Effects of soil management practices on soil fauna feeding activity in an Indonesian oil palm plantation

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Abstract

Optimizing the use of available soil management practices in oil palm plantations is crucial to enhance long-term soil fertility and productivity. However, this needs a thorough understanding of the functional responses of soil biota to these management practices. To address this knowledge gap, we used bait lamina method to investigate the effects of different soil management practices on soil fauna feeding activity, and whether feeding activity was associated with management-mediated changes in soil chemical properties in a 15-year-old oil palm plantation. We examined the four management zones (1) empty fruit bunch (EFB) application along the sides of harvesting paths; (2) chemical fertilization within palm circles; (3) understory vegetation with pruned fronds in inter-row areas; (4) no input in cleared part of harvesting paths. Our results showed significantly higher soil fauna feeding activity under the EFB application compared to other management practices, and this was associated with improved soil chemical properties and soil moisture conditions. Principal component analysis on soil properties indicated that 71.2% of variance was explained by the first two principal components (PCs). Soil pH, base saturation and soil moisture contributed positively to PC1, while exchangeable aluminum and hydrogen contributed negatively to PC1. The results demonstrate that different soil management practices at the tree-scale have the ability to create spatial complexity in soil fauna feeding activity, and its associated soil chemical properties. This suggests that the practice of EFB application plays an important role in enhancing soil ecosystem functioning in oil palm plantations, which may ultimately contribute to sustainable palm oil production.

Keywords

Empty fruit bunch, EFB, bait lamina, soil biological process, chemical fertilizer, sustainable palm oil

1. Introduction

Palm oil is one of the most widely used vegetable oils, with an increasing demand for use in food products, cosmetics, and as a biodiesel feedstock (FAO, 2015; Mukherjee and Sovacool, 2014). Over the past few decades, oil palm plantations have expanded rapidly (Gilbert, 2012). Future projections predict that the expansion will continue in response to increased demand based on global population growth, with further developments in Africa and Latin America (Sayer et al., 2012). The land-use changes associated with the expansion of oil palm cultivation have resulted in the loss of natural vegetation and ecosystem degradation (Foster et al., 2011). This expansion has seen soil ecosystems decline in soil fertility, increase in erosion, and suffer from a loss of soil biodiversity (Comte et al., 2012; Savilaakso et al., 2014). These conditions may be mitigated by optimizing soil management practices within oil palm plantations (Basiron, 2007); however, the effects of these practices on soil ecosystem processes and soil properties are largely unknown.

The spatial arrangements of oil palm planting and the different management practices, which are designed primarily for fertilization and plantation maintenance, create distinct management zones within plantations. This gives rise to spatial heterogeneity in the chemical and physical properties of the soil and variability in microhabitats at the tree scale (**Figure 1**). The cleared harvesting paths are used for agriculture-related traffic, resulting in tracks of largely bare soil. In the alternate inter-row areas, understory vegetation is allowed to grow and pruned palm fronds are added regularly to prevent soil erosion and to return organic matter to the soil (Frazão et al., 2013). The palm circle, a weed-free area surrounding each palm with a radius of approximately 2 m, is where chemical fertilizers are applied and provides access for harvesting. A common practice is to apply residues from the palm oil mill, namely empty fruit bunches (EFB), along the sides of harvesting paths (Chiew and Shimada, 2013). The EFB is a wet, cellulose-rich oil palm mill residue that is used as an organic fertilizer and mulch substrate. The application of EFB, as with other crop residues, has been shown to increase soil pH, base saturation, cation exchange capacity, and soil water content (Comte et al., 2013; Teh et al., 2010). Therefore, EFB may be preferable to the application of chemical nitrogen fertilizers, which have a tendency to acidify soils in oil palm plantations by replacing soil base cations with ammonium and urea (Nelson et al., 2011).

The decomposition of crop residues is facilitated by decomposer microorganisms and soil animals. These nutrient mineralization processes are crucial for ecosystem functions and services in agricultural ecosystems, including soil carbon stabilization, nutrient cycling and primary productivity (Hättenschwiler et al., 2005). In oil palm ecosystems, a specific termite species, *Macrotermes gilvas*, is reported as the major litter-dwelling fauna for leaf litter decomposition in Malaysian oil palm plantations (Foster et al., 2011). Other studies reported that the abundance and diversity of soil microorganisms and soil-dwelling fauna such as earthworms, Coleoptera, and Dermaptera are increased by crop residue application, suggesting their functional roles in organic matter decomposition (Carron et al., 2015a, 2015b; Situmorang et al., 2014). Despite the increase in studies of soil fauna in the oil palm ecosystem that has emerged in the past decade, the functionality of soil-dwelling organisms in litter decomposition remains largely unknown.

We used the bait lamina method to measure the litter feeding ability of soil-dwelling organisms. This method involves inserting perforated plastic sticks filled with bait substrates into the soil, where the bait is exposed to the activities of soil organisms (Von Törne, 1990). The perforation of baits reflects the potential litter decomposition ability of soil-dwelling fauna (Birkhofer et al., 2011; Römbke et al., 2006). This method is therefore complementary to the widely used litterbag method, which examines the litter decomposing activity of litter-dwelling fauna.

The composition and activity of soil fauna both reflect and are influenced by the availability of nutrients and chemical properties of the soil, such as acidity, cation concentrations and moisture (Lavelle et al., 2006; Ponge, 2013). Soil management practices such as EFB application in oil palm plantations have been shown to increase the soil's organic carbon, nutrient contents and pH (Comte et al., 2013; Frazão et al., 2014), while these changes are also related to soil macrofauna abundance (Carron et al., 2015a). Further examination of how soil fauna activity responds to changes in soil chemical properties under different management practices is crucial to understand the mechanisms underlying soil management practices and their effects on the functionality of soil fauna.

In this study, we compared four management practices to examine their effects on soil fauna feeding activity and soil chemical properties: (1) empty fruit bunch, (2) chemical fertilization, (3) understory vegetation with pruned fronds and (4) no input. Specifically, we asked: Do different soil management practices in oil palm plantations affect soil fauna feeding activity? And do different soil chemical and environmental conditions under these management practices explain soil fauna feeding activity? We hypothesized that EFB and palm frond application would provide favorable conditions (e.g., higher soil nutrient pools and soil moisture conditions) to increase soil fauna activity compared to other management practices.

2. Material and methods

2.1 Site description

The study was carried out on a Roundtable on Sustainable Palm Oil (RSPO)-certified oil palm plantation (0° 32’26.50” N 101°04’19.80”E) in Riau Province, Sumatra, Indonesia (**Supplementary S1**). The plantation was established in 1998 and the oil palm trees were 15 years old at the time of sampling. The density of palm trees was approximately 143 palms per ha, planted in staggered lines with palms at the points of a 9 m equilateral triangle. The climate of this region is described as tropical humid, with an average rainfall of 2350 mm/year (226 mm/month during October-March, 166 mm/month during April-September), and the average monthly temperature ranges from 26 to 29°C (year 2000-2013). The plots all exhibited the same soil type, namely Inceptisols (Typic Dystrudepts), within the loamy lowland soil class.

Fertilization management practices have been carried out consistently on this plantation over 8 years based on a mineral nutrient plan. The mineral nutrient status of the palms is monitored by annual leave tissue analysis to optimize vegetative growth and productivity. Every two years, fresh EFB from palm oil processing mills is transported to the field and applied at a rate of 420 kg/tree along the sides of harvesting paths. EFB contains 0.3 % N, 0.03% P, 0.8% K, 0.05% Mg, and 0.05% Ca (Caliman et al., 2001). Rock phosphate is applied on top of EFB immediately following the EFB application. Chemical fertilizers including urea, kieserite or dolomite (Mg fertilizers), as well as micro-nutrients (boron and iron), are manually applied on the soil surface of palm circles. Urea is applied systematically in alternating years with EFB application (i.e., in years when EFB is not applied), and its application rate is based on the calculation of the nutrient balance each year. Kieserite or dolomite and the micro-nutrients are applied once or twice each year (i.e., during the February-March and September-October periods); the application frequencies and rates depend on prior nutrient analyses of palm leaves. No chemical fertilizers or organic matter are applied on the cleared harvesting paths. In areas of understory vegetation, pruned fronds are piled on top of the vegetation on a weekly basis. The application rate of each management practice and time since the last application is shown in **Table 1**.

2.2 Field sampling and laboratory analysis

The sampling took place from July to August 2013. Three 30 x 100 m sampling plots within the plantation were selected with a minimum distance of 150 m between each plot. There were approximately 30 palm trees per plot. Six focal trees within each plot were randomly chosen for sampling. At each focal tree, four management zones were sampled, corresponding to the following soil management practices: (1) EFB application along the sides of harvesting paths, (2) chemical fertilization within palm circles, (3) understory vegetation with pruned fronds in inter-row areas, and (4) no input in cleared part of harvesting paths (**Figure 1**). The effects were examined at the tree scale, as management practices are performed in a zonal pattern around each palm tree as described above. The majority of the previous studies on soil management practices in oil palm plantations are at plot or landscape scale (Abu Bakar et al., 2010; Comte et al., 2013; Pauli et al., 2014). Capturing the spatial heterogeneity in soil properties at tree scale is critical to scale up from point samples to block or landscape scale, as variations at small scales can be as great as those at larger scales (Nelson et al., 2013).

Soil fauna feeding activity in each of the four management zones was measured using the bait lamina method (Terra Protecta GmbH, Berlin, Germany) (Von Törne, 1990). The method uses thin PVC sticks (1 x 6 x 120 mm) with 16 apertures of 1.5 mm diameter and 5 mm apart, filled with standardized bait made of cellulose powder, bran flakes and active carbon in a ratio of 70:27:3. A total of 432 sticks were inserted for 6 days of exposure. At each sampling point, a matrix of six bait lamina sticks were placed 12 cm apart in a 12 cm x 24 cm grid. The sticks were inserted vertically until the top aperture was just below the soil surface, and the bottom aperture was at a depth of 8 cm below the soil surface. After collection, bait consumption was recorded by assessing each aperture; feeding activity was recorded as 0 (without perforation = no evidence of feeding) or 1 (partial or complete perforation = evidence of feeding). Results from 0-5 cm depth (the upper 10 perforations of each stick) were used in all analyses to correspond to soil chemical properties, which were measured at 0-5 cm depth. Soil temperature, moisture and electrical conductivity were measured three times during the bait lamina exposure period using a WET sensor (Delta-T Device, Cambridge, UK).

From the six focal trees sampled for feeding activity in each plot, three trees were randomly chosen for soil chemical analysis. Litter and humus above the soils were removed before sampling the soils at 0-5 cm soil depth. The measured soil chemical properties were: soil pH, organic C concentration, total N concentration, C/N ratio, total and available P concentration, total K, cation exchange capacity (CEC), exchangeable base cation concentrations (Ca, Mg, K, Na), base saturation of the four base cations (Ca, Mg, K, Na), and exchangeable acidic cations (H and Al). The soil pH was determined using a pH meter with a soil to water ratio of 1:1. The soil organic carbon concentration was measured using the Walkley-Black method (Nelson and Sommers, 1982). The total soil P concentration was analyzed using 25% HCl extraction and a spectrophotometer. The total N concentration was extracted by H_2SO_4 and analyzed by flow injection analysis (FIA). The available P was extracted by the Bray-1 method and FIA. The exchangeable bases (Ca, Mg, K, and Na) were extracted by 1M ammonium acetate ($NH_4C_2H_3O_2$) and analyzed using atomic absorption spectrophotometry (AAS) (van Reeuwijk, 1993). The cation exchange capacity (CEC) was determined using the ammonium replacement method (CH_3COOH, pH = 7.0) (Thomas, 1982). Base saturation of four cations (Ca, Mg, K and Na) was obtained by dividing the sum of cations by CEC. The exchangeable H and Al was analyzed by the NaOH and HCl titration methods.

2.3 Statistical analysis

Generalized additive mixed models were used in order to assess the effects of soil management practice on soil fauna feeding activity, and to include non-linear effects of soil depth on the feeding activity. Binomial distribution was used because feeding activity was fitted as a binary variable. The feeding activity was modelled with different management practices as fixed effects; management practices nested within focal trees and sampling plots were fitted as random effects. Feeding depth was included as cubic regression spline smoothers separated by each management practice (Zuur et al., 2009). Subsequently, to test whether feeding activity differed between management practices, we fitted each management practice was a reference at a time, and the differences between the reference and other management practices were compared using z-values.

The effects of soil management practices on soil chemical properties were examined using linear mixed effects models. Each soil variable was fitted as a response variable, and was log- or square-root- transformed where necessary to meet the assumptions of parametric tests. Management practice was fitted as a fixed effect, and nested within sampling plots, which were modelled as random effects. Adjusted *P*-values were generated from post-hoc Tukey analysis.

Lastly, we examined whether the measured soil chemical variables explained soil fauna feeding activity. As most of the soil chemical variables were inter-correlated (**Supplementary S2**), principal components analysis (PCA) was performed to account for multi-collinearity. The principal components were then used as new continuous explanatory variables, which are considered mutually orthogonal and uncorrelated, and successively explain the maximum residual variation (Sena et al., 2002). Principal component 1 (PC1) was fitted into a generalized mixed effects model as the fixed effect, including sampling plot as the random effect and feeding activity as the response variable to test whether soil chemical properties explained soil fauna feeding activity. The *P*-values were generated from comparing the full model to the model without the explanatory variable. All the analyses were carried out using the R (R Core Team, 2013) with the packages *nlme* (Pinheiro et al., 2015), *gamm4* (Wood and Scheipl, 2014), *ade4* (Dray and Dufour, 2007) and *lme4* (Bates et al., 2015).

3. Results

3.1 Effects of soil management practices on soil fauna feeding activity

On average across all the sampling plots, 46 ± 4% of baits in the bait lamia sticks had been perforated after 6 days of exposure. Soil management practice significantly explained differences in soil fauna feeding activity ($P < 0.05$) **(Table 2)**, with significantly higher activity under EFB application than the other management practices **(Figure 2)**. For all the management practices, feeding activity significantly declined with increasing soil depth (**Table 2**). Feeding activity under chemical fertilization had a steeper depth gradient compared with the other management practices (**Figure 2**).

3.2 Effects of management practices on soil chemical properties

Among the 18 soil variables measures, nine were significantly affected by soil management practices (**Table 3**). Soil moisture, pH, total P, exchangeable Na, base saturation and electrical conductivity decreased in the order of areas of EFB application, areas with no input, areas of chemical fertilization and areas of understory vegetation, while exchangeable H and Al increased in this order. Soil temperature was significantly lower in areas with understory vegetation compared to all other management zones.

3.3 Effects of soil chemical properties on soil fauna feeding activity

Eigenvalues from PCA analysis indicated that the first two principal components (PCs) accounted for 71.2% of the variance of the data (PC1: 45.7% ; PC2: 25.5 %). Soil moisture, base saturation, pH, exchangeable Na, Mg and Ca, electrical conductivity and total P were positively correlated with PC1 scores, while exchangeable H and Al were negatively correlated with PC1 scores (**Supplementary S3**). The position of the soil management practices in the orthogonal space defined by the two axes showed that areas under EFB application had relatively higher PC1 scores than other management practices (**Figure 3**). The scores of PC1 significantly and positively explained soil fauna feeding activity (X^2_3=14.14, p=0.0001) (**Figure 4**).

4. Discussion

Land conversion from forests to oil palm plantation results in a reduction in soil species richness and alterations in community composition, which lead to changes in soil biological activities and functions that are crucial for sustaining soil fertility and ecosystem services (Foster et al., 2011). Limiting the expansion of oil palm into forests is very important to preserve forest species, but it is also crucial to implement suitable management practices within oil palm plantations to support both biodiversity and the activities of fauna. In this study, we found that soil fauna feeding activity was influenced by different soil management practices in oil palm, and the responses were closely associated with soil chemical fertility and soil moisture. Soil fauna feeding activity was greatly enhanced by EFB application, while no differences were found between chemical fertilization, palm frond application and areas without input.

4.1 Soil fauna feeding activity and bait lamina feeders

We showed that feeding activity across management practices and soil depths ranged from 35-50% after 6 days of incubation. This is slightly higher than the mean feeding activity of 15-30% after 4-day exposure in Amazonian forests (Römbke et al., 2006). In contrast, previous studies report that feeding activity in temperate climate conditions is much lower than in tropical conditions. For example, an overall mean activity of 8.5% was observed after 34 days of incubation in Oxfordshire, UK, although the bran flakes in the bait powder were replaced by leaf powder from the trees in the experimental woods (Simpson et al., 2012). Similarly, 6-25% of feeding activity after 14 days' exposure were observed in grasslands in Germany (Birkhofer et al., 2011), and 5-40 % of feeding activity after 22 days' exposure in South African vineyard soils (Reinecke et al., 2002). These results indicate that feeding activity greatly changes with climatic conditions.

Soil fauna feeding activity within the soil was increased by EFB application, which may be associated with increased abundance or changes in the community composition of soil-dwelling fauna. Our result is in line with a previous finding from a nearby oil palm site, showing that the abundance of soil macrofauna, including ants, earthworms and Coleoptera, was increased by EFB application (Carron et al., 2015b). This suggests EFB application increased soil macrofauna abundance, which may lead to higher overall feeding activity. However, no direct evidence has been found on which soil fauna taxa are the main bait lamina feeders in the oil palm ecosystem. The only documented study in a tropical area showed that the abundance of soil oribatid mites was positively associated with soil fauna feeding activity in Amazonian forests (Römbke et al., 2006). This result suggests that not only macrofauna but also microarthropods can be possible bait lamina feeders, as some soil microarthropods are important saprophagous detritivores for organic litter decomposition in the tropics (Swift et al., 2008). Evidence from lab manipulation and temperate system also showed that the feeding activity can be influenced by macrofauna, mesofauna and their interactions (Birkhofer et al., 2011; Helling et al., 1998). Further studies examining the direct linkage between soil fauna taxa and soil fauna feeding activity in the oil palm ecosystem are needed.

4.2 Soil fauna feeding activity and soil chemical properties

Principal component analysis showed that soil moisture, concentration of base cations and pH were the three major soil chemical variables that positively contributed to principal component 1 (PC1) (**Supplementary S3**). A subsequent analysis showed that soil fauna feeding activity was positively explained by PC1 (**Figure 4**), suggesting that soil fauna feeding activity was positively explained by these three variables. The concentration of base cations (i.e. Ca, Mg, K) plays a key role in shaping tropical soil fauna community composition in the tropical ecosystems (Ashford et al 2013). For example, these base cations can displace Al and H ions from soil surfaces, resulting in increased soil pH (Zhi-An et al., 2008). As the soils in our study site were highly acidic (pH = 4.6 ± 0.1), the increase in soil pH was likely to attract more pH-sensitive soil organisms (Bardgett, 2005). Carron et al (2015b) also showed that soil macrofauna abundance was positively related to soil Ca concentrations at a nearby oil palm site.

Compared to tropical forest ecosystems, soil fauna communities in oil palm plantations are subject to more extreme and more variable microclimates, due to to the lack of plant diversity, large bare soil area and more open oil palm canopy (Foster et al., 2011). Indeed, the average soil moisture at our study site was very low (23.4 ± 1.23%). Higher soil fauna feeding activity was found at areas under EFB application, where soil moisture was higher than other management zones. This result indicates that fauna assemblage and functioning are enhanced in wetter soils. Similar observation is also found in temperate forest, where soil fauna feeding activity is increased by higher soil moisture (Simpson et al., 2012).

4.3 Soil fauna feeding activity in response to soil management practices

The increase in soil fauna feeding activity under EFB application was associated with high concentrations of base cations and soil moisture. EFB is rich in Ca, Mg and K (Moradi et al., 2014), and its application on the surface soil triggers both the rapid release of base cations and an increase in soil pH (Comte et al., 2013). EFB is also an effective vapor barrier against moisture loss and favors water infiltration, as it is normally applied in a form of mat covering the bare soil surface (Mulumba and Lal, 2008).

Palm fronds contain easily decomposed leaflets and less-easily decomposed rachis, with the overall residue quality and mass loss rates similar to that of EFB (Moradi et al., 2014). These characteristics led to our hypothesis that the soil properties under palm frond application could be similar to those under EFB application. In contrast, we found the soils under palm fronds had the lowest soil moisture, pH and base saturation of all the management practices, with soil fauna feeding activity the same as chemical fertilized areas and areas with no input. We suggest the presence of ground vegetation under palm fronds to be the major reason for these differences. EFB was applied directly on the surface soil, where organic matter decay and nutrient cycling by decomposer microorganisms and litter transformers were likely to be most active. In contrary, pruned fronds were stacked on top of dense ground vegetation at the thickness of 30-40 cm, away from litter-dwelling and belowground fauna. The long distance between fronds and the soil surface may also prevent frond-released nutrients from entering the soil. In addition, the rooting system of understory vegetation can take up much of the nutrients and water from the soil. Carron et al (2015b) also found that the soil's chemical fertility was not enhanced by palm frond application in oil palm plantations.

Soil fauna feeding activity was significantly lower under chemical fertilization compared to EFB application. Interestingly, although not statistically different from the area of palm fronds and harvesting path, the feeding activity under chemical fertilization decreased sharply with soil depth, reaching a plateau after 2 cm, compared to the gradual decline in feeding activity with depth seen under the other management practices. This finding is in line with studies showing negative effects of chemical fertilizers on soil biota and their activities (Birkhofer et al., 2008; Sánchez-Moreno and Ferris, 2007). The lower soil fauna feeding activity was associated with substantially lower pH and base cation concentrations in palm circles, which was likely a consequence of the addition of urea-based fertilizers that induce nitrification and soil acidification (Barak et al., 1997; Nelson et al., 2010). Although nutrients such as Mg and Ca in the form of dolomite were applied, their potential liming effects were not detected. This may be due to the low application rates, and potentially high leaching rates of chemical fertilizers in oil palm plantations.

It is to be noted that in this study we tested whether soil management practices are likely to influence soil fauna feeding activity via alternations of soil chemical properties. At the same time, soil fauna feeding activity can influence soil chemical properties by regulating organic matter decomposition processes. Further manipulation experiments are necessary to understand explicitly which mechanisms are more dominant in the oil palm agroecosystem.

4.4 EFB application in oil palm plantations

We showed that EFB application enhanced soil fauna feeding activity and soil chemical properties. Previous studies also revealed its positive effects on soil organic carbon, soil structure and the oil palm productivity (Caliman et al., 2001; Comte et al., 2013). Despite these advantages, the use of EFB in the field as an organic fertilizer has been limited. Due to its bulky characteristics, the storage, transportation and field application of EFB are cumbersome and expensive (Moradi et al., 2015). EFB is therefore only distributed to plantations that are close to palm oil mills. EFB is also suggested to create pest problems by providing habitat for the pests (Menon et al., 2006), as well as releasing greenhouse gases when decaying in landfills (Chiew and Shimada, 2013).

One of the possible solutions to deal with current EFB application problems may lie in the development of composting technologies. The composting processes of EFB reduce it 50%~75% by volume, into sheet-like or dry solid forms (Chiew and Shimada, 2013). However, without the original fruit shell structure, whether these compost forms of EFB have similar abilities to create microclimates and microhabitats supportive of soil biological activities, are largely unknown. Furthermore, the composting processes may result in substantial nutrient loss. The development of compost technologies and further research evaluating their ecosystem supporting-functions are important for sustainable palm oil production.

5. Conclusions

Land conversion from forests to oil palms has led to negative impacts on soil fauna assemblage and their functions (Fitzherbert et al., 2008). Implementation of suitable management practices is therefore crucial for sustainable development of oil palm cultivation. Previous studies showed that landscape management such as maintaining riparian reserves and integration of cattle into oil palm plantation have positive influence on soil biodiversity and ecosystem functioning (Gray et al., 2015, 2014; Slade et al., 2014).

In the current study, we examined the effects of soil management practices, including empty fruit bunch (EFB) application, palm frond application and chemical fertilization on soil fauna feeding activity and soil chemical properties. We found that EFB greatly enhances soil fauna feeding activity and is associated with increased concentrations of base cations and soil moisture. The elevated biological activity has strong potential to contribute to ecosystem functions such as litter decomposition, nutrient cycling and organic carbon stabilization, and ultimately palm oil productivity. The application of crop residue in oil palm ecosystems may therefore also have a role to play in enhancing the soil resilience to climate change effects, such as drought and flooding, as well as further human disturbances, such as those associated with second and third replanting cycles in Southeast Asia.

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Figures and Tables

Figure 1 The layout of an oil palm plantation. Harvesting paths and areas of understory vegetation are in alternate inter-rows. Palm trees are planted in triangular spacing, approximately 9 m apart. The trunks are surrounded by cleared weed-free circles where chemical fertilizers are applied. Empty fruit bunches are applied along the sides of harvesting paths.

File name: FIG1-resubmission.PPTX

Figure 2 Variation (mean ± SE) of soil fauna feeding activity as a function of soil depth under three management practices. Each data point represents the mean of bait perforations of 108 bait lamina sticks (six sticks under each sampling tree, and six trees at each of the three sampling plots). The lines are model-predicted values generated from a generalized linear additive mixed model.

File name: FIG2-resubmission.pdf

Figure 3 Principal component analysis (PCA) for soil chemical variables and the sampling points according to management practices in the plane formed by the first principal component (PC1) and the second principal component (PC2). Bivariate confidence ellipses were drawn to show the similarities of soil chemical properties in each management zone.

* Al: exchangeable Al concentration (cmol kg^{-1}); BS: base saturation (%); Ca: exchangeable Ca concentration (cmol kg^{-1}); CEC: cation exchange capacity (cmol kg^{-1}); CN: C/N ratio; Cond: electrical conductivity (ms m^{-1}); H: exchangeable H concentration (cmol kg^{-1}); K: exchangeable K concentration (cmol kg^{-1}); Mg: exchangeable Mg concentration (cmol kg^{-1}); Mois: soil moisture (%); Na: exchangeable Na concentration (cmol kg^{-1}); OC: organic C concentration (%); P: available P concentration (cmol kg^{-1}); Temp: temperature (°C); TN: total N concentration (%); TP: total P concentration (cmol kg^{-1}); TK: total K concentration (cmol kg^{-1}).

File name: FIG3-resubmission.pdf

Figure 4 Soil fauna feeding activity as a function of principal component 1 (PC1). PC1 is formed by principal component analysis of soil chemical properties. A generalized mixed effects model was used, including feeding activity as a response variable, principal component 1 (PC1) as a fixed effect, and the sampling plot as a random effect. Binomial distribution was used as feeding activity was fitted as a binary variable.

File name: FIG4-resubmission.pdf

Table 1 Application rates of aboveground inputs, the equivalent amount of nutrients applied, and time since the last application of each management practice.

Management practice	**Management zone**	**Aboveground input**	**Application rate (kg tree^{-1}yr^{-1})**	**Nutrient application rate (kg tree^{-1}yr^{-1})**					**Time since the last application (month)**
				N	P	K	Mg	Ca	
Empty fruit bunch (EFB)	One side of harvesting path	EFB*	210	0.57	0.06	0.17	0.11	0.11	12
		Rock phosphate *	0.75	0	0.15	0	0	0	12
Palm frond	Inter-row	Palm frond ***	237	0.57	0.05	0.71	0.08	0	1
Chemical fertilizer	Within palm circle	Urea*	0.50	0.23	0	0	0	0	24
		Kieserite / Dolomite **	0.50	0	0	0	0.06	0.10	4
No input	Cleared part of harvesting path	None	-	-	-	-	-	-	-

* Mean annual application rate of EFB, rock phosphate and urea, which were applied every 2 years.

** Mean annual application rate of kieserite or dolomite, which were applied once or twice per year.

*** Estimated mean annual application rate of palm frond and its nutrient composition after (Moradi et al., 2014).

Table 2 Effects of management practices and soil depth on soil fauna feeding activity using a generalized additive mixed model. Management practice was modelled as a fixed effect, with management practice nested within focal trees and sampling plots as random effects. Feeding depths were included as cubic regression spline smoothers separated by each management practice. Chi-square tests and the associated *P*-values were extracted from the coefficient table of the model.

Variable	**df**	X^2	***P***
Explanatory variable			
Management practice	3	13.5	<0.005
Smoother			
Smoother EFB	1.00	18.3	<0.005
Smoother Palm frond	1.00	9.34	<0.005
Smoother Chemical fertilizer	2.70	31.7	<0.005
Smoother No input	1.55	12.6	<0.005

The degrees of freedom and *P*-values for the smoothers are estimates. The higher the degree of freedom the more non-linear the smoother (df=1 indicates a linear smoother).

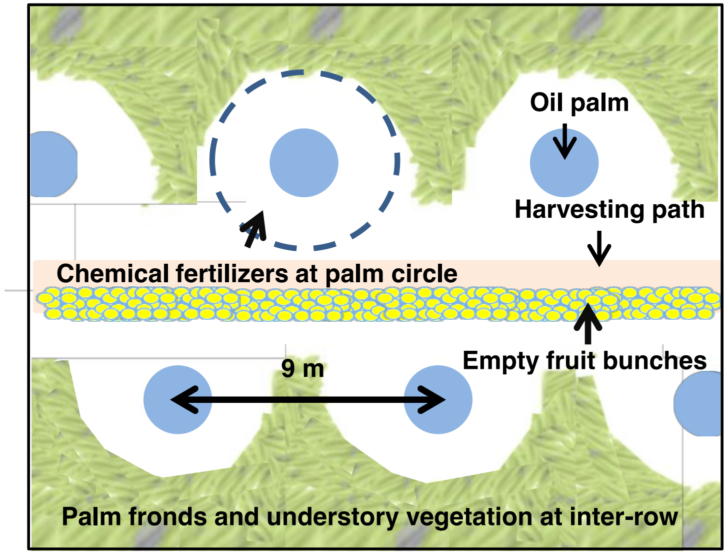
Table 3 Soil chemical variables under each soil management practice at 0-5 cm soil depth. Values are means ± 1SE. Overall means are the average of values from all the management practices. The *P*-values were results from linear mixed effects models performed on the mean value of variables for each management practice (n=3). Within rows, means followed by the different lower case letters are significantly different at $P < 0.05$ (shown in bold).

Soil chemical variable	**Management practice**				**Overall mean**	***P*-value**
	Empty fruit bunch (EFB)	**No input**	**Chemical fertilizer**	**Palm frond**		
Soil moisture (%)	25.4 ± 0.47 a	27.6 ± 2.26 a	21.9 ± 1.79 b	18.5 ± 1.04 c	23.4 ± 1.23	**0.001**
pH	5.07 ± 0.04 a	4.73 ± 0.19 ab	4.38 ± 0.23 bc	4.16 ± 0.08 c	4.59 ± 0.12	**0.009**
Total P (mg kg^{-1})	931 ± 145 a	187 ± 74.2 b	138 ± 51.0 bd	53.6 ± 1.10 cd	328 ± 112	**0.002**
Exchangeable Na (cmol kg^{-1})	0.11 ± 0.02 a	0.09 ± 0.01 ab	0.07 ± 0.01 bc	0.06 ± 0.01 bc	0.08 ± 0.01	**0.018**
Base saturation (%)	65.6 ± 14.4 a	38.8 ± 8.06 ab	22.1 ± 4.70 bc	16.2 ± 3.97 c	35.7 ± 6.90	**0.021**
Electric conductivity(ms.m^{-1})	40.0 ± 2.18 a	21.3 ± 0.75 b	24.3 ± 0.26 c	15.3 ± 1.11 d	25.2 ± 2.81	**<0.0001**
Exchangeable H (cmol kg^{-1})	0.21 ± 0.04 a	0.31 ± 0.14 a	0.70 ± 0.24 b	0.69 ± 0.09 b	0.48 ± 0.09	**0.027**
Exchangeable Al (cmol kg^{-1})	0.19 ± 0.12 a	1.65 ± 0.78 b	2.89 ± 0.93 b	3.20 ± 0.53 b	1.98 ± 0.46	**0.003**
Soil temperature (°C)	28.5 ± 0.60 a	28.6 ± 0.60a	28.6 ± 0.58 a	28.2 ± 0.52 b	28.5 ± 0.25	**0.006**
Organic carbon (%)	5.17 ± 0.80	5.11 ± 1.28	6.61 ± 1.13	5.92 ± 0.47	5.70 ± 0.45	0.367
Total nitrogen (%)	0.36 ± 0.07	0.33 ± 0.08	0.39 ± 0.05	0.36 ± 0.05	0.36 ± 0.03	0.698
CN ratio (%)	14.8 ± 0.55	16.2 ± 1.13	17.3 ± 1.26	16.8 ± 0.59	16.3 ± 0.49	0.339
Available P (mg kg^{-1})	46.7 ± 5.11	38.6 ± 20.2	38.0 ± 18.0	18.6 ± 1.55	35.5 ± 6.67	0.372
Total K (mg kg^{-1})	148 ± 70.5	49.1 ± 1.16	84.4 ± 0.59	94.3 ± 11.1	94.0 ± 18.6	0.121
CEC (cmol kg^{-1})	14.7 ± 2.43	14.8 ± 1.37	23.6 ± 5.55	20.6 ± 3.04	18.4 ± 1.86	0.063
Exchangeable Ca (cmol kg^{-1})	6.56 ± 1.62	3.57 ± 0.20	3.17 ± 0.86	2.10 ± 0.74	3.85 ± 0.65	0.063
Exchangeable Mg (cmol kg^{-1})	2.30 ± 0.24	1.74 ± 0.76	1.37 ± 0.31	0.96 ± 0.44	1.59 ± 0.25	0.315
Exchangeable K (cmol kg^{-1})	0.35 ± 0.15	0.16 ± 0.01	0.22 ± 0.02	0.30 ± 0.05	0.26 ± 0.04	0.176

Appendix A. Supplementary data

The following are Supplementary data to this article:

File name: MMC1-resubmission.DOC


Oil palm
Harvesting path
Chemical fertilizers at palm circle
Empty fruit bunches
9 m
Palm fronds and understory vegetation at inter-row

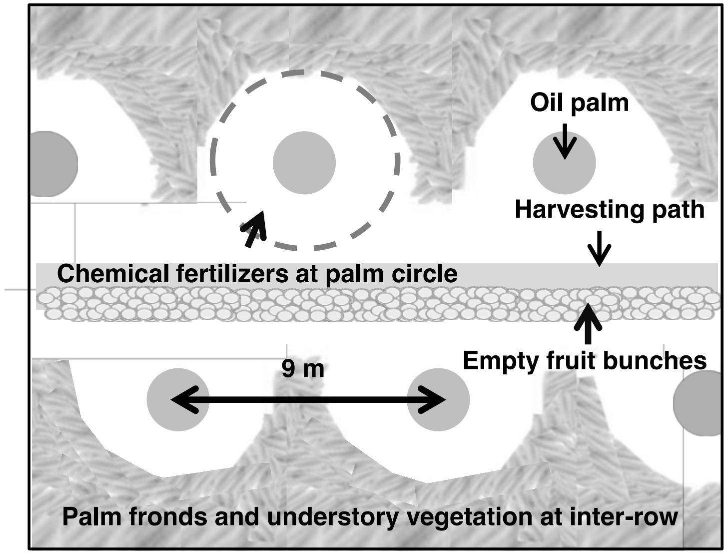
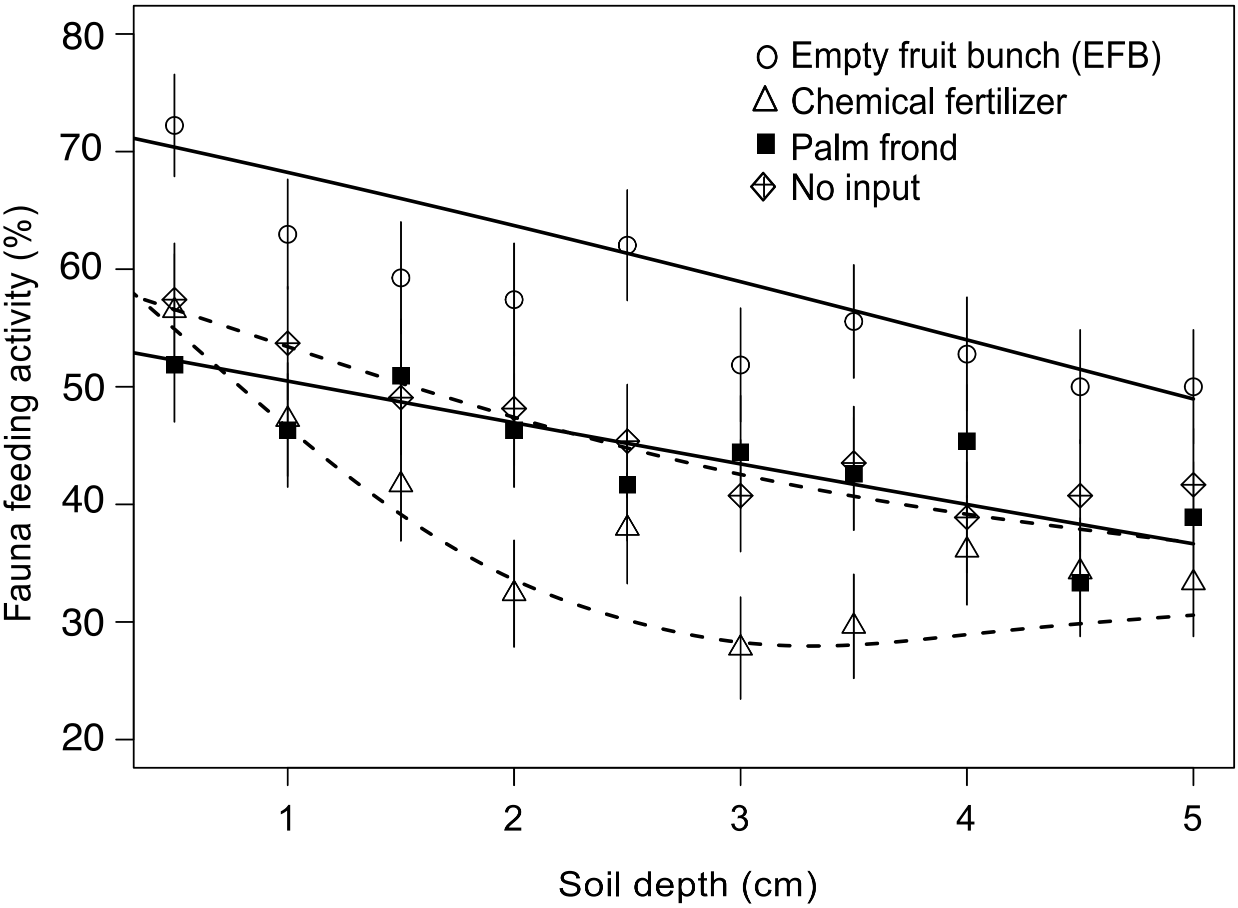

Oil palm
Harvesting path
Chemical fertilizers at palm circle
Empty fruit bunches
9 m
Palm fronds and understory vegetation at inter-row

Figure 2-resubmission



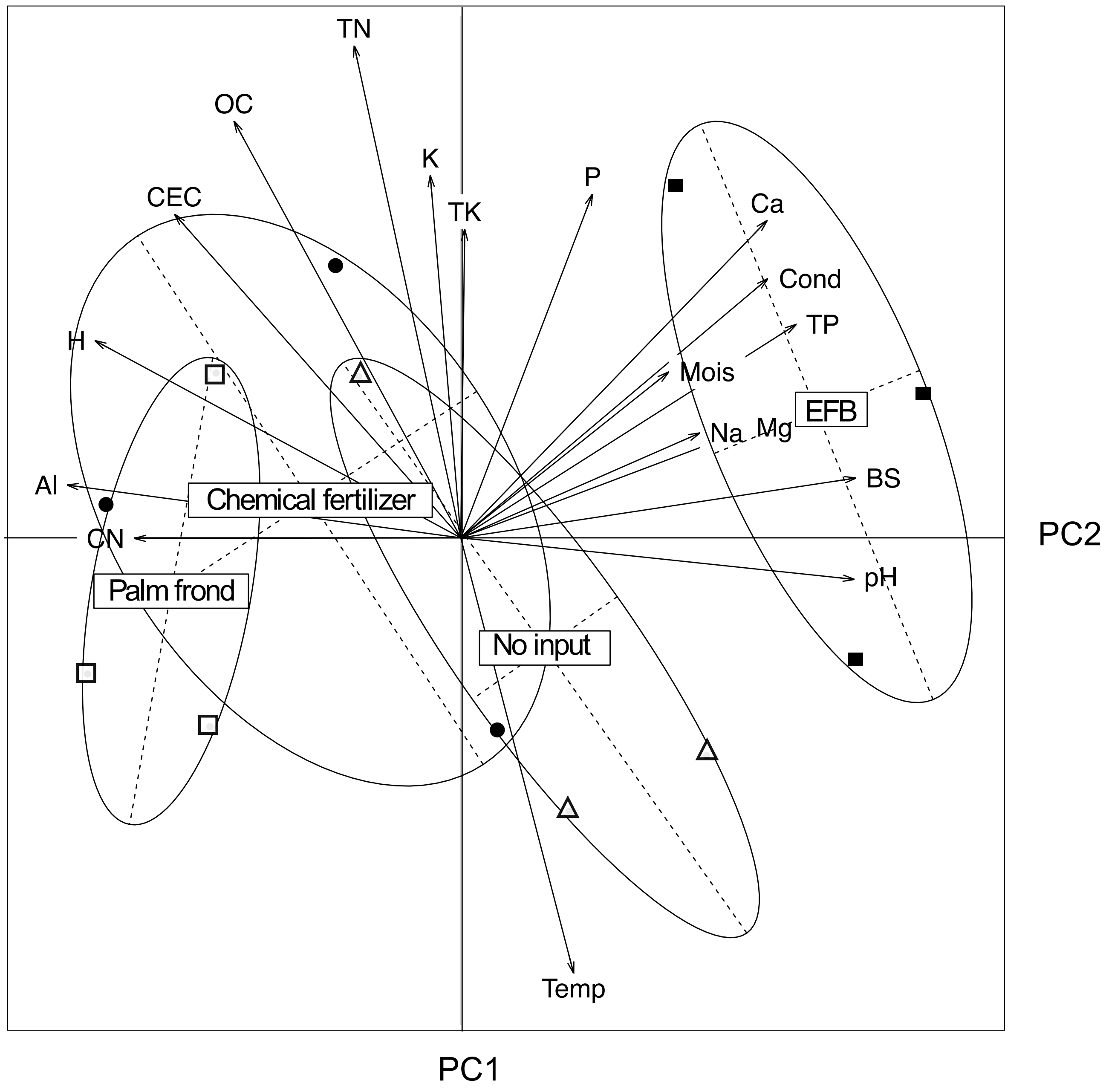

TN
OC
K
P
CEC
TK
Ca
Cond
TP
H
Mois
EFB
Na
Mg
BS
Al
Chemical fertilizer
CN
PC2
pH
Palm frond
No input
Temp
PC1

Figure 4-resubmission