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EXCESSIVE USE OF FERTILIZER CAN INCREASE LEACHING PROCESSES AND MODIFY SOIL RESERVES IN TWO ECUADORIAN OIL PALM PLANTATIONS

By BERNARD DUBOS†, DIDIER SNOECK *and* ALBERT FLORI

CIRAD, UPR Systèmes de pérennes, F-34398, Montpellier, France

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SUMMARY

In the oil palm plantations of Ecuador, two factorial trials (namely CP06 and CP08) were used to assess the effects of N, P and K fertilization on the soil chemical characteristics after 10 years of fertilizer application. The use of ammonia-based fertilizers has resulted in a drop in soil pH, which has reached 1.2 units in one of the two trials. A drop in cation exchange capacity (CEC) was also found, and a loss of exchangeable cations that probably reflected leaching of excess N as nitrates. The use of KCl enriched the soil in K, which contributed to impoverishment in Ca and Mg. In both trials, the highest N and K application rates had no significant effect on yield in comparison with an intermediate fertilization rate; however, their effects on the fertilized soil significantly increased the risk of N and cation leaching towards the deep soil layers. We also compared the effects of the N, P and K factors on soil properties outside the fertilizer application zone. In both trials, the mineral reserves played a major role in meeting the needs of the control palms, which had not been fertilized for 10 years, as no significant yield drop has been observed except in trial CP06 when no KCl was applied. However, uptake of nutrient in the control plots did not lead to significant impoverishment of the soil.

INTRODUCTION

There are increasing concerns about the environmental impact of farming, whether it is in a temperate or tropical climate. Excessive use of fertilizers has often been blamed for its effects on the quality of the atmosphere and of water resources. In particular, the role of fertilizers in the processes of oxygen depletion on the seabed and their threat to the animal species has been shown in the Nitrogen Cascade project (Galloway *et al.*, 2003; UNEP, 2003).

Tropical tree crops offer some advantages that might limit negative effects on the surrounding environment: rapid establishment of a cover crop and permanent soil cover over long cycles reduce the areas exposed to leaching, runoff and erosion provided adequate practices be taken (PORIM, 1994). However, the annual rainfall, which generally exceeds 2000 mm, and the intensity of daily rainfall are aggravating factors, along with the difficulties in precisely determining fertilizer requirements in all areas of a plantation.

Early on, fertilization in oil palm plantations has proven to be a powerful lever to ensure high yields. Potassium fertilization, mainly in the form of potassium chloride

†Corresponding author. Email: bernard.dubos@cirad.fr

(KCl) and nitrogen mainly in the form of urea are a major concern for growers, who use leaf analyses to determine annual fertilizer requirements. K requirements for mature palms vary between 0.3 and 3.0 kg K palm^{-1} yr^{-1} and N requirement between 0.25 and 1.75 kg N palm^{-1} yr^{-1} (Goh and Härdter, 2003), i.e. rates of fertilizer can reach 700 and 530 kg ha^{-1} for KCl and urea, respectively. Although studies have shown the nutrient leaching phenomena (Banabas *et al.*, 2008; Schroth *et al.*, 2000; Tung *et al.*, 2009), controlled release fertilizers are rarely used by the profession especially in mature palm. However, given the ever-increasing cost of fertilizers and the concerns of civil society about sustainable crop management sequences, studies have become necessary to measure the efficiency of fertilization and its impacts on the environment. It was in this spirit that we used two long-duration fertilization trials to investigate the effects of the main N, P and K fertilizers on the characteristics of soils after several years of fertilization.

MATERIALS AND METHODS

The trials

Two long-duration fertilization trials were set up by the DANEC company in Ecuador. The protocols were applied 3 years after replanting following an initial cycle of *Elaeis guineensis* oil palms. Trial CP06 is located in the Ecuadorean Amazon Basin (76°36′W, 0°17′S), where, for phytosanitary reasons (existence of Bud Rot), the interspecific hybrid *E. guineensis x Elaeis oleifera* has been used. Trial has been planted in 2000 at a density of 128 palms ha^{-1} on alluvial deposits with a clay texture (Average contents determined by Cirad laboratory, Montpellier, France: Clay 55%, Silt 34%, Sand 11%). The mean annual rainfall (3309 mm – 1980–2013) and sunshine (1437 h – 1980–2013) are sufficient and well distributed throughout the year. Trial CP08 located in the western part of the country on the Andean foothills (79°26′W, 0°13′N), has been planted with *E. guineensis* in 1997 at a density of 143 palms ha^{-1}. The soil, formed from volcanic ash deposits, has a very balanced texture (Average contents determined by Agrobiolab, Quito, Ecuador: Clay 32%, Silt 31%, Sand 36%). The annual rainfall (2754 mm – 1980–2013) is sufficient there but is not regularly balanced between the first half of the year (2200 mm) and the second (554 mm). The annual sunshine measured with a Campbell–Stokes sunshine recorder (957 h – 1980–2013) is very low compared with the norms generally accepted for oil palm growing.

Both trials are single-replication factorial experiments with confounded blocks. Trial CP06 is a N3 P3 K3 factorial design with 27 plots; trial TT08 is a N2 P2 K3 Mg3 factorial design with 36 plots. Plots are made of six rows of six palms, of which the 16 central palms are used for yield observations. The N, P, K and Mg factors have been studied at 2 or 3 levels each (Table 1), with the lowest level (zero value) always used as controls (without fertilizer).

Fertilizer applications

For CP06, in the last 8 years, N was applied four times in the form of urea and four times in the form of ammonium nitrate depending on the years. For CP08, N was

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Table 1. Amount of nutrient (kg $palm^{-1}$ yr^{-1}) according to the levels of the factors studied in trials CP06 and CP08 during the last 8 years.

Trial	CP06			CP08		
Nutrient	0	1	2	0	1	2
N	0	0.45	1.35	0	1.35	
P	0	0.20	0.60	0	0.30	
K	0	0.50	1.50	0	0.75	1.50
Mg				0	0.16	0.32

applied in the form of urea apart from the penultimate year (ammonium nitrate). For both trials, P was mostly applied in the form of TSP and from 2011 to 2013 in the form of a partially acidulated phosphate. K was applied in the form of KCl in both trials. Mg was applied in the form of kieserite in CP08.

The rates applied increased rapidly to take into account the growth of the oil palms over the life of the trials, but they remained constant over the last 8 years prior to soil sampling. The quantities of equivalent nutrients for each rate studied are shown in Table 1.

In each trial, fertilizers were applied according to the plantation standard practices. For CP08 trial, the topography increases the risk of nutrients runoff if applied in the inter-row used for harvesting activities. For that reason, fertilizers were applied in the planting row between the weeded circles (Figure S1 in Supplementary material available online) avoiding frond piles to reduce volatilization risks when urea is applied. In CP06, where topography is perfectly flat, fertilizers were applied in the weeded circle as for the surrounding commercial blocs.

Observations on palms

Fresh Fruit Bunch (FFB) production was monitored by individual bunch weighing starting from 3 years in each trial. Trials have been observed up to 13 and 16 years old for CP06 and CP08, respectively. The effects of each type of fertilizer on productivity were assessed by analysing the mean of the last 3 years observed (2011 to 2013).

Effects of fertilizers on palm nutrition were assessed by analysing leaflets contents on the same period. Results presented only refer to the main effects of N, P and KCl fertilizers on the corresponding nutrient (i.e. respectively on N, P and K and Cl). To detect eventual deficiencies, we compared mean contents associated to each fertilizer rate to general optimum contents for mature oil palm. For *E. guineensis,* we used references from Fairhurst *et al.* (2004) and for *E. guineensis x E. oleifera* from Dubos *et al.* (2013).

Soil sampling

Soil samples were taken in each trial once the effects of the fertilizers on mineral nutrition were considered stabilized after the protocol had been applied for at least 10 years, i.e. in 2013 for CP06 and in 2011 for CP08. A delay of 4 months was respected between the sampling operations and the last fertilizer application. In each selected plot, two soil samples were taken by carefully mixing height samples in the topsoil layer (0–25 cm for CP06 and 0–20 cm for CP08). The first sample (FERT) corresponds to the zone in which the fertilizers were applied, inside the weeded circle for CP06 and between the circles in the planting row for CP08 (Figure S1). The second sample (NO-FERT) was taken outside the fertilized zone, in the harvesting inter-row for CP06 to avoid both fertilizer and frond pile. In CP08 trial, as the inter-row was not suitable for erosion purpose, NO-FERT samples were taken on the edge of the frond pile. Sampling design and relationship with organic matter are thus not exactly comparable, between sites, mainly because the fertilizer management standards differ in the two plantations. The results of the analyses are referred to as FERT and NO-FERT, respectively in the rest of this article.

The samples from CP06 were taken for all the combinations of the three levels of each factor, i.e. 27 analyses for FERT and for NO-FERT. The samples from CP08 were taken for only the combinations of levels 0 and 1 for N and P factors and levels 0 and 2 for K and Mg factors, i.e. 16 analyses for FERT and for NO-FERT.

Soil analyses

The soils were analysed at the CIRAD laboratory (Montpellier, France) for the following variables: pH (pH_{water} in a 1:5 (v/v) soil: water extract – ISO 10390:2005), organic and total carbon determination after dry combustion (Dumas method – ISO 10694: 1995), total nitrogen content determination after dry combustion (Dumas method – ISO 13878: 1998), total P dissolution in highly mineral acids after dry combustion (NF X31-147: 1996) and colourimetric determination (ISO 11263:1995), available P extracted by a mixture of sodium hydrogenocarbonate and ammonium fluoride (Olsen Dabin method – Internal PopS04 method), cation exchange capacity (CEC) and exchangeable cations (measured at the soil pH by exchange with cobalt hexamine trichloride – ISO 23470:2011).

Statistical analyses

The effect of the factors was tested by an analysis of variance and, when it appeared significant at the 5% limit, the means of the fertilizer rates were compared by the Tukey test. The values between which the difference was not significant are shown in the tables with the same letter.

RESULTS

Effects of fertilizers on yields of fresh fruit bunches (FFB)

An analysis of the yields in CP06 showed that only the KCl application had a significant effect (Table 2), at the end of the trial. A comparison of the leaf contents (Table 3) showed that the differences in yield may be due to a dual K and Cl deficiency as K and Cl contents without KCl applications are well below optimum contents.

In trial CP08, fertilizer application had significant effects on N, P and Cl contents and despite contents were below optimum levels obtained in general conditions,

Table 2. Effects of factors on average yield (kg FFB palm $^{-1}$ yr^{-1}) observed from years 11 to 13 in trial CP06 and years 14 to 16 in trial CP08. Yields obtained with K1 and K2 were found significantly higher than yield with K0 in trial CP06. No significant differences have been observed during the whole life of the trial CP08.

	CP06			CP08			
Rate	N	P	K	N	P	K	Mg
0	207	208	186 b	189	186	185	186
1	221	218	221 a	189	192	194	189
2	204	207	226 a			188	193
p value	0.319	0.566	**0.021**	0.96	0.293	0.334	0.556

Table 3. Main effects of treatments on leaf contents (% D.M.) averaged from 2011 to 2013. Rates refer to N-fertilizer for N contents, P-fertilizer for P contents and KCl fertilizer for K and Cl contents. Optimum contents are from Fairhurst *et al.* (2004) for CP06 and Dubos *et al.* (2013) for CP08.

	N		P		K		Cl	
Rate	CP06	CP08	CP06	CP08	CP06	CP08	CP06	CP08
0	2.389	2.257 b	0.151 b	0.149 b	0.457 b	1.172 a	0.360 b	0.357 b
1	2.401	2.360 a	0.155 a	0.153 a	0.681 a	0.986 b	0.806 a	0.746 a
2	2.447		0.158 a		0.790 a	0.986 b	0.921 a	0.751 a
p value	0.141	**0.001**	**0.006**	**0.019**	**0.001**	**0.000**	**0.000**	**0.000**
Optimum	2.50	2.50	0.153	0.154	0.70	0.90	0.50	0.50

factors had no significant effect on yields (Table 2). The drop in K content after KCl application is probably due to the high content of exchangeable Ca in soil. Similar findings were mentioned by Breure and Rosenquist (1977) and Dubos *et al.* (2011), respectively in Papua New Guinea and Colombia. These authors observed a drop in leaf K contents concomitant with an increase in leaf Ca and Cl contents.

Characteristics of non-treated soil

The general characteristics of the soils in the two trials are illustrated by the soil analysis results for the two plots used as unfertilized controls since the start of the trial (Table 4). The soil in CP06 was acid. It was poor in cations; in particular, K and Mg were below the norms recommended for oil palm (Paramananthan, 2003). Although the soil contained ample total carbon, the CEC was very low and the sum of exchangeable bases only accounted for a small proportion of it. The soil in CP08 was moderately acid. It was better for the exchangeable bases and they accounted for a large share of the CEC. No major differences were found between FERT and NO-FERT for the variables total C, total N and the CEC in trial CP06, whereas in trial CP08 the contents were higher in the NO-FERT zone.

Effect of fertilizers on soil characteristics in the FERT zone

Acidifying effect of nitrogen in the form of urea or ammonium nitrate. The nitrogen applications had an acidifying effect in both trials. The drop in pH was significant for CP08

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Table 4. Characteristics of the topsoil in the unfertilized control plots (respectively N0P0K0 and N0P0K0Mg0 in trials CP06 and CP08) according to the sampling site (FERT and NO-FERT).

		CP06		CP08	
		FERT	NO-FERT	FERT	NO-FERT
pH_{water}		5.3	5.2	6.0	5.8
C_{total}	g kg^{-1}	35.4	41.7	14.7	27.0
N_{total}	g kg^{-1}	43.6	48.7	16.1	27.9
P_{total}	mg kg^{-1}	1778	1830	495	763
P_{Olsen}	mg kg^{-1}	7.8	1.4	3.0	12.0
Ca[a]	cmol kg^{-1}	0.86	2.36	6.43	9.01
Mg[a]	cmol kg^{-1}	0.16	0.57	0.95	1.33
K[a]	cmol kg^{-1}	0.04	0.04	0.39	0.33
Na[a]	cmol kg^{-1}	0.09	0.16	0.13	0.12
Al[a]	cmol kg^{-1}	0.97	0.77	0.01	0.01
Mn[a]	cmol kg^{-1}	0.15	0.17	0.15	0.26
H[a]	cmol kg^{-1}	0.06	0.06	0.01	0.02
Sum[b]	cmol kg^{-1}	1.15	3.13	7.90	10.78
CEC[a]	cmol kg^{-1}	5.25	6.40	7.82	10.73
S %[c]		21.9	48.9	100.0	100.0

pH_{water}: 1:5 soil:water (v:v) extract; C and N measured after dry combustion (Dumas method); [a]exchangeable cations and CEC measured at the soil pH by exchange with cobalt hexamine trichloride; [b]Sum of exchangeable cations; [c]Saturation rate (Sum/CEC).

Table 5. Effects of N fertilizer on soil pH, CEC and exchangeable cations in the FERT zone (*p*-value: significant results are shown in bold. Means followed by the same letter are not significantly different, according to the Tukey test).

		CP06				CP08		
		N0	N1	N2	*p* value	N0	N1	*p* value
N applied (kg $palm^{-1}$ yr^{-1})		0	0.45	1.35		0	1.35	
pH water		4.95	4.80	4.63	0.089	5.88 a	4.71 b	**0.000**
Ca [a]	cmol kg^{-1}	1.563a	0.751b	0.500b	**0.002**	4.953 a	1.805 b	**0.000**
Mg [a]	cmol kg^{-1}	0.538	0.390	0.306	0.088	1.101 a	0.525 b	**0.001**
K [a]	cmol kg^{-1}	0.426	0.438	0.37	0.776	1.108	0.785	0.054
Al [a]	cmol kg^{-1}	1.637b	2.374ab	2.972a	**0.016**	0.028 b	0.946 a	**0.002**
Mn [a]	cmol kg^{-1}	0.199	0.236	0.209	0.879	0.211 b	0.466 a	**0.021**
H a	cmol kg^{-1}	0.089b	0.106ab	0.126a	**0.008**	0.015 b	0.109 a	**0.000**
Sum [b]	cmol kg^{-1}	2.59a	1.64ab	1.24b	**0.012**	7.296 a	3.271 b	**0.000**
CEC [a]	cmol kg^{-1}	5.89	5.73	5.86	0.770	7.50 a	4.90 b	**0.000**
S % [c]		44.1a	28.7b	21.2b	**0.005**	96.3 a	66.0 b	**0.004**

pH_{water}: 1:5 soil:water (v:v) extract; C and N measured after dry combustion (Dumas method); [a] exchangeable cations and CEC measured at the soil pH by exchange with cobalt hexamine trichloride; [b] Sum of exchangeable cations; [c] Saturation rate (Sum/CEC).

(Table 5). The application of 1.35 kg N $palm^{-1}$ yr^{-1} led in both situations to a pH close to 4.6–4.7. The variation in pH came from a significant increase in H^{+} along with the increase in exchangeable Al. It went hand in hand with a drop in exchangeable bases in both trials. In CP08, the drop in all the bases was significant or almost significant (K). Due to the much lower contents of bases in the N0 treatment, the

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Table 6. Effects of K fertilizer on exchangeable cations in the FERT zone (p-value: significant results are shown in bold. Means followed by the same letter are not significantly different, according to the Tukey test).

		CP06				CP08		
		K0	K1	K2	P value	K0	K2	p value
K applied (kg palm^{-1} yr^{-1})		0	0.5	1.5		0	1.5	
Ca	cmol kg^{-1}	1.090	0.903	0.821	0.343	4.041 a	2.716 b	**0.007**
Mg	cmol kg^{-1}	0.366	0.419	0.449	0.660	0.986 a	0.640 b	**0.012**
K	cmol kg^{-1}	0.030 b	0.193 b	1.010 a	**0.000**	0.261 b	1.631 a	**0.000**
Total	cmol kg^{-1}	1.49	1.52	2.28		5.29	4.99	

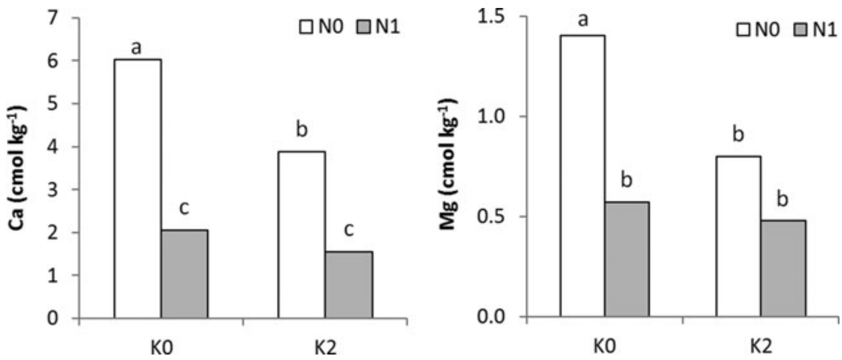

Figure 1. Combined effects of K and N fertilizers on Ca and Mg exchangeable in CP08 trial (FERT zone). Interactions K×N were significant with p value of 0.040 and 0.035 for Ca and Mg, respectively. Means followed by the same letter are not significantly different, according to the Tukey test).

effect was less marked for CP06, even though the Ca content was three times lower with N2 compared to N0. A significant drop in the CEC was found in CP08, which did not happen in CP06 due.

KCl effect. The application of 1.5 kg of K palm^{-1} yr^{-1} caused a significant rise in exchangeable K in both trials (Table 6) which reached 1 cmol kg^{-1} in CP06 and largely exceeded it in CP08. In CP08, where the native contents were high, the concentrations of Ca and Mg fell significantly. The sum of cations could be considered as constant (K2 = 94% of K0) indicating a substitution of Ca and Mg by K ions. Conversely, the sum of cations increased by over 50% (K2:K0) in CP06 without any apparent exchange with Ca and Mg.

There was no significant effect of KCl on the other variables in either of the trials, especially the pH and CEC.

Two significant interactions were found in CP08 (Figure 1) for K and N on the Ca and Mg contents. They showed that the effect of KCl on the drop in Ca and Mg contents was mainly expressed in the absence of N fertilizer when the concentrations were high. This effect was considerably reduced by N fertilizer, which had a major effect on the Ca and Mg contents.

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Table 7. Effects of P fertilizer on soil P contents in the FERT zone (*p*-value: significant results are shown in bold. Means followed by the same letter are not significantly different, according to the Tukey test).

	CP06				CP08		
	P0	P1	P2	*p* value	P0	P1	*p* value
P applied (kg palm^{-1} yr^{-1})	0	0.2	0.6		0	0.3	
P Olsen mg kg^{-1}	7.6 b	33.6 b	134.3 a	**0.000**	8.4 b	38.3 a	**0.031**
P Total mg kg^{-1}	1663 b	1856 b	3186 a	**0.000**	616	913	0.175

Table 8. Effects of K fertilizer on exchangeable cations in the NO-FERT zone (*p*-value: significant results are shown in bold. Means followed by the same letter are not significantly different, according to the Tukey test).

	CP06				CP08		
	K0	K1	K2	*p* value	K0	K2	*p* value
K applied (kg palm^{-1} yr^{-1})	0	0.5	1.5		0	1.5	
Ca cmol kg^{-1}	0.818	0.894	1.132	0.315	9.091	6.976	0.179
Mg cmol kg^{-1}	0.204	0.203	0.217	0.969	1.225	1.069	0.454
K cmol kg^{-1}	0.046	0.059	0.074	0.083	0.358 b	0.531 a	**0.013**
Total cmol kg^{-1}	1.068	1.157	1.423		10.674	8.576	

P effect. The P fertilizer application contributed in both trials to significant increase of the available P contents and part of the application was transferred in a less soluble form as revealed by the total P (Table 7).

Effect of fertilizers on soil characteristics in the NO-FERT zone

The effects of fertilization in the NO-FERT zone were much less frequent than in the FERT zone. Particularly, in both trials, we found that the K concentrations increased with the KCl rates (Table 8). The effect was significant for CP08, but it only showed a tendency in CP06.

DISCUSSION

After 10 years without N, P or Mg applications, no significant drop was found in FFB yields with N0, P0 and Mg0 in comparison with fertilized palms. Trial CP06 showed that in the absence of KCl, a K and Cl deficiency reduced yield at the end of the trial. Foliar levels significantly increased compared with controls for N (CP08), P (CP06 and CP08), K (CP08) and Cl (CP06 and CP08) when fertilized with N, P and KCl, whatever the dose. These results indicate that some of the fertilizer was absorbed by culture, which is reflected in the case of CP06 by an increase in yield with KCl. Our designs do not allow to know if, beyond dose 1, yields have not increased because the contents had reached the optimum levels or if nutrient losses became very important because of the use of simple, water-soluble fertilizers. The doses 2 of urea, phosphates and KCl we tested are frequently used by the industry (Goh and Härdter, 2003), but we have to conclude that they are not giving better results than doses 1.

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Economically speaking, they were not justified and, given the effects observed on the soil characteristics, they were even potentially dangerous. Indeed, our results showed that the high rates of urea and KCl caused soil acidification and modified the balance between cations. Consequently, rates N2 and K2 should be considered excessive. They might lead to environmental risks of varying intensity depending on the environmental conditions, as clearly illustrated in the differences observed for both trials.

Risks linked to N application

No significant increase in soil N was seen in either trial after the N fertilizer applications. This may have been either (i) because N was taken up by the palms, or (ii) because the excess N not taken up has migrated below the soil layer analysed. It will be lost for the crop if there are no underlying roots (palm or regrowth) to take it up.

It is commonly accepted that excess N can be leached deeply into the soil. In particular, Tung *et al.* (2009) found leaching of N in the form of NH_4 down to a depth of 120 cm when NH_4Cl was applied in weeded circles in Malaysia. Schroth *et al.* (2000) measured nitrate losses down to 150 cm in soils with a low CEC in Amazonia. Banabas *et al.* (2008) measured N losses mainly in the form of NO_3 at a depth of 1.5m. Nitrate leaching below the layer occupied by roots leads to a drop in pH when it generates leaching of Ca or Mg whose positive charges are compensated for by exchangeable H (Sumner, 2009). Several authors (Kee *et al.*, 1995; Nelson *et al.*, 2010) reported drops in pH of 0.5 and up to more than one unit due to the very widespread use of ammonia-based fertilizers for oil palm. Acidification is not a problem in itself since the oil palm is not very sensitive to a low pH (Nelson *et al.*, 2010) and because the toxicity threshold (pH $<$ 3–3.5) identified by Poon (1983) in acid sulphate soils is only reached in exceptional cases.

The results of our trials showed a drop in soil pH and an impoverishment in Ca and Mg in the FERT zone (Table 5). These typical effects of nitrate leaching therefore suggested that the excess N in the FERT zone had effectively migrated below the studied layer and had only been taken up very slightly by the crop, whose productivity did not increase.

This process was accompanied by a concomitant drop in the CEC by about 35% for CP08, which promoted cation leaching. In CP06 trial, no significant drop of CEC was observed, maybe due to high organic C contents in the fertilized zone. Depending on the nature of the underlying soil and soil organic matter content, the excess of N application could therefore lead to leaching of nitrates, and also of K and Mg cations, which are two major nutrients for oil palm nutrition.

Risks linked to KCl application

KCl is the fertilizer most widely used on oil palm to meet its K requirements, but also Cl when that nutrient is deficient. The application rates can reach 3 kg K palm^{-1} yr^{-1} under certain exceptional circumstances. Our results (Table 6) showed that the application of 1.5 kg K palm^{-1} yr^{-1} helped to increase the soil K very significantly. In trial CP06, the increase in exchangeable K per kg of K applied was 2.5 times greater between K1 and K2 than between K0 and K1. In both trials, the contents obtained with K2 largely exceeded 1 cmol kg^{-1}, i.e. a very high value (Goh, 2004) in the range of soils where oil palm is grown.

Enrichment of K in the surface horizon promotes Ca and Mg leaching (Ng *et al.*, 2011; Omoti *et al.*, 1983). Fallavier and Olivin (1988) studied cation leaching in the laboratory on a varied range of soils from Ivory Coast, Ecuador and Indonesia. They confirmed that KCl application led to an increase in exchangeable K which caused the movement of Ca and especially exchangeable Mg, as we found in CP08. In addition, Kee *et al.* (1995) and Tung *et al.* (2009) found K leaching in the soil down to depths of 60 and 120 cm beneath fertilized weeded circles.

The results for CP08 (Figure 1) showed that some interactions between fertilizers can occur and intensify nutrient leaching, which has already been reported by several authors: KCl application can increase N leaching (Omoti *et al.*, 1983); use of NH_4Cl can be conducive to K migration below 30 cm (Anuar *et al.*, 2008). The data available in the literature report great variability in the estimation of N and K losses by leaching, with 1.6% and 5.3%, respectively for Tung *et al.* (2009) up to 34% and 18%, respectively for Omoti *et al.* (1983). This clearly shows that, irrespective of the soil and climate conditions that might lie behind these disparities, it is necessary to avoid excess fertilization, especially when it is of no economic interest.

Effect of P fertilization

The phosphate applications had a significant effect on exchangeable P in the two trials. In trial CP06, the highest rate was twice as high as the one in CP08 (Table 7) and it produced a significant increase in total P due to the uptake of excess P in a less mobile form. Ng *et al.* (2011) also found that repeated applications of rock phosphate in Malaysia had increased the stock of total P and available P (Bray-2) in the surface horizon of soils. The increase in exchangeable P per kg of P applied between P0 and P1 in the two trials was 130 mg kg^{-1} in CP06 and 100 mg kg^{-1} in CP08. With 252 mg kg^{-1} between P1 and P2 for trial CP06, the variation was around twice as great. The same calculations applied to total P between P0 and P1 gave 966 and 989 mg kg^{-1}, respectively, as opposed to 3326 mg kg^{-1} between P1 and P2 in CP06. Even though the P excesses remained limited to the surface horizon and did not migrate far down, they still remained exposed to runoff and were therefore a potential risk of river pollution (Goh *et al.*, 2003.)

Variation in soil reserves

Our results showed that there was no significant effect of the fertilizers on unfertilized soil, apart from K, whose contents increased with KCl (Table 8). This effect was due to the mineralization of pruned fronds whose composition was enriched in K by KCl inputs (Table 3). For CP08, the sampling point was clearly located in the frond-recycling zone (Figure 1) and the results were therefore coherent. On the other hand, in CP06, the sampling point for NO-FERT was distant from the frond pile, yet the

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KCl effect was almost significant ($p = 0.083$). We explained this unexpected result by the fact that the vertical growth of *E. guineensis x E. oleifera* is slow and the harvesters had carried out partial pruning of the frond tips to facilitate their movements. This practice, which lasted for up to 10 years, can explain the recycling of some of the organic matter from the fronds over the entire area. This hypothesis is consistent with the C and N contents, along with the CEC, which were quite similar in the FERT and NO-FERT zones of the control plot (Table 4). Therefore, nutrients were effectively transferred from one zone to another inside the plot. This process was suggested by Tan *et al.* (2014) in Malaysia to explain why the K contents measured under frond piles was similar to those under weeded circles fertilized with KCl.

Over a period of 10 years, the FFB production in CP08 was never significantly reduced by an N, P, K or Mg deficiency, unlike in CP06, where a K and Cl deficiency ultimately occurred. We believe that the reserves in the soil enabled maintaining the productivity of the unfertilized control palms and that the difference in performance between the two trials for the K deficiency is explained by the higher reserves in trial CP08. The capacity of the soil reserves to meet the needs of the crop over several years during a second oil palm cycle was shown by Dubos and Flori (2014) in Ecuador and Colombia. However, even though the soil reserves had been tapped into, it was not possible to show any significant impoverishment in cations and P when analysing the effect of the factors on the NO-FERT zone. This absence of results indicates that the degree of uptake over a period of 10 years was limited and remained below the precision of the laboratory analyses and below the residual error due to sampling.

It is reasonable to worry about the evolution of soil reserves over the long term and Foster (2003) considered that not fertilizing is a highly non-sustainable practice. However, our study clearly illustrated the difficulties of detecting changes in soil when they are of low amplitude and when they require long time steps to show up. Deliberations on the sustainability of soil reserves should consider this dimension and be based on experimental designs in which the prior state of the soil needs to be estimated with good accuracy. The difficulties involved in assessing the decline in soil fertility were largely reported by Hartemink (2006), who provided a reminder that the quality of studies depends on the soil sampling, the analysis methods and the interpretation of the results. Yet, it is only by confronting those difficulties that it will be possible to make headway in constructing sustainability indicators for soil reserves and participate in assessing the impact of oil palm crops on the environment.

It is usual to rely on long-duration fertilization trials to optimize mineral nutrition in oil palm plantations. These designs also provide an excellent basis for examining the effects of fertilization practices on the characteristics of cultivated soil. In the two trials, we investigated effects of fertilizer on both FERT and NO_FERT zones; it has been difficult to compare results between sites as sampling positions were different because of field management and planting material reasons. Our results suggest that designs need to be adapted in order to assess both the changes in soil reserves and the intensity of fertilizer applications, along with interactions between nutrients. The consequences for nutrient losses and, generally speaking, the parameters involved in soil fertility (Hartemink, 2006), need to be assessed case by case in order to improve fertilization efficiency. It is indeed a matter of respecting the balance existing between what is needed to meet biomass productivity requirements, without being detrimental for soil reserves, and for environmental constraints (water table pollution by nitrates, greenhouse gas emissions, contamination of surface water by phosphates). These concerns call for designing protocols in which the compartments where the products involved in exchanges (fertilizers and recycled biomass) are precisely defined. It also seems necessary to explore the soil beyond the layer colonized by roots in order to determine the migration of nutrients to deeper layers. The zones involved in root uptake also need to be integrated, either by using a descriptive model (Jourdan and Rey, 1996) or by using indirect methods such as those proposed by Nelson *et al.* (2006), analysing soil water depletion.

CONCLUSIONS

The results obtained in the two trials set up on soils with contrasting characteristics lead us to conclude that, over a period of 10 years, the reserves played a major role in limiting the impacts of nutrient deficiencies which, in the absence of fertilization, would reduce yields. However, we were unable to measure the beginnings of an impoverishment of the surface horizon reserves, which would confirm this process.

In addition, while everything indicated that the maximum N, P and K contents that were tested were of no interest for improving yields, we were able to measure, in comparison with a moderate application rate, the changes induced by those rates on the properties of the fertilized soil. These results confirmed that we need to continue questioning the intensity of fertilization in oil palm plantations and that we need to continue improving its efficiency. Fertilizer efficiency is both linked (i) to absorption processes and yield response, (ii) to leaching processes in relation with soil properties, fertilizer management and fertilizer properties. This approach, which calls for appropriate experimental designs, goes hand in hand with studies on the environmental impact of fertilization.

SUPPLEMENTARY MATERIALS

For supplementary material for this article, please visit http://dx.doi.org/10.1017/S0014479716000363.

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