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Nutrients and Contaminants in Soils of Current and Former Oil Palm Production Systems from Indonesia

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Abstract: Palm oil production in Southeast Asia often occurs on nutrient-poor, acidic soils converted from primary forest. Both the agricultural conversion and the production of oil palm are subsidised in Indonesia. As well as depleting soil organic C and plant nutrients, agricultural production on these soils can result in the accumulation of trace elements (TEs)—including micronutrients and non-essential trace elements—from the use of TE-containing agrichemicals including phosphate fertilisers and Cu fungicides. We tested the hypothesis that palm soils will have lower C concentrations than forest soils, as well as accumulation of TEs including Cu, Zn and Cd. Soil samples from active and abandoned oil palm plantations in Sumatra, Indonesia, were analysed for general soil properties as well as TE concentrations. Soils were acidic and low in key nutrients, with production likely to be limited by deficiencies of N, P, K, Mg and Mo, present at some sites in mean concentrations as low as 0.021%, 118 mg kg⁻¹, 778 mg kg⁻¹, 1023 mg kg⁻¹ and 0.095 mg kg⁻¹, respectively. Mean organic C was lower (2.0–3.3%) than reported values in nearby forest soils (7.7%). Soils under palm production contained elevated levels of Cu, Zn, As and Pb up to 38, 91, 9.0 and 28 mg kg⁻¹, respectively, likely due to agrichemical use. The correction of nutrient deficiencies in palm production would require significant fertiliser inputs, which would exacerbate TE accumulation and reduce the net economic revenue from oil production. Our data have shown that in the plantations we have sampled, soils have become degraded. These tropical, weathered, and naturally nutrient-poor soils are ill suited to intensive production that requires high ongoing nutrient inputs. These findings have implications for the sustainability of a regionally significant production system across Southeast Asia.

Keywords: *Elaeis guineensis*; palm oil; fertilisers; trace elements; heavy metals



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1. Introduction

Since 1990, most tropical soils used for agricultural production (90%) were formerly under indigenous forest [1], of which 86% were converted to oil palm (*Elaeis guineensis*) and rubber (*Hevea brasiliensis*) plantations [2]. Indonesia and Malaysia are the largest palm oil producers [3]. Indonesia provides financial incentives to convert forest to palm plantations and subsidises oil palm production [4]. Palm conversions result in the destruction of forest ecosystems with resulting impacts on megafauna habitat and biodiversity [5–8]. However, there is a lacuna of information on the effects of oil palm production on tropical soils [9]. In particular, trace elements (TEs), which occur at <1000 mg kg⁻¹ in living tissue [10], can accumulate in soils as a result of repeated applications of agrochemicals in which the TE is an active ingredient or a contaminant. Trace elements can be both deleterious or beneficial to the health of plants, animals and ecosystems, depending on their concentration, speciation and associated mobility within the environment. Some TEs are non-essential and will pose toxicity risks if allowed to accumulate past toxic thresholds, while others are

essential for plants and/or animals in certain doses; however, they can still become toxic when they accumulate past health-based thresholds. Thus all trace elements can become potentially toxic depending on their concentrations and exposure routes present within the environment [11].

Both the fertilisers and composts that are used to increase soil fertility as well as applied pesticides may contain trace elements (TEs) as contaminants, including Zn, As, Cd and Pb in NPK fertilisers [12], or active ingredients such as Cu in Cu-based fungicides [13]. Trace elements may accumulate in soils over time [14] and increase the risk of food-chain transfer of toxic elements [15], particularly if Soil Guideline Values (SGVs) for TEs are exceeded. In different agricultural systems requiring high input rates of TE-containing agrichemicals, the accumulation of TEs in soil has posed risks for production: in New Zealand dairy farms which have historically used high rates of phosphate fertilisers, Cd now limits production in some regions [16], while in some regions of France, viticultural production is limited by the accumulation of Cu due to repeated Cu pesticide use [17]. If similar inputs and accumulation has occurred under oil palm agriculture, TEs may come to limit production in oil palm producing soils.

Typically, indigenous forests overlie acidic soils with low concentrations of plant nutrients that require capital lime and fertilisers to enable production [18,19]. Following conversion, soil organic matter usually decreases [20,21]. Soil organic matter has been found to decrease by up to 42% when converted from forest to oil palm [22]. Oil palm is an intensive crop, requiring maintenance nutrient inputs of N (215–286 kg ha⁻¹), P (143–215 kg ha⁻¹), K (358–429 kg ha⁻¹), Mg (215–286 kg ha⁻¹) and B (14–29 kg ha⁻¹) [23]. These input requirements may increase when palm is cultivated on nutrient-poor soils [3,23]. Cultivation on Histosols also requires inputs of Cu and Zn to meet plant nutrient requirements [24], and the use of Cu-based fungicides is recommended to treat oil palm pests including *Ganoderma* spp. [13,25]. In a survey of farmers, the most frequently used fertilisers in smallholder oil palm production in Indonesia were subsidised NPK (15-15-15) and urea, with farmers citing financial limitations as a key factor of fertiliser choice [26]. Oil palm soils can contain Cu, Zn and Cd up to 69, 107 and 5.2 mg kg⁻¹, respectively [27]. Maximum potential yields for palm oil have been calculated at between 10 and 18 t oil ha⁻¹ yr⁻¹; however, commercial yields are in the range of 5–7 t oil ha⁻¹ yr⁻¹ [28], and smallholder yields are as low as 4 t oil ha⁻¹ yr⁻¹ [29]. Without subsidies, oil palm production on low-fertility tropical soils may not be viable [30–32].

We hypothesise that the conversion of forest soils to palm oil or rubber plantation will result in the accumulation of TEs, particularly Cu, Zn and Cd, as well as the depletion of organic C. We further hypothesise that soils at sites that are under current production will have higher N concentrations than sites where the production of oil palm has been abandoned.

We aimed to determine the chemical composition and plant nutrient status of soils under active production and those which have been abandoned in Indonesia, and to compare these with published data from forest soils, international SGVs and oil palm production systems in other regions, as well as soils under rubber production.

2. Materials and Methods

2.1. Site Descriptions

Soil samples were collected from four *E. guineensis* plantation sites on the Indonesian island of Sumatra in May 2019 (Figure 1). Samples were obtained under the conditions of anonymity of land ownership, and following this, Figure 1 identifies the locality from where samples were collected. The sampling region has mean annual rainfall of 2950 mm [33]. All palm sites had soils classed as Acrisols under the FAO soil classification system [34], representing some 90% of soils in oil palm growing regions of Indonesia. Acrisols are taxonomically related to Oxisols under the USDA soil classification system [35]. These soils typically form in humid, tropical climates and old undulating landscapes, and are characterised by a subsurface accumulation of kaolinitic clays. They are typically highly

leached, low in plant nutrients, highly erodible and contain high levels of Al. As such, agricultural production on these soils can be challenging. The sites were chosen to give an indication of the range of soil conditions present under both current and former oil palm plantations with varying management practices and landscape features. For a summary of the site characteristics of the plantations sampled, see Table 1.

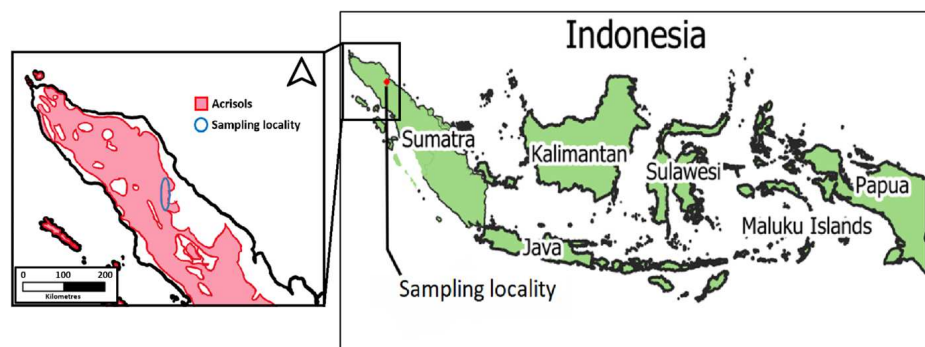


Figure 1. Map of Indonesia showing sampling locality in Sumatra with the extent of Acrisol soils over the north of the island. Adapted from [34].

Table 1. Site characteristics of sampled oil palm plantations.

Site Abbreviation	Site A	Site B	Site C	Site D
Site status	Abandoned, trees remaining	Abandoned, trees remaining	Active, smallholder	Ex-plantation, no trees remaining
Soil type (FAO classification)	Acrisol	Acrisol	Acrisol	Acrisol
Soil type (USDA classification)	Oxisol	Oxisol	Oxisol	Oxisol
Slope	$\leq 12^\circ$	$\leq 12^\circ$	$< 4^\circ$	$\leq 9^\circ$
Years in production	ca. 30	ca. 30	ca. 20	ca. 12
Recent management history	No amendments applied and unharvested for past 3 years	No amendments applied and unharvested for past 3 years	Amendments applied and weeds cleared with pesticides within last year	Oil palm trees removed, area under regeneration with no amendments applied for past 3 years
Number of samples collected	25	25	10	25

Sites A and B were both abandoned oil palm plantations that still contained abandoned oil palm trees. These sites were on the forest edge of Gunung Leuser National Park and were formerly under corporate management. For the previous three years, the sites had been unmanaged with no fertiliser applied. Prior to this, according to the plantation age map [36], these sites were under production since ca. 1996–1998. Trees were thus ca. 30 years old. These sites were adjacent to each other and were separated northeast (Site A)/southwest (Site B). Future reforestation was planned at these sites. As such, the sites were overgrown with understory plants and no amendments had been applied to the soil for at least three years. These sites were >100 ha in area, hilly and steep in places with slopes up to approximately 12° , and samples were taken from both in areas in which *E. guineensis* trees remained, based on accessibility and practicality.

Site C was an active smallholder oil palm plantation site on the forest edge, near to Gunung Leuser National Park. This site was adjacent to a small village and river and had been under *E. guineensis* production since ca. 2001 [36]. The site was <10 ha in area and had a slope of $<4^\circ$.

Site D was also an abandoned plantation and was classed as an ex-oil palm plantation, as the majority of oil palm trees has been removed at the time of sampling. Like the other plantations, this site bordered Gunung Leuser National Park. Production at the site had been abandoned and the area had transitioned into a mix of permaculture and reforestation. No amendments had been applied to the soil for at least three years. According to data on

remaining surrounding plantations from a map of plantation age [36], this site had likely been under production since at least 2009. This site was hilly with slopes up to 9°, and samples were collected here based on accessibility and practicality.

Control samples outside of plantations and in natural forest could not be collected, as permits were not granted to take soil samples from within the National Park. As such, we used published data from soils under nearby Gunung Leuser National Park [37,38] as well as from a rubber plantation in North Sumatra as a comparison site. Rubber cultivation often occurs adjacent to oil palm cultivation; however, it typically uses lower inputs of agrichemicals, particularly fertilisers [39]. The rubber trees at this site were ca. 10 years old at the time of sampling and data were from 32 samples. The soils from this site were Ultisols under the USDA classification system. Ultisols are similar to Acrisols/Oxisols, but feature a translocated clay layer below the surface horizon [40].

2.2. Analytical Methods

2.2.1. Sample Collection and Preparation

After clearing away the surface litter, soil samples were collected to 150 mm depth using a spade and placed in zip-lock plastic bags. Samples were taken at least 20 m apart from inter rows between trees. As each site varied in area, more samples were taken from the larger sites to achieve representativity of soils at each site. We took 25 samples from Sites A, B and D, and 10 samples from Site C, as this site was smaller in area. Samples were oven dried at 105 °C until a constant weight was achieved. Samples were then crushed using a mortar and pestle and passed through a 2 mm stainless steel sieve [41] for all analyses excluding PSA.

2.2.2. Pseudo-Total Element Concentrations

Microwave digestion was used to analyse pseudo-total elemental concentrations (hereafter referred to as total concentrations) in all samples following EPA Method 3051A [42]. The microwave used was an Ultrawave Single Reaction Chamber Microwave Digestion Unit. For each sample, 0.20 g (± 0.01 g) was weighed into a digestion tube and 5 mL 70% HNO₃ was added. Samples were left to pre-digest overnight, before being digested for 25 min at 230 °C [43]. Two reagent blanks and two Standard Reference Material (SRM) samples [44,45] were included with every 11 samples for quality assurance.

2.2.3. Ca(NO₃)₂-Extractable Element Concentrations

A Ca(NO₃)₂ extraction was used to measure phytoavailable concentrations of TEs in palm soil samples. This analysis used 0.05 M Ca(NO₃)₂ [46]. Here, 5.00 g (± 0.05 g) of soil was weighed into a 50 mL centrifuge tube, and 30 mL of 0.05 M Ca(NO₃)₂ was added. Tubes were placed on an oscillating shaker for two hours, then centrifuged at 4559 g for ten minutes. Four reagent blanks were included in every analysis.

Soil adsorption coefficients (K_D) were calculated for TEs soils at Sites A, B, C and D based on total and Ca(NO₃)₂ extractable (soluble) concentrations using the sorbed/soluble concentration quotient.

2.2.4. pH

The pH of soil was measured using a pH electrode according to the pH in H₂O method [41]. Five g of soil was measured into a beaker, and 12.5 mL of Milli-Q water was added (soil to water ratio of 1:2.5). Samples were then stirred vigorously for at least 1 min and left to stand overnight. A Hach HQ440d multi pH probe was then used to take the pH measurement of each sample.

2.2.5. Cation Exchange Capacity and Base Saturation

The method described by Hendershot and Duquette [47] was used to analyse samples for Cation Exchange Capacity (CEC). For each sample, 2.00 g (± 0.01 g) of soil was weighed into a 50 mL centrifuge tube and 20.00 mL 0.1 M BaCl₂:2H₂O was added. Samples were

shaken on an oscillating shaker for 2 h, before being centrifuged at 4559 g for 10 min. Following this, samples were analysed using MP-AES for Na, Mg, Al, K, Ca, Mn and Fe. Effective CEC was calculated from this. Base Saturation (BS) was calculated as the percentage of CEC made up of base cations, i.e., Na, Mg, K and Ca. At least two reagent blanks were included in every analysis.

2.2.6. Total Carbon and Nitrogen

Total C and N of soils was analysed with a CN828 Elemental Analysis using a Combustion C and N analyser. Blanks and SRMs [48] were analysed with samples.

2.2.7. Particle Size Analysis

A laser diffraction method was used to analyse soils for particle size distribution. The method used for PSA was developed in collaboration by the University of Canterbury sedimentology and engineering departments, and follows the overview given by Bohren and Huffman [49] and Pansu and Gautheyrou [50]. Samples were deflocculated in 50 g L⁻¹ sodium hexametaphosphate (Calgon) on an oscillating shaker for 24 h. They were then vortexed and placed on a magnetic stirrer plate to ensure all particles were in suspension. The sample was then analysed using a Saturn DigiSizer 5200 using the Fraunhofer method [49]. Drops of the deflocculated sample were dropped into the liquid sample handling unit of the machine until the optimum obscuration was achieved (12–17%), and sample analysis was run. A Wentworth size chart was used to determine silt, sand and clay soil fractions, and soil was categorised according to USDA classification [51].

2.2.8. Elemental Determination

Macroelements (P, K, S, Ca, Mg, Al and Fe) were analysed using inductively coupled plasma mass spectrometry (ICP-MS) and microwave plasma atomic emission spectroscopy (MP-AES). Recoveries of SRMs ranged from 30 to 169% of certified values. Supplementary Materials Table S1 gives a complete list of the elements and their respective recoveries. Trace elements (Cr, Mn, Co, Ni, Cu, Zn, Ge, As, Sr, Mo, Pd, Ag, Cd, Te, Cs, Ce, Re, Ir, Hg and Pb) were analysed using ICP-MS, inductively coupled plasma optical emission spectrometry (ICP-OES) or MP-AES. Recoveries ranged from 37 to 164% of certified values. The limit of quantification for analyses was 0.01 mg kg⁻¹.

2.3. Statistical Analysis

R (version 4.1.0) [52] was used for all statistical analyses. One-way parametric analysis of variance (ANOVA) was carried out to compare means between sites using the package multcomp [53]. Where assumptions of normality were not met, data were log-transformed (natural log). When data did not meet assumptions of homoscedacity, a non-parametric permutation ANOVA was used; however, no difference was found between parametric and non-parametric tests with regard to the significance of results, and the parametric ANOVA was concluded to be robust. Tukey's Honest Significant Difference test was used to determine significant differences in soil variables between sites.

A principle component analysis (PCA) was used to determine which soil factors were the most important variants between sites and whether agrichemical-borne elements were important. Only variables which could be measured across all sites were included, so the PCA did not include Ca(NO₃)₂ extractable element concentrations, CEC, BS or particle size data. The PCA was run for total elemental concentrations and soil variables in R using the package factextra [54]. Incomplete sets of elemental data were removed prior to running the PCA.

Log-transformed data from each site were used to create correlation matrices and correlograms using the R packages Hmisc [55] and corrplot [56]. Any soil variables with missing or below-detection values were excluded from this analysis. A probability value of 0.01 (chosen over 0.05) was used to determine statistically significant correlations in this analysis, as there were multiple comparisons made; thus there was a higher chance of in-

correctly identifying significant relationships between variables (Type 1 error). Significance codes were used to identify statistically significant correlations: S* indicates $p < 0.01$, while S** indicates $p < 0.001$.

3. Results and Discussion

3.1. General Soil Properties and Soil Carbon

Soil samples from all sites were acidic, with pH ranging from 4.6 to 5.4 (Table 2). This is within the range of 4.5–5.5 and comparable to the mean of 5.1 previously reported in oil palm plantations in Gunung Leuser National Park [37,38]. The rubber plantation soils (pH 5.2) were within the preferred pH range for *H. brasiliensis* of 5.0–6.0 [37]. Under acidic soil conditions, Al becomes increasingly soluble as Al^{3+} : this is supported by a strong negative correlation between $Ca(NO_3)_2$ extractable Al and pH ($r = -0.86$ S**) for all soils. In kaolinitic soils at $pH < 5.5$, Al^{3+} and Mn^{2+} toxicity may inhibit plant growth, making agricultural production challenging [18,57].

Table 2. Mean general properties of soils at each site including major soil elements (standard error of the mean in parentheses). Sites that share the same superscript letter(s) for a single variable are not significantly different from each other.

Site		A (n = 25)	B (n = 25)	C (n = 10)	D (n = 25)	Rubber Plantation (n = 32)
Particle size distribution	Sand (%)	8.3(1.4) ^a	5.6(1.0) ^a	27(1.3) ^b	50(2.5) ^b	—
	Silt (%)	58(1.4) ^b	55(0.99) ^b	57(1.3) ^b	35(1.8) ^a	—
	Clay (%)	33(2.2) ^b	40(1.7) ^b	17(1.3) ^a	15(0.92) ^a	—
pH		5.4(0.11) ^c	4.8(0.061) ^{ab}	5.1(0.097) ^{bc}	4.6(0.047) ^a	5.2(0.076) ^c
CEC (cmol (+) kg ⁻¹)		25(1.5) ^c	30(0.80) ^d	4.3(0.63) ^a	10(0.67) ^b	—
BS (%)		70(5.5) ^c	33(4.7) ^b	43(8.5) ^{bc}	21(3.4) ^a	—
Total Al (mg kg ⁻¹)		29,207(868) ^b	31,022(1144) ^b	32,307(1241) ^b	25,174(1855) ^a	67,371(2379) ^c
$Ca(NO_3)_2$ extractable Al (mg kg ⁻¹)		110(24) ^{ab}	308(30) ^c	36(7.1) ^a	194(16) ^b	—
Total Fe (mg kg ⁻¹)		28,530(696) ^c	31,149(1017) ^c	23,084(420) ^b	16,847(1007) ^a	23,921(334) ^b
$Ca(NO_3)_2$ extractable Fe (mg kg ⁻¹)		0.42(0.095) ^a	0.64(0.18) ^a	0.045(0.015) ^a	4.2(0.95) ^b	—

There were significant differences in soil texture between sites: soils at Site C were silt loams while soils at Site D ranged from silt loam through to sandy loam (Figure 2). Soils at Sites A and B contained significantly more clay than other sites. The sand, silt and clay fractions of soils ranged from 15 to 40%.

The soils under rubber production had significantly less C (1.3%) than the palm sites (2.0–3.3%). The C concentrations for the soils of the four palm sites presented in Table 3 were comparable to the mean C concentration of 2.1% reported for tropical Oxisols [58]. The significantly lower C concentration under the rubber plantation may be a result of soil type, as tropical Ultisols typically have a lower mean C (1.9%) [58]. The C concentrations at Sites A–D were similar to C concentrations of Indonesian oil palm soils in Gunung Leuser National Park area reported in the literature: Asnur [37] reported the majority of soils in a palm production area within Leuser were within the range of 1–2%, while Wasis [38] reported a mean organic C concentration of 0.57%, decreased from 7.7% following conversion from forest to oil palm. This loss in organic C is typical of soils following conversion to agriculture [59], particularly in tropical regions [20] and specifically in Sumatra [60]. However, the optimal soil C range for oil palm production is 1.5–2.0% according to Corley and Tinker [3], and 1.2–1.5% according to Goh and Po [61]. In this case, any reduction in soil C following agricultural conversion may be beneficial for palm production, with unfavourable implications for climate change [20,59].

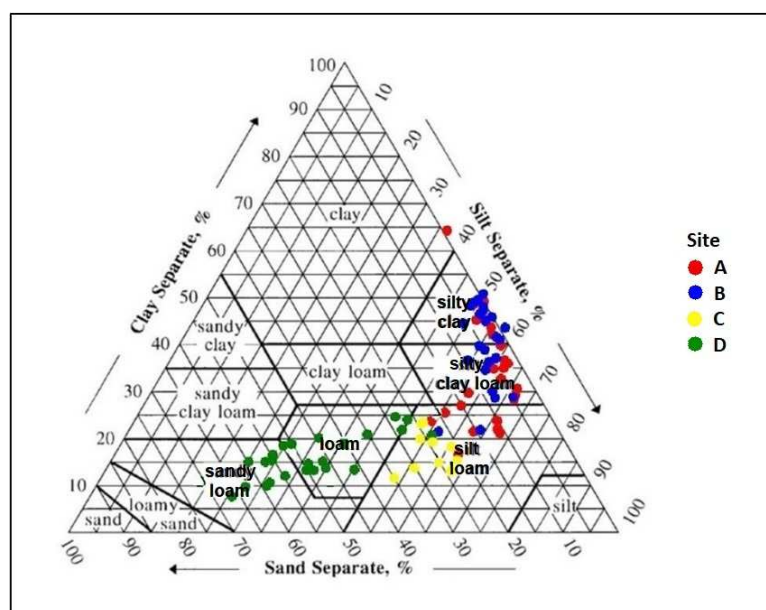


Figure 2. Soil texture classes of soil samples from palm sites, according to the USDA classification.

Table 3. Mean soil characteristics, including total and $\text{Ca}(\text{NO}_3)_2$ extractable plant macronutrients, at each site (standard error of the mean in parentheses). Sites that share the same superscript letter(s) for a single variable are not significantly different from each other.

Site	A (n = 25)	B (n = 25)	C (n = 10)	D (n = 25)	Rubber Plantation (n = 32)
Total C (%)	3.2(0.23) ^c	3.3(0.23) ^c	2.1(0.11) ^b	2.0(0.14) ^b	1.3(0.027) ^a
Total N (%)	0.23(0.023) ^c	0.23(0.020) ^c	0.035(0.0090) ^a	0.021(0.0057) ^a	0.12(0.0032) ^b
C:N ratio	14	14	60	95	11
Total P (mg kg^{-1})	296(21) ^b	305(17) ^b	299(13) ^b	118(30) ^a	323(14) ^b
$\text{Ca}(\text{NO}_3)_2$ extractable P (mg kg^{-1})	0.030(0.0040) ^b	0.021(0.0029) ^{ab}	0.037(0.0031) ^b	0.013(0.0033) ^a	—
Total K (mg kg^{-1})	4252(303) ^d	2316(106) ^c	1883(176) ^{bc}	778(67) ^a	1612(25) ^b
Total S (mg kg^{-1})	266(16) ^c	358(139) ^{bc}	170(9.5) ^b	116(7.6) ^a	306(6.5) ^c
$\text{Ca}(\text{NO}_3)_2$ extractable S (mg kg^{-1})	2.6(1.3) ^a	1.8(0.85) ^a	0.45(0.39) ^a	1.1(0.42) ^a	—
Total Ca (mg kg^{-1})	9422(1400) ^d	5468(996) ^{cd}	2439(564) ^{bc}	1286(416) ^a	1202(117) ^{ab}
$\text{Ca}(\text{NO}_3)_2$ extractable Ca (mg kg^{-1})	65(5.6) ^c	6.6(2.4) ^b	0.0001(<0.001) ^{ab}	1.9(1.9) ^a	—
Total Mg (mg kg^{-1})	3005(156) ^c	2637(101) ^c	2747(405) ^c	1023(102) ^a	1185(49) ^b

Cation exchange capacity was significantly different between all four palm sites, in the order Site C < Site D < Site A < Site B. The CEC of the ex-palm site (Site D) ($10 \text{ cmol (+) kg}^{-1}$) was comparable to published oil palm soil data of $8.2 \text{ cmol (+) kg}^{-1}$ [38], while abandoned sites (Sites A and B) (25 and $30 \text{ cmol (+) kg}^{-1}$, respectively) were closer to published CEC data for natural forest ($26 \text{ cmol (+) kg}^{-1}$). All values were higher than those reported from an oil palm plantation in Western Ghana of 3.0 and $2.3 \text{ cmol (+) kg}^{-1}$ [62]. There is disagreement in the literature regarding the optimal soil CEC for oil palm production. Optimal ranges vary from 12 to $15 \text{ cmol (+) kg}^{-1}$ [61,62] to $>24 \text{ cmol (+) kg}^{-1}$ [3].

Both the clay content and the C concentration of soil samples increased in the order Site D < Site C < Site A < Site B (Table 3 and Figure 2). There was a positive correlation between the clay content of soils and C, which is consistent with clay minerals protecting organic matter from degradation [63,64], effectively affording soils with a higher clay content a higher C-holding capacity [65]. Across all soils, there were positive correlations between

C and clay content ($r = 0.43$ S**), C and CEC ($r = 0.51$ S**), and clay content and CEC ($r = 0.68$ S**).

3.2. Plant Macronutrients

The average soil N ranged from 0.021% (ex-oil palm plantation, Site D) to 0.23% (abandoned sites, Sites A and B) (Table 3). The optimal soil N concentrations for oil palm growth ranged from 0.12% [61] to >0.15% [23]. The active site (Site C) did not contain higher N concentrations relative to the ex-oil palm site (Site D) and contained significantly lower N than the abandoned sites A and B. This falsified our hypothesis that the active site would contain higher N concentrations than the abandoned sites. Soils at both smallholder and ex-plantation sites (Sites C and D) were deficient in N, which would have contributed to reduced yields of palm oil. This is supported by the high C:N ratios at these sites of 60 and 95, respectively, which indicate that N may undergo rapid immobilisation in these soils [66]¹. In comparison, oil palm plantation soils in Nigeria had C:N ratios of 5 [67]. Nitrogen deficiency has been reported in smallholder plantations in Indonesia similar to Site C and attributed to sub-optimal fertiliser applications [23]. It is likely that the soils of the ex-plantation and smallholder sites (Sites C and D) may have experienced N depletion following a change in oil palm cultivation and subsequent inappropriate nutrient management. Wasis [38] reported a decrease in soil N from 0.32% to 0.06% following agricultural conversion in the Leuser region.

The average total P in soils ranged from 118 mg kg⁻¹ (Site D) to 323 mg kg⁻¹ (rubber plantation) (Table 3). The range of mean P concentrations in all soils was low compared to the world average of 650 mg kg⁻¹ [68] and to the range of 200–1500 mg kg⁻¹ [69]. Deficiencies in soil P exist in smallholder plantations in Indonesia [23], and P deficiency is common in crops grown on weathered acidic soils including Acrisols/Oxisols and Ultisols [70]. These soils typically have capacity for high P fixation, resulting in reduced plant uptake of P. Fertilisers are usually scattered on the soil surface in oil palm plantations around the base of palms. This, combined with management practices such as weed clearing and growing on landscapes with a >6° slope has high potential to result in soil and fertiliser run-off during rainfall events and may limit production [3,26,38,71–73]. As Sumatra experiences ca. 3000 mm of rainfall annually [74], high erosion rates are common in this region [75]. Soil erosion in oil palm plantations removes topsoil as well as soil P and may lead to eutrophication of nearby surface water. Phosphorus limitation in cereal crops has been shown to lead to global yield gaps [76], and generally, P deficiency is recognised as an important factor affecting crop yields [77]. Following this, it is likely that the low P concentrations in the oil palm soils may be contributing to yield limitations at these sites.

Potassium and Mg at all sites were below global average soil concentrations of 14,000 and 5000 mg kg⁻¹, respectively [68]. Low K and Mg concentrations are typical of weathered, acidic soils with low-K parent materials and high K and Mg leaching, due to high precipitation [70]. Woittiez et al. [23] reported K deficiencies in >80% of smallholder plantation soils surveyed in Indonesia, as well as visual signs of Mg deficiency. Globally, K outputs from soil exceed K inputs, and this is especially pronounced in Global South countries where access to K fertilisers is more limited than in the Global North [78]. Woittiez et al. [23] identified K deficiency as a potential leading cause of sub-optimal yields in smallholder oil palm plantations and attributed this to the use of subsidised NPK fertilisers with poor nutrient balances for oil palm requirements. It is possible that a lack of access to K fertilisers adequate for palm and rubber production is responsible for the low K concentrations in soils from the palm and rubber sites.

3.3. Total Trace Element Concentrations

Except for elevated concentrations of Zn and Pb, TE concentrations (Table 4) in palm soils were generally similar to background concentrations. No concentrations of TEs in palm soils exceeded SGVs for agricultural soils.

Table 4. Mean TE concentrations of soils of each site (standard error in parentheses). Mean concentrations in mg kg^{-1} . Sites that share the same superscript letter(s) for a single variable are not significantly different from each other.

Site	A (n = 25)	B (n = 25)	C (n = 10)	D (n = 25)	Rubber Plantation (n = 32)
Cr	34(1.1) ^c	25(0.90) ^b	27(1.4) ^{bc}	50(3.7) ^d	5.03(0.20) ^a
Mn	281(56) ^b	519(87) ^c	876(82) ^d	28(3.7) ^a	2995(52) ^e
Co	19(2.3) ^c	19(1.5) ^c	16(0.36) ^c	3.4(0.42) ^a	8.9(0.12) ^b
Ni	29(2.0) ^d	30(1.5) ^d	13(0.61) ^c	7.9(0.58) ^b	4.5(0.40) ^a
Cu	19(1.4) ^c	38(0.86) ^d	5.6(0.69) ^b	1.1(0.22) ^a	6.6(0.49) ^b
Zn	91(3.7) ^b	91(3.8) ^b	75(5.2) ^b	19(1.4) ^a	213(5.7) ^c
Ge	0.86(0.051) ^b	1.0(0.79) ^b	1.05(0.36) ^b	0.54(0.028) ^a	1.7(0.034) ^c
As	3.8(0.14) ^{bc}	4.3(0.16) ^c	9.0(0.59) ^d	3.7(0.28) ^{ab}	3.1(0.12) ^a
Sr	24(2.2) ^c	14(1.4) ^b	48(13) ^d	6.1(0.67) ^a	4.3(0.16) ^a
Mo	1.5(0.17) ^b	2.0(0.15) ^c	0.13(0.0068) ^a	0.30(0.080) ^a	0.095(0.0038) ^a
Cd	0.14(0.026) ^{bc}	0.087(0.024) ^{ac}	0.085(0.029) ^{ab}	0.026(0.0073) ^a	0.16(0.012) ^b
Ce	22(1.9) ^a	23(2.5) ^a	55(1.6) ^b	17(0.83) ^a	139(1.9) ^c
Pb	16(0.70) ^b	17(1.2) ^b	28(1.8) ^c	5.8(1.2) ^a	51(0.53) ^d

Abandoned and smallholder sites (Sites A, B and C) all contained soil concentrations of Zn and Pb above background levels of 50 and 10 mg kg^{-1} , respectively [68]. Although elevated, concentrations of Zn and Pb did not surpass SGVs. However, Zn concentrations were present at these three sites at >50% of the limits (a benchmark used in environmental monitoring) [79] for Denmark and the EU, indicating that accumulation should be monitored at the remaining active smallholder site (Site C) and further Zn inputs to soils should be limited to prevent accumulation which could impede production. Our concentrations were comparable to published values of 99 mg kg^{-1} Zn in Malaysian palm soils [80] and 14 mg kg^{-1} Pb in Nigerian palm plantation soils [81]. Soils from the smallholder site (Site C) also contained As above the background level of 5 mg kg^{-1} [82], but below SGVs for the US (18 mg kg^{-1}), Canada (17 mg kg^{-1}) and New Zealand (20 mg kg^{-1}) [83]. Again, as As in the smallholder site (Site C) soil was present at >50% SGVs, inputs should be monitored here. No reports could be identified for the comparison of As in palm plantation soils. The natural background concentration of Cu in soil is 20 mg kg^{-1} [68], which was surpassed in soils at one abandoned site (Site B). The concentrations here breached 50% of SGV levels for Canada (63 mg kg^{-1}) and the US (70 mg kg^{-1}) [83]. Copper was reported up to 69 mg kg^{-1} in Nigerian palm plantations [81]. The elevated Cu, Zn, As and Pb were likely a result of agrichemical use during palm production at these sites. Zinc, As and Pb are all common contaminants of phosphate fertilisers [12], while Cu is a common active ingredient in pesticides used in horticultural production [84], and in particular, the production of oil palm [13,25]. One abandoned site (Site B) may have had higher rates of fungicide application, leading to its significantly higher soil Cu concentrations.

Deficiencies in Mo, defined as <2 mg kg^{-1} [82], were present at all sites except one of the abandoned sites (Site B). Our total Mo concentrations were comparable to those of Golow et al. [85] from palm plantations in Ghana. Several TEs measured in our soils were present at concentrations less than or comparable to natural background levels in soils. These included Cr (5.03–50 mg kg^{-1}), Co (3.4–19 mg kg^{-1}), Ni (4.5–30 mg kg^{-1}), Ge (0.54–1.7 mg kg^{-1}) and Cd (0.026–0.16 mg kg^{-1})—all non-essential plant TEs—with average backgrounds of 100, 40, 22, 2 and 0.06 mg kg^{-1} , respectively [68,86–88]. These measured TE concentrations were comparable to those reported in palm plantation soils in Nigeria, Ghana and Papua New Guinea [80,81,89,90].

For all TEs except As, Mo, Cd and Ce, soils from the ex-plantation site (Site D) had significantly lower mean total concentrations compared to other palm sites (Sites A, B and C). Despite being present in higher concentrations compared to some other sites, these

TEs were below background concentrations in the ex-plantation site (Site D) (6, 2, 0.06 and 49 mg kg⁻¹ for As, Mo, Cd and Ce, respectively) [68,91]. In general, the ex-plantation site (Site D) had no elevated concentrations of TEs above expected background concentrations. Trace elements at this site were lower compared to the other sites, as it is no longer in production and the trees have been cleared—a process which may have resulted in the erosion and run-off of topsoil [92] and any associated TEs contained there [75].

There were significant differences between rubber and palm sites for total Cr, Mn, Co, Ni, Zn, Ce and Pb, presented in Table 4. Concentrations of Cr and Ni were lower in the rubber plantation compared to all four palm soils, while Mn, Zn, Ce and Pb were higher in the rubber plantation. The mean Mn, Zn, Ce and Pb concentrations in the rubber plantation (2995, 213 and 139 mg kg⁻¹, respectively) were higher than global background levels (850, 50, 49 and 10 mg kg⁻¹, respectively) [68,91]. The Mn concentration present here was higher than would be expected from geogenic sources [93], while Zn concentrations at this site exceeded the SGVs for agricultural land from Canada (200 mg kg⁻¹), the EU (94 mg kg⁻¹ added Zn)², the US (160 mg kg⁻¹) and Denmark (100 mg kg⁻¹) [83]. These Zn concentrations may be phytotoxic, and this may limit production at the rubber site [94]. The elevated Mn and Zn in the rubber plantation may be a result of fungicides—namely mancozeb—used to treat pests including *Corynespora cassiicola* which causes leaf fall disease in rubber trees [95]. Mancozeb is an ethylenebisdithiocarbamate compound containing Mn and Zn as active ingredients [96,97]. Dithiocarbamate compounds (including Zn dithiocarbamate) [98] are used in rubber production to accelerate vulcanisation (hardening) [99]; thus if used in the rubber plantation, they may have led to Mn and Zn inputs in soils through direct prolonged or repeated accidental or careless exposure of these compounds to soils.

While Ce has no specified toxicity thresholds in soil [100], it has been found to decrease germination speed and reduce plant biomass, particularly in tropical acidic soils [101], and to be increasingly taken up into the roots and shoots of plants as soil pH decreases [102]. An HC₅ (hazardous concentration for 5% of plant species) value of 281.6 mg kg⁻¹ was calculated for tropical Oxisols and Inceptisols [101]. As such, Ce concentrations in soils from the rubber plantation may not yet impact production; however, they have potential to do so in the future if accumulation continues. Lead concentrations in the rubber plantation, while elevated—likely as a result of phosphate fertiliser use [12,103]—did not breach international SGVs³ (70 mg kg⁻¹ in Canada, 120 mg kg⁻¹ in US, 166 mg kg⁻¹ added Pb in EU and 300 mg kg⁻¹ in New Zealand) [83] and are unlikely to affect production; however, they may pose issues in the future if allowed to accumulate past SGVs.

Given the low pH of the soils, both non-essential and essential cations will be relatively soluble [104]. Ca(NO₃)₂ extractable concentrations of TEs, used to calculate K_D values, are presented in Supplementary Materials Table S2. When calculated K_D values were compared to K_D values for arable or pasture soils, Mn, Ni, Zn, Sr, Cd, Ce and Pb (arable/pasture soil K_D: 22,000, 3000, 6000, 190, 3000, 88,000 and 25,000, respectively) [104,105] were more soluble in palm soils at all sites (Table 5). Cobalt was more soluble in abandoned and ex-plantation sites (Sites A, B and D) (arable soil K_D 1800) [104], while Mo was more soluble at the smallholder and ex-plantation sites (Sites C and D) and less soluble at abandoned sites (Sites A and B) compared with arable soils (K_D 240) [104]. Toxicity of these TEs may occur at lower concentrations than SGVs suggest in these palm soils due to the acidic soil environment and associated increase in solubility and plant uptake. Additionally, P may become even less plant available in these soils due to its strong specific adsorption onto oxyhydroxides which occurs in acidic environments [69].

Chromium was less soluble in palm soils compared with arable soils (K_D 270) [104]. Compared to other TEs, Cu was less soluble in palm soils, particularly at the smallholder site (Site C). This may be due to Cu association with organic matter and Fe and Al oxides in these soils, which strongly bind Cu, decreasing its mobility [106]. Therefore, Cu may be less available to plants, and the exceedance of SGVs at Site B may not result in any negative effect on oil palm yield, despite high total concentrations.

Table 5. Soil adsorption coefficients—or K_D —of TEs at each site under oil palm production. K_D values for Cd and Mn unable to be quantified.

Site	A	B	C	D
Cr	3179	2651	2900	5849
Co	279	195	2344	156
Ni	46	26	1389	25
Cu	904	358	5643	933
Zn	72	42	172	52
Ge	649	128	481	148
As	127	46	150	61
Sr	23	26	83	35
Mo	420	1615	43	28
Ce	658	102	615	106
Pb	175	76	257	37

Total and $\text{Ca}(\text{NO}_3)_2$ extractable concentrations of Pd, Te, Re, Ir and Hg are presented in Supplementary Materials Table S3. These TEs were present in concentrations $<0.1 \text{ mg kg}^{-1}$ and were considered to have no environmental consequences. Total Ag and Cs for the rubber plantation soils are also presented in Supplementary Materials Table S3.

3.4. Factors Controlling the Variation between Sites

Principal component one (PC1) explained 53.9% of the variation between soils and was dominated by Mn, Zn, Pb, Ce and Cr in descending order (Figure 3a). Principal component two (PC2) explained 31% of the variance and was dominated (in descending order) by Ca, Cu, Ni, Sr, Co and Ce. The five sites formed distinct groups in the PCA plot (Figure 3b), with some overlap occurring between the two adjacent abandoned sites (Sites A and B). Soils from the rubber plantation had distinct chemistry, separating it from the four sites under palm production. This is attributed to the history of land use and production.

The chemistry of the oil palm sites (Sites A, B, C and D) separated out according to a combination of edaphic and anthropogenic factors when a PCA was carried out using only soils from the four palm sites (see Supplementary Materials Figure S1 for PCA results of palm sites including general soil parameters).

3.5. Intra-Site Correlations

Correlograms for all five sites are presented in Figure 4. All correlations presented are statistically significant ($p < 0.01$). Soil variables are grouped by hierarchical clustering, whereby similarly behaving variables which share common correlations are grouped closer together.

At abandoned and smallholder sites (Sites A, B and C), there was a common positive correlation between P and C ($r = 0.66 \text{ S}^{**}$, 0.64 S^{**} and 0.79 S^* , respectively). At abandoned sites (Sites A and B), P was positively correlated with N ($r = 0.62 \text{ S}^{**}$ and 0.56 S^* , respectively). As organic P in soils positively correlates with organic matter, the correlations at the smallholder and abandoned sites indicate that soil P at these sites was mostly associated with organic matter in the soil and was unavailable to plants [107]. Carbon, N and S were mutually positively correlated at all palm sites ($0.63 < r < 0.94 \text{ S}^* \text{--} \text{S}^{**}$), indicating that most of the N and S in soils at these sites were also organically associated. In the rubber plantation, C and N positively correlated ($r = 0.61 \text{ S}^{**}$); however, there were no other significant correlations between C, N, P and S. This indicates that in contrast to the palm sites, N, P and S in soils from the rubber plantation were associated with the mineral phase of the soil and may have been more plant available.

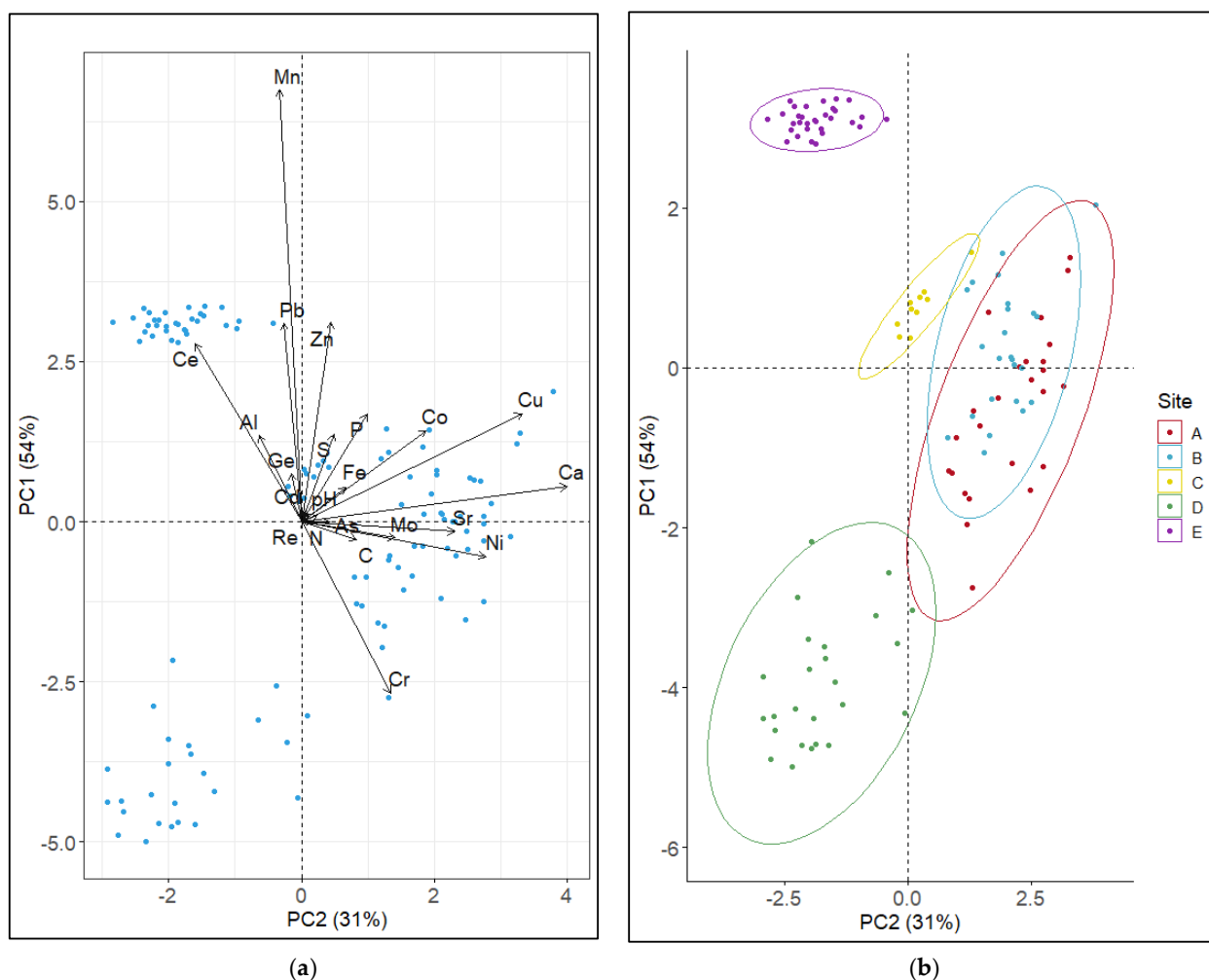


Figure 3. (a) Loading plot showing variables and their influence on principal components 1 and 2. Figure 3b (b) PCA plot with sites identified by colour. Ellipses represent 95% confidence around the mean.

There is some evidence of agricultural correlation with TEs in the palm plantation soils when P is used as a proxy for agriculture. Phosphorus correlated positively with Co ($r = 0.52 S^*$), Mn ($r = 0.58 S^*$), Zn ($r = 0.51 S^*$) and Cd ($r = 0.72 S^{**}$) at one abandoned site (Site A), with Mo at the smallholder site (Site C) ($r = 0.81 S^*$) and with Sr ($r = 0.67 S^{**}$) at the ex-plantation site (Site D). All of these TEs are present within fertilisers, and thus these correlations are typical of past or present agricultural sites [12,108]. Where P does not correlate with TEs, we reject the hypothesis that TEs are fertiliser-derived and conclude that any present are likely geogenic.

Correlations existed between variables which would typically be expected in soils [109,110]: BS positively correlated with pH at all four palm sites ($0.59 < r < 0.91 S^*-S^{**}$). Although not shown in Figure 4, soil pH also correlated negatively with $\text{Ca}(\text{NO}_3)_2$ extractable Al at abandoned sites (Site A $r = -0.93 S^{**}$, Site B $r = -0.89 S^{**}$) and the smallholder site (Site C $r = -0.95 S^{**}$), and correlated negatively with extractable Fe at both abandoned sites (Site A $r = -0.74 S^{**}$, Site B $r = -0.66 S^{**}$). Calcium positively correlated with both BS ($0.88 < r < 0.96 S^{**}$) and pH ($0.71 < r < 0.99 S^{**}$) at all palm sites.

Concentrations of $\text{Ca}(\text{NO}_3)_2$ extractable cationic TEs including Cr, Ni, Cu, Zn and Cd (see Supplementary Materials Table S2) typically negatively correlate with pH, as increasing soil pH can lower the availability of TEs in soil solution [111,112]. While $\text{Ca}(\text{NO}_3)_2$ extractable TEs were not included in the correlograms, this was the case at one abandoned site (Site A), where pH negatively correlated with $\text{Ca}(\text{NO}_3)_2$ extractable

Cr ($r = -0.51 S^*$), Ni ($r = -0.65 S^{**}$), Zn ($r = -0.85 S^{**}$) and Ce ($r = -0.55 S^*$). At the other abandoned site (Site B), pH negatively correlated with $\text{Ca}(\text{NO}_3)_2$ extractable Cu ($r = -0.55 S^*$) and Zn ($r = -0.58 S^{**}$), while at the smallholder site (Site C), pH negatively correlated with $\text{Ca}(\text{NO}_3)_2$ extractable Ge ($r = -0.86 S^*$) and Ce ($r = -0.87 S^*$).

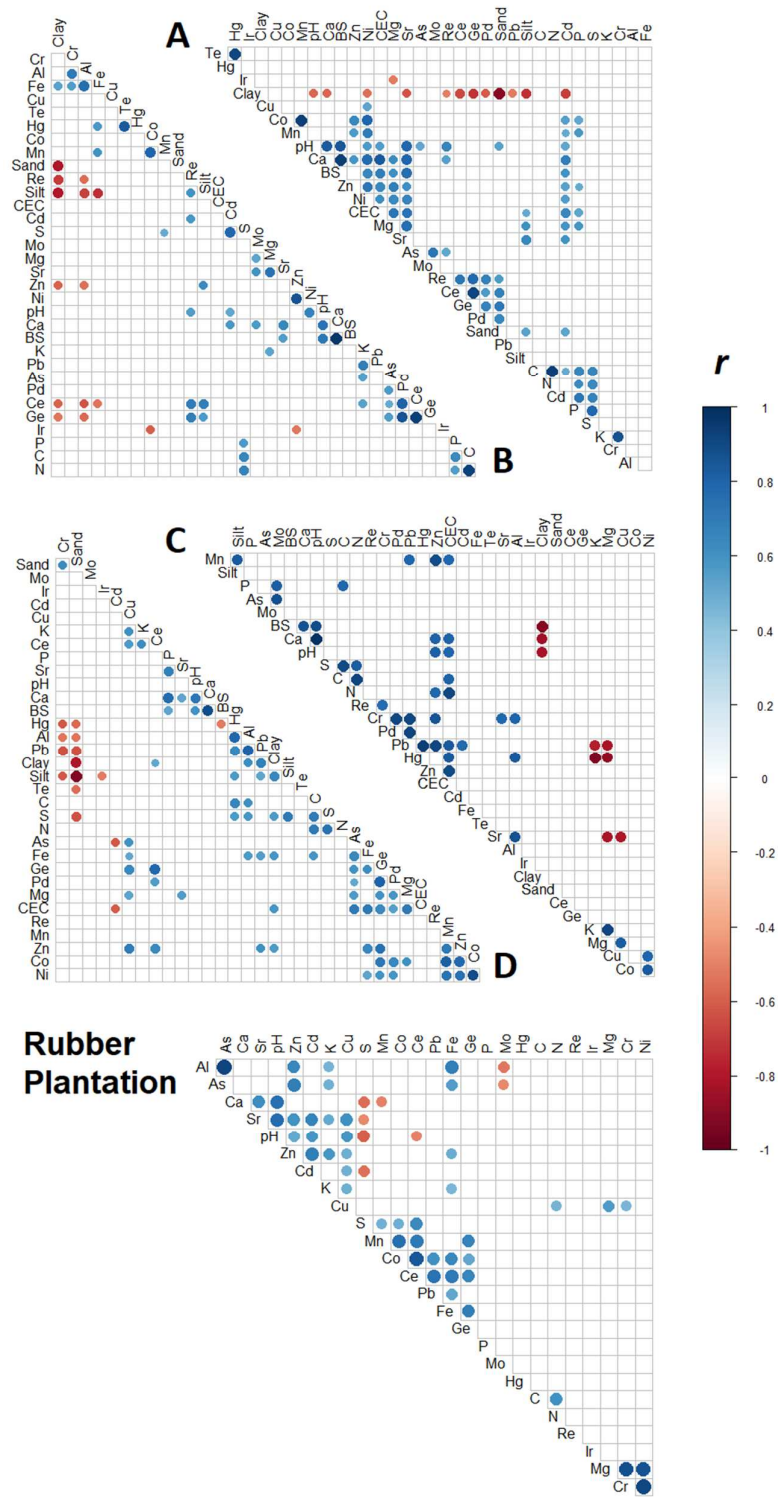


Figure 4. Correlograms showing intra-site correlations ($p < 0.01$) between variables, grouped by hierarchical clustering. Plots (A–D) contain data from plantations (A–D), while the bottom plot contains data from the rubber plantation.

4. Conclusions

The chemical composition and plant nutrient status of the soils we have investigated under oil palm and rubber production have shown that these soils had low fertility and were nutrient poor. Generally, they were acidic with low P concentrations. Soil N, P and S were associated with organic matter in palm production soils, which was low compared to published data on forest soils from this region. Production at palm sites is likely to be severely limited by a deficiency in N, P, K, Mg and Mo in soils. Consistent with our hypothesis, there was evidence of agriculturally derived TEs accumulating in both rubber and palm soils. Manganese, Zn, Ce and Pb were significantly higher in rubber soils, likely due to the application of these TEs as ingredients or contaminants in agrichemicals at this site. These TEs may already limit production. In addition, palm soils contained elevated concentrations of Cu, Zn, As and Pb. Based on K_D values, most TEs were more soluble in soils under oil palm production compared to other arable production, likely due to the low pH of these tropical soils. Consequently, toxicity thresholds may be reached at lower concentrations than SGVs suggest. Soils under rubber production were chemically distinct from soils under palm production and the chemistry at palm sites was consistent with that of soils with a short fertiliser history. While our sites varied in terms of landscape elements and prior or current management, the trends in the data were consistent. This indicates that nutrient deficiencies may be present in oil palm production soils throughout Indonesia. Correction of nutrient deficiencies in these oil palm plantations would necessitate significant fertiliser inputs in soils which would be of considerable cost and negatively affect the economic revenue gained through oil palm production. These inputs would also lead to increased TE loadings in soils, exacerbating issues of TE accumulation. As Cu, Zn, As and Pb were already elevated at both active and former oil palm production sites, likely as a result of fertiliser use, these TEs in particular are likely to accumulate past SGVs and eventually limit production with increased fertiliser inputs. This has implications for the sustainability of a regionally significant production system across Southeast Asia. Subsidised oil palm production may not be economically viable, but it still results in the degradation of significant areas of tropical ecosystems for production that are challenged by low soil fertility, and sometimes abandoned. Further work should determine whether oil palm production would be economically viable without subsidies, particularly on soils converted from primary forest. Such an analysis should include quantification of the costs and ecological impacts of applying sufficient fertiliser to enable economically viable palm production, including the resultant TE loading to soils. This analysis should consider local ecosystem values and the opportunity costs associated with the loss of forest ecosystems that provide numerous ecosystem services.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/land12122144/s1>, Table S1: SRM recoveries of elements; Table S2: $\text{Ca}(\text{NO}_3)_2$ extractable concentrations of trace elements in soils under palm production; Table S3: Additional trace elements analysed; Figure S1: PCA results of four palm sites including general soil parameters.

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Notes

- ¹ Mineral N (NH₄ and NO₃) could not be measured due to the inability to import fresh soil into our laboratory.
- ² This SGV applies to soil with pH 5.5, CEC 15 cmol (+) kg⁻¹ and 15% clay content.
- ³ SGVs specific to Indonesia were not identified.

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