FERTILIZER RECOMMENDATION SYSTEMS FOR OIL PALM: ESTIMATING THE FERTILIZER RATES

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Fertilizer management constitutes the largest field cost item in well-run oil palm plantations in Malaysia. 85 % or more of this production cost goes into the purchase of fertilizers alone. It is therefore essential that agronomists use an objective and scientific fertilizer recommendation system, which is capable of computing the optimal fertilizer rates that are repeatable for the same conditions and do not vary substantially between them. The development of such a fertilizer recommendation system has been in fact the focus of many agronomists in Malaysia since the first fertilizer response trial on oil palm was laid down in 1929.

This paper describes in detail some major fertilizer recommendation systems such as the French system, Foster system, PORIM Open system and INFERS. These systems are based on leaf analysis, soil analysis, nutrient balance approach, plant nutrient demand principles or their combinations. Only INFERS fertilizer recommendation system explicitly computes the nutrients required to correct nutrient deficiency and meets the growth demand of oil palm, and nutrient losses through environmental processes. This paper also highlights the necessity of using supplementary measurements and some heuristic rules to optimize the fertilizer rates generated by the fertilizer recommendation systems.

Our present knowledge of oil palm nutrition allows the production of site-specific fertilizer recommendations. Therefore, we should not rely on ad-hoc methods to draw up the fertilizer rates or provide the same fertilizer rates to palms on very different environments. The major fertilizer recommendation systems are sensitive to the reliability of the input data for precise estimation of fertilizer rates and compromises such as maintaining large field sizes and skipping leaf analysis of some fields should not be made except when they are due for replanting.

"The continuing pressures of high fertilizer prices since the "energy crisis" have demanded a critical search for possible measures to economize on and maximize benefits from fertilizer inputs. The past attitude of a large insurance margin in manuring because of relatively cheap supplies is no longer tenable."

Ng Siew Kee (1977)

This perceptive statement presented at the conference on "International development in oil palm" organized by the Incorporated Society of Planters in 1976 is still relevant today although the reasons for the high fertilizer prices may differ. The phrase "a large insurance margin in manuring …. is no longer tenable" implies the necessity of a system of working out the optimum fertilizer rates correctly, which forms the main purpose of this paper.

Fertilizer response trials, which provide critical information for developing fertilizer recommendation systems, were first laid down in Malaysia in 1929 on oil palm planted in 1922 and 1923 (Belgrave, 1937). Since then, many trials have been conducted on a wide range of soil types, climate, palm ages, and fertilizer types and rates in Malaysia. The results have been used to draw up general fertilizer schedules for oil palm on different soil types and palm ages (Rosenquist, 1966; Hew and Ng, 1968), and to develop systems to compute the optimum fertilizer rates for oil palm (Foster *et al*., 1986; Kee *et al*., 1994; Corley and Tinker, 2003; Foster, 2003). Similarly, CIRAD (Centre de Cooperation Internationale en Recherche Agronomique pour le Developpement) has been conducting fertilizer response trials on oil palm in other parts of the world especially Africa, Indonesia and South America resulting in a method to predict the fertilizer rates based on leaf analysis (Caliman *et al*., 1994). Apart from these published work, it is also known that private research companies and organizations have developed their own proprietary fertilizer recommendation methods for oil palm, which are probably variants of the above systems.

This paper describes only the major methods to predict the fertilizer rates required for oil palm. The principles behind each method and their advantages and disadvantages are briefly described. Interested readers should refer to the excellent write-up on the subject by Corley and Tinker (2003) and Foster (2003) for further details. In fact, this paper quotes them unashamedly and almost verbatim in many instances. However, it complements the above work by including methods to predict fertilizer rates and shows their computations in a cookbook manner.

FERTILIZER RECOMMENDATION SYSTEMS

The main objectives of a fertilizer recommendation system are (Goh *et al*., 1999a):

1. To supply each palm with adequate nutrients in balanced proportion to ensure healthy vegetative growth and optimum economic FFB yields.

2. To apply the fertilizers in the prescribed manner over the areas of the estate that are likely to result in the most efficient uptake of nutrients.

3. To integrate the use of mineral fertilizers and palm residues.

4. To minimize negative environmental impacts related to over-fertilization, land degradation, and pollution from heavy metals such as cobalt and eutrophism by P application.

These multi-objectives demand that the fertilizer recommendation systems for oil palm entail more than just the computation of optimum fertilizer rates. The other major components in the system are fertilizer management which includes correct timing, placement and methods of fertilizer application and right source of fertilizer, recommendation of optimum growing conditions for the oil palm to maximize nutrient uptake, and monitoring of growth, nutrition and yield targets.

Therefore the fertilizer recommendations seen on the estates, which often appear to be taken for granted, require a good understanding of the general principles governing the mineral nutrition of oil palm (Corley and Tinker, 2003; Goh *et al*., 2003a) and methods to maximize fertilizer use efficiency (Goh *et al*., 1999a; Goh *et al*,, 2003b). The other papers in this workshop will discuss the above topics while the tenet or basic principle of fertilizer recommendation system i.e. the system and computation to derive optimal fertilizer rates, is the focus of this paper.

APPROACHES TO ASSESS THE FERTILIZER REQUIREMENTS OF OIL PALM

The fertilizer requirements of oil palm depend on many interrelated factors that vary from one environment to another (Foster, 2003). Even in superficially similar agro-ecological environments, the yield responses of oil palm to fertilizers can vary substantially (Foster, 2003). Thus, the easiest way to determine the fertilizer requirements of oil palm is from fertilizer response trials but it is difficult and costly to conduct them in all the different environments where oil palm is grown. The other alternative is to use some variables that are related to the fertilizer requirements of oil palm based on sound principles of soil fertility and mineral nutrition of plants. There are essentially three diagnostic or prognostic approaches to estimate the optimum fertilizer rates for oil palm i.e. soil analysis, leaf analysis and nutrient balance or a combination of these methods.

Soil analysis approach

The soil physical, chemical and mineralogical properties have been used either as a diagnostic tool to group the soil types and approximate their soil nutrient supply to oil palm (Hew and Ng, 1968) or as a prognostic tool to predict the yield response curve of oil palm to fertilizer rates (Foster *et al*., 1985a and 1985b). Both methods are briefly described below.

Soil analysis as a diagnostic tool

The early fertilizer recommendation system for oil palm was largely based on soil analysis results and nutrient balance approach. The underlying premise is that the soil can continuously supply a proportion of nutrients to the palms with negligible depletion of soil nutrients. Thus, it makes the assumption that the soil nutrients taken up by the palms can be replenished by soil weathering processes and biological activities. However, the soil nutrient supply varies substantially depending on its fertility status. For example, the fertile Selangor series soil can supply 1376 g potassium (K)/palm/year which is equivalent to the amount of K in fresh fruit bunches (FFB) of 268 kg/palm/year (Table 1).

On the other hand, the highly weathered Munchong series soil can only supply 302 g K/palm/year or equivalent to 70 kg FFB/palm/year.

Table 1: Soil K supply to oil palm without manuring

Soil	Taxonomy	Soil K (g/palm)[1]	Soil K supply (g/palm/yr)	Equivalent FFB (kg/palm/yr) to soil K supply
Selangor	Typic Tropaquept	67190	1376	268
Briah	Typic Tropaquept	88650	994	194
Munchong	Tropeptic Haplorthox	2430	302	70
Kuantan	Haplic Acrorthox	8280	609	141
Malacca	Typic Gibbsiorthox	28610	604	140

[1] – Soil K was extracted with 6M HCl, and calculated to a depth of 90 cm except for Malacca series soil where the volume of laterite (50 %) was taken into account.
Note – Figures were recalculated from Teoh and Chew (1988) by Goh *et al*. (1994)

It is also well-recognized that soil fertility is affected not only by soil nutrient content but also texture, structure, consistency, terrain, moisture status and mineralogy. This is shown in Table 1 where Briah series soil has higher K content but supplies lower amount of K to the palms compared with Selangor series soil probably due to its silty clay texture, firmer consistence and poorer soil structure (Goh *et al*., 1994). It is not the purpose of this paper to discuss this subject in detail but the principles were illustrated by Hew and Ng (1968) when they drew up a tentative fertilizer schedule for oil palm (Table 2).

Table 2: Fertilizer schedule (kg/palm/year) for oil palm replant at 8 years after planting on different soil groups with legume covers

No	Soil group	Ammonium sulphate	Christmas Island rock phosphate	Muriate of potash	Kieserite
1	Sandy colluvium, Holyrood, Lunas	2.73	1.82	3.36	1.82
2	Batu Anam, Marang, Durian	2.73	1.82	2.95	1.59
3	Rengam, Harimau, Kulai, Serdang, Jerangau, Ulu Thiram, Bungor, Tampoi	1.82	1.59	2.95	1.59
4	Munchong, Batu Lapan, Batang Merbau, Jempol, Katong	1.82	1.36	2.95	1.36
5	Kuantan, Segamat, Prang	1.59	1.14	3.64	0.91
6	Briah, Sitiawan, Sogomana, Manik	1.82	1.14	2.73	0.91
7	Selangor, Kangkong	1.59	0.45	2.73	0.45
8	Organic clay, mucks, shallow peat	2.73	1.36	2.73	0.91
9	Peat over 1 m	2.73	1.82	3.64	0.91

Soil groups 1 to 4 generally follow textural classes of sandy loam, silty clay, sandy clay loam to sandy clay, and clay respectively. Groups 4 to 7 can be separated by soil mineralogy as follows: kaolinite, iron and aluminium oxide, mainly illite and montmorillonite (Ng, 1977). Although the above fertilizer schedules may not be valid today due to newer planting materials with higher yield potentials, management practices and the concept of maximizing site yield potential, their relative differences are probably still applicable.

To avoid over-application of fertilizer and mining of soil nutrients especially phosphorous (P), K and magnesium (Mg), a general classification table for soil nutrients is usually drawn up (Table 3).

Table 3: Classification of soil nutrient status for oil palm

Nutrient	Very low	Low	Moderate	High	Very high
PH	< 3.5	3.5-4.0	4.0-4.2	4.2-5.5	> 5.5
Organic C (%)	< 0.8	0.8-1.2	1.2-1.5	1.5-2.5	> 2.5
Total N (%)	< 0.08	0.08-0.12	0.12-0.15	0.15-0.25	> 0.25
Total P ($\mu g\ g^{-1}$)	< 150	150-250	250-350	350-500	> 500
Available P ($\mu g\ g^{-1}$)	< 10	10-25	25-40	40-60	> 60
Exchangeable K (cmol kg^{-1})	< 0.08	0.08-0.20	0.20-0.25	0.25-0.30	> 0.30
Exchangeable Mg (cmol kg^{-1})	< 0.08	0.08-0.20	0.20-0.25	0.25-0.30	> 0.30
CEC (cmol kg^{-1})	< 6	6-12	12-15	15-18	> 18

After Goh and Chew (1997) with modifications for available and total P.

The interpretation of the above soil nutrient classification, in particular for nitrogen (N), P, K and Mg, is explained in Table 4.

Table 4: Interpretation of soil nutrient status for fertilizer recommendations

Nutrient status	Interpretation
Very low	Nutrient deficiency symptoms are likely. Yields are very low or crops may fail. Definite fertilizer response. Increase fertilizer rate to corrective level.
Low	Nutrient deficiency symptoms may occur. Fertilizer response is likely. Increase fertilizer rate.
Moderate	Hidden hunger is likely. May respond to fertilizer. Maintain fertilizer rate or increase slightly.
High	No response to fertilizer input. Reduce fertilizer rate or maintain soil fertility, if grower can afford it.
Very high	Nutrient imbalance or induced nutrient deficiency symptoms may occur. Fertilizer input is usually not required except to correct for nutrient imbalance.

Apart from single soil nutrient classification, soil nutrient ratios have also been used to diagnose or provide a rough indication of the likelihood of a nutrient deficiency in the oil palm. For example, soil exchangeable Mg/K has to be above two to avoid magnesium deficiency on acid soils in West Africa (Tinker and Ziboh, 1959; Tinker and Smilde, 1963) and a variety of other soils in other parts of the world (Dubos *et al.*, 1999; Goh *et* *al*., 1999b) although it did not fit some Malaysian soils such as Rengam series (Corley and Tinker, 2003). Tinker (1964) further found that the activity ratio equation $\frac{K}{\sqrt{Ca+Mg}} + \sqrt[3]{Al}$ was a good guide to potassium status on acid sands soils of West Africa.

Despite the above, the actual fertilizer rate for each nutrient status will depend on the nutrients, palm age, soil types, terrain, soil moisture status and expected nutrient losses. Soil nutrient analysis is therefore rather subjective and those using it usually fall back to fertilizer response trials and experiences for further guidance and in general, would not use it in the first instance to decide on fertilizer rates in an existing plantation (Corley and Tinker, 2003). Apart from this, soil nutrient variation is extremely high between soil types (Law and Tan, 1973; Goh *et al*., 1996) and within the palm area (Goh *et al*., 1996), and error in sampling a fertilized field is too large (Foster and Chang, 1977) making interpretation difficult and probably unreliable.

Soil analysis as a prognostic tool

Foster (2003) described a soil-based system to predict the optimum N and K rates for oil palm in West Malaysia. This system was developed by Foster and his associates at MARDI and later at PORIM, using around 50 factorial fertilizer experiments in West Malaysia. This large array of experiments was conducted by the oil palm industry in the late 1960s to early 1980s. The system, which is statistical in nature, attempts to re-construct the yield response curve to N and K fertilizer inputs based on site characteristics. Since the inland and alluvial soils have different soil mineralogy, they also have different sets of equations to predict the yield responses to N and K rates. The system essentially has three steps (Foster *et al*., 1985a and 1985b):

1) Predict yield without N and/or K (starting point of the system)
2) Predict yield response to N at non-limiting K and vice-versa
3) Predict yield at any combination of N and K fertilizers

The variables required by the set of equations are shown in Table 5. They can be separated into variable site characteristics and permanent site characteristics. The former (X1 to X8) are factors which control the FFB yields without N or K fertilizer inputs (i.e. dependant on soil N and K only) whereas the latter (X2, X8, X9 to X14) are factors which determine the efficiency of the response (FFB/kg nutrient applied) and probably, fertilizer recovery (Corley and Tinker, 2003).

Table 5: Variable and permanent site characteristics that affect the yield responses to N and K fertilizers in West Malaysia

Variable	Site characteristics	Type of characteristics
X1	Palm age (year)	Variable
X2	Planting density (palm/ha)	Variable
X3	Consistency score	Permanent
X4	Drainage score	Variable
X5	Organic matter (%)	Variable
X6	Extractable K (cmol/kg)	Variable
X7	Total extractable bases (cmol/kg)	Variable
X8	Annual rainfall (mm/year)	Variable
X9	Slope score	Permanent
X10	Root growth impedance score	Permanent
X11	Clay (%)	Permanent
X12	Silt (%)	Permanent
X13	Total extractable cations (cmol/kg)	Variable
X14	Average rainfall (mm) during 3 months after fertilizer application	Variable

The equations for computing the yield response curves of oil palm to N and K fertilizer inputs on alluvial and sedentary soils in West Malaysia are shown in Table 6.

Table 6: Equations to compute the yield response curves of oil palm to N and K inputs in West Malaysia

Soils	Purpose	Equation	Formula	Remark
Alluvial	Yield (Y) without K fertilizer	1	$Y = 22.50 - 2.720X_4 + 9.662X_6 + 0.002599X_8$	Y at K_0N_{max}
	Yield (Y) without N fertilizer	2	$Y = 20.44 - 3.022X_4 + 0.004535X_8$	Y at N_0K_{max}
	K response (dY/dK) at non-limiting N	3	$dY/dK = 1.836 - (0.01591X_{13} - 0.007733X_{12})Y - 0.2356X_{12} + 0.4095X_{13} - 0.001566X_{14}$	At step 1, use Y value from Equation 1
	N response (dY/dN) at non-limiting K	4	$dY/dN = 9.739 - (0.4630 + 0.01491X_4 - 0.0001409X_8)Y + 0.01029X_{11} - 0.1086 \times 10^{-5}X_7^2$	At step 1, use Y value from Equation 2
	Yields (Y_{NK}) at any combination of N and K fertilizers	5	$Y_{NK} = 268.5 - 19.93\ Y_{N.Kmax} - 9.824\ Y_{Nmax.K} + 0.7609\ Y_{N.Kmax} * Y_{Nmax.K} + 0.3884\ Y^2_{N.Kmax} - 0.01409\ Y^2_{N.Kmax} * Y_{Nmax.K}$	Values for variables from equations 3 and 4
Sedentary	Yield (Y) without K fertilizer	6	$Y = 9.823 - 5.221X_4 + 4.300X_5 + 50.04\ (X_6/X_7)$	Y at K_0N_{max}
	Yield (Y) without N fertilizer	7	$Y = 93.81 - 1.652X_1 - 0.1957X_2 - 9.101X_3 - 0.01160X_8$	Y at N_0K_{max}
	K response (dY/dK) at non-limiting N	8	$dY/dK = 3.455 - (0.1183 + 0.01541X_9)Y - 0.03820X_{12} + 0.0006146X_8$	At step 1, use Y value from Equation 6
	N response (dY/dN) at non-limiting K	9	$dY/dN = 8.780 - (0.1991 + 0.02405X_4 - 0.02252X_{10})Y - 0.8927X_9 - 0.001137X_8$	At step 1, use Y value from Equation 7
	Yields at any combination of N and K fertilizers	10	$Y_{NK} = -22.71 + 1.10\ Y_{N.Kmax} + 2.627\ Y_{Nmax.K} - 0.04656\ Y^2_{N.Kmax} + 0.0008651Y^2_{N.Kmax}*Y_{Nmax.K} - 0.06913\ Y^2_{Nmax.K} + 0.0007513\ Y_{N.Kmax} * Y^2_{Nmax.K}$	Values for variables from equations 8 and 9

Adapted from Foster *et al*. (1985a and 1985b)

Although the above equations appear relatively complicated, the steps to construct the yield response curve are straightforward. The computations of N and K rates using the system are illustrated with typical site characteristics of a sedentary soil derived from granite (Foster, 2003) as shown in Table 7.

Table 7: Characteristics of a typical sedentary soil derived from granite in Malaysia (Foster, 2003)

Characteristic	Score or value	Variable identity
Palm age (year)	12	X1
Planting density (palms/ha)	148	X2
Soil drainage class	0	X4
Soil consistency class	0	X3
Slope class	0.5	X9
Soil organic matter (%)	2.5	X5
Silt (%)	6.0	X12
Extractable K (cmol/kg)	0.06	X6
Total extractable bases (cmol/kg)	1.20	X7
Root growth impedance class	0	X10
Annual rainfall (mm/year)	2000	X8

Class: 0 = no limitation; 1 = moderate limitation; 2 = severe limitation

The step by step computations of yield response curve to N and K fertilizers are shown below.

Step 1: Calculate the yield in the absence of K or N at non-limiting level of the other nutrient using Equations 6 and 7, respectively.

a) $Y_{K=0} = 9.823 - 5.221 * 0 + 4.300 * 2.5 + 50.04 (0.06/1.20) = 23.075$
b) $Y_{N=0} = 93.81 - 1.652 * 12 - 0.1957 * 148 - 9.101 * 0 - 0.01160 * 2000 = 21.82$

Step 2: Calculate the yield response to K at non-limiting N (Nmax) and vice-versa using Equation 8 and Equation 9, respectively

a) $dY/dK = 3.455 - (0.1183 + 0.01541 * 0.5)Y - 0.03820 * 6.0 + 0.0006146 * 2000$
   $Y = Y_{K=0} = 23.075$ (from Step 1(a)), therefore
   $dY/dK = 3.455 - (0.1183 + 0.01541 * 0.5) * 23.075 - 0.03820 * 6.0 + 0.0006146 * 2000$
   $= 1.347$
   Therefore, $Y_{K=1} = Y_{K=0} + dY/dK$
   $= 23.075 + 1.347$
   $= 24.422$
b) Now, calculate $Y_{K=2}$ by repeating Step 2 (a) but substituting Y with $Y_{K=1}$ as follows:
   $dY/dK = 3.455 - (0.1183 + 0.01541 * 0.5)Y - 0.03820 * 6.0 + 0.0006146 * 2000$
   $Y = Y_{K=1} = 24.422$ (from Step 2(a)), therefore
   $dY/dK = 3.455 - (0.1183 + 0.01541 * 0.5) * 24.422 - 0.03820 * 6.0 + 0.0006146 * 2000$
   $= 1.178$

Therefore, $Y_{K=2} = Y_{K=1} + dY/dK$
$= 24.422 + 1.178$
$= 25.600$

c) Repeat the above calculation until $Y_{K=8}$ or to a desirable K rate. Please note that $Y_{K=8}$ is FFB yield at 8 kg of muriate of potash and other nutrients at non-limiting level.
d) Repeat above calculation for $Y_{N=n}$ using Equation 9

Although Foster *et al*. (1985b) provide a general solution to solve the above differential equations by integration, which results in an exponential model, it loses insight of how the equations work as shown above. Upon completing the calculations in Step 2, a table of yield responses to N and K fertilizers at non-limiting levels of other nutrients should be obtained as shown below (Table 8).

Table 8: Yields at different N or K rates at non-limiting levels of other nutrients

K rate (kg/palm/yr)	Yield at $Y_{Nmax.K}$	N rate (kg/palm/yr)	Yield at $Y_{N.Kmax}$
0	23.08	0	21.82
1	24.42	1	23.54
2	25.60	2	24.91
3	26.63	3	26.01
4	27.53	4	26.89
5	28.32	5	27.60
6	29.00	6	28.16
7	29.60	7	28.61
8	30.13	8	28.98

Note: K as muriate of potash and N as ammonium sulphate

Step 3: Calculate yields at different combinations of N and K fertilizers using Equation 10.

a) $Y_{NK} = -22.71 + 1.10\ Y_{N.Kmax} + 2.627\ Y_{Nmax.K} - 0.04656\ Y^2_{N.Kmax} + 0.0008651 Y^2_{N.Kmax} * Y_{Nmax.K} - 0.06913\ Y^2_{Nmax.K} + 0.0007513\ Y_{N.Kmax} * Y^2_{Nmax.K}$

For N = 0 and K = 1, then $Y_{N.Kmax} = Y_{0.Kmax} = 21.82$ and $Y_{Nmax.K} = Y_{Nmax.1} = 24.42$ (Table 8). Substituting these values into above equation gives

$Y_{01} = -22.71 + 1.10 * 21.82 + 2.627 * 24.42 - 0.04656 * 21.82^2 + 0.0008651 * 21.82^2 * 24.42 - 0.06913 * 24.42^2 + 0.0007513 * 21.82 * 24.42^2$
$= 21.89$

b) Similarly, calculate yields at other combinations of N and K rates by substituting the respective values in Table 8 into Equation 10.

Upon completing the calculations in Step 3, a matrix of yields at different combinations of N and K fertilizer rates should be obtained as shown in Table 9.

Table 9: Fresh fruit bunch yields predicted for a sedentary soil derived from granite with typical site characteristics in Malaysia.

Ammonium sulphate (kg/palm/yr)	Muriate of potash (kg/palm/yr)								
	0	1	2	3	4	5	6	7	8
0	21.2	21.9	22.4	22.7	22.8	22.9	22.9	22.9	22.8
1	21.7	22.6	23.2	23.6	23.9	24.1	24.2	24.3	24.3
2	22.0	23.0	23.8	24.3	24.7	25.0	25.2	25.3	25.4
3	22.1	23.3	24.1	24.8	25.3	25.6	25.9	26.0	26.2
4	22.2	23.5	24.4	25.1	25.7	26.1	26.4	26.6	26.8
5	22.2	23.6	24.6	25.4	26.0	26.4	26.8	27.0	27.3
6	22.2	23.6	24.7	25.5	26.2	26.7	27.1	27.4	27.6
7	22.2	23.7	24.8	25.7	26.4	26.9	27.3	27.6	27.9
8	22.2	23.7	24.9	25.8	26.5	27.1	27.5	27.8	28.1

Based on Table 9, different optimum N and K fertilizer rates can be computed based on the expected return to fertilizer inputs. Foster (1995) assumed that the larger plantation companies can afford to take higher risk (20 % return) and therefore, will opt for higher rates of fertilizer compared with smallholders who will take lower risk (100 % return). This is because increasing fertilizer rate results in a decreasing yield response since an exponential model was used in the above computation.

Foster (2003) cautioned that this method is applicable within the environments where the trial data were collected i.e. in West Malaysia. Also, it only provides a first approximation of the initial fertilizer rates for the site. The fertilizer rates should be monitored and fine-tuned by leaf analysis results as described in the next section. Apart from this, Chew *et al*. (1992) pointed out that this system depended on statistical relations, and not on a basic understanding of the underlying mechanisms for plant nutrient uptake, growth and yield. It contains some unusual relationships such as increasing root growth impedance will increase the yield response to N fertilizer as shown in Equation 10 and on alluvial soils, palms receiving lower annual rainfall will have higher yields.

Leaf analysis approach

Foster (2003) stated "The assessment of nutrient deficiencies using foliar diagnosis is an entirely empirical system". Despite this, leaf analysis is perhaps the most common diagnostic tool to determine the nutritional status of oil palm and estimate the appropriate fertilizer rates. This is because of significant relationship between leaf nutrient concentration and FFB yield at a site (Foster and Chang, 1997). Foster (2003) further illustrated this with a contour map (Figure 1) of leaf N and K with FFB yield where the highest yield appears to be critically dependent on the exact leaf nutrient composition (Corley and Tinker, 2003). Figure 1 also shows that high yields demand extreme precision in leaf composition i.e. only a small range of leaf N and K will result in high yields as against those with lower yields. This implies that each nutrient has a maximum concentration, and when all nutrients reach their highest values, then maximum yield has been attained (Corley and Tinker, 2003).

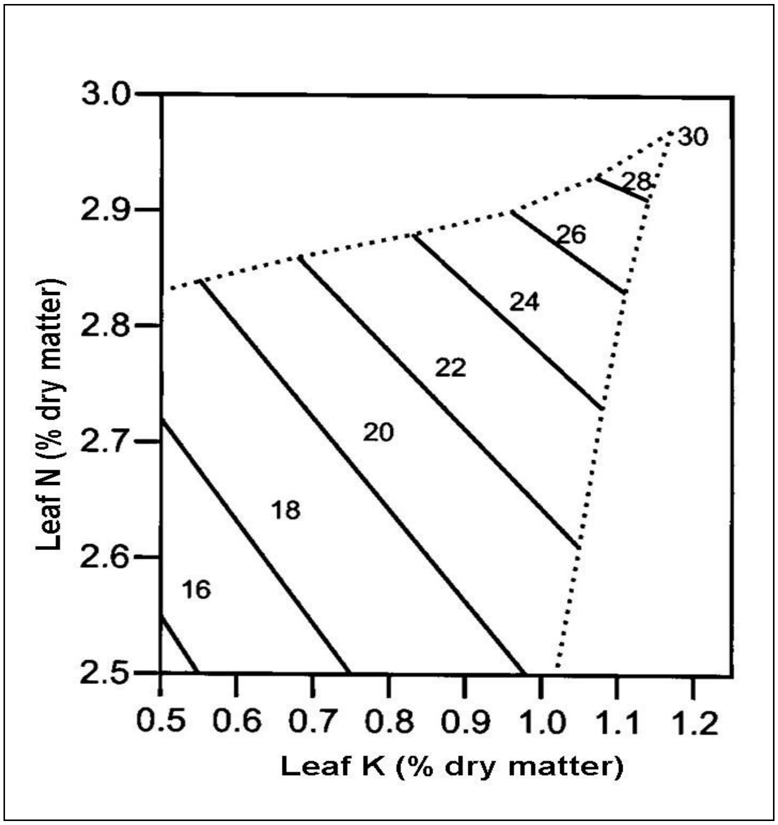


Figure 1: Yield isoquants (lines of equal yield) for N and K concentrations in the leaves of oil palm in a trial on a granite-derived soil in Malaysia (after Foster, 2003).

The major obstacle in using leaf analyses is that the optimum nutrient concentration varies substantially between soil types, terrain, palm age, climate, season, frond age, sampling methods etc (Rajaratnam *et al*., 1977; Teoh *et al*., 1982; Foster, 2003). Therefore, simplistic or careless application of foliar analysis will produce misleading results (Foster, 2003). To prevent this, the method of leaf sampling including the choice of frond, sampling unit, choice of palms and time of sampling has been standardized, and various interpretation methods have been developed such as single nutrient critical level, nutrient ratios, DRIS and total leaf cations. In this paper, we shall describe three of them that are still widely practised.

French (CIRAD) system

This fertilizer prediction system is based on the early work by Prevot and Ollagnier (1954, 1957). The basic principle used is to lay down factorial fertilizer response experiments on important soil types within the plantations (Caliman *et al*., 1994). The results are usually fitted to a Mitscherlich equation, Yield = $a - b \exp(-cX)$

where a is the maximum yield achievable at the site, a - b gives the yield without fertilizer input and c defines the shape of the response curve. The economically optimum fertilizer rate (EOR) can be calculated from the above curve. Leaf analyses are carried out on the trials, and response curves of the leaf analysis results are used to determine the critical level corresponding to the EOR. This critical leaf level is applicable to sites with similar processes of mineral nutrition as the trial. Since it is difficult to conduct fertilizer response trials on all unique sites in a plantation, the critical leaf level is extrapolated to other sites.

The French system also has an interesting method for the longer term adjustment of fertilizer rates by using an equation that predicts the fertilizer rate which causes the leaf analysis results to converge progressively to the critical level (Corley and Tinker, 2003). The equation is:

Dn = Dn-1 + a (Nn-1 – Nn) + b (Nc – Nn)

where *Dn* is the application rate in year *n*, *Nn* is the leaf nutrient level in year *n*, *Nc* is the critical level, and *a* and *b* are constants. The fertilizer rate in year *n* is therefore adjusted from that in year *n-1*, in accordance with the change in the leaf analysis results and their difference from the critical level. It is assumed that eventually, *Nn* = *Nn-1* and *Nn* = *Nc*.

While the system is simple, the following can lead to misleading outcomes

1. The constants, *a* and *b*, probably vary substantially with space and time.
2. The leaf nutrient levels could be distorted by dilution and concentration effects apart from seasonal variation etc as discussed earlier.
3. The uncertainty of whether to use single nutrient values or ratios.
4. The effect of interaction between nutrients on the optimum fertilizer rate. Thus, the possibility of imbalanced nutrition cannot be discounted.

In fact, Tampubolon *et al*. (1990) found that the P/N ratio in the leaflets was the best criterion for predicting phosphate deficiency. The general relationship between the critical levels of leaf N and P is:

Leaf P (%) = 0.0487 Leaf N (%) + 0.039

Thus, the effect of changes in leaf N affects N status directly and P status indirectly.

As an example, the equation of the French system is fitted using N data from a NP factorial fertilizer trial on Batang (lateritic) Family soil (Typic Plinthudults (Petroferic)) in Kunak, Sabah as follows:

Dn – Dn-1 = a (Nn-1 - Nn) + b (Nc-Nn)

The constants, a = -10.67 and b = 12.84. The coefficient of correlation, r = 0.45.

The computation of N rate (kg ammonium chloride (AC)/palm/year) is shown in Table 10 for two N status of oil palm, low and sufficient. The data were obtained from single plots measured in 1993 and 1994 from the above fertilizer response trial.

Table 10: Estimated N rate (kg AC/palm/yr) for oil palm on Batang (lateritic) Family soil in Kunak, Sabah using the French system

Cases	Input				Output	
	Dn-1	Nn-1	Nn	Nc	Dn – Dn-1	Dn
Low N	2	2.48	2.53	2.65	2.07	4.07
Sufficient N	4	2.68	2.73	2.65	-0.49	3.51

Foster system

As discussed earlier, Foster *et al*. (1988) developed a leaf analysis system to complement or modify the initial fertilizer rates predicted by the soil based system. The Foster system essentially uses the total leaf cations (K, Ca and Mg) as an internal reference point for various nutrients such as N, K and Mg. The total leaf cations (TLC) method overcomes the effect of palm age and site factors on the optimum leaf nutrient levels. The strong relationships between N and TLC, and TLC and water-holding capacity of the soils cannot be explained physiologically or in biophysical terms (Corley and Tinker, 2003). Nevertheless, this novel approach appears to be more efficient and sensitive in detecting nutrient deficiency and yield response compared with single critical nutrient approach and DRIS index.

There are four steps in Foster system (Foster, 2003) as follows:

1. Seasonal correction
2. Calculation of TLC
3. Calculation of potential yield responses and nutrient deficiencies
4. Adjusting the fertilizer rates

In seasonal correction, the concentration of N, P, K, Ca and Mg (% dry matter basis) is first corrected based on monthly or bimonthly reference data of leaf analyses of selected fields in the plantation. For example, if the leaf K level is 0.92 % in the sampling month while the annual mean is 0.95 %, then the leaf K level of the sample should be increased by 0.03 % (Foster, 2003).

TLC (cmol/kg dry matter) is calculated as follows:

$$TLC = \left(\frac{\text{Leaf K (\%)}}{39.1/1} + \frac{\text{Leaf Mg (\%)}}{24.3/2} + \frac{\text{Leaf Ca (\%)}}{40.1/2}\right) \text{x}\, 1000$$
$$= \left(\frac{\text{Leaf K (\%)}}{39.1} + \frac{\text{Leaf Mg (\%)}}{12.15} + \frac{\text{Leaf Ca (\%)}}{20.05}\right) \text{x}\, 1000$$

In general, K and Mg deficiency can be assessed based on their proportion of TLC where < 25 is considered deficient, 25 to 30 low and > 30 sufficient (Foster, 2003). However, a better approach is probably to base the classification of nutrient deficiency on the expected yield response from the proportion of nutrient to TLC (Foster, 2003).

A quadratic equation, containing the single nutrient at specific TLC value, can be derived from Figure 2 to relate leaf nutrient to FFB yield responses. For example, the present author estimates the quadratic equation which relates the yield response (Y) to leaf N (%) at TLC value of 80 based on Figure 2 as follows:

$$Y = 171.1 - 117.2 \text{ (Leaf N)} + 20 \text{ (Leaf N)}^2$$

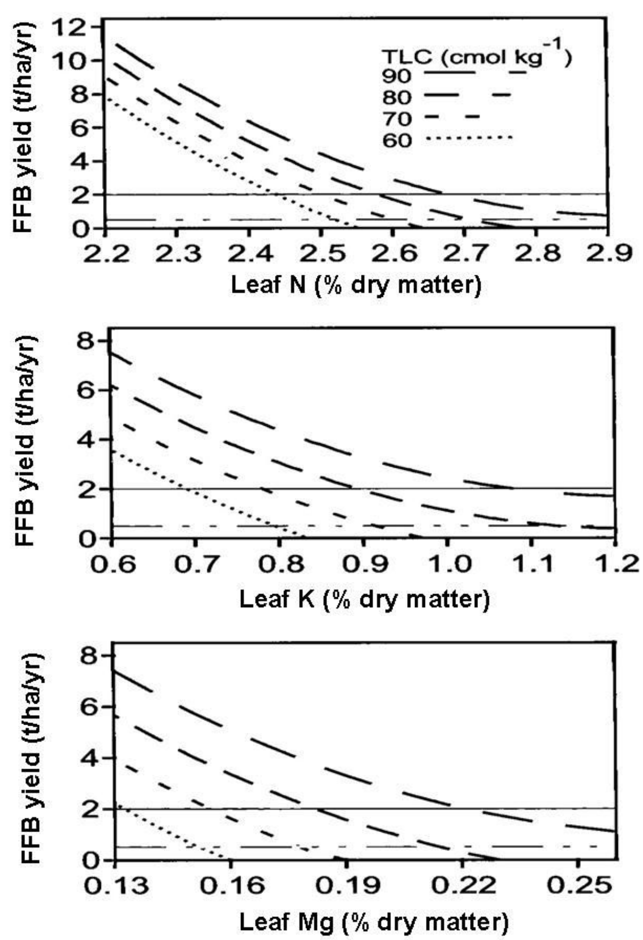


Figure 2: Predicted maximum yield response to fertilizer in relation to leaf nutrient status and total leaf cations (TLC) in Malaysia (after Foster, 2003)

Based on the estimated potential yield responses, nutrient deficiencies can then be classified and corrected as shown in Table 11.

Table 11: Classification of nutrient deficiency, FFB yield responses and appropriate fertilizer adjustments for urea, triple superphosphate (TSP), muriate of potash (KCl) and kieserite to normal application rates applied (after Foster, 2003)

Nutrient deficiency rating	Potential yield response (t/ha/yr)	Fertilizer adjustment (kg/palm/yr)
Excessive	0	-0.5 to -1
Satisfactory	0 to 1	0
Low	1 to 2	0 to 1
Deficient	2 to 3	0 to 2
Very deficient	> 3	0 to 3

Foster (2003) cautioned that if any nutrient is found to be very deficient, or more than one nutrient is deficient, then the deficiency rating of only the most deficient nutrient is considered to be valid. However, if no more than one nutrient is deficient, then all nutrients can be classified with reasonable confidence. This implies that the system only works if the nutritional state of the palm is near the optimum. Otherwise, the most deficient nutrient is detected and corrected first, and others in subsequent years by a stepwise technique (Foster, 1995).

The amount of an individual fertilizer required to correct a particular deficiency depends on those environmental factors especially soil and climate that affect fertilizer recovery efficiency (Foster, 2003). Local fertilizer response trials as described under the French system can be used to determine fertilizer recovery efficiency in a particular area. Because of errors involved in individual predictions, Foster (2003) recommended that smallholders increase fertilizer rates only if a nutrient is classified as deficient. However, for large plantations, fertilizer increases are likely to be economical when averaged over a number of fields, even when nutrients are classified as low.

The same two examples used to demonstrate the French system earlier are reused to illustrate the computation of N fertilizer rate (kg AC/palm/year) using the Foster system (Table 12).

Table 12: Two cases of oil palm on Batang (lateritic) Family soil with different fertilizer inputs and leaf nutrient concentrations to demonstrate Foster system.

Cases	Input						Output	
	N rate	Leaf N (%)	Leaf K (%)	Leaf Mg (%)	Leaf Ca (%)	TLC	N status	Adjustment (kg/palm/yr)[1]
Low N	2	2.53	0.94	0.21	0.49	65.8	Low	1.29
Sufficient N	4	2.73	0.81	0.15	0.50	58.0	Excessive	-1.29

1 Assume a volatilization loss of 30 % from urea has been taken into account in Table 11

Based on the Foster system, the optimum N rate for palms with low N status is around 3.29 kg AC/palm/year while the French system predicts a higher optimum rate of 4.07 kg

AC/palm/year. The Foster system also predicts that Mg is just sufficient in the case with sufficient N but excessive in low N condition despite the relatively low leaf Mg concentrations. Similarly, no yield response to K is expected for both cases.

The Foster system is highly dependent on accurate and representative leaf analysis results. It therefore faces the same problems associated with leaf analysis as discussed earlier. Also, it does not consider the nutrient demand for growth and FFB yield explicitly.

PORIM (MPOB) Open system

The PORIM Open system, which is also known as Open (Tarmizi *et al*., 1999), is similar to Foster's soil and foliar based systems described earlier. However, the adjustment to previous fertilizer rate is carried out in a stepwise procedure rather than following a classification table as shown above (Table 10). The three steps in the PORIM Open system to adjust the initial fertilizer rate presumably calculated based on the soil characteristics are as follows:

1. Compute the TLC values as shown earlier. Based on the TLC values, the critical leaf levels are computed for identification of the most deficient nutrient.
2. Correct the most deficient nutrient by adding the appropriate nutrient and predicting the change in leaf nutrient composition.
3. Go back to step (1) until all nutrients are in sufficient status.

In the example given for Foster system (Table 12), the critical leaf N, K and Mg levels are computed first based on the TLC and nutrient relationship as shown in Figure 2 earlier. Foster *et al*. (1988) set the upper limit for leaf critical level at the yield response of 0.5 t/ha/year and lower limit at 1.5 t/ha/year although in a later paper, they set the lower limit at 2 t/ha/year (Foster, 1995). The results are shown in Table 13.

Table 13: Upper and lower leaf critical levels for N, K and Mg in the low N input scenario shown in Table 12

Nutrient	Upper limit	Lower limit
N (%)	2.56	2.03
K (%)	0.86	0.77
Mg (%)	0.17	0.15

Based on Table 13, only N shows deficient status (2.53 % against the critical upper limit of 2.56 %) and therefore requires correction. This is done by assuming the change in leaf nutrient contents due to various fertilizer inputs as estimated by Foster *et al*. (1988) (Table 14).

Table 14: Expected changes in leaf nutrient composition due to one kilogram of fertilizer input.

Fertilizer (1 kg/palm/yr)	Leaf nutrient concentration (%)				
	N	P	K	Mg	Ca
Ammonium sulphate	+ 0.05	+ 0.002	+ 0.01	0	0
Christmas Island rock phosphate	+ 0.015	+ 0.004	0	0	+ 0.01
Muriate of potash	0	0	+ 0.06	- 0.01	- 0.01
German kieserite	0	0	- 0.10	+ 0.07	0

The stepwise method to determine the fertilizer rate for the oil palm is shown below (Table 15).

Table 15: Stepwise method to determine the fertilizer rate to maintain optimum leaf nutrient composition of oil palm

Step	Nutrient	Leaf nutrient concentration (%)					Nutrient status		
		N	P	K	Mg	Ca	N	K	Mg
0	AC = 2.00	2.53	0.152	0.94	0.21	0.49	D	S	S
1	AC = 2.63	2.57	0.159	0.95	0.21	0.49	S	S	S

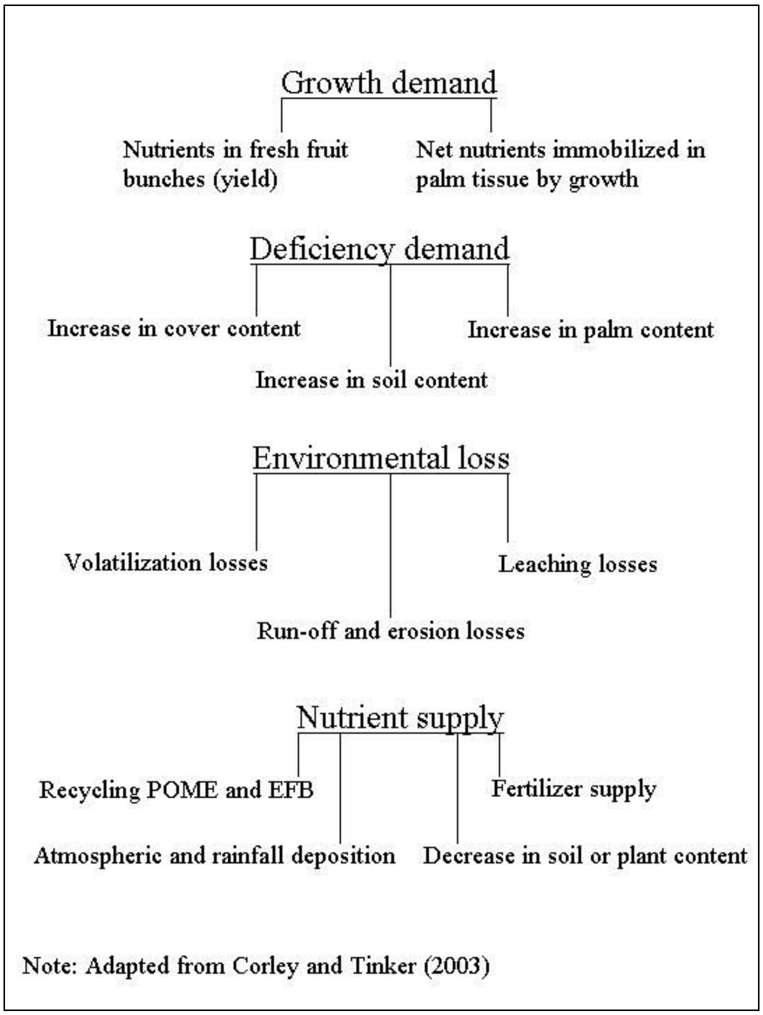
Note: D denotes deficient and S denotes sufficient status

Since the PORIM Open system is also dependent on leaf analysis results, it has the same problems as the Foster system as discussed earlier. Apart from this, it is highly dependent on the relationship between fertilizer input and changes in leaf nutrient composition. This relationship is unlikely to be a constant across time and space.

Nutrient balance approach

The methods to estimate the fertilizer rates, which have been described so far, are all empirical and therefore, should be used within the same environments where they have been developed. This limitation is partially overcome by methods which are based on the principles of plant nutrition. One of these methods is called INFERS (Kee *et al*., 1994) which follows the nutrient balance approach and plant nutrient demand. These are the foundations of modern plant nutrition in the field, and recently have been advanced for dealing with soil nutrient depletion in African agriculture in general (Smaling *et al*., 1999; Corley and Tinker, 2003). Although a number of past papers have discussed nutrient balance approach (Hew and Ng, 1968; Ng, 1977), only the INFERS model has been described briefly by Kee *et al*. (1994) and Corley and Tinker (2003) to illustrate the approach for oil palm.

The nutrient balance approach specifically attempts to balance the nutrient demand with the nutrient supply. In the oil palm agro-ecosystem, the components of nutrient demand are plant nutrient uptake for growth and production, nutrient losses through soil processes such as runoff and leaching (environmental losses) and nutrient immobilization (Figure 3). The components of nutrient supply are precipitation, pruned fronds, applied by-products such as empty fruit bunches. Any shortfall between nutrient supply and demand is met by fertilizer input. Ng (1977) considered the major variables in the nutrient balance sheet to be soil nutrient supply to the oil palm and plant nutrient demand.



Note: POME denotes palm oil mill effluent while EFB denotes empty fruit bunches

Figure 3: Nutrient cycles for nitrogen in oil palm plantations

Plant nutrient demand is the requirement for essential elements by a growing plant (Corley and Tinker, 2003). It can be separated into two processes: growth demand and deficiency demand (Tinker and Nye, 2000). The underlying theory of these two "demands" is quoted verbatim from Corley and Tinker (2003) as follows:

Nutrient amount (content) in palm, $N = XW$ and uptake rate = $\frac{d(N)}{dt} = X\frac{dW}{dt} + W\frac{dX}{dt}$

where N is the total nutrient in the palm, W is the mass, X is the fractional content of the nutrient and t is time. The first term in the uptake rate represents the growth demand because the nutrient percentage remains constant as the plant grows at a rate $\frac{dW}{dt}$. However, during the correction of a nutrient deficiency, the second term applies, as the weight is a constant with varying nutrient concentration. In fact, both processes probably occur at the same time. Without the differentials and ignoring change in structure of plant material, a simple approximation for the uptake is:

$$X_2 (W_2 - W_1) + W_1 (X_2 - X_1) = X_1 (W_2 - W_1) + W_2 (X_2 - X_1) = X_2W_2 - X_1W_1$$

for times t1 and t2 and the meaning of the terms remains the same.

The main components of growth demand in the oil palm are nutrients immobilized in palm tissue by growth and nutrients exported in the FFB. The major components of deficiency demand are increase in palm nutrient content to correct nutrient deficiency and increase in soil nutrients. Changing the present state in these four components to the optimum level and maintaining the optimum state are the central tenets of INFERS model. That is, these four components, FFB yield, growth (palm size), nutrient concentration in palm (usually the leaf nutrient concentration in Frond 17 is used as an indicator) and soil nutrient concentration, form the targets in INFERS. Since these targets differ according to palm age, environment and economic situation, the palm nutrient requirements will also vary. Coupled with different fertilizer use efficiency, the fertilizer rates required for each field will change accordingly. This is indeed the essence of site-specific fertilizer recommendations. A brief description of INFERS module for computing fertilizer rates using N as an example is provided below. The detailed structure of INFERS is provided by Kee *et al*. (1994) and Corley and Tinker (2003) while the research which supports the model has been well described by Corley and Tinker (2003).

Since INFERS is based on the principle of plant demand and nutrient supply, the four targets to be achieved or maintained must be set correctly. The first target is usually based on the site yield potential using a model called ASYP (Kee *et al*., 1999). The growth rate is based on the increasing dry weight of Frond 17 as determined from its dimension (Corley *et al*., 1971) with palm age. It should be noted that the growth rate of oil palm and the maximum frond dry weight depend on the environment. This information is freely available from many experiments conducted on oil palm in Malaysia. The target for the leaf nutrient concentration in Frond 17 may be based on single nutrient critical levels for different environment and palm age or TLC method as described earlier. Since four targets are used in the model, the computed fertilizer rates are less sensitive to changes in leaf nutrient concentration compared to the earlier methods discussed above. The target for soil nutrient contents depends on the soil nutrient classification table (Table 3) or user's preference for nutrient buildup, maintenance or depletion although INFERS does not in principle aim to deplete soil nutrients.

The main nutrient demand in the oil palm agroecosystem is probably by the plant. The plant nutrient demand can be separated into four components: canopy, trunk, root and FFB. The equations to calculate the palm N demand are shown below. The figures in subscript, 1 and 2, denote time 1 (present state) and time 2 (a year later).

1. Nutrient demand of the canopy

Canopy N growth demand (g N/palm) = 0.155* (Pinnae N $(\%)_1$) (Frond17 dry weight $(g)_2$ – Frond17 dry weight $(g)_1$)

Canopy N deficiency demand (g N/palm) = (0.155 * (Frond17 dry weight $(g)_2$) – 236.817)* (Pinnae N $(\%)_2$ – Pinnae N $(\%)_1$)

where Frond 17 dry weight is measured using the non-destructive method of Corley *et al*. (1971) and Pinnae N is obtained from the standard leaf nutrient analysis adopted by the oil palm industry in Malaysia (Foster, 2003).

2. Nutrient demand of the trunk

Trunk N growth demand (g N/palm) = 0.01 * Trunk N concentration $(\%)_1$ (Trunk dry weight $(g)_2$ – Trunk dry weight $(g)_1$)

Trunk N deficiency demand (g N/palm) = 0.01 * Trunk dry weight $(g)_2$ (Trunk N concentration $(\%)_2$ – Trunk N concentration $(\%)_1$)

The trunk N concentration (%) is estimated by the linear-plateau model as follows:

a) Trunk N concentration (%) = 1.369 – 0.117 (age (yr))
   for palm <= 8.5 years old
b) Trunk N concentration (%) = 0.351
   for palm > 8.5 years old

The trunk dry weight is estimated by the equations proposed by Corley and Bruere (1981) as follows:

a) Trunk volume (cm^3) = Π x d^2 x h /4

where d = trunk diameter (cm), usually measured at 1m above the ground

h = trunk height (cm), usually measured to Frond 41

b) Trunk density (g/cm^3) = 0.083 + 0.0076 (age (yr))

c) Trunk dry weight (g) = Trunk volume x Trunk density

The above equations indicate that for palm above 8.5 years old, a constant value for growth demand of trunk may be used since height increment, diameter and N concentration in the trunk are constants and increase in trunk density is relatively small. Also, there is no deficiency demand due to constant trunk N concentration.

3. Nutrient demand of the roots

The N concentration in the roots of oil palm is relatively constant across palm age and soil types at about 0.39 %. Thus, oil palm roots are assumed to have no deficiency demand.

The growth demand of the oil palm roots is calculated using an empirical equation based on root:shoot ratio as follows:

Root:shoot ratio = 1.92 (Palm age (yr))$^{-1.11}$

The difference in root weights between year 1 and year 2 is multiplied by the constant root N concentration to give the root N demand. It should be noted that the above equation to compute the root weight is based on palms with relatively good nutrition. It is known that root:shoot ratio tends to be higher for palms in poor nutritional state.

4. Nutrient demand of the FFB

At present, it is assumed that the N concentration of FFB is not affected by palm age or nutrition, and remains constant at 3.195 g N per kg FFB. Therefore, there is only growth demand by the production of FFB as follows:

FFB N growth demand (g N/palm) = FFB (kg)$_2$ x 3.195

The soil nutrient demand generally involves two soil processes; soil nutrient build-up and soil nutrient losses. Soil nutrient build-up may be necessary if the soil nutrient status is low or where the soil activity ratio indicates nutrient imbalance as discussed earlier. The soil nutrient losses in the oil palm agroecosystem mainly arise from erosion, runoff and leaching. Corley and Tinker (2003) consider these losses as environmental losses or demand. The erosion and runoff losses can be estimated using the model suggested by Morgan *et al*. (1984) and leaching losses by Burn's model (Burns, 1974). Although these sub-models are built into INFERS model, they require many state variables and parameters, and therefore are beyond the scope of this paper. In general, soil N losses through the above processes should not exceed 10 % if the fertilizer is properly applied and correctly timed. N volatilization losses from urea or urea based fertilizers can be considered as part of soil N demand but they are usually taken into account after computing the final fertilizer rate assuming no losses initially. That is, if one expects volatilization losses to be about 30 %, then the final N fertilizer rate is adjusted 30 % upwards.

The major nutrient supply in the oil palm agroecosystem is shown in Figure 3. INFERS assumes that nutrient supply from the atmospheric and rainfall deposition is small and no decrease in soil or plant nutrient content is expected unless done on purpose. For example, it is sometimes necessary to deplete, say soil exchangeable Ca and Mg which may be too high and causing poor K uptake as in ultrabasic soils or the palms on peat soils have too high N and too low K, by the appropriate fertilizer withdrawal. Similarly, the residual value of large dressings of phosphate rock and ground magnesium limestone (Goh *et al*., 1999b) can be up to three years' demand and these nutrients can probably be omitted in such cases (Corley and Tinker, 2003). The nutrient supply from by-products such as empty fruit bunches (EFB) and palm oil mill effluent (POME) is well known and can be easily accounted for.

The computations of nutrient balance are subject to errors as in all mathematical and statistical models, and depend on reasonable or achievable targets. Thus, to prevent over manuring, INFERS has set a maximum N uptake rate of 1180 g per palm per year as measured under good environmental conditions.

The conversion of nutrient requirement of oil palm to fertilizer equivalent depends on the expected fertilizer efficiency at the site. Since fertilizer efficiency varies across sites, it is ideal that fertilizer response trials on similar soil types are available in the vicinity. In general, the N fertilizer efficiency in Malaysia varies from 30 to 70 %. This wide range in fertilizer efficiency is due to the very different environments where they were measured e.g. fertile coastal clays to infertile Malacca series soils. In reality, the average fertilizer efficiency over three years or more within a site is relatively similar. Therefore, the fertilizer efficiency at a site may be estimated from past fertilizer history and nutrient uptake rate as a first approximation as described step-by-step below.

1. Figure 4 below shows a hypothetical response curve of nutrient uptake to fertilizer input. It generally follows a modified Mitscherlich equation or a linear-plateau model. Under an ideal situation, we should know three points:

Point A: Nutrient uptake without fertilizer input i.e. soil nutrient supply
Point C: Targeted nutrient uptake at the correct fertilizer rate
Point B: Average last two to three years nutrient uptake at applied fertilizer rates

Point A and point C are usually unknown from past historical data although point A can be estimated using Foster's soil based system as discussed earlier. However, point B and the targeted nutrient uptake line are known.

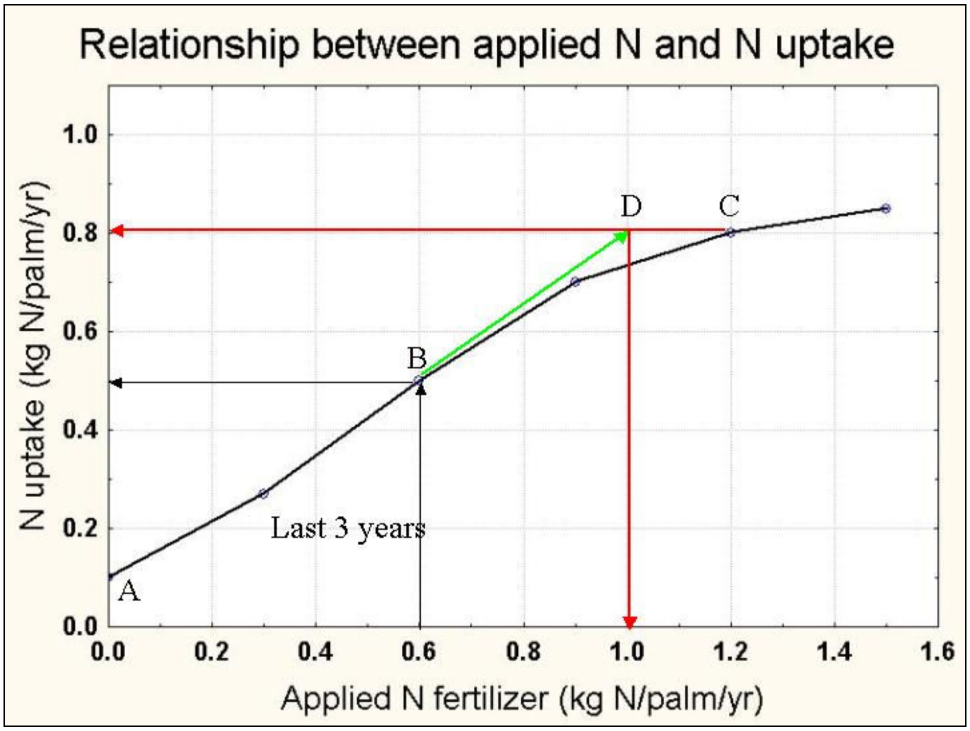


Figure 4: A hypothetical response curve of N nutrient uptake to N fertilizer input and a method to predict the N fertilizer rate for the following year

2. Point B can be calculated based on the model described earlier using the actual yield, dry weight and nutrient concentration in Frond No. 17.
3. The targeted nutrient uptake is calculated based on the targeted yield (site yield potential), dry weight and nutrient concentration in Frond No. 17 for the site.
4. We can then draw a tangent passing through point B to the targeted nutrient uptake line. The point where it cuts (point D) gives the estimated fertilizer rate. This generally underestimates the fertilizer requirement due to higher environmental demand (Corley and Tinker, 2003) with increasing fertilizer rate. We have not fully addressed this issue although a 10% higher rate for N and K appears satisfactory.
5. Another problem which has not been solved is the known fact that fertilizer use efficiency (FUE) declines with increasing fertilizer rate. It generally follows a declining exponential model, FUE = exp(-kF), where F is the fertilizer rate (kg/palm/yr) and k is a constant. This constant is mainly affected by fertilizer sources and environment.
6. This method avoids the necessity to estimate the fertilizer use efficiency and soil nutrient supply directly. However, it is highly dependant on a reasonable starting value (point B) and the targets to avoid over fertilization.
7. A reasonable point B can be obtained if one follows the six tools available to monitor palm health, and changes in soil nutrients and fertilizer use efficiency as listed below:

   a) Leaf nutrient status
   b) Soil nutrient status

c) Nutrient deficiency symptoms
d) Vegetative growth rate and canopy sizes (Classification)
e) Yield (site yield potential)
f) Fertilizer efficiency

An example showing the computation of N fertilizer rate (kg AC/palm/year) using INFERS model for the low N scenario as provided in the earlier illustrations of fertilizer recommendation systems is given below. The required variables measured in 1993 and 1994, and targets for 1995 are given in Table 16 and the calculated nutrient uptake and fertilizer rate are shown in Table 17. For simplicity, it is assumed that the soil N status is satisfactory and therefore, soil N demand is equaled to zero.

Table 16: Measurements made on oil palm planted in 1979 on Batang (lateritic) Family soil to demonstrate INFERS model

Variables	1993	1994	1995 (Target)
Leaf N (%)	2.48	2.53	2.65
Frond dry weight (g)	4.30	4.44	4.80
FFB yield (kg/palm/yr)	239	197	250
Average palm girth (cm)	202	202	202
Average height increment (cm)	51	51	51
N fertilizer rate (kg AC/palm/yr)	2	2	-

Table 17: Computed N uptake and N fertilizer rate based on variables in Table 16 using INFERS model

Component	Past history (1994 – 1993)	Target (1995)
N uptake (g N/palm/yr)	883	1195[1]
N input (g N/palm/yr)	500	-
N uptake/N input	1.77	1.77
N fertilizer rate (kg AC/palm/yr)	2	2.67
N environmental losses (%)	-	10
Final N rate (kg AC/palm/yr)	2	2.94

[1]: The maximum N uptake rate of 1180 g N/palm/year is used since the target exceeds it.

The calculated N fertilizer rate is similar to that of Foster's system but it is the only known fertilizer recommendation system for oil palm that accounts for both deficiency ad growth demands explicitly. It also avoids the problem of dilution or concentration effect of leaf nutrient due to changing canopy sizes. The relatively low N fertilizer rate in the present example is due to the relatively high soil N supply as shown by the past historical data. In general, higher N rate is recommended to account for the decline in fertilizer use efficiency with increasing fertilizer rate due to higher N environmental losses if the first approximation method is used as discussed above. This implies that the model tends to underestimate the fertilizer requirements of oil palm when the initial fertilizer rates are far below the optimum rates. However, the error gets smaller as the recommended fertilizer rates move towards the optimum rates and from experience, the model outputs converge within 3 years under the worst scenario.

INFERS model requires at least 3 targets as discussed above, and if they are wrongly set, then the estimated fertilizer rates will be incorrect. Thus, it requires the agronomist to know the fields well, have a good understanding of oil palm physiology and agronomy, be aware of the management practices and resources available, and have the ability to judge the reliability of the data for the model and decision making including the impact of spatio-temporal variation.

Ad-hoc methods

The fertilizer recommendation systems described so far are mainly quantitative and provide a first approximation of the fertilizer rates required to maintain optimum or targeted nutritional status of the palms. However, ad-hoc methods are also commonly used in the oil palm industry to estimate the fertilizer rates. They usually follow some general guidelines as listed below:

1. Nutrient balance approach based on the destructive sampling results of Ng and Thamboo (1967) and Ng *et al*. (1968). It assumes that the nutrient concentrations in the various components of oil palm remain constant across environments. Thus, palm age and FFB yield cause the main variation in the initial fertilizer rates.
2. In areas with high yield potential, the fertilizer rates are also increased accordingly based nutrient balance approach.
3. Similarly, young immature palms and palms dated for replanting are considered to have low fertilizer requirements whereas young mature palms and fully mature palms with high yields have high fertilizer requirements.
4. The soil types and analysis results are then used to modify the fertilizer rates based on estimated soil nutrient supply as discussed earlier and results of fertilizer response trials on different soil types. In general, no or little yield response to fertilizer is expected from the humic coastal soils such as Selangor series soils while good yield response to N, P, K and Mg is usually obtained from the sandy inland soils such as Serdang series. Also, high fertilizer requirement is assumed on light texture inland soils compared with heavy texture riverine soils.
5. The climatic impact on fertilizer requirements of oil palm remains controversial but it is generally held that oil palm in low rainfall region has low fertilizer requirements due to lower productivity.
6. The field and palm conditions are also used to adjust the fertilizer rates. For example, very high fertilizer rates (corrective rates) are given to correct severe nutrient deficiency symptoms observed in the fields during the visit or if the palm canopy sizes are considered below par. Similarly, factors which may reduce fertilizer use efficiency are noted and due considerations given when formulating the fertilizer recommendations.
7. Finally, the foliar analysis results are used to modify the fertilizer rates if necessary. Single nutrient critical level or nutrient ratio is the most common method to detect incipient nutrient deficiency of oil palm.

The classification of the current oil palm nutrient deficiency status is assessed by some or all of the above information. The fertilizer rates are then modified accordingly usually based on a classification table between fertilizer rates and nutrient deficiency status as provided in Table 11 or its variants.

The above guidelines can be regarded as heuristic rules and their integration may result in many fuzzy combinations of potential outcomes. Thus, the final fertilizer rates depend largely on individual decisions, perceptions or experiences, which unfortunately are usually unclear. For example, a plot of FFB yields and N fertilizer rates in 21 fertilizer response trials on inland and coastal soils in West Malaysia shows no relationship between them due to different soil fertility and environmental conditions (Figure 5). This illustrates the difficulty in using ad-hoc methods to determine the fertilizer rates for oil palm and their use should be minimized. In fact, to the best of the author's knowledge, no one has put forth evidence to support these methods of fertilizer recommendation system for oil palm.

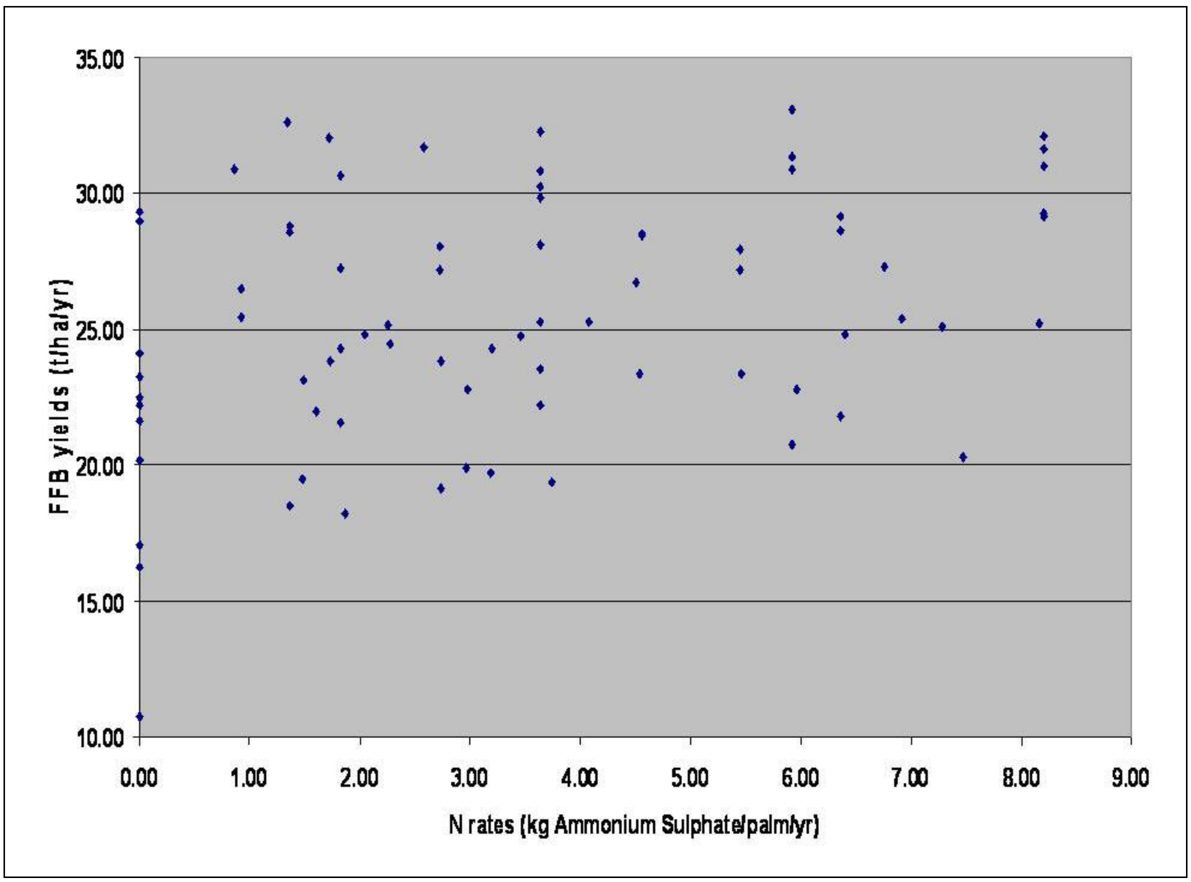


Figure 5: The effect of N fertilizer rates on FFB yields in 21 fertilizer response trials on inland and coastal soils in West Malaysia (data from PORIM-Industry trials conducted between 1960s and 1980s).

CONFIRMATION OF FERTILIZER RATES

The four quantitative methods of fertilizer recommendation system for oil palm are subjected to errors in their computations of fertilizer rates, which are common to all models. Therefore, some supplementary information may be required to determine whether the outputs from the above methods are reasonable. Below are some examples of useful supplementary information to fine tune the fertilizer rates.

Teoh and Chew (1988) have shown that rachis K is more sensitive than leaf K in detecting K deficiency in oil palm especially when soil exchangeable Ca and Mg are high in relation to soil exchangeable K. The critical rachis K concentration is 1.60 % if the outer epidermal layer of the rachis is removed, otherwise it is between 1.10 and 1.20 % (Foster and Probowo, 2002). The latter authors also showed that rachis P concentration is more reflective of the P nutrient status of the palms with a critical level of 0.10 %.

The fertilizer recommendation systems for oil palm generally assume satisfactory growing conditions for the palms. If there are limitations which reduce nutrient uptake or increase nutrient losses, they should be taken into account in determining the final fertilizer rates. For example, good leguminous covers have been shown to reduce the N fertilizer requirement of oil palm due to improvement in soil properties and N supply from the legumes (Hew and Ng, 1968). Similarly, if the computed fertilizer use efficiency is very low and the palm nutritional status remains deficient despite relatively high fertilizer rates, then the limitations causing it must be identified and solved first as further increase in fertilizer rates may be uneconomical.

Oil palm is now grown on very diverse soil types and some of them may require specific attention. Some examples are as follows:

1. Peat soils (fibric to hemic) may produce a large flush of nitrogen from the second year after planting onwards, owing to mineralization of the peat, and the nitrogen application should be reduced to avoid N/K imbalance (Corley and Tinker, 2003)
2. In coastal soils in West Malaysia, the soil exchangeable Ca and Mg are usually high, and no Mg addition is needed (Corley and Tinker, 2003)
3. In ultrabasic soils, the application of acidic fertilizers such as ammonium sulphate and the use of diammonium phosphate as a P and N source, appear beneficial on a commercial scale although there is no published evidence to support the practice.

The fertilizer rates recommended to the oil palm must be profitable. The estimation of fertilizer economics is simple in principle but the perennial nature of oil palm can cause problems (Corley and Tinker, 2003). Fertilizers supplied to young palms may enhance their health and give a larger yield well into the future. Hew *et al*. (1973) and Lo and Goh (1973) suggested that the cost of fertilizer should be discounted into the future, but the effects on future responses are not sufficiently well understood to make this fully accurate (Corley and Tinker, 2003). The latter authors further suggest that it is advisable to continue a fertilizer policy for several years rather than amending it each year in line with oil, kernel and fertilizer prices. Nevertheless, the economics of applying fertilizers should be computed and the simplest equations are provided by Corley and Tinker (2003) as follows:

The net gain from 1 t of FFB is Vnet = a + b –c where *a* and *b* are the sale value of palm oil and kernels, respectively, and c is the additional costs in handling 1 t of FFB and its product, as in transport and milling costs.

Then, Profit = GVnet – (F + A + H)
where *G* is the gain in yield per ha, and *F* and *A* are the purchase costs and the application costs of fertilizer and *H* is the extra harvesting costs.

Foster (1995) recommended a profit margin of at least 20 % to ensure profitability due to errors in the computation of fertilizer rates and large palm to palm variation.

Minimizing errors in fertilizer recommendations

The interplay of many factors and data in determining the fertilizer rates for oil palm demands accurate information for precise recommendations. An important determinant for this is the size of manuring block or management unit. It has been well established that the size of manuring block should not exceed 40 ha (Ng and Ratnasingam, 1970). In fact, with the planting of oil palm on more heterogeneous soils and the advent of precision agriculture for oil palm, the size of manuring block should be even smaller for more precise fertilizer recommendations (Goh *et al*., 2000) although sadly the current industry trend appears otherwise. In a survey on Malaysian oil palm plantations carried out by the Malaysian Palm Oil Association (MPOA), the management units commonly exceeded 100 ha (Goh *et al*., 2002). This trend must be reversed if we wish to improve efficiency and profitability in our oil palm industry.

It is also important that a leaf sample is taken from each manuring block with mature palms at least once a year for analysis unless the palms are due for replanting. No exception should be made because the costs and labour requirement to collect and analyze the leaf samples are relatively small compared with the cost of wrong fertilizer recommendations. The use of past leaf analysis results to predict the current leaf analysis results and then using them to estimate the fertilizer rates for the following year will likely incur large error and is therefore unacceptable. In fact, if the seasonal variation in leaf nutrients is unknown in the environment, then bimonthly (or quarterly) leaf sampling of a few representative fields is recommended in order to adjust the leaf nutrient concentrations (Foster, 2003).

It is also useful to collect the soil samples for nutrient analysis at least once in five years. This is to ensure that the soil nutrient status is satisfactory for palm growth and production, and no severe depletion of soil nutrients has occurred.

A good relational or object-orientated database is necessary to store historical agro-management inputs and outputs in each manuring block and the agronomic information including the soil analysis results. This information can be summarized into a sheet to be brought to the field for better assessment of the palms, identification of yield limitations and factors affecting the fertilizer use efficiency (Appendix 1).

Finally, the agronomist making the fertilizer recommendations must have a good understanding of the basic principles of soil and plant nutrition in order to interpret the data and use the fertilizer recommendation systems correctly, and more importantly, knows what to look for in the fields in regard to oil palm nutrition. It is also important that the estate manager understands the differences in fertilizer rates between his fields or manuring blocks even though they may appear small. He must not be tempted to average the recommended fertilizer rates and then use the average fertilizer rate for all the fields in his estate under the guise of ease of management and field supervision. This is because an over-application of 0.25 kg ammonium nitrate/palm/year will cost the estate an additional RM 25/ha/year while its under-application may result in an average yield loss of say 0.5 t FFB/ha/year which is equivalent to RM 190/ha/year at the current high fertilizer costs and palm oil prices.

CONCLUSIONS

The fertilizer recommendation systems for oil palm are by no means perfect or finalized, and some subjectivity through the use of heuristic rules is at present still necessary. However, it does not negate the effectiveness of these fertilizer recommendation systems in providing reasonable and probably optimum fertilizer rates to the oil palm if correctly employed, and variation in the recommendation of fertilizer rates for the same conditions among agronomists should be small. Thus, the nearly similar fertilizer recommendations for the whole estate or even company should be a thing of the past as we move towards site-specific fertilizer recommendations and precision agriculture. Further challenging research is now needed to test these fertilizer recommendation systems under more diverse environments where oil palm is now grown and to understand and model the fertilizer use efficiency of oil palm in order to reduce the uncertainties that may arise from their use.

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APPENDIX 1: STANDARD AAR ASSESSMENT FORM OF AGRONOMIC INFORMATION, AGROMANAGEMENT INPUTS AND OUTPUTS FOR A MANURING BLOCK

Date : 05/05/2004
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APPLIED AGRICULTURAL RESEARCH SDN. BHD.
(No Syarikat : 90455-D)

Appendix : 1

BATU LINTANG ESTATE

Manuring Block History Report

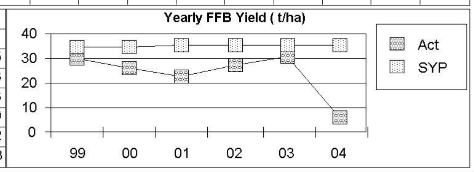
Block : 1 PM1991A 1	**Density** : 132	**Soil** : MUNCHONG,LOCAL ALLUVIUM	
Hectarage : 38.00	**Planting Material** : DxP AA	**Planting Distance** : 9.1x9.1x9.1 @	

Soil Analysis Results

Year	Area	Depth (cm)	pH Water	C (%)	N (%)	C / N Ratio	P (ppm) Total	P (ppm) Avail.	Exch. cations K	Exch. cations Ca	Exch. cations Mg	CEC (m.e.%)	Remarks
1998	PC	0-15	4.51				209	31.30	0.26		0.36		
1998	PC	15-45	4.06				120	14.30	0.17		0.20		
1998	IR	0-15	4.75	0.74	0.10	7.40	164	30.70	0.10	1.13	0.39	4.70	
1998	IR	15-45	4.40	0.53	0.07	7.57	124	14.80	0.10	0.72	0.24	4.10	
2001	PC	0-15	4.43				240	22.00	0.38		0.28		
2001	PC	15-45	4.24				146	8.10	0.35		0.17		
2001	IR	0-15	4.60	0.97	0.10	9.70	175	11.50	0.23	0.74	0.18	4.50	
2001	IR	15-45	4.48	0.76	0.08	9.50	190	7.30	0.22	0.47	0.13	4.80	

Year	Leaf Analysis Results: Ash	N	P	K	Mg	Ca	B	Cl	Canopy: L.A	Dry Wt	LAI	Size	Vig.	Nutrients applied (kg/palm): N	P2O5	K2O	MgO	Minor
1999	6.66	2.47	0.161	0.99	0.22	0.70	11.40		18.56	4.99	12.42	8	8	1.07	1.49	1.80	0.56	0.06
2000	7.01	2.76	0.166	0.95	0.25	0.80	14.20			5.15		7	7	1.26	0.00	1.95	0.34	0.05
2001	6.14	2.72	0.170	0.99	0.25	0.78				5.91		8	6	1.10	0.00	1.65	0.00	0.00
2002	6.78	2.70	0.160	1.03	0.24	0.75				5.52		7	7	1.18	0.00	2.25	0.00	0.00
2003	5.97	2.69	0.166	0.93	0.24	0.72	16.80			5.61		8	8	1.18	0.75	2.25	0.72	0.00
2004	6.38	2.63	0.160	0.97	0.24	0.75				6.02				1.18	0.00	2.40	0.00	0.00

Year	Yearly FFB Yield (t/ha): Density	FFB/ha	Bch/ha	Av. Wt.	SYP	Rainfall: mm	Days
1999	136	30.66	1786	17.17	34.69	4073	185
2000	136	26.29	1547	16.99	35.25	3374	183
2001	132	22.98	1259	18.25	35.49	3185	143
2002	132	27.89	1431	19.49	35.58	3141	150
2003	132	30.92	1553	19.91	35.52	3110	172
3-2004	132	6.55	330	19.85	35.38	582	38



Canopy: Size	Vig.	Frd.No	Loss	Palm: Uni.	Loss	Etiol.	Soil: T-Soil	Cons	Drain	Management Practices: Legume	PC	IR	F.App	Pruning: Qlty	Freq.	Yield: Bch/p	Reco.
1	1	<=8	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	2	9~16	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
3	3	17~24	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
4	4	24~32	4	4	4	4	4	4	4	4	4	4	4	4		4	4
5	5	>=33	5	5	5	5	5	5	5	5	5	5	5			5	5
6	6	Mature <=33															
7	7	33~37															
8	8	38~41															
9	9	42~45															
10	10	>=46															

Comments : ....

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Deficiency Symptoms

Nutri.	Slight: Few	Many	Moderate: Few	Many	Severe: Few	Many	Correction Required
N							
K							
Mg							
B							
Other							