Agriculture, Ecosystems and Environment 169 (2013) 58–68

Contents lists available at SciVerse ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Landscape-scale assessment of soil response to long-term organic and mineral fertilizer application in an industrial oil palm plantation, Indonesia

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ARTICLE INFO

Article history:
Received 14 June 2012
Received in revised form 14 February 2013
Accepted 26 February 2013
Available online 30 March 2013

Keywords:
Oil palm
Soil chemical properties
Long-term fertilizer application
Organic and mineral fertilizers
Landscape-scale approach

ABSTRACT

Organic fertilizers improve soil fertility in oil palm plantations, based on small-scale (<30 ha), short-term (3–5 yr) studies, but the response is not equal across soil classes. Since organic fertilizers are costly to handle and apply, relative to mineral fertilizers, producers need to know where and how frequently to apply organic fertilizers to improve soil fertility. This study assessed the soil response to long-term mineral and organic fertilizer applications in an industrial oil palm plantation. A landscape-scale approach was developed to cope with unavailable historical soil data, variability in fertilizer application sequences and diverse soil classes across the plantation. Soil response to fertilizer application was inferred from (i) a one-off soil survey, (ii) record of fertilizer sequences, and (iii) knowledge of the biogeochemical processes underlying the measured soil response. Low-fertility Ferralsols responded significantly to continuous organic fertilizer application, with greater improvement in the loamy-sand uplands than sandy-loam lowlands. In the loamy-sand uplands discontinuing organic fertilizer applications significantly decreased the organic carbon concentration without reducing the pH, base saturation or nutrient concentrations, but organic carbon was protected from mineralization by slower drainage and fine texture in the sandy-loam lowlands. We conclude that organic fertilizers should be applied regularly to loamy-sand uplands to sustain soil fertility.

1. Introduction

Since the 1960s, the rapid expansion of oil palm (*Elaeis guineensis*) cultivation in Southeast Asia has provided food and employment for several million people and contributed to the development of poor countries. However, it has also raised environmental concerns regarding deforestation, loss of biodiversity, greenhouse gas emissions, and the degradation of soil and water quality (Sheil et al., 2009; Tan et al., 2009). Soil degradation is of concern because oil palm is cultivated predominantly on tropical soils that are highly acidic and have low buffering capacities (Harter, 2007). Due to the low inherent fertility of these soils and the high nutrient removal in harvested products, fertilizer input is necessary to sustain high yields and typically constitutes 40–65% of total field upkeep costs (Caliman, pers. com). When mineral fertilizers are utilized, they can contribute to soil acidification, which causes a further decline in pH and reduces the buffering capacity of these low-fertility tropical soils (Barak et al., 1997; Nelson et al., 2010; Oim and Dynoodt, 2008).

There are two sources of organic fertilizer available to commercial oil palm plantations that operate a processing mill. Palm oil mill effluent (POME) is the wastewater emitted from the mill, which contains organic carbon (including oil and fat), nutrients, suspended solids and microorganisms. For every 1 ton of crude palm oil produced, 2.7 tons of POME are generated (Caliman, pers. com). Empty fruit bunches (EFB) are another mill byproduct, generated at a rate of 1 ton per ton of crude palm oil produced. Research underway since the 1980s demonstrates that POME and EFB can be substituted for mineral fertilizers to sustain oil palm yields and soil

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http://dx.doi.org/10.1016/j.agee.2013.02.010

fertility by significantly increasing the soil pH, water holding capacity, organic carbon content, total nitrogen content, cation exchange capacity (CEC), available phosphorus content and exchangeable non acidic cations (Abu Bakar et al., 2011; Okwute and Isu, 2007; Teh Boon Sung et al., 2011; Thambirajah et al., 1995; Zaharah and Lim, 2000). These positive responses are attributed to an improvement in the soil moisture regime, soil structure, organic matter content and microbial activity, as well as addition of nutrients and a reduction in soil erosion and nutrient losses (Lim and Chan, 1987; Caliman et al., 2001; Chiew and Rahman, 2002). For this reason, organic fertilizer application is an important practice for oil palm cultivation.

Fertilizer management in an oil palm plantation requires an annual plan for each block (25–30 ha) within the plantation for the duration of the tree's lifespan (25 years). Thus, each block receives a specific fertilizer sequence. On a multiannual period, blocks receive mineral fertilizers only, organic fertilizers only (a uniform fertilizer sequence), or they receive alternating mineral and organic fertilizer applications (called a mixed fertilizer application sequence). Generally, mineral fertilizers are applied throughout the entire plantation, whereas the organic fertilizers tend to be applied to blocks in close proximity to the mill due to the limited supply and the higher cost to transport over long distances, relative to mineral fertilizers. These constraints result in POME and EFB application based on transportation costs, which ignores the fact that the soil response to fertilizer applications differs according to the soil type (texture, buffering capacity) (Salomon, 1999; Wrona, 2006), Industrial oil palm plantations in Southeast Asia commonly extend over thousands of contiguous hectares with distinct topographical positions and soil classes. Assessing the soil response to fertilizer applications in this large, perennial cultivation system requires both long-term and landscape-scale field studies, which are scarce. Agronomic trials have compared applications of mineral fertilizer only to organic fertilizer only over relatively short (3–5 yr) study periods (Cristancho et al., 2011; Dolmat et al., 1987; Kheong et al., 2010). Soil responses to mixed fertilizer sequences in industrial oil palm plantations are largely unknown. Moreover, agronomic trials often focused on oil palm yields, were conducted on the plot-scale (10–30 ha) and were performed on a single soil class rather at larger spatial scales and across multiple soil classes, which is more representative of industrial plantations (Abu Bakar et al., 2011; Budianta et al., 2010; Loong et al., 1987).

Research results from classical, small plots of homogeneous soils often proved to be of limited relevance when applied to non-level, heterogeneous landscapes. Advances made in landscape-scale soil research (mainly due to the integration of breakthroughs from relevant disciplines such as hydrology, geomorphology and geology) have allowed pedologists to focus on soil properties and processes that cannot be understood apart from their spatial and temporal context (Pennock and Veldkamp, 2006). This implies consideration of land forms and land use to understand how soils change through space and time (e.g. Veldkamp et al., 2001; Follain et al., 2007).

Previous studies showed that organic fertilizer applications significantly improved soil fertility status at the plot-scale. Plantation managers wishing to make better use of organic fertilizers need to know how long-term fertilizer applications (uniform and mixed fertilizer sequences) affect soil responses across the landscape, considering the inherent soil variation within the oil palm plantation. This requires landscape-scale soil studies, which were rarely carried out in large-scale oil palm plantations in South-East Asia. The present study aims to assess the soil response to fertilizer management as a function of soil spatial heterogeneity and through time, to understand the variability in soil fertility status at the plantation-scale. This study hypothesized that (i) the effect of mineral vs. organic fertilizer sources on soil properties can be detected even in large-scale commercial plantations, (ii) the response of soil properties to fertilizer sources depends on the soil type and land form characteristics.

This paper describes a landscape-scale approach that was developed to assess the effect on soil fertility of long-term application of organic and mineral fertilizers in uniform or mixed fertilizer sequences. This approach relied on (i) a one-off soil survey to describe soil types and soil fertility (0–15 cm depth) status within defined land units (called blocks), (ii) an expert index to assign a value to the historical fertilizer sequence in each block and (iii) statistical analysis to compare the soil response to fertilizer sources, within soil classes. Then, the results were interpreted and synthesized in the form of a conceptual model that considers soil biogeochemical processes. The landscape-scale approach was tested in a 4000 ha industrial oil palm plantation in Indonesia, with the goal of providing recommendations for targeted application of organic fertilizers within the plantation to sustain and improve the soil fertility status.

2. Materials and methods

2.1. Site description

2.1.1. Study area

The study area was located in the Petapahan area in the Kampar District, Riau Province, in the Sumatran Central Basin (Fig. 1). Until 1970, tall *Dipterocarp* forests dominated 95% of the Petapahan area (Suyanto et al., 2004). Land use in Riau Province has changed rapidly over the past two decades as logged-over forests were cleared for timber and oil palm cultivation (Potter and Badcock, 2001). Since 1991, the oil palm plantation area has doubled in the Petapahan area (Suyanto et al., 2004). Soils are Ferralsols (FAO/ISRIC/ISSS, 1998) that were developed on recent alluvium, with peat deposits in small depressions (Blasco et al., 1986). The relief is flat to slightly undulating. The site has a tropical humid climate with an average annual rainfall of 2400 mm (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.

This study was undertaken on a 4000-hectare, 15-year-old industrial oil palm plantation. The plantation is divided into 154 blocks for management. The average block size is 26 ha. Oil palm density averages 141 palms ha^{-1} across the plantation.

2.1.2. Preliminary soil classification

There was no accurate soil map available to delineate pedological units within the study area, nonetheless local discrimination between main soils of the study site is possible on the basis of the soil texture classes. Field observations suggested that soil spatial distribution was linked to land form. An interpolation method was used to analyze the spatial distribution of soil textures. A digital elevation model was used as an independent layer in a final cross-analysis of the soil texture and topographic derivatives maps that allowed us to propose a pedogeomorphological categorization of the landscape.

Input data came from 73 composite soil samples taken along a regular 1-km grid in the plantation surroundings with georeferenced positions and from 118 composite soil samples taken within the plantation blocks. At each sampling point, 3 sub-samples were collected (0–15 cm depth) and mixed to produce a composite soil sample of the point. Mean semivariograms were established and fitted using exponential models (Fig. 2).

Geostatistics (Krige, 1951; Mathéron, 1965; Goovaerts, 1999; Webster and Oliver, 2000) were applied to identify the spatial pattern in soil texture (based on the sand and clay content). The semi-variogram function ($\gamma(|h|)$ (Eq. (1)) was used to quantify the spatial variation of a regionalized variable z, in $N(h)$ number of