CROP RESIDUE MANAGEMENT IN OIL PALM PLANTATIONS: SOIL QUALITY, SOIL BIOTA AND ECOSYSTEM FUNCTIONS

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ABSTRACT

The application of crop residues is one of the most common agricultural practices used to maintain soil ecosystems and crop productivity. This thesis focuses on the oil palm (*Elaeis guineensis*) agroecosystem, an important tropical crop that has expanded rapidly over the past four decades. Both land conversion and business-as-usual practices within the plantations have contributed to soil degradation. The application of oil palm residues, such as empty fruit bunches (EFB) and oil palm fronds, are thought to have positive effects on the soil ecosystem; yet there is currently a deficit of knowledge on their effectiveness. This thesis aims to examine the effects of oil palm residue application on soil physicochemical properties, soil biota, and ecosystem functions. It reports the results of extensive field trials, sample collection, and statistical analysis of crop residue applications in oil palm plantations in Central Sumatra, Indonesia.

Four key results emerged from the thesis. First, in this study site land conversion from secondary forest to oil palm does not affect litter decomposition rate, but positively influences soil fauna activity. Second, there is greater soil fauna activity following EFB application than oil palm fronds or chemical fertilizers, and the fauna activity is highly associated with changes in soil chemical properties and soil moisture conditions. Third, EFB application enhances soil ecosystem functions, through the direct provision of organic matter, and by influencing soil biota. Finally, over 15 years of application, EFB appears to be effective in maintaining or increasing annual crop yield in comparison to chemical fertiliser treatment. Temporal changes in crop yield under EFB application appear to be associated with climatic conditions and soil organic carbon. Overall, these findings improve our understanding of the potential of oil palm residue applications to increase soil quality, soil biota, and ecosystem functions. They also provide useful information for a wider audience of soil ecologists, agricultural managers, and policy makers to improve sustainable management of the oil palm ecosystem.

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PREFACE

The structure of this thesis fulfils the requirements for a DPhil submitted by papers in Biological Sciences, as recognized by the University of Oxford. It comprises of an introductory chapter which includes a literature review, four core research papers in manuscript formats, and a general discussion chapter. References are combined in the Bibliography at the end of the thesis. Supplementary materials are found at the end of each chapter. At the time of submission, Chapter 3 is published in Agriculture, Ecosystems and Environment. Chapter 2, 4 and 5 are in preparation for publication.

Chapter 1:
General introduction

Chapter 2:
Hsiao-Hang Tao, Jake L. Snaddon, Eleanor M. Slade, Resti Wahyu, Jean-Pierre Caliman, Kathy J. Willis (2015) The impacts of forest conversion to oil palm on soil ecosystem functions in Sumatra, Indonesia. *in prep.*

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Chapter 4:
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Chapter 5:
Hsiao-Hang Tao, Jake L. Snaddon, Eleanor M. Slade, Jean-Pierre Caliman, Rudi H. Widodo, Suhardi, Kathy J. Willis. Effects of crop residue addition on oil palm productivity under a changing climate. *In prep.*

Chapter 6:
General Discussion

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CHAPTER 1 GENERAL INTRODUCTION

Soil is a crucial natural resource that underpins both ecosystem functions and services in agroecosystems (Wall et al., 2012). Appropriate soil management practices are therefore important to sustain healthy agricultural ecosystems and crop production, and to improve the resilience of soil to climate change and anthropogenic threats (Magdoff and Weil, 2004). Incorporation of crop residues into the soil is an agricultural practice which has been implemented for many years (Haynes and Naidu, 1998; Kumar and Goh, 1999); however, the influence of this practice on the soil ecosystem remains unclear, and very little quantitative evidence exists to demonstrate its effectiveness.

Oil palm (*Elaeis guineensis*) is the focal crop in this study. Oil palm is one of the most important economic crops in the tropics, especially in Southeast Asia (Gilbert, 2012; Sayer et al., 2012). The oil palm industry has brought development and an economic boom to Southeast Asia since the 1970s (Sheil et al., 2009). On the other hand, the process of land conversion from forest to oil palm, as well as daily management practices in the plantations, have contributed to adverse environmental impacts (Barnes et al., 2014). The resulting soil degradation is especially of great concern, as it includes a reduction in soil quality, soil biota community, and ecosystem functions (Foster et al., 2011; Guillaume et al., 2015). Applying oil palm residues such as empty fruit bunches (EFB) and oil palm fronds in the plantations may have a high potential to improve soil conditions (Carron et al., 2015b; Comte et al., 2013). Despite its importance, the existing evidence on the effects of this management practice is scarce. This thesis aims to examine in detail, the effects of oil palm residue incorporation on soil quality, soil biota and ecosystem functions, using data collected from Sumatran oil palm plantations and field trials.

This introductory chapter provides an overview of the research background, and synthesizes existing literature to highlight the knowledge gaps. Research aims and objectives of this thesis, the study area, and methodological approaches are then introduced.

1. SOIL MANAGEMENT FOR SUSTAINABLE AGRICULTURE

Soil is a vital natural resource that provides ecosystem functions and services in terrestrial ecosystems. It is the essence of life and health for the well-being of humankind, and the primary source of our food production (Liu et al., 2006). Soil contains a variety of organisms, which interact with each other and with their physical-chemical environment (Bardgett, 2005). Through these interactions, important ecosystem functions such as litter decomposition, nutrient cycling, and soil carbon sequestration are delivered (Amundson et al., 2015). These fundamental ecological processes lead to final ecosystem services and goods, such as soil fertility, and crop productivity (Mace et al., 2012).

Agriculture is one of the principal causes of soil degradation. It is estimated that around 38% of cultivated area in the world has degraded soils (Miller and Gardiner, 2007). Agricultural management practices such as extensive use of chemical fertilizers, removal of organic matter, intensive tillage, and machinery use, can negatively influence the soil. Degraded soils have characteristics such as greater soil compaction, salinization, losses of organic matter and nutrients, as well as a reduction in soil biodiversity (Blanco-Canqui and Lal, 2009; Liu et al., 2006; Ludwig et al., 2011).

Several management practices have been implemented in agricultural fields to improve soil ecosystems and crop productivity. These include reduced or no-tillage, enhanced ground cover, crop residue incorporation, farm species diversification, crop rotation, and the use of organic fertilizers (Kassam et al., 2013). Another common practice to improve soil quality is crop residue application (Blanco-Canqui and Lal, 2009). The organic matter derived from crop residues is thought to provide an important source of organic carbon and nutrients to the soil (Ilieva-Makulec et al., 2006; Moore et al., 2004). Crop residue application can also influence soil chemical properties, habitat structure, and microclimate conditions (Ashford et al., 2013; Bardgett, 2005; Lavelle et al., 1995). However, the benefits of adding crop residues to soils is largely unknown for many cropping systems.

2. OIL PALM AND SOIL DEGRADATION

Oil palm (*Elaeis guineensis*) originates from West Africa, but is now an economic tree crop throughout South-East Asia (Phalan et al., 2013), where it was introduced in the 1970s. Palm oil can be extracted from the seeds embedded within fruit bunches, and is widely used in food, cosmetics, detergents, and feedstock for biofuel. In the last four decades, the global land area of oil palm plantations has tripled, reaching 16.4 million ha in 2014, equivalent to 10% of the world's permanent cropland area (FAO, 2015; Sheil et al., 2009). Currently, more than half of the world's plantations are located in Malaysia and Indonesia, which accounts for 85% of the 46.5 million tons of crude palm oil produced worldwide (FAO, 2015)

The palm oil industry brings opportunities for development and economic growth in many production regions (Sayer et al., 2012). However, both land conversion from forest to oil palm, as well as daily management practices within the plantations, have contributed to negative environmental impacts. Loss of natural vegetation, reduction in biodiversity, water pollution, and greenhouse gas emissions are critical issues that exist in many oil palm plantations today (Edwards et al., 2010; Foster et al., 2011; Sheil et al., 2009; Shuit et al., 2009).

Among all the environmental issues that oil palm brings, soil degradation is of the greatest concern (Comte et al., 2012; Hartemink, 2005; Savilaakso et al., 2014). It has been reported that the palm oil industry negatively influences soil physical and chemical properties. For example, the common practice of ground cover removal to facilitate fertilizer application and harvest activities has led to surface runoff and soil erosion (Aweto, 1995; Frazão et al., 2014; Sommer et al., 2000). Heavy machinery used for establishing plantations also increases soil compaction (Tanaka et al., 2009). Moreover, the intensive application of nitrogen fertilizers can acidify soils and reduce the buffering capacity of the soil (Barak et al., 1997; Nelson et al., 2010; Oim and Dynoodt, 2008). Although the net primary production of oil palm is relatively high, more than one-half of the biomass production is usually removed through the harvest of oil palm fruit, leading to decreases in soil carbon stock (Guillaume et al., 2015; Kotowska et al., 2015; van Straaten et al., 2015).

Land convertion from forest to oil palm has also influenced soil fauna assemblages and the processes associated with soil ecosystem functions (Fitzherbert et al., 2008; Foster et al., 2011; Savilaakso et al., 2014). For example, in Danum Valley, Malaysian Borneo, the functional structure and assemblage of ants, termites and beetles was significantly different between oil palm plantations and old growth forests (Gray et al., 2015; Hassall et al., 2006; Luke et al., 2014). Soil biota in oil palm plantations are tend to be dominated by a few abundant generalists, invasive species, and pests (Fitzherbert et al., 2008). For example, the invasive earthworm *Pontoscolex corethrurus* was the only earthworm species found in some Malaysian oil palm plantations (Sabrina et al., 2009a). The reduced species composition and functionality in oil palm plantations suggest such systems may be less resilient to cope with future global changes (Barnes et al., 2014).

3. CROP RESIDUE MANAGEMENT IN OIL PALM PLANTATIONS

The majority of oil palm plantations in Southeast Asia follows an unique spatial arrangement in order to facilitate fertilizer application and harvesting activities (**Figure 1**). Typically, the area of an oil palm plantation is composed of three management zones: the palm circle, the harvesting path, and the inter-row area. The palm circle is a weed-free area surrounding each palm, with a radius of approximately 2 m. This area is cleared to facilitate fruit harvesting and to apply chemical fertilizers. The harvesting path is also a weed-free area approximately 5 m wide, which allows for agriculture-related traffic. The inter-row area is where pruned oil palm fronds are stacked and understorey vegetation is freely grown. EFB is spread at one or both sides of harvesting paths as an organic fertilizer, as well as a means of biomass waste disposal (**Figure 2**).

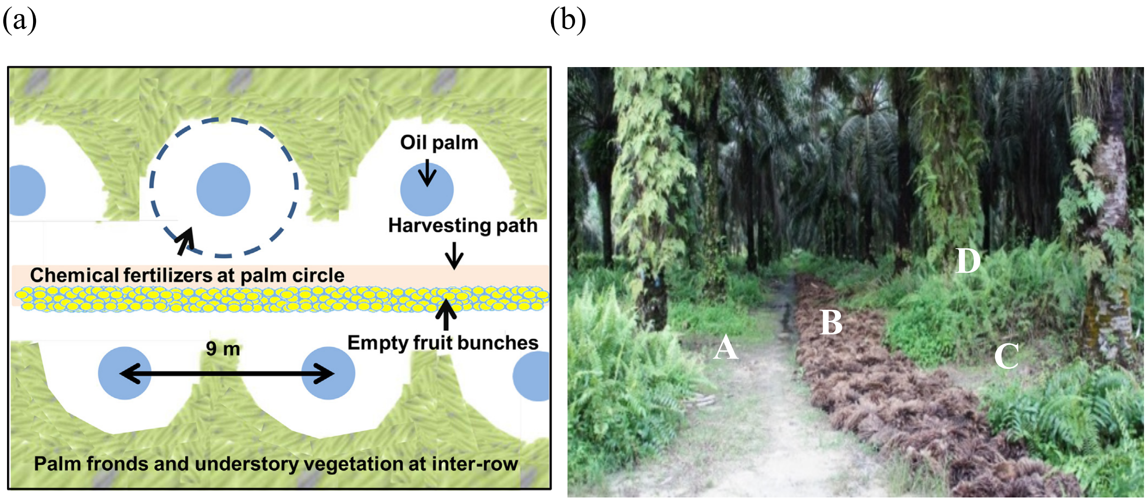

Figure 1: Layout of an oil palm plantation (a), and management zones of an oil palm plantation with EFB application (b): a cleared harvesting path (A), an EFB-applied zone along one side of the harvesting path (B), a palm circle applied with chemical fertilizers (C), and an inter-row area applied with pruned palm fronds, where understorey vegetation is freely grown (D).

Figure 2 EFB spread along the harvesting path (a), and pruned oil palm fronds piled at the inter-row area (b) of an oil palm plantation.

In this thesis, I focus on the management use of two particular oil palm residues: EFB and oil palm fronds as follows:

(1) Empty fruit bunch (EFB)

EFB is a main by-product from palm oil extraction. One ton of fresh fruit bunches processed for palm oil extraction can produce 220-250 kg of EFB (Corley and Tinker, 2015). EFB contains high amounts of lignocellulose and nutrients (**Table 1**), and is used as a soil amendment in oil palm plantations, to provide organic carbon and nutrients to the soil (Chiew and Shimada, 2013). EFB tends to be applied in plantations, which are close to the palm oil mills, in order to reduce transportation costs (Pardon et al., 2016). EFB application rates range between 30-60 t ha^{-1} yr^{-1}, and EFB is spread manually or mechanically along the sides of harvesting paths of mature plantations (Pardon et al., 2016). Supplementary nitrogen fertilizers may be applied on top of the EFB to accelerate the decomposition process (Corley and Tinker, 2015). EFB with supplementary nitrogen fertilizers losses 50% of dry biomass after 2-3 months, and the total decomposition occurs within 6-12 months (Pardon et al., 2016). The decomposition of EFB without the addition of N fertilizer was reported to loss 50% of the dry biomass after 3-4 months of field application in Malaysia (Moradi et al., 2014b).

(2) Oil palm fronds

Oil palm fronds are pruned once every three weeks to create space for the growth of fresh fruit bunches, as a standard practice in commercial oil palm plantations. Similar to EFB, oil palm fronds are rich in carbon and nutrients and can be seen as an effective soil amendment (**Table 1**). Mature oil palms produce 20-24 fronds per year, equivalent to the annual dry weight of 15-35 ton ha^{-1} (Corley and Tinker, 2015). After they are pruned and piled in the inter-row area, palm fronds lose 50% of dry matter within 3-8 months, and decompose fully within 12-18 months (Khalid et al., 2000; Moradi et al., 2014b).

Table 1 The nutrient composition of EFB and oil palm frond.

Nutrient content	EFB	Oil palm frond
	Dry weight (%)	Dry weight (%)
Nitrogen	0.44-0.94	1.24
Phosphorus	0.02-0.05	0.05
Calcium	0.2-0.36	0.64
Magnesium	0.2-0.36	0.07
Potassium	1.3-2.2	1.51
Sodium	0.03	0.02
pH	6.3-7.2	NA
Water content	64-73	65.6
Organic carbon	45-49	50
Cellulose	14-65	NA
Hemicellulose	13-34	NA
Lignin	7.8-34	22.5
Volatile matter	70-84	NA

Source: Chang et al. (2014), Moradi et al. (2014), Kavitha et al. (2013), Budianta et al. (2013), Piarpuzán et al. (2011), Pardon et al. (2016). NA: no information was found in the literature.

4. A SYSTEMATIC REVIEW OF THE EFFECTS OF OIL PALM RESIDUE APPLICATION ON THE SOIL ECOSYSTEM

4.1 INTRODUCTION

Despite an increasing number of studies on oil palm residue management published in recent decades, there has been no comprehensive synthesis of these papers and the data contained in them, to examine the overall effects of this management practice on the soil ecosystem (Chang, 2014; Chiew and Shimada, 2013). There is a need to compile such data to inform field management, highlight research gaps and identify further research directions. A systematic review was therefore performed to extract the results from these papers, to provide a synthesis of the current evidence on EFB and oil palm fronds. A total of thirteen papers was included in this review, with data from sixteen study sites, spanning Malaysia and Indonesia (**Table 2**).

The objectives were to 1) assess the current knowledge regarding the effects of EFB and oil palm frond application on the soil ecosystem, 2) synthesize the evidence to date on the effects of quantity and duration of EFB and oil palm frond application on soil chemical properties, and 3) identify current knowledge gaps. The main findings of these studies can be broadly split into an examination of i) soil chemical properties, including soil organic carbon, total nitrogen, cation exchange capacity, and soil pH; ii) soil physical properties, such as soil bulk density and aggregate stability; and iii) soil biota and soil ecosystem functions, such as abundance and diversity of soil organisms. Existing studies on the effects of crop residue application on oil palm yield were also examined, to understand the potential trade-offs between crop yield and the soil ecosystem improvement under crop residue application (**Table 2**).

Table 2 Thirteen studies included in this review

Reference	**Study location**	**Experimental setup**	**Treatment type**	**Soil properties**
(Abu Bakar et al., 2010)	Peninsular Malaysia	Treatment plots of a 10-year field trial	EFB, chemical fertilizer	Soil chemical properties, crop yield
(Comte et al., 2013)	Central Sumatra, Indonesia	Plantations with EFB and chemical fertilizer treatment	EFB, chemical fertilizer	Soil chemical properties
(Pauli et al., 2014)	Sumatra, Kalimantan, Indonesia	Treatment plots of a four-year field trial	Best management practices, standard estate practices [a]	Soil chemical properties
(Budianta et al., 2010)	South Sumatra, Indonesia	Treatment plots of a two-year field trial	EFB, chemical fertilizer, no input	Soil chemical properties
(Teh et al., 2011)	Peninsular Malaysia	Treatment plots of a six-month field trial	EFB, EFB compost, oil palm frond	Soil chemical properties, soil physical properties
(Haron et al., 1998)	Peninsular Malaysia	Management zones within a plantation	Palm frond (inter-row zone), chemical fertilizer (palm circle), no input (harvesting path)	Soil chemical properties
(Carron et al., 2015a)	Central Sumatra, Indonesia	Management zones within a plantation	Palm frond (inter-row zone), chemical fertilizer (palm circle), no input (harvesting path)	Soil chemical properties, soil biota
(Carron et al., 2015b)	Central Sumatra, Indonesia	Plantations with EFB and chemical fertilizer treatment	EFB, chemical fertilizer	Soil chemical properties, soil biota
(Chiew and Rahman, 2002)	N.D.	Treatment plots of a 2-year field trial	EFB, chemical fertilizer	Soil chemical properties, crop yield

Reference	**Study location**	**Experimental setup**	**Treatment type**	**Soil properties**
(Nelson et al., 2013)	Papua New Guiana, Indonesia	Management zones within a plantation	EFB (EFB-applied zone), palm frond (inter-row zone), chemical fertilizer (palm circle), no input (harvesting path)	Soil ecosystem functions
(Moradi et al., 2015)	Peninsular Malaysia	Treatment plots of a 3-year field trial	EFB, EFB compost, palm frond	Soil physical properties
(Situmorang et al., 2014)	Central Sumatra, Indonesia	Plantations with EFB and chemical fertilizer treatment	EFB, chemical fertilizer	Soil biota
(Donough et al., 2009)	Sumatra, Kalimantan, Indonesia	Treatment plots of a four-year field trial	Best management practices, standard estate practices [a]	Crop yield

[a] Treatment plots with best management practices were applied with EFB and oil palm fronds, as well as reduced amount of chemical fertilizers. Treatment plots with standard estate practices were applied with full amount of chemical fertilizers.

* N.D. : Not identified in the study.

4.2 MATERIALS AND METHODS

4.2.1 SEARCH STRATEGY

The primary data sources in this literature review are peer-reviewed studies, and papers from conference proceedings. Sources of publications were bibliographic databases such as Thomson Reuter's Web of Science, and search engine Google Scholar (**Table 2**). Search terms of "empty fruit bunch" and "palm frond" were used. For inclusion in the review, studies had to report:

1) Experimental treatments with EFB, oil palm fronds or both, with a reference treatment of chemical fertilizer treatment or no input,
2) The corresponding changes in soil chemical properties, soil physical properties, soil biota or soil ecosystem functions, and
3) The quantity and duration of treatments.

Data collected from field trials and commercial oil palm plantations were included. Only studies published in English were included, and no time or geographic limitation was applied **(Table 2**).

4.2.2 DATA SYNTHESIS

Effects of the quantity and duration of EFB and oil palm frond application on soil chemical properties were synthesized from 13 data points of seven studies (**Table 2**). The overall crop residue effects on soil physical properties, soil biota, and ecosystem functions were not statistically tested, due to the scarcity of the data. Studies that measured four key soil chemical properties were examined: soil organic carbon, total nitrogen, cation exchange capacity, and soil pH. The modelling approach was to examine: 1) whether soil chemical properties increase with higher amount of nutrient inputs from crop residue addition; and

2) whether the response of soil chemical properties to crop residue treatment change with the time since application.

The absolute and percent changes in soil chemical properties in response to crop residue application relative to the reference treatment of the same study, were collated before the data synthesis. Through this approach, the intrinsic differences in soil chemical fertility between each study site were taken into account, to clearly identify the treatment effects.

Similarly, the absolute differences in the nutrient input between the crop residue treatment and reference treatment of each study were calculated. The application quantity of crop residues was converted into the equivalent quantity of carbon, nitrogen, and total base cations, using the information of nutrient composition of crop residues reported in the particular study. When the nutrient composition of crop residues was not reported in the study, existing data of conversion rates were used (see **Table 1)**. The nutrient composition of chemical fertilizers was also used in order to calculate the quantity of nutrient input from the reference treatments (**Table 3;** Rankine and Fairhurst, 1999). When not stated in the text, the oil palm density was assumed as 140 palm ha^{-1}, and the rate of oil palm fronds production was 15 ton ha^{-1} yr^{-1} (Moradi et al., 2014b).

Linear regression models were used to test whether differences in the quantity of nutrient inputs from crop residues contributed to changes in the corresponding soil chemical properties. The absolute changes in soil chemical properties as the response variable, and the amount of nutrient inputs as the explanatory variable. Specifically, the changes in soil organic carbon and total nitrogen were modelled against the extra carbon and nitrogen input from crop residue application, compared to the reference treatment. Similarly, soil cation exchange capacity and pH were modelled against the extra base cation input from crop residue application, compared to the reference treatment. It is to note that the relationships between organic carbon input and soil organic carbon concentrations were non-linear. As a result, the explanatory variable of soil organic carbon were log-transformed to better fit the pattern.

The effects of duration of crop residue application on soil chemical properties were further examined using linear regression models. The quadratic terms of the explanatory variables were used when necessary to better fit the pattern. The effects between EFB and oil palm frond application were not compared, due to the scarcity of existing data, and also because some studies used combinations of both crop residues. All the analyses were carried out using R 3.3.1 (R Core Team, 2016).

Table 3 Nutrient composition of common chemical fertilizers used in oil palm plantations

Fertilizer	Nutrient content						
	C	N	P	Ca	Mg	K	Na
Urea		46%					
MOP						50%	
Kieserite					15%		
Dolomite				22%	13%		
Rock phosphate			32%	50%			

Source from: (Rankine and Fairhurst, 1999). MOP: potassium chloride (KCl); Kieserite: magnesium sulfate ($MgSO_4$•H_2O); Dolomite: calcium magnesium carbonate, $CaMg(CO_3)_2$.

4.3 SOIL CHEMICAL PROPERTIES

4.3.1 Effects of the quantity of crop residue application on soil chemical properties

The majority of studies showed positive effects of crop residue application on soil organic carbon, total nitrogen, cation exchange capacity, and soil pH, compared to chemical fertilizer treatment or no input (**Table 4-6**, **Figure 3**). These findings indicate that evidence to date supports the hypothesis that oil palm crop residue is an effective source of soil organic carbon and nutrient, through decomposition and nutrient mineralization (Caliman et al., 2001; Moradi et al., 2014b). Evidence from these studies to date also demonstrates that the changes in soil organic carbon were positively correlated with the quantity of carbon provided from crop residues ($F_{1,10} = 5.58$, $p = 0.04$, $R^2 = 0.36$), suggesting the response of soil organic carbon to oil palm residue addition is dosage-dependent (**Figure 3**).

Evidence from studies to date showed that soil cation exchange capacity and pH did not change with the quantity of base cation input from the crop residue application (**Figure 3**). This indicates that the nutrient retention capacity of the soil remained similar, while there was a large amount of base cation input from crop residues with higher quantity. The excess nutrients, therefore, are likely to be lost through pathways such as leaching, surface runoff, erosion, or volatilization (Allen et al., 2015; Guillaume et al., 2015; Pardon et al., 2016). The cation exchange capacity in the soil is known to increase with higher amounts of soil organic matter and clay minerals (Parfitt et al., 2008). Results from the synthesis indicate that the soil organic carbon concentration enhanced by high quantity of crop residues did increase cation exchange capacity. It is likely due to low soil pH conditions in some of these studies, as soil pH is known to regulate the influences of organic matter on cation exchange capacity (Helling et al., 1995).

Similarly, evidence from studies to date show that soil total nitrogen levels did not significantly increase with higher quantity of nitrogen inputs from crop residues. A possible reason is that the nitrogen may be largely immobilized by soil microorganisms, due to the high C/N ratio of EFB and oil palm fronds (Moradi et al., 2004) (**Table 1**). Immobilization of nitrogen within 10 months of EFB application has also been observed in Malaysian and

Indonesian oil palm plantations (Caliman et al., 2001; Zaharah and Lim, 2000). The unchanged soil nitrogen level may also be due to the limited capacity of soil to hold the nutrients, and that the nitrogen can be lost through leaching, runoff, and volatilization (Pardon et al., 2016).

Table 4. Summary of carbon input and soil organic carbon concentrations under oil palm residue treatments and reference treatments.

Reference	**Input: Organic carbon (ton ha^{-1} yr^{-1})**					**Soil response : soil organic carbon (%)**			Years of application
	Crop residue treatment		Reference treatment		Input difference [a]	Crop residue treatment	Reference treatment	Actual and percent increase [d]	
	Type	Quantity	Type	Quantity					
(Abu Bakar et al., 2010)	EFB	9.8	Chemical	0	9.8	2.50	1.50	1.00 (66.7)	10
		20			20	2.80	1.50	1.30 (86.7)	
(Comte et al., 2013)	EFB	20	Chemical	0	20	4.20	2.80	1.40 (50.0)	7
(Pauli et al., 2014)	EFB+ Frond + Chemical	NA	Chemical	NA	NA	2.20	2.20	0 (0)	4
(Budianta et al., 2010)	EFB	17.6	No input	0	17.6	2.64	1.53	1.10 (72.5)	1-4
(Carron et al., 2015b)	EFB +Chemical	13.2	Chemical	0	13.2	3.08	1.95	1.13 (57.9)	2
(Haron et al., 1998)	Frond	4.8	No input	0	4.8	0.82	0.84	-0.02 (-2.4)	5
						2.47	1.53	0.94 (61.4)	10
						3.09	2.00	1.09 (54.5)	20
(Carron et al., 2015a)	Frond +Chemical	7.5	Chemical [b]	0	7.5	2.00	2.30	-0.30 (-13.0)	N.D.
			Chemical [c]			2.00	1.60	0.40 (25.0)	25

[a] Input difference: the difference in the quantity of nutrient input between the crop residue treatment and reference treatment of each study. [b] The reference treatment was the chemical fertilizer treatment in the palm circle. [c] The reference treatment was the chemical fertilizer treatment at the harvesting path. [d] The actual increase and percent increase (%, in parentheses) are the differences in soil organic carbon concentrations between the crop residue treatment and reference treatment of each study. Frond: oil palm frond; Chemical: chemical fertilizers; N.D.: not identified.

Table 5. Summary of nitrogen input and soil nitrogen concentrations under oil palm residue treatments and reference treatments.

Reference	**Input: Nitrogen (kg ha^{-1} yr^{-1})**					**Soil response: soil total nitrogen (%)**			Years of application
	Crop residue treatment		Reference treatment		Input quantity difference [a]	Crop residue treatment	Reference treatment	Actual and percent increase [d]	
	Type	Quantity	Type	Quantity					
(Pauli et al., 2014)	EFB+ Frond + Chemical	283	Chemical	146	137	0.17	0.16	0.01 (6.25)	4
(Abu Bakar et al., 2010)	EFB	153	Chemical	192	-39	0.15	0.13	0.02 (15.4)	10
		306		192	114	0.22	0.13	0.09 (69.2)	
(Comte et al., 2013)	EFB	135	Chemical	196	-61	0.24	0.12	0.12 (100.0)	7
(Budianta et al., 2010)	EFB	176	No input	0	176	0.23	0.13	0.10 (76.9)	1-4
(Haron et al., 1998)	Frond	124	No input	0	124	0.09	0.08	0.01 (14.8)	5
						0.20	0.14	0.06 (39.0)	10
						0.20	0.13	0.07 (53.1)	20
(Carron et al., 2015a)	Frond + Chemical	49	Chemical [b]	43	6	0.14	0.18	-0.04 (-22.2)	N.D.
		49	Chemical [c]	126	-77	0.14	0.11	0.03 (27.3)	
(Carron et al., 2015b)	EFB + Chemical	239	Chemical	54	185	0.22	0.07	0.15 (214.3)	2

[a] Input difference: the difference in the quantity of nutrient input between the crop residue and the reference treatment of each study. [b] The reference treatment was the chemical fertilizer treatment in the palm circle. [c] The reference treatment was the chemical fertilizer treatment at the harvesting path. [d] The actual increase and percent increase (%, in parentheses) are the differences in soil nitrogen concentrations between the crop residue and the reference treatment of each study. Chemical: chemical fertilizers. N.D.: not identified.

Table 6. Summary of base cation inputs, soil CEC and pH under oil palm residue and reference treatments

Reference	**input: Base cation (kg ha^{-1} yr^{-1})** [e]					**Soil responses**		Years of application
	Crop residue treatment		Reference treatment		Input quantity difference [a]	CEC	pH	
	Type	Quantity	Type	Quantity		Unit (cmol/kg) and percent increase [d]	Unit and percent increase [d]	
(Abu Bakar et al., 2010)	EFB	520	Chemical	518	2	3.0 (37.5%)	1.0 (22.2%)	10
		1040			522	5.5 (68.8%)	2.0 (44.4%)	10
(Comte et al., 2013)	EFB	455	Chemical	284	171	4.0 (57.1%)	0.5 (12.5%)	7
(Teh et al., 2011)	EFB	3280	Frond	351	2930	0.9 (N.D.)	1.0(N.D.)	1-6 month
(Budianta et al., 2010)	EFB	936	No input	0	936	0.2 (1.6%)	1.0 (19.1)	1-4
(Pauli et al., 2014)	EFB + Frond + Chemical	505	Chemical	212	293	0 (0)	0 (0)	4
(Carron et al., 2015a)	Frond + Chemical	229	Chemical [b]	59	170	-3.8 (-44.4%)	-0.1 (-2.0%)	N.D.
		229	Chemical [c]	175	54	1.4 (43.3%)	-0.2 (-4.0%)	N.D.
(Carron et al., 2015b)	EFB + Chemical	727	Chemical	164	563	1.8 (228.6%)	0.2 (3.8%)	2

[a] Input difference: the difference in the quantity of nutrient input between the crop residue and reference treatment of each study. [b] The reference treatment was the chemical fertilizer treatment in the palm circle. [c] The reference treatment was the chemical fertilizer treatment at the harvesting path. [d] The actual increase and percent increase (%, in parentheses) are the differences in cation exchange capacity and pH between the crop residue and the reference treatment of each study. [e] The base cation input was calculated as the sum of four base cations if applicable: potassium, calcium, magnesium, and sodium. Chemical: chemical fertilizers. Frond: oil palm fronds. N.D.: not identified. CEC: cation exchange capacity.

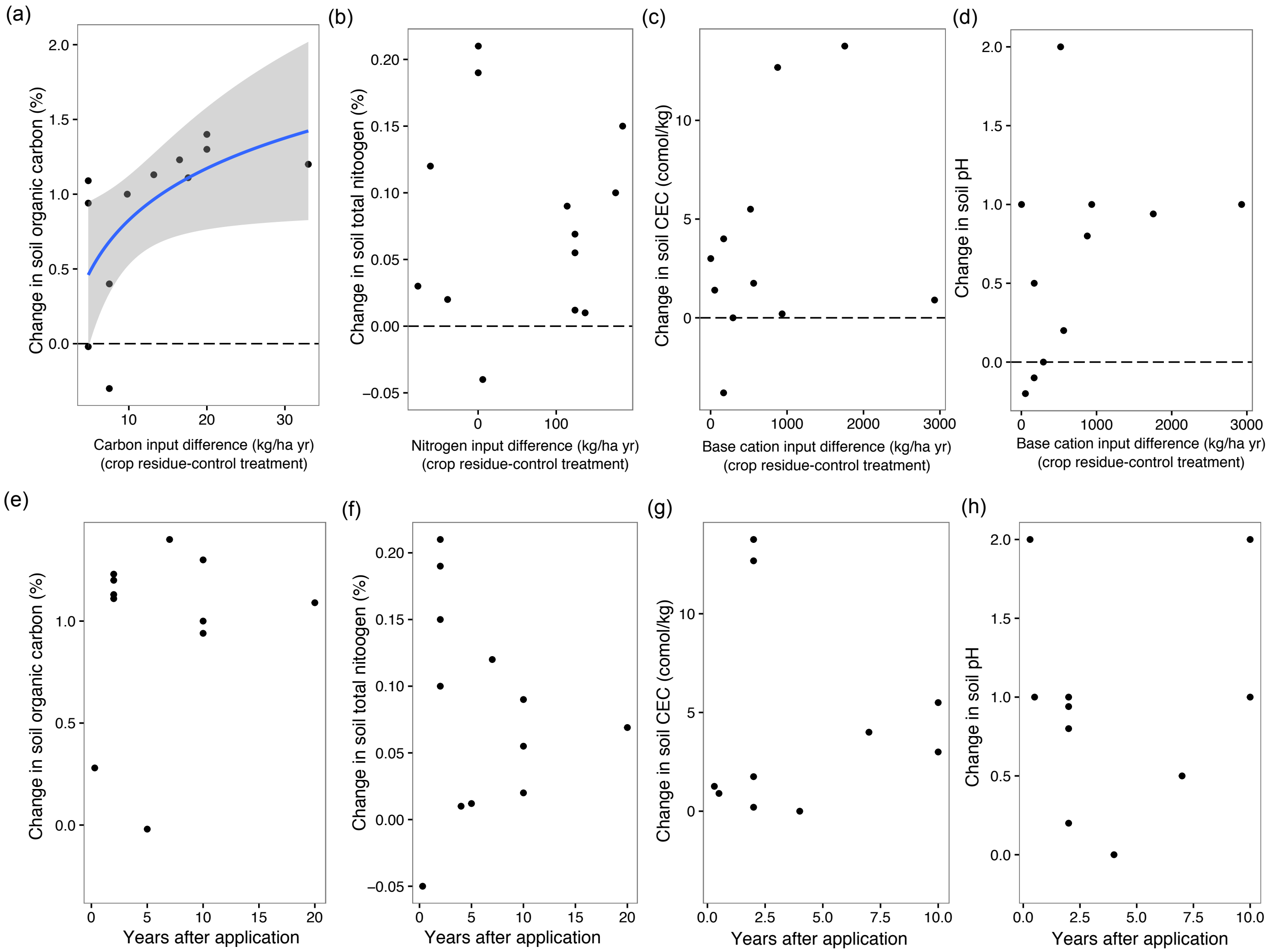

Figure 3 Effects of the nutrient quantity (a-e), and the duration (e-h) of crop residue application on soil organic carbon (a, e), total nitrogen (b, f), cation exchange capacity (c, g), and soil pH (d, h).

4.3.2 Effects of the duration of crop residue application on soil chemical properties

The duration of EFB and oil palm frond application of the field trials of the reviewed studies ranged between 15 weeks to 20 years (**Table 4-6**). Most of the studies measured the responses of soil chemical properties once after the application. Only one study was found to use the "space-for-time" approach (chrono-sequence approach) to examine plantations with different duration of EFB application (Carron et al., 2015b). The authors examined commercial plantations applied with EFB from 0-24 months, and found a steady increase in soil organic carbon over time.

After compiling the data points from the reviewed studies, it was apparent that soil organic carbon did not change with the duration of crop residue application (**Figure 3**). This finding suggests that the organic carbon may have a fast turnover rate, or the low carbon storage capacity of the soil (Goodrick et al., 2015; Ni'matul et al., 2015). Similarly, total nitrogen, cation exchange capacity, and soil pH did not respond to the duration of the crop residue application, suggesting that the exceeding nutrients may be largely lost due to the low nutrient retention capacity, or through oil palm uptake (Pardon et al., 2016).

The other possible explanation for the lack of the relationships between the duration of crop residue application and soil chemical properties may be due to the differences in the site characteristics of each study. For example, soil types, age of oil palm, climatic conditions, and previous land use type can largely influence the effects of crop residue application on the soil ecosystem (Blanco-Canqui and Lal, 2009). To reduce the data variability, repeated measurements of soil chemical properties throughout the crop residue application period at same study sites are needed.

4.3 SOIL PHYSICAL PROPERTIES

Positive effects of oil palm residue application on soil physical properties were observed in three studies (Carron et al., 2015b; Moradi et al., 2015; Teh et al., 2011). In an Indonesian oil palm plantation, for example, the application of EFB for two years appears to have enhanced soil physical properties through transforming a mineral soil layer into an organic matter-rich surface layer with decreased bulk density (Carron et al., 2015b). Moreover, other studies in Malaysian oil palm plantations, which compared the effects of EFB with oil palm fronds have found greater aggregate stability, water holding capacity, and saturated hydraulic conductivity under EFB application (Moradi et al., 2015; Teh et al., 2011). These authors suggest that the improvements in soil physical properties under EFB application may be due to the increase in soil organic carbon, and the enhancement of soil biological processes. For example, Moradi et al. (2015) suggested that the soil organic carbon derived from EFB may stabilize micro- and macro-aggregates by binding humic substances and other microbial by-products. Moradi et al. (2015) also observed that the increase in aggregate stability under EFB application was paralleled with soil microbial population growth, suggesting that the excretion of mucilaginous products by microorganisms may be effective in binding soil particles and thus in improving soil structure.

4.4 SOIL BIOTA AND SOIL ECOSYSTEM FUNCTIONS

There are two studies to date that have demonstrated the positive influences of EFB application on soil microorganisms, microfauna, and macrofauna (Carron et al., 2015b; Situmorang et al., 2014). In these studies, EFB application appears to enhance bacterial populations associated with symbiotic N fixation and cellulose degradation, compared to the chemical fertilizer treatment (Situmorang et al., 2014). Carron et al. (2015b) also found temporal successions and shifts in dominant functional groups of soil macrofauna and nematodes, over two years of EFB application in an Indonesian plantation. Specifically, a marked decrease in earthworm, millipede, and nematode populations was observed after six months of application, followed by a subsequent increase toward the end of the application. Carron et al. (2015b) suggested that the changes in soil communities under EFB is likely to be associated with the changes in soil chemical properties. For example, a decline in earthworm abundance after 0-6 months of EFB application paralleled with a decrease in soil organic carbon; while the recovery of earthworm abundance following 18-24 months of application was positively correlated to the clay content of the soil. Therefore, these findings indicate that EFB application may influence soil biota through enhancing soil organic carbon and mediating soil physicochemical properties. However, these possible relationships have not yet been quantitatively examined.

No studies to date have examined the effects of EFB and oil palm frond application on soil ecosystem functions. There have been some indirect findings, however, to suggest there may be significant impacts. For example, a study of soil respiration in oil palm plantations in Papua New Guinea found a higher soil respiration rate in areas underneath the EFB (Nelson et al., 2013). However, this study did not distinguish between root respiration and heterotrophic respiration by soil organisms. A significant research gap that has emerged from the existing literature, therefore, is the effects of oil palm residues on the soil processes that underpin ecosystem functions, such as litter decomposition, soil fauna activity, and microbial respiration.

4.5 CROP YIELD

Results from three studies have shown positive effects of EFB application on crop yield of Malaysian and Indonesian oil palms (Abu Bakar et al., 2010; Chiew and Rahman, 2002; Donough et al., 2009). Abu Bakar et al. (2010) also found that the effects of EFB addition on crop yield was dosage-dependent. Specifically, EFB application at a rate of 44 ton ha^{-1} yr^{-1} for ten years significantly improved crop yield compared to chemical fertilizer treatment, while EFB application at a lower rate of 22 ton ha^{-1} yr^{-1} did not show significant improvements in crop yield. The authors of these studies suggested that EFB application may improve crop yield through increasing soil organic carbon and nutrient availability (Abu Bakar et al., 2010; Chiew and Rahman, 2002; Donough et al., 2009), yet these possible associations have not been statistically tested.

4.6 KEY FINDINGS FROM EXISTING LITERATURE

Overall, the critical information from existing literature on the effects of oil palm residue application on soil physicochemical properties, soil biota and soil ecosystem functions is summarized below:

1. Evidence to date suggests that EFB and oil palm frond application positively influences soil chemical properties, including soil organic carbon, total nitrogen, cation exchange capacity, and soil pH. Soil organic carbon is positively correlated with the quantity of carbon provided from crop residues. In contrast, soil total nitrogen, cation exchange capacity, and pH do not appear to change with the quantity of nutrient input from crop residues.
2. EFB and oil palm frond application improves soil physical properties, such as soil aggregate stability and water holding capacity.

3. EFB and oil palm frond application can contribute to temporal successions and shifts in dominant groups of soil biota, as well as the abundance of the soil biota.
4. EFB application can enhance crop yield after 2-10 years of treatment, but the effects are dependent on the application rate.

4.7 KNOWLEDGE GAPS

Three key knowledge gaps were identified from the literature review:

1. The effects of crop residue application on the overall soil ecosystem functions in oil palm plantations. Specifically, how does crop residue application influence soil ecosystem functions by altering soil physicochemical properties and soil biota? Does shifting from chemical fertilizer treatment to crop residue application lead to changes in the potential relationships between these key components?
2. The temporal changes in soil chemical properties under crop residue application. Specifically, how does crop residue application affect the temporal variability in soil chemical properties? Does the magnitude of the effects change with different application rates of crop residues?
3. The effects of crop residue application on crop yield. Specifically, how does crop residue application influence total crop yield, and the temporal variability in this yield? Does crop residue application influence crop yield via soil abiotic properties? In addition to crop residue application, what are other determining factors, such as climatic conditions, may contribute to temporal changes in crop yield?

Answers to these questions will contribute to the vital knowledge of the effects of crop residue application on soil quality, soil biota, ecosystem functions and crop yield in oil palm plantations. The findings can be useful information for improving sustainable development of oil palm plantations.

5. RESEARCH AIMS AND OBJECTIVES

Given the key knowledge gaps identified from the literature review, the primary goal of the work presented in this thesis is to understand the mechanisms underlying the effects of oil palm residue application on soil fertility, soil biota and their ecosystem functions for sustaining the oil palm ecosystem.

The main research questions addressed in this thesis are as follows:

1. What impacts does forest conversion to oil palm have on soil ecosystem functions – specifically those associated with litter decomposition rate and soil fauna feeding activity? **(Chapter 2)**
2. How does soil fauna feeding activity respond to different soil management practices in oil palm plantations? **(Chapter 3)**
3. What are the cascading effects of EFB application on soil physicochemical properties, soil biota, and ecosystem functions? **(Chapter 4)**
4. How does 15 years of EFB application influence crop yield and the temporal variations in this yield under a changing climate? (**Chapter 5**)

6. THESIS OUTLINE

Chapter 2 aims to understand how the land conversion from secondary forest to oil palm may lead to changes in two soil ecosystem functions: leaf litter decomposition rate, and soil fauna feeding activity. I examined these ecosystem functions in (1) a secondary forest, 2) an oil palm plantation with chemical fertilizer treatment, and 3) an oil palm plantation with EFB application in Central Sumatra, Indonesia. A litterbag experiment was used to determine leaf litter decomposition rates, and a bait lamina assay was used to examine the foraging activity of soil communities. The understanding of these soil ecosystem functions in secondary forest is important, as it reveals the nutrient cycling processes in the natural ecosystem before the agricultural development in this study area. This information serves as a crucial baseline for further exploration on how soil management practices influence soil processes within the oil palm agroecosystem, in subsequent chapters.

Chapter 3 aims to understand the underlying mechanism of how soil management practices contribute to variations in soil fauna feeding activity in different management zones of oil palm plantations. I compared the fauna activity under (1) EFB application zones; (2) palm circles with chemical fertilizers; (3) inter-row areas with pruned oil palm fronds; and (4) cleared harvesting paths without fertilizer input. I further examined whether the variations in soil fauna feeding activity in different management zones were associated with soil chemical properties. This chapter is important to understand how soil management practices may influence soil ecosystem functions within the oil palm plantations, and to identify the soil management practice with the highest potential for enhancing soil ecosystem functions of oil palm plantations. Understanding the links between soil chemical properties and soil fauna feeding activity also provides a basis for a more detailed examination of soil ecosystem functions in the next chapter.

Chapter 4 aims to understand the cascading effects of EFB application on soil abiotic properties, soil biota, and ecosystem functions under EFB application. The indicators examined in this study were: (1) soil abiotic properties, including soil organic carbon, total nitrogen, soil pH, base saturation, aggregate stability, and bulk density; (2) soil biota, including soil mites and earthworms; (3) soil ecosystem functions, including soil fauna feeding activity, and soil microbial respiration. The measurement was conducted at the end of a 15-year EFB trial in Sumatra, Indonesia. I hypothesized that EFB application would enhance these soil ecosystem functions by providing food resources, altering soil physicochemical properties, and influencing soil biota communities. The changes in the relationships of these key components were examined using structural equation modelling. The results could contribute to vital knowledge on the underlying mechanisms of EFB application effects on soil ecosystem functions of oil palm plantations.

Chapter 5 aims to understand how crop productivity responds to EFB application under a changing climate. Specifically, I examined whether 15 years of EFB application contributed to an increase in total crop yield, and how the application may influence the temporal variability of the yield. I further examined the determining factors for temporal changes in crop yield, including climatic conditions, and soil organic carbon levels that may be mediated by EFB application. To answer these questions, I used existing data of crop yield, soil chemical properties, and climatic variables collected throughout 15 years of EFB application at a field trial in Sumatra, Indonesia. These results provide useful baseline information to understand the crop production performance under degrading soil conditions and changing climate.

7. STUDY AREA AND METHODOLOGICAL APPROACH

7.1 STUDY AREA

The study was carried out in oil palm plantations and field trial plots in Riau Province, Central Sumatra, Indonesia (**Figure 4**). These plantations were established between 1987-1998, and are certified by the Roundtable on Sustainable Palm Oil (RSPO). The climate of this region is described as tropical humid, with an average rainfall of 2350 mm yr^{-1}, and average monthly temperature ranging from 26-29°C. The soils are Inceptisols (Typic Dystrudepts), within the loamy lowland soil class.

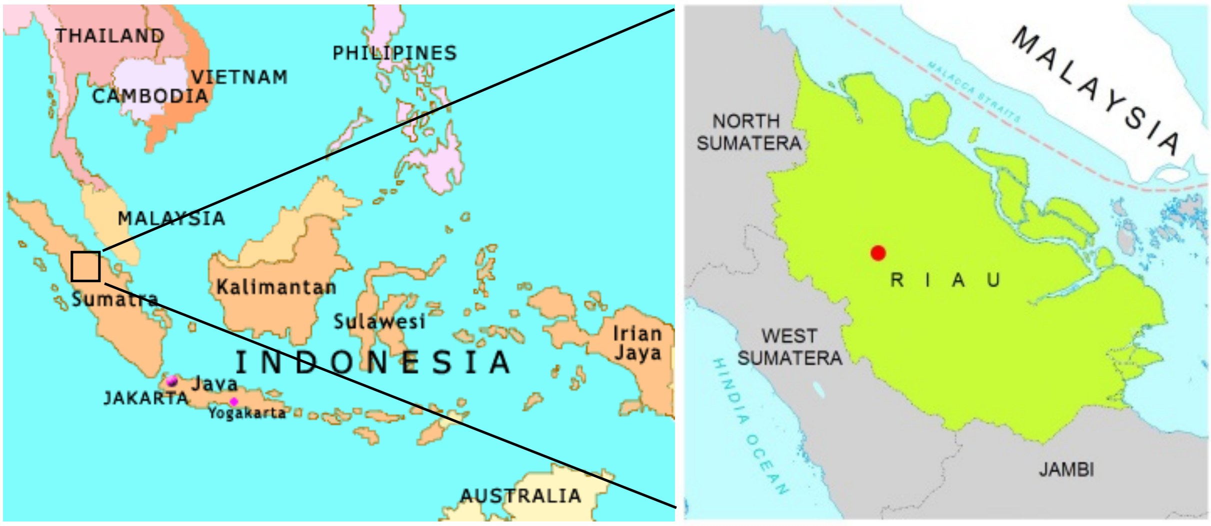

Figure 4. Map of the study site in Central Sumatra, Indonesia. The box represents the location of Riau province. The study site, shown in the red dot, is located within the Riau province.

7.2 DATA COLLECTION AND ANALYSIS

For Chapter 2 and 3, field data was collected from oil palm plantations in the Rama Rama Estate, and a nearby Dipterocarp forest, during July-August 2013. Chapter 4 and Chapter 5 used a long-term EFB field trial in the Palapa Estate. Data for Chapter 4 was collected during September-October 2014. Data for Chapter 5 was collected by the SMART Research Institute during 1998-2013.

The field trial for Chapter 4 and Chapter 5 covered a total area of 60 ha, and was composed of five replicate blocks, with treatment plots randomly allocated within each block (**Figure 5**). The treatment plots include (1) Low-EFB treatment with an application rate of 210 kg tree^{-1} yr^{-1}, equivalent to 30 t ha^{-1} yr^{-1}, (2) Medium-EFB treatment with an application rate of 420 kg tree^{-1} yr^{-1}, equivalent to 60 t ha^{-1} yr^{-1}, (3) High-EFB treatment with an application rate of 630 kg tree^{-1} yr^{-1}, equivalent to 90 t ha^{-1} yr^{-1}, and (4) Chemical fertilizer treatment without the addition of EFB, as the reference treatment of the trial.

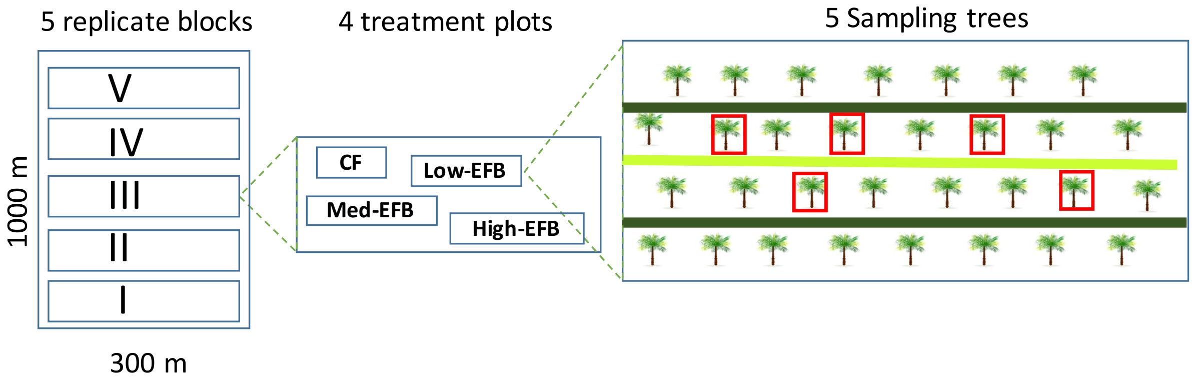

Figure 5. Diagram of the long-term EFB field trial used in Chapter 4 and 5. CF: chemical fertilizer treatment.

The field sampling involved the measurement of soil chemical, physical, and biological properties. Soil samples were collected using augers or metal rings. Soil chemical and physical analyses were conducted in the laboratories of the SMART Research Institute. Earthworms were collected and measured following the Tropical Soil Biology and Fertility method (Swift et al., 2008). Soil mesofauna were extracted using modified Tullgren funnels developed in the field. Soil microbial respiration was determined by the soil burst assay (Solvita respiration kit, Woods End Laboratory, USA), and soil fauna feeding activity measured using the bait lamina assay (Terra Protecta GmbH, Berlin, Germany). Statistical analyses including mixed effects models, principal components analysis, and structural equation modelling were used in this study.

CHAPTER 2

THE IMPACTS OF FOREST CONVERSION TO OIL PALM ON SOIL ECOSYSTEM FUNCTIONS IN SUMATRA, INDONESIA

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ABSTRACT

Land use change from tropical forests to oil palm plantations has been shown to affect soil properties that underpin ecosystem functions, such as nutrient cycling. However, the effects of this land conversion on nutrient cycling-associated soil processes remain largely unknown. In this study, we examined leaf litter decomposition rate and soil fauna feeding activity in: 1) a secondary forest, 2) an oil palm plantation with chemical fertilizer treatment, and 3) an oil palm plantation with empty fruit bunch (EFB) application, in Central Sumatra, Indonesia. Within the oil palm plantations, leaf litter decomposition and soil fauna feeding activity were examined at three management zones: palm circles, harvesting paths, and palm frond-applied zones, as well as an EFB-applied zones in oil palm plantation with crop residue application. Our results showed that litter decomposition rate did not differ between secondary forest and oil palm plantations. In contrast, soil fauna feeding activity was significantly lower in secondary forest compared to EFB-applied zones of oil palm plantation with EFB application, and was also lower than all the management zones of oil palm plantation with chemical fertilizer treatment. The different responses of the litter decomposition rate and the soil fauna feeding activity to land use change indicate the complexity of the soil processes that contribute to nutrient cycling and soil fertility.

keywords: bait lamina assay, land use change, soil moisture, litterbag, soil fauna feeding activity, leaf litter decomposition

1. INTRODUCTION

Large areas of natural forests have been converted to agricultural fields in the tropics (Gibbs et al., 2010). In Southeast Asia, the reduction in forest cover and forest fragmentation is primarily due to the establishment of oil palm (*Elaeis guineensis*) (Gilbert, 2012; Sayer et al., 2012). Forest conversion to oil palm has raised various environmental concerns, and soil degradation is one of the most pressing issues (Hartemink, 2005; Sayer et al., 2012). For example, converting forest to oil palm can negatively influence soil abiotic properties, including a reduction in soil organic carbon level, an increase in soil compaction, and soil acidification (Guillaume et al., 2015; Hardwick et al., 2015; Nelson et al., 2010; Tanaka et al., 2009). Land conversion from forest to oil palm can also influence the functional structure and assemblage of soil fauna (Fitzherbert et al., 2008; Foster et al., 2011; Gray et al., 2015). However, very few studies to date have examined the changes in the underlying soil processes and functions following land conversion (Gray et al., 2015; Gray and Lewis, 2014).

Litter decomposition is fundamental for nutrient cycling and carbon sequestration (Sayer, 2006; Swift et al., 1979). The rate of litter decomposition is mainly regulated by three elements: litter quality, climate, and decomposer organisms (Couteaux et al., 1995). In oil palm plantations, the microclimate and activities of decomposer organisms are influenced when converting primary and secondary forest to oil palm in Malaysian Borneo (Hardwick et al., 2015; Hassall et al., 2006; Luke et al., 2014). Leaf litter type also changed from mixed forest species to oil palm fronds upon land conversion. Therefore, litter decomposition processes are likely to differ between these two land uses. Few studies, however, have examined litter decomposition between the forest and oil palm ecosystems, and the results from these studies are contradictory (Foster et al., 2011; Violita et al., 2015).

Oil palm plantations have unique soil management zones that may exhibit different litter decomposition processes, due to variations in nutrient input, microclimate, and human disturbance. Three major management zones of oil palm plantations are palm circles, harvesting paths, and the inter-row area. The palm circle is the weed-free area which surrounds palm trunks, and is the main area receiving chemical fertilizers. The harvesting path is used for daily traffic and agricultural activities. The inter-row area is where pruned oil palm fronds are piled and understory vegetation is freely grown. In some oil palm plantations, additional oil palm residues are applied as organic fertilizers. The major oil palm residue is empty fruit bunch (EFB), a by-product of palm oil extraction. EFB is generally mulched at one side of harvesting paths. Previous studies reveal that the soil management zones of oil palm plantations differ in soil abiotic and biotic properties, such as soil organic carbon, soil pH, and soil fauna abundance (Carron et al., 2015a; Goodrick et al., 2015; Ni’matul et al., 2015). However, to date little is known about the potential variations in litter decomposition of these management zones.

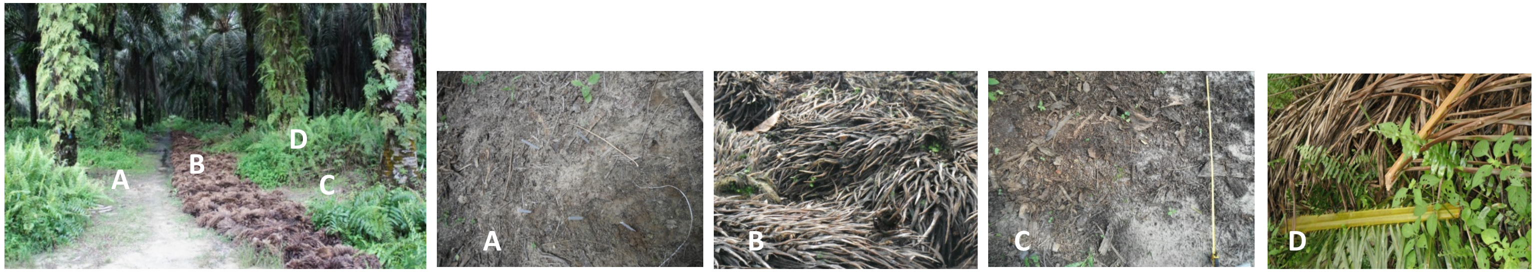
The aim of this study was to understand how forest conversion to oil palm influences litter decomposition, with a detailed examination on spatial variations between management zones of oil palm plantations. We examined litter decomposition in: 1) a secondary forest, 2) an oil palm plantation with chemical fertilizer treatment, and 3) an oil palm plantation with EFB application, in Central Sumatra, Indonesia. We examined litter decomposition processes using two techniques: a litterbag experiment and a bait lamina assay. The litterbag experiment is common method for measuring leaf litter decomposition rate (Moreira et al., 2008). The bait lamina assay uses standard bait (cellulose, active carbon, and bran flakes) to determine foraging activities of soil fauna (Von Törne, 1990).

2. MATERIALS AND METHODS

2.1 SITE DESCRIPTION

The research was undertaken in two oil palm plantations and a nearby secondary forest in Kampar District, Riau Province, Sumatra. The climate of this region is tropical humid with an average rainfall of 2400 mm year^{-1} (230 mm month^{-1} in the wet season, 140 mm month^{-1} in the dry season), and the average monthly temperature ranges from 26 to 32°C (Comte et al., 2013). The secondary forest is dominated by Dipterocarp species, and is co-managed by the Indonesian Department of Forestry, the SMART Research Institute and the local communities. The secondary forest was young with open canopy, with a substantial degree of human disturbance (eg. traffic, planting of economic crops). The soil type of the secondary forest is Typic Dystrudepts with the loamy upland soil class (USDA soil classification system). The adjacent 20-year old oil palm plantations were converted from the Dipterocarp forest in 1992 and have been managed by SMART Research Institute. The management practices and fertilizer input of the four management zones within the oil palm plantations are detailed in **Table 1**.

Table 1. Summary of the fertilizer input for each management zone of the oil palm plantation with chemical fertilizer treatment, and the oil palm plantation with EFB application at our study site.



	Management zone	Description	Fertilizer input (kg tree^{-1} year^{-1})	
			Oil palm with chemical fertilizer treatment	Oil palm with EFB application
A	Harvesting path	A weed-free area which facilitates traffic and agricultural activities.	Rock phosphate (2.5)	None
B	EFB-applied zone	One side of the harvesting path applied with EFB. This zone is only found in oil palm plantations with crop residue application.	None	EFB (210) Rock phosphate (1)
C	Palm circle	A weed-free area surrounding palm trunks.	Urea (1.5) Kieserite / Dolomite (1)	Urea (0.5) Kieserite / Dolomite (1)
D	Palm frond-applied zone	The inter-row area with oil palm frond.	None	None

Kieserite: magnesium sulfate ($MgSO_4 \cdot H_2O$); Dolomite: calcium magnesium carbonate, $CaMg(CO_3)_2$.

2.2 EXPERIMENTAL DESIGN

Three sampling plots were randomly chosen within the secondary forest. The size of the forest sampling plots was 400 m^2 (20 m x 20 m). Each sampling plot was at least 300 m from other sampling areas, 50 m from forest edge, and 100 m from the nearest stream. Within each sampling plot, six sampling points were chosen, which were at least 10 m apart from the adjacent sampling point. This design led to a total of 18 sampling points in the secondary forest.

Sampling plots for oil palm plantations were selected using the following criteria: i) The soil types were the same, namely Typic Dystrudepts; ii) Sampling plots of oil palm plantation with EFB application have had EFB applied yearly or every two years for at least eight years, and the last application was in 2012 (i.e. within 6-18 months of the field study); iii) Sampling plots of oil palm plantation with chemical fertilizer treatment were manually applied with chemical-fertilizers, rather than using aerial fertilization.

Based on the selection criteria, three sampling plots were selected for oil palm plantations with chemical fertilizer treatment, and three sampling plots were selected for oil palm plantations with EFB application (**Supplementary S1**). The size of the oil palm sampling plots ranged between 2000 to 9000 m^2. These sampling plots were at least 150 m apart. Six focal palms within each sampling plot were selected, and the distance between each focal palm was at least 9 m apart. At each focal palm, litter decomposition rate and soil fauna feeding activity were measured within the nearest management zones of the harvesting path, palm circle, and palm frond-applied zone. For oil palm plantations with EFB application, the EFB-applied zone was also measured. This design led to a total of 72 sampling points in the oil palm plantation with EFB application, and 54 sampling points in the oil palm plantation with chemical fertilizer treatment.

The field measurements were carried out in July 2013, during the dry season. For the litterbag method, each bag (20 × 20 cm) was made of 1.5 mm fiberglass mesh (Premier Netting, Norfolk, UK). The mesh allows access by bacteria, fungal hyphae, nematodes, protozoa, and mesofauna such as Acari, Collembola, while restricting access by macrofauna (>2 mm) (Swift et al., 1979). The substrate in the litterbags was fresh oil palm fronds, collected from commercial oil palm plantations before the experiment. The midribs of the fronds were removed, and the remaining parts were cut into pieces of 4 × 2 cm. The leaf pieces were then oven-dried at 70 °C for 3- 4 days, before putting 15 g dry weight into each bag. The litterbags were sealed by stapler and Nylon line.

At each of the sampling points, two litterbags were placed with the distance of 30 cm of each other, beneath the litter layer. One of the litterbags were collected after 17 days of incubation, and the other was collected after 45 days. Following retrieval, each litterbag was air- dried for 1-2 days. The sand and dirt on the surface of the litter substrate were then brushed and sieved. The substrate was then dried at 70 °C for 3 days before weighing.

The bait lamina sticks (Terra Protecta GmbH, Berlin, Germany) were PVC strips (1 × 6 × 120 mm) with 16 apertures of 1.5 mm diameter and 5 mm apart (Kratz, 1998) (**Supplementary S2**). The bait used in the apertures was made of cellulose powder, bran flakes and active carbon (70:27:3). At each of the sampling points, a matrix of six sticks was placed in a 12 cm x 24 cm grid, in which the sticks were 12 cm apart from each other. The sticks were inserted vertically until the top aperture reached just below the soil surface, and the bottom aperture was at a depth of 8 cm below the soil surface. A total of 864 sticks were used at 144 sampling points. All the sticks were inserted into the soil on 16 July 2013 and collected after 6 days of exposure, and each aperture was recorded as 0 (without perforation) or 1 (partial or complete perforation). At each of the sampling points, soil moisture, electrical conductivity and soil temperature were measured three times during the bait lamina exposure period using a WET sensor (Delta-T Device, Cambridge, UK).

2.3 STATISTICAL ANALYSIS

All the analyses were carried out using the *lme* and *glmer* functions in the *lme4* package for the R software version 3.0.2 (R Core Team, 2012).

Generalized linear mixed effects models were used to test whether leaf litter decomposition rate differed between secondary forest and various management zones of oil palm. Two types of oil palm plantations were examined: oil palm with EFB application, and oil palm with chemical fertilizer treatment. For oil palm with EFB application, four management zones were examined: EFB applied zone, palm circle, palm frond-applied zone, and harvesting path. For oil palm with chemical fertilizer treatment, three management zones were examined: palm circle, palm frond-applied zone, and harvesting path. The land use type (including management zones of oil palm and secondary forest) was fitted as the fixed effects, and the remaining leaf mass of litterbags was fitted as the response variable. As the remaining leaf mass of litterbags is proportional data, the binomial distribution was used in the model. The random effects included sampling points nested within each of the three sampling plots. The two collection time points (17 and 45 days after the litterbag incubation) were also included as the random effects to account for repeated measures. The model in the R-syntax was therefore: remain leaf mass of litterbag~ management zones of oil palm and secondary forest + (1|plot/sampling point) + (1|day of litterbag collection), family=binomial. The explanatory power of the fixed effect was tested by comparing with a null model.

Similarly, generalized linear mixed effects models were used to test whether soil fauna feeding activity differed between secondary forest and oil palms. Datasets of oil palm with the chemical fertilizer treatment and oil palm with EFB application were compared with secondary forest in separate models. The soil fauna feeding activity was fitted as a binomial response variable. The explanatory power of the fixed effect was tested by comparing with a null model.

We further examined how soil environmental conditions differed between secondary forest and oil palms using linear mixed effects models. Soil environmental variables included soil moisture, electric conductivity, and soil temperature. Soil environmental variables were obtained from secondary forest and oil palm with crop residue addition, but not from oil palm with chemical fertilizer treatment. Finally, we used linear regression models to examine the relationships between soil fauna feeding activity and each soil environmental variable.

3. RESULTS

3.1 LEAF LITTER DECOMPOSITION

The mean leaf mass loss of litterbags after 17 and 45 days across the land use type was 78 ± 1.1% (mean ± SE), and 62 ± 1.9%, respectively (**Figure 1**). The decomposition rate did not differ between secondary forest and management zones of oil palms with EFB application, and oil palms with chemical fertilizer treatment over time (**Table 2**).

3.2 SOIL FAUNA FEEDING ACTIVITY

The mean soil fauna feeding activity across land use types, management zones and soil depths was 41% after 6 days of incubation. The soil fauna feeding activity across soil depths was 27 ± 1.1%, 41± 0.7%, and 42 ± 0.6% for secondary forest, oil palm with chemical fertilizer treatment, and oil palm with EFB application, respectively.

Soil fauna feeding activity differed significantly between the land use types (**Table 2**). The *post-hoc* comparisons revealed that all the management zones of the oil palm with chemical fertilizer treatment had significantly higher soil fauna feeding activity than secondary forest (**Figure 2a**). Compared with the management zones of oil palm plantation with EFB application, soil fauna feeding activity in the secondary forest was significantly lower than the EFB-applied zones (**Figure 2b**). Within the oil palm plantation with EFB application, the fauna activity in the EFB- applied zone was significantly higher than other management zones, while fauna activity was significantly lower in palm circles than other management zones (**Figure 2b**).

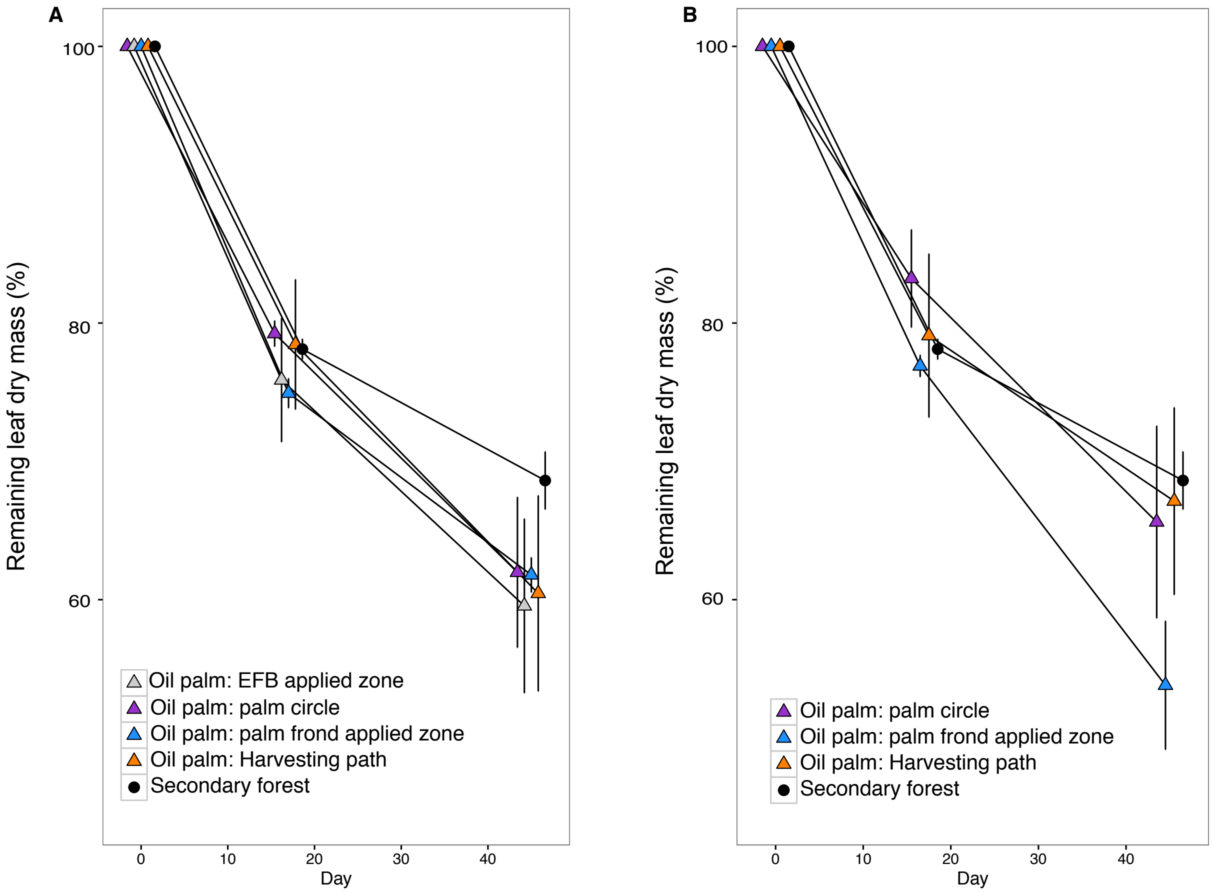


Figure 1. The remaining leaf mass of litterbags (mean ± SE) using oil palm fronds as the substrate after 17 days and 45 days placing on the soil surface of secondary forest, oil palm with chemical fertilizer treatment, and oil palm with EFB application. (a) Comparisons between secondary forest, and four management zones of oil palm with EFB application (n=3). (b) Comparisons between secondary forest, and three management zones of oil palm with chemical fertilizer treatment (n=3).

Table 2 Summary of the model outputs from mixed effects models of percent mass loss, soil fauna feeding activity, and soil environmental variables in the function of the land use type. NumDF: the numerator degrees of freedom. DenDF: the denominator degrees of freedom.

Linear mixed effects model	**NumDF**	**DenDF**	**F-value**	**P-value**
Soil moisture~ land use				
Land use	4	68	66.7	< 2.2e-16 ***
Soil electric conductivity~ land use				
Land use	4	68	22.1	9.699e-12 ***
Soil temperature~ land use				
Land use	4	68	22.9	4.853e-12 ***

Generalized linear mixed effects model	**deviance**	**Chisq**	**Chi-DF**	**P-value**
Remaining leaf mass of litterbag~ land use (secondary forest, oil palm with EFB application, and oil palm with chemical fertilizer treatment)				
	236.82	*11.27*	*7*	*0.127*
Soil fauna feeding activity ~ land use (secondary forest and oil palm with EFB application)				
Land use	10685	106.1	4	< 2.2e-16 ***
Soil fauna feeding activity ~ land use (secondary forest and oil palm with chemical fertilizer treatment)				
Land use	8921	177.71	3	< 2.2e-16 ***

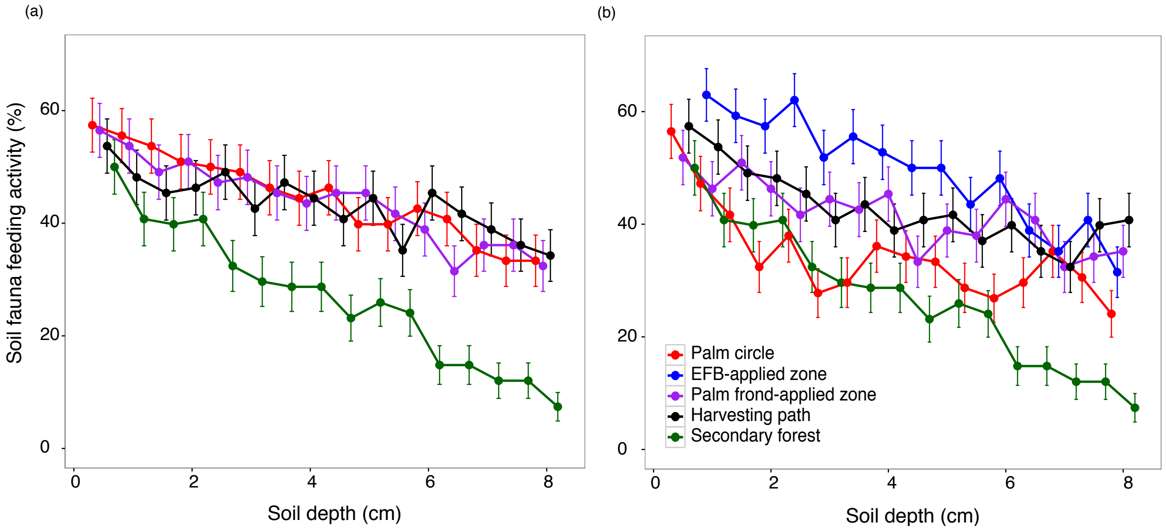


Figure 2. Variations (mean ± SE) of soil fauna feeding activity in the oil palm plantation with chemical fertilizer treatment and the secondary forest (a), and in the oil palm plantations with EFB and the secondary forest (b) (n=3).

3.3 SOIL ENVIRONMETNAL VARIABLES

Soil moisture, soil electric conductivity, and soil temperature at 10 cm soil depth were compared between secondary forest and the oil palm with EFB application. The soil environmental variables for the oil palm with chemical fertilizer treatment were not compared because the data were not obtained. All the soil environmental variables differed significantly between the secondary forest and oil palm with EFB application (**Table 2**). The *post-hoc* comparisons showed that soil moisture in the secondary forest was significantly lower than all the management zones of oil palm (**Figure 3**). In addition, soil moisture was significantly higher in EFB-applied zones and harvesting paths, compared to palm circles and palm frond applied-zones. The EFB applied-zone had significantly higher electric conductivity compared to the rest of the management zones and secondary forest. Soil temperature in the secondary forest was significantly lower than all of the management zones of oil palm.

Linear regression further revealed that soil moisture significantly and positively explained the soil fauna feeding activity ($F_{1,88}$=10.43, p-value < 0.05, $R^2 = 0.11$) (**Figure 4**). Soil electric conductivity ($F_{1,88} = 1.40$, p-value = 0.23) and soil temperature ($F_{1,88} = 0.08$, p-value = 0.77) did not significantly explain the soil fauna feeding activity.

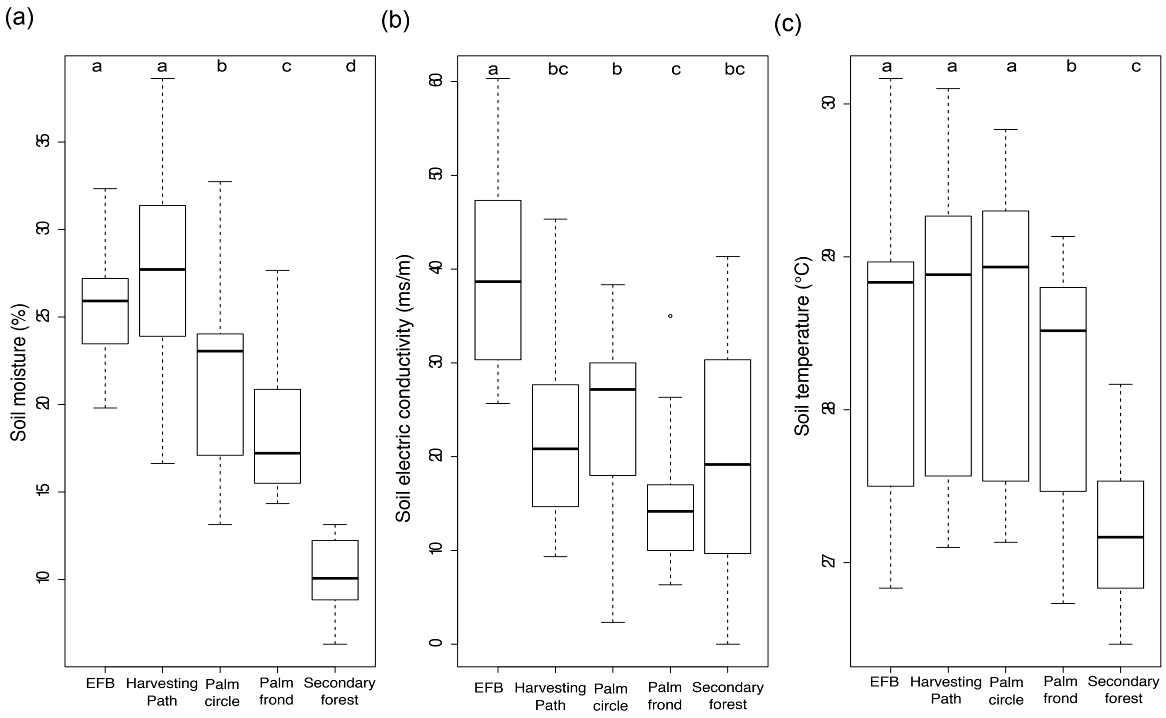


Figure 3. Soil moisture, soil electric conductivity, and soil temperature and secondary forest and management zones of oil palm plantation with EFB application.

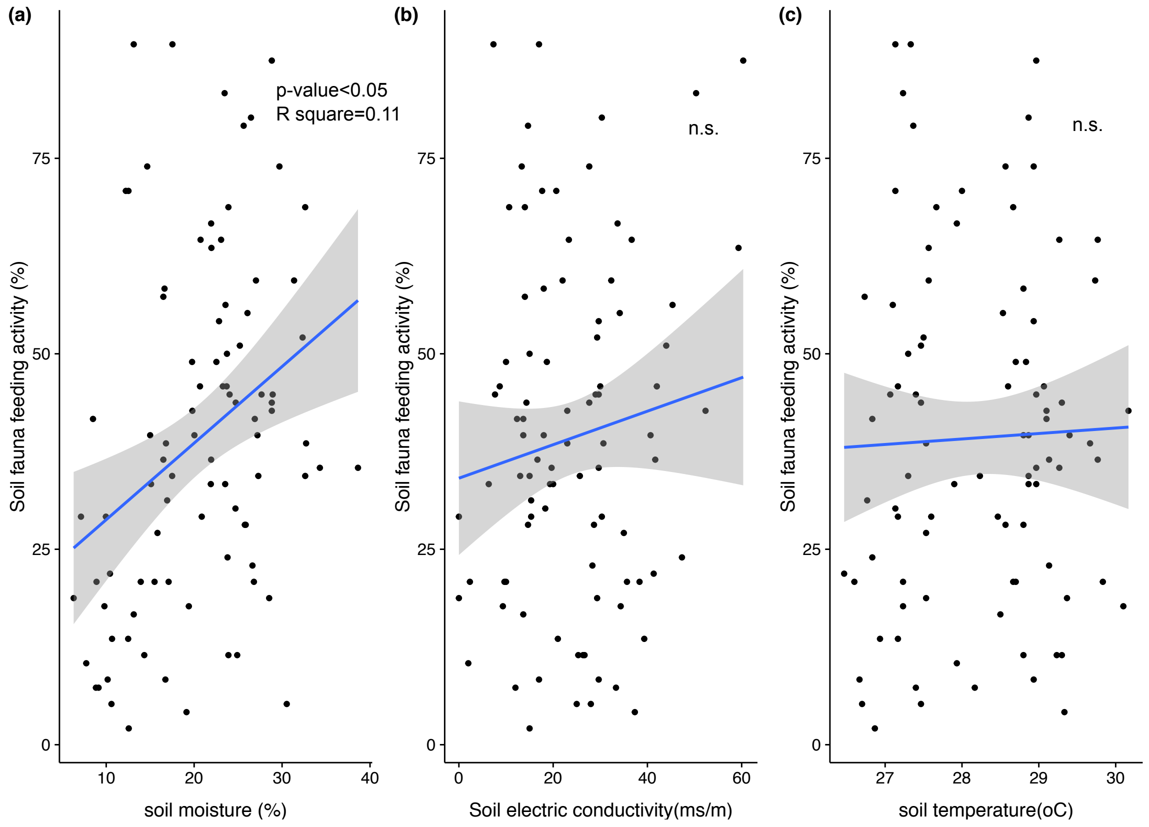


Figure 4. Soil fauna feeding activity in function of soil moisture (a), soil electric conductivity (b), and soil temperature (c).

4. DISCUSSION

4.1 LEAF LITTER DECOMPOSITION

In the litterbag experiment, oil palm fronds were used as the substrate of litterbags for both secondary forest and oil palm plantations, to compare the litter decomposition rate between the land use types. Results showed that leaf litter decomposition rate did not differ between the secondary forest and oil palm plantations, after 17 and 45 days of incubation underneath the litter layer. This finding is similar to a study in Malaysian Borneo, where freshly fallen *Shorea johorensis* (*Dipterocarpaceae*) leaves were used as the substrate of litterbags for both Dipterocarp forests and oil palm plantations for 280 days, placing in the leaf litter layer (Foster et al., 2011). In comparison, another study that used different leaf litter for lowland forest and oil palm sites in Sumatra showed that leaf litter quality was a major determinant for the litter decomposition rate (Violita et al., 2015). The authors used freshly fallen leaves from forest trees as the substrate of litterbags in the forest sites, while using oil palm leaves as the substrate in the oil palm sites; and the results demonstrated that the decomposition rate of forest leaves on the forest floor was significantly higher than the decomposition rate of oil palm fronds on the soil surface of oil palm plantations over a 12-month period. The authors further showed that the faster litter decomposition process in the forest floor was positively associated with the higher N content and C/N ratio of the forest leaves, implying that the litter quality had regulated the rates of litter decomposition in these two land uses. This suggests that the similar levels of decomposition rates between secondary forest and oil palm in our study were due to the use of the same leaf litter as the substrate for both sites.

Higher soil moisture and temperature were observed in the oil palm plantation with EFB application, compared to the secondary forest. However, these changes did not lead to higher leaf litter decomposition rate. This finding is in contrast with previous studies of other tropical ecosystems, which demonstrated pronounced effects of microclimate on leaf litter decomposition (Parsons and Congdon, 2008; Powers et al., 2009; Yeong et al., 2016). We therefore suggest that the quality of litter substrate, or the activities of decomposer organisms are possibly more important to regulate leaf litter decomposition rate compared to climatic conditions at our study site. It has been shown that land use change from primary and secondary forest in Malaysia and Indonesia has lead to changes in the diversity and community composition of decomposer organisms (Hassall et al., 2006; Luke et al., 2014). Further studies are needed to examine the regulatory functions of litter decomposers on the leaf litter decomposition rate, and the possible interactive effects of climatic conditions, litter substrate quality, and decomposer communities on leaf litter decomposition at our study site.

4.2 SOIL FAUNA FEEDING ACTIVITY

In contrast to the similar rates of leaf litter decomposition found between the secondary forest and oil palm, the soil fauna feeding activity at our study site differed between the two vegetation types. In particular, soil fauna feeding activity in the secondary forest was significantly lower than the EFB-applied zone of the oil palm with EFB application. Similarly, the feeding activity in the secondary forest was lower than all the management zones of the oil palm with chemical fertilizer treatment. These results are in line with a study in Brazilian Amazon, which demonstrated that mixed-species tree plantations had higher soil fauna feeding activity than primary and secondary forests (Römbke et al., 2006).

We demonstrated that the increased soil fauna feeding activity at the EFB-applied zones of oil palm is positively associated with soil moisture (**Figure 4**). Another finding in temperate forests also demonstrated the positive relationships between soil fauna feeding activity and soil moisture (Simpson et al., 2012). Our results indicate that EFB mulched on the soil surface serves as an effective vapour barrier against moisture loss, which may provide microclimate conditions for soil fauna and their foraging activities. In addition to modification of microclimate of the soil, EFB addition may also enhance the activity of soil fauna by increasing resource availability, or by mediating soil nutrient levels (Abu Bakar et al., 2010; Chiew and Rahman, 2002; Geissen and Brümmer, 1999; Moradi et al., 2014b). This is an important finding and a knowledge gap that are further addressed in Chapter 3 and Chapter 4.

4.3 LITTERBAG EXPERIMENT AND BAIT LAMINA ASSAY

The results from the litterbag experiment and the bait lamina assay have presented two findings of the litter decomposition process, which might seem to be contradictory. That is, when comparing secondary forests and oil palm, aboveground processes of decomposition do not vary, whereas there is clearly a significant difference in the soil fauna feeding activity.

To understand this finding, it is important to consider the methodological challenges associated with the measurement of litter decomposition. In particular, litterbags and bait lamina assays use different quality of litter substrate; the incubation duration and location of the substrate were also different. These differences may result in the measurement of different focal decomposer groups and their activities. For example, litterbags contain substrates with relatively large sizes, and the litterbags are normally placed on the soil surface beneath the litter layer, from several months to two years in tropical ecosystems (Foster et al., 2011). The decomposition rate derived from the litterbag experiment, therefore, represents the shredding activities of litter transformers, and the enzymatic degradation ability of microfauna and micro-organisms (Lavelle et al., 1993; Wohl et al., 2004). In contrast, the substrate of the bait lamina assay is easily digestible, and the sticks are inserted into the mineral layer of the soil for a relatively shorter period (i.e. six days in our study). Therefore, the soil-dwelling fauna are likely to feed directly on the bait lamina without the prior shredding activities of litter transformers (Römbke et al., 2006). The resulting soil fauna feeding activity may represent the rapid foraging activities of the soil-dwelling macrofauna and mesofauna to the belowground labile organic matter (Birkhofer et al., 2011; Simpson et al., 2012).

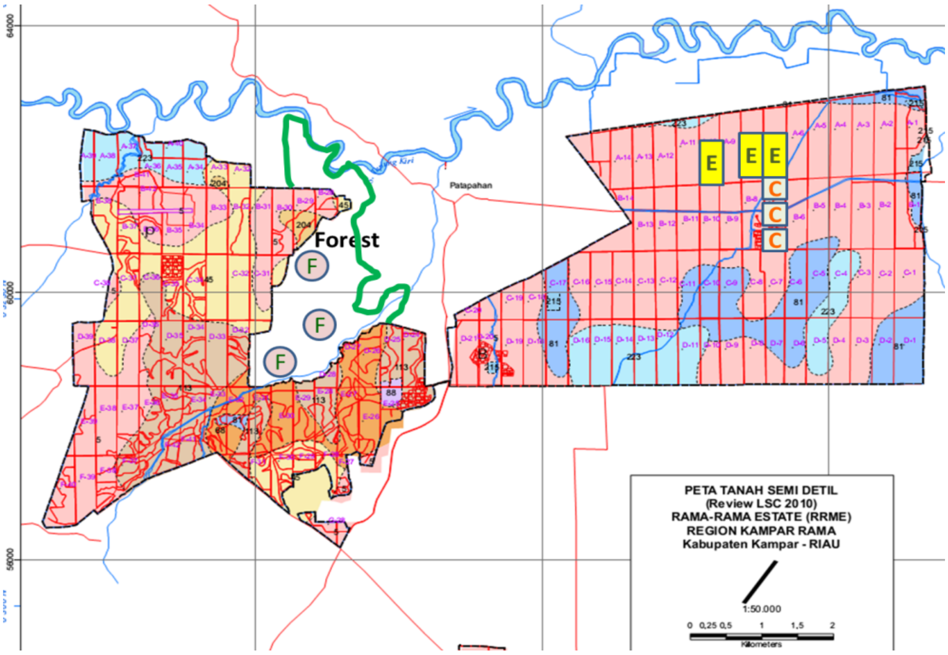
To summarise, this chapter has provided new data on two key elements in nutrient cycling: leaf litter decomposition rate and soil fauna feeding activity in secondary forest and oil palm plantations in Sumatra. The litterbag experiment showed that litter decomposition rate did not differ between the secondary forest and the oil palm. On the other hand, the bait lamina assay showed that soil fauna feeding activity was significantly lower in the secondary forest compared to the EFB- applied zones of oil palm with EFB application. The fauna activity in the secondary forest was also lower than all the management zones of oil palm with chemical fertilizer treatment. The different responses of the litter decomposition rate and the soil fauna feeding activity to land use change indicate the complexity of the soil processes that contribute to nutrient cycling and soil fertility.

5. ACKNOWLEDGMENTS

This study was supported by the Department of Zoology, University of Oxford and the PT-SMART Research Institute (SMARTRI). We thank Moya Burns for advice on statistical modelling and Carla Romeu Dalmau for advice on experimental design. We thank Pak Pujianto, Pak Suhardi, Ibu Ribka and other staff at the SMARTRI for the use of the facilities and field assistance.

6. SUPPLEMENTARY MATERIALS

Supplementary S1. Sampling plots in the secondary forest (denoted as F), the oil palm plantation with chemical fertilizer treatment (denoted as C), and the oil palm plantation with crop residue application (denoted as E) in Central Sumatra, Indonesia.



Supplementary S2. (a) A bait lamina stick containing 16 apertures filled with bait lamina (b) When bait lamina sticks are inserted vertically into the soil, the top aperture reached just below the soil surface, and the bottom aperture is at the depth of 8 cm.


(a) (b)

CHAPTER 3

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 the 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 four management zones: (1) empty fruit bunch (EFB)-applied zones, (2) palm circles with chemical fertilizers, (3) oil palm frond applied-zones, and (4) harvesting paths with no input. Our results showed that soil fauna feeding activity was significantly higher under EFB application than 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 aluminium 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 soil chemical properties. This suggests that the practice of EFB application plays an important role to enhance soil ecosystem functions in oil palm plantations, which may ultimately contribute to sustainable palm oil production.

Keywords: Empty fruit bunch; EFB; bait lamina; 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 (Guillaume et al., 2015); 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 oil 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, 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 (Carron et al., 2015b). EFB is a wet, cellulose-rich oil palm mill residue that is used as an organic fertilizer and mulch substrate.

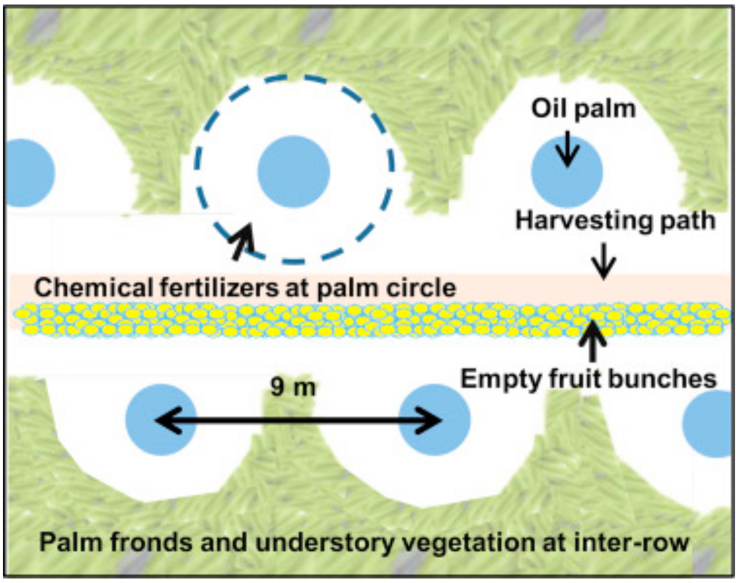

Figure 1 The layout of an oil palm plantation. Harvesting paths and areas of understory vegetation are in alternate inter-rows. Oil palms are planted in triangular spacing, approximately 9 m apart. The trunks are surrounded by cleared weed-free circles where chemical fertilizers are applied. EFB are applied along one side of harvesting paths.

Litter decomposition and nutrient mineralization are important ecosystem functions to sustain soil fertility and crop yield in agroecosystems (Hättenschwiler et al., 2005). These functions are underpinned by various soil organisms and their activities, such the feeding activity of organic matter that contributes to carbon and nutrient turnover. In Indonesian oil palm plantations, the abundance and diversity of soil microorganisms, earthworms, beetles, and earwigs are increased by crop residue application, suggesting the functional roles for these organisms in organic matter decomposition (Carron et al., 2015a, 2015b; Situmorang et al., 2014). A specific termite species, *Macrotermes gilvas*, was also reported as the major litter-dwelling fauna for leaf litter decomposition in Malaysian oil palm plantations (Foster et al., 2011). Despite an increase in the number of studies of soil fauna within the oil palm ecosystem in the past decade, the functional role of these soil organisms in decomposition and nutrient mineralization processes remains understudied.

The composition and activity of soil fauna are influenced by the availability of nutrients and chemical properties of the soil, such as soil acidity, cation concentrations, and soil moisture (Lavelle et al., 2006; Ponge, 2013). A previous study by Carron et al (2015b) has shown that the temporal succession of earthworm populations over two years of EFB application was associated with changes in soil organic carbon and clay content in an Indonesian oil palm plantation, indicating the close links between soil biota and abiotic environment of the soil. In addition, management practices of oil palm frond application and chemical fertilizer treatment have shown to result in different soil chemical properties and soil biota communities (Carron et al., 2015a). It is therefore suggested that different soil management practices may lead to variations in soil abiotic properties, which in turn influence soil biota and their activities.

In this study, we compared four management zones to examine their effects on soil fauna feeding activity and soil chemical properties: (1) EFB-applied zones, (2) palm circles with chemical fertilizers, (3) oil palm frond-applied zones, and (4) harvesting path with no input. Specifically, we asked: do different soil management practices in oil palm plantations influence 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 oil palm frond application would provide favourable conditions (e.g., higher soil nutrient pools and soil moisture conditions), which lead to higher soil fauna feeding activity compared to other management practices.

2. MATERIALS 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.

Soil 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 (magnesium 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 oil palm 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 × 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 palms within each plot were randomly chosen for sampling. At each focal palm, four management zones were sampled, corresponding to the following soil management practices: (1) EFB-applied zones, (2) palm circles with chemical fertilizers, (3) oil palm frond-applied zones, and (4) harvesting path with no input (**Figure 1**). The effects were examined at the tree scale, as management practices are performed in a zonal pattern around each palm as described above.

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	
EFB	One side of harvesting path	EFB[a]	210	0.57	0.06	0.17	0.11	0.11	12
		Rock phosphate [a]	0.75	0	0.15	0	0	0	12
Oil palm frond	Inter-row	Oil palm frond [c]	237	0.57	0.05	0.71	0.08	0	1
Chemical fertilizer	Within palm circle	Urea[a]	0.50	0.23	0	0	0	0	24
		Kieserite / Dolomite [b]	0.50	0	0	0	0.06	0.10	4
No input	Cleared part of harvesting path	None	-	-	-	-	-	-	-

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

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

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

* Kieserite: $MgSO4 \cdot H2O$; Dolomite: $CaMg(CO_3)_2$.

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 × 6 × 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 was placed 12 cm apart in a 12 cm × 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 to 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 palms sampled for feeding activity in each plot, three palms 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 the hydrogen chloride extraction method and the available P by the Bray-1 method. The total nitrogen was determined by the Kjeldahl method (Bremmer and Mulvaney, 1982). The exchangeable bases (Ca, Mg, K, and Na) were extracted by the ammonium acetate method (van Reeuwijk, 1993). The exchangeable Al was determined by titration with sodium hydroxide (Barnhisel and Bertsch, 1982). The cation exchange capacity (CEC) was calculated by summing concentrations of the four base cations, exchangeable H and Al. Base saturation of four cations (Ca, Mg, K and Na) was obtained by dividing the sum of cations by CEC.

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 distributions were 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 palms 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 as 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 management practices nested within focal palms and sampling plots were modelled as random effects. Adjusted *P*-values were generated from a *post-hoc* Tukey analysis.

Lastly, we examined whether 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. Principal component 1 (PC1) was fitted into a generalized mixed effects model as the fixed effect, including sampling plot as the random effect. 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, 2016) 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 were perforated after 6 days of exposure. Soil management practice significantly explained differences in soil fauna feeding activity (X^2=13.5, *p-value* < 0.005), with significantly higher activity under EFB application than all other management practices (**Table 2, Figure 2**). For all the management practices, feeding activity significantly declined with increasing soil depth. Feeding activity under chemical fertilization had a steeper depth gradient compared with the other management practices (**Figure 2**).

Table 2. Effects of management practice and soil depth on soil fauna feeding activity using a generalized additive mixed model.

Variable	**df**	X^2	***p*-value**
Explanatory variable			
Management practice	3	13.5	<0.005
Smoother			
Smoother EFB	1.00	18.3	<0.005
Smoother Oil 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 management practice type was modelled as a fixed effect, with management practice nested within focal palms 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. 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).

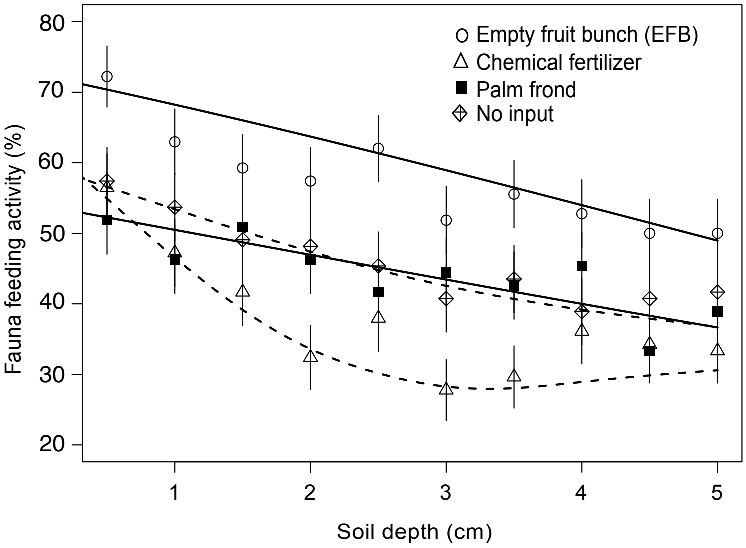

Figure 2. Variations (mean ± SE) of soil fauna feeding activity as a function of soil depth under four management practices. Each data point represents the mean of bait perforations of 108 bait lamina sticks (six sticks under each focal palm, and six focal palms at each of the three sampling plots).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

3.2 EFFECTS OF MANAGEMENT PRACTICES ON SOIL CHEMICAL PROPERTIES

Among the 18 soil variables that we measured, 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 EFB-applied zones, harvesting paths with no input, palm circles with chemical fertilizer treatment, and palm frond-applied zones, whereas exchangeable H and Al increased in this order. Soil temperature was significantly lower in oil palm frond-applied zones 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 accounted for 71.2% of the variance of the data (PC1: 45.7%; PC2: 25.5%). Soil moisture, base saturation, pH, base cation concentrations, 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 ($X^2 = 14.14$, p-value = 0.0001) (**Figure 4**).

Table 3. Soil chemical variables under each soil management practice at 0–5 cm soil depth.

Soil chemical variable	**Management practice**				**Overall mean**	***p*-value**
	EFB	**No input**	**Chemical fertilizer**	**Oil 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

Values are means ± SE. 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-value* < 0.05 (shown in bold).

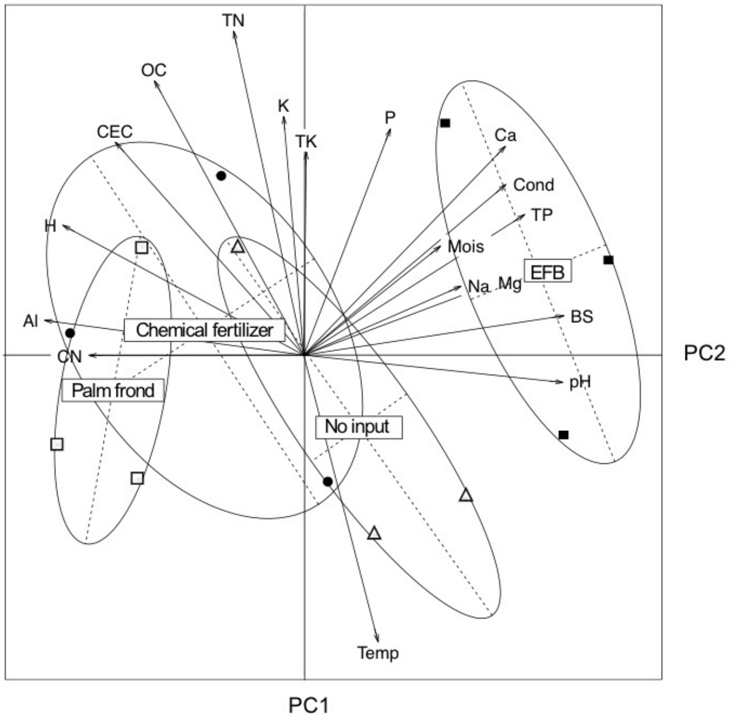

Figure 3. PCA analysis for soil chemical variables and the sampling points according to management practices in the plane formed by PC1 and PC2. Bivariate confidence ellipses were drawn to show the similarities of soil chemical properties in each management zone.

*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})

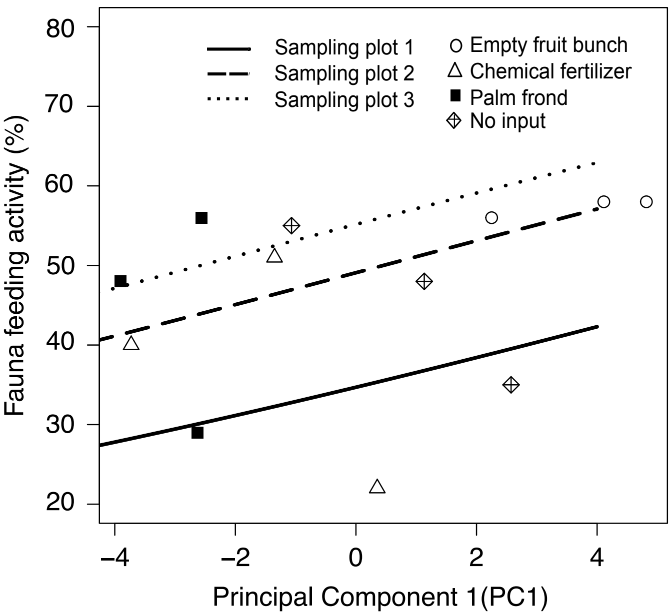

Figure 4. Soil fauna feeding activity as a function of PC1. PC1 is extracted from the PCA of soil chemical properties. A generalized mixed effects model was used, including feeding activity as a response variable, PC1 as a fixed effect, and the sampling plot as a random effect. Binomial distribution was used as feeding activity was fitted as a binary variable.

4. DISCUSSION

Optimizing the use of soil management practices is crucial to sustain soil ecosystem functions and crop production in oil palm plantations. In this study, we found that soil fauna feeding activity was influenced by different soil management practices, and the fauna activity was positively associated with soil base cation contents and soil moisture. Soil fauna feeding activity was greatly enhanced by EFB application, indicating the potential role of this management practice to restore soil biological activities in the oil palm ecosystem.

4.1 SOIL FAUNA FEEDING ACTIVITY AND SOIL BASE CATIONS

Soil fauna feeding activity was significantly increased with base cation concentrations and soil pH. This result is in line with previous findings in other tropical ecosystems, which demonstrated that base cation level is a major determinant for tropical soil fauna communities (Ashford et al 2013). Carron et al. (2015b) also observed that soil macrofauna abundance was positively related to soil calcium levels in a nearby oil palm plantation. Similarly, Geissen and Brummer (1999) reported that soil fauna feeding activity was elevated by increased level of soil pH and base cation contents in a temperate forest.

Among all the management practices, soil fauna feeding activity was the highest under EFB application, and this was associated with higher soil base cation levels and soil pH in the EFB-applied zones. This result indicates that EFB application enhanced soil fauna feeding activity through increasing soil nutrient levels and mitigating soil acidity. EFB contains high concentrations of base cations, which are released rapidly to the soil during the decomposition (Caliman et al., 2001; Lim and Zaharah, 2000). In Malaysian oil palm plantations, EFB was found to release 90% of potassium within 6 months of the field application (Lim and Zaharah, 2000). The addition of EFB to the soil, therefore, is likely to enhance fauna feeding activity through increasing soil base cation levels.

Oil 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., 2014b). In contrast, soil nutrient levels under palm fronds were the lowest among all the management practices, and the soil fauna activity under palm frond application was lower than EFB application. This may be due to the presence of the ground vegetation at the inter-row area, where oil palm fronds were applied. As the palm fronds were stacked on top of the ground vegetation, which were at the thickness of 30–40 cm, this may prevent the frond-released nutrients from entering the soil. Moreover, understory vegetation is likely to take up much of the nutrients from the soil, which reduced the available nutrients in the soil (Corley and Tinker, 2015).

The soil fauna feeding activity was the lowest in the palm circles, compared to other management zones. Specifically, the fauna activity decreased sharply with soil depth and reached a plateau at the depth of 3 cm, compared to the gradual decline of fauna activity with soil depth seen at other management zones. The negative effects of chemical fertilizer application on soil biota and their activities have also been found in many other agroecosystems (Birkhofer et al., 2008; Sánchez-Moreno and Ferris, 2007). Results from this study showed that the reduced soil fauna feeding activity in the palm circles was likely to be associated with lower base cation concentrations and pH of the area. These degraded soil conditions are possibly due to the use of urea-based fertilizers, which are known to reduce soil pH and the nutrient retention capacity of the soil (Barak et al., 1997; Nelson et al., 2010). Our results therefore suggest that the standard practice of using urea-based fertilizers in commercial oil palm plantations may lead to a reduction in soil ecosystem functions and soil fertility in a long run.

4.2 SOIL FAUNA FEEDING ACTIVITY AND SOIL MOISTURE

Compared to the tropical forest ecosystem, soil fauna communities in oil palm plantations are known to subject to more extreme and variable microclimates, due to the lack of plant diversity, large areas of bare soil, and a more open canopy (Foster et al., 2011). Results from this study showed that soil fauna feeding activity positively increased with soil moisture, suggesting that the assemblage and functioning of soil fauna were enhanced in a less water-limiting environment of the oil palm plantation. The positive relationships between soil fauna feeding activity and soil moisture have also been observed in temperate forests (Simpson et al., 2012). The increased soil fauna feeding activity under EFB application was positively associated with the higher soil moisture in the EFB-applied zones. This finding indicates that EFB applied to the soil may be effective in preventing water loss from the soil (Mulumba and Lal, 2008), and therefore create a more preferable microclimate for soil fauna and their functioning.

5. CONCLUSIONS

Land conversion from forest to oil palm has led to negative impacts on biodiversity and ecosystem functions (Fitzherbert et al., 2008). Implementation of suitable management practices is therefore important for sustainable development of oil palm cultivation. In the current study, we examined the effects of different soil management practices, including EFB application, oil palm frond application, and chemical fertilizer treatment, on soil fauna feeding activity and soil chemical properties. We found that EFB greatly enhances soil fauna feeding activity, and this is associated with increased concentrations of base cations and soil moisture. These results suggest that the practice of EFB application has a high potential to enhance soil ecosystem functions in oil palm plantations, which may ultimately contribute to sustainable palm oil production.

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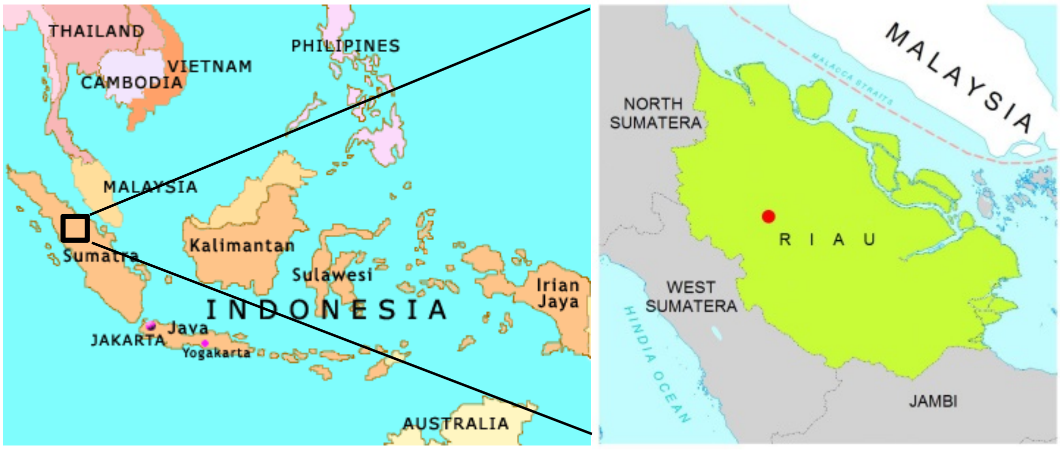
7. SUPPLEMENTARY MATERIALS

Supplementary S1 Map of the study site in Sumatra, Indonesia.



Supplementary S2 Spearman’s correlation coefficients between soil chemical variables

#	Variable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	Mois																	
2	Temp	- 0.12																
3	Cond	0.52	0.04															
4	pH	0.42	0.45	0.55														
5	OC	0.06	- **0.62**	0.17	- **0.61**													
6	TN	0.17	- **0.78**	0.19	- 0.36	**0.88**												
7	CN	- 0.10	- 0.28	- 0.4	- **0.81**	0.48	0.25											
8	TP	0.57	0.11	**0.69**	**0.87**	- 0.25	0.05	- **0.58**										
9	TK	- 0.41	- 0.48	0.22	- 0.28	0.38	0.32	- 0.12	- 0.22									
10	P	0.41	- 0.18	0.57	0.47	0.24	0.51	- 0.28	**0.78**	- 0.07								
11	CEC	- 0.05	- **0.69**	- 0.08	- **0.77**	**0.88**	**0.73**	**0.60**	- 0.44	0.45	- 0.01							
12	Ca	**0.64**	- 0.12	**0.78**	**0.68**	0.07	0.3	- **0.65**	**0.81**	0.10	**0.73**	- 0.10						
13	Mg	0.38	0.27	0.55	**0.65**	- 0.21	- 0.13	- **0.75**	0.55	0.04	0.36	- 0.24	**0.78**					
14	K	- 0.27	- **0.78**	0.08	- 0.37	0.46	0.53	0.03	- 0.16	**0.85**	- 0.01	**0.61**	0.08	- 0.12				
15	Na	**0.78**	0.10	0.49	0.37	- 0.04	- 0.04	- 0.13	0.40	- 0.37	0.1	- 0.16	0.42	0.38	- 0.33			
16	BS	0.55	0.37	**0.62**	**0.95**	- 0.49	- 0.27	- **0.83**	**0.81**	- 0.22	0.44	- **0.68**	**0.78**	**0.76**	- 0.35	0.51		
17	H	- 0.31	- **0.61**	- 0.26	- **0.91**	**0.85**	**0.67**	**0.70**	- **0.64**	0.42	- 0.14	**0.91**	- 0.4	- 0.51	0.54	- 0.29	- **0.85**	
18	Al	- 0.38	- 0.36	- 0.55	- **0.95**	**0.64**	0.42	**0.83**	- **0.78**	0.08	- 0.31	**0.73**	- **0.67**	-0.66	0.2-	- 0.35	- **0.93**	**0.90**

Numbers in bold display *p*-values < 0.05. 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}).

Supplementary S3 Results of PCA analysis for loadings of soil chemical variables to the first principal component (PC1) and the second principal component (PC2).

Soil chemical variable	**PC1**	**PC2**
Soil moisture (%)	0.18	0.14
Soil temperature (°C)	0.10	- 0.37
Electrical conductivity(ms m^{-1})	0.26	0.22
pH	0.34	- 0.04
Organic C (%)	- 0.19	0.36
Total N (%)	- 0.09	0.36
CN ratio (%)	- 0.09	0.42
Total P (mg kg^{-1})	0.29	0.18
Total K (mg kg^{-1})	0.003	0.26
Available P (mg kg^{-1})	0.11	0.29
Cation exchange capacity (cmol kg^{-1})	- 0.25	0.28
Exchangeable Ca (cmol kg^{-1})	0.26	0.27
Exchangeable Mg (cmol kg^{-1})	0.24	0.09
Exchangeable K (cmol kg^{-1})	- 0.03	0.31
Exchangeable Na (cmol kg^{-1})	0.20	0.09
Base saturation (%)	0.34	0.05
Exchangeable H (cmol kg^{-1})	- 0.31	0.17
Exchangeable Al (cmol kg^{-1})	- 0.34	0.05

CHAPTER 4

LONG-TERM EFFECTS OF CROP RESIDUE APPLICATION ON SOIL BIOTA AND ECOSYSTEM FUNCTIONS IN THE OIL PALM AGROECOSYSTEM

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ABSTRACT

Crop residue application in oil palm plantations is an important soil management practice that has high potential to improve soil ecosystem functions. Few studies, however, have explored the cascading effects of oil palm residue application on soil ecosystem functions. To address this research gap, we examined the effects of the addition to the soil of a major oil palm residue, empty fruit bunches (EFB), on soil abiotic properties, soil biota and soil ecosystem processes. The study was carried out in a long-term field trial of an Indonesian oil palm plantation. The treatments include EFB application with three application rates, and a chemical fertilizer treatment. We used structural equation modelling to evaluate the mechanistic pathways that mediate cascading effects of this management technique. Compared to chemical fertilization, 15 years of EFB application improved physicochemical properties, compared to chemical fertilizer treatment. EFB application decreased earthworm biomass and influenced soil mite community composition. EFB application enhanced soil fauna feeding activity by increasing the total density of soil mites. EFB application also directly increased soil microbial respiration rates, compared to chemical fertilizer treatment. These results suggest that compared to chemical fertilization, EFB application enhances soil ecosystem functions through direct provision of food resources to the soil biota. These findings indicate the high potential of EFB application as a sustainable management practice to restore soil ecosystem functions in oil palm plantations.

Keywords: empty fruit bunch, fauna feeding activity, microbial respiration, earthworm, mite, sustainable oil palm

1. INTRODUCTION

Crop residue application in agricultural fields is a common soil management practice which supports nutrient cycling, carbon sequestration, and plant growth (Diacono and Montemurro, 2010; Liu et al., 2006). Soil biota and their activities, such as microbial respiration and soil fauna activity, are important to these soil ecosystem functions (Bardgett, 2005). Soil microorganisms are key agents of decomposition because they mineralize organic matter, while microarthropods such as soil mites enhance nutrient mineralization by feeding on organic matter, microorganisms and other animals (Coleman et al., 2004; Corral-Hernández et al., 2015). Soil macrofauna such as earthworms facilitate decomposition by shredding plant residues, which increase the surface for microbial colonization, as well as modifying microhabitats for decomposer organisms (N. Eisenhauer, 2010). Crop residue addition to the soil can influence the soil biota and their functions by providing food resources, and by altering abiotic properties of the soil environment (Ashford et al., 2013; Ilieva-Makulec et al., 2006; Lavelle et al., 2006; Moore et al., 2004). The cascading effects of crop residue addition on soil abiotic properties, soil biota, and ecosystem functions, are fundamental to sustainable crop production in agroecosystems (Turmel et al., 2015).

Oil palm is an important tropical crop that provides one-fifth of vegetable oil worldwide (Koh and Wilcove, 2007). The expansion of oil palm plantations in Southeast Asia, however, has negatively influenced soil fertility, and soil biota assemblage and functions (Barnes et al., 2014; Fitzherbert et al., 2008; Guillaume et al., 2015; Violita et al., 2015). Oil palm residues have been applied in some oil palm plantations to restore soil conditions (Fairhurst and Härdter, 2003). One of the major oil palm residues is empty fruit bunches (EFB), the fruit bunch shell after palm oil extraction (Abu Bakar et al., 2010). Previous studies in Malaysian and Indonesian oil palm plantations have shown that EFB application positively affects soil physicochemical properties, and also influences abundance and temporal successions of soil fauna (Carron et al., 2015b; Comte et al., 2013; Moradi et al., 2015; Rosenani et al., 2011; Teh et al., 2011).

Few existing studies, however, have examined the cascading effects of EFB application on soil abiotic properties, soil biota, and soil ecosystem functions (Carron et al., 2015b; Tao et al., 2016). Tao et al. (2016) demonstrated that eight years of continuous EFB application in a Sumatran oil palm plantation increased soil fauna feeding activity, and the positive effects were associated with increased soil pH, base cation concentrations, and soil moisture. At a nearby study site, Carron et al. (2015b) observed that the temporal changes in earthworm biomass under EFB application was related to soil clay content and organic carbon level. However, a thorough understanding of the cascading effects of EFB application on the soil ecosystem is still needed.

To fill the research gap, we examined the changes in soil abiotic properties, soil biota, and soil ecosystem functions following EFB application, using a 15-year field trial of an oil palm plantation in Sumatra, Indonesia. EFB treatments with three application rates were compared to each other, and to a chemical fertilizer treatment as the reference control. We aimed to address two research questions: First, how does 15 years of EFB application influence soil abiotic properties, soil biota, and soil ecosystem functions? Second, do the relations between these soil properties change under the EFB application?

2. MATERIALS AND METHODS

2.1 SITE DESCRIPTION

The study was carried out in an oil palm plantation in Sumatra, Indonesia (0° 56’0” N 101°18’0”E). The oil palm plantation was established in 1987 and is certified by the Roundtable on Sustainable Palm Oil (RSPO). The previous land use of this area was secondary lowland tropical forest dominated by Dipterocarp species. The climate of this region is described as tropical humid, with a mean temperature of 26.8 $^{\circ}$C and average rainfall of 2400 mm year^{-1}. The soils are Inceptisols (Typic Dystrudepts), within the loamy lowland soil class (USDA soil classification system).

2.2 EXPERIMENTAL DESIGN

The 15-year trial began in 1998, when the age of oil palms was 11 years. Field sampling and measurements were conducted at the end of the trial during September-October 2014. The field trial was established at two adjacent oil palm commercial plots, at a flat area with limited possibility of leaching and runoff. The field trial covered a total area of 36 hectares (1200 m length × 300 m wide) and was composed of five replicate blocks. Each replicate block was composed of four treatment plots, resulting in a total of 20 treatment plots (5 replicate blocks × 4 treatment plots) in the field trial for soil sampling. The replication number is five in this nested design.

The four treatment plots within each replicate block were: Low-EFB treatment (210 kg tree^{-1} year^{-1}, equivalent to 30 t ha^{-1} yr^{-1}), Medium-EFB treatment (420 kg tree^{-1} year^{-1}, equivalent to 60 t ha^{-1} yr^{-1}), High-EFB treatment (630 kg tree^{-1} year^{-1}, equivalent to 90 t ha^{-1} yr^{-1}), and chemical fertilizer treatment without EFB application. Each treatment plot is composed of 36 palm trees (8 palm trees at 4 rows), with the plot size approximately 80 m length x 40 m wide. A total of five oil palms in the central two rows of each treatment plot were used as focal palms for sampling (for the spatial distribution of the focal palms see **Supplementary S1**). There was at least one palm tree between two focal palms, to avoid the spill over effects. Each treatment plots were surrounded by 1.5 m ditches to prevent the interference by adjacent treatment plots.

For EFB treatment plots, EFB was applied once a year for 15 years at one side of the harvesting paths, followed by urea application on the top of EFB. Urea is used to reduce the C/N ratio for accelerating EFB decomposition. The application rate of the Low-EFB treatment is similar to standard operations in the oil palm industry, whereas Medium-EFB and High-EFB treatments represent a range of alternative application rates of EFB. The chemical fertilizer treatment was similar to standard estate practices without the application of EFB. The application rate, frequency, application location and type of chemical fertilizer are detailed in **Table 1**. The fertilizers were applied within palm circles twice a year (i.e. during the February-March and September-October periods) throughout the trial period.

A total of ten indicators for soil abiotic properties, soil biota, and soil ecosystem functions were measured in this study (**Table 2)**. All the soil properties were examined in the soil mineral rather than litter layer, since the response of soil-dwelling fauna communities and their processes under soil management practices are relatively unknown in the oil palm ecosystem (Carron et al., 2015b; Tao et al., 2016).

In order to examine the localized effects of EFB on the soil ecosystem, the soil properties were examined beneath EFB at one side of harvesting paths of EFB treatment plots. For chemical fertilizer treatment plots, soil properties were examined at the equivalent positions as EFB treatment plots. The application of chemical fertilizers in oil palm plantations has shown limited spill-over effects (Carron et al., 2016). Therefore, we assumed that chemical fertilizers applied within palm circles do not influence soil properties at harvesting paths, where soil measurements took place.

Table 1. Application rates of fertilizer input for each treatment and the equivalent nutrient application rates.

Code	Treatment	Application rate (kg tree^{-1} year^{-1})	Nutrient application rate (kg tree^{-1} year^{-1})*					
			C*	N	P	K	Mg	Ca
Chemical fertilizer	Chemical fertilizer with no application of EFB	Urea 3.5		1.61				
		TSP 1			0.26			0.14
		MOP 5			0.75	2.50		
		Kieserite 2					0.32	
Low-EFB	Low application rate of EFB (30 ton ha^{-1}yr^{-1}))	EFB 210	102	0.56	0.064	1.7	0.1	0.1
		Urea 0.02		0.01				
Medium-EFB	Medium application rate of EFB (60 ton ha^{-1}yr^{-1})	EFB 420	204	1.12	0.13	3.4	0.2	0.2
		Urea 0.04		0.02				
High-EFB	High application rate of EFB (90 ton ha^{-1}yr^{-1})	EFB 630	306	1.68	0.19	5.1	0.3	0.3
		Urea 0.06		0.03				

Carbon and nutrient content of empty fruit bunches are referenced from (Comte et al., 2013; Moradi et al., 2014b). TSP: triple super phosphate (Ca(H2PO4)2•H2O); MOP: muriate of potash, potassium chloride (KCl); Kieserite: magnesium sulfate (MgSO4·H2O).

Table 2. Indicators for soil abiotic properties, soil biota and soil ecosystem functions in this study.

Indicators
1. Soil abiotic properties
Organic carbon content (%)
Total nitrogen content (%)
Soil pH
Soil base saturation (%)
Aggregate stability (%)
Bulk density (g/cm^3)
2. Soil biota
Soil mite density (individual/m^2)
Earthworm biomass (g/m^2)
3. Soil ecosystem functions
Soil microbial respiration (ppm)
Soil fauna feeding activity (%)

2.3 SOIL ABIOTIC PROPERTIES

Six soil abiotic properties were measured: soil carbon content, soil nitrogen content, soil pH, soil base saturation, aggregate stability, and bulk density. One soil sample was collected at a depth of 0-15 cm under each focal palm. The five soil samples for each treatment plot were bulked to form a composite sample before laboratory analyses. Soil organic carbon concentration was measured using the Walkley-Black method (Nelson and Sommers, 1982). Total nitrogen was determined by the Kjeldahl method (Bremmer and Mulvaney, 1982). Soil pH was determined using a pH meter with a soil to water ratio of 1:1. The concentrations of exchangeable base cations (Ca, Mg, K, and Na) were extracted in 1M ammonium acetate ($NH_4C_2H_3O_2$) and analyzed using atomic absorption spectrophotometry (AAS) (van Reeuwijk, 1993). The exchangeable Al was determined by titration with sodium hydroxide (Barnhisel and Bertsch, 1982). The cation exchange capacity (CEC) was calculated by summing concentrations of the four base cations, exchangeable H and Al. The base saturation of four cations (Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}) was obtained by dividing the sum of cations by CEC.

Soil aggregate stability was analyzed using the wet sieving method (Eijkelkamp, the Netherlands). The soil samples were sieved through 0.25 mm mesh for the measurement. Unstable aggregates were extracted by physical shaking for fixed amounts of time, while stable aggregates were extracted by sodium hydroxide. Aggregate stability was calculated as the percentage of stable aggregates weight over total aggregate weight (stable + unstable aggregates). Bulk density was measured by comparing the fresh weight and dry weight of fixed volume of the soil samples.

2.4 SOIL BIOTA

Earthworms and soil mites were examined as the focal soil biota groups in our study, for their key functions in the soil ecosystem (Coleman et al., 2004), and their abundance in the mineral layer of the soil at our study site. The earthworms were sampled from 25 x 50 cm monoliths, following a modified Tropical Soil Biology and Fertility (TSBF) method (Moreira et al., 2008). Under each focal palm, the organic layer on the top-soil was removed by a shovel, and a soil monolith of 10 cm depth was excavated. Earthworms were caught by hand in the field. The fresh weight of each earthworm was measured, before storing in a 90% ethanol solution in the laboratory. The taxonomy of earthworms were identified by experts.

At each focal tree, three soil samples for soil mite extraction were collected using soil cores (diameter 7.5 cm, length 4.2 cm) and were pooled before the extraction. We used modified Berlese-Tullgren funnels to extract soil mites over a 48-hour period. Soil mites were then identified into taxonomic groups at the suborder level (Krantz and Walter, 2009). Other microarthropod groups collected from the same extraction, i.e. Collembola and Formicidae, were not used for analysis, as the numbers were too low for meaningful representations.

2.5 SOIL ECOSYSTEM FUNCTIONS

Two indicators of soil ecosystem functioning were measured: soil fauna feeding activity, and soil microbial respiration. Soil fauna feeding activity was measured using the bait lamina method (Terra Protecta GmbH, Berlin, Germany) (Von Törne, 1990). The bait lamina method allows a rapid assessment of direct feeding rates of soil macro- and meso-fauna, which reflects the speed of litter decomposition and soil biological activities (Reinecke et al., 2008; Simpson et al., 2012). 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. Under each focal palm, six bait lamina sticks were placed 40 cm apart in a row. 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. The sticks were inserted for 3 days of exposure, and 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).

Soil microbial respiration is an important soil processes that is highly associated with the nutrient mineralization and carbon sequestration (Hanson et al., 2000). Soil samples of 0-

10 cm depth under each focal palm were collected and air-dried for one week before sieving through 2 mm mesh sieves. Soil microbial respiration was measured using the laboratory soil burst respiration kit (Solvita, USA).

2.6 STATISTICAL ANALYSIS

All statistical analyses were performed in R.3.3.1. Mixed effects modelling was performed using function *lme* for the *nlme* package (Bates et al., 2015). The post-hoc test was performed using the *multcomp* package (Hothorn et al., 2008). The Structural equation modelling was performed using the *piecewiseSEM* package (Lefcheck, 2016). Statistical tests were evaluated using $\alpha = 5\%$.

All data were checked for assumptions for normality, and transformed to correct the heterogeneity in the residuals. The variables of earthworm biomass and soil mite density were log (x+1)-transformed. Bulk density was square-root transformed. The rest of the variables were log-transformed.

To examine the effects of EFB application on soil abiotic properties, soil biota, and soil ecosystem functions, linear mixed effects models were used. The treatment type (Low-EFB, Medium-EFB, High-EFB, and chemical fertilizer treatment) was fitted as fixed effect (categorical), with treatment plots nested within replicate blocks as the random effects. Significant overall effects of the treatment type were further explored using a post-hoc Tukey test.

Structural equation modelling was performed to test the cascading effects of EFB application on soil abiotic properties, soil biota, and the soil ecosystem functions. We used this approach to evaluate pre-existing theory, as a key aspect of hypothesis testing using observational data (Grace et al., 2012). The analysis was "mediation focused", in order to investigate the mediating pathways to increase our understanding of the causal knowledge by examining indirect effects (Grace et al., 2012). We built a metamodel to make explicit the relation between theoretical entities (Grace et al., 2012) (**Supplementary S2**). We then built an *a prior* model with potential relations among the variables based on theoretical knowledge and our hypotheses (**Supplementary S3**). We used stepwise removal of non-significant relationships, and tested the effects of these removals on Akaike information critetion (AIC) and model fit (**Supplementary S4, S5**). The most parsimonious model was selected when deletion of any of the relationships generated ΔAIC < 8 (Shipley, 2013) (**Supplementary S6**). Three application rate of EFB and chemical fertilizer treatment were fitted as continuous variable (0, 30, 60, 90). Random effects of treatment plots nested within replicate blocks were included in each of the composite models. Model goodness-of-fit was examined by the Shipley's test of d-separation, using Fisher's C statistics with X^2 distribution (Lefcheck, 2016).

3. RESULTS

3.1 SOIL ABIOTIC PROPERTIES

After 15 years of application, soil pH, base saturation, aggregate stability and bulk density differed significantly among treatments (**Table 3**). The *post-hoc* comparisons showed that soil pH, base saturation and aggregate stability were significantly higher under EFB treatments of all application rates, compared to the chemical fertilizer treatment (**Figure 1**). In contrast, bulk density was significantly lower under EFB treatments of all application rates than in the chemical fertilizer treatment. Soil organic carbon and total nitrogen levels did not significantly differ among the four treatments.

Table 3. Model outputs of linear mixed effects models examining the effects of four treatments (Low-EFB, Medium-EFB, High-EFB, and chemical fertilizer treatment) on soil abiotic properties, soil biota and soil ecosystem functions. The treatment type was fitted as a fixed effect, with focal palms nested within treatment plot and replicate block as the random structure. The *p*-value highlighted in bold indicate that the response variable differs significantly from 0 at *p*-value <0.05.

Response variable	Treatment effect	
	F-value	*p*-value
Soil abiotic properties		
Soil organic carbon	$F_{3,12} = 0.40$	0.7500
Soil total nitrogen	$F_{3,12} = 0.91$	0.4700
pH	$F_{3,12} = 17.0$	**0.0001**
Base saturation	$F_{3,12} = 32.0$	**<0.0001**
Aggregate stability	$F_{3,12} = 7.00$	**0.0057**
Bulk density	$F_{3,12} = 58.1$	**<0.0001**
Soil biota		
Earthworm biomass	$F_{3,12} = 5.73$	**0.0114**
Total mite density	$F_{3,12} = 5.80$	**0.0110**
Oribatid mite density (excluding Astigmata mite)	$F_{3,12} = 5.21$	**0.0155**
Soil ecosystem functions		
Soil fauna feeding activity	$F_{3,12} = 7.32$	**0.0057**
Soil microbial respiration	$F_{3,12} = 19.7$	**0.0001**

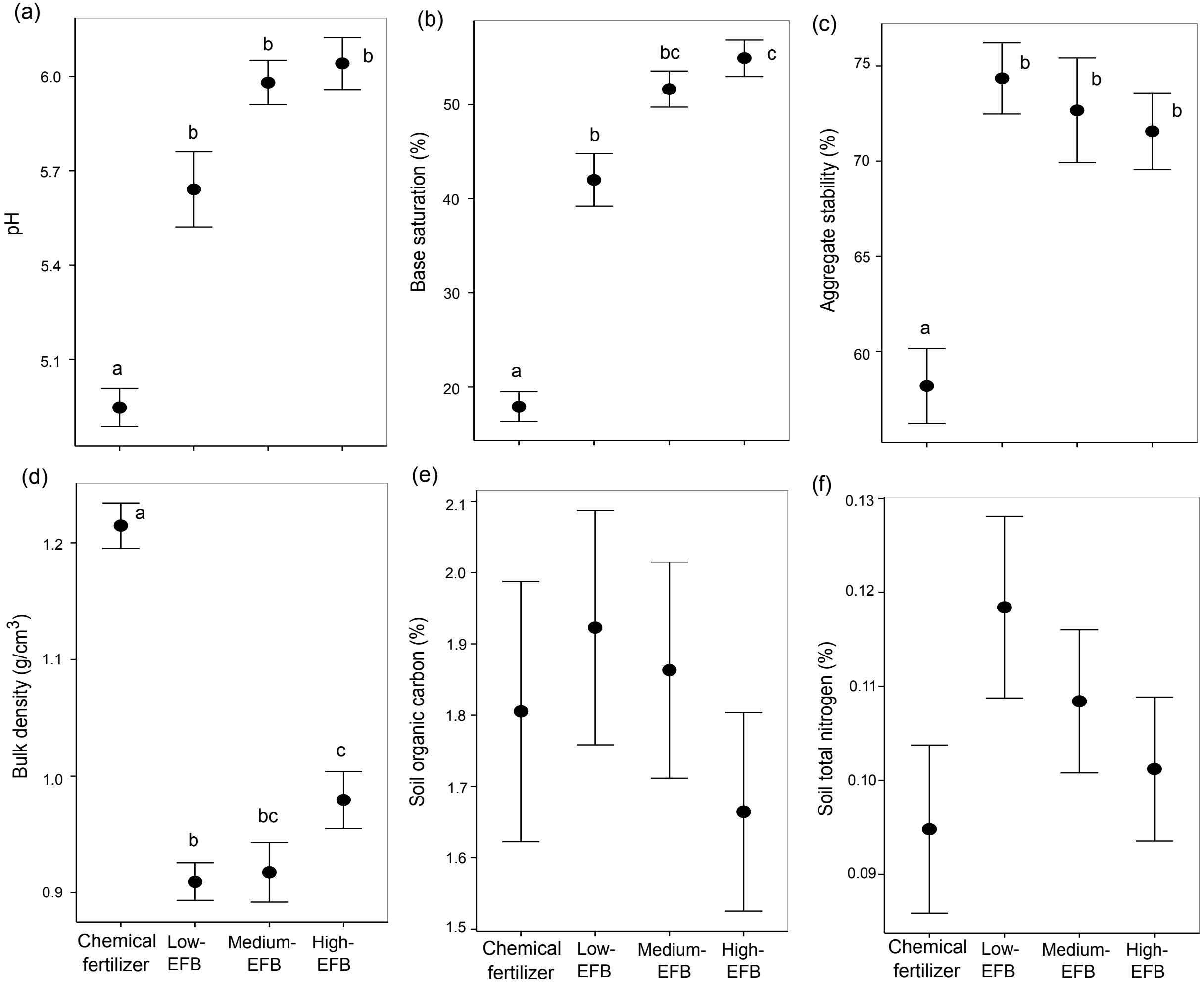

Figure 1. Soil pH (a), base saturation (b), aggregate stability (c), bulk density (d), soil organic carbon (e), and soil total nitrogen (f) under four treatments (mean ± SE). Different letters indicate significant Tukey's HSD differences between the treatments at α=5 %.

3.2 SOIL BIOTA AND SOIL ECOSYSTEM FUNCTIONS

Total earthworm biomass under Medium-EFB and High-EFB treatments was significantly lower compared to the chemical fertilizer treatment, whereas no significant differences were detected between the Medium-EFB and chemical fertilizer treatment (**Table 3, Figure 2**). Across all the treatment plots, the dominant earthworm population was the peregrine endogeic species *Pontoscolex corethrurus*.

A total of 1168 individual mites were extracted, with a mean density of 909 (ind/ m^2). The *post-hoc* comparisons showed that the total mite density under the chemical fertilizer treatment was significantly lower than Low-EFB and High-EFB treatments, whereas no significant differences were detected between the Medium-EFB and chemical fertilizer treatment (**Table 3, Figure 2**). Four mite suborders were found: Astigmata, Oribatida, Mesostigmata, and Prostigmata. Astigmata and Oribatida were the dominant groups, accounting for 68% and 22% of all the specimens, respectively. The density of Oribatida alone was significantly higher under the Low-EFB treatment, compared to the chemical fertilizer treatment and Medium-EFB treatment. The dominant group of Astigmata in our samples was *Astigmata hypopus* (Supercohort Desmonomatides, Orbatida).

Soil fauna feeding activity under Low-EFB and Medium-EFB treatments was significantly higher than the chemical fertilizer treatment (**Table 3, Figure 2**). Soil microbial respiration was significantly higher in EFB treatments with all application rates than under the chemical fertilizer treatment (**Table 3, Figure 2**).

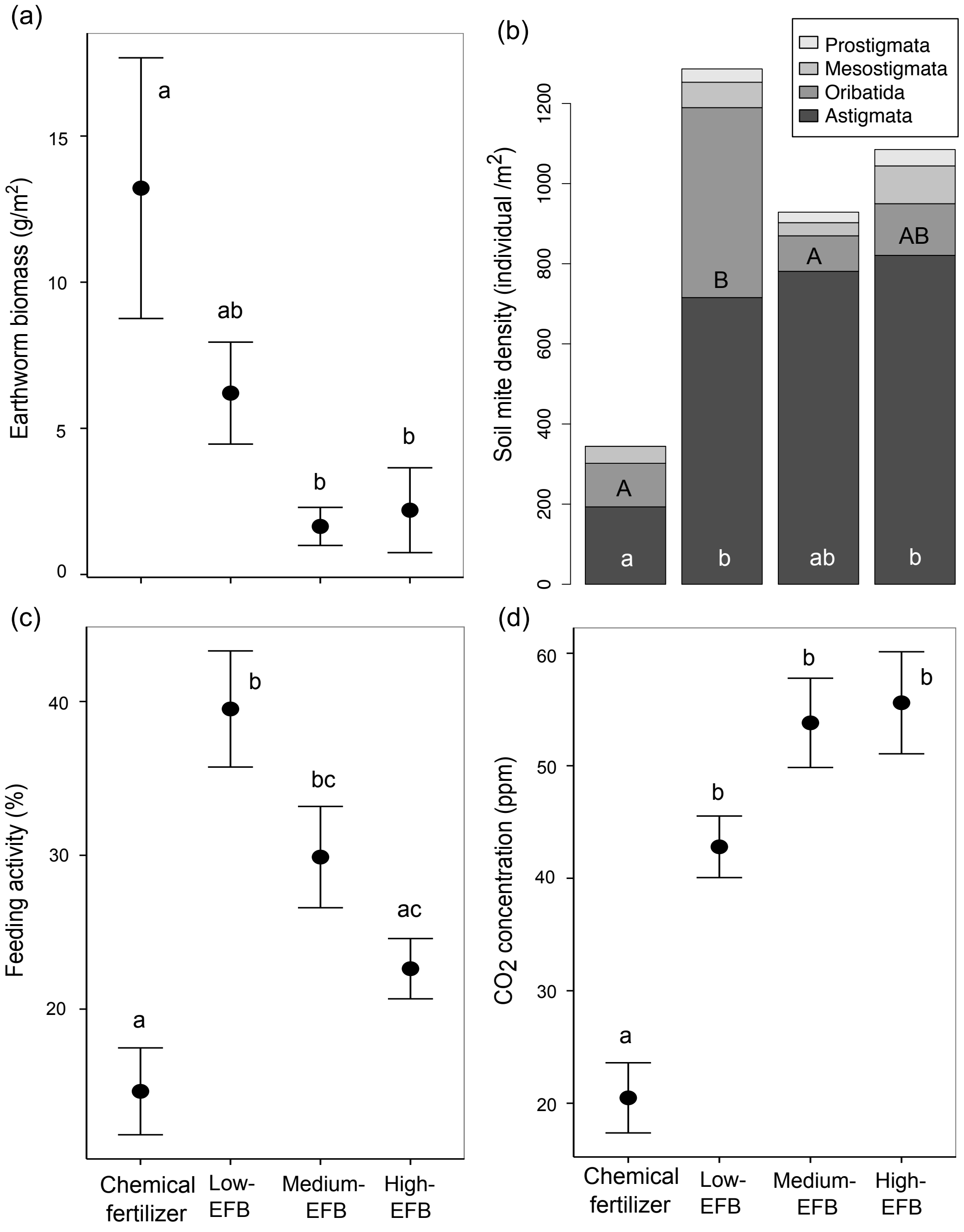

Figure 2. Earthworm biomass (a), soil mite density (b), soil fauna feeding activity (c), and soil microbial respiration (d) under four treatments (mean ± SE). Different letters indicate significant Tukey's HSD differences between treatments at α=5 %. In (b), the lower case letters represented statistical differences in the density of total soil mite, while the upper case letters represented the differences in the density of Oribatida.

3.3 CASCADING EFFECTS OF EFB APPLICATION ON THE SOIL ECOSYSTEM

Structural equation modelling was used to examine the cascading effects of EFB application on the soil ecosystem (**Figure 3, Supplementary S4-S6**). The structural equation modelling showed that EFB application increased soil moisture, soil pH, and bulk density. EFB application directly reduced earthworm biomass but increased soil mite density. The increased soil mite density in turn enhanced soil fauna feeding activity. EFB application both directly increased soil fauna feeding activity, as well as by increased soil pH, increased mite density, and reduced bulk density. Similarly, EFB application directly increased soil microbial respiration, as well as by increased soil moisture, soil pH, soil fauna feeding activity, and reduced soil bulk density.

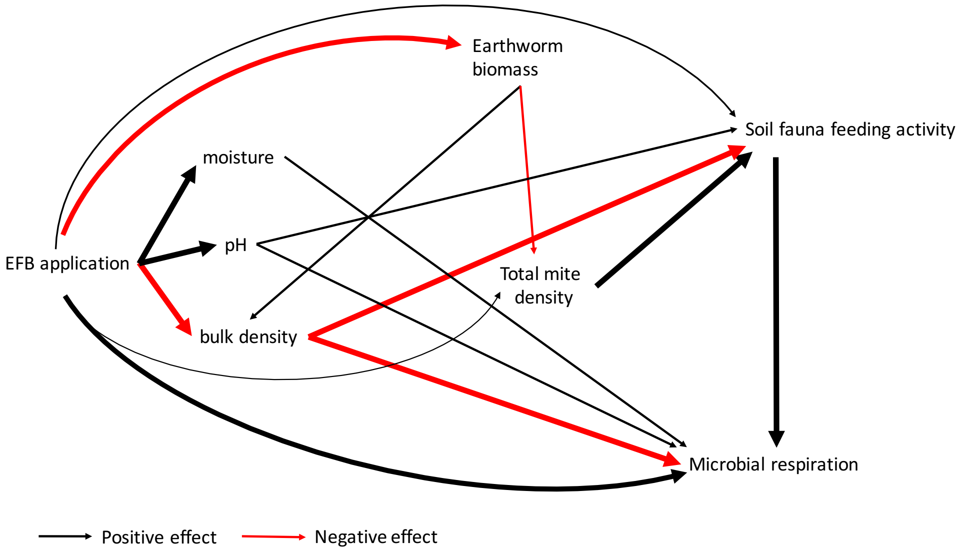

Figure 3. The final, most parsimonious model for exploring the cascading effects of EFB application. Structural equation model examining the cascading effects of EFB application on soil ecosystem functions. Arrows represent unidirectional relationships among variables. Positive relationships were denoted by black arrows, negative relationships by red arrows, and non-significant relationships (p-value>0.05) by dashed arrows. Arrow widths are proportional to the standardized regression coefficients, given in the associated box. Conditional coefficients of determination (r^2) of each endogenous variable is reported. The models were well supported (Fisher's C: 14.87, df=12, p-value=0.25).

4. DISCUSSION

This study gives an insight into the cascading effects of EFB addition on soil ecosystem functions in the oil palm agroecosystem. The results demonstrate that EFB application enhances soil ecosystem functions, directly through providing of food resources, as well as by altering soil biota. These findings improve our understanding of the links between soil abiotic properties, soil biota, and soil ecosystem functions in the oil palm ecosystem, and also highlight the potential of EFB application as a sustainable soil management practice to improve soil ecosystem functions.

4.1 SOIL ABIOTIC PROPERTIES

Our results showed that EFB application over 15 years significantly increased soil pH and base saturation. This is in line with previous findings in other Malaysian and Indonesian oil palm plantations (Abu Bakar et al., 2010; Carron et al., 2015b; Comte et al., 2013), confirming the capacity of EFB in releasing base cations to alleviate soil acidification and improve nutrient retention of the soil (Moradi et al., 2014b; Nelson et al., 2011). EFB application also enhanced soil aggregate stability and decreased bulk density, in line with previous findings in other Malaysian and Indonesian oil palm plantations (Carron et al., 2015b; Moradi et al., 2015; Teh et al., 2011). On the other hand, EFB application did not markedly increase soil organic carbon or nitrogen levels at our study site. This finding agrees with a previous study of four years of best management practices with EFB application in Indonesian oil palm plantations (Pauli et al., 2014). In contrast, EFB application for 8-10 years significantly improved soil organic carbon and nitrogen levels in other Malaysian and Indonesian oil palm plantations (Abu Bakar et al., 2010; Comte et al., 2013). The unchanged soil organic carbon and nitrogen levels under EFB application at our study site may be due to the loss of EFB-derived organic carbon through an increased decomposition rate or soil erosion (Berhe et al., 2007; Guillaume et al., 2015; Smith et al., 2012).

4.2 EARTHWORMS

The total earthworm biomass was significantly reduced under EFB treatments of all rates, compared to the chemical fertilizer treatment. Another study in a nearby oil palm plantation also found a decrease in earthworm population after six months of EFB application; although the population recovered within 18-24 months of the application (Carron et al., 2015a). The reasons for the decline at our study is still unclear. An explanation is that the decomposing EFB may release phenol compounds that are toxic to earthworms (Sabrina et al., 2012). The sharp fibers of EFB may also create a less suitable microhabitat for the earthworms. Moreover, the addition of EFB may create a pH shock, or a change to more anoxic conditions in the soil, which are less favorable for earthworms (Carron et al., 2015a).

The endogeic earthworm species, *Pontoscolex corethrurus,* dominated our study site regardless of the treatment type. *P. corethrurus* is a peregrine species that is widely spread in disturbed or cultivated areas in the humid tropics (P Lavelle et al., 1987), including oil palm plantations (Sabrina et al., 2009a). It is classed as a “compacting species” which produces large and compact casts, and therefore increases soil bulk density and macro-aggregates, especially when organic residues are absent in the environment (Alegre et al., 1996; Chauvel et al., 1999; Hallaire et al., 2000). We therefore hypothesized that the dominance of *P. corethrurus* may negatively influence soil structure and chemical properties. However, results from structural equation modelling did not show significant impacts of earthworm biomass on soil physicochemical properties. This indicates that earthworms were not having large effects on the soil environment at our study site, possibly because the population size of *P. corethrurus* was relatively small.

4.3 SOIL MITES

The density of soil mites was significantly higher after 15 years of EFB treatments under all application rates, compared to the chemical fertilizer treatment. EFB application also influenced the soil mite community structure. Specifically, the relative density of Astigmata and Oribatida mites, which are important fungivorous and detritivorous groups, were enhanced by EFB application. These findings are in line with studies of other cropping systems, which demonstrated that the addition of soil amendments and organic residues altered the density, diversity and assemblage of soil mites (Minor and Norton, 2004; Sánchez-Moreno et al., 2009; Scheunemann et al., 2015). One of the important predatory mites, the Prostigmata, were not found in our extractions under the chemical fertilizer treatment. In contrast, individuals of Prostigmata were found under Low-EFB, Medium-EFB and High-EFB treatments. The re-appearance of Prostigmata under EFB application indicates the restored regulatory functions of the soil food webs, which are essential to control the population growth of other organisms, and to regulate the turnover rate of energy and organic matter (Wissuwa et al., 2012).

The density of total soil mites was not influenced by earthworm biomass (**Figure 4**). This contrasts with our hypothesis, as endogeic earthworms have previously been shown to impact negatively on soil mites, mainly through competition for food resources, consumption of individuals and eggs, reduction in microbial biomass, and changing soil physical structure that disturbs soil mites (N. Eisenhauer, 2010). A possible reason is that the population size of earthworms was too small to have a significant impact on the mites. Another explanation is that the soil mite populations might be more affected by bottom-up control of resource provision, compared to top-down forces, as which were the case in other studies (Mueller et al., 2016; Shao et al., 2015).

4.4 SOIL FAUNA FEEDING ACTIVITY

Results from structural equation modelling suggested that EFB application enhanced soil fauna feeding activity by increasing the density of soil mites (**Figure 4**). In addition, the increase in soil mite density was a direct effects of EFB addition, rather than through the alterations of the soil physicochemical properties. These results suggest that the food resources provided by EFB may directly increase the foraging activities of detritivorous mites, such as Astigmata and Oribatida. The positive relationships between the density of detritivorous mites and soil fauna feeding activity have also been observed in Amazon forests and plantations (Römbke et al., 2006). Similarly, results from temperate ecosystems and laboratory manipulations have shown that microarthropods, including soil mites, are one of the major feeders on the bait lamina assay (Helling et al., 1998; Kratz, 1998). The enhanced soil fauna feeding activity under EFB application implies a more rapid turnover of carbon and nutrients, which may in turn alter the available nutrients in the soil, and ultimately the growth of the oil palms.

Soil fauna feeding activity was not significantly influenced by earthworm biomass (**Figure 4**). This result contrasts with findings in temporal ecosystems and laboratory manipulations, which found earthworms to be a major feeder of the bait lamina assay (Forster et al., 2004; Gestel et al., 2003). For instance, in temperate grasslands, earthworms were found to facilitate soil fauna feeding activity via their positive effects on Collembola populations, possibly through improving soil habitats for Collembola (Birkhofer et al., 2011). One of the possible reasons for the contrasting findings between these studies and our findings can be due to the different functionality of the dominant earthworm species. The dominant species, *P. corethrurus,* at our study site was likely to have adverse effects on soil properties, compared to the majority of earthworm species serving as ecosystem engineers in temperate grassland and undisturbed systems (Alegre et al., 1996; Chauvel et al., 1999; Hallaire et al., 2000).

4.5 SOIL MICROBIAL RESPIRATION

Our results demonstrated that soil microbial respiration rate was positively and directly influenced by EFB application, relative to the chemical fertilizer treatment (**Figure 4**). Soil microbial respiration was also positively explained by soil organic carbon and nitrogen levels, although EFB application did not significantly affect soil organic carbon and nitrogen levels. These results indicate that soil microbial respiration was enhanced by the resource availability from EFB, as well as the levels of soil organic matter. Studies in Malaysian oil palm plantations have also demonstrated soil organic carbon content and microbial biomass nitrogen as the main determining factors of soil microbial respiration (Adachi et al., 2006; Smith et al., 2012). Moreover, a study in oil palm plantations of Papua New Guinea also showed higher soil respiration underneath EFB placement, although the relative contributions of respiration from heterotrophic and autotrophic sources were not identified (Nelson et al., 2013). Structural equation modelling showed that neither soil mite density nor earthworm biomass significantly affected soil microbial respiration, which indicates that microbial respiration at our study site was regulated more by the bottom-up forces of resources availability, rather than top-down forces in the detrital food web.

4.6 IMPLICATIONS

Positive effects of EFB application on soil abiotic properties, soil biota, and ecosystem functions were observed in this study. These results indicate the high potential of EFB application to improve the soil ecosystem in oil palm plantations. To maximize the positive effects of EFB application, further studies are needed to determine the optimal application rate, frequency, and duration of this practice, in order to provide guidelines for field operations. Moreover, the use of EFB in commercial oil palm plantations is currently limited, due to its availability and the relatively high costs of transportation and field applications (Chiew and Shimada, 2013). Technology development, such as transformation of EFB into composts, can be useful to provide alternative management practices, and further research to evaluate the effectiveness of these practices on the soil ecosystem is needed for sustainable oil palm production.

5. ACKNOWLEDGMENTS

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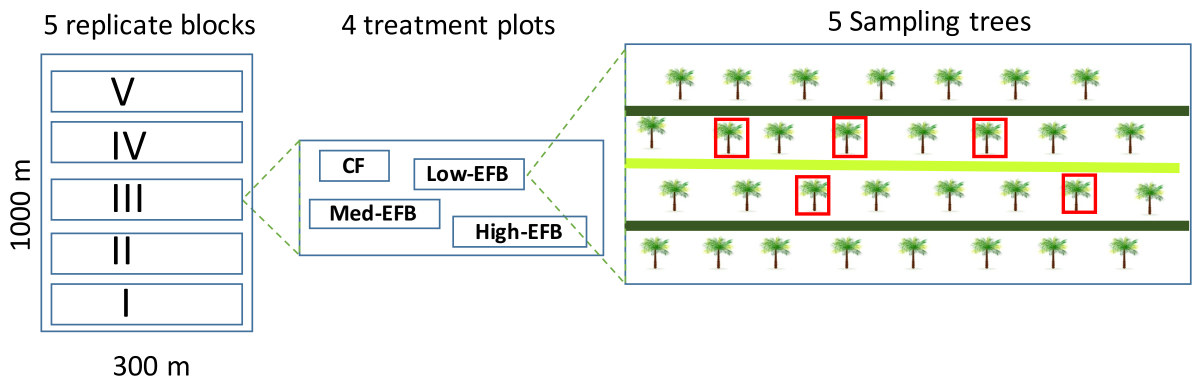
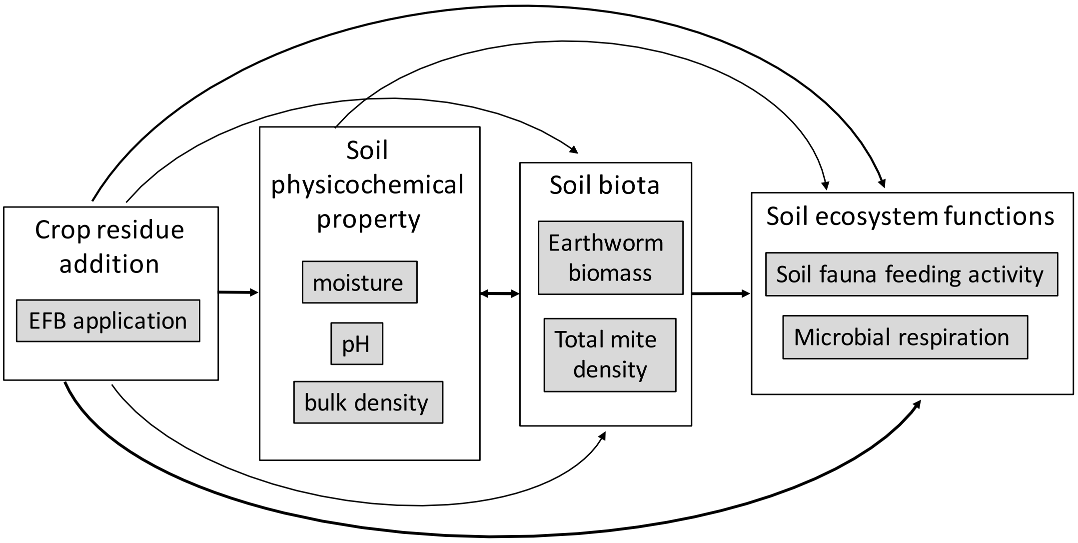
6. SUPPLEMENTARY MATERIALS

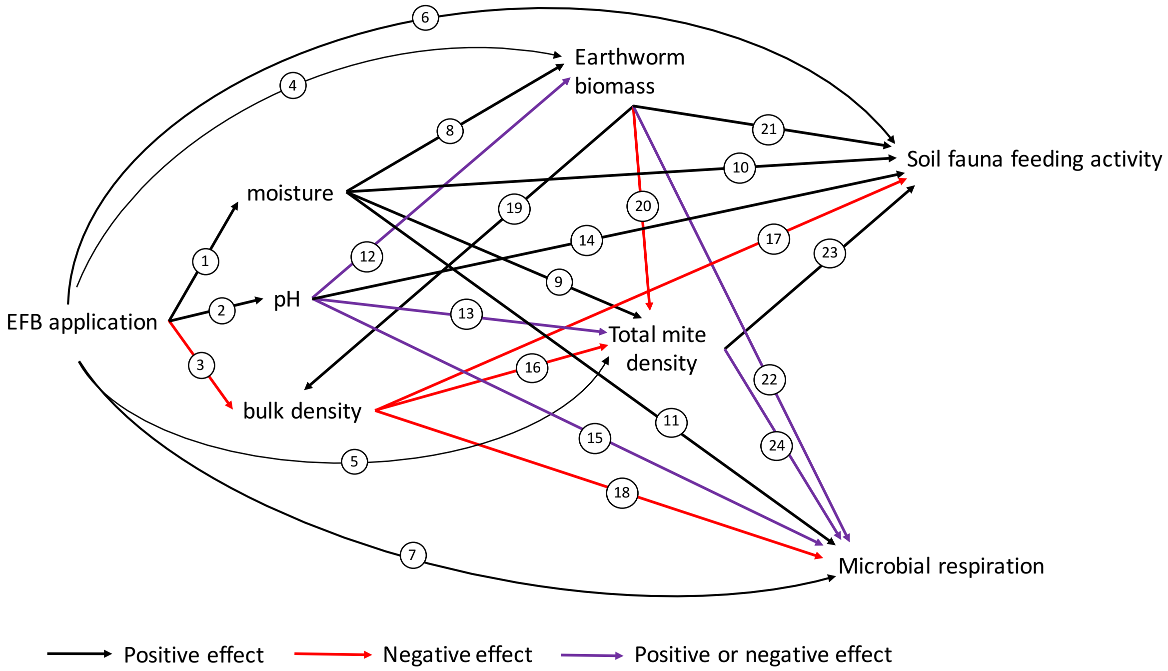
Supplementary S1. Diagram of the field trial used this study. CF: chemical fertilizer treatment.



Supplementary S2 A metamodel for the modelling of crop residue addition effects on soil properties.



Supplementary S3. The *a prior* model with potential relations between the considered variables and the hypothesized mechanisms.



Soil abiotic properties

Crop residue addition may positively affect soil moisture by preventing soil water evaporation (**1**) (Turmel et al., 2015). Crop residue addition may enhance soil pH by releasing base cations (**2**) (Butterly et al., 2013). Crop residue addition may negatively affect soil bulk density by increasing soil water content (**3)** (Turmel et al., 2015). Earthworm species of *Pontoscolex corethrurus* may increase soil density by producing large and compact casts (**19**) (Nico Eisenhauer, 2010).

Earthworm biomass

Crop residue addition may increase earthworm biomass by providing readily available organic matter (**4**) (Edwards, 2004), or through alterations of soil moisture (**8**) (P. Lavelle et al., 1987) and soil pH (**12**) (Marichal et al., 2012).

Soil mite density

Crop residue addition may increase soil mite population by providing readily available organic matter (**5**) (Coleman et al., 2004), or through altering soil abiotic properties, such as soil moisture (**9**) (Bedano et al., 2006), soil pH (**13**) (Coleman et al., 2004), and soil bulk density (**16**) (Bedano et al., 2006). *Pontoscolex corethrurus* as an endogeic earthworm may reduce the soil mite density by consuming individuals and eggs or competing for food resources (**20**) (Nico Eisenhauer, 2010). *Pontoscolex corethrurus* may also negative influence soil mites via increasing soil bulk density (**19, 16**) (Nico Eisenhauer, 2010).

Soil fauna feeding activity

Organic matter addition may increase the soil fauna feeding activity by providing food resources (**6**), or through altering soil abiotic properties such as soil moisture (**10**), soil pH (**14**), and soil bulk density (**17**) (Geissen et al., 1999; Reinecke et al., 2008; Simpson et al., 2012; Tao et al., 2016). Soil mite density may increase the soil fauna feeding activity through direct feeding (**23**) (Römbke et al., 2006). Earthworm species of *Pontoscolex corethrurus* may increase the soil fauna feeding activity by direct feeding on the bait lamina (**21**). In contrast, *Pontoscolex corethrurus* may reduce the soil fauna feeding activity by reducing the soil mite populations (**20, 23**) (Birkhofer et al., 2011).

Soil microbial respiration

The addition of crop residue can provide food sources which increase microbial respiration (**7**) (Cookson et al., 1998). Crop residue addition may also increase microbial respiration by altering soil moisture (**11**) (Kaneko et al., 1998), soil pH (**15**) (Birkhofer et al., 2012), and (**18**) bulk density (Torbert and Wood, 1992). Earthworms may influence soil microbial community by direct feeding, disruption of fungal hyphae, and competing for food resources (i.e. resource competition) (**22**) (Bohlen et al., 2004). The earthworm species of *Pontoscolex corethrurus* may negatively influence microbial community by increasing soil bulk density (**18, 19**) (Bohlen et al., 2004). The soil mite populations may positively or negatively influence soil microbial respiration (**24**) (Kaneko et al., 1998).

Supplementary S4 Statistics for linear models and pairwise relations among variables. The relationships are represented by regression plots. Plots are plotted with lines when the effects are significant (p-value < 0.1). Note: the models are simple regression models without random effects.

Response variable	Predictor	Multiple R^2	P-value	Correlation r^2
Mite	Treatment		**0.02896**	
	pH	0.03339	0.07	0.18
	Bulk density	0.08533	**0.003693**	**-0.29**
	Moisture	0.01199	0.2988	0.11
	Earthworm	0.04306	**0.05101**	**-0.24**
Earthworm	Treatment		**0.01333**	
	pH	0.0575	**0.02132**	**-0.24**
	Bulk density	0.03225	**0.08672**	0.17
	Moisture	0.03347	**0.08988**	**-0.23**
Soil fauna feeding activity	Treatment		**0.003441**	
	Mite	0.14	**0.0003571**	**0.37**
	Earthworm	0.05554	**0.03306**	**-0.29**
	pH	0.0237	0.1474	0.15
	Bulk density	0.1547	**0.0001259**	**-0.39**
	Moisture	0.004824	0.5154	0.08
Microbial respiration	Treatment		**2.94E-05**	
	Mite	0.07561	**0.006414**	**0.27**
	Earthworm	0.04661	**0.03875**	**-0.21**
	pH	0.1514	**6.30E-05**	**0.39**
	Bulk density	0.3232	**6.83E-10**	**-0.57**
	Moisture	0.1195	**0.0006022**	**0.35**

Supplementary S5 Model seleciton procedure and statistics for the strucutral equation model. Model 10 was selected as the most parsimonious model, as further deletion of explantory terms resulted in the Delta AIC < 8.

Model	Regression deleted	df	AIC	AICc	Delta AIC	Delta AIC compared with	Fit (P-value)	Missing path suggest
A-prior model		8	119.67	370.215			0.047	Respiration~activity (added to F1 model)
Model 1		6	109.62	382.191	11.976	F0	0.728	None
Model 2	Fauna activity~moisture	8	107.71	358.255	23.936	F1	0.883	None
Model 3	Mite~moisture	10	105.97	336.579	21.676	F2	0.949	None
Model 4	Mite~pH	12	104.64	317.14	19.439	F3	0.969	None
Model 5	Mite~bulk density	14	102.69	298.69	18.45	F4	0.99	None
Model 6	Respiration~mite	16	100.84	281.763	16.927	F5	0.996	None
Model 7	Earthworm~moisture	18	99.35	266.461	15.302	F6	0.998	None
Model 8	Respiration~earthworm	20	98.98	253.409	13.052	F7	0.997	None
Model 9	Earthworm~pH	22	96.36	239.119	14.29	F8	1	None
Model 10	**Activity~earthworm**	**24**	**95.49**	**197.028**	**42.091**	**F9**	**0.999**	**None**
Model 11	Mite~earthworm	26	96.97	191.57	5.458	F10	0.996	None
Model 12	Respiration~moisture	26	95.39	189.99	7.038	F10	0.999	None
Model 13	Bulk density~earthworm	26	94.44	189.04	7.988	F10	1	None
Model 14	Activity~pH	26	98.2	192.8	4.228	F10	0.99	None

Supplementary S6 Results of the final, most parsimonious model (Model 10) as illustrated in Supplementary S5, with unstandardized path coefficients (estimates), standard error of the regression weight, and level of significance for the regression weight (*p*-value).

response	predictor	estimate	std.error	p.value	
moi.log	dosage	0.459	0.133	0.004	**
ph.log	dosage	0.678	0.119	0	***
bul.sqrt	dosage	-0.529	0.165	0.006	**
bul.sqrt	ear.log	-0.095	0.082	0.251	
ear.log	dosage	-0.38	0.098	0.002	**
mit.log	dosage	0.233	0.158	0.162	
mit.log	ear.log	-0.083	0.111	0.459	
act.sqrt	mit.log	0.279	0.097	0.006	**
act.sqrt	bul.sqrt	-0.254	0.121	0.04	*
act.sqrt	dosage	-0.257	0.144	0.097	
act.sqrt	ph.log	0.207	0.154	0.185	
res.log	dosage	0.548	0.13	0.001	***
res.log	act.sqrt	0.267	0.079	0.001	**
res.log	bul.sqrt	-0.218	0.094	0.024	*
res.log	ph.log	-0.222	0.116	0.06	
res.log	moi.log	0.083	0.082	0.316	

CHAPTER 5

EFFECTS OF CROP RESIDUE ADDITION ON OIL PALM YIELD UNDER A CHANGING CLIMATE

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ABSTRACT

Soil degradation and climate change have the potential to drive a decline in oil palm yields over the next few years. Application of empty fruit bunches (EFB), an oil palm residue, is a widely used management practice for improving soil conditions. Understanding how crop yield responds to the application of EFB under a changing climate is therefore of importance for sustainable palm oil production. Crop yield under 15 years of EFB application and chemical fertilizer treatment were compared in a field trial at an Indonesian oil palm plantation. EFB application enhanced the total crop yield, compared to the chemical fertilizer treatment over the 15 years of measurement. However, EFB application reduced the temporal stability of crop yield; there was greater between-year variability in crop yield under the EFB than the chemical fertilizer treatment. Throughout the application period, crop yield followed distinct temporal changes, which were associated with the climatic conditions. Soil organic carbon, which was positively influenced by EFB application, also explained the temporal changes in crop yield. These findings indicate the importance of taking both total crop yield and temporal stability in this yield into account for optimized field implementations. These results also suggest the complexity of determining factors for oil palm yield, and the importance of further research on soil management practices, in order to manage the uncertainties of crop yield under degrading soil environments and changing climate.

Keywords: Empty fruit bunch, soil organic carbon, relative humidity, sustainable oil palm

1. INTRODUCTION

Oil palm (*Elaeis guineensis*) is one of the most important economic crops in the tropics, for its use in food, cosmetics, and feedstock for biofuel (Kurnia et al., 2016; Sayer et al., 2012; Sheil et al., 2009). The area of oil palm planting has expanded rapidly during the past few decades, with the global land area reaching 16.4 million ha in 2014, equivalent to 10% of the world's permanent croplands (FAO, 2015; Sheil et al., 2009). Currently, more than half of the world's plantations are located in Malaysia and Indonesia, which accounted for 85% of the 56 million tons of crude palm oil produced worldwide in 2013 (FAO, 2015). Oil palm expansion is expected to continue over the next decades (Carter et al., 2007; Corley, 2009). Therefore, maintaining high crop yield combined with environmentally-friendly practices, or the concept of sustainable intensification, is important to improve the revenue for the industry and smallholder farmers, supply the continuing rising demand, and reduce the required area for new plantations (Bhagwat et al., 2012; Donough et al., 2009).

Soil degradation may negatively influence oil palm yield, and is a major concern for the industry (Sheil, 2008). It has been reported that oil palm plantations have led to declines in soil organic carbon, loss of biodiversity, and altered nutrient cycling after conversion from tropical forests (Allen et al., 2015; Fitzherbert et al., 2008; Guillaume et al., 2015; Violita et al., 2015). These changes are due to common practices used in oil palm plantations, such as extensive use of chemical fertilizers, removal of harvesting biomass, and clearance of understorey vegetation (Hartemink, 2005; Nelson et al., 2011). The disturbed soil properties and processes may reduce the availability of nutrients in the soil, which in turn may negatively influence palm growth and productivity. However, few studies have attempted to relate the changes in soil properties to oil palm yield (Nelson et al., 2011).

The application of empty fruit bunches (EFB), a by-product from palm oil extraction, is one of the soil management practices aimed at mitigating soil degradation (Caliman et al., 2001; Teh et al., 2010). In Malaysian and Indonesian oil palm plantations, EFB application for 4-10 years has been shown to improve soil carbon and nutrient content relative to chemical fertilizer treatments (Abu Bakar et al., 2010; Comte et al., 2013; Pauli et al., 2014). Oil palm yield has also been shown to be enhanced after applying EFB for 2-10 years in Malaysia and Indonesia (Abu Bakar et al., 2010; Chiew and Rahman, 2002; Donough et al., 2009). However, it remains unclear how oil palm yield varies with EFB application through time, and whether the changes are associated with the soil properties that EFB mediates. It is also unknown whether EFB application influences the temporal variability of the crop yield, which is important because variations in crop yield can greatly reduce economic returns (Olivin, 1986 in Fairhurst and Härdter, 2003).

In addition to soil properties, the palm oil yield is also influenced by climatic conditions (Corley and Tinker, 2015). It is known that rainfall, temperature, and solar radiation are major limiting factors for biomass production and partitioning of oil palm (Goh, 2000 in Corley and Tinker, 2015). For example, seasonal changes in rainfall are reported to explain 55% of yield variations in some Malaysian oil palm plantations (Chow, 1992). Inter-annual variations in temperature and rainfall, due to El Niño (Southern Oscillation), have also been shown to influence oil palm yield with lagged effects (Cadena et al., 2006; Shanmuganathan and Narayanan, 2012). Understanding how crop yield responds to soil management practices under a changing climate is key to predicting future production and to make appropriate management decisions.

The aims of this study were to (i) understand how total crop yield responds to EFB application over time, and how EFB influences the temporal variability of crop yield; (ii) identify soil properties that are associated with the effects of EFB application on crop yield; and (iii) understand other determining factors for temporal variations in crop yield, such as climatic conditions and palm age.

2. MATERIALS AND METHODS

2.1 SITE DESCRIPTION

The study was carried out in an oil palm plantation in Sumatra, Indonesia (0° 56’0” N 101°18’0”E). The oil palm plantation was established in 1987 and is certified by the Roundtable on Sustainable Palm Oil. The previous land use of this area was secondary forest dominated by Dipterocarp species. The climate of this region is described as tropical humid, with a mean temperature of 26.8 °C and average rainfall of 2400 mm year^{-1}. The soils are Inceptisols (Typic Dystrudepts) (USDA soil classification system), within the loamy lowland soil class.

2.2 EXPERIMENTAL DESIGN

The 15-year trial began in 1998, when the oil palms were 11 years old. Field sampling and measurements were conducted at the end of the trial during September-October 2014. The field trial was established at two adjacent oil palm commercial plots, at a flat area with limited possibility of leaching and runoff. The field trial covered a total area of 36 hectares (1200 m length x 300 m wide) and comprised five replicate blocks. Each replicate block was composed of four treatment plots, resulting in a total of 20 treatment plots (5 replicate blocks x 4 treatment plots) in the field trial for soil sampling. The replication number is five in this nested design.

The four treatment plots within each replicate block were: Low-EFB treatment (210 kg tree^{-1} year^{-1}, equivalent to 30 ton ha^{-1} yr^{-1}), Medium-EFB treatment (420 kg tree^{-1} year^{-1}, equivalent to 60 ton ha^{-1} yr^{-1}), High-EFB treatment (630 kg $tree^{-1}$ $year^{-1}$, equivalent to 90 ton ha^{-1} yr^{-1}), and chemical fertilizer treatment without EFB application. Each treatment plot is composed of 36 palm trees (8 palm trees at 4 rows), with the plot size approximately 80 m length x 40 m wide. A total of five oil palms in the central two rows of each treatment plot were used as focal palms for sampling. There was at least one palm tree between two focal palms, to avoid the spill over effects. Each treatment plots were surrounded by 1.5 m ditches to prevent the interference by adjacent treatment plots.

For EFB treatment plots, EFB was applied once a year for 15 years at one side of the harvesting paths, followed by urea application on the top of EFB. Urea is used to reduce the C/N ratio for accelerating EFB decomposition rate. The application rate of Low-EFB treatment is similar to standard operations in the oil palm industry, whereas Medium-EFB and High-EFB treatments represent a range of alternative application rates of EFB. The chemical fertilizer treatment was similar to standard estate practices without the application of EFB. The application rate, frequency, application location and type of chemical fertilizer are detailed in **Table 1**. The fertilizers were applied within palm circles twice a year (i.e. during the February-March and September-October periods) throughout the trial period.

2.3 MEASURES OF OIL PALM YIELD AND SOIL PROPERTIES

The fresh fruit bunch weight was used as the indicator for palm oil yield in our study, as there is a fixed ratio between the weight of fresh fruit bunches and the weight of extracted palm oil for the same variety (Squire, 1986). The fresh fruit bunches from the 12 focal palms at each treatment plot were harvested and weighed throughout the trial period. The annual fresh fruit bunch yield was calculated as the weight of total fresh fruit bunch weight in a certain year. The total crop yield was obtained by summing the 15 years of annual fresh fruit bunch weight of each treatment plot.

Table 1 Application rates of EFB and chemical fertilizers for each treatment, and the equivalent nutrient application rates.

Code	Treatment	Application rate	Nutrient application rate (kg palm^{-1} year^{-1})*					
		(kg tree^{-1} year^{-1})	C*	N	P	K	Mg	Ca
Chemical fertilizer	Chemical fertilizers; no application of EFB	Urea 3.5		1.61				
		TSP 1			0.26			0.14
		MOP 5			0.75	2.50		
		Kieserite 2					0.32	
Low-EFB	Low application rate of EFB (30 ton ha^{-1}yr^{-1})	EFB 210	102	0.56	0.064	1.7	0.1	0.1
		Urea 0.02		0.01				
Medium-EFB	Medium application rate of EFB (60 ton ha^{-1}yr^{-1})	EFB 420	204	1.12	0.13	3.4	0.2	0.2
		Urea 0.04		0.02				
High-EFB	High application rate of EFB (90 ton ha^{-1}yr^{-1})	EFB 630	306	1.68	0.19	5.1	0.3	0.3
		Urea 0.06		0.03				

The carbon and nutrient composition of EFB were referenced from (Comte et al., 2013; Moradi et al., 2014b). TSP: triple super phosphate ($Ca(H_2PO_4)_2 \bullet H_2O$); MOP: Muriate of Potash, potassium chloride (KCl); Kieserite: magnesium sulfate ($MgSO_4 \cdot H_2O$).

Over the trial period, soil samples were measured five times, at palm ages of 13, 16, 19, 23 and 26 years (equivalent to 2, 5, 8, 12, and 15 years of EFB application). For each treatment plot, one soil sample was collected at 0-15 cm depth under each of the 12 focal palms, and the 12 samples were pooled to form a composite sample for soil chemical analyses. Soil organic carbon concentration was measured using the Walkley-Black method (Nelson and Sommers, 1982). Base saturation was calculated as the ratio of the four base cations (sum of Ca, Mg, K, and Na) to the cation exchange capacity (sum of Ca, Mg, K, Na, H and Al). The concentrations of exchangeable bases (Ca, Mg, K, and Na) were measured with the ammonium acetate method (van Reeuwijk, 1993).

In order to examine the localized effects of EFB on soil properties, soil samples were taken from the area beneath the EFB (one side of harvesting paths) in the EFB treatment plots. In the chemical fertilizer plots, soil samples were collected at the equivalent positions as in the EFB treatment plots. The application of chemical fertilizers in oil palm plantations has been shown to have limited spill-over effects (Carron et al., 2016). Therefore, we assumed that the chemical fertilizers applied within the palm circles do not influence soil properties at the harvesting paths, where soil sampling took place.

The climatic variables were measured at a meteorological station approximately 5 km from the trial site throughout the application period. Annual values of maximum temperature, minimum temperature, mean temperature, rainfall, and relative humidity were used in the analyses to understand their possible associations with the performance of crop yield.

2.4 STATISTICAL ANALYSIS

We used R 3.2.2 (R Core Team, 2016) for conducting the statistical analyses, with the *lmer* function in the *lme4* package. The significant overall effects of the treatment type were examined by the *post-hoc* Tukey test, using the *ghlt* function in the *multcomp* package. Three hypotheses were tested: first, whether EFB application influenced crop yield through the application period (H1); second, whether EFB application influenced crop yield through altering soil organic carbon levels (H2); and third, whether EFB application affected the temporal stability in crop yield (H3).

Before testing the three hypotheses of EFB application, we explored the possible determining roles of climatic conditions on crop yield and soil organic carbon (SOC), to consider fitting them as covariates for the models. To test whether climate conditions affected crop yield, we used linear mixed effects models to fit three climatic variables (annual mean temperature, rainfall, and relative humidity) separately with crop yield, with random effects included for the application year and replicate block. Lagged effects for one or two years of each climatic variable were explored, as climate has shown to have delayed effects on oil palm yield previous studies (Corley and Tinker, 2015). We found that relative humidity was the only climatic variable which significantly explained crop yield, with lagged effects of two years. We therefore included relative humidity as covariate into the models for testing H1.

To test H1, we used linear mixed effects models. The interactions of treatment type and application year, and relative humidity were included as fixed effects. The quadratic and cubic terms of application year and their interactions with treatment type were also included in the model, to capture the temporal dynamics of the crop yield. The application year and replicate block were included as the random effects. The random intercept of application year accounted for the temporal correlations of the repeated measures; therefore, we did not include the error structure of auto-correlations in the model. The fixed effects of the full model were specified as ~treatment * year+ treatment* year^2+ treatment* year^3+

humidity. We used stepwise deletion to drop non-significant variables and using the anova function to compare the two best models, before comparing the final, the most parsimonious model with the null model.

To test H2, we firstly tested whether the treatment had an effect on SOC (H2.1). Subsequently, whether SOC had an effect on crop yield (H2.2). If the null hypotheses of H2.1 and H2.2 were rejected, we then suggest that treatment influences yield through altering SOC. Before testing H2.1, we explored the potential role of climatic conditions on SOC, as climate may either affect crop yield through providing favourable conditions for palm growth, or through altering SOC levels (i.e. by affecting litter decomposition and nutrient release) (Couteaux et al., 1995). We fitted each of the climatic variables as the fixed effects. Models with no lagged effect, lagged effects of one year, or lagged effects of two years of each climatic variable were explored, as climate may have lagged effects on soil conditions (Couteaux et al., 1995). None of the climatic variables significantly explained SOC, suggesting climatic conditions may directly affect crop yield, rather than through altering SOC. Therefore, we did not include climatic variable in the models for testing H2.1, while we included relative humidity in H2.2 as a covariate.

To test H2.1, we used linear effects model, including the interaction of treatment type and application year as fixed effects, specified as treatment*year in the R syntax. For testing H2.2, we then included SOC and relative humidity as the fixed effects, as specified as ~SOC+ humidity in the R syntax. We also tested the lagged effects of SOC for one and two years, as soil properties have been shown to have delayed effects on crop growth (Ref)

To test H3, we examined the inter-annual variability in oil palm yield under different treatments over 15 years. Temporal stability of crop yield for each treatment plot, or the coefficient of variation, was defined as was μ/σ, where μ is the temporal mean of crop yield, and σ is the temporal standard deviation over 15 years. A high temporal stability of crop yield therefore represents a lower between-year variability in crop yield over time. The temporal stability, temporal mean and temporal standard deviations of crop yield were compared across treatments using linear mixed effects models, with the replicate block as a random effect.

3. RESULTS

3.1 CROP YIELD

Over 15 years of trial period, the total crop yield of five plots for each treatment was highest in the Medium-EFB (2161 t ha^{-1}), followed by the High-EFB (2137 t ha^{-1}), Low-EFB (2088 t ha^{-1}), and the chemical fertilizer treatment (2040 t ha^{-1}) (**Table 2**). The annual crop yield marginally differed among treatments ($F_{3,202}$= 2.41, p-value= 0.068) (**Figure 1, Supplementary S1**). The *post-hoc* test showed that the annual crop yield was higher under the Medium-EFB treatment (28.8 ± 0.60 t $ha^{-1}yr^{-1}$) than the chemical fertilizer treatment (27.2 ± 0.51 t $ha^{-1}yr^{-1}$). No differences in crop yield were found among the Low-EFB, High-EFB treatments and the chemical fertilizer treatment. Temporal stability, temporal means and temporal standard deviations of the annual crop yield did not differ among treatments, although temporal stability was qualitatively the highest under the chemical fertilizer treatment (**Figure 2**).

Table 2 Weight of a fresh fruit bunch (FFB), number of FFB per year, annual FFB averaged across 15 years, and total FFB weight of all the treatment plots over 15 years. Values are the means of treatment plots with standard errors.

Treatment	Average FFB weight (kg/bunch)	FFB number (bunch ha^{-1} yr^{-1})	Annual FFB weight (ton ha^{-1}yr^{-1})	Total FFB weight from 1998-2013 (ton ha^{-1})
Chemical fertilizer	26.02 ±0.30	1059 ± 26	27.20± 0.51	2040
Low-EFB	25.30 ±0.26	1110 ± 27	27.84±0.59	2088
Medium-EFB	26.40 ±0.24	1098 ±25	28.82±0.60	2161
High-EFB	26.01 ±0.34	1116 ±33	28.49±0.65	2137

* The average weight of a FFB was calculated by dividing the annual FFB weight by the number of FFB per year. The total FFB weight was calculated by summing annual FFB weight from 1998 to 2013 of all the plots (five plots per treatment).

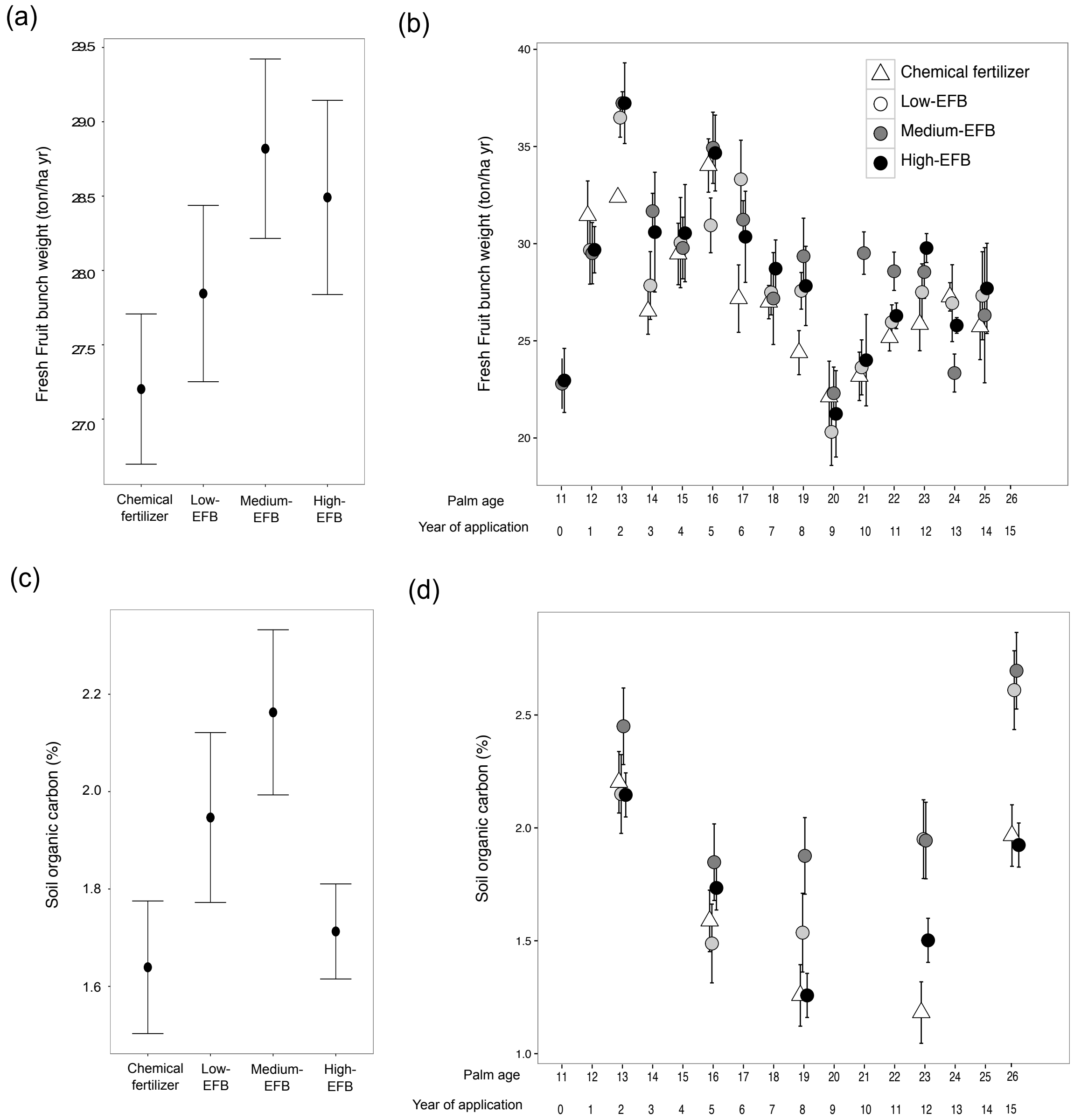

Figure 1. Means and standard errors (n=5) of the annual fresh fruit bunch weight (a), soil organic carbon (c) and base saturation (e) under four treatments over 15 years of application, and annual fresh fruit bunch weight (b), and soil organic carbon (d) as a function of the age of oil palm.

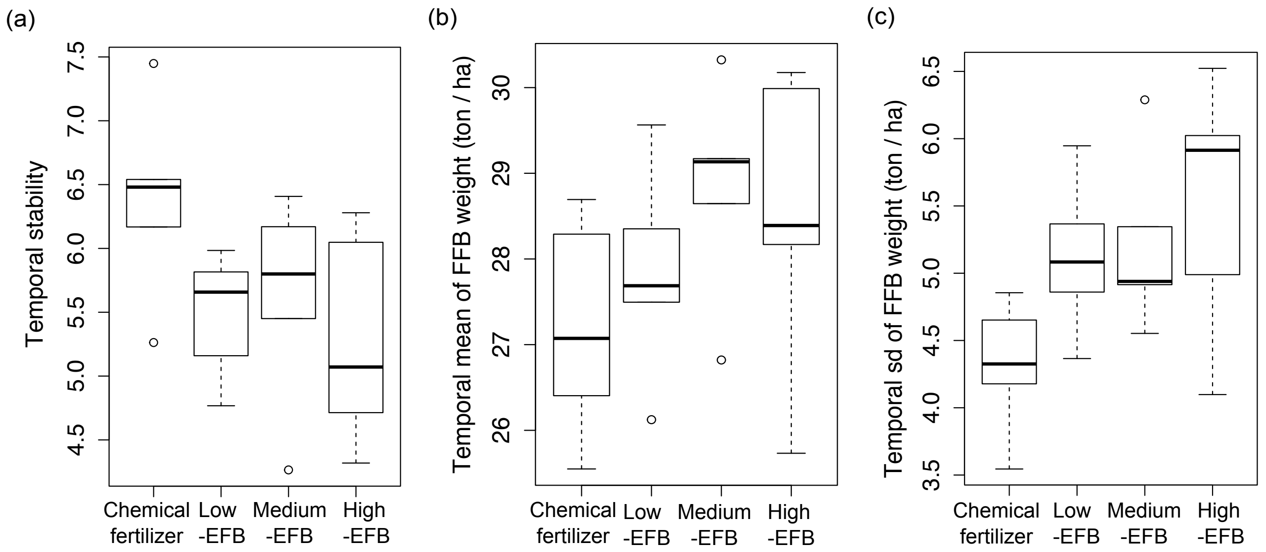

Figure 2 Temporal stability (a), temporal means (b) and temporal standard deviations (c) of annual fresh fruit bunch weight over 15 years under four treatments. No significant differences in temporal stability ($F_{3,12}$=2.35, p-value = 0.12), temporal means ($F_{3,12}$=1.27, p-value = 0.33) and temporal standard deviations ($F_{3,12}$=2.83, p-value = 0.08) among treatments were detected.

3.2 SOIL FERTILITY

To understand whether EFB application influences crop yield through altering soil organic carbon level, we firstly tested whether EFB application had an effect on SOC; subsequently, whether SOC had an effect on crop yield. We found that soil organic carbon at 0-15 cm depth significantly differed among treatments over the application period (**Figure 1**). The *post-hoc* comparisons showed that soil organic carbon was significantly higher under the Medium-EFB treatment (2.16 ± 0.17%; mean ± SE), compared to the chemical fertilizer treatment (1.64 ± 0.14%). Soil organic carbon positively explained the annual crop yield with lag effects of two years (**Figure 3**). As both soil organic carbon and the annual crop yield were the highest under Medium-EFB treatment over the trial period, these results suggest that EFB application, especially under the medium application rate, may improve annual crop yield through increasing soil organic carbon.

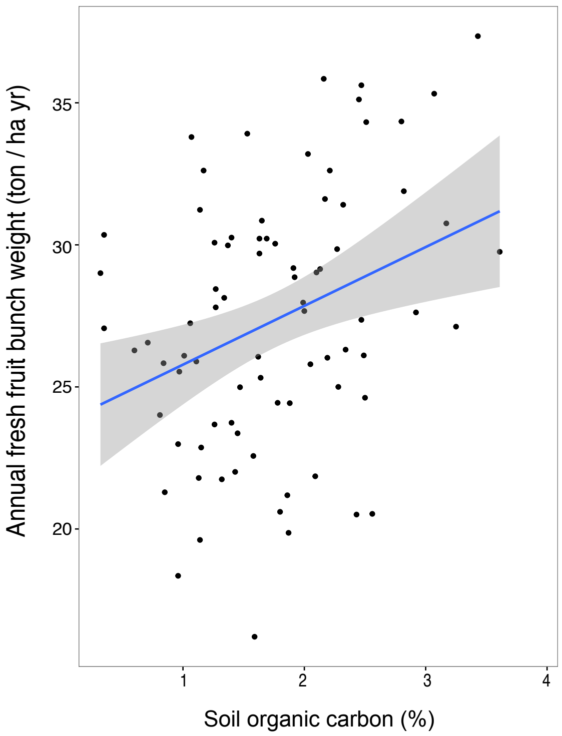

Figure 3 Annual crop yield as a function of soil organic carbon. The relationships were modelled with lag effects of two years. Linear mixed effects models were used, with year since application and replicate block as the random structure. Soil organic carbon positively explained the annual fresh fruit bunch weight over time.

3.3 CLIMATIC VARIABLES

Over the trial period, from palm age of 13 to 26 years, the mean annual temperature remained at similar levels, while annual minimum temperature and annual rainfall decreased from palm age 13 to 19 (between 2 to 8 years of application), followed by an increase from palm age of 20 to 26 (**Figure 4a**). Relative humidity fluctuated throughout the application period (**Figure 4b**). Annual minimum temperature and annual rainfall did not significantly explain annual crop yield, while relative humidity positively explained the annual crop yield with lag effects of two years ($F_{1,9} = 25.84$, p-value < 0.05) (**Figure 4c**). However, relative humidity did not significantly explain the annual crop yield of the same year ($F_{1,11} = 0.09$, p-value $= 0.76$) or with time lags of one year ($F_{1,10} = 0.69$, p-value $= 0.42$).

4. DISCUSSION

Over a 15-year application period, EFB appears to be more effective in increasing total crop yield, in comparison to the chemical fertilizer treatment. However, there was greater temporal variability in crop yield under EFB application. Temporal changes in crop yield under EFB application appear to be associated with climatic conditions and soil organic carbon.

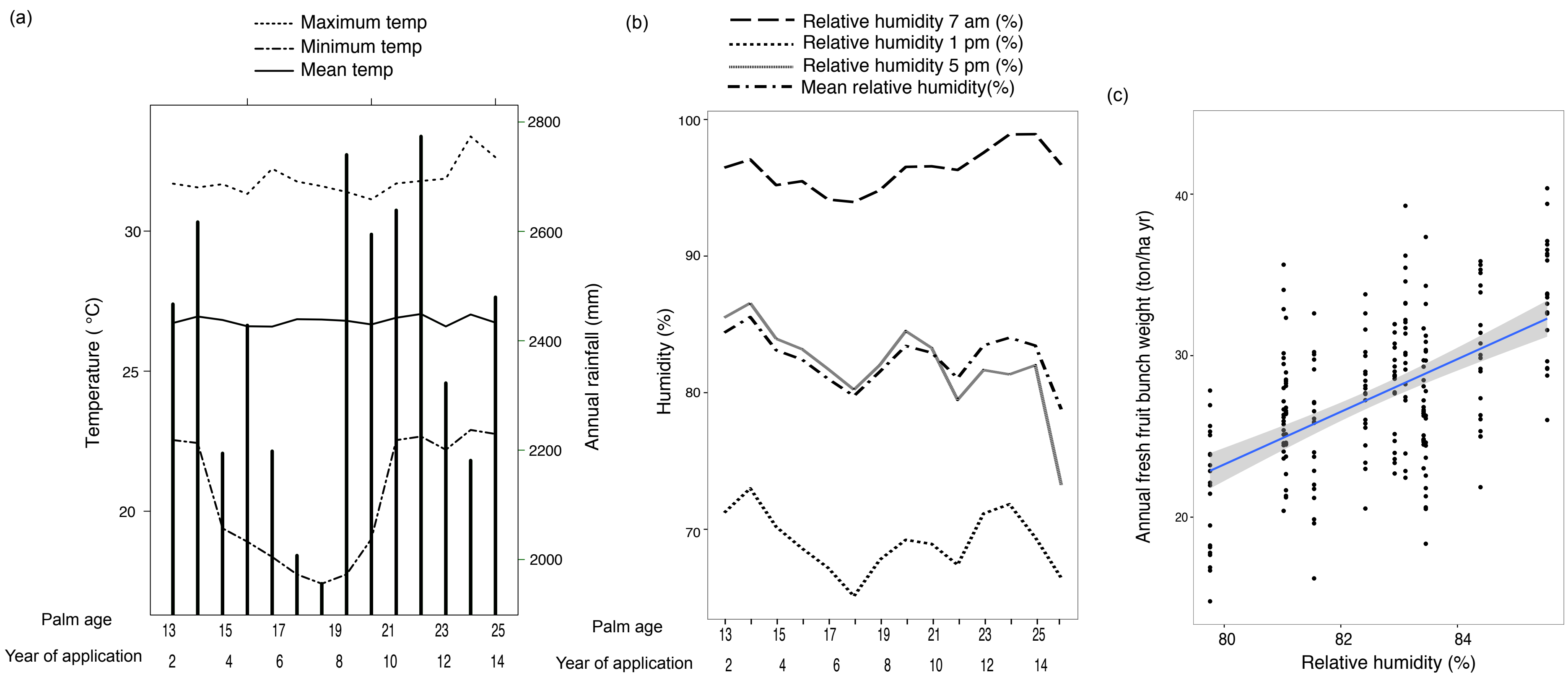

Figure 4 Annual temperature and rainfall (a) and relative humidity (b) over the trial period. The relative humidity positively explained the annual fresh fruit bunch weight with lag effects of two years ($F_{1,9} = 25.84$, *p*-value < 0.05) (c).

4.1 EFB APPLICATION EFFECTS ON CROP YIELD

Over a 15-year trial period, the total crop yield and annual crop yield was highest in the Medium-EFB treatment, followed by High-EFB, Low-EFB, and the chemical fertilizer treatment (**Table 2**, **Figure 1a**). Although the treatment effects were not statistically different, this result indicates the potential of EFB application to improve oil palm yield, and suggests the responses may be dosage-dependent. Previous studies have also shown similar results. For example, EFB application at 37.5 t $ha^{-1}yr^{-1}$ together with inorganic nitrogen and potassium fertilizers enhanced crop yield in a Malaysian oil palm plantation (Chiew and Rahman, 2002). Abu Bakar et al. (2010) further showed that crop yield was significantly higher under 10 years of EFB application at the rate of 44 ton ha^{-1} yr^{-1}, compared to EFB application at the rate of 22 t ha^{-1} yr^{-1} and a chemical fertilizer treatment (Abu Bakar et al., 2010). At some study sites in Indonesian oil palm plantations, applying best management practices including EFB addition for 12-22 months significantly increased crop productivity (Donough et al., 2009).

Despite the positive effects of EFB application on the total crop yield, the temporal stability of the yield was lower under EFB application compared to the chemical fertilizer treatment, although the difference was not statistically significant (**Figure 2a**). This can be due to higher temporal variations in the input of nutrients derived from EFB, because the rates of nutrient mineralization from organic matter largely depend on the C/N ratio of the substrate, climatic conditions, and decomposer activities (Hättenschwiler et al., 2005). Therefore, the high variability in nutrients released from EFB may lead to greater temporal fluctuations in soil carbon and available nutrients, which may result in crop production with greater inter-annual variability. In comparison, chemical fertilizers may serve as a more stable and readily available mineral nutrient source, which contributes to a more stabilized crop yield over time.

4.2 CROP YIELD AND SOIL PROPERTIES UNDER EFB APPLICATION

Results from this study also showed that soil organic carbon significantly explained crop yield with time lags of two years. In addition, both soil organic carbon and the annual crop yield were the highest under Medium-EFB treatment over the trial period. These results suggest that EFB application, especially under the medium application rate, may improve annual crop yield by increasing soil organic carbon. Enhanced soil organic carbon levels under EFB application have been reported previously in both Malaysian and Indonesian oil palm plantations (Abu Bakar et al., 2010; Carron et al., 2015b; Comte et al., 2013). Direct evidence of the correlations between soil organic carbon level and oil palm yield has not been found in previous studies, yet the positive effects of soil organic carbon on crop yield have been reported in wheat, barley, maize, and rice in other regions (Lal, 2010). Higher levels of soil organic carbon may improve crop yield by enhancing soil nutrient retention ability and improving soil properties to facilitate root growth (Magdoff and Weil, 2004).

Soil organic carbon followed an initial decrease and a subsequent recovery over the trial period, regardless of the treatment type. This temporal pattern, described as the soil carbon transitional curve, has also been observed in oil palm plantations in Sumatra, Kalimantan, and Papua New Guinea (Ni'matul et al., 2015). This transitional curve is suggested to be a result of an initial decline in soil organic carbon inherited from the preceding land use, and a gradual build-up of carbon from the current land use (Noordwijk et al., 2015). Specifically, soil organic carbon from preceding land use can be lost through erosion and decomposition, and subsequently recovers through the accumulation of aboveground and belowground inputs (Guillaume et al., 2015; Noordwijk et al., 2015).

4.3 CLIMATIC CONDITIONS EFFECT ON CROP YIELD

The annual crop yield gradually decreased from palm age of 16 years, and reached the lowest production at the age of 20 years (**Figure 1b**). This pattern paralleled with changes in annual relative humidity, annual rainfall and daily minimum temperature (**Figure 4**). Results from this study showed that relative humidity was positively related to the annual crop yield with lag effects of two years, indicating the pronounced effects of climatic conditions on the crop production. During the period of yield decline, the relative humidity decreased from 84 % to 79 %, while the minimum temperature dropped from 22.5 % to 17.4 ºC, and annual rainfall decreased from 2773 mm yr^{-1} to 1955 mm yr^{-1}. This implies a soil water deficit condition in a cooler environment, which is sub-optimal for oil palm growth and fruit production (Goh, 2000 in Corley and Tinker, 2015). Therefore, it is likely that the unfavourable environmental conditions may be one of the major reasons for the early decline of crop yield from the palm age of 16 years.

We found an unexpected increase in annual crop yield from palm age of 23 to 26 years. The recovery pattern of crop yield is rarely reported in previous findings, as oil palm yield normally follows a gradual decrease after oil palm age of 18 years (Henson and Dolmat, 2003). We suggest that this may be a result of the increases in relative humidity, annual rainfall, minimum temperature and soil organic carbon between palm age of 20 to 26 years. Other determining factors associated with management practices, may have also led to the increase. For example, increased frequency in pruning and harvesting intensity can positively influence oil palm yield (Corley, 1973; Rankine and Fairhurst, 1999; Squire, 1986).

5. CONCLUSIONS

In this study, we found that EFB application over a 15-year period enhanced total crop yield in comparison to a chemical fertilizer treatment. In addition, EFB application appears to enhance the annual crop yield by increasing soil organic carbon. These findings indicate the high potential of EFB application to improve crop yield. However, EFB application also led to higher inter-annual variations in crop yield. It is therefore important to take both total crop yield and temporal stability in this yield into account for optimized field implementations. In addition to soil organic carbon, the temporal changes in crop yield also appear to be influenced by climatic conditions. These observations indicate the importance of further research on optimal management practice, in order to manage the uncertainty of crop yield under degrading soil environments and changing climate.

6. ACKNOWLEDGMENTS

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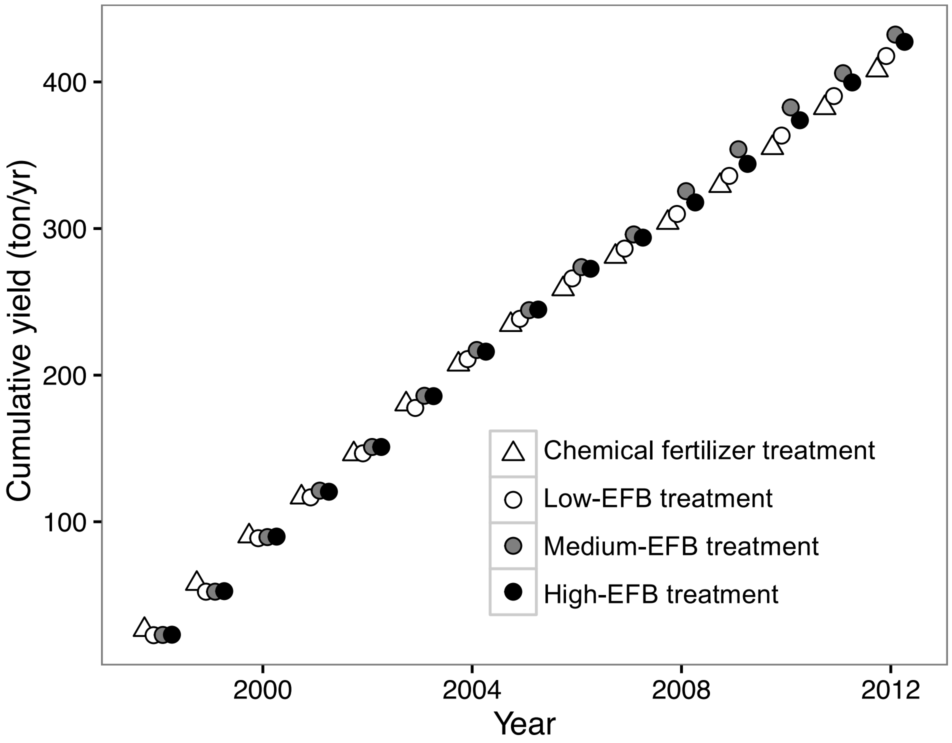
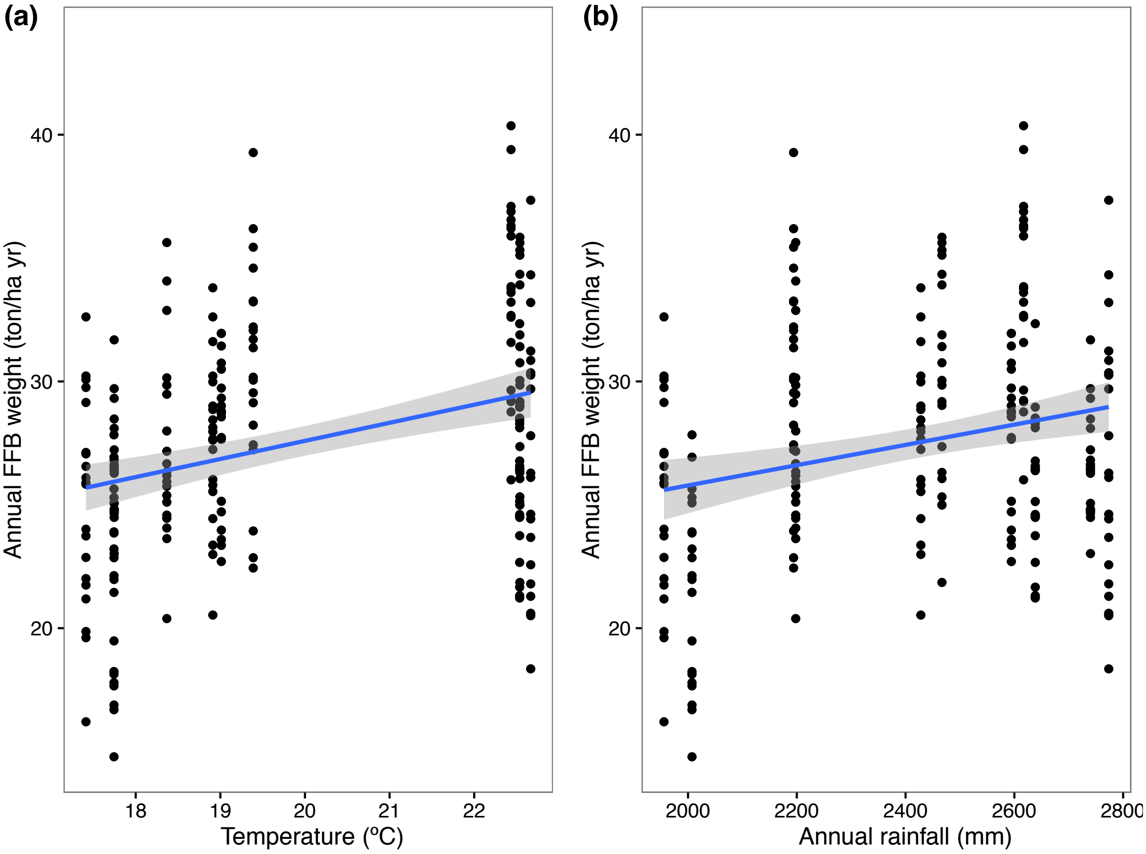
7. SUPPLEMENTARY MATERIALS

Supplementary S1. Cumulative oil palm yield over 15 year of treatment of chemical fertilizer, Low-EFB, Medium-EFB, and High-EFB treatments.



Supplementary S2 The annual fresh fruit bunch weight as a function of annual minimum temperature and annual rainfall using linear mixed effects models, with a lag effect of two years. Annual minimum temperature ($F_{1,9} = 3.14$, *p*-value = 0.11) and annual rainfall ($F_{1,9} = 1.48$, *p*-value = 0.25) did not significantly affect the annual fresh fruit bunch weight.



CHAPTER 6 GENERAL DISCUSSION

Land use conversion and extensive use of chemical fertilizers in oil palm plantations have resulted in soil degradation. The use of oil palm residues as organic fertilizers in the plantations to reduce the amount of chemical fertilizers is thought to mitigate soil degradation; however, the effects on soil quality, soil biological properties, and crop yield remains unclear. This thesis focused on a widely used oil palm residue, empty fruit bunch (EFB), in order to determine its effectiveness as a method for improving sustainable development of oil palm. Four research questions were addressed in this thesis:

1) What impacts does forest conversion to oil palm have on soil ecosystem functions – specifically those associated with litter decomposition rate and soil fauna feeding activity?

2) How does soil fauna feeding activity respond to different soil management practices in oil palm plantations?

3) What are the cascading effects of EFB application on soil physicochemical properties, soil biota, and ecosystem functions in response to EFB application?

4) How does 15 years of EFB application influence crop yield and temporal variations in this yield under a changing climate?

Three key findings are further discussed below:

Optimal application rate of EFB to enhance soil ecosystem and crop yield

The studies in this thesis showed that the positive effects of EFB application on the soil ecosystem and crop yield were highly dependent on the application rate. Three application rates of EFB were examined: Low-EFB treatment (30 t ha^{-1} yr^{-1}), Medium-EFB treatment

60 t ha^{-1} yr^{-1}), and High-EFB treatment (90 t ha^{-1} yr^{-1}). Interestingly, the Low-EFB and Medium-EFB treatment were more effective in enhancing soil properties and crop yield, compared to the High-EFB treatment. For example, after 15 years of continuous treatment, soil fauna feeding activity, soil mite density, and soil organic carbon appear to be the highest under the Low-EFB treatment, followed by the Medium-EFB treatment. The annual and cumulative crop yield over 15 years were also highest under Medium-EFB treatment, followed by the High-EFB treatment. These results suggest that the optimal application rate of EFB depends on certain soil parameter or crop yield to be prioritized for sustainable development. In addition, the positive effects of EFB treatment on soil and crop yield may be decreased when the application rate is exceeding a threshold level. The application rates of Low-EFB and Medium-EFB treatments are within the range of frequent application rate practiced in oil palm plantations, between 15 and 60 t ha^{-1} yr^{-1} (Pardon et al., 2016). Results from this work therefore suggest that the current practice of EFB application in commercial plantations can be optimal in improving the soil ecosystem and crop yield.

Temporal changes in soil organic carbon under EFB application

Over 15 years of treatment, soil organic carbon followed a strong temporal pattern with an initial decrease and a subsequent recovery, regardless of the treatment type. This transitional curve is suggested to be contributed by an initial decline in soil organic carbon inherited from the preceding land use, and a gradual build-up of carbon from the current land use (Noordwijk et al., 2015). Specifically, soil organic carbon from preceding land use can be lost through erosion and decomposition, and subsequently recovers through the accumulation of aboveground and belowground inputs (Guillaume et al., 2015; Noordwijk et al., 2015). This temporal pattern was also observed in oil palm plantations in Sumatra, Kalimantan, and Papua New Guinea (Ni'matul et al., 2015). These results indicate a time lag of few years from the addition of oil palm residues to the accumulation of soil organic carbon in oil palm plantations. In terms of the field application of EFB, a continuous application of EFB or other oil palm residues over the life cycle of oil palm plantations is therefore recommended for the accumulation of soil organic carbon. The minimized disturbance of soil surface during the replanting phase of oil palm is also essential to enhance carbon sequestration.

Crop yield stability under EFB application

Compared to chemical fertilizer treatment, EFB application for 15 years either maintains or increases the annual and cumulative crop yield, while the yield stability remains at the similar levels. It is to note, that EFB treatment contains not only EFB but also limited amount of chemical fertilizers, especially nitrogen sources, to increase the C/N ratio of the organic matter to enhance microbial decomposition. Replacing parts of chemical fertilizer inputs with oil palm residues, therefore, may not only enhance soil sustainability, but also may achieve similar or higher levels or even higher levels of crop yield. Further research to design site-specific nutrient supply schemes with integrated chemical fertilizer and EFB is needed for more sustainable oil palm development with maintained or increased revenues.

6.2 FUTURE OUTLOOK

The findings from this thesis as well as several previous studies suggest the potential of EFB application in enhancing soil properties and ecosystem functioning in oil palm plantations, compared to standard estate practices in which only chemical fertilizers are used. Despite the emerging evidence of the advantages of EFB application, the use of this important crop residue on commercial oil palm plantations is still limited (Chiew and Shimada, 2013).

One of the reasons for this is that EFB has competing alternative uses. For example, it can be used as fuel for generating energy for oil palm mills, raw material for pulp and paper, as well as feedstock for bioethanol (Chang, 2014; Chiew and Shimada, 2013; Menon et al., 2006). Decisions on the use of EFB for these purposes often involve trade-offs between transportation costs, greenhouse gas emissions, and the economic returns in each scenario (Chang, 2014; Chiew and Shimada, 2013; Do et al., 2014).

In recent years, transforming raw EFB into compost has been suggested as an incentive to increase the use of EFB as a soil amendment (Chiew and Shimada, 2013). Compost has reduced weight and volume, which not only reduces the cost of field transportation and operation, but also enables wider distribution of the crop residues to oil palm plantations that are far away from the oil palm mills (Kavitha et al., 2013; Moradi et al., 2012; Sabrina et al., 2009b). Some studies, however, suggest that EFB-derived composts are less effective to improve soil physical properties, due to the lack of complexity in their physical structure (Moradi et al., 2014a; Teh et al., 2010). Further research is therefore needed to advance composting technology, and to identify the advantages and disadvantages of these alternative techniques on soil fertility and ecosystem functions.

Another aspect of EFB application which needs further research is its effects on greenhouse gas emissions. In the tropical environment with high temperature and humidity, the microbial decomposition of EFB is rapid and can release a large amount of carbon dioxide. In addition, anaerobic decomposition may occur with thick layers of EFB, when the emission of nitric oxide and methane can be substantial (Pardon et al., 2016). Further research is needed to quantify the greenhouse emissions from EFB application, and to identify the optimal application rate, frequency, and spatial arrangement of EFB for effective reduction in the greenhouse gas emissions.

Research focused on other potential soil management practices for sustainable development of oil palm is also needed. Many of the practices have been implemented in the field; however, their quantitative effects on the soil, water, and crop yield is rarely studied. For example, the use of leguminous species as a cover crop in immature oil palm plantings has been widely implemented to mitigate soil erosion, and to maintain soil water content (Agamuthu and Broughton, 1985). The minimized use of heavy machines on plantations has also been advocated to reduce soil compaction and disturbances (Carron et al., 2016). In addition, maintaining growth of understory vegetation is another strategy that an increasing number of plantations are employing to improve soil microclimate and soil biodiversity (Donough et al., 2009). Research is largely needed to evaluate these approaches, and to identify the best use of the practices, in order to provide useful and clear information for practitioners. Further research on these management practices is especially needed for immature oil palm plantations and re-planting areas, where soils are generally more degraded and infertile than mature oil palm plantations (Snaddon et al., 2013).

Beyond the focus of the soil ecosystem, other management practices, research tools, and innovations have been developed to improve ecosystem functions and services of oil palm plantations in general, and further research is needed. For example, a series of 'best management practices' have been suggested to intensify crop productivity while minimizing negative environmental impacts, in line with the concept of sustainable intensification (Donough et al., 2009; Pauli et al., 2014; Sheil et al., 2009). At the landscape level, the concept of 'High Conservation Value' (HCV) areas in the oil palm landscape to preserve natural habitats is widely adopted by sustainable certified oil palm companies, and the HCV area has been shown to enhance soil biological functions (Gray and Lewis, 2014; Yaap, 2010). Research tools such as remote sensing have also been used to identify the suitability of areas to establish plantations (Lee et al., 2014; Obidzinski et al., 2012).

Innovations and re-considerations of the current oil palm cropping system are also blooming (Bhagwat and Willis, 2008). For example, the concepts of transforming oil palm monoculture into cattle-integrated plantations, or integrating agroforestry and mixed cropping principles into current practices, may lead to fundamental changes biodiversity, ecosystem functions, and crop production of the oil palm cultivation (Edwards et al., 2010, 2014; Slade et al., 2014).

Finally, the challenge of oil palm cultivation is not only to develop the scientific evidence base needed to minimize its impacts on the ecosystem, but also to improve the welfare of local people (Bhagwat et al., 2012; Lindsay et al., 2012; Sayer et al., 2012). Much of the future expansion of oil palm is likely to take place in regions where local governance is relatively weak, and where there are issues of uncertain land tenure and ineffective spatial planning (Feintrenie et al., 2010). Good governance relating to smallholder tenure security, access and benefit sharing, and forest conservation is therefore crucial (Sayer et al., 2012). Raising the environmental awareness of consumers may also shape the emergence of an industry that is more socially- and environmentally-aware, such as the establishment of Roundtable on Sustainable Palm oil (RSPO) (Sayer and Maginnis, 2005).

Although there is still a long way to go, with many improvements to be made, continuous efforts and collaborations between scientists, policymakers, consumers, and the industry are the key to equitable and sustainable palm oil production.

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