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Title: Soil fertility changes following conversion of grassland to oil palm

Running head: Soil fertility changes under oil palm

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Summary text:

Oil palm plantations are expanding rapidly throughout the humid tropics. Conversion of grasslands is environmentally preferable to conversion of forests, but the effects on soil fertility of grassland-to-oil palm conversion are unknown. Our assessment of the impact on soil fertility of up to 25 years of oil palm cultivation on prior grasslands in Papua New Guinea showed ~~some~~ slight acidification and loss of ~~cations~~exchangeable magnesium. These impacts can be readily managed to ensure long-term sustainability of soil fertility under oil palm.

Soil fertility changes following conversion of grassland to oil palm

Nelson PN, Banabas M, Nake S, Goodrick I, Webb MJ, Gabriel E

Abstract

Impacts of palm oil industry expansion on biodiversity and greenhouse gas emissions might be mitigated if future plantings replace grassland rather than forest. However, the trajectory of soil fertility following planting of oil palm on grasslands is unknown. We assessed the changes in fertility of sandy volcanic ash soils (0-0.15 m depth) in the first 25 years following conversion of grassland to oil palm in smallholder blocks in Papua New Guinea, using a paired-site approach (9 sites). There were ~~consistent and~~ significant decreases in soil pH (pH 6.1 to 5.7) and exchangeable magnesium content following conversion to oil palm but no significant change in soil carbon contents. Analyses to 1.5 m depth at 3 sites indicated little change in soil properties below 0.5 m. There was considerable variability between sites, despite them being in a similar landscape and having similar profile morphology. Soil Colwell P and exchangeable K contents decreased under oil palm at sites with initially high contents of C, N Colwell P and exchangeable cations. We also assessed differences in soil fertility between soil under oil palm (established after clearing forest) and adjacent forest at two sites. At those sites there was significantly lower soil bulk density, cation exchange capacity and exchangeable calcium, magnesium and potassium under oil palm, but the differences may have been due to less clayey texture at the oil palm sites than the forest sites. ~~The soil acidification and loss of essential cations observed following conversion of grassland to oil palm on these soils could be readily prevented or remedied with changed management~~Cultivation of oil palm maintained soil structure and fertility in the desirable range, indicating that it is a sustainable endeavor in this environment.

Additional key words: soil acidification, sustainability, soil degradation, land use effects on soil, Papua New Guinea, exchangeable cations

Introduction

Oil palm (*Elaeis guineensis* Jacq.) and other crops are expanding in the tropics, often at the expense of forest (Koh and Wilcove 2008). While clearing forest provides income from timber and initially fertile soils for productive agriculture, this practice is becoming less desirable because of negative impacts on biodiversity and greenhouse gas emissions (Sayer et al. 2012). Grasslands are seen as desirable locations for the expansion of oil palm plantings over the coming decades (Corley 2009; Chase and Henson 2010; Wicke et al. 2011). However, successful establishment of these plantations and maintenance of their productivity will rely on soil fertility being maintained or improved. There is very little information on whether soil fertility improves or declines when grasslands are converted to oil palm. Conversion of grasslands to ~~field crops~~sugarcane can lead to a decline in soil fertility (Hartemink 1998), but replacement of grassland by trees has been shown to improve soil properties, particularly organic matter content, in many instances (van der Kamp et al. 2009; Don et al. 2011; Jagoret et al. 2012). The oil palm-cover crop system compares favourably to alternative crops in terms of its effects on soil fertility, due to near-continuous soil cover, high net primary production, no need for soil tillage, little compaction and low requirements for fertiliser and pesticide inputs (Henson 1994; Corley and Tinker 2003; de Vries et al. 2010). However, soil acidification and structural deterioration have been observed following replanting of oil palm on savannah (Dufour and Olivin 1985; Caliman et al. 1987) and a decline in soil carbon stocks~~-~~ has been found after conversion of Amazonian pasture to oil palm (Frazão et al. 2013). In other studies, soil organic matter contents have been found to remain stable or increase under oil palm (Haron et al. 1998; Law et al. 2009; Smith et al. 2012; Goodrick et al. ~~2013~~2014). There are also limited studies on changes in soil fertility when forest is converted to oil palm. In general, soil fertility tends to remain stable after forest is converted to oil palm, but few rigorous studies have been carried out, and changes undoubtedly depend on soil type and other environmental conditions (Corley and Tinker 2003).

To maintain or improve soil fertility in agricultural systems we require an understanding of the processes and rates of change involved under current management regimes. In this study, we tested the hypothesis that there is no change in soil fertility following conversion of grassland to oil palm. We used a paired-site approach, measuring soil properties in oil palm plantations established on grassland (between 6 and 25 years previously) and in adjacent remnant grassland, and examining the difference between the two as a function of time since the oil palm had been planted. In addition, we assessed changes in soil fertility following conversion of forest to oil palm over a similar time frame, but with fewer sites.

Methods

Study sites

The study was carried out at 11 sites in Papua New Guinea, of which 9 were grassland-to-oil palm sites in Oro Province, and two were forest-to-oil palm sites in the Hoskins district of West New Britain Province (Table 1). Each site had paired sampling areas, one in an oil palm smallholder block and the other in adjacent grassland or forest, which was assumed to have the same soil properties as the oil palm block at the time of planting. Soil sampling and analysis was initially carried out for 16 grassland-to-oil palm sites with oil palm ages ranging from 1 to 25 years. However, $\delta^{13}C$ analyses of all samples indicated that 7 of the sites had been forest at some time in the past ($\delta^{13}C$ <-18‰). Examination of aerial photos taken in 1953 further indicated that those sites had not been uniform grassland at that time. Therefore, a paired comparison might not be valid at those sites, as we could not be sure that the oil palm and adjacent grassland were initially under the same vegetation. Data from those sites were excluded from further analysis and are not presented here (they are available from the author on request). The grassland and forest sampling areas were as close as possible to their paired oil palm block.

All study sites have humid tropical climate and recent volcanic ash soils (Bleeker, 1983). At the Oro sites, annual rainfall is approximately 2380 mm (Sangara, 1986-2005), with a wet season in October-May and a dry season in June-September (average monthly rainfalls of 244 mm and 107 mm, respectively). At the Hoskins sites, annual rainfall is approximately 3248 mm (Kumbango, 1997-2004), with monthly averages of 334 mm in October-May and 145 mm in June-September. The Oro sites were in a flat landscape with Vitrand soils formed in alluvially redeposited tephra, having mineralogy dominated by plagioclase, with smectite as a minor component. The Hoskins sites were in an undulating landscape with Vitrand soils developed in air-fall tephra consisting of predominantly amorphous material (glass) and plagioclase, with some allophane at depths below 0.2 m. Both regions would most likely have forest vegetation if not for human interventions. The forest sites had large trees at the time of sampling, but they had most likely been logged or cleared for food gardens in the past. The grassland in Oro is dominated by *Imperata cylindrica* and *Sacharum* species and is maintained as grassland by regular burning. The sites had been grassland for at least 58 years prior to sampling (according to aerial photos taken in 1953) and probably much longer than that, according to oral history.

At each site a pit was dug to 1.5 m depth in each of the sampling areas (vegetation types) and morphology of the soil profiles described (colour, structure, consistence, roots and pores for each horizon) to ascertain if the two sampling locations at each site had been the same when oil palm was planted. In Oro Province, profile morphology was not discernibly different between the two locations in every site pair, and was also very similar between sites. The profiles were uniform or gradational in texture, mostly sand to sandy loam. At each site, the oil palm and grassland profiles had the same texture group for each horizon (down to approximately 1 m depth) and similar colour, with each horizon being within one hue category of each other (mostly 10YR, some 2.5Y, moist), two value units of each other (grading from 2-4 at the surface to 4-6 at depth) and one chroma unit of each other (grading from 1-3 at the surface to 1-6 at depth). The only exception was site 6, where the deepest horizon (0.4-0.7 m depth to bottom of pit) was 2.5YR2/1 in the oil palm area and 2.7YR5/1 in the grassland area. In the Hoskins district the soils had distinct horizons, approximately 0.2-

0.5 m thick, corresponding to tephra deposition events and buried A horizons. Texture ranged from pumice gravel to clay, and the oil palm sampling areas had texture generally two or more groups lighter than the adjacent forest areas.

The selected oil palm sampling areas were all smallholder blocks of about 2 ha that had been planted in triangular spacing (120-140 palms ha^{-1}), together with herbaceous legume cover crop, between 6 and 25 years prior to sampling. At about 5 years of age the oil palm canopy closes over and the stand is considered mature. Once harvesting begins (at about two years of age), management of the oil palm crop creates distinct zones. A zone of 1-2 m radius around the palm stem (the ‘weeded circle’) is kept bare to facilitate harvesting. Smallholders generally keep the weeded circle bare by hand slashing. Prior to harvesting, the oldest frond(s) are pruned to facilitate access to ripe fruit bunches. These fronds are placed in the frond pile, creating a zone of high organic matter inputs. Between every second row is a harvest path, which is bare and compacted due to the passage of wheelbarrow and foot traffic. Together, the weeded circle, frond pile and harvest path comprise approximately 30 % of plantation area. The remaining area, here designated the ‘between-zones’ area, is covered with herbaceous understory (including the legume cover crop that was sown originally) that is not disturbed, apart from slashing of large woody weeds. Creeping understory plants also grow over the frond pile. Fertiliser is spread by hand. During the immature phase it is spread closely around palms. During the mature phase it is spread mostly on the between-zones and frond pile zones. Fertiliser had been applied to most blocks, in the form of ammonium sulfate in Oro and ammonium nitrate in Hoskins. The recommended rate in Oro is a total annual rate of 1.0, 1.5, 2.0 and 3.0 kg ammonium sulphate per palm in the 1st, 2nd 3rd and 4th (and subsequent) years after planting. The recommended annual rate of ammonium nitrate for mature palms (4th and subsequent years) in Hoskins is 2 kg per palm. No other fertilisers or soil amendments had been applied. Oil palm is felled at approximately 25 years after planting and the field then replanted; the older plantings sampled were at this stage.

Sampling and analysis

Soil samples were collected in 2010, from 4 different locations under both grass and oil palm (Oro sites) or forest and oil palm (Hoskins sites) and were combined into one composite sample for analysis. In the oil palm blocks, at each of the 4 locations, samples were taken separately from the weeded circle, frond pile and ‘between zones’ areas (the ‘patch’ approach to account for tree-scale variability; Nelson et al. 2014). Sampling depth increments were 0-0.05 and 0.10-0.15 m at all sites. These depths were chosen because the surface layer is where the greatest changes in fertility could be expected and where most root activity occurs (Nelson et al. 2006). At the sites where oil palm had been in place longest (Sites 1, 8 and 9), samples were also taken at 0.05-0.1, 0.15-0.2, 0.2-0.5, 0.5-1.0 and 1.0-1.5 m. Where there was a significant litter layer, especially in the oil palm frond pile, the soil surface was identified as the depth where plant litter fragments were < 10 mm in size. Soil bulk density was measured by oven drying and weighing soil cores (70 mm diameter x 50 mm length). Soil chemical analyses were carried out in Australia following sterilisation by gamma irradiation (50 kGy) to satisfy quarantine requirements.

Samples were analysed for pH, electrical conductivity (EC), total C and N content, exchangeable cations and Colwell P using methods described by Rayment and Lyons (2011). Soil pH and electrical conductivity (EC) were measured in a 1:5 soil:water suspension. Total C and N contents were measured by combustion using a Costech Elemental Analyser. Exchangeable cations (Al, Ca, K, Mg and Na) were extracted using 0.01 M silver thiourea and analysed by inductively coupled plasma optical emission spectroscopy. Effective cation exchange capacity (ECEC) was calculated as the sum of exchangeable cations. Colwell P was extracted using 0.5 M sodium bicarbonate and analysed colorimetrically.

Values for parameters under oil palm were derived from values for the weeded circle, frond pile and between zones by calculating an area-weighted average. The average proportion of the plantations in these zones, across all sites, was 12.0% weeded circle, 10.5% frond pile and 77.5% between zones (including harvest path).

Statistics

The original intention was that the grassland-to-oil palm data be analysed by regression of soil parameters, expressed as the difference between oil palm and grassland, against time under oil palm, with 25 points. However, after removal of the sites having grassland soil $\delta^{13}C$ values <-18‰, the remaining 9 sites fell into two groups according to age under oil palm: 6-12 years and 25 years. We therefore carried out paired t-test comparisons of oil palm (area-weighted mean) and grassland for each of these groups.

The effect of site on the difference between oil palm and grassland was tested using multiple linear regression. For each regression, the dependent variable was the difference between oil palm and grassland and the independent variables were time under oil palm and the first two principal components of the site data, from principal component analysis. Principal component analysis was conducted to reduce the site data into two parameters (principal components) representing most of the between-site variation. It was carried out using all measured parameters (normalised) at both depths, for the grassland site. Because there were essentially two oil palm age groups, the age factor tested the change between the first (6-12 years) and second (25 years) groups.

Analysis of variance was used to test the significance of differences between zones in all the oil palm blocks and, for the forest-to-oil palm sites, to test the effects of effects of vegetation, management zones and depth.

Results

Following conversion of the grassland to oil palm, soil pH and exchangeable Mg content were the only parameters to change significantly (Figure 1). Mean pH decreased under oil palm at both depths during the first 12 years (0.4 units at 0-0.05 m and 0.3 units at 0.1-0.15 m, $p<0.06$) but did not decrease further thereafter. Mean exchangeable Mg content did not change significantly during the first 12 years, but declined from 3.7 to 1.6 $cmol_c$/kg by 25 years (at 0.1-0.15 m). In the oil palm blocks, soil pH and exchangeable Mg contents were considerably higher under the frond pile soil than other zones, in all sites with oil palm 10 years old or older. A similar clear differentiation between the frond pile and other oil palm management zones developed over time for most of the parameters measured.

The lack of consistent trajectory of most soil parameters with time under oil palm suggested an effect of site, which (as summarised in the principal components analysis) was indeed significant for P and K. Overall, mean Colwell P content did not change under oil palm at either depth (Figure 1), but there was a significant site effect at 0-0.05 m depth (p=0.049 for PC1). The greatest decrease in mean Colwell P (most negative mean oil palm values in Figure 1g) was at sites 1 and 4 and the greatest increase (most positive mean oil palm value in Figure 1g) was at site 7, which corresponded with their high and low values of PC1, respectively (Table 1). The loadings for PC1 show that it was dominated by bulk density (-ve) and EC, total C, total N, Colwell P and ECEC (+ve) (Table 2). There was also a significant site effect for K. Although soil exchangeable K content initially decreased under oil palm (6-year old site), there was no difference when the whole 6-12-year old age group was considered (Figure 1). The difference in exchangeable K content at 0.1-0.15 m was significantly related to site (p=0.042 for PC1). The greatest decrease in mean exchangeable K content was at sites 1 and 4, corresponding with high values of PC1 (Table 1). Thus, the decrease in Colwell P and exchangeable K contents under oil palm were greatest at the sites with initially high contents of C, N Colwell P and exchangeable cations.

No significant effects of vegetation or site were detected for soil bulk density, total C or N content, or ECEC (Table 3). There was no change in mean bulk density with time under oil palm at either depth, but values were lower at 0-0.05 m depth under the oil palm frond pile than elsewhere at most sites. Overall, there was no significant change in mean soil C or N contents under oil palm, despite considerable increases under the frond pile at 0-0.05 m. There was a slight upward trend in N content at 0.05 m in the 6-12 year period (p=0.089) and a slight downwards trend in C at 0.1-0.15 m after 25 years (p=0.053). Mean ECEC did not change significantly under oil palm at either depth, despite considerable increases under the frond piles at most sites at both depths. Although the pair-wise comparison showed no significant effect of oil palm at 25 years, there was a significant downward trend between the two age categories, of -0.15 $cmol_c$/kg.year at 0-0.05 m depth (p=0.056) and -0.65 $cmol_c$/kg.year at 0.1-0.15 m depth (p=0.032). Changes in exchangeable Ca are not shown but they corresponded closely with changes in ECEC (Ca = 0.73 ECEC + 5.4, r^2=0.978).

Based on data from sites 1, 8 and 9, the effects of oil palm on soil fertility occurred mostly within the top 0.5 m (Figure 2). Relative to grassland, pH decreased in the top 0.2 m of soil in the weeded circle and between zones areas but stayed the same or increased under the frond pile (Figure 2). Soil C content in the top 0.5 m stayed the same or decreased under oil palm, except under the frond pile, where it increased in the top 0.2 m (Figure 2). There was very little C below 0.5 m under all vegetation types. ECEC tended to decrease under oil palm, down to 0.2 m, except for the weeded circle, where it stayed the same or increased. ECEC was low and unaffected by vegetation below 0.5 m. Decreases in ECEC under oil palm were due to decreases in the content of all non-acidic cations. Colwell P content also decreased under oil palm but, unlike the other parameters, the decrease occurred throughout the profile. Electrical conductivity was closely related to C content, as it was for surface soil at all sites.

In the forest-to-oil palm (Hoskins) sites, the oil palm sites had significantly lower soil bulk density, exchangeable Ca, K and Mg and ECEC than the forest sites (Table 4), but these differences may have been due to lighter texture at the oil palm sites. ~~All~~ In the oil palm blocks, all soil parameters differed significantly between zones ~~in the oil palm blocks~~, except for pH and exchangeable Mg.

Discussion

Conversion of grassland to oil palm was accompanied by slight decreases in soil pH and exchangeable cation contents. In the first 12 years following conversion grassland, pH decreased but ECEC stayed the same, then in next 12 years, pH stayed the same but exchangeable Ca, Mg and ECEC decreased. During the first 6-12 years there appeared to be an increase in soil nitrogen content under oil palm, possibly related to fertiliser inputs and the legume cover crop, which can fix large amounts of nitrogen before the oil palm canopy closes over (Corley and Tinker 2003). Bulk density at these sites was very low to start with, and no machinery had been used in these smallholder blocks. Erosion is unlikely to degrade soil fertility at these sites due to their low slope, permeable soil and high ground cover. With time under oil palm, soil properties became significantly different between the frond pile and the other zones. Soil organic matter content and related properties improved significantly under the frond pile, to 0.15 m depth. Differences between management zones show the importance of sampling all these areas carefully to assess soil fertility under oil palm. It was difficult to delineate zones, so the calculated mean values for oil palm (weighted for zone areas) need to be examined with caution (Nelson et al. 2014).

A decrease in soil pH was the main consequence of oil palm cultivation. Soil acidification may be accelerated under oil palm compared to non-agricultural management due to nitrogen cycling processes (addition of reduced N from fertiliser and biological nitrogen fixation, followed by nitrification and loss of nitrate by leaching) and uptake and sequestration of non-acidic cations in palm biomass and harvested fruit bunches (Nelson et al. 2010a,b). The difference between oil palm and grassland would be further widened by annual addition of ash to the grassland soil due to burning. The occurrence versus absence of burning may have had a greater effect than the effects of fertiliser application and harvesting in the oil palm blocks, because a similar difference in soil pH has been found between grasslands and regenerating forests (with no fertiliser or harvesting) under similar climate in Kalimantan (van der Kamp et al. 2009). The decrease in pH under oil palm was greater in the grassland-to-oil palm (Oro) sites than in in the forest-to-oil palm (Hoskins) sites, again suggesting that grassland burning was more important than management of the oil palm blocks. A difference in pH buffering capacity between the Oro and Hoskins sites may also have played a role though, because the Hoskins sites had higher carbon content at the surface, and pH buffering capacity is controlled mostly by organic matter content in these soils (Nelson and Su 2010).

The soil pH values reached under oil palm were not low enough to be of concern for oil palm productivity (Corley and Tinker 2003) but growth of more sensitive crops such as taro (the most desirable staple in the region of the study) might be affected. Thus it is worthwhile considering management regimes that arrest the decline in pH, such as application of liming materials, or changed fertiliser management. Wider distribution of pruned fronds may also be effective. Application of dolomite would counter acidification as well as the decreases in exchangeable Ca and Mg encountered. In contrast to our study, Tanaka et al. (2009) found increases in soil Ca and P under oil palm, as compared to forest, which they attributed to the use of fertilisers.

Although there was no clear trend in topsoil C content following conversion of grassland to oil palm, soil C stocks (0-1.5 m depth) increased at 7 of the 9 sites (Goodrick et al. ~~2013~~2014). Goodrick et al. (~~2013~~2014) attributed that change to greater inputs under oil palm than grassland due to application of fertiliser and cessation of burning, and high persistence of the grassland-derived organic matter.

There was considerable scatter in the trajectory of soil fertility parameters with time under oil palm, even though we removed sites with uncertain prior vegetation history. The scatter was presumably due to differences between sites and within sites (between the grassland and oil palm sampling areas). The measured parameters, as summarized by ~~principle~~ principal components analysis, went some way towards explaining the effect of sites in the case of Colwell P (0-0.05 m) and exchangeable K (0.1-0.15 m), but not the other parameters. Other differences between sites could include soil properties below 0.15 m depth and depth to water table, which was >1.2 m at all sites at the time of observation, but which may be shallower at times. These parameters may have influenced plant growth and thereby properties of the surface horizon. Another possible reason for the scatter in data may have been that 4 sampling locations were not sufficient in number to account for spatial variability at each site.

The observed decline in fertility could be arrested with changed management, but options such as application of liming agents are unlikely to be economic in the near future as oil palm is tolerant of soil acidity. The soil properties encountered under old oil palm stands are still conducive to high production. Nitrogen fertilisers are currently chosen on price (per unit N) alone, but where prices are similar, less acidifying sources ~~could~~ can be chosen. Palm oil mill byproducts are effective in improving fertility of sandy soils (Comte et al. 2013) but ~~the milling company currently applies all of that produced to its own plantations near the mill~~it is not economic to transport them far from the mill.

In conclusion, the only consistent and significant change in soil fertility during the 25 years following conversion of grassland to oil palm in the study area was acidification and a subsequent decrease in exchangeable cation contents in surface layers. Soil pH and exchangeable cation contents did not reach excessively low levels under oil palm during the 25-year period studied, but they may need to be managed to prevent them becoming a problem for plant growth in the future~~, especially if crops less acidity-tolerant than oil palm are to be grown~~. There are several ways to prevent or reverse soil acidification, such as management of fertiliser and organic residues, and we recommend that growers consider these to ensure the soil remains fertile for a broad range of crops. Based on maintenance of soil structure and fertility, oil palm cultivation in this environment appears to be a sustainable endeavor.

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References

Bleeker P (1983) ‘Soils of Papua New Guinea’(Commonwealth Scientific and Industrial Research Organisation and Australian National University Press: Canberra)

Caliman JP, Olivin J, Dufour O (1987) Degradation of sandy ferralitic soils in oil palm cultivation through acidification and compaction – correction methods. Proceedings of 1987 International Oil Palm and Palm Oil Conference, Kuala Lumpur, pp 287-293.

Chase LDC, Henson IE (2010) A detailed greenhouse gas budget for palm oil production. *International Journal of Agricultural Sustainability* **8**, 199-214.

Comte I, Colin F, Grünberger O, Follain S, Whalen JK, Caliman J-P (2013) Landscape-scale assessment of soil response to long-term organic and mineral fertilizer application in an industrial oil palm plantation, Indonesia. *Agriculture, Ecosystems and Environment* **169**, 58-68.

Corley RHV (2009) How much palm oil do we need? *Environmental Science and Policy* **12**, 134-139.

Corley RHV, Tinker PB (2003) ‘The Oil Palm.’ (4th edition). (Blackwell Publishing Company: Oxford)

de Vries SC, van der Ven GWJ, van Ittersum MK, Giller KE (2010) Resource use efficiency and environmental performance of nine major biofuel crops, processed by first-generation conversion techniques. *Biomass and Bioenergy* **34**, 588-601.

Don A, Schumacher J, Freibauer A (2011) Impact of tropical land-use change on soil organic carbon stocks – a meta-analysis. *Global Change Biology* **17**, 1658-1670.

Dufour O, Olivin J (1985) Evolution of soils in oil palm plantation on savannah. *Oléagineaux* **40**, 113-123.

Frazão LA, Paustian K, Pellegrino Cerri CB, Cerri CC (2012) Soil carbon stocks and changes after oil palm introduction in the Brazilian Amazon, *GCB Bioenergy* **5**, 384-390.

Goodrick I, Nelson PN, Banabas M, Wurster C, Bird MI (~~2013~~2014) Soil carbon balance following conversion of grassland to oil palm. *Global Change Biology Bioenergy* doi: 10.1111/gcbb.12138.

Haron K, Brookes PC, Anderson JM, Zakaria ZZ (1998). Microbial biomass and soil organic matter dynamics in oil palm (*Elaeis guineensis* Jacq.) plantations, West Malaysia. *Soil Biology and Biochemistry* **30**, 547-552.

Hartemink AE (1998) Soil chemical and physical properties as indicators of sustainable land management under sugar cane in Papua New Guinea. *Geoderma* **85**, 283-306.

Henson IE. 1994. ‘Environmental impacts of oil palm plantations in Malaysia.’ PORIM Occasional Paper No. 33. (Palm Oil Research Institute of Malaysia: Kuala Lumpur)

Jagoret P, Michel-Dounias I, Snoeck D, Todem Ngnogué Hervé, Malézieux E (2012) Afforestation of savannah with cocoa agroforestry systems: a small-farmer innovation in central Cameroon. *Agroforestry Systems* **86**, 493–504.

Koh LP, Wilcove DS. (2008) Is oil palm agriculture really destroying tropical biodiversity? *Conservation Letters* **1**, 60-64.

Law MC, Balasundram SK, Husni MHA, Ahmed OH, Harun MH (2009) Spatial variability of soil organic carbon in oil palm. *International Journal of Soil Science* **4**, 93-103.

Nelson PN, Su N (2010) Soil pH buffering capacity: a descriptive function and its application to some acidic tropical soils. *Australian Journal of Soil Research* **48**, 201-207.

Nelson PN, Banabas M, Scotter DR, Webb MJ. 2006. Using soil water depletion to measure spatial distribution of root activity in oil palm (*Elaeis guineensis* Jacq.) plantations. *Plant and Soil* **286**, 109-121.

Nelson PN, Berthelsen S, Webb MJ, Banabas M. 2010a. Acidification of volcanic ash soils under oil palm in Papua New Guinea: effects of fertiliser type and placement. In 'Proceedings of the 19th World Congress of Soil Science; Soil Solutions for a Changing World*'* (Eds RJ Gilkes, N Prakongkep) pp. 8-11. (International Union of Soil Science: Brisbane)

Nelson PN, Webb MJ, Orrell I, van Rees H, Banabas M, Berthelsen S, Sheaves M, Bakani F, Pukam O, Hoare M, Griffiths W, King G, Carberry P, Pipai R, McNeill A, Meekers P, Lord S, Butler J, Pattison T, Armour J, Dewhurst C. 2010b. 'Environmental sustainability of oil palm cultivation in Papua New Guinea.' ACIAR Technical Report No. 75. (The Australian Centre for International Agricultural Research: Canberra)

Nelson PN, Webb MJ, Banabas M, Nake S, Goodrick I, Gordon J, O'Grady D, Dubos B. 2014. Methods to account for tree-scale variation in soil- and plant-related parameters in oil palm plantations. *Plant and Soil* **374**, 459-471.

Rayment GE, Lyons DJ (2011). 'Soil chemical methods: Australasia.' (CSIRO Publishing: Collingwood)

Sayer J, Ghazoul J, Nelson P, Boedhihartono AK (2012) Oil palm expansion transforms tropical landscapes and livelihoods. *Global Food Security* **1**, 114-119.

Smith DR, Townsend TJ, Choy AW, Hardy IC, Sjogersten S (2012) Short term soil carbon sink potential of oil palm plantations. *GCB Bioenergy* **4**, 588-596.

Tanaka S, Tachibe S, Wasli MEB, Lat J, Seman L, Kendawang JJ, Iwasaki K, Sakurai, K (2009) Soil characteristics under cash crop farming in upland areas of Sarawak, Malaysia. *Agriculture, Ecosystems and Environment* **129**, 293-301.

van der Kamp J, Yassir I, Buurman P (2009) Soil carbon changes upon secondary succession in *Imperata* grasslands (East Kalimantan, Indonesia). *Geoderma* **149**, 76-83.

Formatted: English (U.K.)

Wicke B, Sikkema R, Dornburg V, Faaij A (2011) Exploring land use changes and the role of palm oil production in Indonesia and Malaysia. *Land Use Policy* **28**, 193-206.

List of figures

Figure 1. For the Oro (grassland-to-oil palm) sites, difference between soil pH (a & b), exchangeable Mg (c & d), exchangeable K (e & f) and Colwell P (g & h) under oil palm (OP) and adjacent grassland (GL) versus age of the oil palm, showing values for the oil palm frond pile (FP), weeded circle (WC) and between zones (BZ) areas and the area-weighted mean of those zones, at two depths. Tables show, for the young (6-12 years) and old (25 years) groups of sites, means of the actual values for grassland and area-weighted oil palm and the probability that there is no difference between them (p value for a paired t-test). There were significant effects of site (PC1) for Colwell P at 0-0.05 m and exchangeable K at 0.1-0.15 m.

Figure 2. For the 3 Oro (grassland-to-oil palm) sites with 25-year old palms, depth profile of soil C content, pH and effective cation exchange capacity (ECEC) under grassland and oil palm, under the frond pile (OP-FP), weeded circle (OP-WC) and between zones (OP-BZ).

Table 1. Location of the Oro (grassland-to-oil palm) sites, showing age of the oil palm stands (years after planting, YAP) and site factor (Eigen value for PC1, accounting for 45.8% of variation in soil parameters among the grassland sites)

Site	Region	Lat. (˚S)	Long. (˚E)	YAP	Eigenvalue
1	Oro	8.72	148.21	25	1.65
3	Oro	8.82	148.29	12	0.79
4	Oro	8.73	148.37	6	5.89
5	Oro	8.71	148.25	12	-3.68
6	Oro	8.84	148.45	11	-1.30
7	Oro	8.78	148.36	9	-5.09
8	Oro	8.75	148.21	25	0.21
9	Oro	8.72	148.19	25	4.61
11	Oro	8.71	148.21	10	-2.78
17	Hoskins	5.63	150.17	22	na
18	Hoskins	5.62	150.16	13	na

na = not applicable

Table 2. Loadings for the first principal component (PC1) for the grassland sites. Only loadings > │0.2│ are shown.

Parameter	Loading
Bulk density (0-0.05 m)	-0.259
Bulk density (0.10-0.15 m)	-0.234
Colwell P (0-0.05 m)	0.219
Exch. Mg (0.10-0.15 m)	0.219
EC (0-0.05 m)	0.227
Total C (0-0.05 m)	0.229
ECEC (0.10-0.15 m)	0.231
Col. P (0.10-0.15 m)	0.232
Total C (0.10-0.15 m)	0.240
Total N (0.10-0.15 m)	0.250
Total N (0-0.05 m)	0.254
EC (0.10-0.15 m)	0.280

‘EC’ is electrical conductivity, ‘ECEC’ is effective cation exchange capacity, ‘S’ is 0-0.05 m depth and ‘D’ is 0.10-0.15 m depth.

Table 3. For the Oro (grassland-to-oil palm) sites, mean values of parameters for which there was no significant effect (p=0.05) of vegetation or site (PC1) and, for each age group, the probability that there is no difference between the sites with different vegetation (two-tail p value for a paired t-test). Values for oil palm are area-weighted averages of the zone values.

Parameter	Depth (m)	YAP	Grass-land	Oil palm	p
Bulk density (kg/m^3)	0-0.05	6-12	792	745	0.189
		25	759	824	0.426
	0.1-0.15	6-12	879	823	0.151
		25	879	854	0.887
C content (g/kg)	0-0.05	6-12	55.5	58.4	0.418
		25	55.7	52.4	0.567
	0.1-0.15	6-12	44.8	44.0	0.860
		25	45.8	40.9	0.053
N content (g/kg)	0-0.05	6-12	3.4	4.2	0.089
		25	3.8	3.4	0.428
	0.1-0.15	6-12	2.8	3.3	0.158
		25	3.0	2.5	0.316
ECEC ($cmol_c$/kg	0-0.05	6-12	7.6	9.0	0.308
		25	21.3	11.2	0.280
	0.1-0.15	6-12	4.8	7.4	0.093
		25	12.8	8.2	0.084
EC (µS/cm)	0-0.05	6-12	88	107	0.117
		25	112	101	0.635
	0.1-0.15	6-12	61	66	0.690
		25	78	67	0.104

‘YAP’ is years after planting of oil palm, ‘ECEC’ is effective cation exchange capacity and ‘EC’ is electrical conductivity (1:5 soil:water).

Table 4. For the Hoskins (forest-to-oil palm) sites, analysis of variance for soil properties, showing significance (p values) of the effects of vegetation, ie. forest versus oil palm (mean of zones, weighted for relative areas), depth (0-0.05 versus 0.1-0.15 m) and their interaction, and mean values for the four categories. Significant p values (<0.05) are underlined.

Factor	Bulk density	pH	Total C	Colwell P	ECEC	Exch. Al	Exch. Ca	Exch. K	Exch. Mg
				p value					
Vegetation	0.037	0.400	0.077	0.391	0.032	0.280	0.049	0.015	0.030
Depth	0.011	0.847	0.002	0.076	0.001	0.001	0.001	0.007	0.016
Vegetation.depth	0.725	0.069	0.513	0.546	0.182	1.000	0.177	0.489	0.261
				Mean					
	(kg/m^3)		(g/kg)	(mg/kg)	(cmol$_c$/kg)				
Forest (0-0.05 m)	689	6.52	61.7	44.8	31.7	0.4	25.6	1.2	4.4
Forest (0.1-0.15 m)	787	6.14	21.8	9.3	9.8	0.2	7.5	0.5	1.5
Oil palm (0-0.05 m)	607	5.94	81.4	25.8	20.2	0.3	17.2	0.6	1.8
Oil palm (0.1-0.15 m)	722	6.40	32.3	5.7	6.0	0.1	5.3	0.1	0.4

‘ECEC’ is effective cation exchange capacity.

Figure 1

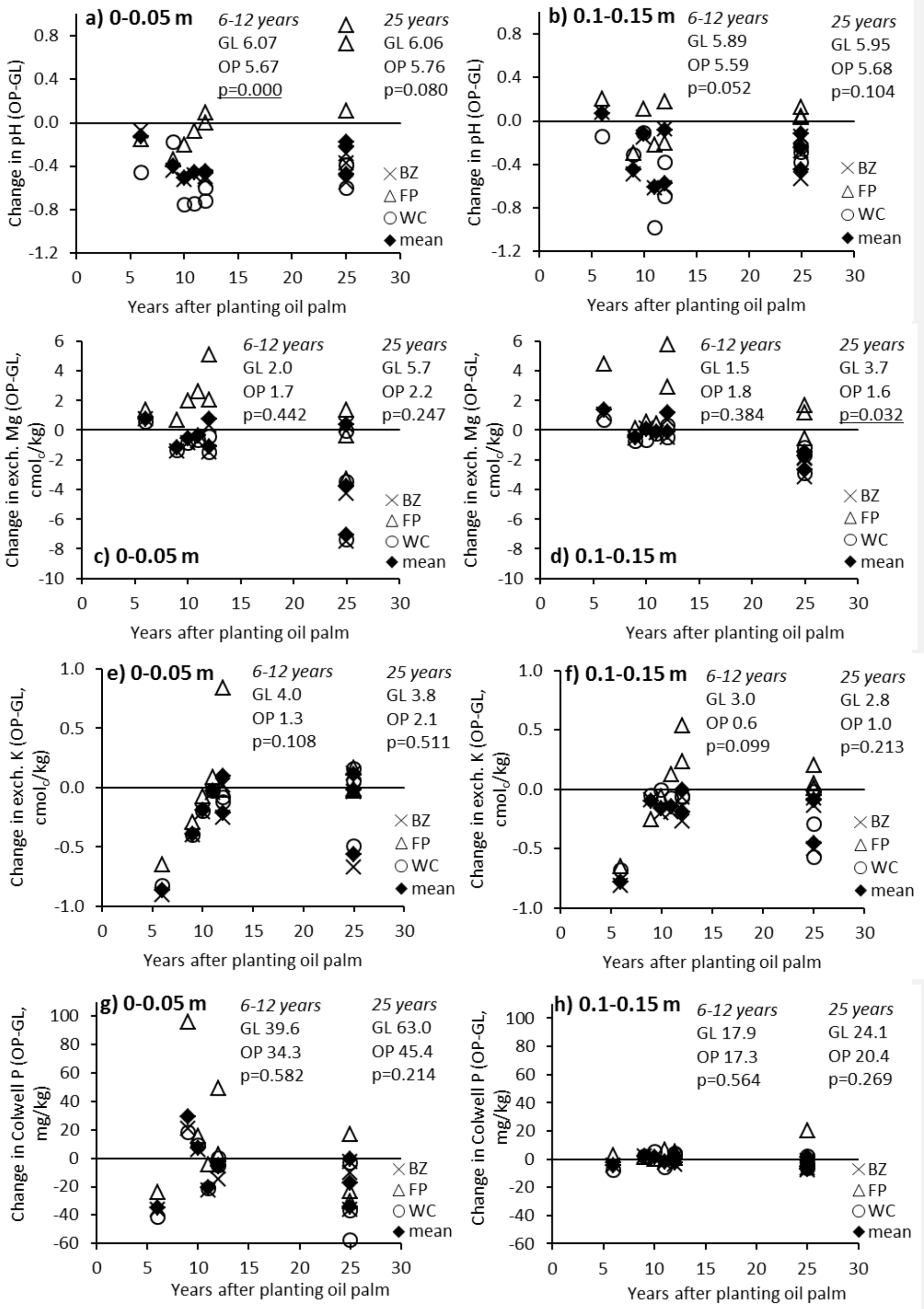
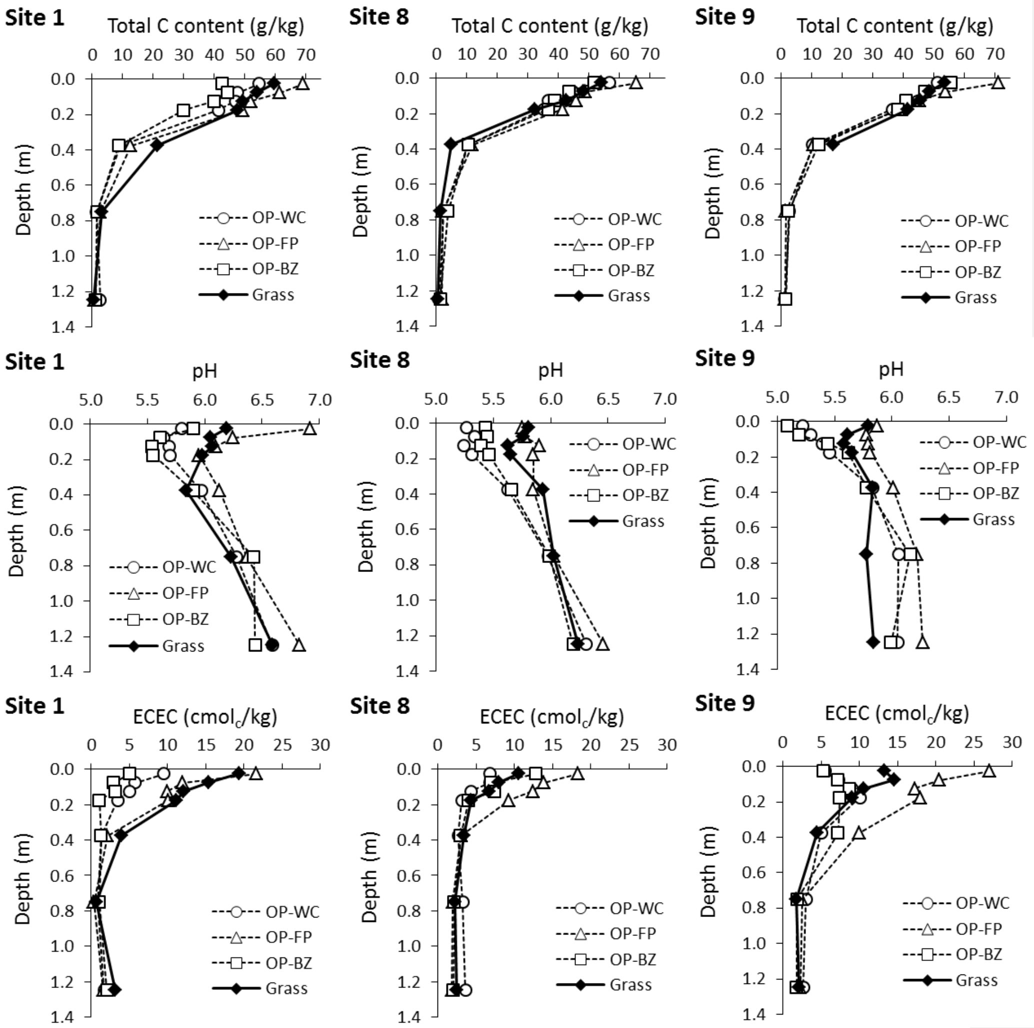

a) 0-0.05 m
6-12 years
GL 6.07
OP 5.67
p=0.000
25 years
GL 6.06
OP 5.76
p=0.080
Change in pH (OP-GL)
0.8
0.4
0.0
-0.4
-0.8
-1.2
× BZ
△ FP
○ WC
◆ mean
b) 0.1-0.15 m
6-12 years
GL 5.89
OP 5.59
p=0.052
25 years
GL 5.95
OP 5.68
p=0.104
c) 0-0.05 m
6-12 years
GL 2.0
OP 1.7
p=0.442
25 years
GL 5.7
OP 2.2
p=0.247
Change in exch. Mg (OP-GL, cmolc/kg)
6
4
2
0
-2
-4
-6
-8
-10
d) 0.1-0.15 m
6-12 years
GL 1.5
OP 1.8
p=0.384
25 years
GL 3.7
OP 1.6
p=0.032
e) 0-0.05 m
6-12 years
GL 4.0
OP 1.3
p=0.108
25 years
GL 3.8
OP 2.1
p=0.511
Change in exch. K (OP-GL, cmolc/kg)
1.0
0.5
0.0
-0.5
-1.0
f) 0.1-0.15 m
6-12 years
GL 3.0
OP 0.6
p=0.099
25 years
GL 2.8
OP 1.0
p=0.213
g) 0-0.05 m
6-12 years
GL 39.6
OP 34.3
p=0.582
25 years
GL 63.0
OP 45.4
p=0.214
Change in Colwell P (OP-GL, mg/kg)
100
80
60
40
20
0
-20
-40
-60
h) 0.1-0.15 m
6-12 years
GL 17.9
OP 17.3
p=0.564
25 years
GL 24.1
OP 20.4
p=0.269
0
5
10
15
20
25
30
Years after planting oil palm

Figure 2


Site 1
Site 8
Site 9
Total C content (g/kg)
0 10 20 30 40 50 60 70
pH
5.0 5.5 6.0 6.5 7.0
ECEC (cmol$_c$/kg)
0 5 10 15 20 25 30
Depth (m)
0.0 0.2 0.4 0.6 0.8 1.0 1.2 1.4
OP-WC
OP-FP
OP-BZ
Grass