 60 t EFB ha^{-1} y^{-1} for 15 years increased yields with 5.9% which might be associated with SOC increase compared to the sole use of mineral fertiliser (Tao et al., 2017). Another study from Malaysia reported an increase of SOC in the topsoil from 1.49 to 2.73% after application of 300 kg EFB $palm^{-1}$ y^{-1} for 10 years (Bakar et al., 2011).

However, little is known about the implications of different management approaches on the development of SOC stocks of oil palm plantations. In this study, the SOC stocks of Indonesian plantations managed with BMP were compared with stocks under the current management practices (CMP) typical of large plantations and of plantations under smallholder management practices (SHMP). Oil palm plantations are often divided into different management zones, namely weeded circle (WC), interrow (IR), frond stack (FS) and harvesting path (HP), which may have differing levels of SOC at different soil depths. The parts of the management zones IR and FS that receive organic inputs, such as organic residues (pruned fronds, POME and EFB) or compost, may store more SOC, resulting in a specific SOC pattern, but the effects of the management zones on the development of SOC stocks in different plantation systems is not well documented. Furthermore, there is growing evidence that higher amounts of SOC can be sequestered in deeper soil horizons (Yu et al., 2019; Jobbágy and Jackson, 2000). Therefore, this study also examined the vertical distribution of SOC in subsoil (~70 cm).

The overall objective of this research was to identify the management practices that allow SOC stocks of oil palm plantations to be increased. It was hypothesised that BMP result in higher SOC stocks than the CMP and SHMP systems. The research questions of the present study were: i) How do different management regimes influence SOC stocks of oil palm plantations? ii) What are the intra-plantation dynamics of SOC stocks under different types of management practices? and iii) How does soil depth influence SOC stocks of oil palm plantations?

2. Materials and methods

2.1. Description of the study sites

Our study area is located about 20 km from the city of Medan (UTM zone 47N; 482579E; 384835N) in North Sumatra, Indonesia (Fig. 1). This study area is under humid tropical climatic condition. The average precipitation and temperature are annually 2294 mm and 26.4 °C, respectively. The landscape is characterised by undulating hills, with elevations 25–50 m above sea level. Soils are developed from volcanic ash (rhyolitic) (Tohiruddin and Foster, 2013) and are classified as Ultisols according to the soil taxonomy of USDA (KPRI, 2020; Soil Taxonomy USDA, 2010; Soil Survey Staff, 1975) with a sandy loam texture. The previous vegetation of the locations included in this study was rubber. The study was conducted on the commercial oil palm plantation of the Begerpang estate, which belongs to PT Perusahaan Perkebunan London Sumatra Indonesia Tbk (LONSUM), and on surrounding plantations managed by smallholders.

Soil sample was collected from plantations under three different management practices: i) best management practices (BMP), ii) current management practices (CMP) and iii) smallholder management practices (SHMP). BMP and CMP were undertaken in LONSUM, and SHMP were undertaken on the plantations managed by independent smallholders. The smallholder plantations were selected based on their proximity to LONSUM, palm age, previous land use (the previous land use was rubber for all the selected sites for the BMP, CMP and SHMP systems), soil type and the similarity with LONSUM's common management practices.

Most of the plantations under LONSUM were managed with high doses of inorganic fertilisers. However, the remainder had been managed for a long time according to BMP principles, receiving a combination of inorganic fertilisers and organic amendments for better production, improved nutrient recycling and maintenance of soil fertility (see below). It is this latter practice that is regarded as the best management practice.

2.2. Standard management system in oil palm plantations

The oil palms in our study area were planted in a triangular pattern with 9-m inter-planting distance following in a staggered design at a density of 145–150 palms ha^{-1} (depending on the plantation). To facilitate systematic management and to ease of the different activities that are commonly carried out in the oil palm plantations, these are usually divided into four management zones (Fig. 2).

Every palm was surrounded by a weed-free circle, which is the key place for the application of inorganic fertilisers and referred to as weeded circle (WC). For mature plantations, inorganic fertilisers were applied by hand spreading two times per year. In mature plantations, pruning was carried out once or twice a month along with harvesting. The pruned fronds were stacked in heaps in the area normally referred to as the between-palm area, which is a common management practice in Indonesia. Hence the between-palm area was covered by pruned fronds in all sampling plots thus, referred to here as the frond stack (FS) zone. One side of the palm row is referred to as the interrow (IR), and the other side is the harvesting path (HP) which is a path for harvesting and other

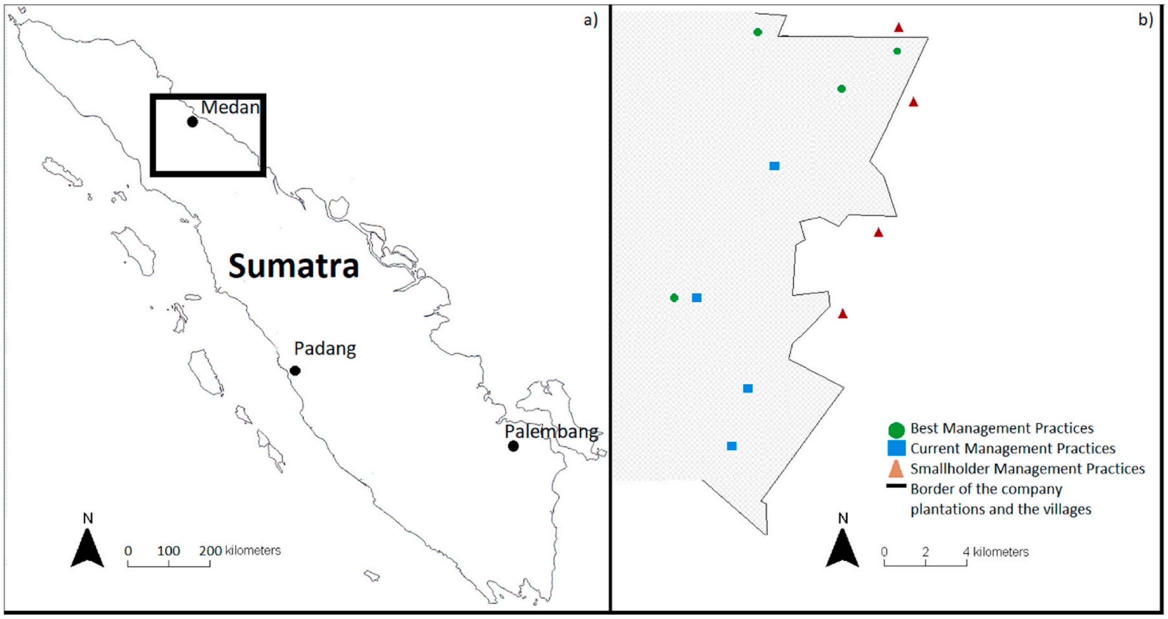

Fig. 1. Map of the study location (black square) in North Sumatra, Indonesia (a); the different sampling sites on oil palm plantations in North Sumatra (b).

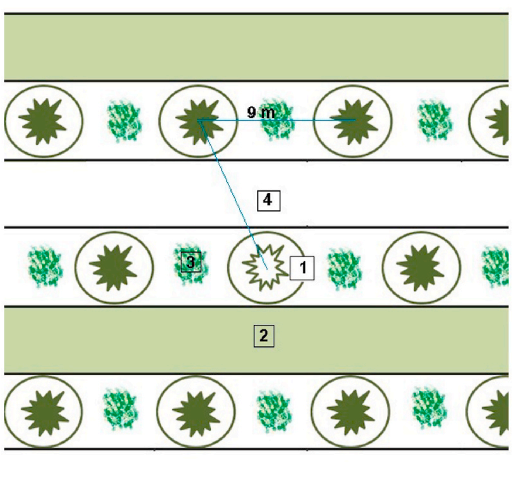

Fig. 2. Layout of the oil palm plantation. Management zones: 1) weeded circle, 2) interrow, 3) frond stack and 4) harvesting path.

management activities. The fresh fruit bunch (FFB) from mature palms were harvested once every 7–10 days. On average, the WC, IR, FS and HP management zones corresponded to approximately 18%, 38%, 16% and 38% of the area on all the investigated oil palm plantations.

2.2.1. Best management practices (BMP)

The BMP fields were planted with the cultivar Tenera (*dura x pisifera*) in 2001–2002 at a density of 135 palms ha^{-1}. Fertiliser types and application rates depended on the growth stage and nutrient status, the latter of which was evaluated by foliar analysis. After planting, leguminous cover crops were grown for the first few years to provide soil cover and ensure that soil fertility was maintained. Once a year for 15 years, 26 t ha^{-1} enriched mulch (EMU) was applied in the interrows to maintain the nutrient status of the plantation and control erosion (S Table 1). EMU is partially decomposed organic residue from a conventional open windrow system (Silalahi and Foster, 2006). It is a mixture of POME and pressed EFB (3:1 ratio by weight) (Tohiruddin and Foster, 2013). POME was added every day on top of the pressed EFB during the co-composting time (30 days). The physical and chemical properties of EMU are presented in Table S1. Inorganic fertilisers (1 kg urea (62 kg N ha^{-1} y^{-1}), muriate of potash (68 kg K ha^{-1} y^{-1}) and rock phosphate (22 kg P ha^{-1} y^{-1}) palm^{-1} y^{-1}) were broadcast in two applications a year covering all management zones following the BMP nutrient management scheme (Donough et al., 2009) for better fruit bunch production.

2.2.2. Current management practices (CMP)

Standard management practices were followed. The fields were planted in 2001–2002 with the cultivar Tenera (*dura x pisifera*) at a density of 135 palms ha^{-1}. Fertiliser types and application rates depended on the growth stage and nutrient status, the latter of which was evaluated by foliar analysis. After planting, leguminous cover crops were grown for the first few years to provide soil cover and sustain soil fertility. Inorganic fertilisers (3 kg urea (186 kg N ha^{-1} y^{-1}), muriate of potash (203 kg K ha^{-1} y^{-1}) and rock phosphate (65 kg P ha^{-1} y^{-1}) palm^{-1} y^{-1}) were applied in two split applications a year to reach the highest fruit bunch production. There were no attempts to return EFB or compost to the field.

2.2.3. Smallholder management practices (SHMP)

Standard management practices were followed. Plant density at the SHMP sites was 135–145 palm ha^{-1}. The sites were converted from rubber in 2001–2002, and the cultivar was unknown. No leguminous cover crops were grown in the early stage of the plantation and EFBs from the mill were not returned. Small amounts of inorganic fertiliser (mostly urea) were applied according to market availability or the farmer's financial situation. Household and livestock (mostly cow dung) residues were applied in the WC zone when available. The IR zone was covered with grass, and very clean harvesting paths were observed in the sampling plots.

2.3. Soil sampling and processing

Soil samplings were carried out in June and July 2014. Interviews were conducted with the manager of LONSUM's Begerpang estate to collect necessary information and data on current management and past plantation related management history. Smallholder farmers were randomly selected from a list of farmers based on the above-mentioned criteria. Four replicate sites for each oil palm management system (BMP, CMP and SHMP) were selected carefully in terms of the likeness of palm age (12–13 years old plantations), soil texture (similarity checked by the feel method (Soil science society of America, 2008)), structure (granular), elevation (≤40 m), and the distance to nearby LONSUM's sampling plots (the sites were not more than 4 km apart, Fig. 1).

Organic inputs (pruned fronds, organic residue, compost) in the oil palm plantation area commonly spread into four different management zones (WE, FS, IR, HP), hence the carbon status of these management zones are varied (Rahman et al., 2018; Khasanah et al., 2015). To capture the intra plantation variation on SOC, a rectangular plot (18 m × 16 m) was established at each site and within this plot, the soil was collected from the four management zones at a distance of 1 m (WC), 4.5 m (IR), 4 m (FS) and 4.5 m (HP) from the oil palm base. The areas under each of the four management zones were measured for each plot. In the present study, it was decided to collect samples from soil layers down to 70 cm following the recommendation from Wendt and Hauser (2013) who emphasise the need to sample to at least 60 cm to avoid erroneous conclusions on changes in SOC stocks due to differences in soil compaction as a result of management practices. Therefore, from each management zone, undisturbed, volume specific soil samples were collected using 100 cm^3 soil cores from five soil depths of the 70-cm deep soil pits (0–5, 5–15, 15–30, 30–50 and 50–70 cm). These samples were used for the determination of bulk density. Samples were oven-dried in the BLRS laboratory in Bah Lias Research Station under LONSUM and weighed. Stones and roots were separated and weighed. Bulk densities of samples containing stones were corrected based on the assumption that the stones had a bulk density of 2.6 g cm^{-3} (Bruun et al., 2013). Non-volume specific soil samples were also collected from the middle part of the soil layers. These soil samples were oven dried in the BLRS laboratory and crushed, sieved through a 2-mm mesh and used for determining soil pH and soil texture, C and N concentration.

2.4. Laboratory analyses and SOC stock calculations

Total nitrogen and SOC were measured using Isotope ratio mass spectrometer (±0.2% accuracy and precision) attached with an elemental analyser (Isoprime100 IRMS, UK attached with Pyrocube, Elementar, Germany). Soil pH was measured in a 1:5 soil: deionised water suspension according to Thomas (1996) and a laser diffraction technique was used to determine the soil texture by using Malvern Instruments which differentiated the clay (<2 μm)) sand (>63 μm) and silt (2–63 μm) fractions. These analyses were carried out in laboratories at the Department of Plant and Environmental Sciences and Department of Geosciences and Natural Resource Management at the University of Copenhagen. The SOC stocks in the top 70 cm of the soils were calculated using the fixed-depth approach according to the equation as follows:

SOC stock (t ha^{-1}) = SOC concentration (%) × soil bulk density (g cm^{-3}) × thickness of a soil layer (cm)

The total SOC stock at a depth of 0–70 cm was calculated by the sum of the SOC stocks in the 0–5, 5–15, 15–30, 30–50, 50–70 cm layers. To ensure comparison of the same soil mass and eliminate changes in SOC caused by bulk density interference, the equivalent soil mass approach was also followed to calculate total SOC stocks for 0–30 cm and 70 cm depths of soil (Ellert and Bettany, 1995). The equivalent soil mass approach eliminates the overestimation or underestimation of SOC stocks caused by management-induced changes in soil bulk density. Soil SOC stocks were also computed using the weighted average, which was in accordance with the different management zone's area share (%) (weeded circle, interrow, frond stack, harvesting path).

2.5. Statistical analyses

For statistical analysis, Statistical Analysis System (SAS) software version 9.4 (SAS Institute Inc., 2002–2012 USA) was used in this study. PROC MIXED in SAS software was used to examine the differences in SOC stocks between different management practices, different management zones and different depths by performing analysis of variance (ANOVA) with the general linear model (GLM) procedure. Where differences between treatments were identified, Tukey's HSD test was used to determine the significance of the differences at the 95% level ($P < 0.05$). Simple regression was also undertaken to check the correlation between bulk density and SOC in different soil depths. The independence, normality and homogeneity of variance of the dataset were examined, and all the data met the assumptions without transformation. PROC UNIVARIATE test was used to test normality, while the test of equality of error variance of PROC GLM procedure was used to test homogeneity of variance.

3. Results

3.1. Soil characteristics

The average values of soil pH, bulk density, texture and SOC values, under BMP, CMP and SHMP in the different management zones were presented in Table 1. In the BMP system, the SOC content in the top 15 cm was observed to be significantly higher ($p < 0.05$) in the IR zone than in any of the other zones. However, the SOC content in the FS and WC zones in the CMP system was 22% and 36% higher than in the IR and HP zones, and 12% and 30% higher than in the SHMP system (Table 1). The SOC concentration fell with greater soil depth. In contrast, there was an increasing trend in bulk density with increased soil depth increases for all zones and management practices. SOC concentration exhibited a strong negative correlation to soil bulk density (Fig. S1), with increasing soil depth for all oil palm management systems. Nitrogen % was always higher in the upper 0–5 cm layer (S Table. 2) for all the management systems. For the BMP system, IR had a higher nitrogen % than the other management zones in the upper layer (0–5 cm). In the CMP and the SHMP systems, nitrogen % was higher in the FS and WC management zones, respectively. The C:N ratio in the topsoil (0–5 cm) was higher in all the management systems compare to the subsoils (S Table 2). The range of soil pH was found to vary between 4.4 and 6.8, indicating a weak acidic to the neutral soil environment. There were no differences in clay content between the sites averaged across layers, and correlations with SOC concentration were weak ($R^2 = 0.35$). Similarly, the relationship between Clay + Silt (%) and SOC % were also weak (Fig. S2).

Table 1
Soil physical and chemical characteristics. BMP, CMP and SHMP represent best management practices, current management practices, smallholder management practices respectively. WC = weeded circle, FS = frond stack, IR = interrow and HR = harvesting path. FFB = fresh fruit bunch.

Sites	Depth (cm)	Bulk density ($g\ cm^{-3}$)				Carbon (%)				Soil texture fractions			Soil pH	FFB yield ($t\ ha^{-1}$)
		WC	FS	IR	HP	WC	FS	IR	HP	(%) Clay	(%) Silt	(%) Sand		
BMP	0–5	1.04 ± 0.01	0.98 ± 0.04	0.98 ± 0.07	0.88 ± 0.01	2.31 ± 0.31	2.18 ± 0.15	3.04 ± 0.79	1.85 ± 0.32	5.9 ± 1.39	27.8 ± 4.70	66.2 ± 6.05	6.01 ± 0.21	27 ± 0.65[a]
(n = 4)	5–15	1.09 ± 0.02	1.03 ± 0.02	1.10 ± 0.05	1.00 ± 0.05	1.49 ± 0.11	1.47 ± 0.11	1.75 ± 0.23	1.37 ± 0.13	4.8 ± 0.71	18.5 ± 2.32	76.6 ± 2.88	5.82 ± 0.31	
	15–30	1.13 ± 0.02	1.13 ± 0.02	1.11 ± 0.04	1.11 ± 0.06	1.01 ± 0.08	1.21 ± 0.06	1.23 ± 0.08	0.91 ± 0.09	7.2 ± 1.23	21.7 ± 2.12	70.9 ± 3.28	5.84 ± 0.36	
	30–50	1.17 ± 0.03	1.18 ± 0.03	1.15 ± 0.04	1.15 ± 0.05	0.60 ± 0.05	0.71 ± 0.06	0.57 ± 0.06	0.52 ± 0.05	6.4 ± 1.48	22.0 ± 3.41	71.4 ± 4.62	5.73 ± 0.17	
	50–70	1.20 ± 0.03	1.23 ± 0.04	1.20 ± 0.05	1.22 ± 0.04	0.40 ± 0.01	0.42 ± 0.04	0.38 ± 0.05	0.32 ± 0.04	3.6 ± 1.19	19.0 ± 3.42	77.3 ± 4.61	5.78 ± 0.15	
CMP	0–5	1.04 ± 0.05	0.97 ± 0.05	0.95 ± 0.02	0.98 ± 0.03	2.03 ± 0.15	2.62 ± 0.16	1.71 ± 0.11	1.63 ± 0.16	3.3 ± 0.41	17.4 ± 0.82	79.1 ± 1.16	5.69 ± 0.16	26 ± 0.63[a]
(n = 4)	5–15	1.09 ± 0.05	0.96 ± 0.06	1.03 ± 0.03	1.03 ± 0.03	1.48 ± 0.14	1.63 ± 0.08	1.36 ± 0.06	1.11 ± 0.04	5.5 ± 0.50	20.9 ± 1.47	73.5 ± 1.95	5.35 ± 0.14	
	15–30	1.15 ± 0.05	1.04 ± 0.04	1.10 ± 0.03	1.09 ± 0.03	0.90 ± 0.07	1.11 ± 0.04	1.03 ± 0.05	0.72 ± 0.05	3.4 ± 0.47	17.6 ± 1.65	78.8 ± 2.01	5.16 ± 0.15	
	30–50	1.19 ± 0.06	1.13 ± 0.02	1.15 ± 0.03	1.13 ± 0.03	0.56 ± 0.04	0.69 ± 0.04	0.59 ± 0.07	0.36 ± 0.06	5.2 ± 1.02	14.5 ± 0.66	80.1 ± 0.97	5.18 ± 0.19	
	50–70	1.24 ± 0.05	1.20 ± 0.02	1.20 ± 0.03	1.24 ± 0.03	0.39 ± 0.03	0.39 ± 0.02	0.32 ± 0.04	0.25 ± 0.03	3.4 ± 0.49	15.5 ± 2.84	81.0 ± 3.28	5.22 ± 0.14	
SHMP	0–5	0.91 ± 0.05	0.91 ± 0.03	0.87 ± 0.03	0.92 ± 0.06	2.31 ± 0.24	1.94 ± 0.25	1.60 ± 0.05	1.32 ± 0.15	2.4 ± 1.14	15.5 ± 4.11	82.0 ± 5.16	5.79 ± 0.29	18 ± 0.85[b]
(n = 4)	5–15	1.04 ± 0.01	1.00 ± 0.01	0.90 ± 0.02	1.04 ± 0.0	1.24 ± 0.12	1.34 ± 0.11	1.21 ± 0.02	0.82 ± 0.07	4.7 ± 1.53	20.4 ± 5.92	74.9 ± 7.41	5.35 ± 0.18	
	15–30	1.10 ± 0.01	1.00 ± 0.02	0.96 ± 0.04	1.07 ± 0.04	0.88 ± 0.09	0.87 ± 0.09	0.83 ± 0.03	0.67 ± 0.05	2.4 ± 0.41	14.1 ± 1.57	83.3 ± 1.9	5.20 ± 0.23	
	30–50	1.17 ± 0.01	1.08 ± 0.03	1.03 ± 0.04	1.14 ± 0.03	0.44 ± 0.04	0.53 ± 0.04	0.45 ± 0.02	0.39 ± 0.01	2.9 ± 1.07	15.3 ± 3.87	81.7 ± 4.29	5.10 ± 0.34	
	50–70	1.19 ± 0.01	1.10 ± 0.03	1.08 ± 0.03	1.20 ± 0.02	0.24 ± 0.01	0.32 ± 0.04	0.28 ± 0.03	0.27 ± 0.05	2.9 ± 0.59	16.0 ± 2.04	81.0 ± 2.51	5.12 ± 0.39	

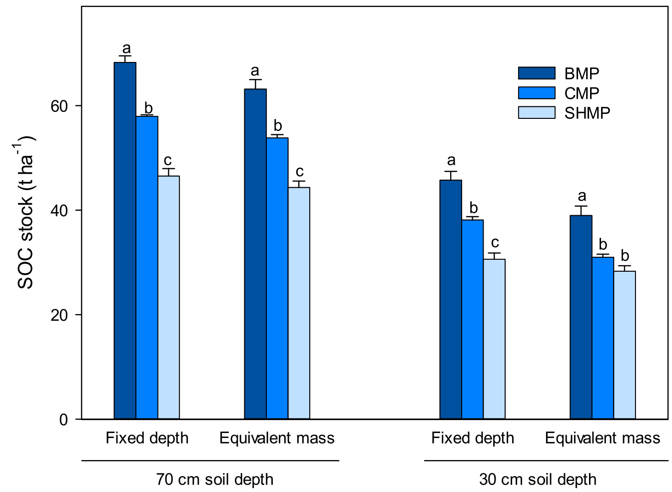

Fig. 3. Total soil organic carbon (SOC) stocks in the upper 70 cm and 30 cm of the soil under different management systems (BMP = best management practices, CMP = current management practices, SHMP = smallholder management practices), calculated by the fixed-depth approach and equivalent soil mass approach according to the relative areas of the four management zones (weeded circle, frond stack, interrow and harvesting path). Different letters denote significant differences between management systems ($p < 0.05$).

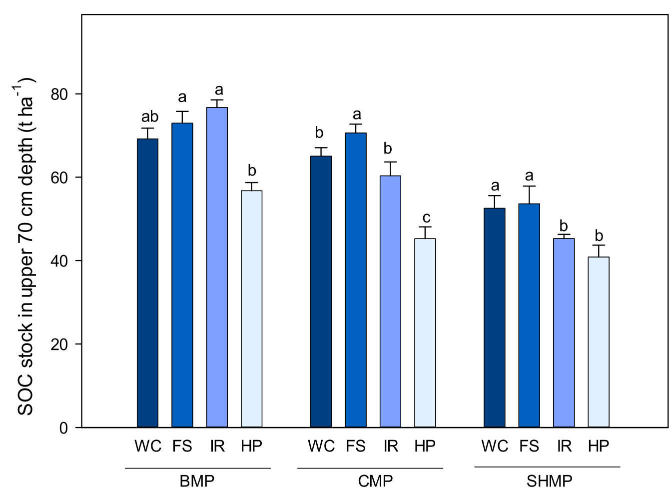

Fig. 4. Soil organic carbon (SOC) stocks in different management zones (WC = weeded circle, FS = frond stack, IR = interrow and HP = harvesting path) at different depths and for different management systems of oil palm. Different letters indicate significance ($p < 0.05$) of the SOC stock in the upper 70 cm in the different management zones per management system (BMP = best management practices, CMP = current management practices, SHMP = smallholder management practices).

3.2. Yield

FFB production of the BMP (27 t ha^{-1}) and CMP (26 t ha^{-1}) system was significantly higher than that of the SHMP system (18 t ha^{-1}; $p < 0.01$) (Table 1). There was a positive linear relationship between SOC and FFB yield ($y = 0.40x+0.49$, $R^2 = 0.85$) (Fig. S3).

3.3. SOC stocks in different oil palm management systems

In accordance with the fixed-depth approach, SOC stocks under the different management systems also showed significant differences in the upper 30 cm of the soil, turning out to be 10–15% greater than when using the equivalent soil mass approach (Fig. 3). Both approaches showed SOC stocks were significantly different ($p < 0.05$) between BMP and CMP system. However, according to the fixed-depth approach, the CMP system had a significantly ($p < 0.05$) larger SOC stocks than the SHMP systems, but according to the equivalent soil mass approach, there was no significant difference.

Total SOC stocks of the BMP system (68 t ha^{-1}) in the top 70 cm were significantly larger ($p < 0.05$) than of the CMP (−15%) and SHMP (−31%) systems when SOC was calculated using the fixed-depth approach. A similar trend was also observed when SOC was calculated using the equivalent soil mass approach (Fig. 3).

The fixed-depth approach resulted in 4–7% higher soil SOC stocks in the top 70 cm soil depth compared to the equivalent soil mass approach (Fig. S4). However, no significant differences were found between the values of these two methods. For this reason, hereafter only results of SOC stocks calculated by the more routinely utilised fixed-depth method are presented.

3.4. Different management zones and SOC stocks

SOC stocks were found to differ significantly ($p < 0.01$) between management zones, with the lowest stocks always found in the HP zone (Fig. 4). In the BMP system, the SOC stock was largest in the IR zone and significantly different from the stock in the HP zone ($p < 0.05$). In the CMP system, the FS zone stored significantly ($p < 0.05$) more SOC than any of the other zones. However, in the SHMP system, both the FS and the WC zones had significantly larger SOC stocks than the IR and HP zones ($p < 0.05$).

3.5. SOC stocks at different soil depths in oil palm plantations

SOC stocks in each soil layer of the BMP system were significantly ($p < 0.05$) larger in the corresponding layers of the CMP and SHMP system (Fig. 5). SHMP system consistently had the lowest SOC stocks in each soil layer. SOC stocks were largest in the top 30 cm soil and decreased with increasing soil depth. In each management system, the 5–15 and 15–30 cm layers stored significantly more carbon than the other layers ($p < 0.05$), and the least carbon was stored in the 50–70 cm layer.

4. Discussion

4.1. Calculation method of SOC stock and soil depth

This study used two methods to measure SOC stock: i) the fixed-depth approach and ii) the equivalent soil mass approach. Both the fixed-depth approach and the equivalent soil mass approach showed significant differences in SOC stocks at 70 cm soil depth between the different management systems (Fig. 3). The advantage of the equivalent soil mass approach is that it enables comparison of the same mass of soil which eliminates the effect of changes in the bulk density in different soil layers (Ellert and Bettany, 1995). However, the present study did not find any significant difference between the two methods (Fig. S4). To allow a comparison of the results of the present study with the most commonly reported results based on the routinely used fixed-depth approach are used in the discussion.

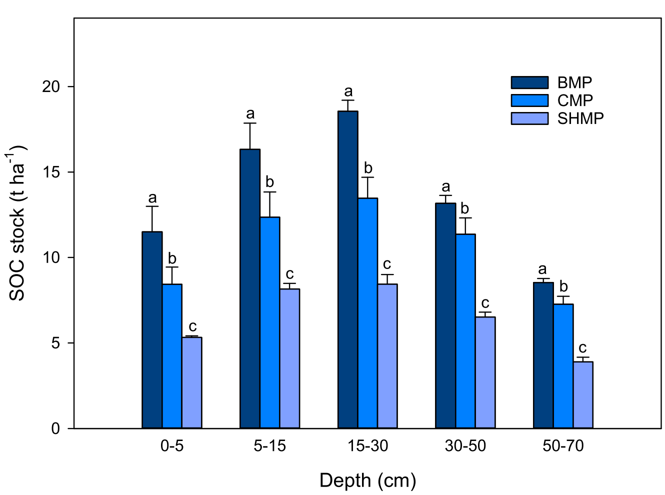

Fig. 5. Soil organic carbon (SOC) stocks at different depths at different management systems averaged over management zones. Different letters indicate significant differences ($p < 0.05$) between the same soil layers of different management systems (BMP = best Management Practices, CMP = current Management Practices, SHMP = smallholder management Practices).

Differences in SOC stocks of the investigated oil palm management systems were found in each of the investigated soil depth intervals (BMP > CMP > SHMP) hence also below the upper 30 cm that represent the standard sampling depth for studies of effects of management on SOC (Fig. 5). Oil palm roots can extend vertically by up to 2 m (Jourdan and Rey, 1997) and degraded roots are a significant source of SOC in deeper soil layers (Germer and Sauerborn, 2008). Root biomass of 16 t ha^{-1} to a soil depth of 60 cm has been reported from oil palm plantations in Malaysia (Germer and Sauerborn, 2008; Khalid et al., 1999). A recent study of Malaysian oil palm plantations by Rahman et al. (2018) found that SOC stocks are also affected below a soil depth of 30 cm soil depth. While it would be of interest to investigate the SOC stock change as deep as oil palm roots can go in the soil, the present study was confined to up to a depth of 70 cm depth, which was as deep as it was practically possible to sample. This provided a more in-depth view of both the topsoil and the subsoil SOC stock as affected by different management systems. We recommend that a 70 cm sampling depth should be followed for similar studies in the future.

4.2. Variation in SOC stocks of the different management systems

In this study, the BMP system stored significantly more SOC than the CMP and SHMP systems. The lowest SOC stock was found in the SHMP system, which had a 31% lower SOC stock than the BMP system. Owing to improved nutrient management with the regular application of balanced fertilisers, regular and frequent pruning and the recycling of crop residues, intensive management systems such as BMP and CMP have higher biomass production (fruit bunch and frond) (28–30 t ha^{-1} yr^{-1}), which results in higher carbon inputs at a faster rate than the SHMP system (Tao et al., 2017; Kunhamu, 2011; Fairhurst and McLaughlin, 2009; Fairhurst, 2003). Oil palm roots can be a large source of SOC as root biomass of 16 t ha^{-1} to a soil depth of 60 cm has been reported from oil palm plantations in Malaysia (Germer and Sauerborn, 2008; Khalid et al., 1999). It was also assumed that the better nutrient management in the BMP system may have favoured root growth, which may have contributed to the build-up of more SOC in this system. The added EMU may have contributed further to SOC accumulation due to the large soil contact area coverage, which may have enhanced its decomposition rates, and later its transfers to the mineral soil as particulate or dissolved organic carbon (Haron et al., 1998). This might have facilitated higher carbon accumulation rates in the BMP system than in the CMP and SHMP systems. Previous studies also agree that C inputs are the strongest predictor of SOC accumulation rates due to management practices in croplands (de Moraes et al., 2015; Hok et al., 2015; Maillard and Angers, 2014; Virto et al., 2012). Similarly, a meta-analysis by Fujisaki et al. (2018) reports that improved management practices that involve higher C inputs usually lead to increased SOC stocks. Previous study found the BMP system is to be an environmentally sustainable practice as it lowers the global warming potential value by 50% through replacing 50% of its inorganic fertilisers with organic amendments (Rahman et al., 2019).

4.3. Differences in SOC stocks between different management zones

The SOC stocks varied in different management zones owing to the different amounts of organic residues that were added to each zone in the oil palm plantations. The largest SOC stock in the BMP system was found in the IR (77 t ha^{-1}) zone, where large amounts of EMU were applied, compared with the HP zone (57 t ha^{-1}) where no inputs were added. The higher total SOC stock in the BMP system compared to the other systems was strongly influenced by the addition of EMU to 38% of the plantation area (IR zone). In the CMP and SHMP systems, no organic residues were applied at the study sites. The addition of 26 t EMU ha^{-1} in the BMP system has been shown to maintain soil organic matter content and thereby may have contributed to increasing SOC stocks by 21% and 40% more than the CMP and SHMP systems. The smallest SOC stock in the IR zone of the SHMP system may have partly resulted from the absence of leguminous crops compared with both the BMP and CMP systems, where these were grown during the first few years after establishment. In line with this, previous studies have reported that nitrogen addition in soil increases SOC stock by 4–17% by stimulating microbial activities that initially accelerate the decomposition of fresh litter and of labile organic matter (Yu et al., 2020; Lu et al., 2011; Janssens et al., 2010; Berg and Matzner, 1997). These leguminous cover crops might play a role in building up SOC stock by increasing N supply and belowground dead root material after plant senescence and death in the IR zone in the BMP and CMP systems, something that is absent from the SHMP system.

The practice of the continuous addition of pruned fronds in the FS zone may have facilitated to the accumulation of the SOC stocks here under all management practices. The BMP, CMP and SHMP systems stored 22%, 23% and 35% more SOC stock in the FS zone than in the HR zone respectively. This is in accordance with Rahman et al. (2018) and Aljuboori (2013) who reported that the large input of fronds led to increases of 16–26% in the SOC stock beneath the frond stack over time relative to the other management zones in Malaysian oil palm plantations. These findings are also corroborated by Khasanah et al. (2015) and Frazao et al. (2013, 2014), who reported similar variations of the SOC stocks in different management zones in Indonesia and Brazil respectively.

In the SHMP system, the WC zone stored more SOC than the other management zones. This is most likely due to two of the smallholder farmers adding household and livestock residues to the weeded circle. The application of inorganic fertilisers in the smallholder systems was limited due to the high cost of fertilisers and limited financial capacity of smallholder farmers – constraints that have been reported as determining fertiliser applications on smallholder oil plantations throughout the region (Euler, 2016; Bruun et al., 2013; FAO, 2005). Smallholders in the study area believe that the oil palm roots only stay within the WC zone, therefore they focus their fertiliser application in this zone, whereas commercial plantations apply a large number of fertilisers across the plantation.

The WC zone in the BMP and CMP systems in the present study did not receive additional organic residues. Considering the negligible inputs of aboveground litter and organic materials in the WC zone, the SOC stock in the BMP and CMP systems must largely have come from root materials. Nitrogen fertilisation and the radiative root growth pattern might have facilitated the fine (fasciculate) root growth in the soil surface of the weeded circle (de Carvalho et al., 2014; Jourdan and Rey, 1997). In the present study, the HP zone only received C inputs from the extended root, which spread 640 cm from the palm base (Safitri et al., 2018). At all plantation sites, this zone had the lowest SOC stock because no carbon inputs were applied there.

4.4. Effect on yields

The highest FFB yield was found in the BMP system, where the SOC stock was also highest compared to the other oil palm management systems (Table 1). However, the differences were only significant between BMP and SHMP. There have been reports on the positive effects of SOC on the crop yield of annual crops, such as rice, wheat, maise, and peas (Lal, 2010a, 2010b; Lal, 2004). The present findings also provide important empirical evidence for the positive effect of SOC stocks on yields in oil palm. SOC improves soil structure and quality through increased retention of water and nutrients, resulting in greater plant productivity (Lal, 2006), which may also be the case in the present study. The addition of EMU has been shown to maintain soil organic matter content and may therefore have contributed to increased SOC stocks and enhanced fertiliser use efficiency (Tohiruddin and Foster, 2013). Application of organic inputs such as EMU may have influenced nutrient availability by adding to the total amount of nutrients and controlling net mineralisation-immobilisation patterns (Gruhn et al., 2000; Palm et al., 1997). The combined use of inorganic fertiliser and EMU as mulching material may have improved moisture retention and nutrient supply capacities of the soil, which in turn improved the FFB yield under the BMP system. This is in agreement with Hijbeek et al. (2018), who report that the nitrogen fertiliser replacement value of organic amendments may be greater after application of a combination of organic amendments and inorganic fertilisers. A previous study by Tao et al. (2017) reports a rise in yield by increasing soil organic carbon, particularly after application of 60 t EFB ha^{-1} year^{-1} on an oil palm plantation in Riau Province in Indonesia.

Residue management, such as frond stack application practices, may also have helped increase crop yield (Tohiruddin and Foster, 2013). In line with this, Lehtinen et al. (2017) report that organic fertilisers act as 'slow-release' fertilisers that are known to provide slow but nevertheless effective nitrogen mineralisation (Lehtinen et al., 2017) and result in yield increases. These dynamics also help minimise nitrogen losses to groundwater and into the atmosphere. While the application of organic amendments along with inorganic fertilisers appeared beneficial in the present study, a reduction in the use of inorganic fertilisers may affect yield and requires further study. Irrespective of the management system, a positive correlation was identified between yield and SOC stocks. It is therefore recommended that measures such as the combined application of organic and inorganic fertilisers be used as a strategy to increase SOC stocks as well as yield. In particular, the SHMP that had the lowest SOC stock and FFB yield in the present study could benefit from following the BMP principles of utilising fronds, recycled waste materials from plantations and mills, and EMU (where possible) fertiliser as measures to increase SOC stock and FFB yield.

However, smallholder plantations only use inorganic fertiliser to a limited extent due to its high price and lower availability. Inadequate and unbalanced fertiliser application practices have been reported by Woittiez et al. (2017) in Kalimantan and Jambi provinces in Indonesia. In line with a previous study (Woittiez et al., 2019), independent smallholders in the present study were not aware of the existence of the BMP system and its advantages. FFB production under SHMP was found to be 33% lower than in the BMP system, which may not only be a result of the lower application of inorganic fertilisers and organic inputs, but also of the way in which the organic inputs were applied. For example, in the SHMP system, compost was only applied in the weeded circles, which may have hindered productivity since the feeder roots spread 640 cm horizontally from the palm base (Safitri et al., 2018). Previous studies have reported several sub-optimal management practices performed in SHMP systems that may affect yields. For example, Papenfus (2002) reports that companies commonly use planting material (*dura x. pisifera = Tenera*) and seedlings from their own company, whereas this planting material is unknown to smallholders. This is true for the present study as well. Similarly, infrequent harvesting and milling is another factor affecting yield in SHMP (Lee et al., 2013; Euler et al., 2016). Smallholder farmers mostly depend on the mill tractor to collect the fruit or arrange community transport to the mill. The fruit might be over ripe or not sufficiently mature to harvest, thus affecting yield. LONSUM has its own mill and harvests as required or maintains a weekly harvesting schedule. Several authors have also reported delayed replanting (Koczberski and Curry, 2003) and limited inorganic fertiliser use (Euler et al., 2016; Koczberski and Curry, 2003; Papenfus, 2002) in the SHMP system, which was also the situation for smallholder farmers in the present study.

The present study suggests that crop residues need to be retained if substantial gains in SOC stock under plantations are to be achieved. The importance of the BMP typical of the study area is that they increase SOC stocks as well as economic returns. Finally, it is important to raise awareness of the BMP among smallholder farmers, something that was found to be limited in the study area.

5. Conclusions

SOC stocks of oil palm plantations are affected by management practices. Plantations under BMP stored more SOC in the upper 0.7 m of the soil than plantations under the other investigated management regimes. The intra-plot management zones that received organic mulch and pruned fronds stored more carbon than other zones within the same management system. Application of crop residues, such as fronds and EMU in BMP plots, contributed to the recycling of nutrients and organic matter. Retention of crop residues in the BMP system may also improve soil quality and yields. While the present study suggests that the application of organic amendments along with inorganic fertilisers is beneficial, a reduction in the use of inorganic fertilisers may affect yield. Future long-term studies should focus on soil macro and micronutrient dynamics in relation to yield stability in BMP system with potential carbon sequestration in several oil palm rotations. To ensure that independent smallholder farmers take this opportunity of simultaneously improving their yield and SOC stocks, they need to be made aware of the benefits of BMP and barriers to smallholder adoption of the system should also be investigated.

Credit author statement

Niharika Rahman: Conceptualization, Data curation, Formal analysis, Writing - original draft. Ken E. Giller: Writing - review & editing. Andreas de Neergaard: Writing - review & editing. Jakob Magid: Writing - review & editing. Gerrie van de Ven: Writing - review & editing. Thilde Bech Bruun: Investigation, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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