Changes in soil quality indicators under oil palm plantations following application of 'Best Management Practices' in a four-year field trial

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Abstract

Increasing the yield of existing oil palm plantations is one means of accommodating some of the growing demand for palm oil. The International Plant Nutrition Institute (IPNI) has developed and tested a process to deploy a series of 'best management practices' (BMPs) that cover a range of agronomic practices intended to intensify oil palm production and improve yield at a given site using cost-effective, practical methods. Many of these BMPs include techniques that should also improve soil quality, such as the addition of organic matter to the soil surface, and improved timing and tailored application of mineral and organic fertilisers. Six plantations in Kalimantan and Sumatra applied BMPs prescribed by IPNI (BMP treatment), and standard management practices (REF treatment) in paired blocks of oil palm over four years; 30 pairs of blocks were included in the research. Soils were sampled in both treatments before and after the field trial, from beneath weeded circles surrounding individual palms and beneath frond piles in between rows of palms, at 0-20 cm depth and 20-40 cm depth. Soils were tested for a range of properties, including soil pH, % soil organic carbon (% SOC), total N, available P, and exchangeable cations. No clear, consistent differences were found in the degree of change in soil properties between BMP and REF treatments over four years. However, improvements in some soil properties were noted for both treatments, particularly for soil pH and % SOC. There was no significant deterioration in the measured soil properties over the four years. The results suggest that appropriate management practices for oil palm can improve several aspects of soil quality. Further research on the mechanisms by which BMPs can improve soil quality, and monitoring over longer periods of time is recommended to give plantation managers a clearer picture of the potential 'co-benefits' that can be obtained with adoption of BMPs designed to increase oil palm yield.

Keywords

Oil palm; Southeast Asia; soil quality; nutrient management; intensification; best management practices BMP

Highlights

- 'Best' and standard oil palm management practices compared for effects on soil
- No significant deterioration in measured soil properties over four years of management
- In both management treatments soil pH and % soil organic carbon increased
- Appropriate oil palm management techniques can help improve soil quality
- 4R Nutrient Stewardship is a key aspect in sustainable intensification

1 Introduction

Oil palm (*Elaeis guineensis*) supplies around 30% of the world's vegetable oil (USDA-FAS, 2013), of which a small percentage is used for biodiesel. Indonesia and Malaysia are the world's biggest producers of palm oil, accounting for 87% of the total global annual production of 53 Mt (USDA-FAS, 2013). Future demand for vegetable oil has been projected at between 201 to 340 Mt per year by 2050 (Corley, 2009), based on growing demand for edible oil and biodiesel. Demand for vegetable oils has increased steadily since the mid- 1970s; during the same period demand for palm oil has grown exponentially owing to the relatively low cost of producing palm oil compared with other vegetable oils, and its lower price on international markets (Carter et al., 2007). The demand for palm oil as a biodiesel has been propelled in part by mandates in a number of countries (including the European Union) to ensure that a certain percentage of diesel fuels are sourced from biomass (Koh and Ghazoul, 2008; Ewing and Msangi, 2009; Caroko et al., 2011; Mekhilef et al., 2011). Production of palm oil has increased largely through rapid expansion of the area cultivated to oil palm. For example, estimates using remote sensing suggest that areas planted with or cleared for oil palm plantations in Kalimantan expanded from 903 km^2 in 1990, to 8 360 km^2 in 2000, and to 31 640 km^2 in 2010 (Carlson et al., 2012).

Scenarios for accommodating the future demand for palm oil have often emphasised the likelihood of further expansion of the area under oil palm plantations (Koh and Wilcove, 2008; Corley, 2009). Past expansion of oil palm plantations has resulted in the conversion of intact tropical forest, logged forest, multispecies agroforests (such as rubber) and peatlands (Koh et al., 2011; Carlson et al., 2012); estimates of the proportion of oil palm plantations converted from forest in areas of Malaysia and Indonesia range between 55% (Koh and Wilcove, 2008) and 90% (Carlson et al., 2012). Future expansion of first generation biofuel feedstocks into extant forests, peatlands and agricultural areas has been criticised in relation to adverse impacts on biodiversity (Fitzherbert et al., 2008; Danielsen et al., 2009) and carbon storage in soil and biomass (Fargione et al., 2008; Carlson et al., 2012), potential impacts on food security (Ewing and Msangi, 2009; Chalmers and Archer, 2010) and even global phosphorus reserves (Hein and Leemans, 2012). In the case of oil palm, a number of methods have been suggested to mitigate these issues, such as establishing new plantations only on ‘degraded’ lands (Germer and Sauerborn, 2008; Nair et al., 2011), maintaining a mosaic landscape for improved biodiversity values (Foster et al., 2011), and examination of biofuel policy settings in developed nations to ensure prices for vegetable oils remain affordable to the most vulnerable communities (Kretschmer et al., 2012).

In addition to expansion of cropped area, a complementary means by which some of the future demand for palm oil may be met is to increase the productivity of existing plantations in terms of oil per unit land area per unit time (Donough et al., 2011). Between 1974 and 2005, global crude palm oil yields have increased at an average rate of 1% per year, representing a relatively slow rate of growth in yield (Carter et al., 2007). Further improvements in yield could potentially be made through genetic modification (e.g. recent work by Singh et al. (2013) on mapping the oil palm genome identified a gene that regulates oil yield) or through improved efficiency and management (Carter et al., 2007). Average yield for oil palm is around 4 t crude palm oil ha^{-1} in Indonesia and Malaysia (Corley, 2009). However, some estates with areas of around 2,000 ha have obtained oil yields in a good year of 8 t ha^{-1}, with averages over five year periods of between 5-6 t ha^{-1} (Donough et al., 2009). Such high yields are thought to be linked to better management in these estates, rather than more suitable biophysical conditions

(Donough et al., 2009). 'Better management practices' at in oil palm have been put forward as a means of improving yields and addressing nutrient deficiencies (Griffiths and Fairhurst, 2003).

The International Plant Nutrition Institute (IPNI) has developed and tested a process to deploy a series of 'best management practices' (BMPs) within a commercial production environment that cover a range of agronomic practices (see online Supplementary material for further details) intended to intensify the production systems in order to decrease the gap between actual and potential yield at a given site using cost-effective, practical methods (Donough et al., 2009). BMPs aim to increase the productivity of the crop through canopy management and nutrient management, as well as increase recovery of the crop produced in the field, as described in the online Supplementary material. Implementation of BMPs is 'site-specific', as they are tailored to address the particular production constraints and biophysical conditions of individual locations. Four years of field trials over a wide range of conditions demonstrated that BMPs increased yields of fresh fruit bunches (FFB) compared with the use of 'standard' management practices (Pasuquin et al., 2014).The difference in yield between blocks managed using BMPs and blocks managed using standard estate practices were largely ascribed to increased crop recovery in the first year of field trials, and in later years due to greater recovery and improved crop productivity (Pasuquin et al., 2014).

In addition to cost-effective improvement in yields, the application of BMPs aimed at nutrient management (Table S1 in online Supplementary material) should also help to minimise the environmental impact of oil palm production, through more efficient use of external inputs and production resources (Donough et al., 2009), and may also contribute to improvement in soil quality and nutrition in oil palm plantations over the longer term (Oberthür et al., 2012). The application of techniques to use available environmental resources more intensely, rationalise external inputs while maintaining or increasing crop yield per unit area has been referred to as the 'sustainable intensification' of agriculture (Caviglia and Andrade, 2010; Tilman et al., 2011). A number of recent papers and reports have discussed the potential for sustainable agricultural intensification to improve environmental quality (e.g. Cassman et al., 2003; RSUK, 2009; Burney et al., 2010; Caviglia and Andrade, 2010; Foley et al., 2011; Tilman et al., 2011). However, few studies provide field-based evidence of the impacts of sustainable intensification on soil or water quality: most field studies emphasise improvements in agricultural productivity. This research contributes to partially filling this important gap in published knowledge with the results of a multi-year study on the influence of BMPs (as a means of sustainable intensification) on soil properties in several oil palm plantations in Kalimantan and Sumatra.

Reviews of the on-site environmental impacts of oil palm plantations highlight potential impacts on soil quality, soil erosion, water quality and biodiversity (Hartemink, 2003; Hartemink, 2005; Nelson et al. 2010; Comte et al. 2012). However, there is relatively little published research based on field data collected from commercial plantations. Although detailed soil analyses are routinely undertaken on many oil palm estates (Hartemink, 2003; Ng et al., 2011), relatively little of this information has been analysed and published in the peer-reviewed literature. Agricultural management practices on perennial plantations have the potential to improve aspects of soil quality (such as nutrient availability, drainage and soil pH) but these are relatively rarely reported in the literature (Hartemink, 2003). Two of the key aspects of BMPs that may influence soil quality and soil fertility in oil palm plantations are tailored management of fertilisers, and the application of organic matter to the soil surface in the form of empty fruit bunches (EFB; a waste product from the milling of FFB), pruned palm fronds and compost.

Oil palm requires regular inputs of nutrients to maintain high yields following removal of nutrient-dense FFB, particularly where plantations are established on soils with low inherent fertility. As a result, application of inorganic fertilisers is generally required, and can form a major component of plantation expenditure (Rankine and Fairhurst, 1999; Goh and Teo, 2011). Oil palm plantations have potential for high nutrient fluxes and off-site loss of applied fertilisers (Comte et al., 2012). Over-application of nitrogenous fertilisers can lead to additional cost, as well as soil acidification, leaching of nutrients, generation of ozone at ground level, and potential increases in N_2O emissions (depending on application rate and soil type) (Omoti et al., 1983; Melling et al., 2007; Hewitt et al., 2009; Nelson et al., 2011). Soil acidification is a particular concern in oil palm; for example on permeable soils in a high rainfall zone of Papua New Guinea, soil pH in the upper 20 cm of soil declined between 0.52 and 0.96 pH units over four years, likely due to leaching of nitrate from ammonium-based fertiliser (Nelson et al., 2011). Key soil nutrients may decline over time where nutrient removal exceeds input (Hartemink, 2005). Sound fertiliser management in oil palm can help to maintain key soil nutrients such as P and K at appropriate levels (Ng et al., 2011).

Decomposition of pruned fronds can provide N, P, K and Mg to the soil (Rankine and Fairhurst, 1999), while EFB can replenish soil organic matter and provide inputs of N and K (Rankine and Fairhurst, 1999; Singh et al., 2010). Addition of organic materials has been suggested as a low-cost form of liming for cultivation of acidic tropical soils (Mokolobate and Haynes, 2002). The application of organic fertilisers in oil palm plantations is associated with an increase in soil pH, SOC and total N, increased exchangeable K, Ca and Mg, and decreased exchangeable Al (Chiew and Rahman, 2002; Bakar et al., 2011; Comte et al., 2013). Organic matter has a high cation exchange capacity (CEC), giving it an important role in the retention and supply of key macro- and micronutrient cations (Nelson et al. 2010). Among nine major first generation biofuels, oil palm was the most sustainable with respect to soil quality, based on the quantity of organic matter in the soil one year after application of crop residues (de Vries et al., 2010). BMPs in oil palm include management of organic as well as mineral fertilisers (Table S1 in online Supplementary material).

The dearth of detailed, published, field-based research on the influence of commercial oil palm management on soil properties makes it difficult to understand the relationships between soil quality and sustainable intensification of the oil palm system. Further, much of the existing field-based research on oil palm has been conducted at a small spatial scale, such as within fields or experimental plots. Here, we present research on soil properties from commercially-sized oil palm production blocks.

1.1 Objectives

The overall aim of this research is to assess whether the application of management practices designed primarily to increase yield in oil palm plantations also modify soil quality. Specifically, the objectives of this research are to: (1) determine changes in soil properties in areas under site-specific BMPs for oil palm and standard practices; and (2) assess whether change in important soil indicators over time can be attributed to differences in management practices between blocks managed using BMPs, and those managed using standard practices. The results of the research are used to identify potential opportunities to improve soil health and provision of ecosystem services from the application of best management practices in oil palm plantations.

2 Methods

2.1 Study sites

The study sites included three oil palm plantations in Sumatra and three in Kalimantan (Figure 1), representing major growing areas in Indonesia, the country with the largest area planted to oil palm. All six plantations fall within the Köppen climate classification Af (Equatorial Fully Humid) (Kottek et al., 2006). The plantations cover a range of soil types, topographic characteristics and total annual rainfall (Table 1). All plantations were managed within commercial production processes by collaborating oil palm plantation partners. Five collaborating partners were involved in the study; one of these groups managed two plantations. Management of the plantations followed a hierarchical structure typical for oil palm. The smallest unit of management is a ‘block’ (usually 25-30 ha); multiple blocks are grouped into a ‘division’ (500-1 000 ha), and several divisions form an ‘estate’ (typically 2 000 to 5 000 ha). Estates are grouped together to form plantations. The age of oil palm stands, the planting density and the overall site suitability for oil palm varied between and within the six study plantations (Table 2). The soils of the plantations are highly modified as they have been used for agricultural purposes for decades.

Figure 1: Location of study sites

Large squares represent the study sites. 1: North Sumatra 1 (NS1); 2: North Sumatra 2 (NS2); 3: South Sumatra (SS); 4: West Kalimantan (WK); 5: Central Kalimantan (CK); 6: East Kalimantan (EK). For full details of site characteristics see Tables 2 and 3

Table 1: Biophysical characteristics of field-trial plantations

Site no.	Province	Latitude, longitude	Mean annual rainfall (mm yr^{-1}) [a]	Mean annual temperature (°C) [a]	Water deficit status [b]	Dominant soil texture classes	Slope classification
1	North Sumatra	2° 59' N 99° 37' E	1923	26.7	No significant water stress	Sandy clay loam, coarse sandy loam	Mostly flat (0-4%), some undulating (4-12%) sections
2	North Sumatra	1° 4' N 100° 7' E	3072	26.4	No significant water stress	Clay, fine sandy loam, sandy clay, sandy clay loam	Mostly flat to gentle slope (0-4%), some undulating (4-12%) and hilly (24-38%) sections
3	South Sumatra	3° 46' S 104° 54' E	2782	27.1	Severe water deficit in many years	Clay, sandy clay loam	Flat to gentle slope (0-4%) in some areas, undulating (4-12%) in other sections
4	West Kalimantan	1° 25' N 109° 26' E	3080	26.6	No significant water stress	Fine sandy loam, loamy sand	Flat (0-4%) to undulating (4-12%)
5	Central Kalimantan	2° 40' S 111° 15' E	3045	26.8	Water deficit in some years	Coarse sandy loam, loamy coarse sand	Flat to gentle slope (0-4%)
6	East Kalimantan	0° 17' N 116° 11' E	2509	26.6	No significant water stress	Clay loam	Flat (0-4%) to undulating (12-24%) in some areas, hilly (24-38%) in places

Notes:

[a] Climatic variables calculated using long-term averages from WorldClim (Hijmans et al., 2005) by Rhebergen (2012).

[b] Water deficit calculated based on the method of Surre (1968) by author C. Donough (Donough et al., 2011; Rhebergen, 2012)

2.2 Experimental design and management practices

The study compared soil properties in blocks of oil palm managed under ‘best management practices’ (BMP) with blocks managed under ‘standard’ estate practices (denoted as REF or reference). Five pairs of blocks of at least 25 ha were selected for each of the six study sites, giving a total of 30 pairs of blocks (60 blocks in total). Paired BMP/REF blocks were situated in between one and five different estates within each plantation (Table 2). Where multiple estates were sampled within a plantation, the estates were located within approximately 30 km of each other (around one hour by road transport).

Table 2: Oil palm plantation site characteristics

Site no.	No. of estates sampled within plantation	Area (ha) sampled within plantation		Stand density range (palms ha^{-1}) within estates sampled		Stand age at beginning of field trial	Suitability class [b] for oil palm
		BMP [a]	REF [a]	BMP	REF		
1	5	266	281	121-140	136-143	5-12 years	S1
2	3	156	160	124-136	116-132	8-14 years	S2
3	2	259	260	127-137	128-138	15-18 years	S2
4	1	142	147	143	143	8-9 years	S2/3
5	3	124	121	112-138	128-141	8-9 years	S3
6	4	135	135	133-154	135-144	3-12 years	S2

Notes:

[a] BMP and REF denote the principle treatments in this research. BMP = Best Management Practice blocks. REF = reference blocks (i.e., standard management practices). See text for further detail.

[b] Land suitability class attributed by author C. Donough based on expert knowledge . S1 = highly suitable, S2 = moderately suitable, S2/3 = moderate to marginally suitable, S3 = marginally suitable

A paired block approach was taken due to the inherent site variability associated with sampling commercial plantations. Each pair comprised two adjacent, discrete blocks with similar soils and terrain. Where soil survey reports and maps were available, these were used for block selection in combination with an on-site inspection. Where soils data were not available, soils and terrain were assessed during the on-site inspection. Pairs of blocks were selected that were planted in the same year, with the same source of seeds, and with a similar management (especially fertilisation) and yield history. At least the preceding five years of historical data were considered, except in a few cases where the blocks were planted within the last few years.

The size of the blocks depended on the plantation; at most sites, the estates were systematically laid out, with blocks in regular rectangular shapes (typically 1 km long and 250-300 m wide). At the North Sumatra 1 (NS1) plantation, block sizes ranged between 35-79 ha, and most were irregularly shaped. This plantation was first established in 1911 as a rubber plantation and later converted to oil palm; as a result, blocks were not systematically laid out in rectangular units as is common in modern oil palm plantations. At the South Sumatra (SS) plantation (site 3), each block was 50 ha because this plantation combined four 25 ha blocks into a single management unit of 100 ha; half of the 100 ha block was assigned as BMP and the other half as REF.

In each selected pair of blocks the historically higher yielding block was assigned to 'standard' commercial management practices (denoted as REF blocks) and the other block was assigned to best management practices (denoted as BMP blocks). Often the difference in yield between the two blocks was very small. Management practice treatments were assigned in this way to aid eventual integration of BMPs into the commercial process through demonstration of the potential for BMPs to increase yield compared with standard plantation operating procedures. Average yields for BMP vs REF treatments in the six plantations are given in Table 3.

Table 3: Fresh fruit bunch (FFB) yield data for BMP and REF blocks in six plantations

Site no.	Mean FFB yield (t ha^{-1} $year^{-1}$) [a, b]			% yield difference field trial vs pre-project [c]	
	BMP	REF	Δ (BMP-REF)	BMP	REF
1	30.5	29.0	1.5	9%	0%
2	28.4	23.0	5.4	27%	-7%
3	23.7	18.9	4.8	2%	-19%
4	22.3	19.8	2.5	54%	39%
5	20.7	17.1	3.6	72%	31%
6	30.2	27.5	2.7	49%	30%

Notes:

[a] FFB yield data reported in Pasuquin et al. (2014) and provided by author C. Donough

[b] Total field trial duration was 48 months

[c] Pre-project yield data was collected over a variable number of months as follows: Site 1: 19 months; Site 2: 20 months; Site 3: 24 months; Site 4: 24 months; Site 5: 12 months; Site 6: 16 months.

Consideration of data on soils, terrain, yield, oil palm type and age, past management, rainfall, on-site observations and interviews with local management personnel, staff and workers were used to identify limitations to yield in each block and to define the BMPs most likely to increase yield. As all estates were commercial operations with the goal of improving yields, BMPs were block-specific as far as practical but were incorporated into each estate's commercial management procedures. Table 4 outlines the major differences in management practices between BMP and REF blocks, including the type and placement of fertilisers. In BMP blocks all fertilisers, except borate, were applied on the frond heaps. If urea was used as a nitrogen source, it was applied at the outer edge of the weeded palm circles directly onto the soil. In REF blocks placement of fertilisers followed companies' standard operating procedures, most of which applied fertilisers over the soil surface in the weeded circles.

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Table 4: Management practices in BMP and REF blocks

	Plantation and treatment											
	1 North Sumatra 1		2 North Sumatra 2		3 South Sumatra		4 West Kalimantan		5 Central Kalimantan		6 East Kalimantan	
	BMP	REF	BMP	REF	BMP	REF	BMP	REF	BMP	REF	BMP	REF
Management practice												
Harvesting [a]												
Mean harvest interval (days)	7	10	7	12	7	11	8	13	7	11	7	11
Mean number of harvest rounds (harvests year^{-1})	51	37	49	30	50	32	49	31	51	33	52	34
Mean number of harvest days (man days year^{-1})	956	930	525	396	921	674	563	495	296	287	603	464
Fertiliser type and placement												
Fertilisers used [b]	N: Urea, AS; P: RP, TSP; K: MOP; Mg: GML, Kies; B: Borate	N: Urea; P: RP; K: MOP; Mg: Kies; B: Borate	N: Urea, AS; P: RP, TSP; K: MOP; Mg: GML, Kies; B: Borate	N: Urea; P: RP; K: MOP; Mg: Kies; B: Borate	N: Urea, AS; P: RP, TSP; K: MOP; Mg: GML, Kies; B: Borate	N: Urea; P: RP; K: MOP; Mg: Kies; B: Borate	N: Urea, AS; P: RP, TSP; K: MOP; Mg: GML, Kies; B: Borate	N: Urea; P: RP; K: MOP; Mg: Kies; B: Borate	N: Urea, AS; P: RP, TSP; K: MOP; Mg: GML, Kies; B: Borate	N: Urea; P: RP; K: MOP; Mg: Kies; B: Borate	N: Urea, AS; P: RP, TSP; K: MOP; Mg: GML, Kies; B: Borate	N: Urea; P: RP; K: MOP; Mg: Kies; B: Borate
Fertiliser placement - Urea, Borate	Palm circles	Palm circles	Palm circles	Palm circles	Palm circles	Palm circles	Palm circles	Palm circles	Palm circles	Palm circles	Palm circles	Palm circles
Fertiliser placement - other fertilisers	Frond heaps	Palm circles	Frond heaps	Palm circles	Frond heaps	Frond heaps	Frond heaps	Frond heaps	Frond heaps	Palm circles	Frond heaps	Frond heaps
Frond heap location												
Between palms in the row	Yes	No	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
In inter-row area	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Empty Fruit Bunch (EFB) application												
Use of EFBs	Some blocks	-	Some blocks	-	Some blocks	-	Some blocks	-	All blocks	-	Some blocks	-
Location of EFB application	Inter-row area	-	Inter-row area	-	Inter-row area	-	Inter-row area	-	Inter-row area	-	Inter-row area	-
Additional BMPs												
Harvest platforms (on slopes)	-	-	Some blocks	-	Some blocks	-	-	-	-	-	Some blocks	-
Additional drainage	Some blocks	-	Some blocks	-	-	-	Some blocks	-	-	-	Some blocks	-
Felling of unproductive palms	Some blocks	-	Some blocks	-	Some blocks	-	Some blocks	-	Some blocks	-	Some blocks	-
Extra weeding (woody weeds)	Some blocks	-	Some blocks	-	Some blocks	-	Some blocks	-	Some blocks	-	-	-
Extra weeding (trunk epiphytes)	Some blocks	-	Some blocks	-	Some blocks	-	Some blocks	-	-	-	-	-
Felling of diseased palms (Ganoderma)	Some blocks	-	-	-	-	-	-	-	-	-	-	-
Insect pest control	Some blocks	-	Some blocks	-	Some blocks	-	-	-	-	-	-	-
Overall standard of BMP implementation (BMP blocks) or SEP implementation (REF blocks)												
Implementation quality [c]	Good	Good	Good	Good	Fair	Poor	Fair	Fair	Good	Good	Good	Good

Notes:

[a] average values are computed over over 48 months

[b] AS = ammonium sulphate; RP = rock phosphate; TSP = triple superphosphate; MOP = muriate of potash; Kies = kieserite; GML = ground magnesium limestone

[c] As assessed by IPNI agronomists based on regular site visits

The field trial ran for four years at each plantation; the start and end date varied among plantations (Table 5). Plantation companies were responsible for day-to-day management of REF and BMP blocks, with input and advice from consultant agronomists associated with IPNI on BMPs. BMPs to be implemented were discussed and agreed with senior management and at the operational level following site assessments and block selection. A timeframe was agreed for BMP implementation, typically for BMPs to be fully in place at the end of 12 months. BMP implementation took longer at some sites, and could vary between estates within study sites. During BMP implementation, an agronomist from IPNI visited three or four times a year to assess status and progress. Table 4 includes an assessment of the overall standard of management practice implementation.

Table 5: Timing of field trials for plantation sites

Site no.	Province	Commencement of field trial	End of field trial	Months elapsed between initial and final soil sampling [a]
1	North Sumatra	August 2006	July 2010	48
2	North Sumatra	September 2006	August 2010	48
3	South Sumatra	December 2006	January 2011	48
4	West Kalimantan	March 2007	February 2011	46
5	Central Kalimantan	June 2007	May 2011	49
6	East Kalimantan	July 2007	June 2011	48

Notes:

[a] Months elapsed between initial and final soil sampling are not exactly the same as the start and end dates of the field trial. Initial soil samples were taken prior to commencement of the field trial, as follows: Sites 1 and 2 - one month prior; Site 3, 5 and 6 - two months prior; Site 4 - same month. Final soil samples were taken at the conclusion of the field trial, except: Site 3, 4 and 6 - one month prior; Site 5: two months after.

Estimated fertiliser budgets were compiled for the blocks included in the study using plantation data on rates of fertiliser addition and application of EFB and compost. Data for Site 2 (North Sumatra 2) are not available. Table 6 details mean total applications of organic and inorganic sources of N, P and K over the four years of the study. Organic nutrient additions were estimated based on values in the literature for EFB and compost (Rankine and Fairhurst, 1999; Fairhurst and Härdter, 2003; Corley and Tinker, 2007). Total nutrient inputs over four years from inorganic fertilisers applied in the BMP blocks ranged from 414 kg ha^{-1} to 586 kg ha^{-1} for N, 68 kg ha^{-1} to 183 kg ha^{-1} for P, and from 430 kg ha^{-1} to 881 kg ha^{-1} for K (Table 6). Mulching with EFB was implemented only in BMP blocks at Sites 3, 4, 5 and 6 at a target rate of 40 t ha^{-1}, and in some REF blocks at Sites 4 and 5 (typically at a lower rate). The target rate of 40 t ha^{-1} was not always achieved for operational reasons. In Sites 5 and 6, EFB application was most complete; at other sites, EFB application was undertaken only in BMP blocks close to palm oil mills. Records of EFB applications on blocks were kept; Table 6 includes details of estimated amounts of organic N, P and K contained in EFBs and compost applied to the soil surface; the release of nutrients from these organic sources occurred gradually over several months.

Standard procedure for frond management was followed in BMP blocks (Rankine and Fairhurst, 1999). Surplus fronds (i.e. old, dead, damaged or diseased) were removed. Sufficient fronds were retained to provide an optimal leaf area index (LAI) throughout the life of the palm (for oil palm, optimal LAI is between 5 and 6). Old fronds were removed from beneath the lowest harvestable fruit bunch. For palms less than seven years old, three fronds were retained below the lowest harvestable fruit bunch, and lower fronds removed. For palms aged seven to 12 years, two fronds were retained, and for palms of 12 years or more, only one frond was retained below the lowest harvestable fruit bunch. Additionally, fronds that impeded harvesting were also removed. Removed fronds were stacked in frond stacks in between rows of oil palms (see section 2.3 for a description of the layout of the palm rows and frond stacks).

2.3 Field sampling and laboratory analysis

Soil samples were collected at the beginning and at the end of the field trial for each estate, between 2006 and 2011 (Table 5). Sample points were assigned using a fixed grid sampling scheme that samples approximately 1% of the palms in a block (see Appendix 3 in Fairhurst and Härdter, 2003 for further detail). Oil palms are typically planted at a distance of 9 m between palms (approx. 143 palms ha^{-1}) in an equilateral triangle arrangement (i.e. rows are offset). The first palm sampled was usually the fifth palm in the fifth row, with every tenth palm in that row included in the sample. The next row sampled was 10 rows from the first row sampled. In a 25 ha block, there were at least 30 sample points, and at least 36 sample points in a 30 ha block. Sampled palms were permanently marked. At each sample point, soil samples from two locations were collected: (1) at a distance of one metre from the base of the oil palm (i.e. within the weeded circle of 1.5-2 m surrounding each palm); and (2) underneath the palm frond heap placed in the inter-row space nearest the sampled palm. Palm frond heaps are distributed at irregular intervals between rows of oil palms. Most of the feeder roots are under the frond heaps, and nutrients accumulate there from frond decomposition. Soil samples were collected from two depths at each sampling location: 0-20 cm, and 20-40 cm. Samples were collected with a Dutch auger with a 20 cm head. The litter layer was not sampled; there is very little litter within weeded circles. Due to variation in oil palm density and block size, a variable number of samples (typically between 30-36 samples) for each combination of depth and location were collected from each block.

Table 6: N, P and K application in BMP and REF blocks from inorganic and organic fertiliser sources over the four years of the field trial

	Nutrient inputs in kg ha^{-1} over four years [a]

Treatment and nutrient source [b, c]	Site 1 (NS1 [d])	Site 3 (SS)	Site 4 (WK)	Site 5 (CK)	Site 6 (EK)
BMP					
Inorganic N	463	586	558	478	414
Inorganic P	183	68	84	152	136
Inorganic K	721	881	884	430	600
Organic N	-	448	150	790	877
Organic P	-	54	18	95	137
Organic K	-	1 348	453	2 376	2 416
BMP Total N	463	1 034	708	1 268	1 291
BMP Total P	183	122	102	247	273
BMP Total K	721	2 229	1 337	2 806	3 016
REF					
Inorganic N	469	583	552	483	404
Inorganic P	79	68	80	153	132
Inorganic K	621	882	924	435	571
Organic N	-	-	32	18	382
Organic P	-	-	4	2	115
Organic K	-	-	97	55	655
REF Total N	469	583	585	501	785
REF Total P	79	68	84	155	246
REF Total K	621	882	1 021	489	1 226

Notes:

[a] Average values from 5 blocks in each treatment for the 4-year project duration. Stand density ranged between 112 and 154 palms ha^{-1} (see Table 3).

[b] BMP = Best Management Practices; REF = Estate Management Practice; I = Inorganic nutrient source, i.e. various commercial fertilisers; O = Organic nutrient source, i.e. compost or empty fruit bunches (EFB); T = Total i.e. organic + inorganic; N = nitrogen; P = phosphorus; K = potassium.

[c] Values for organic nutrients (N, P, K) are estimates based on the mass of EFB and/or compost applied, using values from the literature (Rankine and Fairhurst, 1999a; Fairhurst and Härdter, 2003; Corley and Tinker, 2007).

[d] Site names: NS1 = North Sumatra 1; SS = South Sumatra; WK = West Kalimantan; CK = Central Kalimantan; EK = East Kalimantan.

Soil samples were bulked for analysis. Soils were air-dried, hand-ground and quartered to reduce the total mass of soil to 500 g for each bulk sample. Half of this sample was sent for analysis, and the other half used for archival purposes. Soils were analysed at a commercial laboratory (Asian Agri group laboratory, at the research centre in Bahilang Estate, Tebing Tinggi, North Sumatra) for a range of soil properties, including: soil texture (using USDA soil classification based on % coarse sand, % fine sand, % clay and % silt); soil pH (KCl solution); % total nitrogen (Kjeldahl digestion); % SOC (Walkley-Black method); available phosphorus (Bray II method); and CEC (pH 7.0; the standard operating procedure used in recognised laboratories that serve the oil palm industry in Indonesia). Additional properties measured included: exchangeable K (flame photometry) and exchangeable Ca and Mg (atomic absorption spectrophotometer).

2.4 Statistical analysis

Summary statistics and graphics were prepared for soil properties in the two treatments (BMP and REF) before and after the initiation of the trial. Summary information was prepared at multiple levels: for all plantations combined, for each plantation, for each estate, and for paired blocks. Soil pH values were converted to H^+ concentrations for calculation of mean soil pH values across multiple sampling locations. Understanding variation at different spatial scales was important due to the variation in biophysical site characteristics that is inherent in field trials conducted on commercial operations where site conditions cannot be controlled.

Changes in individual soil properties between BMP and REF treatments before and after the field trial were assessed using split-plot ANOVA with the software SPSS (IBM, 2012). The difference in measured soil properties between the beginning and completion of the trial was used as the input variable. Within SPSS, the General Linear Module (GLM) and Mixed Model module were used to assess whether there were differences in the degree of change in soil parameters between the beginning and end of the trial between the two treatments BMP and REF (i.e. main factor) for all combinations of soil sampling depth and soil sample location. Treatment, soil depth and soil sample location were incorporated into the model as fixed effects, with paired BMP-REF blocks as random effects. All interactions were assessed. For many of the variables assessed, the data were not normally distributed, and variance of the residuals was often heterogeneous. However, the balanced split-plot ANOVA is robust to these violations of assumptions where p-values are either very large or very small (compared with $\alpha = 0.05$). In cases where the returned p-value for the main factor (i.e. BMP vs REF) was between 0.01 and 0.1, the non-parametric Wilcoxon's Signed Rank test was used to test each combination of soil sampling depth and soil sampling location individually.

3 Results

3.1 Summary data

The mean values (and standard errors of the means) for soil parameters before and after the trial for BMP and REF treatments are represented in Figure 2. Data for the majority of variables were not normally distributed, with most variables positively skewed. Of the main soil properties assessed, soil pH and % SOC displayed increasing trends over time in both BMP and REF treatments (Figure 2). However, the few cases where values decreased, this tended to occur in the weeded circle in the upper 20 cm of soil in both BMP and REF treatments (see for example Figure 2 for total N, available P, CEC, exchangeable Mg and Ca). Values for most variables tended to be lower at greater soil depths.

Soil pH was acidic, with values ranging between 3.0 and 5.6. For all comparisons, mean pH (using the average of H^+ concentration) increased by an average of between 0.10 and 0.22 units over the four years of the study (n=30 for all comparisons). Median pH values for all comparisons increased by between 0.3 and 0.45 units (Figure 2). The magnitude of change in mean and median pH before and after the field trial was similar for all comparisons. The greatest increase in median pH were seen beneath the frond stack at 0-20 cm soil depth in BMP, while smaller increases in median pH were found beneath weeded circles at 20-40 cm for both BMP and REF.

Total N ranged between 0.02 and 0.39%, with higher mean values at 0-20 cm depth (mean % total N = 0.16±0.005 for 0-20 cm depth and 0.09±0.003 for 20-40 cm depth, averaged across BMP, REF, frond stack and weeded circle; standard error calculated for *n*=240). Few clear patterns emerged for the change in % total N over time at 0-20 cm depth, but an increase of between 0.01 and 0.02% was noted at depths of 20-40 cm.

SOC measurements ranged between 0.17 and 5.55%, with mean values at 20-40 cm depth approximately half that found at 0-20 cm depth. SOC increased across all comparisons with time (Before: 1.31%±0.06 (standard error; *n*=240); and After: 1.60%±0.07 (standard error; *n*=240). Standard errors of the mean overlapped for comparisons in the upper 20 cm of soil, but there was minimal overlap for comparisons at 20-40 cm soil depth (Figure 2). SOC after four years tended to be slightly greater beneath the frond stack than within the weeded circle across most comparisons. The greatest change was beneath the weeded circle in the REF treatment at 20-40 cm (mean difference: +0.48% SOC between Before and After samples; *n*=30).

The available P covered a wide range of values between 0.3 and 99.6 mg kg^{-1}. The highest values were in the upper 20 cm of soil in the weeded circle (means ranged between 34.6±6.56 mg kg^{-1} in the BMP treatment at the start of the study to 22.7±3.44 mg kg^{-1} in the REF treatment at the end of the study). Available P in 0-20 cm soil depth in the weeded circle was typically around three to five times higher than for 20-40 cm soil depths, and for 0-20 cm soil depth beneath the frond stack. Available P appeared to decrease over time from 0-20 cm soil within the weeded circles, but increase over time for 0-20 cm soil beneath the frond stacks, and 20-40 cm soil beneath the weeded circles and frond stacks.

CEC values were similar at the beginning and conclusion of the study for many of the sampled combinations, typically around 2 meq 100 g^{-1} soil lower at depths of 20-40 cm compared with 0-20 cm. Exchangeable K increased over the study, with clear differences in concentration for all comparisons except for 0-20 cm depth beneath the weeded circle in the BMP treatment; mean values often being doubled over time. Small increases with time in exchangeable Ca and Mg were noted for all treatments aside from beneath weeded circles at 0-20 cm depth for both BMP and REF; however standard errors of the mean often overlapped for these soil properties.

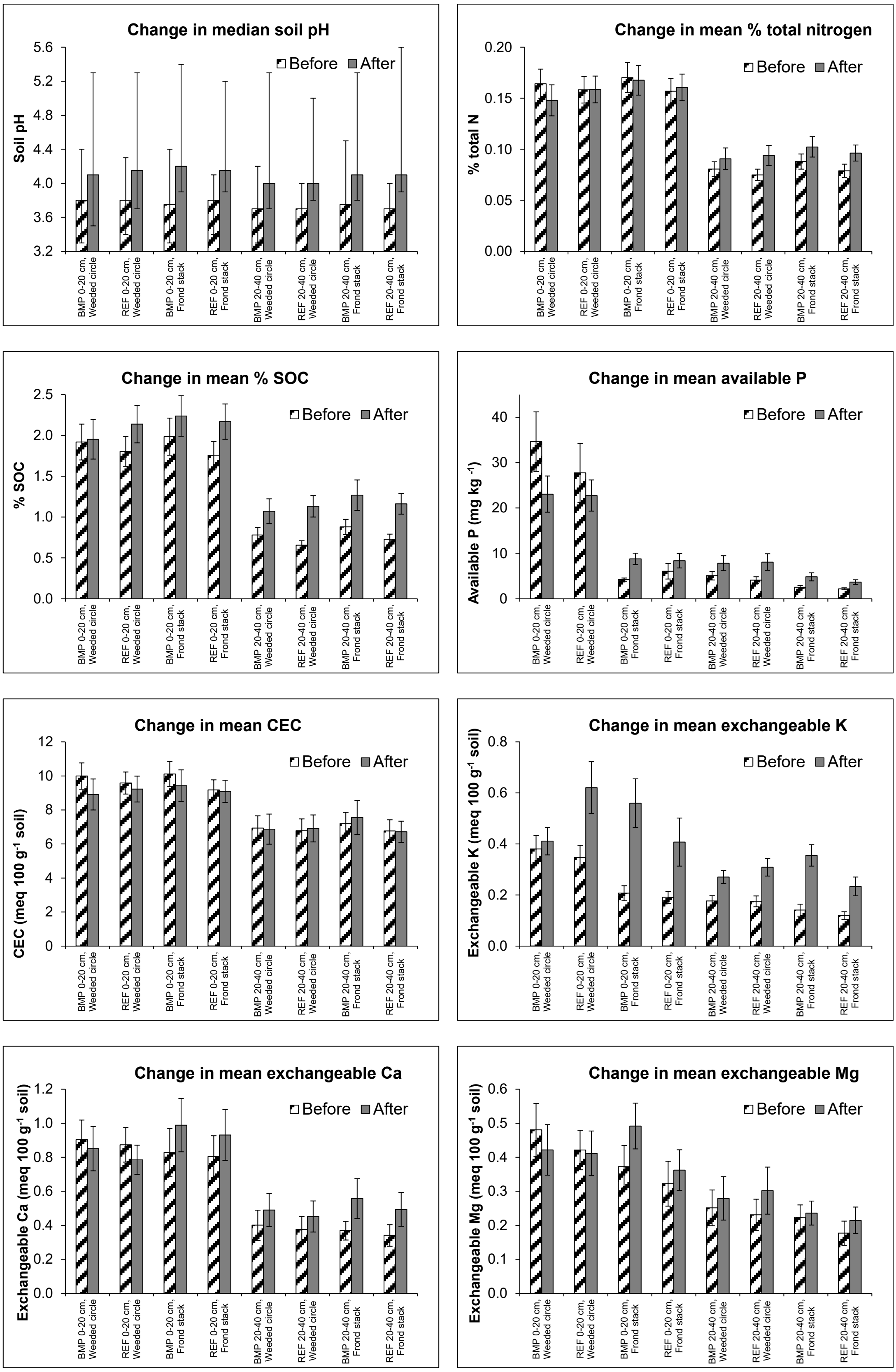

Figure 2: Change in mean or median values of eight soil variables for each unique comparison of management, soil depth and soil sample location

All values shown are means, except for soil pH where the median is depicted. n = 30 for each data point. Error bars represent standard error, except for soil pH where error bars represent range. 'Before' refers to measurements taken at the commencement of the field trial. 'After' measurements were taken four years later at the conclusion of the trial.

Some subtle trends were apparent when comparing values beneath weeded circles and frond heaps for BMP and REF treatments at the conclusion of the field trial. For a number of comparisons (e.g. soil pH, % total N, % SOC, CEC, exchangeable K), values were slightly more favourable in REF than in BMP treatments beneath weeded circles, at both soil depths. However, under the frond heaps, values for these variables were either comparable, or slightly higher for BMP than for REF.

Values for many of the soil properties varied depending on the estate and/or block under comparison. Figure 3 illustrates the variation in mean % SOC for one subset of treatments (in this case, measurements beneath the frond stack at depths of 0-20 cm) between islands and estates. In some estates variability among blocks within the estates was relatively large (for example, Estates 2 and 4), whereas others showed relatively little variability (such as Estates 3 and 6). Figure 3 reinforces the observation that both BMP and REF treatments showed a general trend of increasing % organic C over time, but with different magnitudes in different locations.

3.2 Differences in the magnitude of change in soil properties between treatments

None of the variables showed a significant, consistent effect of treatment on the degree of change in soil properties between the beginning and the end of the field trial (Table 7). Split-plot ANOVA returned a *p*-value for the effect of treatment on % SOC of 0.079. The influence of treatment on % SOC was significant ($p<0.01$) only for samples taken from beneath the weeded circle at 20-40 cm depth while the influence of treatment on total N showed no significant differences across any of the four comparisons.

Whether samples were taken from beneath the weeded circle or frond stack was significant ($p<0.01$) for exchangeable Ca; in this case, the magnitude of change was greater beneath the frond stack. The influence of soil sample location on soil pH indicated significant differences ($p<0.05$) for both BMP and REF at depths of 0-20 cm; in both cases the magnitude of increase in pH was greater beneath the frond stack than from within the weeded circle.

With respect to soil depth, a significant influence ($p<0.01$) was demonstrated for % total N only; the change was greater for samples from 20-40 cm than from samples taken between 0-20 cm. SOC did not return any significant results. CEC decreased more at 0-20 cm than at 20-40 cm for BMP blocks beneath the weeded circles only. For the same subset of comparison, exchangeable K increased more at 20-40 cm than at 0-20 cm. Exchangeable Ca also increased more at 20-40 cm than at 0-20 cm for REF beneath the weeded circles.

High variability among the 30 pairs of blocks in the study was demonstrated by the significant influence of the random effect 'site pair' in all split-plot ANOVAs ($p<0.05$ for all comparisons). As was the case for % SOC (Figure 3), variability for some soil properties was high within some plantations, but less so within others.

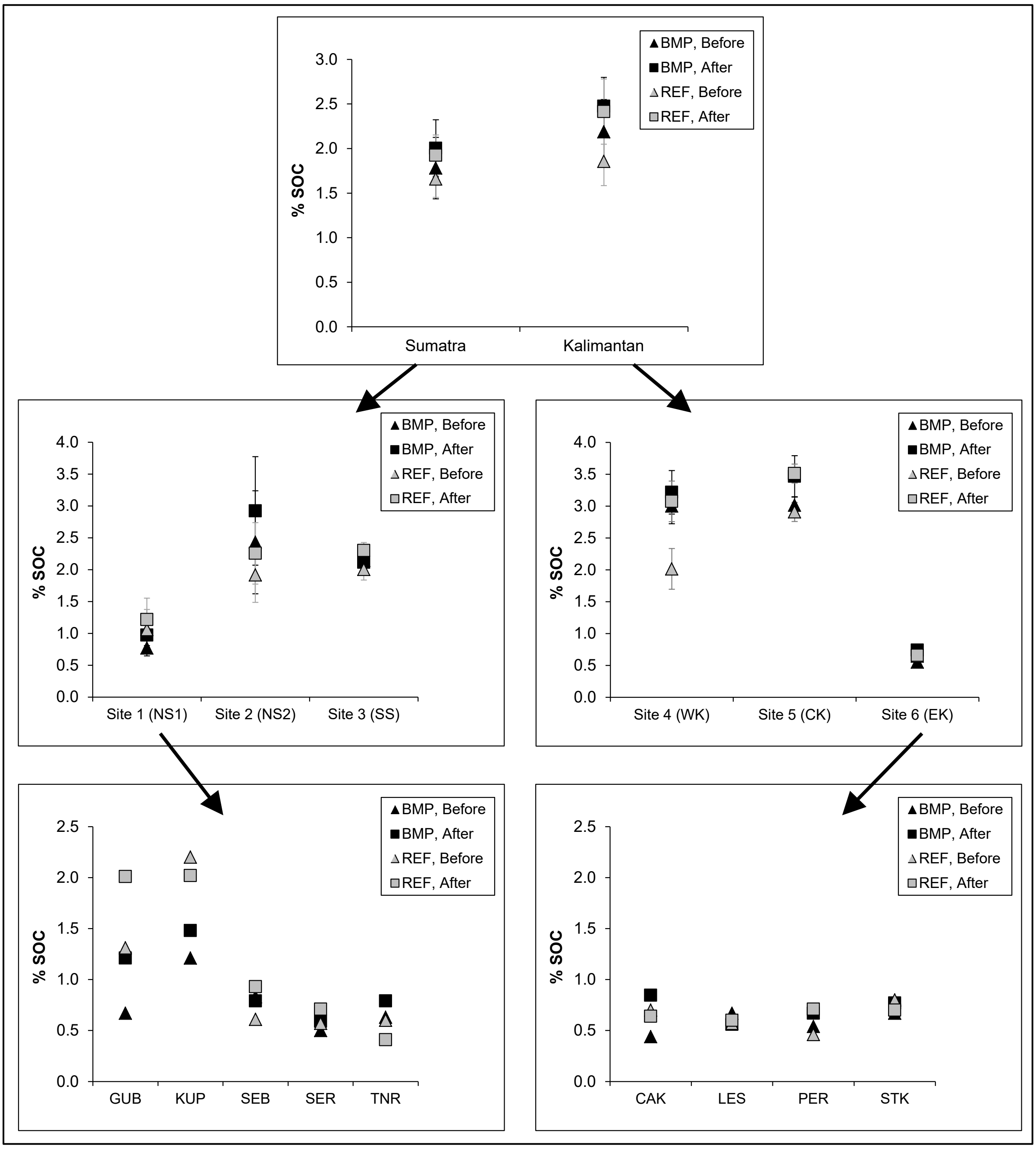

Figure 3: Example of differences in mean % SOC between islands and estates

The topmost figure illustrates mean values for % SOC measured from beneath frond stacks, at depths of 0-20 cm (n=15 for each point). The middle figures illustrate mean values for the variable at each of the six estates in the study (n=5 for each point). Error bars denote standard error. The lower figures show values for the variable in paired blocks within the estate NS1 (at left) and estate EK (at right) (all paired blocks are n=1 except for CAK in Site 6, where n=2).

Table 7: Results of split-plot ANOVA for changes in all soil properties

		Significance for each variable [a]							
Factors	**Levels**	**Δ Soil pH**	**Δ %SOC**	**Δ Total N**	**Δ Avail. P**	**Δ CEC**	**Δ Exch. K**	**Δ Exch. Mg**	**Δ Exch. Ca**
Management	2	NS [b]	$0.01 \le p \le 0.1$	$0.01 \le p \le 0.1$	NS	NS	NS	NS	NS
Sample location	2	$0.01 \le p \le 0.1$	NS	NS	$0.01 \le p \le 0.1$	NS	$0.01 \le p \le 0.1$	$0.01 \le p \le 0.1$	**$p < 0.01$** [e]
Soil depth	2	NS	$0.01 \le p \le 0.1$	**$p < 0.01$** [d]	$0.01 \le p \le 0.1$	$0.01 \le p \le 0.1$	$0.01 \le p \le 0.1$	NS	$0.01 \le p \le 0.1$
Interaction terms [c]									
Management × Sample location		NS	NS	NS	NS	NS	$p < 0.01$	NS	NS
Management × Soil depth		NS	NS	NS	NS	NS	NS	NS	NS
Sample location × soil depth		NS	NS	NS	$p < 0.01$	NS	NS	$p < 0.01$	NS
Management × sample location × soil depth		NS	NS	NS	NS	NS	NS	NS	NS
Results of Wilcoxon's signed rank tests where undertaken [f]									
Management									
Weeded circle, 0-20 cm soil depth			NS	NS					
Weeded circle, 20-40 cm soil depth			**$p < 0.05$**	NS					
Frond stack, 0-20 cm soil depth			NS	NS					
Frond stack, 20-40 cm soil depth			NS	NS					
Sample location									
BMP, 0-20 cm soil depth		**$p < 0.05$**							
BMP, 20-40 cm soil depth		NS							
REF, 0-20 cm soil depth		**$p < 0.05$**							
REF, 20-40 cm soil depth		NS							
Soil depth									
BMP, weeded circle			NS			**$p < 0.05$**	**$p < 0.05$**		NS
BMP, frond stack			NS			NS	NS		NS
REF, weeded circle			NS			NS	NS		**$p < 0.05$**
REF, frond stack			NS			NS	NS		NS

Notes:

[a] Where p-values were between 0.01 and 0.1, Wilcoxon's signed rank test was used to compare among the four combinations of the other two factors.

[b] NS = Not significant, $p > 0.1$

[c] Where interaction terms were significant, pairwise testing was not undertaken to detect differences in variables between factors

[d] Change in total N was greater for 20-40 cm (increasing by 0.015%) than for 0-20 cm (remained almost the same)

[e] Change in exchangeable Ca was greater under the frond stack (increasing by 0.16 units) than under the weeded circles (remained almost the same).

[f] Wilcoxon signed rank tests results: Management comparison - %SOC increased more in REF than in BMP; Sample location comparison - pH increased more beneath the frond stack than beneath the weeded circles; Soil depth comparison - CEC decreased more at 0-20 cm than at 20-40 cm; exchangeable K increased more at 20-40 cm than at 0-20 cm; exchangeable Ca increased more at 20-40 cm than at 0-20 cm. Note $p < 0.05$ was used to denote significance of Wilcoxon's signed rank test.

4 Discussion

There are three key findings from this research. First, contrary to expectations, there were no clear differences in the degree of change in soil properties between BMP blocks and REF blocks after four years. Second, there were consistent changes in a number of soil properties over time noted for both BMP and REF blocks, with many soil quality indicators improving over the four years between the beginning and end of the field trial. These changes were particularly notable for soil pH, % SOC, exchangeable K, and to a lesser degree, total N. Finally, some of the key nutrients decreased within the upper soil beneath the weeded circles (e.g. available P, exchangeable Mg and Ca), perhaps indicating a need for augmented quantities of these nutrients. The first two key findings are discussed in Section 4.1., followed by discussion of the implications for nutrient management and other agricultural management practices in oil palm plantations.

4.1 Impact of oil palm management practices on measured soil quality indicators

There were no consistent, clear differences in changes in the measured soil quality parameters over time between blocks managed under BMP compared with REF. This was an unexpected finding, given that yield was greater in the BMP blocks than in the REF blocks, with the greatest difference occurring after four years (Pasuquin et al., 2014). Further, intensification is often associated with a reduction in a number of indicators of soil quality, which was not noted here. The lack of observable differences between BMP and REF blocks may be attributable to a number of reasons, including: unaccounted for high variation between paired blocks; overlap of management practices between BMP and REF blocks (as reported in Oberthür et al. (2013), some estate managers may have adopted elements of BMPs in blocks managed under standard estate conditions); exclusion of soil quality indicators that might have shown differences between BMP and REF blocks; or poor correlation between soil quality indicators and yield. Although there were no clear differences in soil quality indicators between BMP and REF blocks, there were important changes in soil properties in many locations over the four trial, particularly with respect to soil pH and SOC. While the magnitude of change differed among individual estates and plantations sampled, the direction of change was generally consistent over time. The results provide evidence that oil palm cultivation is not necessarily associated with a decline in soil pH, nor with a loss of SOC in well-managed mature oil palm plantations.Although soil pH measurements prior to establishment of oil palm are not available for the studied sites, they are very likely to have been acidic (for example, Tripathi et al. (2012) report soil pH values in water of between 3.60 and 4.50 for similar, forested terrain in Malaysia).

Oil palm is often cultivated on acidic soils with low buffering capacities, a situation which can be further exacerbated by the application of mineral fertilisers, high rainfall and leaching (Nelson et al., 2011; Ng et al., 2011; Comte et al., 2013). Application of organic matter and efficient application of nitrogenous fertilisers can help alleviate soil acidification in oil palm (Nelson et al., 2010). The increase in soil pH noted in our study may have been related to the application of organic materials to the soil surface, such as empty fruit bunches in some BMP blocks and palm fronds in all blocks. Indeed, a greater increase in soil pH was noted beneath the frond stacks, where abundant organic material was applied, than beneath the weeded circles. Bakar et al. (2011) also noted increases in soil pH values in oil palm following long-term application of organic amendments. Similarly, Comte et al. (2013) reported that soil pH tended to be higher in oil palm blocks where organic fertilisers were the dominant form of nutrient application than in those blocks where predominantly mineral fertilisers were used.

The mechanism by which an increase in soil pH could occur following application of organic materials was not assessed in this research. Potential mechanisms identified in a review paper (Haynes and Mokolobate, 2001) include oxidation of organic acid anions in residues, ammonification of organic N in residues, and specific adsorption of organic molecules produced during decomposition of residues.

Mean values for % SOC reported in this study are comparable with those recorded by Bakar et al. (2011) in Malaysia, but less than those reported by Comte et al. (2013) in a Sumatran plantation. Soil organic carbon showed a clear increasing trend (average of 3 g kg^{-1} total SOC over the field trial). The increase in SOC across all comparisons may be related to the surface application of EFB and palm fronds. While EFB were typically applied at higher rates in BMP blocks than in REF blocks (at around 40 t ha^{-1} $year^{-1}$ in blocks, equivalent to approximately 300 kg $palm^{-1}$ $year^{-1}$), pruned palm fronds were present in both types of blocks, stacked between rows of palms. The increase in SOC was notable even beneath the weeded circles surrounding individual palms, where inputs of organic matter are typically lower than in inter-row areas (Ng et al., 2011), but where root activity tends to be highest (Nelson et al., 2006). Increased SOC in oil palm plantations may have other beneficial effects on soil quality that were not assessed in this study, such as changes in water holding capacity, bulk density, soil aggregation, microbial activity and soil biodiversity. Further research on the relationships between improved SOC and oil palm yield could encourage greater application of organic residues in oil palm plantations. Cost-benefit data on the application of EFB as mulch or as a nutrient source, versus disposal as a waste product could be particularly useful, given that organic residues are typically only applied in blocks that are near or adjacent to oil palm mills (Bakar et al., 2011).

Limited information exists on carbon cycling and storage within established oil palm plantations. Mature oil palm plantations can sequester carbon in root biomass over the short term, although SOC and microbial biomass may be in equilibrium (Smith et al., 2012). Where above-ground biomass is burnt as part of plantation management, an overall loss of SOC can occur (Ng et al., 2011). Our results indicate that SOC is not necessarily depleted by oil palm cultivation in mature oil palm stands, and may actually increase over the short time period assessed (four years). Longer-term data, ideally throughout the 20-25 year growing cycle from initial planting to replanting, would be needed to confirm the extent to which BMPs can actively increase the potential for soil carbon sequestration in land under oil palm cultivation. Additionally, information on the pools and forms of SOC in the soil (labile pools including surface plant residue, buried plant residue and particulate organic matter, stable pools such as humus, and recalcitrant pools such as charcoal and other forms of resistant organic carbon) (Stockmann et al., 2013) are needed to evaluate the longer-term soil carbon sequestration potential in oil palm plantations managed under BMPs. Soil bulk density data are also required to calculate soil carbon stocks under different management regimes. The influence of management practices on soil carbon dynamics and nutrient cycling, especially in relation to the initial and operating conditions under which oil palm plantations can act as a net source or sink of greenhouse gas emissions such as CO_2 and N_2O, remains poorly understood (e.g.

Melling et al., 2007; Crutzen et al., 2008; Nair et al., 2011; Carlson et al., 2012; Khasanah et al., 2012; Smith et al., 2012).

4.2 Nutrient management in oil palm plantations

BMP practices included fertiliser applications tailored to individual blocks, which resulted in them receiving greater nutrient input than REF blocks, mainly due to the addition of organic nutrients from empty fruit bunches (Table 7). However, the soil nutrient values generally do not reflect these treatment differences after four years. For instance, although all comparisons reflected consistently higher values for exchangeable K in the soil at the end of the field trial (Figure 2), there were no significant differences in the degree of change in exchangeable K between BMP and REF treatments, despite the fact that BMP blocks received from 16% (Site 1) to 450% (Site 4) more K over the four years of the trial. Total fresh fruit bunch yield was greater in BMP than in REF treatments (Table 3), which is likely to account for some uptake of additional K applied. Leaf analysis undertaken on the same blocks indicated a gradual increase over time in mean leaf K content in BMP blocks compared with REF blocks (Pasuquin et al., 2014).

Our results lend support to the notion that soil nutrient status is a poor indicator or predictor of oil palm yield, at least for the time-scales assessed in this research. For example, the higher levels of exchangeable K present in REF blocks after the field trial in the upper soil beneath the weeded circle were not associated with greater mean yields in REF. Available P values were similar in BMP and REF, but yields were greater in BMP. Available P values were depleted over time in the weeded circle in both REF and BMP. Given that the higher inputs of N, P and K to BMP blocks are not clearly reflected in soil analyses, further research is needed to ascertain the pathways by which the additional nutrients are taken up by plants (through increased yield or increased growth), or lost from the site through leaching or other pathways. A detailed nutrient budget would assist in interpreting some of the results seen here, and help ascertain the efficiency of nutrient input through the fertiliser regimes used. Sufficiently precise nutrient data were not available to produce such a budget for this study. High rainfall and coarse textured soils at some of the sites may lead to greater losses of applied nutrients.

Where changes in soil nutrient status were significant, they tended to be greater beneath frond stacks, and at 20-40 cm rather than 0-20 cm (e.g. significant differences for total N, exchangeable Ca and K) (Table 7). In the majority of estates, most fertilisers aside from urea and borate were applied to the frond stack (Table 4), which may account for the increase in soil nutrient parameters in this area. Similarly, the few negative changes in soil quality parameters observed over time occurred within the weeded circle (e.g. total P, exchangeable Mg, CEC). In commercial oil palm plantations arranged in a similar fashion to the estates sampled here, oil palm root activity and water uptake tends to be greatest in the weeded circle immediately surrounding each palm, with a decrease in activity and water uptake in the zone between the weeded circle and the frond pile, and a secondary increase in activity beneath the frond pile (Nelson et al., 2006). Root mass tends to decrease sharply with depth, with the greatest root mass concentrated in the upper 30 cm of soil (Nelson et al., 2006). Hence, the zones expected to have greatest root activity and nutrient uptake (beneath the weeded circle in the upper soil layer) experienced less positive change than zones that are likely have lower root activity. The reasons for this are unclear, but may be related to increased uptake of nutrients within weeded circles compared with beneath frond piles, or potentially higher rates of loss of applied fertiliser in weeded circles, where permeability and ground cover may be lowest. Further research on root density and root mass in BMP and REF over time, and in the different sections of the plantation (e.g. weeded circle, frond stack) would help elucidate whether the patterns of root activity noted by Nelson et al. (2006) also hold for the studied plantations.

Values for key nutrients such as exchangeable K and available P were highly variable in time and space. Prior to the field trial, mean values for exchangeable K within the upper 20 cm of soil were classified as 'low' (~0.2 meq $100g^{-1}$ soil) beneath the frond stack and 'very high' (>0.3 meq $100g^{-1}$ soil) within the weeded circle (using values for mature oil palm from Fairhurst and Hardter (2003) and Rankine and Fairhurst (1999)), with considerable variation among all blocks sampled. Following the field trial, mean values for exchangeable K were 'very high' for 0-20 cm soil for BMP and REF blocks, beneath both the weeded circle and frond stack. The high soil K levels at the end of the field trial may indicate reduced need for K input in future years. Conversely, further cultivation without increased P inputs may lead to deficiencies, given the decline in available P.

In the light of these findings, the concept of the '4Rs' in nutrient stewardship is increasingly important for fertiliser application in oil palm. The 4Rs refer to putting the right source of nutrients in the right place, at the right time and at the right rate. Soil nutrient status for the sites surveyed generally falls within the 'moderate' range in the context of oil palm production for soil pH, total N, available P, %SOC, and 'high' for exchangeable K and exchangeable Mg, according to Fairhurst and Hardter (2003) and Rankine and Fairhurst (1999). However, it is possible that current fertiliser rates may not be adequate given the depletion in some key nutrients noted over time. Current oil palm plant nutrition is based on the average response of all palms in a block; however, there is great variation in production from palm to palm, with the result that not all palms in a block will be adequately fertilised under a single fertiliser regime. In this case, it would seem that further consideration of the placement and concentration of fertilisers within the zone of highest root activity surrounding individual palms is needed.

4.3 Variability in site conditions and management practices

The estates sampled in this research were diverse, covering a range of soil types, suitability for oil palm cultivation, topographic characteristics, age of oil palm stands and climatic characteristics (Table 1 and Table 2). This variability was reflected in the significant influence of 'site pair' as a random effect in the ANOVA analyses, and in the varying degrees of change in soil quality indicators between estates. The blocks in this research were stratified according to management treatment, rather than by biophysical characteristics. Due to the small number of available data points (*n*=30), detailed statistical analysis on the potential influence of biophysical site characteristics on changes in soil properties was not undertaken. If further plantations were added to the study in future years such that stratification by soil type, topography or stand age were possible, it would be valuable to note whether soil properties in any combination of these site factors were more or less conducive to change under BMP and 'standard' treatments.

The influence of oil palm management practices on soil properties such as soil pH, organic carbon and nutrient availability is known to vary according to soil type and topographic position (Comte et al., 2013), age of oil palm stand (Smith et al., 2012) and may also be affected by rainfall and hydrological characteristics (Nelson et al., 2011; Comte et al., 2012). Accordingly, the site-specific BMP concept acknowledges that management practices need to be tailored to site conditions, rather than applied uniformly across all blocks in an estate (Donough et al., 2009). The '4R' Nutrient Stewardship Concept (IPNI, 2012) also requires careful consideration of the site-specific context for tailored fertiliser application. Disentangling the effects of variable BMPs, initial site conditions, suitability for oil palm and past management practices over a short period of time (four years) on soil properties is complex. With more time under BMPs, clearer differences in soil properties may become apparent. However, given the differences in yields between BMP and REF blocks, and anecdotal evidence to suggest that plantation managers had adopted at least some components of BMPs in REF blocks, it may be difficult to maintain blocks under 'standard' management practices for longer periods of time. Future research could aim to compare soil quality indicators (particularly key properties such as soil pH, SOC, cations and available P) among plantations that have adopted BMPs with those that have not.

4.4 Conclusions

Sustainable intensification of oil palm is likely to become increasingly important as a means of increasing yield. Best Management Practices, as developed by IPNI and others and implemented in a number of plantations throughout Southeast Asia, can not only increase yield but also have the potential for positive flow-on effects for soil quality and soil health. Measured soil properties in blocks managed using BMPs and 'standard' (REF) estate management practices did not show significant differences in the magnitude of change in soil properties over a four year period. Intensification of agriculture is often thought to result in a decrease in overall environmental quality; these results indicate that where appropriate site-specific management practices are employed, intensification can improve soil quality.

This study is one of the few pieces of research on oil palm management that has taken place within commercial oil palm blocks, embedded within a commercial production process. The research uses a unique, comprehensive set of data on soil properties compiled over four years, using consistent methods across space and time. While undertaking research within the inherently highly variable 'real-world' context can make it more difficult to prise apart the influence of external environmental variables, the use of commercial blocks makes our results highly relevant for those parties interested in improving oil palm management practices.

Despite the overall lack of difference noted in soil properties between BMP and REF blocks, there were substantial positive changes in some key soil properties, most notably soil pH and % SOC. Oil palm plantations have often been noted for an increase in soil acidification and decrease in soil carbon stocks with increasing time under cultivation. We show that oil palm cultivation is not inevitably associated with a decline in soil pH or % SOC. Appropriate management practices, such as combining inorganic and organic fertilisers in the most suitable combinations, and application of pruned fronds to the soil surface, can not only increase yield, but also improve soil health through an increase in soil pH and increased soil carbon over time. Further research on the additional benefits (beyond increased yield) that accrue over the longer term through the use of BMPs may provide valuable evidence to oil palm plantation managers looking to improve yields and reap ‘co-benefits’ such as improved soil and water quality, and reduced expenditure on fertiliser inputs.

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