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Application of oil palm empty fruit bunch effects on soil biota and functions: A case study in Sumatra, Indonesia

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A B S T R A C T

Oil palm (*Elaeis guineensis*) is an important tropical crop which provides one-fifth of the world's vegetable oil, yet its rapid expansion can negatively influence the soil ecosystem. Identifying suitable agronomic management such as crop residue application is important for the sustainable development of oil palm. We examined the effects of adding empty fruit bunches (EFB), a major oil palm residue, on multiple soil abiotic properties, soil biota, and indicators of soil functions. We compared treatments of EFB applications with three application rates, and a chemical fertilizer treatment in a 15–year trial in Central Sumatra, Indonesia. EFB application increased pH and aggregate stability in 0–10 cm soils and decreased the soil bulk density. EFB application increased the abundance of soil detritivore mites, soil fauna feeding activity, and soil microbial activity. EFB application decreased the biomass of a dominant invasive earthworm species, *Pontoscolex corethrurus* (Müller, 1857). Results from structural equation modelling suggested that EFB directly affected soil biota and functions, rather than through altering soil abiotic properties. The effects of EFB application on most soil abiotic properties, soil biota and function indicators were independent of the application rate. Our results revealed that EFB application has a high potential to enhance soil biota and functions in oil palm plantations.

1. Introduction

Soil provides crucial functions and ecosystem services to enhance food security, land restoration, and climate change mitigation, which are key Sustainable Development Goals of United Nations (Keesstra et al., 2016a,b). Various interacting soil organisms and their processes contribute to key soil ecosystem functions, such as nutrient cycling, carbon sequestration, and soil structure maintenance (Bardgett and van der Putten, 2014). In agricultural ecosystems, management practices may influence abiotic soil environment and soil biota, which then alter key soil ecosystem functions and crop production (Birkhofer et al., 2008).

Identifying sustainable management is especially important for tropical production systems which produce 1.7 tons of dry crop yield annually (West et al., 2010). Oil palm (*Elaeis guineensis*) is a wide spread economic crop in Southeast Asia which produces one-fifth of vegetable oil globally (Kurnia et al., 2016; Sayer et al., 2012). The global oil palm land area covers 16.4 million ha, equivalent to ten percent of the world's permanent croplands (FAO, 2015). Land conversion from forest to oil palm can reduce soil biodiversity, increase nutrient leaching, and negatively influence soil carbon storage and fertility (Dislich et al., 2017). To identify and implement suitable soil management for mitigating these negative environmental impacts is important; however, few studies have examined these management practices and their effects on soil biodiversity and ecosystem functions in oil palm plantations (Bessou et al., 2017; Carron et al., 2015; Tao et al., 2016).

In most oil palm plantations in Southeast Asia, chemical fertilizer is used as a major source of nutrients. More recently, crop residues from oil palm have been used as organic fertilizers and mulch substrates to reduce the quantity of mineral fertilizers needed. One of the main oil palm residues from the palm oil extraction process are the empty fruit bunches (EFB), which are the structural part of the fruit bunches

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(Chang, 2014). Several studies have reported the effects of EFB application on soil fertility and yield in Indonesian and Malaysian oil palm (Comte et al., 2013; Moradi et al., 2014a,b; Tao et al., 2017). However, there is little information on the effects of EFB application on soil biota and ecosystem functions (Carron et al., 2015; Tao et al., 2016), and whether the effects are direct or through altering soil abiotic properties. It is also unknown whether the effects are quantity-dependent, i.e., whether the magnitude of the effects depends on the application rate of EFB. For other crops such as apricot, olive, and persimmon, applying crop residue mulch has shown to reduce soil degradation (S. Keesstra et al., 2016a,b; Parras-Alcántara et al., 2016; Ritsema, 2016). Relevant information for oil palm is crucial for plantation managers and policymakers to promote and implement suitable soil management practices to achieve sustainable intensification of oil palm.

Among soil organisms, earthworms can be litter transformers and soil engineers which structure the environment of other soil organisms, whereas soil mites directly feed on crop residues and microorganisms (Coleman et al., 2004). Crop residue application may influence soil microbial respiration and soil faunal feeding activities either by providing food resources, or by altering soil abiotic properties and microhabitats for soil biota; yet such mechanisms have rarely been explored in tropical agroecosystems especially for perennial crops (Kurzatkowski et al., 2004; Römbke et al., 2006). Moreover, the majority of research has focused on the effects of crop residue application on the litter layer rather than the soil mineral layer, despite the fact that carbon sequestration and nutrient cycling also happen in the soil layer (Ashford et al., 2013).

This study aimed to examine the long-term effects of oil palm residue addition on soil biota and functions in the top soil layer. Specifically, we asked: 1) does EFB application influence key soil biota and function indicators? 2) does EFB application directly influence soil biota and functions, or indirectly through altering soil abiotic properties? and 3) do the effects of EFB application on soil biota and functions depend on the application rate? We examined six soil abiotic properties, two soil biota groups, and two indicators of soil functions in a 15-year field trial in an oil palm plantation in Sumatra, Indonesia. We used a structural equation modelling approach (Grace et al., 2012; Shipley, 2013) to examine the potential causal relationships between soil abiotic properties, soil biota and functions. We hypothesized that EFB application may influence soil biota and functions both by directly providing resources, and by modifying soil abiotic properties. The soil biota could also have cascading effects on other soil fauna groups and functions. In addition, we expected that the responses of soil biota and functions to EFB application would be stronger at higher application rates.

2. Materials and methods

2.1. Site description and experimental design

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 has been certified by the Roundtable on Sustainable Palm Oil (RSPO). The previous land use of this area was secondary tropical 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), within the loamy lowland soil class (USDA soil classification system).

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. The field trial covered a total area of 36 ha (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). The replication number was five in a nested design (See **Supplementary S1**).

Each treatment plot (80 m × 40 m) was composed of 36 palm trees, arranged as eight palm trees in four rows. The applications were applied throughout the treatment plot continuously for 15 years. Soil sampling was undertaken at the end of 15 years at five oil palms in the central two rows. There was at least one palm between two focal palms to avoid spill over effects (**Supplementary S1**). Each treatment plot was surrounded by 1.5 m depth ditches to prevent interference by adjacent treatment plots.

The four treatment plots in each replicate block were: Low-EFB treatment applied with EFB (210 kg $tree^{-1}$ yr^{-1}. equivalent to 30 t ha^{-1} yr^{-1}) and urea (0.02 kg $tree^{-1}$ yr^{-1}); Medium-EFB treatment applied with EFB (420 kg $tree^{-1}$ yr^{-1}, equivalent to 60 t ha^{-1} yr^{-1}) and urea (0.04 kg $tree^{-1}$ yr^{-1}); High-EFB treatment applied with EFB (630 kg $tree^{-1}$ yr^{-1}, equivalent to 90 t ha^{-1} yr^{-1}) and urea (0.06 kg $tree^{-1}$ yr^{-1}), and chemical fertilizer treatment applied with a full quantity of chemical fertilizers without adding EFB. EFB as the structural part of fruit bunches after fruit removal contains dry weight of 45–49% C, 0.5–1.0% N, 0.02–0.05% P, 1.3–2.2% K, and 0.2–0.4% Mg (Budianta et al., 2010; Chang, 2014; Kavitha et al., 2013; Moradi et al., 2014a,b; Pardon et al., 2016). Chemical fertilizer treatment included the application of 1.75 kg $tree^{-1}$ yr^{-1} urea (46% N), 0.5 kg $tree^{-1}$ yr^{-1} triple super phosphate (45% P_2O_5, 15% Ca), 2.5 kg $tree^{-1}$ yr^{-1} muriate of potash (61% K_2O, 46% Cl), and 0.05 kg $tree^{-1}$ yr^{-1} Kieserite (16% Mg, S:22%). For detailed description of each treatment see **Supplementary S2**.

In 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 to regulate the EFB decomposition rate. The application rate of the Low-EFB treatment was similar to standard operations in the oil palm industry, whereas Medium-EFB and High-EFB treatments represented alternative application rates of EFB. In the chemical fertilizer treatment, the type and quantity of chemical fertilizers were similar to conventional standard estate practices, and the fertilizers were applied within palm circles (1–2 m radius) twice a year (i.e. during the February-March and September–October periods) throughout the trial period. Harvesting path and palm circle account for approximately 5–15% and 10–15% of the total plantation area, respectively, as the majority of oil palm plantations in Southeast Asia (Nelson et al., 2013).

2.2. Field measurements

We measured ten indicators for soil abiotic properties (soil pH, soil moisture, aggregate stability, bulk density, soil organic carbon and total nitrogen), soil biota (earthworm biomass and soil mite density), and soil ecosystem functions (soil fauna feeding activity and soil microbial activity). We examined these soil properties at the soil mineral layer 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 (Tao et al., 2016). We examined these soil properties beneath EFB at one side of harvesting paths of EFB treatment plots, and at the equivalent positions in chemical fertilizer plots.

2.2.1. Measuring soil abiotic properties

We measured soil moisture using the WET sensor (Delta-T Device, UK). For soil pH, soil organic carbon, soil total nitrogen, and soil aggregate stability, one soil sample was collected at the depth of 0–15 cm under each focal palm. The resulting five soil samples for each treatment plot were bulked to form a composite sample. Samples were air-dried for 4–7 days and sieved through 2 mm and 0.5 mm for soil chemical analysis. 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.

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