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RESEARCH ARTICLE — OPEN ACCESS

Precision agriculture in oil palm plantations: diagnostic tools for sustainable N and K nutrient supply

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Abstract – Predicting the fertilizer requirements of an oil palm plantation has long been a difficult task. Two main methods have emerged. Leaf analyses (LA) were used for fertilization management as early as the 1950s. Leaf contents are compared to optimum references, making it possible to adjust the fertilizer rates applied in each block. Another approach, based on the nutrient balance (NB), is to evaluate and replace nutrients that are exported from the field, or immobilized by the plant. Plantations must adopt environmentally friendly practices; in particular, fertilizer inputs must be estimated with sufficient precision to achieve the highest possible yields, without applying excessive amounts of nutrients in relation to plant demand and the storage capacity of soils. We questioned the relevance of each method for achieving these objectives. We did so using some long-term fertilization trials to compare the optimum N and K rates recommended by each method in the adult phase. It appeared that LA led to moderate rates compared to NB. It also appeared that calculating a precise nutrient balance on a field scale was hampered by a lack of precise information (i) about the biomasses produced and their composition and (ii) about the highly variable outputs of the environmental losses. On the other hand, LA provided a simple indicator of the ability for each block to achieve its potential yield. We believe that this perfectible method is more protective of the environment, without the risk of a significant decrease in yields or a decrease in soil mineral reserves.

Keywords: oil palm / fertilization / nutrient balance / leaf analyses / environmental risk

Résumé – Agriculture de précision pour les plantations de palmier à huile : outils de diagnostic durable des besoins en N et K. L'évaluation des besoins en engrais des plantations de palmiers, exercice toujours difficile, est possible par deux méthodes : les analyses de feuilles (LA) pratiquées depuis les années 1950 qui comparent les teneurs foliaires à des teneurs de référence et modulent la fertilisation parcelle par parcelle et l'établissement d'un bilan des éléments (NB) qui vise à compenser les quantités exportées ou immobilisées par la culture. De nos jours, les plantations sont incitées à avoir des pratiques respectueuses de l'environnement. Pour cela, l'estimation des besoins en engrais doit permettre d'atteindre les plus hauts rendements possibles sans que ces apports n'excèdent la demande de la culture et la capacité de stockage des sols. On s'est interrogé sur la pertinence des deux méthodes en utilisant des essais de fertilisation de longue durée pour déterminer les doses de N et K optimales à l'âge adulte par les deux méthodes. LA conduit à des doses inférieures à celles évaluées par NB. Il ressort aussi que la précision du bilan des éléments à l'échelle de la parcelle se heurte à la difficulté d'estimer finement (i) les biomasses produites et leurs compositions et (ii) la grande variabilité des pertes environnementales. Au contraire, LA est un indicateur simple qui témoigne de la capacité à atteindre le rendement potentiel de chaque parcelle. LA apparaît à la fois un outil perfectible et protecteur de l'environnement sans que son usage expose les plantations à une baisse de productivité ou à une altération des réserves des sols.

Mot clés : palmier à huile / fertilisation / bilan / analyse foliaire / environnement

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Table 1. N and K rates applied and yield response (Mg FFB palm^{-1} yr^{-1}) observed for each N and K level in the selected trials (AK01, BB03, SG01 and TG02 are located in Indonesia, PR01 in Nigeria, PS01 in Peru and TT08 in Ecuador). The yield associated with the optimum N or K rate appears in bold.

						Observed yield according to fertilizer level				
Trial	YOP	Nutrient	Rate (kg palm^{-1} yr^{-1})	Age (1)	Age (2)	0	1	2	3	Pr > F
AK01	1978	N	0–0.46–0.92	6	13–16	18.44[a]	21.33[a]	**23.66**[a]		< 0.001
BB03	1974	N	0–0.69–1.38	4	12–15	23.73[a]	**25.63**[a]	26.12[a]		**0.009**
SG01	1975	N	0–0.69–1.38	3	12–15	**32.02**	33.85	33.51		0.535
TG02	1971	N	0–0.69–1.38	8	15–18	21.31[a]	**25.28**[a]	27.08[a]		**0.001**
TT08	1997	N	0–1.38	7	12–15	**24.45**	24.64			0.811
AK01	1978	K	0.7–1.4	6	13–16		**20.81**	21.48		0.302
BB03	1974	K	0–0.5–1	4	12–15	**24.85**	25.21	25.42		0.746
PR01	1997	K	0–0.75–1.5–2.25	3	15–18	15.30[a]	**18.99**[a]	19.62[a]	19.54[a]	< 0.001
PS01	1983	K	0–0.75–1.5	5	12–15	20.77[a]	**23.19**[a]	23.30[a]		< 0.001
SG01	1975	K	0–0.75–1.5	3	12–15	**31.67**	34.99	32.72		0.203
TG02	1971	K	0–0.5-1	8	15–18	**23.74**	24.43	25.50		0.185
TT08	1997	K	0–0.75–1.5	4	12–15	**24.07**	25.04	24.53		0.605

YOP: year of planting. (1) Age since rates remained constant up to the end of the study period for yield. (2) Age for yield observations.
[a] Not significantly different ($P = 5\%$), according to the Tukey test.

1 Introduction

Oil palm, the main source of vegetable oils, will continue to occupy an important place in the future because of its high productivity and low production costs. Unfortunately, the cultivated areas are mainly located in an equatorial band between the latitudes ten degrees North and South. This area is also the home of equatorial and tropical rainforests. There is therefore a need to increase productivity to minimize the extension of cultivated areas, which could threaten these lands that are essential for biodiversity. The intensification of oil palm cultivation relies on genetic improvement and the adoption of good management practices; among these practices, fertilization with mineral or organic fertilizers plays an important role. The specific objective of fertilization is both:

– to not limit yields and deplete soil reserves if nutrient inputs are lower than the requirements of the plant;
– to avoid excessive amounts, which have a detrimental effect on the environment.

The dilemma between these potential environmental issues can only be overcome by adopting fertilizer recommendation tools that are accurate on a field scale.

The main needs of oil palm plantations are potassium (K) and nitrogen (N). These two nutrients can contaminate groundwater by a leaching process. N is also a potential source of greenhouse gas (GHG) emissions, which can reach 48.7% of total GHG produced per Mg of fresh fruit bunches (FFB) (Choo *et al.*, 2011). Two methods are commonly used to estimate K and N requirements. The first, in use since the 1950s, uses leaflet analysis (LA) to adjust fertilizer rates. Optimum leaf contents and fertilizer rates to achieve the best yield are based on site specific fertilization trial results. The second most common method in Southeast Asia is based on a nutrient balance (NB); it consists in replacing the amounts of nutrients that are immobilized in the palm biomass and exported through FFB production.

The purpose of this paper was to examine the degree of the discrepancies obtained when calculating the optimum N and K rates using both methods. To do this, we used a set of long-term trials in which it was possible both to observe yield responses to K and N fertilization and to calculate a nutrient balance. We sought the sources of the differences between the estimated rates within the principles of each method. We also assessed their consistency, in order to obtain an accurate diagnosis of needs that avoided unjustified fertilizer inputs, while maintaining soil reserves.

2 Materials and methods

We used seven long-term fertilization trials, for which yield data corresponding to the mature period were available, located in Indonesia, Ecuador, Peru and Nigeria (Tab. 1). These trials were studying the effects of 3 or 4 fertilizers, each represented by 2 or 3 rates. They were designed as factorial experiments in a single complete replication with high order interactions confounded with blocks and residual error. The experimental plots comprised 30 to 42 palms, of which the 12 to 20 central palms were used for yield and leaf content results. Under the climate and soil conditions specific to each situation, the aim of these trials was to determine the optimum rates to achieve potential yield, along with the corresponding leaf contents. All these trials were planted with a planting material of the same origin: standard Deli x La Mé available in each of the countries. Our study focused on the N and K nutrients, which account for the largest share of fertilizer inputs in adult oil palm plantations. The N factor was only studied in five trials.

Increasing rates of N and K were applied over long periods in the form of urea and KCl. The fertilizer rates were applied once a year, except for AK01 where the rates were split into two applications. The data used to study the effects of N and K on FFB yields were the 4-year average values obtained under long-term steady-state conditions: these were means for at least 12 to 15 years old and up to 15–18 years old for the longest trials. The corresponding fertilizer rates remained constant for at least 5 years before the beginning of the study periods and more generally for 7 to 9 years.

FFB yields were computed for each trial over the periods studied. When the Anova F tests for K and N effects were significant, we used the Tukey test at the 5% significance threshold to differentiate the mean results for each application rate.

Using two different methods taking into account different objectives, the experimental results were used to calculate the optimum N and K rates under the soil and climate conditions specific to each trial.

LA method: to assess the LA reference contents to be used with this method, we had to determine the optimum fertilizer rates from yield response curves. First, we checked that there were no significant interactions between the N and K factors. Then, we calculated the average yield corresponding to each level of N, and the gain for each N increment, by averaging the results for all levels of K, and vice versa for K and N. Lastly, we selected the minimum N and K rates beyond which there was no significant increase in yield over 4 years. We considered these rates optimum as they resulted in yields close to the maximum yield. The leaf contents reached in each trial with these rates could then serve as a reference for interpreting the leaf analyses of commercial blocks. However, our work only presents the optimum rates obtained in each trial with this method.

NB method: this method is designed to compensate for all the terms of a nutrient balance over the long term. We therefore assessed the quantities of N and K that corresponded to the production of aerial biomass and environmental losses over a representative period of the adult stage. To avoid deviation, we used the same period as for the LA method (Tab. 1). Biomass production was restricted to annual stem growth and FFB production, because for the sake of simplicity we considered, like Ng *et al.* (1999) and as Vis *et al.* (2001), that leaves, roots and male flowers were recycled over short enough time steps not to intervene in the nutrient balance. We also considered that there was no recycling of empty fruit bunches (EFB) or palm oil mill effluent (POME). Data from Tarmizi and Mohd Tayeb (2006) were used to calculate the annual stem N and K requirements. Exports due to FFB production were evaluated using data from Ng *et al.* (1999) for N (3.3 g kg^{-1} FFB) and Teoh and Chew (1987) for K (4.3 g kg^{-1} FFB). When the Anova showed that some N and K levels were not optimum, these were excluded from the calculation to avoid the effects of deficiencies on yields.

For N and K environmental losses, we used the figures mentioned by Ng *et al.* (1999), *i.e.* 21 and 28 kg ha^{-1} respectively for total losses due to erosion, run-off and leaching.

Total N and K outputs were converted to N and K rates (kg palm^{-1} yr^{-1}) using a planting density of 143 palm ha^{-1}.

Due to the lack of precise information per site, atmospheric deposition and the contribution of the legume cover crop for N were not taken into account as inputs. The results of the nutrient balance corresponded to the quantities of N and K that should be returned in mineral form (fertilizer, atmospheric inputs) or organic form (EFB, POME, compost).

3 Results

Table 1 provides the average N and K rates that were studied in each trial, as well as the corresponding yields. Of the five trials studying responses to N input, two showed no significant increase in yield. No N fertilization appeared to be necessary. For two trials, the first fertilizer rate (0.69 kg N palm^{-1} yr^{-1}) gave the upper limit of the inputs, since no significant increase in yield was observed beyond it. The last trial, AK01, indicated a minimum rate of 0.92 kg N palm^{-1} yr^{-1} to achieve the potential yield.

Of the seven trials studying responses to K inputs, four did not show any significant increase in yield compared to the control without fertilizer. Two trials showed significant increases in yields, but a rate of 0.75 kg K palm^{-1} yr^{-1} was sufficient to achieve the potential yield. In the last trial, AK01, there was also no significant increase in yield beyond 0.70 kg K palm^{-1} yr^{-1}.

Table 2 shows the FFB yields that were used for the NB as well as the total N and K outputs obtained by adding the demand for annual stem growth and environmental losses. Yields ranged from 18.6 Mg ha^{-1} yr^{-1} in Nigeria to over 33 Mg in Indonesia, where the climate was more favourable. Yields observed in South America ranged between 23 and 25 Mg ha^{-1} yr^{-1}.

The rates determined with the LA or NB methods under the conditions of each trial are shown in Table 3. There is no comparison for the N rates of trials PR01 and PS01, which do not study this element. The differences between the two methods were substantial when the yield response curves indicated that no input was needed, while the NB method always indicated a non-zero rate. The differences between N rates were modest for three of the trials; they were consistent for SG01 and TT08, since they were equivalent to 4 to 5 kg of ammonium sulphate (21% N). The differences between K rates were systematic, with a maximum equivalent to 3 kg of KCl (50% K).

4 Discussion

Our results led us to conclude that the fertilizer recommendations obtained by two methods applied to seven data sets gave consistently lower quantities when the experimental results were interpreted in the simplest way. The duration of the trials and the age of the study period were sufficient to consider that the applications were in balance with the reserves of the plantation. It appeared that, for several trials, no N or K inputs seemed necessary, because the N and K reserves allowed satisfactory productivity, not differing from the maximum yield observed, on average, over 4 years. This conclusion does not mean that no inputs will be needed in the long term, because of predictable yield losses and soil depletion (Hartemink, 2006). However, the discrepancies

Table 2. N and K budgets for potential FFB yields (FFB contents according to Ng *et al.* (1999) and Teoh and Chew (1987), respectively), annual stem growth (Tarmizi and Mohd Tayeb, 2006), and environmental losses (Ng *et al.*, 1999). FFB demands account for 59% to 72% of the total demand for N and 53% to 67% of the total demand for K.

Trial	Yield FFB Mg ha^{-1} yr^{-1}	Export (kg ha^{-1} yr^{-1}) N	K	Total demand (kg ha^{-1} yr^{-1}) N[a]	K[b]
AK01	23.60	77.9	101.5	120.9	172.5
BB03	25.88	85.4	111.3	128.4	182.3
PR01	18.60	61.4	80.0	104.4	151.0
PS01	23.31	76.9	100.2	119.9	171.2
SG01	33.18	109.5	142.7	152.5	213.7
TG02	26.17	86.4	112.5	129.4	183.5
TG08	24.60	81.2	105.8	124.2	176.8

[a] Including 22 kg for stem growth and 21 kg for environmental demand.
[b] Including 43 kg for stem growth and 28 kg for environmental demand.

Table 3. Recommended N and K rates (kg palm^{-1} yr^{-1}) according to the LA and NB estimation methods.

	According to trial results (LA)				According to NB		Difference NB-LA	
Trial	N level	K level	N	K	N	K	N	K
AK01	2	1	0.92	0.7	0.85	1.21	-0.07	0.51
BB03	1	0	0.69	0	0.90	1.27	0.21	1.27
PR01		1		0.75	0.73	1.06		0.31
PS01		1		0.75	0.84	1.20		0.45
SG01	0	0	0	0	1.07	1.49	1.07	1.49
TG02	1	0	0.69	0	0.90	1.28	0.21	1.28
TT08	0	0	0	0	0.87	1.24	0.87	1.24

between the NB and LA methods suggested that the setting of the nutrient balance should actually be modulated for each situation.

Models including a nutrient balance meet at least the principle of a nutrient repository; the more complex models such as INFERS developed by Applied Agricultural Research in Malaysia include other variables that allow, for example, the correction of soil and plant reserves (Goh, 2004; Corley and Tinker, 2016). When these reserves have become optimum, the quantities of nutrients to be offset are mainly due to growth demand and environmental losses, which justify the choices for our study. However, a literature search indicated that many variables have effects on these budgets; these effects are summarized below.

4.1 Growth demand

As shown in our results (Tab. 2), FFB account for a significant share of the nutrient balance (Corley and Tinker, 2016), especially when soil and climate conditions allow yields exceeding 30 Mg ha^{-1} yr^{-1}. It is therefore important to estimate this budget correctly, but few direct determinations of FFB composition are available. Some are very old, such as those made by Ng *et al.* (1968) for dura palms. Despite this, this reference is still in use, as shown in the NB presented by Ng *et al.* (1999) and Vis *et al.* (2001). However, Tarmizi and Mohd Tayeb (2006) obtained results of around 6% higher for tenera palms. Ng *et al.* (1968) also reported significant variations in the N and K contents of FFB (particularly in the spikelet and stalk components) depending on the production site. These authors attributed the variations of around 10% to soil properties, especially K abundance and fertilization. Citing the same reasons, Teoh and Chew (1987) found K values of 4.32 g kg^{-1} FFB for inland soils and 5.12 g kg^{-1} FFB for coastal soils in Malaysia, a variation of about 15%.

Annual immobilization of nutrients in the stem can also vary substantially from one site to another. This may be due to differences in biomass production, but also to stem composition. Jacquemard and Baudoin (1987) emphasized the importance of the environment on palm stem growth, which results in significant height differences for a given planting material at the same age in Africa or Indonesia. The intensity of the dry season appears to be an important factor, as are soil factors affecting the water supply, which explains the variability that the authors observed within plantations. Differences between progenies have also been reported (Jacquemard and Baudoin, 1987; Ollivier *et al.*, 2017). Lastly, stem growth is not constant during the life of a palm (Jacquemard and Baudoin, 1987). For these reasons, large variations can been found in the literature, as illustrated by the results of Tarmizi and Mohd Tayeb

(2006) – annual dry biomass of 42.5 kg for vertical growth of 80.4 cm yr^{-1} between 9 and 12 years, and Ng and Thamboo (1967); – annual dry biomass of 68.4 kg for vertical growth of 70 cm yr^{-1} between 11 and 15 years old. The abundance of K in the soil may also influence, as shown by Ng *et al.* (1968) when comparing the K budget of the stem on inland soils (50.4 kg ha^{-1} yr^{-1}) and coastal soils (87.5 kg ha^{-1} yr^{-1}) in Malaysia. Lastly, N stored in the stem used for the NB method in the literature ranged from 8.5 kg ha^{-1} yr^{-1} (Kee, 2004) to 29.3 ha^{-1} yr^{-1} (Ng and Thamboo, 1967), while those for K ranged from 30.2 kg. ha^{-1} yr^{-1} (Kee, 2004) to 49.7 ha^{-1} yr^{-1} (Ng and Thamboo, 1967).

To sum up, the FFB contents and stem exports we used for the NB method were not excessive compared to those found in the literature, but they may not have been adapted to the environment of our trials.

4.2 Environmental losses

The most commonly used values for total run-off and erosion losses (Ng *et al.*, 1999; Vis *et al.*, 2001) are those provided by Goh (1992): 17.6 kg N ha^{-1} yr^{-1} and 21.6 kg K ha^{-1} yr^{-1}. They vary substantially with the topography. With barely a slope, Banabas *et al.* (2008) measured average run-off of 1.4 and 6% of incident rainfall at two PNG sites; the corresponding N losses were very low (0.3 and 2.2 kg ha^{-1} yr^{-1}). With more pronounced slopes ranging from 6 to 14%, Kee and Chew (1996) measured total losses between 19.5 and 22 kg ha^{-1} yr^{-1} for N and between 41.6 and 53.8 kg ha^{-1} yr^{-1} for K, depending on fertilization intensity. With slopes ranging between 8 and 18%, they observed run-off losses of between 15 and 22 kg N ha^{-1} yr^{-1} and between 21 and 54 kg K ha^{-1} yr^{-1}. They also measured that erosion losses averaged 10 kg N ha^{-1} yr^{-1} and 0.4 kg K ha^{-1} yr^{-1}.

Slopes, which vary greatly from one block to another, are therefore an important factor. When they reach and exceed 17%, special planting techniques (terraces, contour lines) are essential (Gillbanks, 2003). For lower slopes, it is possible to reduce erosion processes by covering the soil with pruned leaves. On slopes of 6 to 8%, Lim (1989) measured a significant decrease of 22 m^3 soil ha^{-1} yr^{-1} on bare soil to 13 m^3 ha^{-1} yr^{-1} with the best pruned leaf arrangements.

Sandy textures are highly conducive to N and K leaching (Kee, 1977; Foong, 1991; Sharma and Sharma 2013). On the other hand, clay soils are conducive to K adsorption and reduce the risk of leaching losses (Sharma and Sharma, 2013). Olivin and Ochs (1974) came to a similar conclusion by comparing K losses through leaching in the sandy clay soils of Benin and in the tertiary sands of Ivory Coast: 6 months after the application of 2 and 4 kg KCl per palm, all K inputs were still present in the 0–30 cm layer in Benin, while only 35 to 45% of the inputs in Ivory Coast remained. Using a lysimeter, Foong *et al.* (1984) measured actual losses in the mature phase for a clay loam soil. They concluded on low losses (2.90 kg N and 7.54 kg K ha^{-1} yr^{-1}), of which 66 and 70% were recorded during the wettest months (>200 mm). For Banabas *et al.* (2008), annual rainfall should also be taken into account because it generates surplus water, which feeds the drainage system when the rains are higher than the evaporative demand; for two PNG sites, they established that surplus water reached 1015 mm yr^{-1} and 2178 mm yr^{-1} and the measured N losses increased from 37 to 103 kg ha^{-1} yr^{-1}.

This shows that there is great variability in environmental losses depending on the specificities of each site (rainfall, slopes, soil texture). Pardon *et al.* (2016a) conducted a literature search on N fluxes measured in oil palm plantations and concluded that N losses were the most difficult to predict. This conclusion is also apparent when using existing models to assess N losses. For Pardon *et al.* (2016b) the variability of the results was due to the fact that models do not sufficiently take into account all the standard practices and their effects.

4.3 Are the existing diagnostic tools adapted to the challenges of the future?

The use of LA, leaflets or rachis, means observing a deficiency threshold below which yields are reduced by the effect of the deficiency on the metabolism. Experimentally significant differences appear between the yields obtained depending on the treatments. Corresponding contents are considered as deficient or not. By adjusting a response curve according to the Mitscherlich model, it is possible to introduce economic parameters and to define an optimum content in terms of returns per kg of fertilizer. Webb (2009), using a typical NxK factorial fertilizer trial, proposed a conceptual framework to model response surfaces for yields, nutrient contents and fertilizer rates. This approach also made it possible to calculate optimum economic fertilizer application rates and the corresponding nutrient contents.

Although the LA method is considered empirical (Goh, 2004), the diagnosis that is drawn from it is consistent with the physiology of the nutrients in the organs analysed; for example, N and Mg are present in photosynthetic tissues, K in stomatal cells and in transfer organs such as the rachis.

Another underlying idea to explain the relevance of LA is that the contents reflect the abundance and, conversely, the depletion of soil reserves. A level close to the deficiency threshold would indicate that the nutrient can no longer be taken up in sufficient quantity in response to demand.

In its functioning, the LA method does not exclude not fertilizing when the contents for a nutrient are high and this decision is accepted by several authors: Kee (1977) reported situations where the soil reserves were considered sufficient and justified no fertilization for a few years; Teoh and Chew (1987) also concluded that on some soils in Malaysia where no KCl yield response was observed, it was conceivable to suspend fertilization for a few years to avoid luxury K reserves in the stems.

The main weakness of the LA method is to ignore the evolution of the reserves as a whole over the long term and not to worry about soil fertility. However, might there not be variations in the stock of soil nutrients that would be acceptable without needing to talk about nutrient mining? In an attempt to answer this question, Dubos *et al.* (2017b) compared the soil properties of some plots unfertilized for 10 years to those of fertilized plots in a factorial trial studying the effect of N, P and K. They were unable to conclude that there was a depletion of the soil reserves, particularly for K, whereas leaf K contents and yields were significantly lower than those in the fertilized plots. Leaf contents can therefore reflect breaks in nutrition that can be assimilated to the beginnings of a depletion of resources. As pointed out by Hartemink (2006), the resilience of each soil, which determines when soil requires the replenishment of what has been removed or lost, is variable. He also emphasized that not all the properties that determine soil fertility have the same degree of reversibility of a change, and that correcting a drop in exchangeable K is not a difficulty when compared to increasing low organic C. It can therefore be envisaged that there will be acceptable variations in the nutrient reserves of soils, provided that the "set point" leaf contents from which the strengthening of mineral or organic fertilization starts are correctly fixed. In addition, although sampling methods exist (Nelson *et al.*, 2015), the observation of soil reserves by analyses is not easy to implement and use of the LA method could be just as effective.

In the NB approach, the objective is clearly to return to the soil/plant system everything that is taken out. The accuracy of the tool largely depends on the accuracy of the estimates of the different items. As we have seen, there is a lack of data on the composition of growth demand. We have seen that, for K, the richness of the soil and therefore fertilization could have an influence on the stem and FFB contents. Quantifying annual biomass is also fundamental to being able to calculate outputs. The stem growth rate is variable over time and depends on the genetic origin of the palms. Lastly, some authors seem to consider that FFB yield is an objective that will be achieved once nutrients are provided in sufficient quantities. The goal is usually to achieve maximum yield at each site (Corley and Tinker, 2016) and this target can reach 35 t FFB ha^{-1} yr^{-1} (Weng, 2005). Any error in estimating the potential yield of each block will therefore have consequences for the estimate of requirements, especially if the actual yield is found to be limited by another productivity factor.

The main risk of misusing NB is to overestimate the quantities of nutrients needed, even when benchmarking according to the actual yield observed over many years, as we did. This results in excessive use of nutrients without economic benefit. There are also significant environmental risks when the quantities of N and K exceed the requirements of the plant (Armour *et al.*, 2013) and the storage capacity of the soil: acidification of the soil, a drop in CEC and the release of GHG increase with N inputs, and leaching of nitrates and cations can contaminate groundwater.

4.4 Are the LA and NB methods compatible with precision farming?

Whether fertilizer rates are calculated by the LA or the NB method, fertilization recommendations are intended to be applied on a block scale of 50 to 100 ha. It seems difficult to adopt a finer scale in terms of precision agriculture. However, this scale is perfectly compatible with the acquisition of the data that informs both methods. The planting material and the main soil class are generally homogeneous within each block, which makes it possible to refine the biomass production data for NB. The correct interpretation of the leaf K content must also take into account the chemical properties of soils (Dubos *et al.*, 2017a) and the origin of the planting material, since nutrient uptake may vary by up to 30–40% from one type of material to another, for the same level of production (Ollivier *et al.*, 2017). As previously mentioned, environmental losses vary widely depending on the situation, but the parameters that determine them are known as characteristics of the blocks. Losses due to erosion, run-off and leaching depend on the nature of the soil, the topography and the rainfall pattern. Soil texture and permeability may worsen or decrease N and K flow downwards. The nature of clays can also intervene. It is not possible to express the risks on a finer scale within blocks, but it is possible to adopt best farming practices to reduce potential risks on a finer scale. Soil cover is a key factor in controlling run-off and erosion (Sionita, 2014). Understorey vegetation can also play a buffer role by taking up nutrients when conditions are conducive to vegetative growth and restoring them according to maintenance schedules. Depending on the composition of the plant cover on the ground, and in particular the presence or absence of legumes, symbiotic or non-atmospheric nitrogen fixation may take place (Pardon *et al.*, 2016a). These poorly quantified flows are often not taken into account by NB.

It is also possible to adopt anti-erosion techniques, scatter fertilizers, improve soil CEC by organic matter applications, split fertilizer inputs and take into account the rainfall calendar. The goal is to avoid both the wettest months and drought periods, which increase the volatilization of N in ammoniacal form when urea is used (Gillbanks, 2003). The use of controlled release products should be more widely used in leaching contexts. Lastly, the increasing use of organic by-products (EFB, compost), offers interesting prospects for improving the fertility of soils, by acting on their physico-chemical properties and their biota. In blocks, most susceptible to run-off and erosion, EFB applications are recommended.

Ultimately, it seems difficult to accurately assess the environmental losses of each block and supply the NB. Conversely, it is possible to reduce losses by best management practices that take into account within-block variability in terms of the nature of soils and topography. Additionally, for N losses, the most consistent prediction models with *in situ* measurements are those that take into account specific variables such as texture and root depth (Pardon *et al.*, 2016b). This is why we believe that the priority is to minimize environmental losses. It would then be more acceptable to compensate for them by a minimum contribution (NB method), or to consider that in the long term this will have repercussions on the leaf contents and lead to an adjustment of fertilizer rates.

5 Conclusion

The NB method consists in replacing nutrients exported from the field in order to achieve the maximum potential yield and preserve the mineral reserves of soils for the sake of sustainability (Roundtable on sustainable palm oil, 2013). Our simulation based on long-term trials leads us to suspect that needs are overestimated in comparison with the responses of yields to fertilizer rates. We believe that this is related to inaccuracies in the data used in the calculations. More results would therefore be needed to accurately assess growth demand budgets. We also query the feasibility of obtaining an accurate estimate of the environmental losses in each block, due to the number of factors influencing the calculations. We also question the merits of returning nutrients to the soil when they are already abundant, especially if leaf contents are within ranges where local experiments indicate that no increase in yield is expected. It appeared to us that the main risk is that of providing quantities of nutrients that exceed the storage capacities of the soil and plant demand, which could harm the environment. This risk may be greater than that of a depletion of soil reserves.

Faced with these multiple questions, we propose to continue using leaf analyses as a monitoring tool for oil palm fertilization. Their interpretation must be combined with fertilization trials to specify the references of each situation. The LA method generally leads to recommendations that are significantly lower than those calculated from growth demand and environmental losses. However, we believe that the tool is sensitive enough to detect a depletion of soil reserves before it can be measured by soil analysis. The objective is clearly to avoid the risk of excessive fertilization, without significantly deviating from maximum yield.

References

Armour JD, Nelson PN, Daniells JW, Rasiah V, Inman-Bamber NG. 2013. Nitrogen leaching from the root zone of sugarcane and bananas in the humid tropics of Australia. *Agric Ecosyst Environ* 180: 68–78.

Banabas M, Turner MA, Scotter DR, Nelson PN. 2008. Losses of nitrogen fertiliser under oil palm in Papua New Guinea: 1. Water balance, and nitrogen in soil solution and runoff. *Aust J Soil Res* 46(4): 332–339.

Choo YM, Muhamad H, Hashim Z, Subramaniam V, Puah CW, Tan Y. 2011. Determination of GHG contributions by subsystems in the oil palm supply chain using the LCA approach. *Int J Life Cycle Assess* 16(7): 669–681.

Corley RHV, Tinker PB. 2016. The Oil Palm, 5th ed. Chichester, West Sussex, UK: John Wiley and Sons, 680 p. ISBN: 978-1-118-95330-3.

Dubos B, Baron V, Bonneau X, Flori A, Ollivier J. 2017a. High soil calcium saturation limits use of leaf potassium diagnosis when KCl is applied in oil palm plantations. *Exp Agric* 54(5): 1–11.

Dubos B, Snoeck D, Flori A. 2017b. Excessive use of fertilizer can increase leaching processes and modify soil reserves in two ecuadorian oil palm plantations. *Exp Agric* 53(02): 255–268.

Foong SF. 1991. Potential evapotranspiration, potential yield and leaching losses of oil palm. In: Basiron Y, Sukaimi J, Chang KC, et al., eds. Proceedings of the PORIM International Oil Palm Conference. Progress, prospect and challenges towards the 21st century, Kuala Lumpur, Malaysia, pp. 105–119.

Foong SF, Syed Sofi SO, Tan PY. 1984. A lysimetric simulation of leaching losses from an oil palm field. In: Proceeding of the seminar on fertilisers in Malaysian agriculture. Malaysian society of soil science, Serdang, pp. 45–68.

Gillbanks RA. 2003. Standard agronomic procedures and practices. In: Fairhurst T, Hardter R, eds. Oil palm: Management for large and sustainable yields. Singapore: PPI, PPIC and IPI: Potash & Phosphate Institute, pp. 116–150.

Goh KJ. 1992. A model of nutrient balance and dry matter allocation of oil palm in Malaysia (Msc Thesis).

Goh KJ. 2004.Fertiliser recommendation systems for oil palm: estimating the fertiliser rates. In: Chew PS, Tan YP, eds. Presented at the MOSTA Best Practices Workshops – Agronomy & Crop Management, Kuala Lumpur Malaysia, pp. 235–268.

Hartemink AE. 2006. Assessing soil fertility decline in the tropics using soil chemical data. *Adv in Agron*. Elsevier, 179–225.

Jacquemard J, Baudoin L. 1987. Contribution to the study of oil palm vertical growth – A descriptive model. *Oléagineux* 42(10): 343–351.

Kee KK. 2004. Nutrient reserves and recycling from oil palm trunks at replanting. In: New Directions for a Diverse Planet. Presented at the Brisbane, Australia.

Kee KK, Chew PS. 1996. Nutrient losses through surface runoff and soil erosion – Implications for improved fertiliser efficiency in mature oil palms. Presented at the Kuala Lumpur, pp. 153–169.

Kee NS. 1977. Review of oil palm nutrition and manuring. Scope for greater economy in fertilizer usage. *Oléagineux* 32(5): 197–209.

Lim KH. 1989. Soil erosion control under mature oil palms on slopes. Presented at the PORIM International Palm Oil Development Conference, Kuala Lumpur Malaysia, pp. 191–198.

Nelson PN, Banabas M, Goodrick I, Webb MJ, Huth NI, O'Grady D. 2015. Soil sampling in oil palm plantations: a practical design that accounts for lateral variability at the tree scale. *Plant and Soil* 394 (1–2): 421–429.

Ng HCP, Chew PS, Goh KJ, Kee KK. 1999. Nutrient requirements and sustainability in mature oil palms – An assessment. *Planter* 75 (880): 331–345.

Ng SK, Thamboo S. 1967. Nutrient contents in oil palm in Malaya 1. Nutrients required for reproduction: fruit bunches and male inflorescences. *Malays Agric J* 46(1): 3–45.

Ng SK, Thamboo S, De Souza P. 1968. Nutrient contents of oil palm in Malaysia – II Nutrients in vegetative tissues. *Malays Agric J* 46(3): 332–391.

Olivin J, Ochs R. 1974. Le lessivage du potassium et du magnésium en colonnes de terre. Premiers résultats expérimentaux. *Oléagineux* 29(4): 175–182.

Ollivier J, Flori A, Cochard B, *et al.* 2017. Genetic variation in nutrient uptake and nutrient use efficiency of oil palm. *J Plant Nutr* 40(4): 558–573.

Pardon L, Bessou C, Nelson PN, *et al.* 2016a. Key unknowns in nitrogen budget for oil palm plantations. A review. *Agron Sustain Dev* 36(1): 1–21.

Pardon L, Bessou C, Saint-Geours N, *et al.* 2016b. Quantifying nitrogen losses in oil palm plantations: Models and challenges. *Biogeosciences* 13(19): 5433–5452.

Roundtable on sustainable palm oil, 2013. RSPO P&C for the production of sustainable palm oil. Available from: https://www.rspo.org/key-documents/certification/rspo-principles-and-criteria.

Sharma V, Sharma KN. 2013. Influence of accompanying anions on potassium retention and leaching in potato growing alluvial soils. *Pedosphere* 23(4): 464–471.

Sionita. 2014. Water run-off, soil erosion and nutrient losses: impact of slope and ground vegetation. Presented at the ICOPE conference Oil Palm Cultivation – Becoming a Model for Tomorrow's Sustainable Agriculture, Bali, Indonesia. Available from: http://icope-series.com/2014-oral-abstract/09%20-%20TS04%20RibkaErosion-JPC-rev-1022014.pdf.

Tarmizi AM, Mohd Tayeb D. 2006. Nutrient demands of tenera oil palm planted on inland soils of Malaysia. *J Oil Palm Res* 18(1): 204–209.

Teoh KC, Chew PS. 1987. Potassium in the oil palm ecosystem and some implications to manuring practice. Presented at the Kuala Lumpur, 1987 International Oil Palm/Palm Oil Conferences: Progress and prospects, Malaysia: pp. 277–286.

Vis JK, Smith BG, Rao V, Corley RHV. 2001. Sustainable Agriculture – Unilever's view. Presented at the 2001 PIPOC International palm oil congress: Cutting-edge technologies for sustained competitiveness, Kuala Lumpur, pp. 233–243.

Webb MJ. 2009. A conceptual framework for determining economically optimal fertiliser use in oil palm plantations with factorial fertiliser trials. *Nutr Cycl Agroecosyst* 83(2): 163–178.

Weng CK. 2005. Best-developed practices and sustainable development of the oil palm industry. *J Oil Palm Res* 17: 124–135.

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