Agronomic principles and practices of fertilizer management of oil palm

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AGRONOMIC PRINCIPLES AND PRACTICES OF FERTILIZER MANAGEMENT OF OIL PALM

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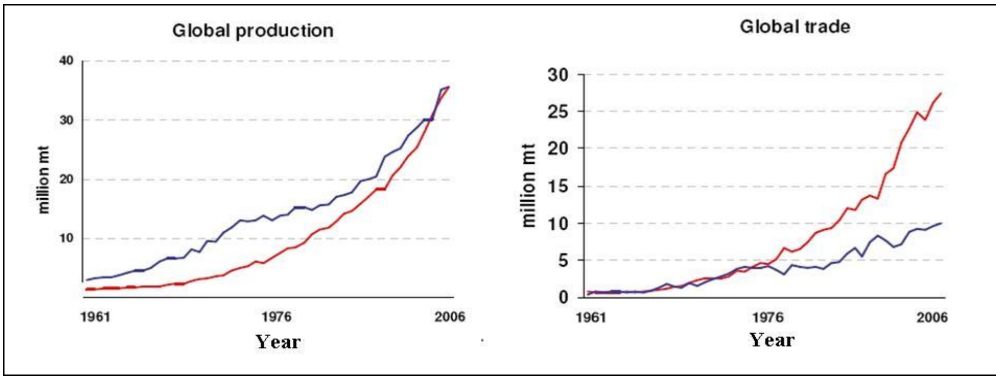
Introduction

The oil palm is quite unlike the other oil crops and probably most agricultural crops in the world, which are mainly grown for domestic markets. The produce from oil palm, on the other hand, is mainly exported and in fact, is the largest traded vegetable oil globally. For example, the global productions of palm oil and soybean oil in 2006 were similar but the global trade of palm oil was nearly three times that of soybean (Figure 1). Thus, apart from bring in the much needed revenues for the countries producing it, palm oil could also be conceived as one of the most important agricultural crops helping to feed the escalating population worldwide. This unique position might have attracted the attention of many stakeholders who are scrutinizing the recommended management practices and their impact on various global issues such as climate change, biodiversity, energy consumption, water consumption and human rights. These management practices include fertilizer use in the oil palm plantations.

The importance of fertilizers for oil palm has been highlighted in many papers by authors working in most parts of the world where it is cultivated. The main reasons for the generally good responses to fertilizers worldwide are two folds.

Figure 1: Global production and trade for palm oil and soybean oil

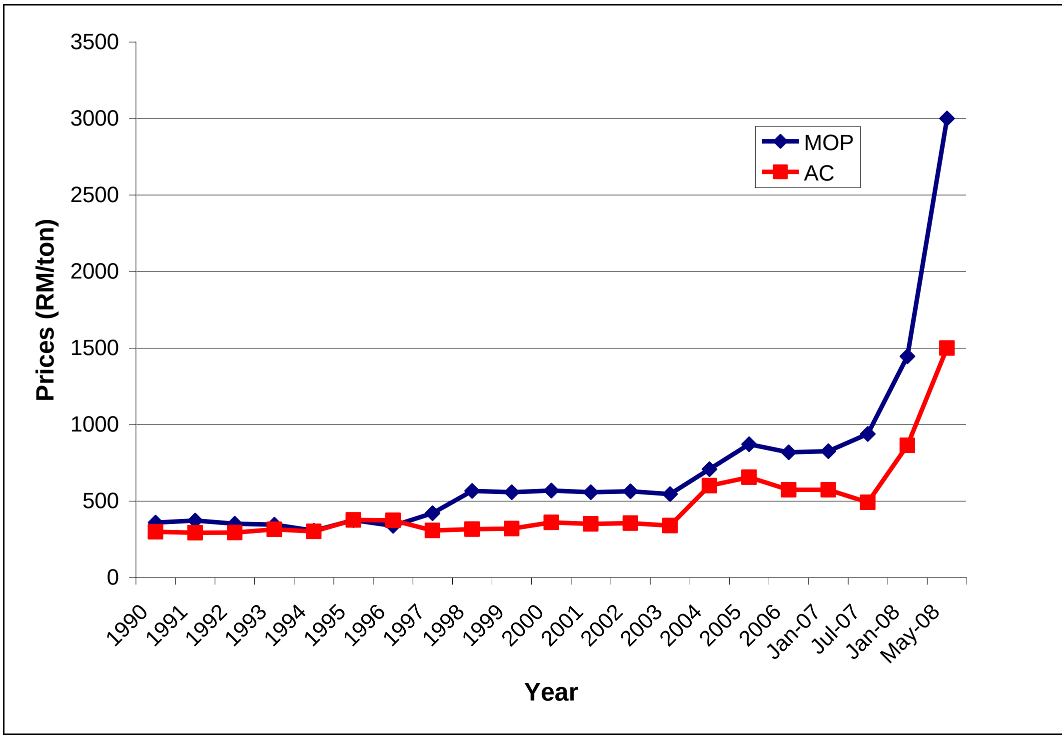


Source: Thoenes (2006)

Firstly, the oil palm has one of the highest dry matter production rates being unrivalled in its ability to convert solar energy into dry matter and vegetable (palm) oil amongst the C3 plants. This process requires a large amount of nutrients which must be supplied by the soil or fertilizers. On the other hand, most soils grown with oil palms especially in Peninsular Malaysia and Sarawak have low soil fertility and therefore, mineral fertilizers are usually necessary to achieve and sustain good palm nutritional status and large yields. In fact, the main premise of growers is that healthy palms will produce optimum FFB (fresh fruit bunch) yield, which is the primary commodity of most plantations.

Currently, fertilizers alone constitute more than 35% of the total production cost of oil palm in Malaysia. The present escalating fertilizer prices of more than 335% and 229% since last year (2007) for ammonium chloride and Muriate of potash respectively (Figure 2), which are the major components required by the oil palm, would increase the cost further and put more pressure on the plantations to economize. The reasons for the soaring fertilizer prices worldwide include new demands for food crops such as maize for ethanol and other biofuels, increase prices of energy and freight, increase use of liquefied natural gas and higher consumption for grain-fed meat in China, India and Brazil. Thus, the practice of putting high fertilizer rate to ensure nutrient sufficiency and act as a safety net may not be tenable now despite the current relatively high palm oil prices.

Figure 2: Price trends of Muriate of potash (MOP) and ammonium chloride (AC) in Malaysia between 1990 and 2008



One of the best means to reduce production cost is to sustain maximum yield at any one site. The maximum yield is usually close to the optimum yield because of the high indirect costs in oil palm management. However, the optimum yield is subject to the vagaries of commodity prices and therefore, difficult to predict, let alone sustain. Hence, we advocate the approach to maximise and maintain the highest yield possible at any one site, which is also known as site yield potential (Goh *et al*., 1994; Goh *et al*., 2002). In combination with judicious fertilizer inputs, it forms one of the central tenets of plantation management because it affords the highest revenue to be attained at the lowest possible cost for an assured best profit. This will help to enhance the attractiveness of the oil palm industry. In fact, the ability of the oil palm industry to compete with others is crucial if we are to attract reliable and skilled workers and reduce the high turn-over of work force. This is vital towards the long-term sustainability of oil palm plantations.

In today's climate of great concern for the environment and the global accountability of the impact of our activities on climate change coupled with the necessity to meet the Principles and Criteria of the Round Table for Sustainable Palm Oil (RSPO), every recommended practice including fertilizer inputs will be scrutinized by all stakeholders.

The above points show that the benefits of sound fertilizer management for oil palm go beyond preventing nutrient deficiency and maintaining healthy palms, which have long been recognised by the industry. Therefore, it is not surprising that the Malaysian oil palm industry has invested millions of dollars in research and development on fertilizer use since the 1920's when oil palm was first commercially grown.

This chapter, which is largely drawn from our earlier papers on similar subject (Goh *et al.*, 1999a; Goh, 2005; Kee *et al*., 2005), discusses the main issues of fertilizer management in oil palm in the face of the changing scenarios in plantation management. It principally updates the paper by Goh *et al*. (1999) and therefore covers the same broad areas of fertilizer management as follows:

a) Agronomic principles in fertilizer management
b) Field practices for sound fertilizer management
c) Criteria and indicators of palm health and good fertilizer management

Agronomic principles in fertilizer management

The agronomic principles of fertilizer management of perennial tree crops such as oil palm encompass the following broad areas:

a) Objectives of fertilizer management
b) Computation of fertilizer rates

c) Choosing the right combination of fertilizers
d) Minimising nutrient losses from applied fertilizers
e) Economics of fertilizer management

The principles behind each of these topics are briefly discussed below.

Objectives of fertilizer management

The objectives of fertilizer management in oil palm used to be straightforward as follows:

a) To supply each palm with adequate nutrients in balanced proportion to ensure healthy vegetative growth and optimum economic FFB yields.
b) 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.
c) To integrate the use of mineral fertilizers and palm residues.

However, various conditions have made achieving the objectives a challenge nowadays. Foremost, the shortage of reliable and skilled workers and staff, and high turn-over in work force have resulted in poor standards of work and/or over generalization of the manuring programmes to reduce instructions in the fields i.e. ease of management. These compromises can negate the value of good fertilizer management.

The environmental concerns raised by non-government organizations which are usually related to over-fertilisation, land degradation, and pollution from heavy metals e.g. cobalt in phosphate rock and eutrophication by P increase the demand for science-based fertilizer recommendations. Similarly, the expansion of oil palm into areas with little information on the soil properties, climate etc dictates the necessity for good fertilizer management e.g. the cultivation of oil palms on ultrabasic soils.

There is also a tendency for the plantations to manage larger manuring blocks which can result in over generalisation. In fact, this approach goes against the current trend of site-specific fertilizer management and precision agriculture worldwide. Similar work in oil palms clearly showed its applicability for the crop (Goh *et al*., 2002; Anuar *et al*., 2008a).

The rising fertilizer prices which increase production costs will put pressure on sustaining the palm nutrition at adequate status and maintaining long-term soil fertility. Thus, greater care in developing and recommending the fertilizer programmes and monitoring palm health and soil nutritional status are required to attain the objectives of good fertilizer management. Thus, the multi-objective nature of fertilizer management demands that the fertilizer recommendation systems for oil palm entail more than just the computation of optimum fertilizer rates (Goh, 2005). The other major components in the system 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 must be correctly implemented. Goh (2005) further stressed that 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 and Hardter, 2003) and methods to maximize fertilizer use efficiency (Goh *et al*., 1999a; Goh *et al*,, 2003).

Therefore, the agronomic principles of an effective fertilizer management should take all the above into account and balance the above needs and objectives with the resources in the estates. The key steps are:

a) Determine the growth and yield targets.
b) Assess the nutrient requirements to attain the above and prevent the occurrence of nutrient deficiency.
c) Assess the management level and resources of the estate.

d) Ascertain the most efficient and cost effective fertilizers and applications of fertilizers to meet the nutrient requirements.
e) Compute the economics of the recommendations and expected results.
f) Monitor the outcome including the economic returns.
g) Decide on further action required and repeat the steps if necessary.

Most of these steps have been described in our earlier papers (Goh *et al*., 1999a) but for completeness and comprehensibility of our lecture, we shall briefly discuss them.

Computation of fertilizer requirement

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 now grown (Goh, 2005). 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 several methods commonly used for the formulation of fertilizer recommendations. These include:

a) Critical leaf and/or soil nutrient level method
b) Optimum nutrient ratio method
c) Yield response function method and
d) Nutrient balance method

In actual practice, derivation of fertilizer rates does not rely exclusively on any one method. An integrated approach, which combines the above methods, is usually adopted and AAR is one of its proponents. Kee *et al*. (1994) and Corley and Tinker (2003) provided a detailed structure of one such approaches called INFERS. In general, this method uses the principles of plant nutrition as its backbone and guidance allowing ones to partially overcome the main limitation of empirical techniques, which can only be used within the same environments where they have been developed. A detailed description of the various methods of estimating the fertilizer rates for oil palms can be found in Goh (2005) and therefore, only a brief discourse on the integrated method is provided below.

Primarily, the nutrient balance method is employed first to compute the nutrient requirements of oil palm in a manuring block. This approach assumes that the oil palm agroecosystem has definite components of nutrient removal (demand) from the system and nutrient return (supply) to the system (Figure 3). It specifically attempts to balance the nutrient demand with the nutrient supply.

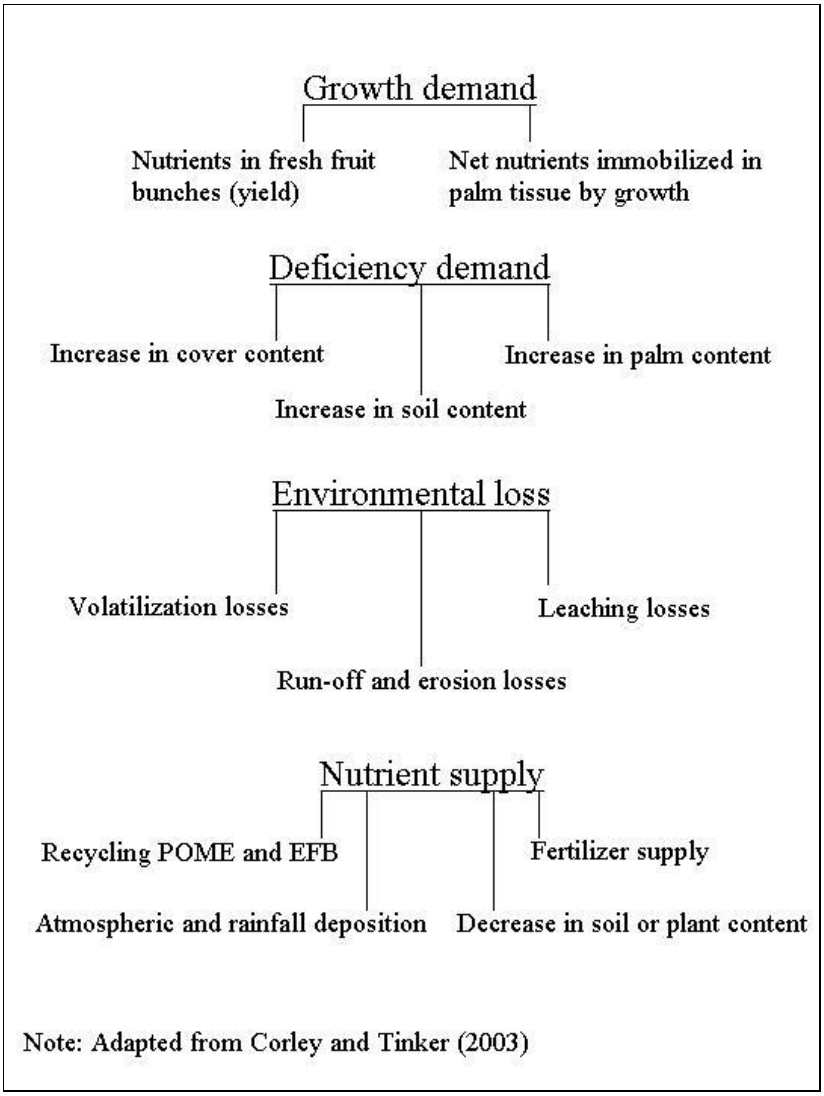
In the oil palm agro-ecosystem, the components of nutrient demand are:

a) Plant nutrient uptake for growth and yield
b) Nutrient losses through leaching, run-off and erosion, and volatilization
c) Nutrient removed by pest damage and
d) Nutrient non-availability and antagonisms.

The components of nutrient supply are:

a) Nutrient returns from the palms, e.g. pruned fronds
b) Nutrient returns from leguminous covers
c) Nutrients from applied by-products e.g. empty fruit bunches
d) Rainfall
e) Soil
f) Fertilizers

Figure 3: Components of nutrient balance in oil palm agroecosystem



The basic principle is then to estimate the total demand of the palm and match it with the nutrient supply by the oil palm agroecosystem excluding the fertilizer component. The shortfall between the nutrient demand and supply, which is also called gross nutrient requirements, should be met by fertilizers. A number of studies have been made to quantify the various components of nutrient demand and supply in the oil palm agroecosystem. Ng

(1977) considered the major variables in the nutrient balance sheet to be soil nutrient supply to the oil palm and plant nutrient demand.

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 two largest components of nutrient demand are Growth and Yield (plant nutrient demand). They are also the first key steps in an effective fertilizer management scheme as outlined earlier. Thus, it is essential that the agronomist estimates the growth rate and yield trend of a manuring block right from the start. A typical example of the growth rate of oil palm using leaf area as the criterion is shown in Figure 4. Coupled with the leaf nutrient concentrations, the agronomist will be able to estimate the nutrient requirements necessary to attain the expected growth. Similarly, the yield profiles in different regions of Malaysia as illustrated in Figure 5 will provide a clue on the nutrient removal per year from the manuring block which should be replaced by fertilizer inputs or soil nutrient supply. Thus, changing the present palm nutritional state in the above components to the optimum level and maintaining the optimum state are the central tenets of nutrient balance approach such as INFERS model.

Figure 4: A typical growth rate of oil palm in Peninsular Malaysia as measured by leaf area per frond

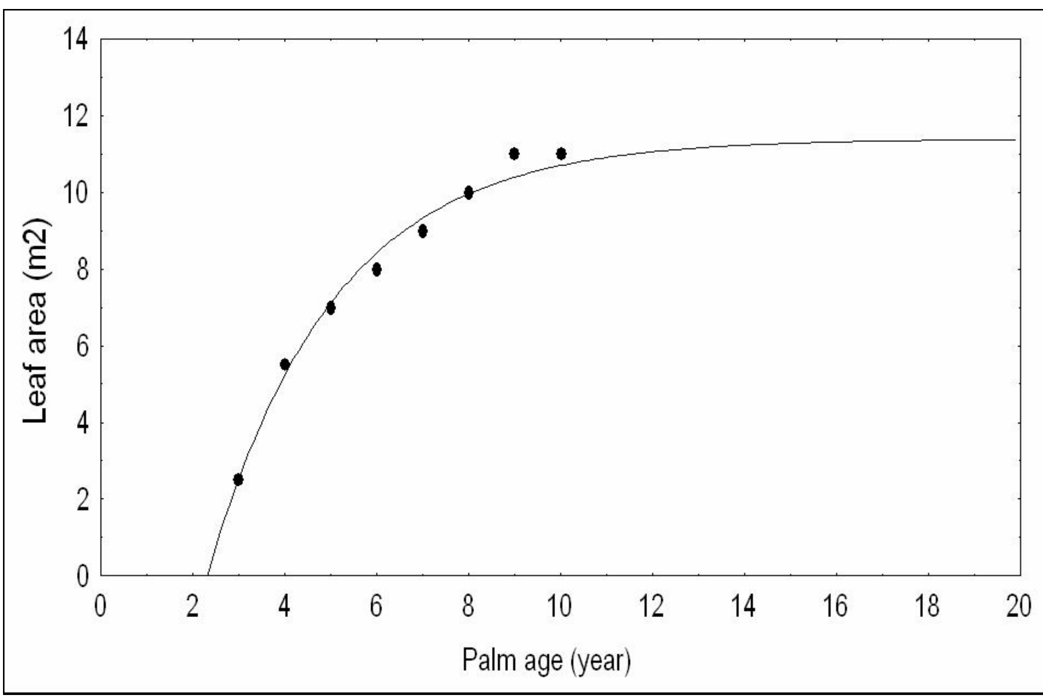
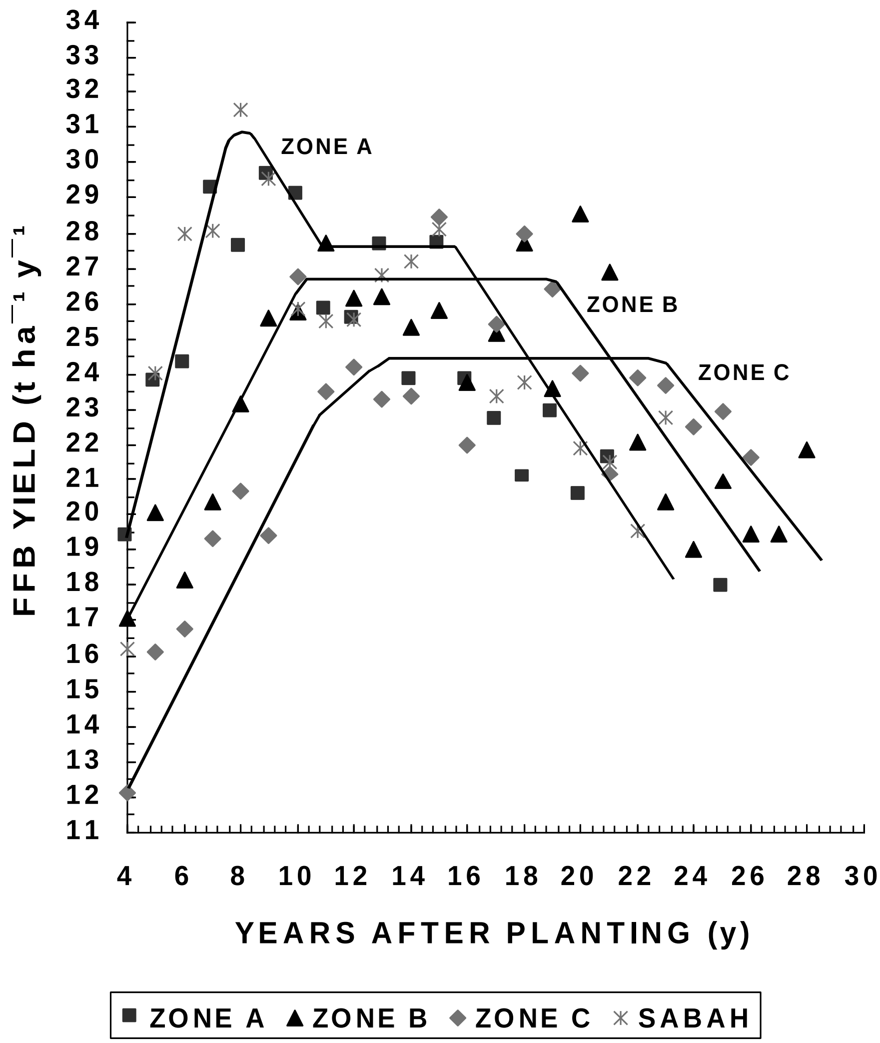


Figure 5: Yield profiles of oil palm in different regions of Malaysia.



Note: Zone A – Region with no distinct dry season including most parts of Sabah

Zone B – Region with occasional dry seasons

Zone C – Region with distinct dry season

Source: Goh *et al.* (1994)

Another important component of nutrient demand is soil nutrient demand, which 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 (Goh, 2005). The soil nutrient losses in the oil palm agroecosystem mainly arise from erosion, runoff and leaching. They are usually less than 10% of nutrient input 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 (Goh, 2005). That is, if one expects volatilization losses to be about 30 %, then the final N fertilizer rate is adjusted 30 % upwards.

On the nutrient supply side, available data suggests that atmospheric returns are probably insignificant. However, pruned fronds can provide substantial nutrients to the palms to the tune of 36% for N and 27% for K on poor inland soils in Peninsular Malaysia. In mature oil palm areas, the last component of nutrient supply is soils. Unfortunately, most Malaysian soils including those from Sabah are inherently poor in nutrients particularly N and P (Table 1 overleaf). Therefore, most of the nutrients required by the palms have to come from fertilizers, usually in mineral forms.

Table 1: A summary of soil chemical properties in the B horizons (508 samples) of common soils in Sabah, Malaysia.

Parameter	Mean	Minimum	Maximum	Unit of parameter	Standard error
pH	4.41	3.40	7.2	-	1.02
Organic C	0.47	0.07	33.0	%	0.07
Total N	0.07	Trace	0.40	%	0.01
Total P	149	15	874	mg kg^{-1}	4.39
Available P	2.18	Trace	38.5	mg kg^{-1}	0.13
Exchangeable K	0.20	Trace	1.00	$cmol_{(+)}$ kg^{-1}	0.01
Exchangeable Ca	1.64	Trace	24.9	$cmol_{(+)}$ kg^{-1}	0.16
Exchangeable Mg	2.39	0.01	29.9	$cmol_{(+)}$ kg^{-1}	0.17
CEC	14.53	1.30	52.3	$cmol_{(+)}$ kg^{-1}	0.34
Base saturation	23.36	0.45	100	%	1.24

Source: Goh *et al*. (1998).

Goh (2005) provided a detailed step-by-step example of computing the fertilizer rate for oil palm. For simplicity, we shall show the computation of nutrient balance and fertilizer requirements to sustain 30 t/ha/yr in a mature oil palm field (Table 2 overleaf) as presented by Ng *et al*. (1999). Here, we assume that the oil palm is in a steady state and grown on a soil with poor fertility. Under steady state condition, the canopy size remains constant and therefore, the nutrient requirements for canopy growth should be met by the nutrients recycled from the pruned fronds. The final analysis shows that the annual fertilizers needed for each palm to satisfy the gross nutrient requirements totalled 10.75 kg and comprise 4.22 kg Ammonium chloride, 0.97 kg Jordan phosphate rock, 3.59 kg Muriate of Potash and 1.97 kg Kieserite.

Table 2: An example of nutrient balance and fertilizer inputs required to sustain 30 mt FFB yield per ha per year in mature oil palm.

Types	Components	Nutrients (kg/palm/yr)			
		N	P	K	Mg
Nutrient demand	Trunk	42.4	4.1	121.6	10.2
	FFB	99.1	15.6	129.6	33.3
	Run-off	15.2	1.0	21.6	2.1
	Leaching	3.4	0.9	6.3	3.4
	Erosion	2.4	Trace	Trace	Trace
	Total 1	162.5	21.6	272.9	49.1
Nutrient supply	Rainfall	17.0	2.4	31.6	4.8
	Total 2	17.0	2.4	31.6	4.8
Nutrient inputs	Nutrient required = Total 1 – Total 2	145.5	19.2	247.6	44.3
	Fertilizer types	AC	JRP	MOP	KS
	Fertilizer equivalent	4.22	0.97	3.59	1.97

Note: AC denotes Ammonium chloride, JRP denotes Jordan rock phosphate, MOP denotes Muriate of Potash and KS denotes kieserite.

Source: Ng *et al.* (1999)

While the nutrient balance approach provides the gross nutrient requirement, it does not work out the fertilizer requirements directly. We need information from fertilizer trials to enlighten us on the optimum fertilizer rates and the yield responses. For example, in Sabah, the oil palms respond mainly to N fertilizer followed by K and P fertilizers (Table 3). The response to N generally exceeds 15 % except on Lumisir Family soil. The latter might be attributed to its high inherent soil fertility status as indicated by the yields in the control plots (no fertilizer). K responses are mainly lower than those experienced in Peninsular

Malaysia. Again, this can be explained by the relatively high soil exchangeable K status as shown in Table 1. These results strongly imply that the agronomist must know and understand the soil properties in the manuring blocks, not just the soil names, to draw up proper and effective fertilizer recommendations to the estates.

Table 3: Yield responses (t FFB/ha/yr) of oil palm to N, P and K fertilizers in Sabah, Malaysia.

Soil types	FAO units	N			P			K		
		-	+	Diff (%)	-	+	Diff (%)	-	+	Diff (%)
Kumansi	Haplic Acrisols	23.6	31.2	32.2	27.9	28.7	2.9	27.5	29.4	6.9
Batang	Ferric Acrisols	28.9	33.8	17.0	31.1	32.7	5.1	-	-	-
Lumisir	Ferric Acrisols	27.9	30.0	7.5	29.1	29.2	0.3	26.4	30.3	14.8
Koyah[1]	Dystric Gleysols	21.1	28.0	32.7	25.3	25.6	1.2	24.8	26.6	7.3
Inanam[1]	Gleyic Acrisols	16.7	20.4	22.2	17.0	20.8	22.4	17.6	20.0	13.6
Buran	Gleyic Luvisols	29.1	33.7	15.8	31.1	31.9	2.6	30.9	32.6	5.5

1: Sites were subjected to fluctuating water table and seasonal flooding.

Note: diff denotes difference; - denotes without respective fertilizer; + denotes with respective fertilizer

Source: Goh and Teo (1997).

We can also predict the fertilizer efficiency in each trial by plotting the gross nutrient requirements against the fertilizer rates as shown in Figure 6 while Table 4 shows the fertilizer efficiencies in some coastal and inland soils in Peninsular Malaysia. The highest K fertilizer efficiency was in Munchong series soil at 83%. This was due to the poor soil K reserve, good yield response to K fertilization and the relatively low K fertilizer input in the trial. The lowest fertilizer K efficiency was found in Briah series soil at 19% due to high fertilizer rates and soil K status. In general, fertilizer efficiency is affected by the gross nutrient requirement, imbalanced nutrition, fertilizer rates, soil fertility and nutrient losses.

Figure 6: Effect of N rates on gross N nutrient requirement of oil palm on Rengam series soil in Peninsular Malaysia

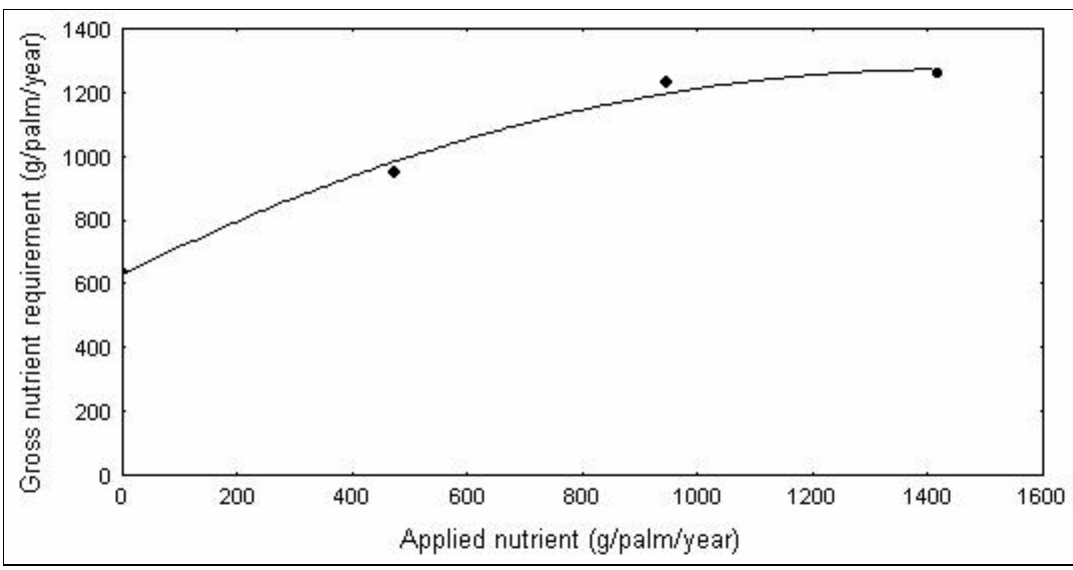


Table 4: Estimated K uptake from fertilizer and K fertilizer efficiency in five soil types in Peninsular Malaysia.

Soil series	Soil Taxonomy	Fertilizer K uptake (kg/palm/yr)	K fertilizer efficiency (%)
Selangor	Typic Tropaquept	0.57	42
Briah	Typic Tropaquept	0.64	19
Munchong	Xanthic Hapludox	1.50	83
Kuantan	Typic Hapludox	0.98	54
Malacca	Petroferric Hapludox	0.78	54

Source: Recomputed from Teoh and Chew (1988).

Collating and assimilating the data from fertilizer trials conducted worldwide have enhanced the confidence of the agronomists to extrapolate the results to other sites with similar conditions and combining them with nutrient balance computation, leaf analysis and soil fertility status to produce the fertilizer recommendations. The fertilizer use efficiency at a site can also be approximated using the past fertilizer history of the manuring block as described in detail by Goh (2005). Interested readers should refer to the paper.

Balanced fertilization

High fertilizer rates alone will not always provide optimum economic returns: a balanced fertilizer program is also essential as illustrated in Table 5. Nitrogen increased yield by 49% in the presence of high K rate. Similarly, there was a 25% yield response to K when high N rate was applied. Both N and K also had beneficial effect on the vegetative dry matter production.

Table 5: Effect of NK interaction on yield and growth of oil palm on Rengam series (Typic Paleudult) soil in Malaysia.

Parameters	Nitrogen levels	Potassium levels			s.e.
		K0	K1	K2	
FFB Yield ($kg\ palm^{-1}\ y^{-1}$)	N0	71.6	65.3	66.3	4.3
	N1	68.4	95.2	95.8	
	N2	79.1	95.8	98.6	
Vegetative growth (kg dry matter $palm^{-1}\ y^{-1}$)	N0	88.9	84.0	89.2	4.0
	N1	96.6	117.4	119.4	
	N2	106.4	120.0	123.0	

Source: After Chan (1982)

Apart from the above, application of K fertilizer will decrease oil to bunch ratio in the absence of N fertilizer (Table 6). However, with sufficient N level, K fertilizer generally increased the oil to bunch ratio to similar level compared to the control. With the higher yield from palms with balance nutrition, the oil yield is also better.

Table 6: Effect of NK interaction on oil to bunch ratio (%) in Malaysia.

Soil series	Soil taxonomy	Potassium levels	Nitrogen levels			LSD
			N0	N1	N2	
Bungor	Typic Paleudult	K0	27.1	23.4	24.0	3.0
		K1	25.0	24.8	24.2	
		K2	23.5	24.6	25.4	
Rengam	Typic Paleudult	K0	26.9	25.6	24.8	3.0
		K1	23.7	24.6	21.3	
		K2	22.8	23.5	24.1	

Source: After Foster et al. (1988)

Positive interactions of K fertilizer with other agronomic practices such as mulching, frequency of application and frond placement have been reported to increase yield between 4% and 14%. While capitalising on synergistic effects will improve yield and fertilizer efficiency, avoidance of antagonistic effects is also necessary to maximise fertilizer use. For example, high K rates have been shown to depress Mg and B uptakes and might decrease yield.

Balanced fertilization for oil palm is not just a function of fertilizer inputs. The soil inherent fertility is probably equally important since oil palms are now grown on very diverse soil types and some of them may require specific attention. Thus, while the principles of plant nutrition dictate that the soil nutrient status and plant nutrient content should not decline with time, it may have to be done on purpose for some soil types. 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 (Goh, 2005). Similarly, the residual value of large dressings of phosphate rock and ground magnesium limestone (Goh and Chew, 1995) can be up to three years' demand and these nutrients can probably be omitted in such cases (Corley and Tinker, 2003). In peat soils (fibric to hemic), a large flush of nitrogen from the second year after planting onwards may occur owing to mineralization of the peat, and the nitrogen application should be reduced to avoid N/K imbalance (Corley and Tinker, 2003). Further discussion on these issues is provided in the other chapters in this book.

Potential nutrient losses and environmental concerns

The recommended fertilizers should be applied in a manner that they are absorbed by the palms at maximum efficiency. This is best done by minimising fertilizer losses in the plantation, which is even more important now in view of the current very high fertilizer prices, shortages of fertilizers and expected economic woes. It should also minimise environmental problems if any.

Nutrients may be lost by surface run-off, leaching through the soil profile, nutrients fixation, volatilisation and immobilisation by ground covers in young oil palm. An understanding of these nutrient loss mechanisms is essential to alleviate them and improve fertilizer use efficiency (Goh *et al*., 1999a).

Surface run-off

On average 11% of N, 3% of P, 5% of K, 6% of Mg and 5% of Ca applied can be lost in surface run-off alone (Table 7). These results were obtained during a low rainfall year with only 1426 mm on a 9% slope. The most susceptible areas for run-off tend to occur in the harvester's path and along the oil palm rows where the soils are more compacted and the ground vegetation is generally sparse. More recent data obtained by AAR also indicate that the mean run-off losses as percentage of the nutrient applied are within the following ranges: 5-8% N, 10-15% K, 4-6% Mg and less than 2 % for P (Table 8). These results show that soluble nutrients such as N, K and Mg are more susceptible to run-off losses. We further found that nutrient losses via surface run-off are highly dependent on the rainfall pattern at the time of fertilizer application, particularly during the first few rains after application and the antecedent moisture status of the soil. Other equally important factors, which might affect run-off, are rainfall intensity and quantity, soil characteristics and slope.

Table 7: Mean nutrient losses through run-off water.

Position in field	Nutrient lost as percent added.					
	N	P	K	Mg	Ca	B
Oil palm row	13.3	3.5	6.0	7.5	6.8	22.9
Harvest path	15.6	3.4	7.3	4.5	6.2	33.8
Pruned frond row	2.0	0.6	0.8	2.7	0.8	3.3
Pruned frond/harvest path	6.6	1.4	3.5	2.2	3.4	12.5
Average for the field	11.1	2.8	5.0	5.6	5.2	20.7
Nutrients applied (kg ha^{-1})	90.2	52.0	205.9	32.8	78.9	2.4

Source: Maene *et al*. (1979)

Table 8: Mean net nutrient losses in the oil palm ecosystem via surface run-off and eroded sediment on Rengam series (Typic Paleudult) soil.

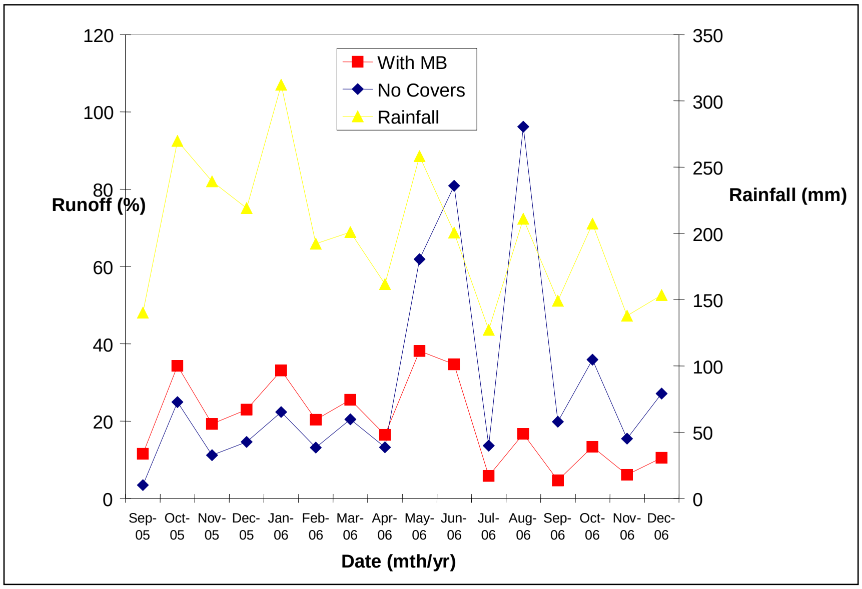
Nutrient	Net annual losses (kg $ha^{-1}y^{-1}$)			Net loss as % of applied fertilizer*
	in runoff	in eroded sediment	Total	
N	4.5 – 7.2	0.5 – 0.8	5 – 8	5 – 8
P	0.7 – 1.1	0.5 – 1.3	1.2 – 2.4	0.8 – 1.6
K	20.8 – 33.0	Trace	21 – 33	9.8 – 15.3
Mg	3.6 – 6.8	0.1	3.7 – 6.9	4.1 – 7.6

* Mean (1992 – 1994) fertilizer input was equivalent to: 101 kg N, 145 kg P, 215 kg K and 90 kg Mg ha^{-1} y^{-1}.

Source: Kee and Chew (1996)

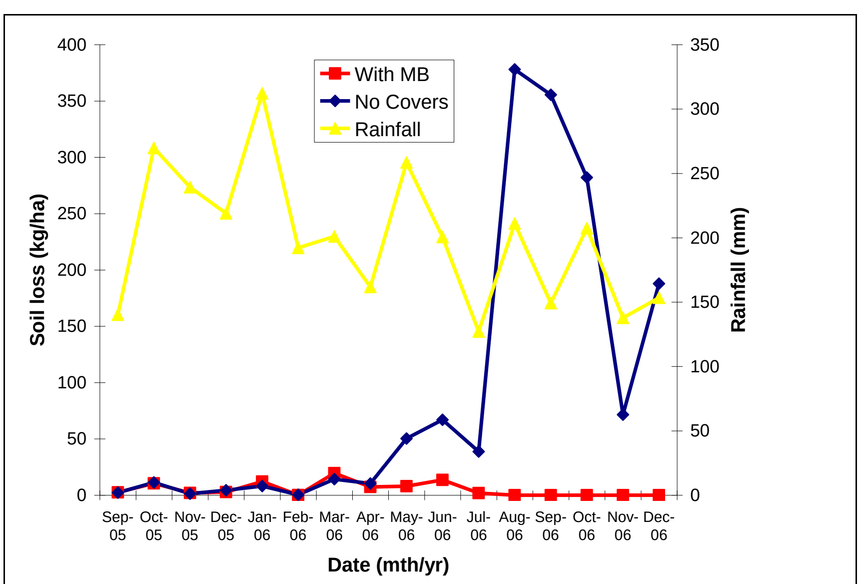
Good ground covers especially leguminous cover crops are essential towards reducing runoff and erosion losses. For example, in the first 18 months after planting, *Mucuna bracteata* could decrease runoff losses by 30% (Figure 7) compared with bare ground (Ng *et al*., 2008). Similarly, soil loss declined from 1484 kg ha^{-1} to only 80 kg ha^{-1}, nearly 19 times lower (Figure 8). Establishment of conventional leguminous cover crops, *Pueraria javanica*, *Calapogonium mucunoides* and *Calapogonium caeruleum* at replanting improve yields by 16 % between 48th and 60th month after field planting (Yacob *et al*., 2008).

Figure 7: Effect of *Mucuna bracteata* (MB) on runoff losses (%) under oil palm replant



Source: Ng *et al*. (2008)

Figure 8: Effect of *Mucuna bracteata* (MB) on soil losses under oil palm replant



Source: Ng *et al*. (2008)

Leaching losses

Little work has been done on the leaching losses of applied nutrients under oil palms. Foong (1993) showed that leaching losses during the first four years of oil palm growth (as % of total nutrient applied) have been found to be about 17% N, 10% K and 70% Mg. Losses are substantially reduced to about 3% N, 3% K and 12% Mg when the palms are fully matured (Table 9). The main reasons for the high leaching losses during the early stage of palm growth are probably poor palm canopy cover, less extensive root system and ground covers are generally not well established especially during the first year after planting. In general, many factors influence the leaching of nutrients including nutrient demand by plant, palm root density, soil pore size, texture, organic matter content, rainfall and amount and timing of fertilizer application (Goh *et al*, 2003). High leaching losses can be expected in coarse-textured soils that are low in organic matter and in high rainfall areas.

Table 9: Leaching losses of nutrients measured in an oil palm lysimeter study.

Palm age (y)	Leaching losses as percentage of applied nutrients			
	N	P	K	Mg
1-4	16.6	1.8	9.7	69.8
5-8	1.2	1.6	2.5	11.5
9-14	3.0	1.5	2.9	15.5

Source: Foong (1993)

P Fixation

Losses due to fixation by the soil involve mainly phosphate fertilizers. The P fixing capacities of some of the common Malaysian soils are shown in Table 10. The amount of P 'fixed' ranged from 208 mg to 1172 mg per kg soil and is related to its clay mineralogy. Although soils with high P fixing capacity improve P dissolution of phosphate rock, they also decrease the soil solution P (intensity), which is required for plant uptake. The general approach is to use less reactive phosphate rock and concentrated application of fertilizer through high rate and banding for these soils. The use of organic matter to improve P dissolution and reduce P fixation (Bah *et al*., 2006) under oil palms are currently being experimented.

Table 10: P sorption capacity and mineralogy of some common Malaysia soils.

P Sorption	Soil	Orders	P fixed ($mg\ kg^{-1}$)	Kaolinite (%)	Gibbsite (%)	Fe_20_3 (%)
	Marang	Ultisol	208	n.d.	-	0.3
	Lanas	Ultisol	247	5.6	-	0.6
Low	Rengam	Ultisol	308	8.6	0.6	1.3
	Tebok	Ultisol	383	11.8	-	0.2
	Serdang	Ultisol	396	13.0	0.2	0.9
	Tok Yong	Ultisol	450	16.8	3.2	2.9
	Harimau	Ultisol	568	16.0	1.0	3.3
	Jempol	Oxisol	571	4.2	-	1.3
Moderate	Bungor	Ultisol	663	9.0	-	2.1
	Lanchang	Ultisol	668	38.6	-	5.2
	Beserah	Ultisol	710	22.9	6.3	2.7
	Munchong	Oxisol	735	31.8	7.7	5.8
	Sg. Mas	Oxisol	928	19.9	0.6	10.0
Strong	Prang	Oxisol	985	40.2	4.0	4.8
	Segamat	Oxisol	1084	33.8	-	7.4
	Kuantan	Oxisol	1172	21.1	9.8	18.8

Source: after Tessens and Shamshuddin (1983)

Volatilisation losses

Volatilisation losses are only significant when urea is surface applied, usually over the compacted weeded palm circles. High volatilisation losses in the oil palm field occurred at high rates of fertilization and on light texture soils as shown in Table 11. To increase the efficiency of urea, it should preferably be buried in the ground. However this practice is only suited to small-scale cultivation and unlikely to be practical and economical on a large plantation. It is much more practical to apply urea and urea-based compound under AA+ plastic mulch which will reduce volatilization loss to a minimal resulting in marked improvement in fertilizer use efficiency and substantial saving in fertilizer input. Correct timing also provides a suitable means to improve the efficiency of applied urea. For example, volatilisation loss is reduced if urea is applied when moderate rains are expected so that the fertilizer may be washed into the soil. Another consideration is the ingredients used in manufacturing urea-based compounds. Any alkaline materials should not be mixed with urea as it would enhance volatilization losses.

Table 11: Urea Volatilisation losses (%) on various soils under oil palm

N rates	Silty clay soils		Sandy clay soil		Sandy clay loam	
	at 3 days	at 7 days	at 3 days	at 7 days	at 3 days	at 7 days
250kg N/ha	29	29	27	38	35	42
500kg N/ha	38	42	35	45	38	48

Source: Chan and Chew (1984)

Immobilisation by ground cover in young oil palm

Weed growth is strongest in high light conditions in immature plantation. The young palms without extensive root systems are less able to compete for nutrients at this stage, which reduce their nutrient uptake and growth (Table 12). One point of interest is that the total N immobilised by the ground covers commonly exceeded run-off losses and immobilisation by young oil palms.

Table 12: Dry matter production and nutrient immoblized by Ground Covers in young oil palms

Vegetation	Dry matter production (kg ha^{-1})	Nutrients immobilised (kg ha^{-1})				Remarks
		N	P	K	Mg	
Grasses	15098	109	19	156	29	Selangor series @ 20mths after planting
Grasses [1]	10437	90	16	128	22	Serdang series @ 12 mths after planting.
Mikania [1]	5986	76	15	120	11	Planted as cover Serdang series @ 12 mths.
Ischaemum [2] *muticum*	11390	73	6	188	9	5 year old palm.
Ischaemum [2] *muticum*	12240	84	-	-	-	1 year old palm.
Asytasia [3] *gangetica*	7300	181	-	-	-	120 days in open conditions.
Asystasia [3] *gangetica*	4300	142				120 days in shade.

Sources:
1. Han and Chew (1982)
2. Teo et al. (1990)
3. Quah (1997)

With respect to interrow vegetation management, spraying out the competitive weeds in the interrow vegetation at immaturity and maturity on Selangor series soil (fertile soil) gave the highest oil palm yields after 4 and 6 ½ years respectively. On the other hand, over spraying

could lead to bare ground conditions which might cause higher leaching losses, reduce soil moisture and result in poorer soil structure. This in turn may lower FFB yield.
AA+ plastic mulch could be used in immature palms to reduce weed competition and scorching of lower fronds due to weedicide toxicity. With the plastic mulch, lower frequency of palm circle weeding is needed resulting in significant saving in the costs of herbicides, which have bludgeon recently.

Economics of fertilizer recommendations

The plantation industry is a business proposition and as such, the economic value of a fertilizer is important. This is because the application of fertilizer necessarily increases the cost of production, which has to be at least offset by an increase in yield in order to be profitable. 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.

Owing to the delay in the effect of fertilizer on yield, the additional return from the increased yield may be realised in full only after 8 months or even a few years. Furthermore, the magnitude of yield response may vary considerably and the economic comparisons of fertilizers should be based on a discounted cash flow or a similar scheme over the specified period (Hew *et al.*, 1973; Lo and Goh, 1973). This, however, can be difficult because fertilizers supplied to young palms may enhance their health and give a larger yield well into the future and such effects on future responses are not sufficiently well understood to make this fully accurate (Corley and Tinker, 2003). Nevertheless, it should still be computed as the fertilizer rates recommended to the oil palm must be profitable.

An example of the economic computation of two sources of fertilizer is provided in Table 13. We choose kieserite versus ground magnesium limestone (GML) to illustrate the point that knowing the agronomic efficiency of a fertilizer as obtained from fertilizer trials is insufficient to recommend its application. Table 13 shows that the agronomic efficiency of

GML based on substitution rate was only 74% as effective as kieserite. However, GML was only one-third the price of kieserite at the time of writing. This favoured GML with the consequent relative economic efficiency reaching 2.5. This meant that GML was 1.5 times more efficient compared to kieserite in economic terms.Using the above approach, an expensive fertilizer may be more economical to use if its agronomic efficiency far outweighs its price ratio compared to its competitors.

Table 13: The relative agronomic and economic effectiveness of GML and Kieserite using oil palm as a test crop.

Parameters	Methods	Results
Relative yield (%)	$\frac{FFB_{GML}}{FFB_{Ks}}$ x 100 at the same fertilizer rate	97.8%
Relative yield Index (%)	$\frac{FFB_{GML} - CONTROL}{FFB_{Ks} - CONTROL}$ x 100 at the same fertilizer rate	83.3%
Substitution rate (SR)	$\frac{\text{RATE OF Ks}}{\text{RATE OF GML}}$ to produce the same yield	0.74
Price ratio (PR)	$\frac{\text{PRICE OF GML}}{\text{PRICE OF Ks}}$ per unit MgO	0.30
Rel. economic efficiency	$\frac{\text{SUBSTITUTION RATE (SR)}}{\text{PRICE RATIO (PR)}}$	2.47

Ks denotes Kieserite

GML denotes Ground Magnesium Limestone

Source: Goh *et al*. (1999b)

Corley and Tinker (2003) also provided a simple equation to compute the economics of any input 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.

Although the above computation is a standard in economics, of late there are counter arguments which suggest that the selection of a fertilizer should be based on its agronomic efficiency instead of economic efficiency. This contrasting proposition stems from the fact that commodity prices are usually unpredictable and therefore, the economic efficiency can vary substantially. Such view is probably a fallacy since decision-making processes in agriculture, like all businesses, are always done in the face of uncertainty, be it prices or weather etc. Moreover, the use of tender fertilizer prices will allay or negate part of the problems. In plantation agriculture, profit considerations are given the highest priority and therefore, the economic efficiency will always take the centre stage.

Additional agronomic principles for young palms

The strategy in young palms, apart from the above, should be:

a) To minimise nutrient requirements by maximising returns from the biomass of the previous crops e.g. rubber, cocoa or oil palm by the shredding and no-burn techniques currently practised in many plantations
b) To promote growth of very good leguminous covers with high P and Mg applications and subsequent large nutrient return including N fixed.

Such an approach would reduce fertilizer requirements of the young palms substantially and improve growth and yields, thereby leading to extensive benefits all round.

Estate and field practices

Getting the fertilizer rates right is only part of the process in an effective fertilizer management in oil palm. With the current high fertilizer prices, it is even more critical that we apply the fertilizers bearing in mind the potential losses as outlined above. The fertilizer recommendations for an estate, which include the strategies and methods, should answer the following questions (Goh *et al*., 1999a):

a) Why apply fertilizers?
b) What fertilizers to apply?
c) Where to apply fertilizers?
d) When to apply fertilizers?
e) How to apply fertilizers?

In fact, these are essential and valid questions which all planters should ask and discuss with their agronomists. It is also the role of the planters to ensure that the fertilizer recommendations are carried out well. As the common adage says "The best fertilizer is the planter's boots and nothing beats walking through the fields".

Manuring block size

The first field practice is to ensure that the manuring blocks are relatively uniform in terms of soil types, terrain, palm sizes, palm age etc. This is because each manuring block is a basic land unit, designed to allow the agronomist to manage the nutrient requirements of the palms effectively and the estate management to implement the fertilizer recommendations efficiently for best results (Kee *et al*., 2005). The manuring blocks should be clearly demarcated by roads for ease of management.

Of late, there is a discernible move towards larger manuring blocks in the estates with many of them exceeding 100 ha. The main reasons for this are unknown although the undertone is that management will be easier especially for large estates. Such practice, which is a form of sweeping generalisation, is definitely wrong and will make a mockery out of fertilizer management. It can also easily negate the hugh investments in cost, time, manpower and equipment in the preparation of precise fertilizer recommendations.

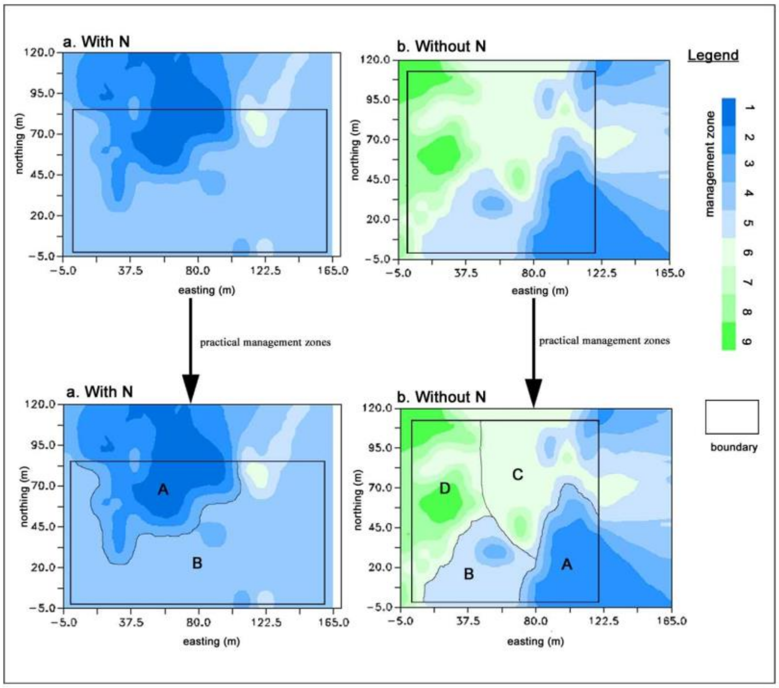
Futhermore, if each manuring block consists of vastly different soil types, terrain etc, then the following four situations may probably occur with a single fertilizer regime:

a) Just sufficient - palms receiving the correct dose of fertilizers
b) Over application - palms receiving too much fertilizers
c) Under application – palms receiving insufficient fertilizers causing nutrient deficiency
d) Imbalance - palms receiving incorrect proportion of fertilizers

Out of these conditions, the last three may result in lower yields and/or profits. They may also cause environmental pollution and land degradation. In fact, good agronomists always regard them as cardinal sins and perhaps, the planters should also adopt the same attitude.

On average, a manuring block should not exceed 40 ha as established since the sixties and be at least 80% uniform. With new technology and site-specific fertilizer recommendations, they can be reduced with minimal burden to estate management (Goh *et al*., 2000). In fact, Anuar *et al*. (2008a) showed that yield maps of oil palm can be easily transformed into management zone maps (Figure 9) based on the classification of spatio-temporal yield variation using geostatistics and a decision key (Table 14).

Figure 9: Practical management zones in areas with N and without N applications based on classified management maps (top two) and a temporal yield stability key (see Table 14)



Source: Anuar *et al*. (2008)

Table 14: A temporal yield stability key to classify management classes for oil palms

Management class	ffb yields ($t\ ha^{-1}\ yr^{-1}$)	CV (%)	Remark
1	y≥30	CV≤35	High, stable yield
2	20<y<30	CV≤35	Moderate, stable yield
3	y≤20	CV≤35	Low, stable yield
4	y≥30	35<CV<45	High, fairly stable yield
5	20<y<30	35<CV<45	Moderate, fairly stable yield
6	y≤20	35<CV<45	Low, fairly stable yield
7	y≥30	CV≥45	High, unstable yield
8	20<y<30	CV≥45	Moderate, unstable yield
9	y≤20	CV≥45	Low, unstable yield

Accurate information

Accurate information of each manuring block and estate kept by the management and data collected by the agronomists with the assistance of the management are necessary for optimum fertilizer recommendations and practices. The information includes the following (Kee *et al*., 2005):

a) palm parameters such as age, planting materials, planting density, vegetative growth measurements, leaf analytical data, palm size and vigour, deficiency symptoms and actual yields achieved;
b) block parameters such as accurate block size (ha), soil types, their distribution and physical properties, soil analytical results, terrain and field conditions (e.g. weeds, drainage);
c) accurate GPS block maps and palm point maps;
d) management history such as previous crop, planting dates and pattern, replanting schedule, past fertilizer history including fertilizer rates, sources, timing of application etc;
e) climatic parameters, namely, rainfall records;
f) pest and disease records such as dates of outbreaks, incidence, frequency, severity, control measures etc;
g) prices of related commodities e.g. pesticides, fertilizers and palm oil

The list of information may appear daunting but with a good database and decision support system, the task of collecting and collating the data is much simpler than thought. It also enables one to significantly utilise the diverse arrays of data for:

a) formulation of fertilizer recommendations
b) judgment of the performances of the palms and estates
c) early recognition of problems and problematic areas

d) building up a knowledge of the fields

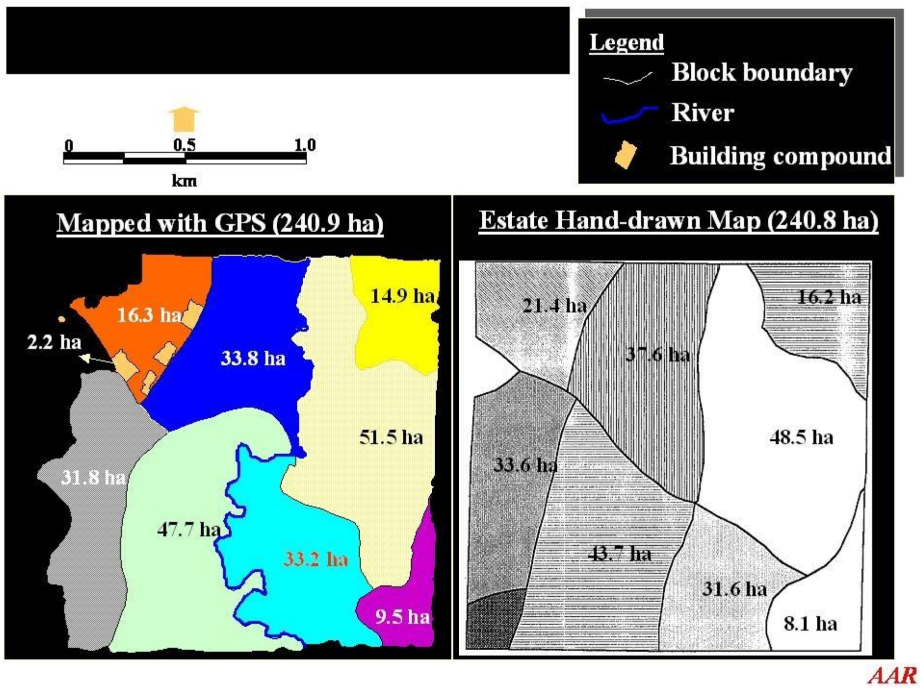
which are essential for optimum management, high productivity and lower costs of production. We can also compute the site yield potential (SYP) of each manuring block and compared it with the actual yield to determine the yield gap and identify the dominant limitation factors that require immediate correction (Goh *et al*., 2002).

A point to note is that the data should be collected at the manuring block scale or smaller. It is quite pointless to record say FFB yields from several manuring blocks together or from a planting of 200 ha or more, and yet attempt to make sense out of the data. It is also important that the area of a manuring block should be precise to less than 1.0 %. This is because all productivity figures, and criteria and indicators of palm health and estate performances are based on the areas of the manuring blocks. Thus, it is essential to have a proper surveyed map of the estate done by qualified surveyors. Alternatively, the estate can be mapped using global positioning system (GPS) which is cheaper, easier and faster (Figure 10 overleaf).

The density of palms in each manuring block should be known at all times. Hence, annual palm census should be carried out and any palms which die in the year should be taken out of the record immediately. In some estates, the number of palms in each row is recorded on the first palm of the row along the road. This enables more accurate distribution of fertilizer bags in the fields.

Hence, the management must keep accurate records of the data at the appropriate scale for the benefit of all.

Figure 10: Comparison of a GPS surveyed map (on the left) with a hand drawn map (on the right) of an oil palm plantation



Strategies to reduce nutrient losses

With the potential large losses of fertilizers in the oil palm agroecosystem, it is only natural that we devise techniques to reduce them and improve fertilizer efficiency. These techniques call for an integration of agronomic practices as briefly described below.

<u>Choice of fertilizer</u>

The choice of fertilizer is largely an economic issue, not only in terms of fertilizer prices but also the likely returns from their applications in the fields. Therefore, the properties of the fertilizers and the agronomic conditions in the plantations such as climate, soils and terrain should also be considered. In the first 18 months after planting, compound fertilizers supplemented with straight fertilizers are usually recommended. In mature palms, the principle should be to supply the nutrients to the palms (only those absorbed by the palms are considered) at the cheapest possible cost.

a) N fertilizer

There are several sources of nitrogen and the more common ones for oil palm are ammonium sulphate (21% N), ammonium nitrate (26% N), ammonium chloride (25% N) and urea (46% N). Various trials showed little differences in fresh fruit bunch (FFB) yield responses to them except for urea. In 12 trials carried out in Malaysia (Table 15), the relative efficiency of urea compared to ammonium sulphate was 80–85% due to large volatilization losses from surface-applied urea (Zin *et al*., 1989). In fact, in areas with high volatilization losses, it is a fallacy to assume that the supply of N to the palms can be met by applying higher rate of urea. This is because volatilization rate also increases with urea rate as shown in Table 11 earlier. However, comparable results between urea and ammonium sulphate as N source for oil palms can be obtained under satisfactory rainfall conditions at time of application in coastal soils (Table 15). For best results, urea should be broadcast when moderate rainfall (10-20 mm/day) is expected within one day after application (Chew and Pushparajah, 1996; Kee *et al*., 2005) as shown in Table 16. It is not advisable to apply urea on dry soils or when very light rain (<5 mm/day) is expected. The use of S-coated urea, B-coated urea or applying a mixture of urea and soluble Ca or Mg salts (that do not increase soil pH e.g. $CaSO_4$, Mg SO_4) is known to reduce volatilization. Lately, some urea compounds with urease inhibitors are also available in the market but their cost effectiveness for oil palms should be determined first. Urea volatilization is also known to reduce substantially when incorporated with triple superphosphate, humic acid and zeolite. The major effects were a reduction of soil pH in the vicinity of the urea granule which will inhibit the urea hydrolysis process, and increased retention of ammonia by zeolite and humic acid. These products, however, have not been shown to be cost effective for oil palms yet.

Table 15: Effectiveness of urea compared with ammonium sulphate (AS) as N source for increasing yield (t/ha/yr) of oil palms in different environmental conditions

Soil and environment	No. of trials	Annual rainfall (mm)	N level				
				AS		Urea	
			0	1	2	1	2
Coastal	3	2147	24.01	25.92	27.30	26.33	26.55
Inland – dry area	4	1888	26.74	27.78	29.84	27.31	26.99
Inland - firm soils	1	2209	18.67	27.56	28.23	26.09	26.54
Inland – wet area	4	3142	19.69	22.21	23.84	23.00	23.75

Source: Recomputed from Zin *et al*., 1989

Table 16: A decision table for urea application in oil palm plantations

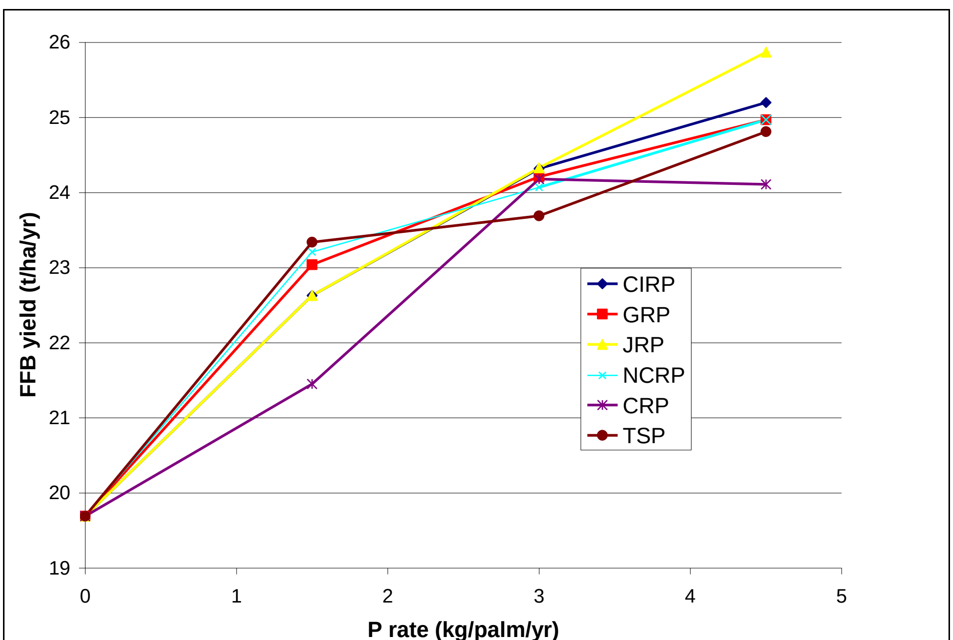
Factors	Conditions for urea application		
	Favourable	Marginal	Unsuitable
Crop canopy cover	Complete	Partial	Open
Ground cover for:			
a) Prill urea	Bare soil	Sparse – moderate vegetation	Thick vegetation – urea cannot fall to ground
b) Granular urea	Bare soil mainly	30 – 75% cover	> 75% cover
Litter on application area	Nil	Partial	Thick
Extent of application area	Overall	100 – 250 kg/ha effective concentration	> 250 kg/ha effective concentration
Soil CEC (cmol(+)/kg)	> 15	10 – 15	< 10
Soil texture	Clay to silty clay	Sandy clay	Sandy clay loam
Soil surface consistent	Friable	Friable to firm	Firm to hard
Soil pH	< 4.5	4.6 – 6.0	> 6.0

Source: Chew and Pushparajah (1996)

b) P fertilizer

An agronomic evaluation of different sources (rock phosphate versus soluble super phosphate) of P fertilizer for mature palms is shown in Figure 11. The results indicated that there was no difference between P sources, although P fertilizer improved palm growth. Nevertheless, the choice of P fertilizer would depend on the cost of fertilizer and the availability of P to meet the demand by the palms and its economic efficiency. For example, water soluble P source is commonly provided to immature palms via compound fertilizers while phosphate rocks are probably more economical for mature palms. Some unpublished work has suggested that high rate of Ca-P might depressed the yields of oil palms on peat and clayey riverine soils.

Figure 11: Effect of P sources on FFB yields of oil palms on Rengam series soils



Source: Re-plotted from Zin *et al*. (2001)

Note: CIRP – Christmas Island rock phosphate; GRP – Gafsa rock phosphate; JRP – Jordan rock phosphate; NCRP – North Carolina rock phosphate; CRP – China rock phosphate; TSP – Triple superphosphate

c) K fertilizer

In mature oil palm plantations, the choice of K fertilizer is usually limited to Muriate of potash. However, in view of the current economic situation and high fertilizer prices, other sources such as soil K if it is sufficient (more than 0.5 cmol kg^{-1}) can be used. This is based on a long term trial which showed that after 7 years of K fertilization, there was a substantial build-up of soil exchangeable K (from 0.2 cmol kg^{-1} in the control to 0.8 cmol kg^{-1}) particularly in the palm circle where the fertilizers were applied. Moreover, well-grown mature palms have a large reserve of K in the trunk, which can be utilised. With careful monitoring of the soil K status, reduction in K fertilizer can be made without much adverse effect on the growth and yield of the oil palm in the short term. For example, withdrawal of K fertilizer up to 4 years before replanting did not affect yields on an inland soil.

The oil palm plantation produces large quantities of by-products in processing the fresh fruit bunches (FFB) to palm oil. On average, every tonne of FFB produces about 220 kg empty fruit bunches (EFB). And 1 tonne of EFB contains an equivalent of 15.3 kg of ammonium sulphate, 2.5 kg of Christmas Island rock phosphate (CIRP), 18.8 kg of Muriate of potash and 4.7 kg of kieserite. Therefore, for mature oil palm, 40 t ha^{-1} of EFB applied in the interrows can supply sufficient nutrients to meet the palm requirement for a year. Supplementary fertilizer applications such as CIRP may be required to balance the palm nutrition. However, to supply K alone to the palms, only 25 to 30 tonnes of EFB per ha are required in most instances.

d) Mg fertilizer

The most common sources of Mg fertilizer in Malaysia are kieserite and ground magnesium limestone (GML). These two materials differ greatly in their solubilities and acid neutralising capacities. Kieserite is more water soluble compared to GML and has better agronomic efficiency. However, GML is favoured as a major Mg source for mature oil palm due to its higher relative economic efficiency compared to kieserite (Goh *et al*., 1999b). For young palms or when quick availability of Mg is desired, then kieserite should be used.

A word of caution to those who use GML as a source of Mg. GML contains high Ca and if it is over-applied or misused, it can be antagonistic to K uptake by the oil palm. The leaf and soil have to be closely monitored to prevent this detrimental effect from occurring and therefore, its use should be left to the experts only.

e) By-product utilisation

Apart from pruned fronds, the oil palm industry produces large quantities of by-product particularly empty fruit bunches (EFB) and palm oil mill effluent (POME). Both EFB and POME contain substantial amounts of nutrients and organic matter which can replenish the soil fertility and meet the nutrient requirements of oil palm. In general, 40 t EFB per ha per year or 450 litres of raw POME per palm per year are applied on poor inland soils. Supplementary P and B fertilizers are usually neccessary to balance the palm nutrition. Lately, compost from EFB and POME is becoming more common in the plantations as increasing number of mills opted to process them to avoid or reduce effluent ponds and obtain carbon credit. The compost can then be applied to the oil palms as a source of recycled nutrients. The average nutrient contents of various by-products from the oil palm agroecosystem are shown in Table 17.

Table 17: Nutrient contents of common by-products from the oil palm plantations

By-products	N	P_2O_5	K_2O	MgO	B
Empty fruit bunches - dry basis (%)	0.8	0.23	2.95	0.33	10
Palm Oil Mill Effluent - anaerobic (%)	0.36	0.27	0.29	0.24	-
Palm Oil Mill Effluent - aerobic (%)	0.15	0.11	0.29	0.15	-
Dried decanter sludge (%)	2	0.68	3	1.05	20

Sources: Gurmit, S. *et al*. (1999); Lim, C.H. *et al*. (1999); Lim, K.H. *et al.* (1999)

Note: The palm oil mill effluent was analyzed on wet basis

The selected fertilizers must then be accurately timed and applied in the fields for best results. This involves correct timing of fertilizers, frequency of application and placement of fertilizers as discussed below.

Frequency of fertilizer application

Applying K fertilizer once a year is sufficient to sustain the growth and yield of oil palm (Table 18). Increasing the frequency of application up to 6 rounds a year does not improve the yield significantly. However, in most oil palm plantations, the actual frequency of fertilizer application depends on the crop requirement, palm age, ground conditions, types of fertilizers and rainfall. This is to minimise the risk of leaching and run-off losses and ensure that sufficient nutrients are available to match the palm nutrient requirements at all times. For example, higher frequency of application is provided to immature palm where palm growth is rapid but the root system is not fully developed. Similarly, only one round of phosphate rock is generally required for mature oil palm due to its good residual value.

Table 18: Effect of frequency of fertilizer application on oil palm yield in Malaysia.

Soil series	Soil taxonomy	Unmanured	Frequency of application (t $ha^{-1}y^{-1}$)				
			F1	F2	F3	F4	F5
a. Munchong	Typic Haplorthox	13.5	18.7	19.6	18.4	-	-
b. Rengam	Typic Paleudult	-	-	23.9	-	24.5	-
c. Seremban	Lithic Hapludult	26.6	-	-	-	27.3	27.6

Source: a) After Teoh and Chew (1985); b) After Foster and Tayeb (1986); c) After Chan *et al*. (1993)

Note: F1 – once in 2 years.
F2 – once a year
F3 – Twice a year
F4 – 3 times a year
F5 – 6 times a year

With the current labour shortage, the aim is to reduce the frequency of fertilizer applications to the minimum without sacrificing on the optimum fertilizer rates and fertilizer efficiency. This is possible via:

a) Even spreading of fertilizers in the designated areas
b) A change in the methods of fertilizer application
c) Proper timing of fertilizer application

These field practices are discussed below.

Placement of fertilizers

Fertilizers should be applied in areas with maximum feeder root distribution to ensure good nutrient uptake and thus, the fertilizer use efficiency. In young palms, N fertilizers should be spread evenly over the weeded palm circle close to the palm base and gradually extended to the palm interrows and frond heaps when their canopies have overlapped and good root development is found there. This recommendation is supported by the results of several trials conducted in Peninsular Malaysia (Table 19 overleaf).

Apart from the harvester's path, the site to apply N and K fertilizers was not critical for mature oil palm above 10 years old due to their extensive and efficient root systems. Therefore, it is advantageous to broadcast N and K fertilizers in the interrrows and over the frond heaps to avoid concentration of nutrients in the palm circles which can lead to higher leaching losses and acidification. Nevertheless, interrow should be free from dense ground vegetation to avoid serious competition for nutrients and water as discussed earlier.

Table 19: Effect of fertilizer placement on FFB yields (t/ha/yr) in Peninsular Malaysia

Nutrient	Soil series	Soil taxonomy	Control	Weeded circle		Alternate avenues	Frond stack
				Inside	Outside		
N	Briah[1]	Endoaquept	15.3	23.1	24.3		
	Rengam[2]	Kandiudult		22.5	21.7		21.6
	Durian[3]	Hapludult	24.0	29.5	29.7		
P	Rengam[2]	Kandiudult		21.2	22.6		21.4
K	Rengam[2]	Kandiudult		21.4	21.7		22.7
	Durian[3]	Hapludult	27.4	27.7	28.1		
	Prang[3]	Acrudox	36.2	37.2	37.1		
	Seremban[4]	Kandiudult	26.2	27.2	27.7		
NK	Munchong[5]	Hapludox	21.2	25.9	24.7		
	Serdang[5]	Kandiudult	15.1	19.9	19.6		
NPK	Selangor[1]	Endoaquept	29.2		32.0	32.1	
	Selangor[1]	Endoaquept		31.1		31.6	
	Carey[1]	Endoaquept		29.6		29.9	

Sources: Reproduced from Goh *et al*. (2003)

Note: [1]Yeow *et al*. (1982); [2]Foster and Tayeb (1986); [3]Chan *et al*. (1993); [4]Chan *et al*. (1995); [5]Teoh and Chew (1985)

Broadcasting of phosphate rock is generally practised for older mature palms as this will increase the likelihood of root contact with rock phosphate particles resulting in better fertilizer efficiency. In hilly terraced areas with mature palms, fertilizers should be broadcast in the terrace itself and between the palms. In areas with platform, the fertilizers should logically be placed around the palms.

The proper areas for fertilizer placement are shown in Table 20. However, they should be amended by the agronomist where necessary according to the actual palm status, field conditions and estate resources including workers and equipment.

Table 20: Proper placements of fertilizers in oil palm plantations

Palm age	Type of fertilizer	Placement area
Immature (≤ 3 yr)	All	Spread evenly within weeded circle around palm.
Young mature (4-9 yr)	N, K, B and kieserite	Broadcast evenly within weeded circle but further from the palm (about 1 metre)
	GML and Rock phosphate	Broadcast just outside and around the palm circle.
Fully mature (≥ 10 yr)	All except urea, kieserite and B	Broadcast evenly in the interrows and over the frond heaps.
	Kieserite, B and urea	Broadcast evenly within the weeded circle but about 1 metre away from palm base.

Method of fertilizer application

Fertilizer application is traditionally carried out manually, the fertilizers broadcast over the sprayed palm circle area or other desired areas. Due to labour shortage and poor quality of workers, and compounded sometimes by increased fertilizer rates, some estates have resorted to:

a) employment of contract application gangs
b) application of fertilizers in the afternoons,
c) fixed number of bags of fertilizer applied by each worker;

practices which were discouraged previously due to problems with supervision and discipline.

Mechanisation of fertilizer application, such as the use of fertilizer spreader and aerial application, offers some solutions particularly for fully mature oil palms of at least 8 years old when the root systems are adequately developed and spread out. Table 21 shows that mechanised spreading of fertilizers gave similar yields compared to manual applications. The other advantages of mechanisation of fertilizer application are:

a) Lower labour requirement, 4 to 5 times less
b) Lower cost per ha, about 50%
c) Faster coverage of land area per day, about 2.5 to 3.5 times more
d) More even spread of fertilizers and most palms will receive their quota of fertilizer
e) Better timing and less frequent fertilizer applications

Table 21: Comparison of FFB yield (t/ha/yr) and fertilizer application methods in oil palm

Methods	Fertilizer regime		Mean
	1	2	
Aerial	23.0	24.7	23.8
Manual	23.9	25.0	24.4
Mechanised	25.2	25.3	25.2
Mean	24.0	25.0	(S.E. = 0.5)
Control			18.1

Note: Regime 1: 2.5 kg Ammonium sulphate/palm/year and 2.5 kg Muriate of Potash/palm/yr.

Regime 2: Twice regime 1.

Source: Modification of work done by Lim and Chan (1992)

There are still many problems associated with mechanisation of fertilizer applications such as maintenance of machine and mechanisation paths, high diesel price, uneven traveling speed of the tractor and alternate solutions when the machines breakdown (no workers to manually apply the fertilizers!). There are many papers which discussed these problems and therefore, they will not be deliberated here. However, it is probably worthwhile to mention that research on finding a solution to obtain even application of fertilizer with mechanical spreader traveling at variable speeds (with a safe maximum speed not controllable by the driver) on rugged terrain should be worthwhile in order to overcome the above problems.

For first year planting to about 18 months, AA+ plastic mulch provides a way to reduce the fertilizer application to only once per year (Table 22). With good and easy supervision during planting, the end results are usually better palm growth and uniformity in the fields.

Table 22: Effect of AA+ plastic mulch on the frond length (cm) of oil palms at 12th and 24th month after planting

Palm age (month)	Treatment		Frond length (cm)	Coefficient of variation (CV)
	Mulch	Fertilizer level		
Trial 1: 12 months old	Nil	0	107a	15.1
	Nil	1	120b	9.6
	Nil	2	121b	11.1
	Nil	3	123b	10.9
	AA+ mulch	0	126b	10.5
	AA+ mulch	1	141c	10.1
	AA+ mulch	2	135bc	11.1
	AA+ mulch	3	134bc	11.9
Trial 2: 24 months old				
Control	0	0	259a	12.5
AA+	0	0	271ab	13.8
AA+	3.5	0	272ab	8.9
AA+	3.5	10	292c	10.2
AA+	7.0	6.5	289bc	7.8
EFB	3.5	10	290bc	10.3

Note: Same letters denote non-significant difference at p-value = 0.05

Another method of fertilizer application which is being propagated is burying the fertilizers around the palm bases. Again, fertilizer application is reduced to once a year. A review of replicated trials testing this method of fertilizer application by Ng and Goh (2003) showed that yields declined between 4 and 17% compared to conventional broadcasting of fertilizers (Table 23).

Table 23: Effect of burying the fertilizers compared with surface application on FFB yields of oil palms across various soil types

Trial	Site	Method of fertilizer application	Avg. yield per year in t/ha (%)	Soil and terrain
BS[1]	Sabah	Normal	26.0 (100)	Tanjong Lipat family on hilly terrain
		Bury (2 rds/yr)	21.5 (83)	
UD[2]	Sabah	Normal (4 rds)	25.4 (100)	Paliu family on undulating terrain
		Bury (2 rds/yr)	23.6 (93)	
FD[3]	Negeri Sembilan	Normal (4 rds/yr)	33.9 (100)	Not available but possibly on Durian series.
		Bury (1 rd/yr)	32.6 (96)	
TW[4]	Sibu	Normal	19.4 (100)	Anderson 3. Flat
		Bury	17.2 (87)	
AAA[5]	Indonesia	Normal	22.5 (100)	Alluvial. Flat
		Bury	19.1 (85)	

Source 1: Soon and Hoong (2002) 2: Kwan (2002) 3: Azmi *et al.* (2002) 4: Lim *et al.* (2003) 5: Manjit *et al* (2002)

Timing of fertilizers

For most of the soluble fertilizers, proper timing of fertilizers holds the most promise for improving efficiency because nearly all the nutrients lost from run-off occur within the first few rain events after application (Kee *et al*., 2005). There is also evidence in Malaysia to show that run-off losses of K in mature oil palm are markedly reduced if applied in dry months or months after low rainfalls. On the other hand, timing of rock phosphate application is usually less critical because of its low solubility and therefore, lower run-off losses.

The general guideline (AAR unpublished) is to avoid fertilizer applications during:

a) Period with high rainfalls of more than 250 mm month^{-1} and low rainfalls of less than 25 mm month^{-1}
b) Months with high rain days of more than 15 days month^{-1}
c) Months with high rainfall intensity of more than 25 mm day^{-1}
d) Periods when the soil is saturated after continuous rains.

These rules have been incorporated into an expert system using probabilistic inferencing, which requires long-term data, to predict the best months to apply fertilizers. Extensive testing of the expert system showed that it provided superior results compared with naïve and K-nearest mean methods (Syed Mustafa *et al.*, 2000). Thus, accurate and long-term rainfall records are therefore essential for working out the ‘best’ months to schedule fertilizer application and reduce risks of losses (Kee, 1995).

Fertilizer applications should also be timed to follow circle-weeding rounds to minimise competition from ground vegetation particularly during the immaturity stage. Fertilizers which are antagonistic in nature with each other such as K, Mg and B should not be applied in the same area at the same time. Similarly, GML should not be broadcast over the K and N fertilizers to avoid K displacement and volatilisation respectively.

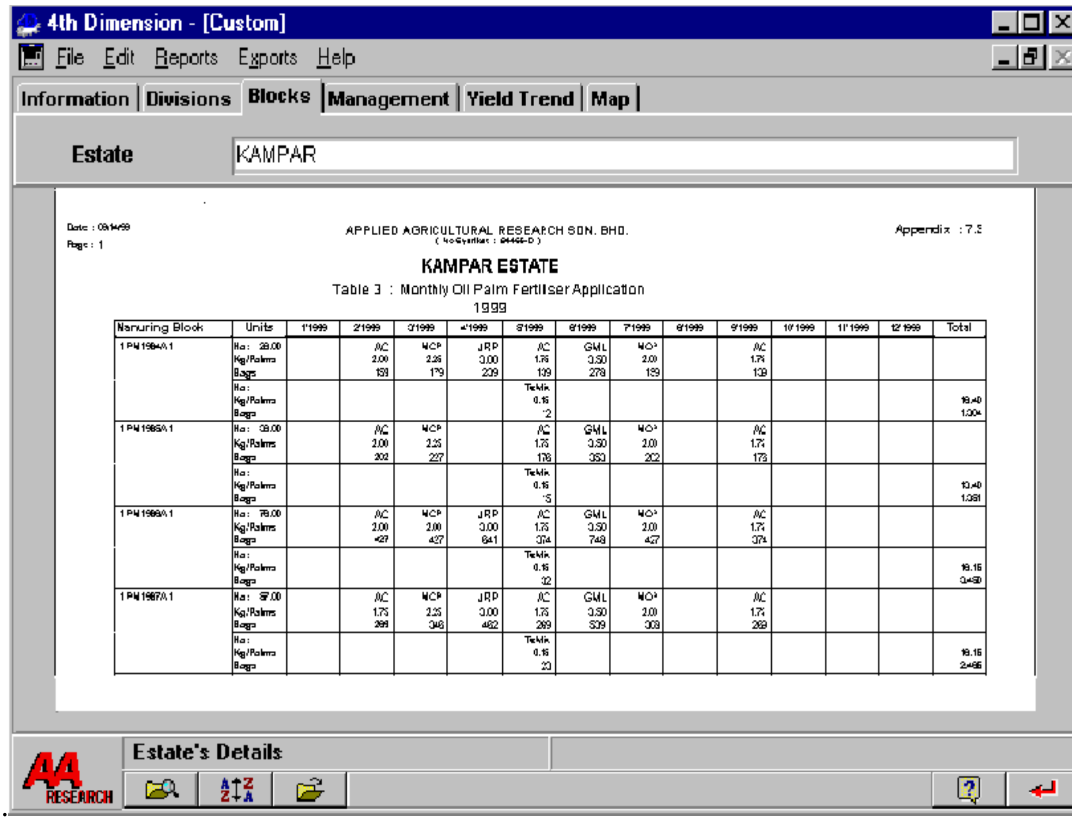
Ordering, delivering and storing of fertilizers

Before the planters can implement the fertilizer recommendations, they must have the fertilizers. Thus, the best, most precise manuring recommendations are of little use if they cannot be timely and well implemented (Kee *et al*., 2005). Delays in fertilizer delivery, lack of storage or poor storage facilities and shortage of workers are the most common factors resulting in severe disruptions to the manuring programme and consequent poor results.

If tender is used to buy fertilizers, it must specify the date of delivery among others such as fertilizer quality. Fertilizers should be ordered early and in some places at least 3 to 6 months ahead. Hence, the estate management should calculate the total tonnage of each fertilizer in each month of application upon receipt of the manuring report if amendments are not required. A purchase order is then placed for the fertilizer indicating clearly the date of delivery. AAR manuring reports provide the above detailed information of fertilizer tonnages and number of bags of fertilizers in each month (Figure 12 overleaf) to reduce paper work in the estate.

A point to note is that fertilizers should always be bought from tested and reliable sources. It is not only important to purchase good quality fertilizers but also be assured of their prompt shipment to the estate.

Figure 12: AAR fertilizer recommendations and schedules including the tonnage of fertilizers and number of fertilizer bags required for each field in an estate



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Appendix : 7.3

KAMPAR ESTATE

Table 3 : Monthly Oil Palm Fertiliser Application

1999

Manuring Block	Units	1/1999	2/1999	3/1999	4/1999	5/1999	6/1999	7/1999	8/1999	9/1999	10/1999	11/1999	12/1999	Total
1 PM 1984A1	Ha: 28.00 Kg/Palms Bags		AC 2.00 159	MCP 2.26 179	JRP 3.00 209	AC 1.76 139	GML 3.50 278	MOP 2.00 139		AC 1.76 139				
	Ha: Kg/Palms Bags					Tekmix 0.16 12								18.40 1,004
1 PM 1985A1	Ha: 38.00 Kg/Palms Bags		AC 2.00 202	MCP 2.25 227		AC 1.75 176	GML 3.50 353	MOP 2.00 202		AC 1.76 173				
	Ha: Kg/Palms Bags					Tekmix 0.16 15								10.40 1,381
1 PM 1986A1	Ha: 78.00 Kg/Palms Bags		AC 2.00 427	MCP 2.00 427	JRP 3.00 641	AC 1.75 374	GML 3.50 748	MOP 2.00 427		AC 1.76 374				
	Ha: Kg/Palms Bags					Tekmix 0.16 32								18.16 3,450
1 PM 1987A1	Ha: 57.00 Kg/Palms Bags		AC 1.75 269	MCP 2.25 346	JRP 3.00 462	AC 1.75 269	GML 3.50 539	MOP 2.00 308		AC 1.76 269				
	Ha: Kg/Palms Bags					Tekmix 0.16 23								18.16 2,486

Timing of delivery date will depend on the estate location and logistics. Just in time for fertilizer application should be practised when transport infrastructure is good. At time of delivery, the total fertilizer weight and the number of bags should be checked against the delivery and purchase orders to ensure that they tally. A sample of the fertilizer, particularly those that appear dubious or which can be adulterated easily such as GML and rock phosphate, should be sent to the laboratory for analysis as soon as the consignment is delivered. The method of sampling should follow SIRIM standards, MS 417, Part 1, 1994. This is to confirm that the nutrients in the fertilizer meet the specification in the tender and to check for the presence of contaminants. A claim should be made if the fertilizer sample does not conform to expectation.

Before the fertilizers are delivered, the estate should ascertain that there is enough space in the store for them. The store should be properly constructed, dry and rain-proof. The fertilizer consignment should be neatly stacked for easy reloading and transferring to the fields for application. It will also reduce wastage, losses and contamination from other fertilizers. Hygroscopic fertilizers such as ammonium chloride must be kept dry to prevent it from caking, which can make application slow, costly and less effective. All lumpy fertilizers should be broken up before application in the fields while those which are severely caked at delivery should be rejected and claimed compensation.

Organisation of fertilizer application

The procedures in planning and organising fertilizer application for manual system are:

a) Check the type of fertilizer to be applied on the day's operation.
b) Calculate the number of bags of fertilizer required for the area.
c) Check that the necessary transport and labour are available for efficient work. Similarly, roads and bridges should be in good order for the distribution of fertilizers in the fields.
d) Ensure that everyone concerned knows the exact rate per palm and how to apply it.
e) Supply each worker with a container of a suitable size with wide brim and make sure he/she knows how many of scoops of fertilizer to apply per palm. The container should be calibrated for the different types of fertilizers as they have different density. Each calibrated container should have different colour to clearly identify them.
f) The container or measure should not be too small to avoid too many scoops per palm because it leaves more opportunity for error. Similarly, a large measure will result in poor spread of fertilizer during application. The ideal size is probably one which allows two to four scoops of fertilizer per palm.
g) Distribute the bags of fertilizer at calculated points along the road, harvester's paths etc so that minimum carrying is necessary. This can be achieved with proper road system and intensity, and good map.

h) Keep the gang working as close together as possible for ease of carrying and supervision.

i) Ensure that all empty bags are collected and returned for counting.

j) At the end of each day's operation, the empty bags should be counted and reconciled with the number issued minus those which are returned to stock unused. Maintained a record of this. Unused bags should not be left in the field overnight.

k) Assess the area covered and determine the reason for any surplus or deficit of fertilizer used.

l) Application should be supervised all the time by a conductor at least. Estate managers and Assistant Managers should check as long and as often as possible, and at least at the commencement and end of each day's work. This is to ascertain that the correct areas and procedures are followed and to reconcile the figures submitted by the staff on work done.

m) Minor changes to the above procedures are necessary for mechanised spreader system but the basic principles remain the same.

Supervision

Good supervision is tantamount the key to successful implementation of the fertilizer recommendations, be it in manual or mechanised application. The supervisory staff including the managers must walk through the fields particularly in the middle of the field, ravine areas and hilltop areas where mistakes are most common.

The importance of close supervision during fertilizer application is underscored in the example provided in Table 24. FFB yield in block 3, which was the nearest to roadside (Row 1 to Row 5), was 327 % above that in block 1 which was the furthest (Row 11 to Row 15) from the road and in the middle of the field. This was a clear case of uneven fertilizer application due to poor supervision in a huge new project in West Kalimantan. With uniform fertilizer application throughout the field, FFB yields could increase by 52%.

Another method is to supply the fertilizer in plastic bags where each has been weighed to match the rate required for each palm. The plastic bags are then distributed and the fertilizer spread in the specified area. After application, the empty plastic bags are then tied to the oil palm fronds which are clearly seen from a distance. This method of delivering fertilizers to the palms appears to result in good uniformity in immature palms although no published work is available to the best of our knowledge. Thus, currently there is no substitute for good and meticulous supervision of field work in the estate.

Table 24: Effect of uneven fertilizer applications on the early yields (8 months of crop) of six years old oil palm in Kalimantan, Indonesia.

Parameters	Block 1	Block 2	Block 3	Mean
Bunch production (per ha)	1518	2305	2843	2222
C.V. %	16.2	10.0	3.7	-
FFB (per ha)	4.03	8.69	13.20	8.64
C.V.	23.9	27.2	14.8	-
Estimated FFB (per ha per yr)	9.9	18.5	25.5	17.97

Note: Each block consisted of 84 palms (7 replicates x 12 palms/replicate).

Block 1 – palms furthest away from roadside (Row 11 to Row 15)

Block 2 – palms second furthest away from roadside (Row 6 to Row 10)

Block 3 – palms nearest to roadside (Row 1 to Row 5)

Feedback

Feedback is one of the keys to successful implementation of the fertilizer recommendations. This is because the responsibility of fertilizer management does not lie with the agronomist alone but ultimately with all concerned. Some of the essential feedbacks for optimum fertilizer management are:

a) Wash-out after fertilizer application, which can happen in tropical countries. Additional fertilizer may be necessary.
b) Delay in fertilizer delivery of more than 2 months. Readjustment of fertilizer schedule and rates should be done.
c) Non-availability of fertilizer in the market or a substantial change in fertilizer price. Another source of fertilizer, fertilizer rate and method of application may be advised.
d) Areas with nutrient deficiency symptoms or unusual appearances of the palms. Corrective manurings or other appropiate measures such as drainage may be recommended.
e) Changes to field practices, planting dates and replanting dates. Modification to the fertilizer recommendations is usually necessary.
f) Regular reporting on palm growth and yields in problem areas. Specific corrective measures may be needed to alleviate or overcome the most limiting factor first.

Common mistakes in fertilizer applications

Many mistakes can happen during fertilizer applications. Some of the more common ones are:

a) Application of fertilizer in heaps or narrow bands and application of lumpy fertilizer.
b) Not all palms received their quota of fertilizer or some palms are not applied with fertilizer, i.e. roadside palms receive more fertilizer compared to those in the middle of the field.
c) Application of fertilizer in wrong areas, e.g. GML in palm circles, N fertilizer in waterlogged spots or on terrace edges.
d) Fertilizer applied too far or too near young palms.
e) Applying fertilizers over the lower fronds in young palms which can result in fertilizer scorch.
f) Fertilizer applied without using calibrated measures.

g) Applying many fertilizers at the same time to catch up with the manuring rounds. This can cause toxicity, imbalance and/or immobilisation of some nutrients, e.g. N and B.
h) Applying fertilizer when the field is full of weeds.

The management should always be on a look out for these errors and prevent them from occurring in the estate.

Criteria and indicators of palm health (fertilizer recommendations)

The planter's boots may be the best fertilizers but walking around the fields is meaningless if the person does not know what to look for nor understand the purpose. We hope we have covered the latter adequately and shall now briefly discuss the former.

Many criteria and indicators of palm health have been developed over the years and six of the most important ones are:

a) Uniformity of palms
b) FFB yields
c) Canopy sizes
d) Leaf nutrient concentrations
e) Soil fertility
f) Field conditions

They also reflect the management standards and inputs in the estates and head-offices. Apart from this, they could be used to assess whether the recommended fertilizer rates are within the adequate range for the palms.

Uniformity of palms

Many factors can cause poor uniformity of palms in the fields. One of the most common is ineffective fertilizer management. This is again well exemplified by the coefficient of variations (CV) between blocks as provided in Tables 22 and 24. CV is a measure of uniformity and the lower it is the better. Results showed that block 3, which is nearest to the road, had the lowest CV of 15%. Thus, fertilizer inputs can narrow the variation in soil fertility leading to better palm uniformity. In general, palms on inland soils should have CV less than 15%. If the CV exceeds 25%, the field either has very variable soil conditions which will warrant re-blocking or there are serious agronomic problems.

Furthermore, there are indications that where palms were better grown due to proper fertilizer management, the annual yield fluctuations may be reduced substantially (Table 25). This will not only ease the management of palms and mills but also the marketing of palm oil.

Table 25: Yearly variations in FFB yields (t/ha/yr) on different soil types in Malaysia.

Soil	Treatment	Year after treatment							Mean	CV (%)
		3	4	5	6	7	8	9		
Briah	Control	33	40	27	20	21	23	22	25.6	20.0
	Optimum	33	33	31	29	26	29	27	30.6	14.2
Bernam	Control	22	20	10	15	11	12	12	14.4	29.3
	Optimum	27	25	17	24	17	19	24	21.7	17.1
Sogomana	Control	31	27	23	25	27	20	32	26.1	15.0
	Optimum	35	36	28	31	31	32	32	32.1	7.5
Rengam	Control	24	22	20	22	26	22	17	21.4	13.5
	Optimum	26	28	28	26	34	32	23	28.3	12.8
Malacca	Control	11	14	12	12	16	18	13	13.0	18.5
	Optimum	21	23	20	24	26	37	28	25.4	21.2

Adapted from Tayeb *et al.* (1990) and Lim *et al.* (1982)

FFB yields

Every effort and input in the plantations should be geared towards producing the optimum or maximum yields at all times. However, it is a common mistake to take the FFB yield at face value and worse still, to use it to judge estate performance. It is most unacceptable or untenable to praise the achievement of say 26 t/ha/yr in an ideal area and condemn the attainment of say 22 t/ha/yr in a poor soil such as Malacca series (shallow lateritic soil). On the other hand, good yield is always an excellent portrayal of management and inputs.

To overcome this dilemma or paradox, AAR has furthered the concept of site yield potential and in fact, has quantified it (Goh *et al*., 2002). The site yield potential is the maximum yield achievable given the site characteristics such as soil properties, climate and resources. By comparing the actual yield against its site yield potential one can objectively judge the performances of the palms and estates, and separate to a large extent the management and agronomic limitations (Table 26). Appropriate actions can then be implemented to correct any deficiency in the field.

Table 26: Examples of some criteria to categorise the yield performance of each field in an oil palm estate

Actual yield/SYP (%)	Management standard	Agronomic problems	Category
> 90	Good	Minor	Good
80 – 90	Satisfactory	Minor	Satisfactory
70 – 80	Fair	Moderate	Fair
50 – 70	Poor	Serious	Poor
< 50	Very Poor	Serious	Very Poor

Canopy size and vigour

FFB yield is a direct function of canopy size and vigour i.e. healthy palms produce optimum FFB yield. Healthy palms are also more efficient in absorbing nutrients from the soils and fertilizers, and generally less susceptible to pests and diseases. It is therefore important to maintain the expected growth rate which commensurate with the prevailing environmental conditions and planting materials. A good guide on the canopy size is shown in Figure 3 using leaf area per palm. However, it should be adjusted for actual frond production rate and growing conditions at the site.

A point to note is that palms grown on poorer soils will tend to maintain higher vegetative dry matter, e.g. frond dry weight, compared to those on richer soils. This phenomenon is also known as the "Overflow Hypothesis", which was first suggested by Corley and co-workers in the seventies.

Palms with large canopies will suppress weed growth and reduce weeding requirement. It may also reduce erosion and run-off losses by trapping some rain-water and breaking the fall of rain-drops (reducing the velocity).

Leaf nutrient concentrations

The leaf nutrient concentrations are usually taken from the pinnae of Frond 17 for mature palms and Frond 1, 3 or 9 for younger palms. It is generally used for diagnosis purposes such as the identification of nutrient deficiency and disorders. Various methods have been developed to interpret the leaf analysis results such as critical leaf nutrient concentrations and nutrient ratios (Goh, 2005). Whichever method is used, one should always remember that the leaf nutrient concentrations are influenced by many factors. Hence, long term trend and knowledge of the fields and management practices are essential to make sound and valid interpretations of the data.

Nevertheless, the leaf nutrient concentrations when combined with the canopy sizes can be used for prognosis purposes and prevent nutrient deficiency and disorders from happening. Perhaps, the most important use of leaf analysis results is early detection of potential nutrient imbalance which is usually not visibly exhibited by the palms. Instead, yield decline will be experienced if it occurs as discussed earlier. Readers are referred to Goh (2005) and Foster (2003) for further details.

Soil fertility

It is a common mistake to assume that soil fertility is only related to soil nutrients. In actual fact, it is a combination of all soil properties including among others, texture, mineralogy, terrain and soil microbial activities. The soil fertility determines the quantity and rate of soil nutrients and fertilizers that are available to the palms.

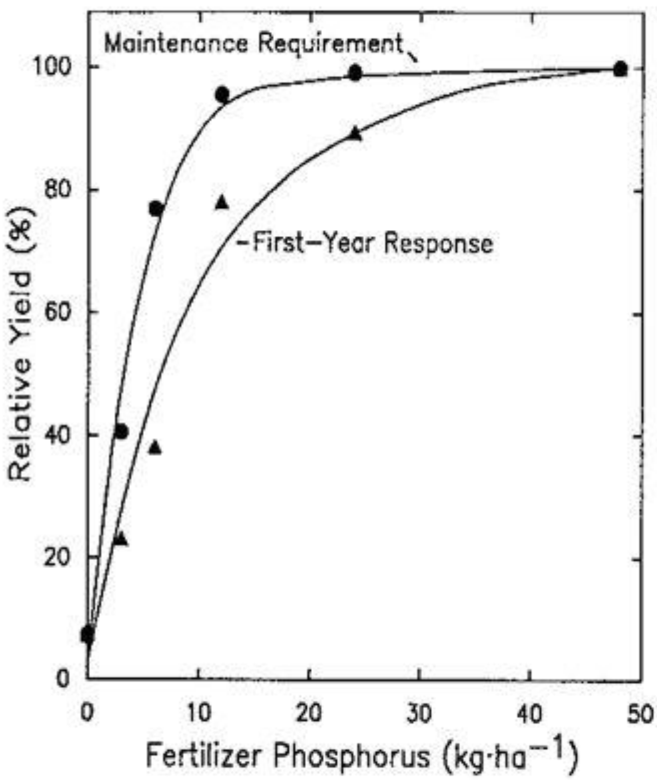
Just like leaf analysis, interpretation of soil nutrient data has been particularly difficult because of:

a) Subjective views on what are desirable soil nutrient levels for oil palm, and the objectives of interpretation are often confused with the individual perception of the risk of being wrong.
b) non-standard analytical methods
c) seasonal variation in soil nutrient contents
d) most fertilizer trials do not include soil analysis results.

Thus, soil test interpretation usually follows some common philosophies:

Build-up and maintenance philosophy (fertilising the soil). The idea is to increase the soil nutrient levels in 1 or 2 years to high soil test levels. Subsequently, in each year we add the expected quantities of nutrients removed by the palms regardless of soil analytical results (Figure 13 overleaf).

Figure 13: Relationship between relative yield and fertilizer P response as influenced by initial yield response and maintenance requirement (after Black).



Source: Black (1992)

Sufficient level philosophy (fertilising the crops). The objective is to add enough nutrients to produce the economic or yield goal of the producer. No fertilizer is recommended if the soil test is at the level where no economic yield response is expected.

Optimum cation saturation ratio philosophy (balanced nutrition). The belief is that for each crop there is a specific cation ratio which provides an optimum soil condition for maximum production.

Over-fertilisation philosophy (risk preference). This is derived from the fact that response curves are steeper below the economic optimum application than above (Figure 13). Thus, increasing the recommended fertilizer rate beyond that indicated by the experimental data to compensate for the fact that losses to the planters from using too little fertilizer are greater than those from adding more fertilizer than is needed. This philosophy also ensures that if the season is a good one, the economic returns will not be sacrificed for lack of nutrients.

Interestingly, these philosophies do not work in most situations on an individual basis. However, when used together or in combination, they can form a sound scientific technique to interpret soil analytical data for manuring recommendations and long-term soil fertility management for optimum palm health.

Therefore, the soil fertility should be regularly monitored and maintained to ensure sustainability of oil palm. Soils can be treated as a bank of nutrients for the palms, the more fertile the better, be it natural or man-made. But over enrichment of the soils must be avoided to prevent environmental pollution, toxicity to the palms and high costs. Interested readers should refer to Goh (1997) and Goh (2005) for further details.

Field conditions

Poor field conditions, be they inaccessibility, inadequate drainage, strong weed competition etc., are good indicators of bad management and inputs. Even if the palms seem satisfactory at the moment, they will not be if the conditions are allowed to persist. Thus, field conditions should be maintained to allow good accessibility for inputs e.g. fertilizers and evacuation of crops, and reduce weed competitions as discussed earlier. This will improve fertilizer use efficiency.

Field conditions also include the palm conditions and fertilizer scorch, weedicide spray damage to the lower fronds, beetle damage to the canopy etc should be prevented to provide optimum growth environment to the palms, particularly at the immature stage. AA+ plastic mulch can reduce weedicide spray damage to the lower fronds in the first year of planting because circle spraying is not required.

Presently, there is little knowledge of the interactions between weedicides and nutrients. Over-zealous use of weedicides and different types of weedicides particularly those with little information on their effects on oil palms should be discouraged.

Strategy in response to high fertilizer prices

In 1976, at the peak of the oil crisis when prices were at all times high, the fertilizer costs increased in tandem. In that year, the Incorporated Society of Planters organized an International Oil Palm Conference where Dr. Ng Siew Kee, a prominent agronomist, made this statement, "*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."* This perceptive statement is again relevant to us today as the current situations mirrored those of the past except for the current relatively high palm oil prices. Thus, there are many more options to take to minimize the negative impact of high fertilizer prices compared to the past as discussed earlier. These options involve a good knowledge of past fertilizer history, soil inherent nutrient contents, soil properties, palm nutritional status and climatic conditions prevailing at the site. In fact, it is a good test of the agronomist's skill and knowledge. Briefly, one or more of the strategies summarized below may be adopted to reduce fertilizer inputs and tap into other nutrient sources available in the oil palm agroecosystem.

1) Palm nutrient reserve: The mature oil palms have substantial nutrients in the trunks in particular K and N. Nazeeb *et al*. (1995) showed that the fertilizer inputs could cease one to two years before replanting on inland and coastal soils, respectively. Similarly, fertilizer response trials conducted on mature palms have commonly shown no yield response for at least the first two years of fertilizer treatments. Teoh and Chew (1988)'s

computation clearly indicated that the palm trunk contained the equivalent of four to six years of the K requirement of oil palm. Therefore, it is probably worthwhile to utilize part of this large nutrient pool to partially meet the nutrient requirement of oil palms.

2) Soil K reserve: All soils contain nutrients which are available to the palms but their nutrient supplying capacity varies substantially between them (Goh *et al*., 1998). However, if soil P, K and Mg contents are high, they can be temporarily utilized or depleted for the palms. For example, soil K concentration in the top 45 cm in the palm circle area may be reduced to about 0.2 cmol(+) per 100 g soil without significant yield decline in most upland soils in Peninsular Malaysia.

3) By-product utilization: By-products are good substitutes for fertilizers and thus, their potential monetary values increase with fertilizer prices. In time of high fertilizer prices, every effort should be made to apply them in the fields in place of fertilizers.

4) Site-specific fertilizer applications: Excessive or under applications of fertilizers will be costly when both fertilizer and palm oil prices are high. Excessive fertilization will lead to fertilizer wastage and probably higher soil nutrient losses. Under fertilization may lead to yield loss. Therefore, at current scenarios, any temptation for generalization of management practices should be avoided.

5) Leguminous cover crops: At planting, leguminous cover crops such as *Mucuna bracteata* should be established to improve soil properties, palm growth and yield, and probably reduce fertilizer inputs. Since *Mucuna bracteata* persists in the interrow areas of mature palms, its beneficial effects should also maintain.

6) AA+ plastic mulch: The benefits of using AA+ plastic mulch improve with high fertilizer prices because of reduced fertilizer losses via soil erosion and run-off. If urea or urea-based compound fertilizer is used, then the AA+ plastic mulch should be able to reduce N volatilization losses due to the physical barrier to air flow and diffusion.

7) Monitoring of fertilizer grades, sources and quality: Close monitoring of the quality and grades of fertilizers is absolutely necessary to ensure that we pay for what we bought and more importantly, we apply the fertilizers as recommended. Similarly, the correct sources of fertilizers including the ingredients in the compound fertilizers should be

used to avoid unnecessary losses or lower fertilizer use efficiency. Thus, a sample of each batch of fertilizer received should be sent to a reliable laboratory for analysis.

8) Tight supervision and correct implementation of fertilizer management practices: These are probably the most important factors affecting the fertilizer use efficiency as discussed above. The impact of improving the fertilizer use efficiency on fertilizer saving is substantial e.g. by increasing it from 40% to 50% will effectively reduce the fertilizer rate by 20% ((1-(40/50))*100).

These strategies require close monitoring of the six indicators of palm health as explained earlier to ensure that the palms are performing to expectation. In principle, nutrients which give low yield responses at the site should be prime candidates for withdrawal first. Also, the principle of soil nutrient build-up is unlikely to be economical in current scenario i.e. risk preference decision making should be advocated. Last but not least, the palms must be in good nutritional balance at most times.

Strategy in response to sustainability Round-table on Sustainable Palm Oil (RSPO)

Nowadays, fertilizers should always be utilized in a manner that will maintain or enhance the sustainability of oil palms. The Round-table on Sustainable Palm Oil (RSPO) has developed the Principles and Criteria (P&C) of sustainable palm oil and recently approved the Malaysian National Interpretation of these principles and criteria in April 2008. The Principles and Criteria that are directly related to fertilizer use in oil palm plantations are Principle 4, Criteria 4.2 to 4.4. These criteria involve soil fertility, soil loss processes and water quality respectively.

Currently, soil fertility is still a qualitative term only in the context of oil palm agroecosystem. Past research mainly concentrated in the soil nutrient aspect of soil fertility ignoring, assuming or holding the other factors such as soil physical properties, organic matter and microbial dynamics constant. Thus, there is no scientific quantification of soil fertility or index for oil palm agroecosystem and the only monitoring tool is geared towards soil nutrient status only. However, this parameter changes tremendously over micro-sites, soil types and time (Anuar *et al*., 2008b). This has resulted in large differences in yield responses to fertilizers between and within soil types resulting in the necessity for site-specific fertilizer inputs. Nevertheless, the oil palms have been shown to be sustainable on a large scale over the past 75 years.

Issues on fertilizer losses via soil processes and water quality are best addressed through improving fertilizer use efficiency. Therefore, any management practices which can improve it should be advocated. Present work generally showed that fertilizer losses through run-off and erosion in oil palm agroecosystem are relatively low and contamination of waterways from fertilizer use is negligible (Lim *et al*., 1999) if recommended management practices are adhered to.

The other concerns are the impact of fertilizer use on greenhouse gas emission and energy use. Little published work is currently available on this subject. Melling *et al*. (2006) showed that the application of urea to oil palms on deep tropical peat would increase the methane emission. However, the amount was small and the emission short-term. Thus, its global impact on climate change is negligible. On energy use, Wood and Corley (1991) showed that the energy use to apply the average N rate of 88 kg ha^{-1} was 6.88 GJ ha^{-1}. However, the current more efficient technology in fertilizer production means a lower energy consumption resulting in a reduction of 2.92 GJ ha^{-1} (de Vries, 2008). In both cases, minimizing fertilizer use will lead to a more sustainable oil palm agroecosystem provided the yield maintained. However, this approach will increase the risk of lower yield because the slope of yield response curve to fertilizer input is sharper at lower fertilizer rate.

Summary and conclusion

Good fertilizer management is the key to high productivity and efficiency in most oil palm plantations. However, its benefits go beyond maintaining healthy palms and yields. It is also a pre-requisite for the sustainability of oil palm and its competitiveness in vegetable oil market and other businesses, particularly in the face of labour shortage and environmental concerns.

Effective fertilizer management involves three key aspects: appreciating the agronomic principles of fertilisation and fertilizer management, proper field practices and understanding the criteria and indicators of palm health. The ability of the agronomist to advise reliably on amounts of fertilizers to use and techniques to reduce losses is a basic requirement underlying all the efforts to minimise use of labour for fertilizer applications and protecting the environment.

But ultimately it is the planters who have to ensure that the fertilizer recommendations and field practices are implemented well. Effective fertilizer management involves everyone in the plantation, from the workers to the top management. It makes each of us a significant player in the industry.

Further developments in fertilizer management are necessary in the near future to achieve its goals. We should be ready for them and appreciate that the survival of an organisation often revolves around its ability to understand and effectively deal with change. However, the temptation to jump at miraculous claims to survive in future must be resisted.

A final remark: the pride and joy of all planters is when we see acres and acres of healthy oil palms and can proudly exclaim, “We are one of those who are responsible for such beautiful and profitable sight”.

Further reading

Two published papers on site yield potential of oil palm and computation of fertilizer rates are included at the back of this chapter for the benefit of our readers.

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CONCEPT OF SITE YIELD POTENTIAL AND ITS APPLICATIONS IN OIL PALM PLANTATIONS

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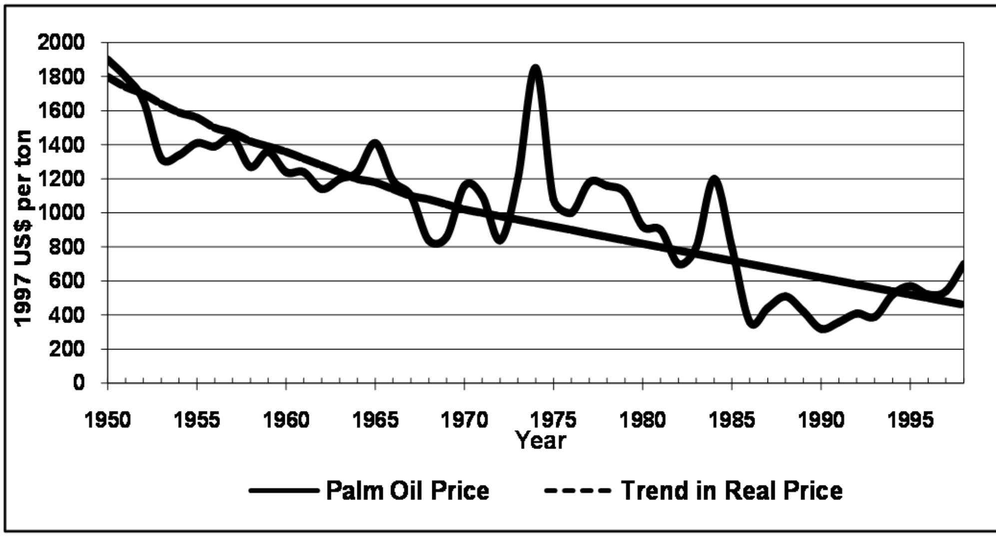
Abstract: The oil palm industry in Malaysia must further improve its productivity and efficiency by maximising land resources in order to be sustainable. Increasing productivity and profitability are largely reliant on maintaining high yield levels. Nevertheless the scenarios of stagnating yields of major plantation groups, ever increasing production cost of crude palm oil and the declining real price trend of palm oil continue to be disconcerting to the industry. One way to mitigate against this disconcerting trend is by reducing the cost of production, which is closely related to productivity per land area. In the case of the oil palm industry, achieving the highest possible yield for any given site or the site yield potential (SYP) could prove to be the best way in maximising our land resources, hence cushioning against the uncertainty of palm oil prices with the reduction of production cost. Information on SYP could also be used as an objective yield target and as a benchmark for evaluation of estate's performances besides being used to draw up appropriate implementations according to priority.

Introduction

The oil palm industry in Malaysia must further improve its productivity and efficiency by maximizing land resources in order to be sustainable. Increasing productivity and profitability, which are largely reliant on maintaining high yield levels, are crucial to a sustainable plantation industry.[1] However, three scenarios continue to be disconcerting for the oil palm industry. Firstly, average yields from the major plantation groups, the 'backbone' of the industry, have stagnated since the mid-1980s. They hovered between 20 and about 22 t fresh fruit bunches (FFB) per hectare per year against the reported genetic yield potential of about 45 t FFB per hectare per year.[2,3] On the other hand, production cost for crude palm oil has increased almost linearly since 1994. This increase is expected to follow through if the monthly wage scheme demanded by the plantation workers is adopted. Thirdly, the real price trend of palm oil according to Fry[4] has been declining since 1960s as shown in Fig. 1.

The main consequence of these scenarios is declining profits, which may lead to non-sustainability of oil palm plantations. One way to mitigate against this disconcerting trend is by reducing the cost of production.

Labour is the biggest cost item in the estate constituting about 47% of the ex-estate production cost. Labour cost over FFB yield per unit area is the main component affecting the ex-estate cost as seen in Fig. 2. Increasing FFB yield per unit area will lead to a corresponding reduction in the ex-estate cost. The best way of realising this is by maximising our land resources, i.e. achieving the highest possible yield for any given site, which is the site yield potential.



Source: Fry (1998)[4]

Figure 1. Real price trend of palm oil since 1950

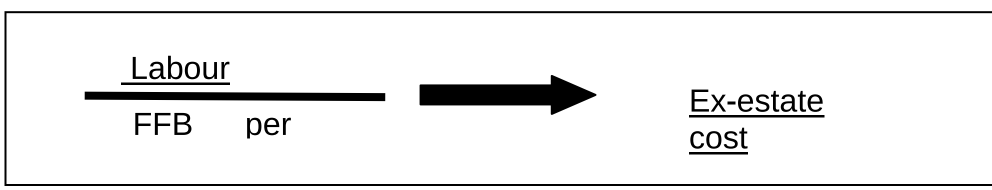


Figure 2. Labour cost over FFB per unit area is the main component affecting ex-estate cost

Definitions of Yield

Genetic Yield

The genetic yield potential of a crop has been defined as the largest yield obtainable if all the environmental conditions and agronomic decisions were perfect and there are no management constraints[5]. Corley computed the genetic yield potential of oil palm to be about 44 to 46 t/ha/yr at peak yield.[3] However, such ideal conditions and yield are seldom attained except in special growth chambers, small experimental plots and probably occurs in less than 1% of oil palm plantings.[6] More realistic FFB yields of 30 – 37 t FFB/ha/yr were reported by Tarmizi *et al.* on a wide range of soils in fertiliser trials and by Ng and Thong, Lee and Toh and Goh *et al.*[7-10] in commercial fields.

Site Yield

While the genetic yield potential is a useful concept particularly to plant breeders, it cannot be used as yield targets on a large scale, which is how the oil palms are currently cultivated and managed.[6] Oil palms are planted under many different environmental conditions and therefore there will be yield limiting factors in these areas. These yield-limiting factors may restrict light utilisation, water availability and rooting activity. Different planting patterns and densities for example can affect light utilisation by the palms as the total leaf area per unit ground area will vary.[11] On the other hand, different rainfall, soils and terrain affect water availability to the palms. Other soil factors such as soil depth, consistence, structure and drainage will affect the palm rooting activity. These yield-limiting factors will limit the achievable yield to a level below the genetic yield potential, i.e. the site yield potential (SYP).[5] The SYP therefore is the maximum yield realisable given a set of site characteristics in a particular environment.[12]

Actual Yield

Agro-management inefficiencies and constraints will reduce yield further and widen the gap between the actual yield and the site yield potential. Examples of these yield-reducing and yield-loss factors are poor palm nutrition, canopy damage by pests and herbicides, poor drainage, weed competition, poor harvesting standards and poor crop recovery. A schematic diagram illustrating the three definitions of yield is portrayed in Fig. 3. Yield-reducing and yield-loss factors are amenable and by correcting these limitations, the actual yields can be improved to the SYP. On the other hand, yield –limiting factors e.g. irrigation in dry regions, are usually difficult and costly to overcome.

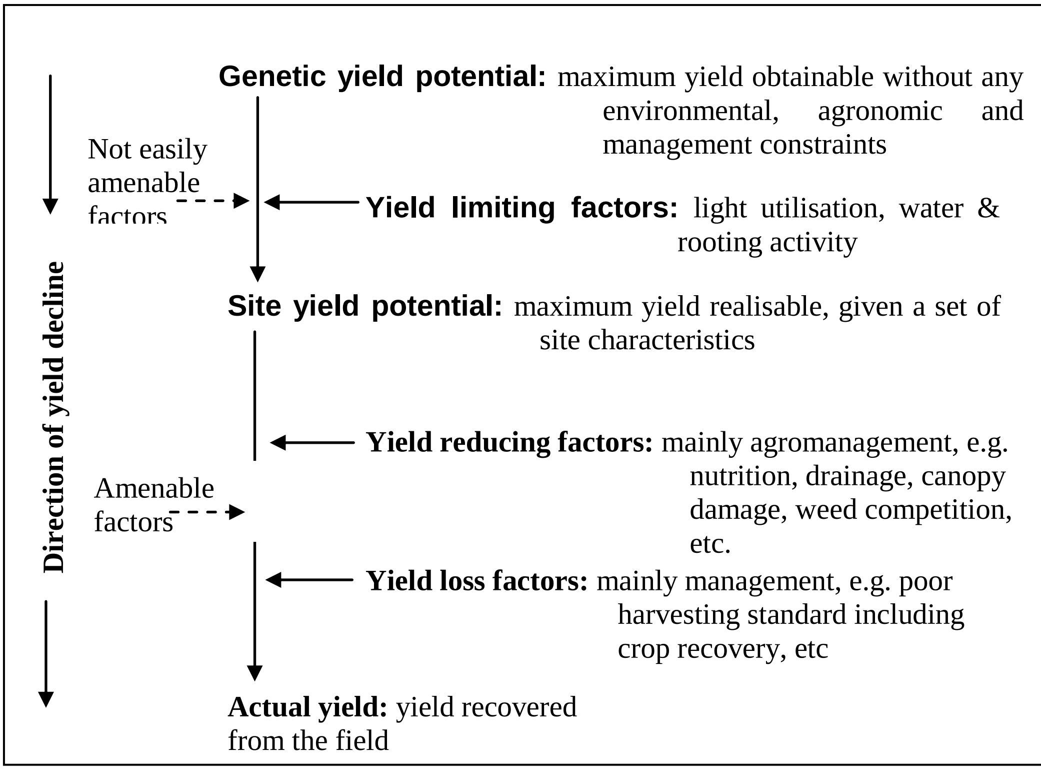


Figure 3. Schematic diagram of different definitions of yield

Concept of ASYP

The ASYP (AAR Site Yield Potential) is an empirical model developed to predict the site yield potential (SYP) of oil palm for any given environment or site characteristics. ASYP is expressed as a function of various plant, soil and environmental factors that may influence yields as follows:

$$ASYP = f\,(F_1 \times F_2 \times F_3 \times \ldots F_n) \times G$$

Where F_1 to F_n are the site-specific factors that influence yields. Each factor has a score from 0 to 1.

G is the genetic yield potential of oil palms (taken as 45 t FFB per hectare per year).[13]

From Light to Yield

For the palms to grow and produce crop, they must have sunlight and soil. Sunlight provides energy for photosynthesis and the soil acts as the medium for water and nutrient supply. Solar radiation needs to be captured efficiently in order to maximise photosynthesis. This is best done by the correct planting density and pattern in the field in order to ensure that optimum light is captured for photosynthesis by the oil palms. According to Tan and Ng, [14] the optimum density is dependent on the degree of inter-palm shading and competition at their respective age and vigour. It is also reported that equilateral triangular plantings give the best cumulative yield. In addition, light use efficiency needs to be optimised through good planting materials.[15]

For the uptake of water and nutrients from the soil, three factors are involved that is the rooting activity of the palms, and nutrient holding capacity and water holding capacity of the soil. These factors can be influenced by soil volume, soil structure, consistency and terrain. One final factor is climate, which affects the rate of photosynthesis and potential amount of water stored by the soil. The latter will affect severity and frequency of moisture stress experienced by the palms, which will have an impact on FFB yield. Fig. 4 summarizes these factors and their relation to dry matter production for both growth and yield.

ASYP Computations

ASYP takes into account all the factors that may influence the yield of oil palms, namely:

(a) Planting materials (e.g. AAR, Golden Hope, Chemara, HRU, etc).
(b) Quality of planting which is dependent on the planting density and planting pattern.
(c) Soil factors, which are influenced by soil volume, structure, consistency and terrain.
(d) Climatic factors by taking into account moisture stress severity and frequency.

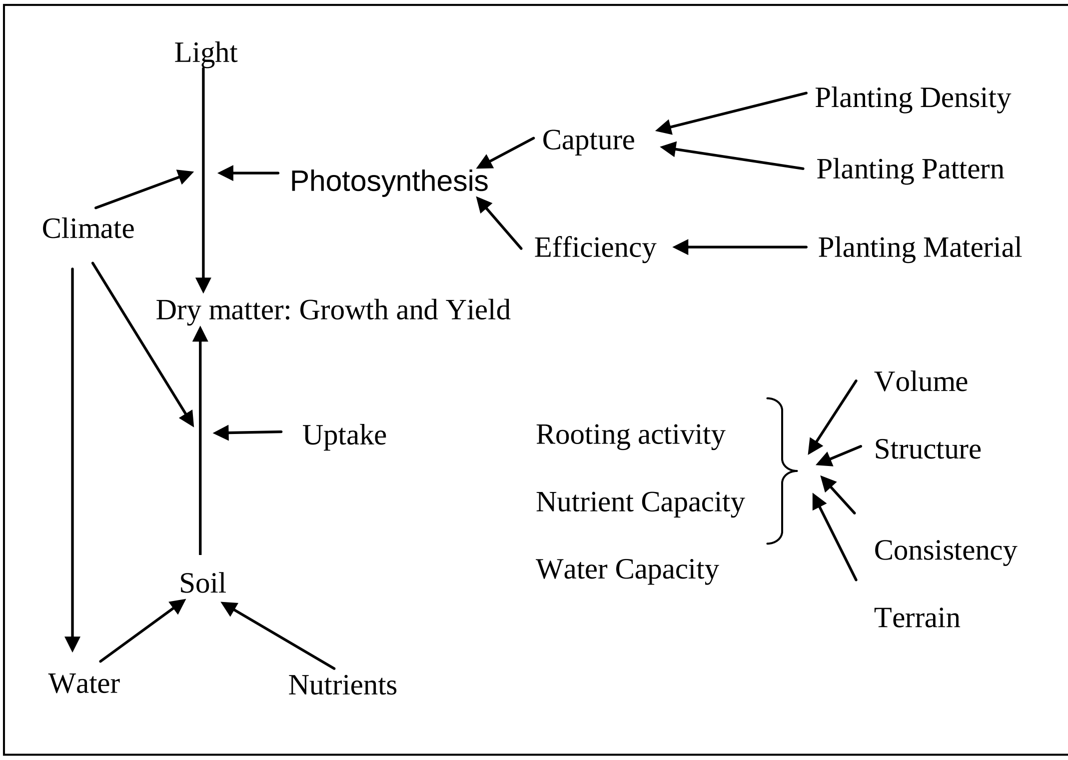


Figure 4: From light to yield, what does it take?

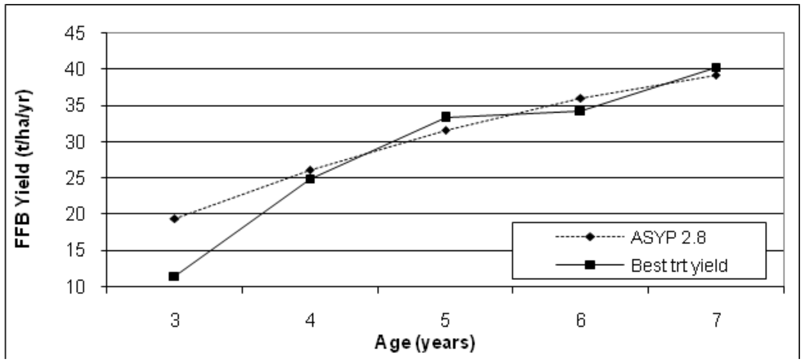
These factors are translated into mathematical equations and along with the historical data, i.e. rainfall data, they are then built into a model. This model, the ASYP 2.8, is programmed into AA AeGIS®, which is a Decision Support System (DSS). Using this model, the site yield potentials of an oil palm field from year 3 to year 30+ after planting can be generated for any set of given site characteristics. An example is known of a 1985 planting of an estate where the site yield potential in year 2000 was 38 t/ha/yr. The AeGIS DSS also contains the yield records of the estates on a per field basis so that actual yields obtained can be easily compared against the SYP. With this, palm and field performances of the estates can be assessed objectively and quickly.

Validation of Results

The accuracy of ASYP computation depends largely on the accuracy of the inputs; namely the yield limiting factors stated earlier. Accurate spatial information of soils and terrain, moisture stress computation etc. will therefore improve the accuracy of the SYP generated by the model.

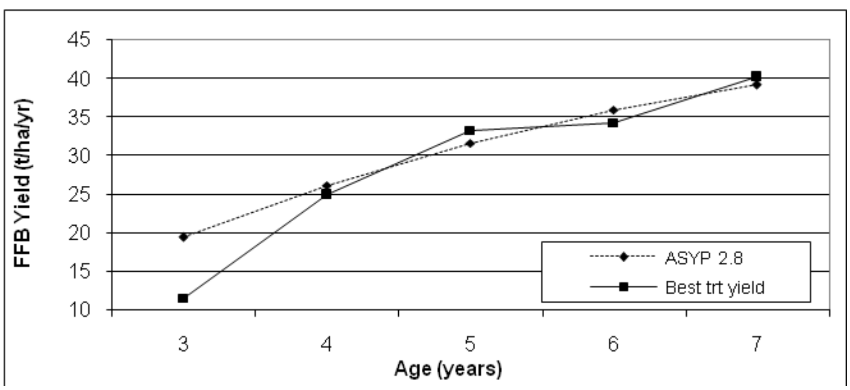
The model was validated using data from three independent trials, i.e. one irrigation trials and two maximum yield trials and in three commercial estates with different rainfall patterns. However, only the results (Figs. 5a and 5b) from the two maximum yield trials carried out in central Selangor (for young palms on Munchong series, Typic Hapludox) and central Johore (for mature palms on Kawang series, Typic Kanhapludult) are discussed as they have the longest, accurate yield records.[13]

For young palms, there was a response to fertiliser applications. Thus, best treatment yields are the best indicator of SYP. Trial results showed that best treatment yields followed closely to the SYP predicted by the ASYP model. The only exception is the yield from the first year of harvesting (Fig. 5a) whereby the actual yield was far below the SYP. This was mainly due to the effects of rhinoceros beetle damage on the palms in the first year after planting. However, for mature palms, there was no response to treatments. Thus, mean trial yields are good indicators of SYP. The mean trial yield fluctuated around the SYP as seen in Fig. 5b. Cumulatively the actual yield achieved was 96% of the SYP. Therefore, ASYP is capable of providing realistic and achievable yield targets for both young and mature palms for a three year period.



Source: Kee *et al.* (1998)[13]

Figure 5a. Comparison of ASYP and actual yields achieved for young palms on Munchong series soils



Source: Kee *et al.* (1998)[13]

Figure 5b. Comparison of ASYP and actual yields achieved for mature palms on Kawang series soils

As more accurate data is obtained for an area, the ASYP can be regenerated to take into account the updated conditions. The accuracy of field yield records in plantations can vary considerably especially for block hectareage.[2] It is important to ensure that block hectarage are correct so that actual yields achieved reflect the actual potential of the block. Actual results can then be compared more realistically for the SYP generated by the model.

Limitations of ASYP

The ASYP model like all models, has its limitations, i.e.

(a) The ASYP model is not a yield-forecasting tool as seasonal yield trend has not been taken into account

(b) The model does not predict accurately for the first year of harvesting and also for palms above 20 years old. This is because for the first year of harvesting, variation in the field is usually greater in terms of growth of palms and number of supplies. Also, the palm age when it is brought into harvesting varies considerably between plantings. For palms over 20 years, over-pruning is usually necessary for harvesting purposes and this has not been taken into account by the model.

(c) The ASYP uses rainfall record of at least ten years. Therefore short-term moisture stress effects are not totally taken into account. Their effects on the growth and yield of oil palms are still not fully understood and thus cannot be modeled.

(d) The effects of by-products utilisation i.e. empty fruit bunches (EFB) and palm oil mill effluent (POME) which can improve poor, shallow or lateritic soils are also not accounted for by the model.[16]

(e) The ASYP assumes a good standard of planting and thus fields, which are poorly planted or planted with inferior quality palms (such as etiolated seedlings etc.), cannot be accurately predicted.

(f) The detrimental effects of flooding are also not included in the model.

Applications of ASYP

As a Benchmark

SYP generated by the model can be used as an objective benchmark to assess palm and estate performances. For example, the actual yield achieved can be expressed as % of the site yield potential. If the figure obtained is 85% or more, the area or estate is likely to have good management standards with only minor or very few agronomic problems as seen in Table 1. However, if it is 50% or less, then that area/estate is likely to have very serious agronomic problems and/or poor management standards.

Table 1. An example of a benchmark to assess performance of an area

Benchmark Criterion (%)	Potential Agronomic Problems	Potential Management Standards
> 85	Minor	Good
70 – 85	Moderate	Good or Satisfactory
50 – 70	Serious	Satisfactory or Fair
< 50	Very Serious	Poor

Note: Benchmark criterion to assess estate performance =

$$\left(\frac{Actual\ Yield}{Site\ Yield\ Potential}\right)\ x\ 100\%$$

Generation of the SYP using the model requires characterization and quantification of all factors that affect SYP. The exercise will quickly identify and quantify the most critical problem or constraint present in the given block. Therefore, if the actual yield is grossly lower compared to the SYP, the factors contributing to ASYP (or yield limiting factors) should be reworked first. If the yield limiting factors were correctly identified, then the yield gaps are likely due to yield reducing and yield loss factors (e.g. manuring and harvesting standards). Appropriate measures to rectify these yield reducing and yield loss factors can then be drawn up to improve yields.

To Set Targets

The SYP is the maximum yield that can be achieved for the given site. Thus, it can be used as an objective yield target for the estates to attain. Thus, we would not expect the oil palms on shallow lateritic soils to yield more than 30 t/ha/yr when the site yield potential for that area is only 22 t/ha/yr, and vice versa. Fertiliser rates to be recommended for each field can therefore be drawn up in relation to the SYP based on the nutrient balance approach. This will avoid both excessive or under application of fertilisers.

To Set Work Priority

Estates have limited resources and manpower. Thus, it is necessary to prioritise the work programme on the estate. The concept of SYP can be used to help set priority of work in the estates. For example, priority of work should be given to fields with the largest yield gaps between the actual yield and the site yield potential instead of fields with the lowest yields. This is because, the lowest yielding field (Field B of Table 2) may already be close to the site yield potential and thus, further improvements are limited. Conversely in Field A, the potential for yield improvement is higher and priority should be given to improve yields in this block.

Table 2. Comparison of fields with different yield gaps

Field	Major Soil Type	Actual Yield (t/ha/yr)	ASYP (t/ha/yr)	Benchmark Criterion (%)
A	Deep clayey soil	22.1	28.0	79
B	Shallow lateritic soil	20.7	22.0	94
C	Alluvial soil	22.9	27.0	85

Table 3. Comparison of estates in different regions / states

Estates in (State)	Average Actual Yield (t/ha/yr)	Average ASYP (t/ha/yr)	Benchmark Criterion (%)
Selangor	22.0	27.0	81
Negeri Sembilan	20.0	21.0	95

In the same way, performances of estates on a regional scale can be compared as shown in Table 3. Estates in Selangor are actually under-performing compared to estates in Negeri Sembilan even though the average yield for Selangor estates is 22.0 t/ha/yr or 10% higher than those in Negeri Sembilan.

Estates can be ranked according to the yield gaps between actual and SYP. Estates with more than 20% yield gaps may be identified for special attention. Within these estates, we can go a step further and investigate the fields with the largest yield gaps. Dominant factors or yield constraints that account for the large differences can then be identified and rectified.

Other Potential Uses of ASYP

The ASYP can also be used as a tool to help in strategic planning e.g. when to replant, by identifying fields with large yield gaps where correction is best done by replanting. This is because the low actual yields could possibly be due to the decrease in density caused by diseases, very tall palms which reduce harvesting efficiency etc. A study on the viability of land conversion to oil palm should also include the SYP for that land so that only those with high SYP should be purchased for long-term sustainability.

General Remarks

In the ASYP model, the site yield potential levels are generally predetermined after planting and very little can be done to change the yield limiting factors after that as they are usually difficult and costly to amend, for example irrigation in dry regions.[2] Thus, work and emphasis should be on eliminating yield reducing and yield loss factors, which are more amenable so that the actual yield achieved is as close as possible to the site yield potential.

Conclusions

In conclusion, ASYP provides an objective yield target for estates and as a benchmark for evaluation of estate performances. It can also be used as a tool to help the management and agronomist to be more focus on the main problems i.e. fields with large yield gaps and not necessary fields with low yields. Dominant factors or yield constraints can then be identified. Appropriate corrections can then be drawn up for implementation according to priority. In addition, the ASYP can also help in planning for example when to replant, and whether or not to acquire a certain piece of land.

The benefits of achieving the site yield potentials are obvious. It can cushion against the uncertainty of palm oil prices, help reduce the cost of production and avoid both under-application (which can be detrimental to the palms) and excessive application (which can be detrimental to the environment) of fertilisers.

Acknowledgements

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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.

A. 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.

B. 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).

C. 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 (µg g^{-1})	< 150	150-250	250-350	350-500	> 500
Available P (µg 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.

D. 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.

E. 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).

F. 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).

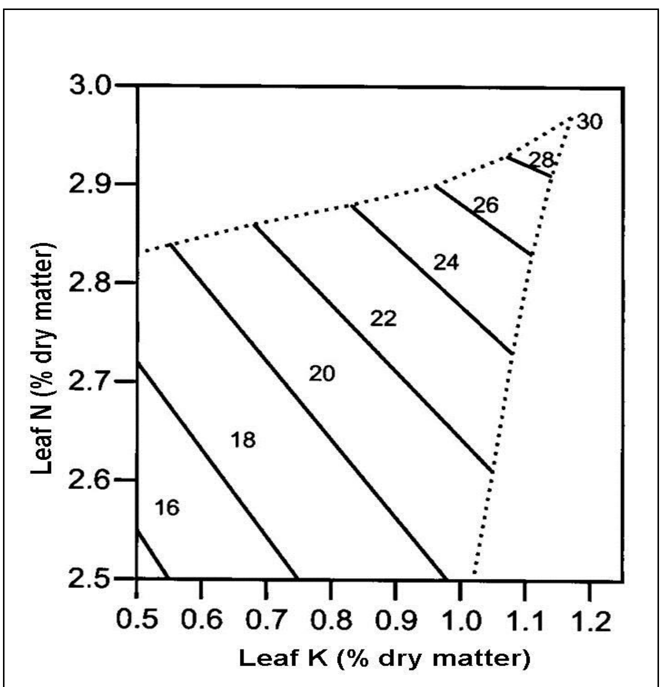


Figure 1: Yield isoquants (lines of equal yield) for N and K concentrations in the leaves of oil palm in a trial on a granite-derived soil in Malaysia (after Foster, 2003).

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.

G. 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,

$$\text{Yield} = a - b\,\exp(-cX)$$

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:

$$D_n = D_{n-1} + a (N_{n-1} – N_n) + b (N_c – N_n)$$

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:

$$\text{Leaf P (\%)} = 0.0487 \text{ Leaf N (\%)} + 0.039$$

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:

$Dn – Dn\text{-}1 = a (Nn\text{-}1 - Nn) + b (Nc\text{-}Nn)$

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

H. 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:

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

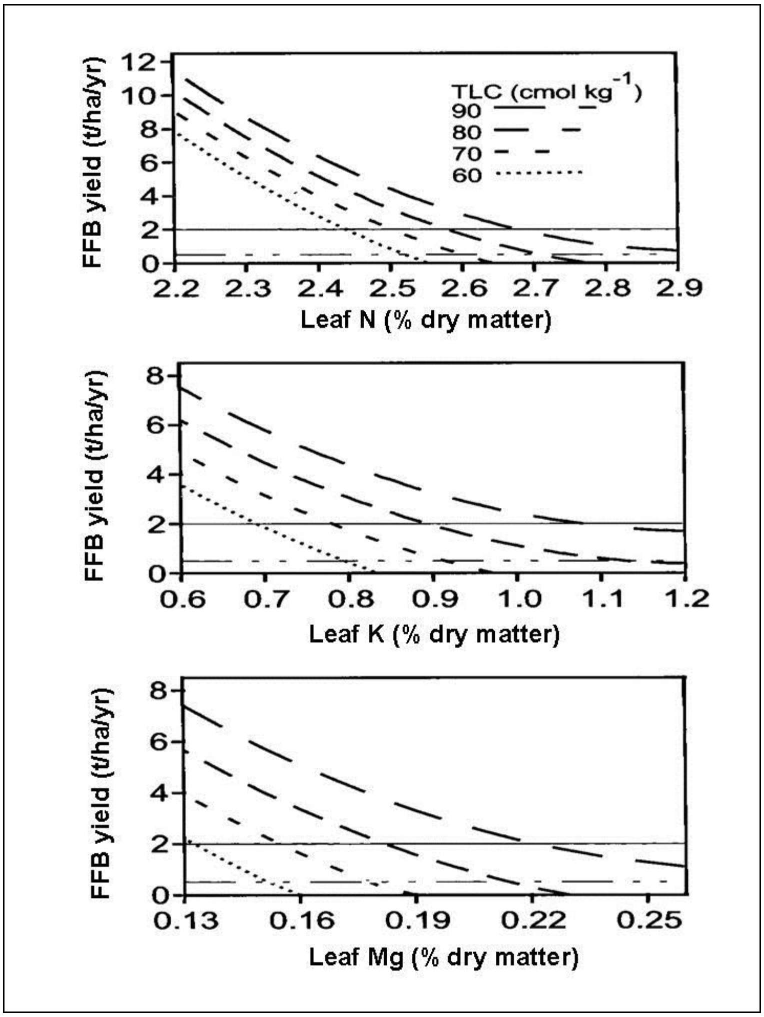


Figure 2: Predicted maximum yield response to fertilizer in relation to leaf nutrient status and total leaf cations (TLC) in Malaysia (after Foster, 2003)

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.

I. 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

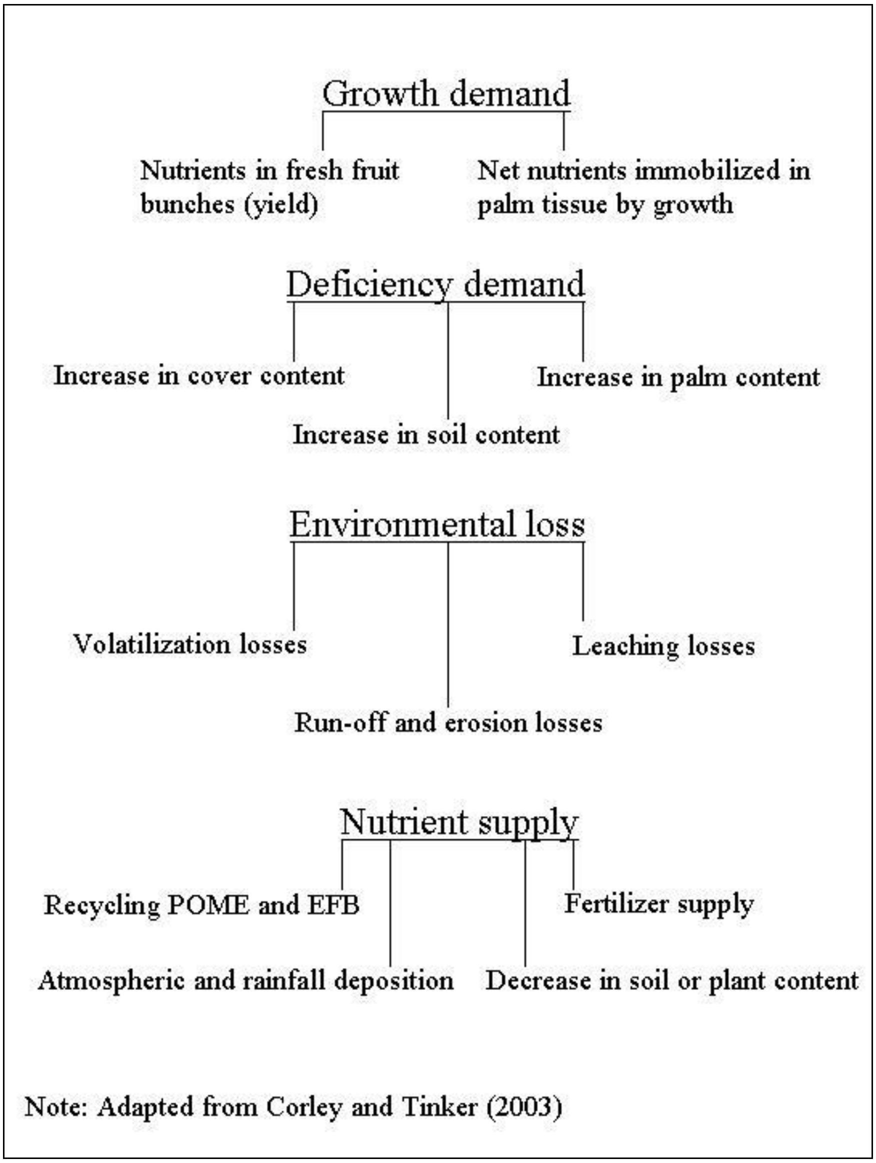
Note: D denotes deficient and S denotes sufficient status

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

$$\text{Canopy N growth demand (g N/palm)} = 0.155^* (\text{Pinnae N } (\%)_1) (\text{Frond17 dry weight } (g)_2 - \text{Frond17 dry weight } (g)_1)$$

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 = $1.92\ (\text{Palm age (yr)})^{-1.11}$

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:

$$\text{FFB N growth demand (g N/palm)} = \text{FFB (kg)}_2 \times 3.195$$

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 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.

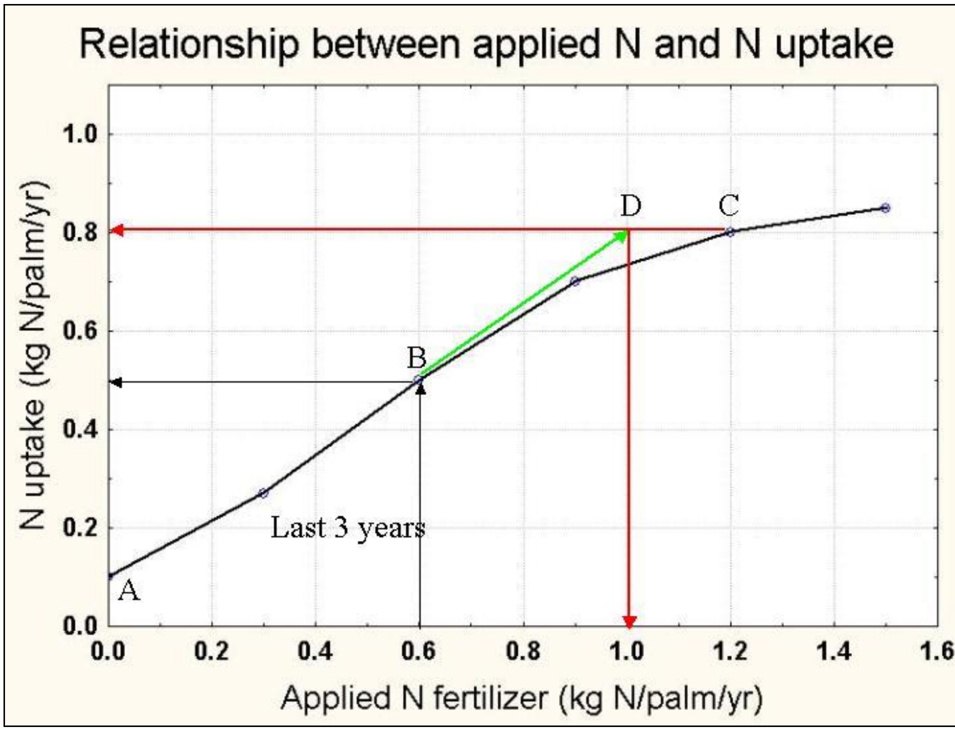


Figure 4: A hypothetical response curve of N nutrient uptake to N fertilizer input and a method to predict the N fertilizer rate for the following year

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 dependent 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 and 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.

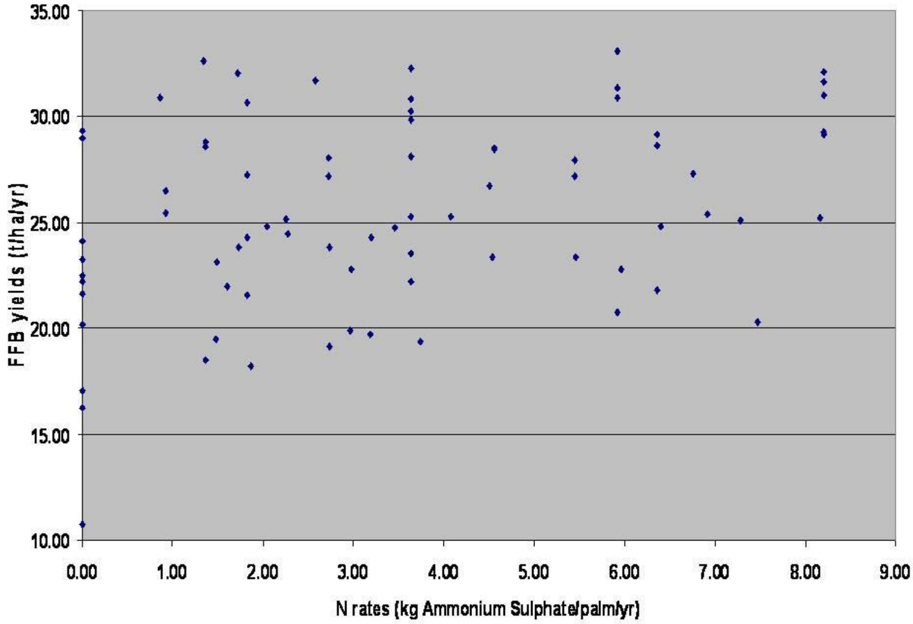


Figure 5: The effect of N fertilizer rates on FFB yields in 21 fertilizer response trials on inland and coastal soils in West Malaysia (data from PORIM-Industry trials conducted between 1960s and 1980s).

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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the tedious task of modifying, verifying and validating INFERS model as and when he had another idea to improve it, only to find out later, more often than not, that he had been wrong.

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Appendix 1: Standard AAR Assessment form of agronomic information, agromanagement inputs and outputs for a manuring block

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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 @	

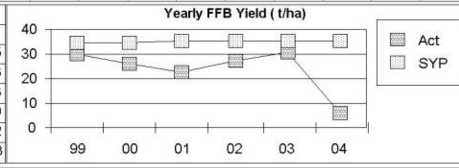
Soil Analysis Results

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	

	Leaf Analysis Results								Canopy					Nutrients applied (kg/palm)				
Year	Ash	N	P	K	Mg	Ca	B	Cl	L.A	Dry Wt	LAI	Size	Vig.	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

	Yearly FFB Yield (t/ha)					Rainfall	
Year	Density	FFB/ha	Bch/ha	Av. Wt.	SYP	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

Yearly FFB Yield (t/ha)



Canopy				Palm			Soil			Management Practices						Yield	
Size	Vig.	Frd.No	Loss	Uni.	Loss	Etiol.	T-Soil	Cons	Drain	Legume	PC	IR	F.App	Pruning Qlty	Pruning Freq.	Bch/p	Reco.
1	1	<=8	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	1	1	2	2
3	3	17~24	3	3	3	3	3	3	3	3	3	3	3	2	2	3	3
4	4	24~32	4	4	4	4	4	4	4	4	4	4	4	3	3	4	4
5	5	>=33	5	5	5	5	5	5	5	5	5	5	5	4		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	Slight Many	Moderate Few	Moderate Many	Severe Few	Severe Many	Correction Required
N							
K							
Mg							
B							
Other							

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