



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



Irina Comte^{a,b,*}, François Colin^c, Olivier Grünberger^d, Stéphane Follain^c, Joann K. Whalen^a, Jean-Pierre Caliman^e

^a Department of Natural Resource Sciences, Macdonald Campus of McGill University, Ste-Anne-de-Bellevue, Quebec, Canada

^b CIRAD (International Cooperation Centre in Agronomic Research for Development), Avenue Agropolis, 34098 Montpellier cedex 5, France

^c Montpellier-SupAgro, UMR-LISAH (Laboratory on Interactions between Soil, Agrosystem and Hydrosystem), 2 place Viala, F-34060 Montpellier cedex 2, France

^d IRD (Research and Development Institute), UMR-LISAH, 2 place Viala, F-34060 Montpellier cedex 2, France

^e PT SMART Research Institute (SMARTRI), Jalan Teuku Umar 19, 28112 Pekanbaru, Riau, Indonesia

ARTICLE INFO

Article history:

Received 14 June 2012

Received in revised form 14 February 2013

Accepted 26 February 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.

© 2013 Elsevier B.V. All rights reserved.

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

* Corresponding author at: Campus SupAgro, Bât 24, 2 place Pierre Viala, 34 060 Montpellier cedex 2, France. Tel.: +33 04 99 61 29 80; fax: +33 04 67 63 21 39.

E-mail address: irinacomte@gmail.com (I. Comte).

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 than at larger spatial scales and across multiple soil classes, which is more representative of industrial plantations (Abu Bakar et al., 2011; Budiarta 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

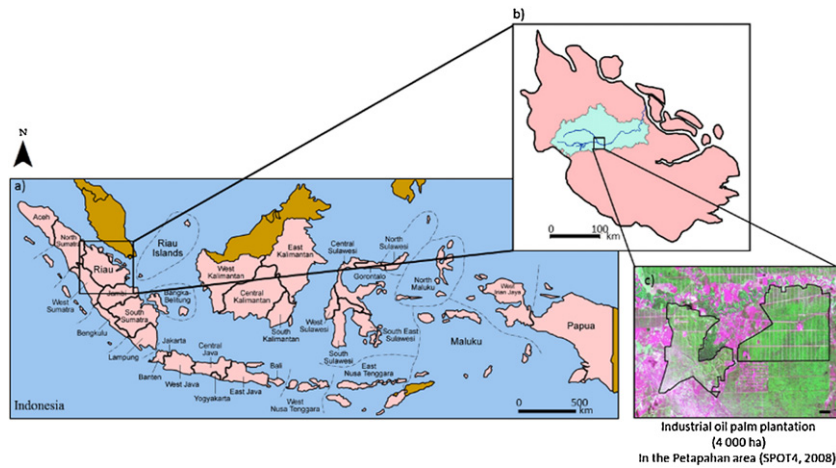


Fig. 1. Location of the study area in Riau province, Indonesia.

paired locations x_i , where the variable value is known $z(x_i)$ and separated by a lag distance h .

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [z(x_i) - z(x_i + h)]^2 \quad (1)$$

Interpolation at the landscape scale was performed with ordinary kriging (Eq. (2)):

$$\hat{z}(x_0) = \sum_{i=1}^n \lambda_i z(x_i) \quad (2)$$

where $\hat{z}(x_0)$ is the value of the variable z at location x_0 , as estimated (1) from the n location of x_i where the value is known and denoted $z(x_i)$ and (2) from the weight of each location λ_i , depending on the variogram model parameters. Then, interpolation was performed via ordinary kriging using Vesper software (Minasny et al., 2005) to determine the spatial distribution of soils with similar texture.

Landform analysis was performed with the Spatial Analyst® extensions of ArcGis 9.3® software. Slope (%) and curvature (m^{-1}) were computed with a SRTM digital elevation model at 90-m resolution. As expected, geomorphological attributes were strongly related to the spatial distribution of soil textures leading to partition the landscape into three pedomorphological categories: (i) loamy-sand soil (100 g kg^{-1} of clay, 750 g kg^{-1} of sand) in the upper part of the colluvial/hillslope domain, (ii) loamy soil (160 g kg^{-1} of clay, 500 g kg^{-1} of sand) in the middle part of the colluvial/hillslope

domain, and (iii) clay soil (510 g kg^{-1} of clay, 110 g kg^{-1} of sand) in alluvial/fluvial domain of the large Tapung Kiri river (Fig. 3).

Field observations were made to describe drainage conditions related to these geomorphological positions. Loamy-sand upland soils have good drainage throughout the year and cover 42% of the plantation area. Loamy lowland soils have a shallower water table; they cover 50% of the plantation area. The remaining 8% of the plantation were composed of poorly drained clay soil.

2.1.3. Fertilizer management

The industrial oil palm plantation applies mineral and organic fertilizers to blocks (Table 1). Additionally, palm fronds and under-story vegetation cut around the palm tree and along paths through the plantation are deposited in frond piles to decompose and recycle nutrients. Mineral fertilizers include urea, rock phosphate (RP), triple super phosphate (TSP), diammonium phosphate (DAP), muriate of potash (KCl), kieserite, dolomite and high-grade fertilizer borate (HGFB). Mineral fertilizers are applied by hand on the soil surface around the tree (the area covered corresponds to the palm circle) or sprayed over the palms from an airplane. Application of

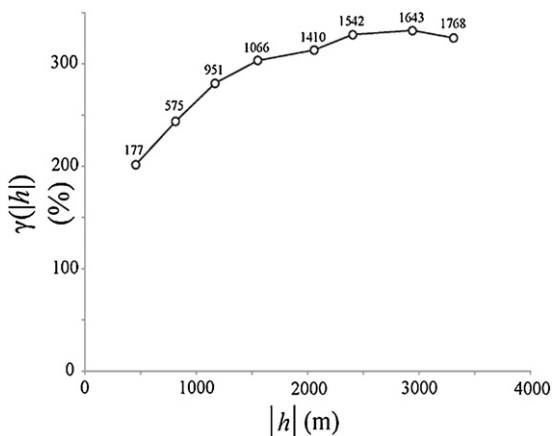


Fig. 2. Semi-variogram of sand variable.

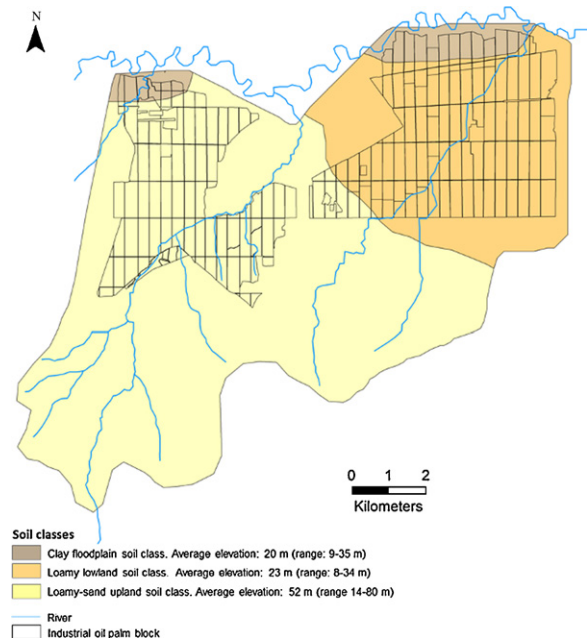


Fig. 3. Categorization of soil classes in the study area.

Table 1
Range of application rates of organic and mineral fertilizers, and the amount of nutrient applied at those rates.

Fertilizer	Application rate (kg ha ⁻¹ year ⁻¹)	Nutrient application rate (kg ha ⁻¹ year ⁻¹)				
		N	P	K	Mg	Ca
POME	750,000	750	225	2175	975	–
EFB	40,000–60,000	108–162	12–18	324–486	20–30	20–30
Urea	35–560	7.4–258	0	0	0	0
TSP	35–350	0	9.1–91	0	0	4.2–50
MOP	35–700	0	3.9–105	17.4–349	0	0
Kieserite	35–280	0	0	0	5.7–45.6	0
RP	105–490	0	15.4–72	0	0	0
DAP	35–560	7.4–119	8.2–132	0	0	0
Dolomite	70–210	0	0	0	7.6–22.8	14–51

After Caliman et al. (2001).

EFB: empty fruit bunch; POME: palm oil mill effluent; TSP: triple super phosphate; MOP: muriate of potash (KCl); RP: rock phosphate; DAP: diammonium phosphate.

urea, TSP and MOP generally occurs twice a year, from February to March and from October to November, while other mineral fertilizers tend to be applied once per year.

Organic fertilizers were POME and EFB. The POME is a brownish colloidal suspension discharged from the mill into open wastewater treatment ponds for anaerobic digestion followed by aerobic digestion (Singh et al., 2010). Then, it is applied through irrigation pipe once (750 m³ ha⁻¹) or twice (2 × 375 m³ ha⁻¹) a year in the alleys between oil palm trees. In terms of fertilizer use, one ton of POME is equivalent to approximately 2.2 kg of urea, 1.5 kg of TSP, 5.8 kg of MOP and 0.6 kg of kieserite (Caliman, pers. com) assuming a density of 1000 kg m⁻³. Total carbon content represents 31.5% of the POME dry matter (Wong et al., 2008). EFB is a wet (about 70% water content) cellulose-rich residue with 65.5% holocellulose, 21.2% lignin, 3.5% ash, 5.6% hot water-soluble substances and 4.1% alcohol-benzene soluble substances on a dry matter basis. Total carbon content represents 44.1% of the EFB dry matter (Thambirajah et al., 1995; Wong et al., 2008). Within a few days of processing at the mill, fresh EFB are surface-applied in the alleys between oil palm trees. Direct application of one ton of EFB to the block is equivalent to approximately 6.1 kg of urea, 1.7 kg of TSP, 16.3 kg of MOP and 3.0 kg of kieserite (Caliman et al., 2001).

2.2. Landscape-scale approach: description and assumptions

A landscape-scale approach was developed to assess soil responses to long-term organic and mineral fertilizer applications, across diverse soil classes and variable fertilizer sequences. This approach permits analysis of soil responses when there is no historical record of soil analysis, but historical fertilizer applications to blocks are known. We assumed that the initial soil fertility level was the same for a given soil class across the plantation.

2.2.1. Attributing a soil class to each block

The block was the basic land unit for agronomic management, so the first step was to assign a soil class to each block in the plantation.

2.2.2. Calculation of the fertilizer application sequence value for each block

We obtained the historical record of fertilizer application for each block from the plantation manager, which included data from a 7-yr period, from 2004 to 2010 inclusive. Some blocks had a uniform fertilizer sequence (mineral fertilizer only, organic fertilizer only) during the study period, but most blocks had mixed fertilizer sequences (i.e., yearly alternation of organic and mineral fertilizer applications). Additionally, the mixed fertilizer sequences have different levels of heterogeneity. For example, a mixed fertilizer sequence of 7 years including 2 years of organic fertilizer applications +2 years of mineral fertilizer applications +2 years of organic

fertilizer applications +1 year of mineral fertilizer applications has greater heterogeneity than a mixed fertilizer sequence including 5 years of mineral fertilizer applications followed by 2 years of organic fertilizer applications. Given the variability among mixed fertilizer sequences in this plantation, blocks that received similar mixed fertilizer sequences were grouped before comparative statistical tests was done. An expert index was conceptualized to calculate and attribute a fertilizer sequence value (FSV) to each block. The FSV expresses (i) the dominance of organic or mineral fertilizer in the fertilizer sequence, and (ii) the level of heterogeneity in the fertilizer sequence.

The expert index calculates the FSV for each block using two coefficients: a time coefficient (Y , in years) and a fertilizer application coefficient (F) (Eq. (3)). The expert index assumed that fertilizer application in the first year of the sequence (Y_1) had the least effect, whereas fertilizer application in the last year of the sequence (Y_n) had the greatest effect on soil fertility status at sampling time Y_n . Thus, the coefficient Y was an integer from 1 to n , with a value of 1 assigned to the first year of the fertilizer application sequence and n assigned to the last year (Y_n) (i.e. the year that soil response was measured). A slightly higher weight was allocated to organic fertilizer application (+2) relative to mineral application (–1) because organic matter addition has long-lasting effect per se (mineralization) (Diacono and Montemurro, 2010; Szott and Kass, 1993), and because nutrient input from organic fertilizers exceeded that from mineral fertilizers of an equal surface area (Table 1). Opposite signs allowed us to distinguish between organic (+) and mineral (–) fertilizer dominance through a fertilizer sequence.

$$FSV = k \sum_{i=Y_1}^{Y_n} Y_i \cdot F_i \quad (3)$$

k : normalization coefficient. Y_i : time (year) coefficient with $\{Y_1; Y_i; Y_n\} = \{1; i; n\}$; F_i : fertilizer application coefficient (mineral fertilizer: $F_i = -1$; organic fertilizer: $F_i = +2$).

By construction, the FSV produces discrete values. The FSV values are negative for mineral dominant sequences and positive for organic dominant sequences. They range between –50 for uniform mineral sequence to 100 for uniform organic sequence. This index is used to classify the blocks according to their fertilizer sequences and leads to compare the soil properties of blocks between each group.

There were 19 different fertilizer application sequences on the 96 blocks considered in this study, and their FSV are presented in Table 1. The lowest FSV was –50 in blocks that received mineral fertilizer only and the greatest FSV was 100 in blocks with organic fertilizer only during the period under consideration (2004–2010, inclusive). A negative FSV indicates the dominance of mineral fertilizer application, while positive FSV indicates the dominance of

Table 2
Calculation of the fertilization sequence value (FSV) based on the expert index, and membership of data analysis sets for each fertilizer sequence.

Fertilization sequence							FSV	Set membership
2004	2005	2006	2007	2008	2009	2010		
M	M	M	M	M	M	M	-50	S ₁ m, S ₂ m, S ₃ m, S ₄ m
EFB	M	M	M	M	M	M	-45	S ₂ m, S ₃ m, S ₄ m
EFB	EFB	M	M	M	M	M	-34	S ₂ m, S ₃ m, S ₄ m
EFB	EFB	EFB	M	M	M	M	-18	S ₃ m, S ₄ m
M	M	M	M	M	EFB	M	-18	S ₃ m, S ₄ m
EFB	EFB	M	EFB	M	M	M	-13	S ₃ m, S ₄ m
M	EFB	M	M	M	EFB	M	-7	S ₄ m
EFB	EFB	M	M	M	EFB	M	-2	S ₄ m
EFB	EFB	EFB	EFB	M	M	M	4	S ₄ o
M	EFB	EFB	M	M	EFB	M	9	S ₄ o
EFB	EFB	EFB	M	M	EFB	M	14	S ₄ o
EFB	EFB	EFB	M	M	M	EFB	20	S ₃ o, S ₄ o
EFB	EFB	M	EFB	M	EFB	M	20	S ₃ o, S ₄ o
EFB	EFB	EFB	M	M	M	POME	20	S ₃ o, S ₄ o
EFB	EFB	POME	M	M	M	POME	20	S ₃ o, S ₄ o
EFB	POME	POME	M	M	M	EFB	20	S ₃ o, S ₄ o
POME	EFB	M	EFB	M	EFB	M	20	S ₃ o, S ₄ o
EFB	M	EFB	M	EFB	EFB	M	30	S ₃ o, S ₄ o
EFB	EFB	EFB	EFB	M	M	EFB	41	S ₃ o, S ₄ o
EFB	POME	EFB	EFB	M	M	EFB	41	S ₃ o, S ₄ o
EFB	POME	POME	POME	M	M	POME	41	S ₃ o, S ₄ o
EFB	EFB	EFB	M	EFB	EFB	M	41	S ₃ o, S ₄ o
EFB	EFB	EFB	EFB	EFB	EFB	M	63	S ₂ o, S ₃ o, S ₄ o
EFB	POME	POME	POME	M	POME	POME	73	S ₂ o, S ₃ o, S ₄ o
EFB	EFB	EFB	EFB	M	EFB	EFB	73	S ₂ o, S ₃ o, S ₄ o
EFB	EFB	EFB	M	EFB	EFB	EFB	79	S ₂ o, S ₃ o, S ₄ o
EFB	EFB	EFB	EFB	EFB	EFB	EFB	100	S ₁ o, S ₂ o, S ₃ o, S ₄ o
POME	POME	POME	POME	POME	POME	POME	100	S ₁ o, S ₂ o, S ₃ o, S ₄ o
EFB	POME	POME	POME	POME	POME	POME	100	S ₁ o, S ₂ o, S ₃ o, S ₄ o

M: application of mineral fertilizers; POME: application of palm oil mill effluent; EFB: application of empty fruit bunches.

organic fertilizer application in a mixed fertilizer sequence. A FSV close to zero indicates a mixed fertilizer sequence with a high level of heterogeneity (Table 2).

2.2.3. Construction of nested sets within each soil class

To better assess the effect of organic vs. mineral historical fertilizer sequences on soil properties, we first aimed to compare the effect of organic vs. mineral fertilizer applications on blocks that received uniform fertilizer sequences. Then, we checked whether the effect observed for blocks with uniform fertilizer sequences would still be discernible when adding blocks with increasing heterogeneity in their fertilizer sequences. To achieve this, within each soil class identified in the plantation, we built nested sets of blocks based on their FSV. Each nested set included two groups of blocks: (1) blocks that received a predominantly organic fertilizer sequence and (2) blocks that had a comparably dominant mineral fertilizer sequence. The first set (S_1) included two block groups: (1) blocks that received a uniform organic fertilizer sequence (S_{1o}) and (2) blocks that received a uniform mineral fertilizer sequence (S_{1m}). The second set (S_2) included blocks with mixed fertilizer sequences having a low level of heterogeneity, in addition to the blocks already included in S_1 . The procedure was repeated by progressively adding blocks with increasing heterogeneity until the last set (S_n), which included all blocks. The spatial variability of fertilizer management across the plantation is illustrated in Fig. 4.

In this study, blocks were allocated to 4 nested sets (S_1 , S_2 , S_3 and S_4) based on their FSV and soil class. The FSV ranges chosen to construct the 4 nested sets were: $S_1 = [-50] \cup [100]$; $S_2 = [-50, -30] \cup [60, 100]$; $S_3 = [-50, -10] \cup [20, 100]$; and $S_4 = [-50, 0] \cup [0, 100]$ (Table 3). The number of soil samples within each set and soil classes are given in Table 4. The clayey soil class received mineral fertilizers only (null sample size from S_{1o} to S_{4o}) and was not considered further in the comparative analysis. Statistical analysis was performed with data from the dominant soil classes, loamy-sand uplands ($n = 126$) and loamy lowlands ($n = 138$).

2.2.4. Soil fertility survey and soil analysis

The next step was to perform a one-off soil survey at the landscape scale to assess the current soil fertility status across the plantation. An one-off soil survey was done in the 4000 ha plantation in 2010. We selected 96 of the 154 blocks within the plantation, and within those blocks collected soil samples at a density of one sampling location per two hectares for assessment of soil fertility status. Due to the heterogeneous structure of the oil palm plantation, a stratified soil sampling method was employed to account for intra-block variability (Maena et al., 1979; Law et al., 2009). This involved taking three sub-samples of soil (0–15 cm depth) from three zones in the vicinity of a palm tree: the palm circle, the harvest path and the frond piles. All sub-samples from a particular

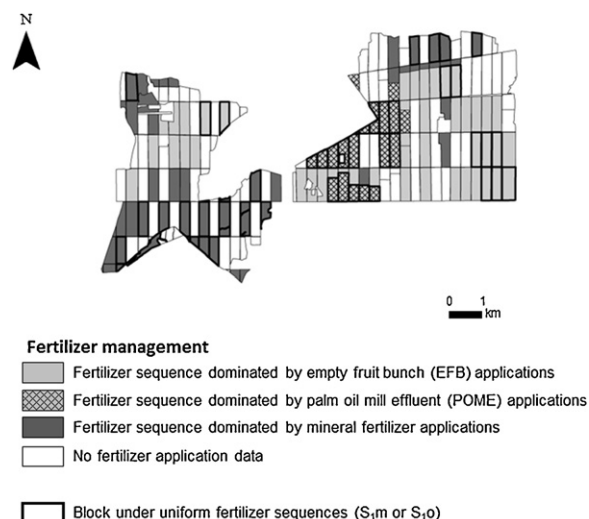


Fig. 4. Fertilizer management in the plantation.

Table 3
Mean \pm standard error values for soil fertility parameters in loamy-sand uplands and sandy-loam lowlands in the industrial oil palm plantation.

	pH	OC (g kg ⁻¹)	TN (g kg ⁻¹)	CEC (cmol kg ⁻¹)	Sum (cmol kg ⁻¹)	BS (%)
Loamy-sand uplands (n = 126)	4.18 \pm 0.38 Moderate	32.1 \pm 19.2 Very high	1.5 \pm 0.7 Moderate	8.2 \pm 4.3 Low	0.88 \pm 0.78	12.2 \pm 12.3
Loamy lowlands (n = 138)	4.25 \pm 0.34 High	62.4 \pm 36.0 Very high	2.6 \pm 1.5 Very high	15.7 \pm 7.7 High	1.81 \pm 1.85	11.9 \pm 10.3
p-Value (Wilcoxon test)	*	*	*	*	*	NS

The classification of pH, organic C (OC), total N (TN) and cation exchange capacity (CEC) was done after Goh and Chew (1997).
Sum: sum of base; BS: base saturation; *: $p < 0.05$; NS: non significant.

Table 4
Number of soil samples in each set and soil class.

Set	Loamy-sand uplands	Loamy lowlands	Clayey floodplain
S ₁ m	39	0	15
S ₂ m	42	21	18
S ₃ m	57	27	30
S ₄ m	72	33	30
S ₁ o	15	48	0
S ₂ o	21	63	0
S ₃ o	24	87	0
S ₄ o	54	105	0

zone (e.g., palm circle) were mixed to obtain a representative sample from that block, and then composited with samples from the same zone, taken from other locations in the block. In total, 288 composite soil samples (96 blocks \times 3 zones) were collected.

Soil fertility properties considered in this study were: the pH, determined in water using a pH meter (soil: water ratio of 1:1); organic carbon (OC) content, measured using the Walkley-Black method (Nelson and Sommers, 1982); Kjeldahl nitrogen (TN) content according to Bremner and Mulvaney (1982); the cation exchange capacity (CEC) was determined using the ammonium replacement method (CH₃COOH, pH = 7.0) (Thomas, 1982); the sum of bases was calculated by summing exchangeable K, Mg, Ca and Na concentrations measured with the ammonium acetate method (van Reeuwijk, 1993); and the base saturation (BS) was calculated

as the ratio of the sum of bases to the CEC. Analytical results represent the nutrient levels and other soil physico-chemical parameters in mineral soil, which did not include undecomposed residues (EFB, fragments of vegetation and other organic residues) since those residues were not included at the time of sampling and visible fragments were removed prior to analysis.

2.2.5. Statistical analysis

Finally, comparative statistical analysis was performed on soil fertility parameters within each soil class, between the groups S₁o and S₁m, from each set S₁ to S_n. Tests were performed on the measured soil fertility parameters (pH, OC, TN, CEC, sum of bases and BS) of the two groups (organic-fertilized blocks (S_im) vs. mineral-fertilized blocks (S_io) when the population size of each group was at least $n = 10$. Data were not normally distributed before and after log transformation, so comparisons (e.g., S₁m vs. S₁o, S₂m vs. S₂o and so on, for each soil class) were based on the non-parametric Wilcoxon test. Statistical analyses were performed using R (R Development Core Team, 2011).

3. Results

3.1. Overall soil fertility status

All soils in the study area were acidic, with pH values between 3.43 and 5.30. Other soil fertility properties varied according to the

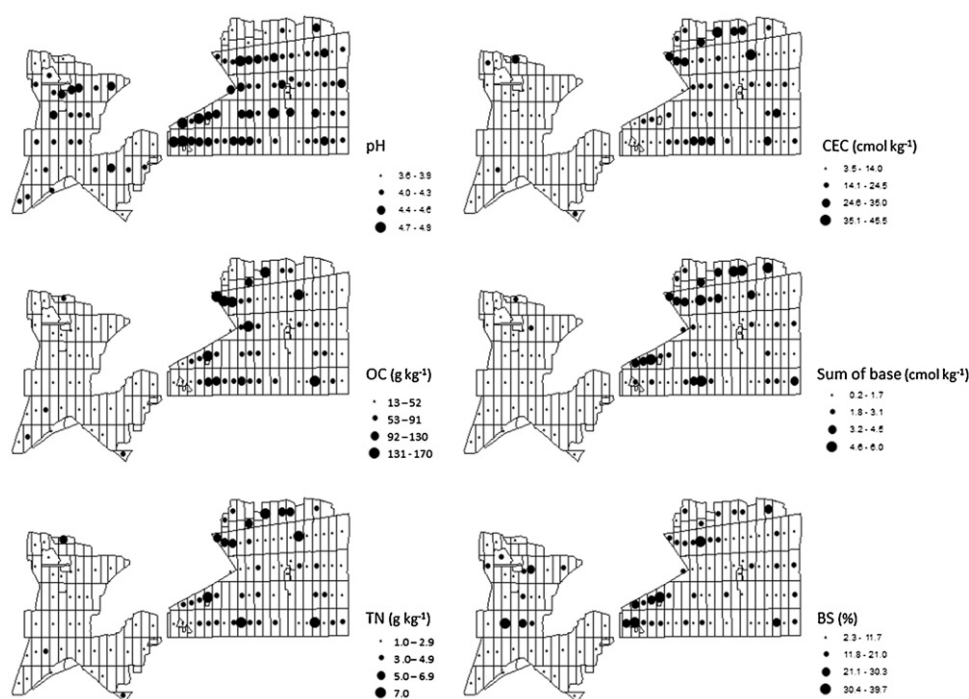


Fig. 5. Spatial distribution of the average values of pH, organic carbon (OC), total nitrogen (TN), cation exchange capacity (CEC), sum of bases (Sum) and base saturation (BS) in the blocks as measured on the soil surface (0–15 cm). The Equal interval method was used to classify the values. For reasons of clarity, the map presents the averaged values from the three positions per block.

soil class: OC was between 8.6 and 499 g kg⁻¹, TN ranged from 4 121 g kg⁻¹, CEC was between 2.1 and 63.1 cmol kg⁻¹, the sum of bases was 0.1–15.1 cmol kg⁻¹, and the BS was 1–93%. Fig. 5 synthesizes the measured soil properties over the plantation by showing average values (from the three sampling positions) per block.

The average values of pH, OC, TN, CEC and sum of bases were significantly greater on the loamy lowlands than on the loamy-sand uplands (Table 3). Considerably pH, OC, TN and CEC values for tropical acidic soils under oil palm (Goh and Chew, 1997), the pH and TN levels were high on the loamy lowlands, but moderate on the loamy-sand uplands. The OC level was very high on both soil classes, while the CEC level was moderate on the loamy lowlands and low on the loamy-sand uplands.

3.2. Effect of organic versus mineral fertilizer on soil fertility in uniform fertilizer application sequences

There was significantly ($p < 0.05$) greater pH, OC, TN, CEC, sum of bases and BS in blocks that received uniform organic fertilizer sequences (S₁o) than uniform mineral fertilizer sequence (S₁m) on the loamy-sand uplands (Fig. 6). There was no S₁m sequence on the loamy lowlands, so it was not possible to compare the effect of uniform fertilizer sequences with organic vs. mineral fertilizer in this soil class.

3.3. Effect of organic versus mineral fertilizer on soil fertility in mixed fertilizer sequences

Mixed fertilizer sequences increased in heterogeneity from S₁ (uniform fertilizer application sequence) to S₄. Fig. 7 shows the fertility parameters value as a function of the level of heterogeneity of the mixed fertilizer sequences. Fields on the loamy-sand uplands receiving predominantly organic fertilizer had significantly ($p < 0.05$) greater pH, TN, sum of bases and BS than those with dominant mineral fertilizer application, even as heterogeneity increased in the fertilizer sequence (Fig. 7). In the loamy-sand uplands, significant differences ($p < 0.05$) in OC and CEC between organic-fertilized and mineral-fertilized blocks at S₁ became non-significant by S₂. Fields on the loamy lowlands had significantly ($p < 0.05$) greater OC, TN, CEC and sum of bases when they received predominantly organic fertilizer, regardless of the homogeneity level, but the difference in pH between blocks fertilized with predominantly organic or mineral fertilizers decreased with increasing heterogeneity and was not significant by S₄. The BS was higher in organic-fertilized than mineral-fertilized blocks in the loamy lowlands at S₃ but not in other nested sets (Fig. 6).

4. Discussion

The key finding from this study is the significant soil response to long-term organic fertilizer application in both loamy-sand uplands and loamy lowlands. This was expected, based on previous studies that document a rapid response to organic fertilizer application on low-fertility tropical soils (i.e., highly weathered, having high iron and aluminum oxide concentration), similar to the Ferralsols considered in this study (Turmel et al., 2011). However, the expected response is based on plot-scale studies where organic fertilizers were applied recently or there were several years of repeated organic fertilizer applications. The novelty of the landscape-scale approach developed for this study is that it allows us to describe soil responses to multi-year fertilizer applications with mixed fertilizer sequences, alternating between mineral and organic fertilizer sources and having an unequal number of applications of each source, across a large spatial area (4000 ha). Results of this study for blocks receiving mixed fertilizer sequences reveal

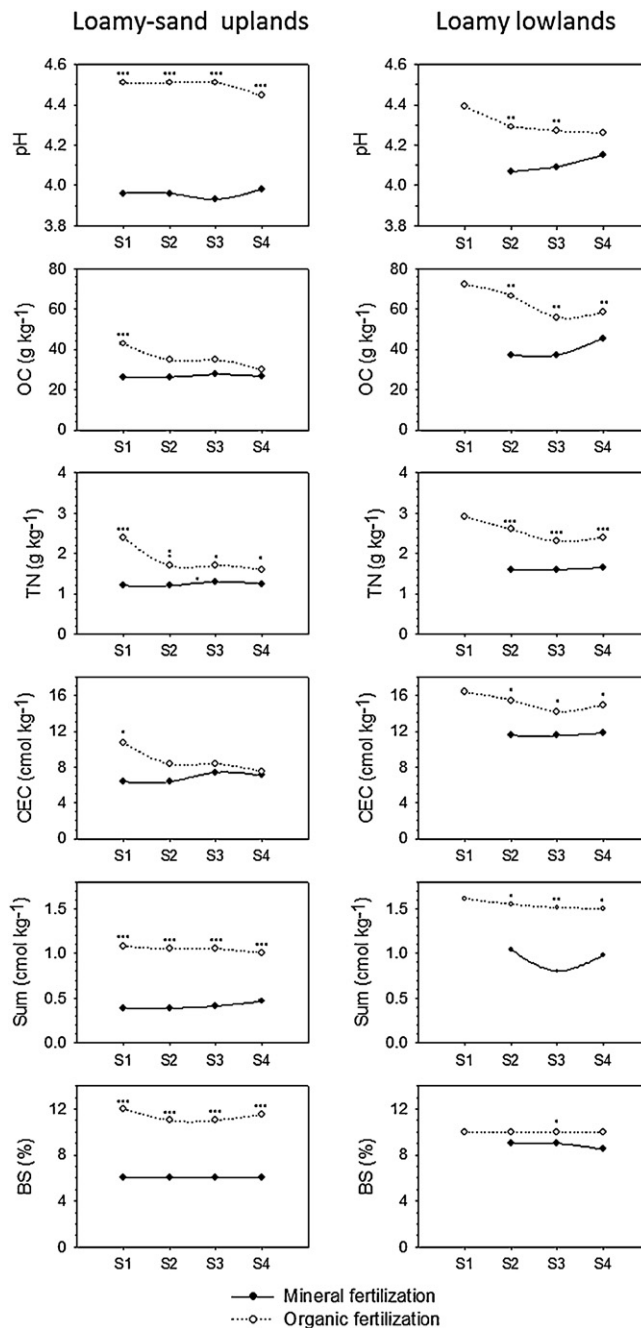


Fig. 6. Evolution of the median values (S_{1,m} and S_{1,o}) of pH, organic carbon (OC), total nitrogen (TN), cation exchange capacity (CEC), sum of bases (Sum) and base saturation (BS) as a function of the level of heterogeneity of the fertilizer application sequence for the loamy-sand upland soil class and the loamy lowland soil class. The dotted lines represent the organic-fertilized blocks, and the continuous lines represent the mineral-fertilized blocks. Graphs show the Wilcoxon test results between organic- and mineral-fertilized blocks (S_{1,m} vs. S_{1,o}): * when $p < 0.05$; ** when $p < 0.01$; *** when $p < 0.001$. Values of i were 1 to 4.

differences in soil responses between loamy-sand uplands and loamy lowlands soil classes. Blocks receiving continuous organic fertilizer sequence had higher levels of OC content and CEC than others. Increasing heterogeneity in the mixed fertilizer sequence led to a decline in pH in the loamy lowlands, and the BS in this soil class was little affected by fertilizer application. These soil responses to fertilizer application are interpreted based on a conceptual model of soil biogeochemical processes in acidic tropical soils (Fig. 7).

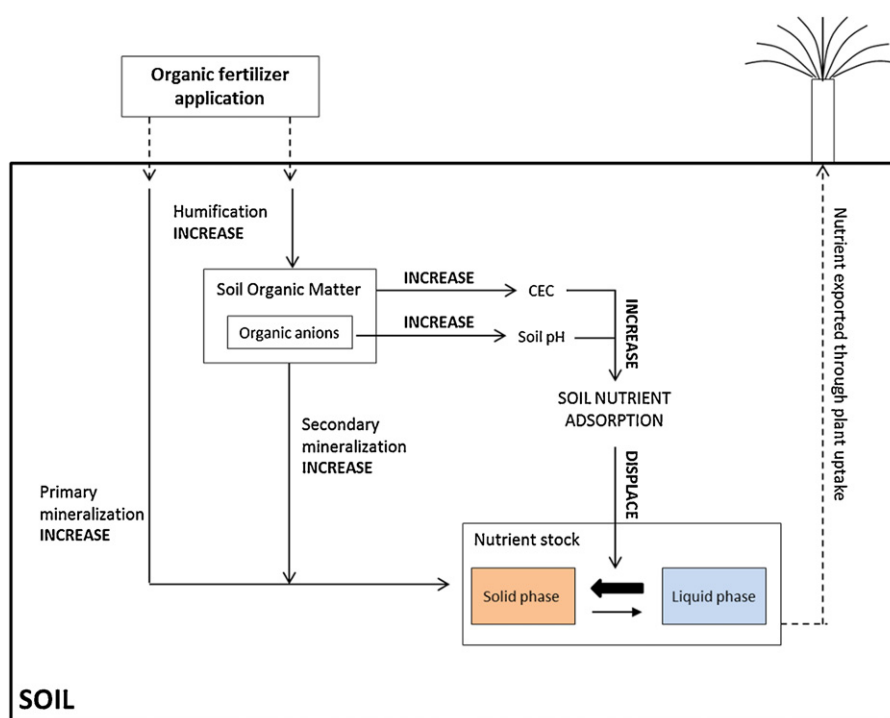


Fig. 7. Conceptual model illustrating how soil biogeochemical processes control the soil response following the addition of organic fertilizers in an acidic soil under tropical humid climatic conditions. The arrows represent biogeochemical processes with causal relationships; the arrows represent nutrient inputs/outputs; and the arrows represent nutrient transfers between soil solid and liquid phases. The thickness of the arrow represents the relative amount of nutrients. The notations INCREASE/DECREASE/DISPLACE describe a biochemical reaction that changed soil properties following the application of organic fertilizer.

4.1. Effect of organic fertilizer application on soil fertility parameters in loamy-sand uplands and loamy lowlands

4.1.1. Soil pH

In the loamy-sand uplands, continuously organic-fertilized blocks had pH values 0.55 units higher than mineral-fertilized blocks, and the difference was maintained even when organic fertilizer application was infrequent. The blocks from loamy lowlands were a little less acidic, around pH 4.1 in blocks with predominantly mineral fertilizer application. Although pH differed significantly between mineral and organic groups in the S_2 and S_3 sets, it did not differ significantly in the S_4 set, because the values converged with increasing heterogeneity of fertilizer sequence. Overall, a greater improvement in soil pH was achieved by applying organic fertilizer to loamy-sand uplands than loamy lowlands.

Organic fertilizers often have a liming effect on acidic soils, and our results are consistent with the significant increase in pH observed following application of POME and EFB (Abu Bakar et al., 2011; Caliman et al., 2001; Okwute and Isu, 2007). There are several processes by which soil pH can be raised when organic matter is added, including denitrification, mineralization and decomplexation of organically-bound metals, mineralization of organic N, sulphate reduction, microbial uptake of mineral N, S or P (van Breemen et al., 1983). Some authors suggested that the increase in soil pH is due to ash alkalinity (organic anion content) in the organic fertilizer (Mokolobate and Haynes, 2002; Noble et al., 1996) or from microbial activity (Yan et al., 1996) because the microbial breakdown of organic anions is a decarboxylation reaction that causes proton consumption (Barekzai and Mengel, 1993). Release of basic cations like K^+ from fresh organic matter can displace the acidic cations Al^{3+} and H^+ from soil surfaces and permit the consumption of H^+ ions, thereby increasing the soil pH (Li et al., 2008; Pocknee and Sumner, 1997; Tang and Yu, 1999). Abu Bakar et al. (2011) attributed the pH increase following EFB to its high K

content. Budianta et al. (2010) noted that anaerobic soil conditions following EFB application could cause a pH increase because this would reduce cations from high valence states to lower states, thus releasing the hydroxide ion and creating a microenvironment with alkaline conditions. However, the effect of EFB on soil reducing conditions would likely be temporary and so is unlikely to explain the long-term effect of organic fertilizers on soil pH, particularly in mixed fertilizer sequences where organic fertilizers were applied infrequently (e.g., S_3 and S_4). Future work on mechanisms underlying the apparent liming effect of POME and EFB should investigate how the non-acidic cations in these materials may contribute to displacement of H^+ ions, followed by proton consumption with organic anions or associated with microbial activity.

Soils from the loamy-sand uplands class were more acidic than those from the loamy lowlands soil class, which was expected. Intensively cultivated loamy-sand soils are sensitive to acidification because they are more vulnerable to leaching, have lower buffering capacity and tend to receive more fertilizer N inputs than loamy or clayey soils (Nawaz et al., 2011). Mineral N fertilizers are implicated in soil acidification because two protons are produced when NH_4^+-N is nitrified to NO_3^--N (Anuar et al., 2008; Thomas and Hargrove, 1984). The application of urea and ammonium-based fertilizers reduces soil pH on oil palm plantations (Caliman et al., 1987; Kee et al., 1995; Nelson et al., 2010), particularly when long-term application of N fertilizers causes a decline in exchangeable K^+ due to the displacement of K^+ by NH_4^+-N that results in K^+ leaching through the soil profile (Anuar et al., 2008). Examining the mixed fertilizer sequences that received predominantly mineral fertilizer showed no difference in soil pH from S_1 to S_4 in the loamy-sand uplands, but a trend of increasing pH from S_2 to S_4 in the loamy lowlands, which may suggest that acidification from mineral N fertilizer was occurring in the loamy lowlands. The liming effect of dolomite applications may limit pH acidification caused by urea applications. Blocks that received urea plus dolomite had pH values

of 4.06 on the SLL ($n = 12$) and 3.88 on the SU ($n = 12$), which was not statistically different from blocks that received urea only (pH = 4.18 on SLL ($n = 9$) and pH 3.99 on SU ($n = 27$), $p > 0.05$, Wilcoxon test). This suggests that dolomite applications did not increase the soil pH in the study region. This suggested that, in this study, dolomite applications did not seem to have a significant effect on the soil pH. The loamy lowlands appeared to have a higher inherent buffering capacity against acidification than the loamy-sand uplands soil class. At the low pH of these soils it is likely to be due mostly to the dissolution of clay minerals and other minerals (Bloom, 2000). This buffering capacity may be ascribed to hydrolysis of pedogenic Al compounds (Wiseman and Püttmann, 2006), which are present in greater concentration in the loamy lowlands than the loamy-sand uplands (data not shown). Aluminum hydroxides (e.g., $\text{Al}(\text{OH})_3$) react with protons to release Al^{3+} and three protons are consumed in the reaction, thus the pH changes at a slower rate than predicted from acidification reactions (Harter, 2007; Thomas and Hargrove, 1984).

4.1.2. Organic C and total N

Organic fertilizers are a source of fresh organic matter, which is gradually mineralized to CO_2 or transformed into stable soil organic matter (Schvartz et al., 2005). Of the two organic fertilizers available in this study, EFB might be expected to decompose more slowly due to its high lignin content (25–30% on a dry weight basis), yet total decomposition of EFB in oil palm plantations occurs in less than 12 months (Haron et al., 1998; Teh Boon Sung et al., 2010). Continuous application of organic fertilizers resulted in 1.6 times more OC in the loamy-sand uplands, but these levels declined rapidly when organic fertilizer application occurred less frequently. Fields in the loamy lowlands soil class had up to 1.8-fold more OC in the mixed fertilizer application sequences with predominantly organic fertilizer application, compared to mineral fertilizer application. Since OC declined significantly between S_1 and the mixed fertilizer sequences in the loamy-sand uplands, but not the loamy lowlands, this suggests that organic fertilizers were more susceptible to mineralization in the loamy-sand uplands. Conditions in the loamy-sand uplands favored mineralization because those soils were typically well drained and aerated, which would favor microbially-mediated mineralization. In contrast, the loamy lowlands had a higher water table, which probably led to the accumulation of organic matter (Sahrawat, 2003). Another difference in the soil classes was the greater clay content in the loamy lowlands than the loamy-sand uplands, which implies organo-mineral associations with clay minerals and/or iron oxides that may sequester OC and protect it from decomposition (Eusterhues et al., 2003; Krull et al., 2001; Wiseman and Püttmann, 2006).

The TN concentration was up to 2 times greater in the loamy-sand uplands blocks and about 1.6 times greater in the loamy lowlands blocks with uniform and mixed fertilizer application sequences dominated by organic fertilizers, compared to mineral fertilizers, which was significant regardless of the level of heterogeneity in the mixed fertilizer sequence. These results seem to suggest that TN is not mineralized and lost from soil at the same rate as OC content in oil palm plantations, but the mechanisms responsible for conserving TN in these soils require further study. Overall, the improvement in OC content from regular application of organic fertilizer was greater in the loamy-sand uplands than loamy lowlands soil class.

4.1.3. Cation exchange capacity and base saturation

The CEC is an indicator of potential nutrient adsorption on organo-mineral complexes, particularly the retention of basic cations (e.g., K, Na, Ca and Mg) by electrostatic forces (Zech et al., 1997). Higher CEC is associated with an increase in soil organic matter and pH (Diacono and Montemurro, 2010; Helling et al., 1964). In

the loamy-sand uplands, blocks receiving continuous organic fertilizer application had the highest CEC value, due to the concomitantly high OC and pH values. There was a decline in the CEC between S_1 and the mixed fertilizer sequences, which mirrored the decline in OC in the loamy-sand uplands. The loamy lowlands had greater CEC when receiving mixed fertilizer application sequences dominated by organic fertilizers, compared to mineral fertilizers, and the pattern of CEC was consistent with the OC concentration in loamy lowlands. This leads us to conclude that CEC was controlled more by the OC concentration than soil pH in both loamy-sand uplands and loamy lowlands in the oil palm plantation. This is consistent with van Wambeke (1979), who noted that most of the CEC in soils dominated by kaolinite and amorphous oxides, such as Ferralsols, is associated with soil organic matter rather than with the mineral components. Labile organic matter is often considered to be the most important source of CEC in tropical soils (Duxbury et al., 1989; Zech et al., 1997). To maintain high CEC values, we recommend regular application of organic fertilizer to loamy-sand uplands.

The CEC was approximately twice as high in the loamy lowlands than the loamy-sand uplands, which is related to the higher clay and organic matter contents in the loamy lowlands. While the sum of bases increased in the loamy-sand uplands and loamy lowlands as a result of organic fertilizer application, the BS was greater in the loamy-sand uplands only. Organic fertilizers are a source of non-acidic cations, but they must be retained in CEC sites to be included in the sum of bases and BS measurements. These results suggest that a greater proportion of non-acidic cations were adsorbed to the solid phase in the loamy-sand uplands than in the loamy lowlands (the remainder of the non-acidic cations in the loamy lowlands were in soil solution, rather than adsorbed to the solid phase). To shift the equilibrium between the solid phase and soil solution will require greater inputs of non-acidic cations in the loamy-sand uplands. We conclude that larger inputs of organic fertilizer or mineral fertilizers containing non acidic cations (particularly K, Ca and Mg) could be helpful to maintain an adequate soil solution concentration of these essential plant nutrients in the loamy-sand uplands, for optimal fertilizer management of oil palm.

5. Conclusion

A landscape-scale approach was used to assess the soil response to long-term mineral and organic fertilizer applications across a 4000-hectare industrial oil palm plantation. This approach required information on the spatial distribution of soil classes and historical fertilizer sequences across the landscape, as well as the biogeochemical processes that explain soil responses to long-term application with uniform and mixed fertilizer sources. We demonstrated a general improvement in soil fertility status with organic fertilizer applications compared to mineral applications in an oil palm plantation, which was expected, and a decline in some soil fertility parameters when organic fertilizers were applied infrequently over a 7-yr period. For instance, the pH, OC and CEC levels in loamy-sand uplands were highest when organic fertilizer was applied continuously and declined significantly ($p < 0.05$) when organic fertilizer was applied infrequently. We recommend regular application of organic fertilizer to maintain OC and CEC in this soil class.

Information on initial soil conditions in fields when the plantation was established and follow-up soil sampling at regular intervals during the life-cycle of oil palm would be helpful in describing the evolution of soil responses and validating predictions from the landscape-scale approach. We recommend that soil sampling campaigns be undertaken within the plantation every 3–5 yrs to track the evolution of soil fertility within blocks and adjust the fertilizer application program accordingly. Since the category

of organic fertilizers included two types (POME and EFB), future investigations to compare mineral fertilizer to each type of organic fertilizer could provide further insight into the strategic use of these limited resources in oil palm plantations. Still, the landscape-scale approach may be the only feasible way to evaluate the long-term soil response to organic vs. mineral fertilizer applications in large commercial plantations. The approach could be extrapolated to describe soil response in other oil palm plantations under similar pedoclimatic conditions, or adapted to assess the soil response to fertilizer sequences in other large perennial crop systems.

Acknowledgments

This study was supported by the Center International de Recherche Agronomique pour le Développement (CIRAD), the Natural Sciences and Engineering Research Council of Canada (NSERC) and the PT-SMART Research Institute (SMARTRI). The authors wish to sincerely thank the staff at the SMARTRI for the facilities they have provided over the course of this research work.

References

- Abu Bakar, R., Darus, S.Z., Kulaseharan, S., Jamaluddin, N., 2011. Effects of ten year application of empty fruit bunches in an oil palm plantation on soil chemical properties. *Nutr. Cycl. Agroecosyst.* 89, 341–349.
- Anuar, A.R., Goh, K.J., Heoh, T.B., Ahmed, O.H., 2008. Spatial variability of soil inorganic N in a mature oil palm plantation in Sabah, Malaysia. *Am. J. Appl. Sci.* 5, 1239–1246.
- Barak, P., Jobe, B.O., Krueger, A.R., Peterson, L.A., Laird, D.A., 1997. Effects of long-term soil acidification due to nitrogen fertilizer inputs in Wisconsin. *Plant Soil* 197, 61–69.
- Barekzai, A., Mengel, K., 1993. Effect of microbial decomposition of mature leaves on soil pH. *Zeitschrift für Pflanzenernährung und Bodenkunde* 156, 93–94.
- Blasco, F., Laumonier, Y., Purnajaya, 1986. International Map of the Vegetation and the Environmental Conditions. Central Sumatra. Sheet no. 2. SEAMEO-BIOTROP, Bogor, Indonesia.
- Bloom, P.R., 2000. Soil pH and pH buffering. In: Summer, M.E. (Ed.), *Handbook of Soil Science*. CRC Press, Boca Raton, FL, pp. B333–B352.
- Bremner, J.M., Mulvaney, C.S., 1982. Nitrogen-Total. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), *Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties*. Am. Soc. Agron., Soil. Sci. Soc. Am., Madison, WI, pp. 595–624.
- Budianta, D., Yasmin Adam Wiralaga, A., Lestari, W., 2010. Changes in some soil chemical properties of Ultisol applied by mulch from empty fruit bunches in an oil palm plantation. *J. Trop. Soils* 15, 111–118.
- Caliman, J.P., Budi, M., Saletes, S., 2001. Dynamic of nutrient release from empty fruit bunches in field conditions and soil characteristics changes. In: *Proceedings of the 2001 PIPOC International Palm Oil Congress*. MPOB, Bangi, pp. 550–556.
- Caliman, J.P., Olivin, J., Dufour, O., 1987. Dégradation des sols ferrallitiques sableux en culture de palmiers à huile par acidification et compaction. *Oléagineux Corps gras Lipides* 42, pp. 393–398.
- Chiew, L.K., Rahman, Z.A., 2002. The effects of oil palm empty fruit bunches on oil palm nutrition and yield, and soil chemical properties. *J. Oil Palm Res.* 14, 1–9.
- Cristancho, J.A., Hanafi, M.M., Syed Omar, S.R., Rafii, M.Y., 2011. Alleviation of soil acidity improves the performance of oil palm progenies planted on an acid Ultisol. *Acta Agric. Scand.* 61, 487–498.
- Diacono, M., Montemurro, F., 2010. Long-term effects of organic amendments on soil fertility. A review. *Agron. Sustain. Dev.* 30, 401–422.
- Dolmat, M.T., Lim, K.H., Zakaria, Z.Z., Hassan, A.H., 1987. Recent studies on the effects of land application of palm oil mill effluent on oil palm and the environment. In: Halim, H.A.H., Chew, P.S., Wood, B.J., Pushparajah, E. (Eds.), *Proceedings of the International Oil Palm/Palm Oil Conferences*. PORIM, and Incorporated Society of Planters, Kuala Lumpur, Malaysia, pp. 596–604.
- Duxbury, J.M., Smith, M.S., Doran, J.W., 1989. Soil organic matter as a source and a sink of plant nutrients. In: Coleman, D.C., Oades, J.M., Uehara, G. (Eds.), *Dynamics of Soil Organic Matter in Tropical Ecosystems NifTAL Project*. University of Hawaii Press, Honolulu, HI, pp. 33–67.
- Eusterhues, K., Rumpel, C., Kleber, M., Kögel-Knabner, I., 2003. Stabilisation of soil organic matter by interactions with minerals as revealed by mineral dissolution and oxidative degradation. *Org. Geochem.* 34, 1591–1600.
- FAO/ISRIC/ISSS, 1998. World Reference Base for soil resources. *World Soil Resources Report*. FAO, Rome88.
- Follain, S., Walter, C., Legout, A., Lemerrier, B., Dutin, G., 2007. Induced effects of hedgerow networks on soil organic carbon storage within an agricultural landscape. *Geoderma* 42, 80–95.
- Goh, K.J., Chew, P.S., 1997. Interpretations of analytical data from soil survey reports for manuring recommendations: some pointers. *Annual Journal/Report 1997*. Royal Johore Planters' Association, pp. 25–30.
- Goovaerts, P., 1999. Geostatistics in soil science: state-of-the-art and perspectives. *Geoderma* 89, 1–46.
- Haron, K., Brookes, P.C., Anderson, J.M., Zakaria, Z.Z., 1998. Microbial biomass and soil organic matter dynamics in oil palm (*Elaeis guineensis* Jacq.) plantations, West Malaysia. *Soil Biol. Biochem.* 30, 547–552.
- Harter, R.D., 2007. Acid soils of the tropics. ECHO Technical Note.
- Helling, C.S., Chesters, G., Corey, R.B., 1964. Contribution of organic matter and clay to soil cation-exchange capacity as affected by the pH of the saturating solution. *Soil Sci. Soc. Am. J.* 28, 517–520.
- Kee, K.K., Goh, K.J., Chew, P.S., 1995. Effects of NK fertiliser on soil pH and exchangeable K status on acid soils in an oil palm ecosystem in Malaysia. In: Date, R.A., Grundon, N.J., Rayment, G.E., Probert, M.E. (Eds.), *Plant-Soil Interactions at Low pH: Principles and Management*. Developments in Plant and Soil Science. Kluwer Academic Publications, The Netherlands, pp. 809–815.
- Kheong, L.V., Rahman, Z.A., Musa, M.H., Hussein, A., 2010. Empty fruit bunch application and oil palm root proliferation. *J. Oil Palm Res.* 22, 750–757.
- Krige, D.G., 1951. A statistical approach to some basic mine valuation problems on the Witwatersrand. *J. Chem. Metall. Min. Soc. S. Afr.* 52, 119–139.
- Krull, E.S., Baldock, J.A., Skjemstad, J.O., 2001. Soil texture effects on decomposition and soil carbon storage. In: Kirschbaum, M.U.F., Mueller, R. (Eds.), *Net Ecosystem Exchange*. CRC Workshop Proceedings. CRC for Greenhouse Accounting, Canberra, pp. 103–110.
- Law, M.C., Balasubram, S.K., Husni, M.H.A., Ahmed, O.H., Haniff Harun, M., 2009. Spatial variability of soil organic carbon in oil palm: a comparison between young and mature stands. *Int. J. Agric. Res.* 4, 402–417.
- Li, Z.A., Zou, B., Xia, H.P., Ding, Y., Tan, W., Fu, S.L., 2008. Role of low-molecular-weight organic acids and their salts in regulating soil pH. *Pedosphere* 18, 137–148.
- Lim, K.C., Chan, K.W., 1987. Towards optimizing empty fruit bunch application in oil palm. In: Chan, K.W., Liao, S.S. (Eds.), *Proceedings of the 1987 PORIM International Palm Oil Congress*. PORIM, Bangui, pp. 232–242.
- Loong, S.G., Mazeeb, M., Letchumanan, A., 1987. Optimising the Use of EFB Mulch on Oil Palms on Two Different Soils. *PORIM International Palm Oil Development Conference*, Kuala Lumpur24–29.
- Maena, L.M., Thong, K.C., Ong, T.S., Mokhtaruddin, A.M., 1979. Surface wash under mature oil palm. In: Pushparajah, E. (Ed.), *Proceedings of the Symposium on Water Agriculture in Malaysia*. Malaysian Society of Soil Science, Kuala Lumpur, pp. 203–216.
- Mathéron, G., 1965. Les variables régionalisées et leur estimation. *Masson & Cie, Paris*, 306 p.
- Minasny, B., McBratney, A.B., Whelan, B.M., 2005. *VESPER Version 1.62*. Australian Centre for Precision Agriculture (ACPA), University of Sydney, Sydney.
- Mokolobate, M.S., Haynes, R.J., 2002. Comparative liming effect of four organic residues applied to an acid soil. *Biol. Fert. Soils* 35, 79–85.
- Nawaz, R., Tripathi, N.K., Parkian, P., 2011. Soil acidity ranking, soil sensitivity and vulnerability to acid deposition in the northeast region of Thailand 2010 International Conference on Biology. In: *Environment and Chemistry*. IACSIT Press, Singapore, 415–419.
- Nelson, D.W., Sommers, L.E., 1982. Total carbon, organic carbon and organic matter. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), *Methods of Soil Analysis Part 2. Chemical and Microbial Properties*. Am. Soc. Agron. Soil Sci. Soc. Am., Madison, WI, pp. 408–411.
- Nelson, P.N., Berthelsen, S., Webb, B.J., Banabas, M., 2010. Acidification of volcanic ash soils under oil palm in Papua New Guinea: effects of fertiliser type and placement. In: Gilkes, R., Prakongkep, N. (Eds.), *19th World Conference Congress of Soil Science, Soil solutions for a changing world*. International Union of Soil Science, Brisbane, Australia, pp. 8–11.
- Noble, A.D., Zenneck, I., Randall, P.J., 1996. Leaf litter ash alkalinity and neutralization of soil acidity. *Plant Soil* 179, 293–302.
- Pocknee, S., Sumner, E., 1997. Cation and nitrogen contents of organic matter determine its soil liming potential. *Soil Sci. Soc. Am. J.* 61, 86–92.
- Oim, L., Dynoodt, R.F.P., 2008. Acidification from long-term use of urea and its effect on selected soil properties. *Afr. J. Food Agric. Nutr. Dev.* 8, 63–76.
- Okwute, L.O., Isu, N.R., 2007. The environmental impact of palm oil mill effluent (POME) on some physico-chemical parameters and total aerobic bioload of soil at a dump site in Anyigba, Kogi State, Nigeria African. *J. Agric. Res.* 2, 656–662.
- Pennock, D.J., Veldkamp, A., 2006. Advances in landscape-scale soil research. *Geoderma* 113, 1–5.
- Potter, L., Badcock, B., 2001. The Effect of Indonesia's Decentralisation on Forests and Estate Crops: Case Study of Riau Province the Original Districts of Kampar and Indragiri Hulu. Center For International Forestry Research, Bogor, Indonesia89.
- Development Core Team, R., 2011. R: A language and environment for statistical computing, reference index version 2.13.1. R Foundation for Statistical Computing, Vienna, Austria, ISBN 3-900051-07-0 <http://www.R-project.org>
- Sahrawat, K.L., 2003. Organic matter accumulation in submerged soils. *Adv. Agron.* 81, 169–201.
- Salomon, E., 1999. Availability of Potassium to Clover and Grass from Soils with Different Potassium Fertilizer Application Histories. Swedish University of Agricultural Sciences, Doctoral thesis. ISSN 1401-6249, ISBN 91-576-5459-X.
- Schvartz, C., Muller, J.-C., Decroux, J., 2005. *Guide de la Fertilisation Raisonnée*. Editions France Agricole, Paris.
- Sheil, D., Casson, A., Maijaard, E., van Noordwijk, M., Gaskell, J., Sunderland-Groves, J., Wertz, K., Kanninen, M., 2009. The impacts and opportunities of oil palm in Southeast Asia. Center for International Forestry Research (CIFOR), Bogor.
- Singh, R., Ibrahim, M., Esa, N., Iiyana, M., 2010. Composting of waste from palm oil mill: a sustainable waste management practice. *Rev. Environ. Sci. Biotechnol.* 9, 331–344.
- Suyanto, S., Applegate, G., Permana, R.P., Khususiyah, N., Kurniawan, I., 2004. The role of fire in changing land use and livelihoods in Riau-Sumatra. *Ecol. Soc.* 9, 15.

- Szott, L.T., Kass, D.C.L., 1993. Fertilizers in agroforestry systems. *Agroforestry Syst.* 23, 157–176.
- Tan, K.T., Lee, K.T., Mohamed, A.R., Bhatia, S., 2009. Palm oil: Addressing issues and towards sustainable development. *Renew. Sustain. Energy Rev.* 13, 420–427.
- Tang, C., Yu, Q., 1999. Chemical composition of legume residues and initial soil pH determine pH change of a soil incorporation of the residues. *Plant Soil* 215, 29–38.
- Teh Boon Sung, C., Goh, K.J., Chien, L.C., Seng, S.T., 2011. Short-term changes in the soil physical and chemical properties due to different soil and water conservation practices in a sloping land oil palm estate. *Pertanika J. Trop. Agric.* 34, 41–62.
- Teh Boon Sung, C., Goh, K.J., Kamarudin, K.N., 2010. Physical changes to oil palm empty fruit bunches (EFB) and EFB Mat (Ecomat) during their decomposition in the field. *Pertanika J. Trop. Agric.* 33, 39–44.
- Thambirajah, J.J., Zulkali, M.D., Hashim, M.A., 1995. Microbiological and biochemical changes during the composting of oil palm empty-fruit-bunches Effect of nitrogen supplementation on the substrate. *Bioresour. Technol.* 52, 133–144.
- Thomas, G.W., 1982. Exchangeable cations. In: Page, A.L. (Ed.), *Methods of Soil Analysis, Part 2. Agronomy Series*, 2nd ed. American Society of Agronomy, Madison, Wis.
- Thomas, G.W., Hargrove, W.L., 1984. The chemistry of soil acidity. In: Adams, F. (Ed.), *Soil Acidity and Liming*, 2nd ed. ASA, CSSA, SSSA, Madison, Wisconsin 3–56.
- Turmel, M.S., Turner, B.L., Whalen, J.K., 2011. Soil fertility and the yield response to the System of Rice Intensification. *Renew. Agric. Food Syst.* 26, 185–192.
- van Breemen, N., Mulder, J., Driscoll, C.T., 1983. Acidification and alkalization of soils. *Plant Soil* 75, 283–308.
- van Reeuwijk, L.P., 1993. Procedures for soil analysis. Technology Paper 9. International Soil Reference and Information Centre, Wageningen, The Netherlands.
- van Wambeke, A., 1979. Management properties of Ferralsols. *FAO Soils bulletin* 23. Food and Agriculture Organizations of the United Nations, Rome.
- Veldkamp, A., Kok, K., De Koning, G.H.J., Schoorl, J.M., Sonneveld, M.P.W., Verburg, P.H., 2001. Multi-scale system approaches in agronomic research at the landscape level. *Soil Tillage Res.* 58, 129–140.
- Webster, R., Oliver, M.A., 2000. *Geostatistics for Environmental Scientists*. John Wiley, New York.
- Wiseman, C.L.S., Püttmann, W., 2006. Interactions between mineral phases in the preservation of soil organic matter. *Geoderma* 134, 109–118.
- Wong, K.M., Abdul Rahman, N.A., Abd-Aziz, S., 2008. Enzymatic hydrolysis of palm oil mill effluent solid using mixed cellulases from locally isolated fungi. *Research Journal of Microbiology* 3, 474–481.
- Wrona, D., 2006. Response of young apple trees to nitrogen fertilizer application, on two different soils. *Acta Hort. (ISHAH)* 721, 153–158.
- Yan, F., Schubert, S., Mengel, K., 1996. Soil pH increase due to biological decarboxylation of organic anions. *Soil Biol. Biochem.* 28, 617–624.
- Zaharah, A.R., Lim, K.C., 2000. Oil palm empty fruit bunch as a source of nutrient and soil ameliorant in oil palm plantations. *Malaysian Agric. J.* 4, 51–66.
- Zech, W., Senesi, N., Guggenberger, G., Kaiser, K., Lehmann, J., Miano, T.M., Miltner, A., Schroth, G., 1997. Factors controlling humification and mineralization of soil organic matter in the tropics. *Geoderma* 79, 117–161.