Fertilizing for maximum return

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INTRODUCTION

Fertilizers are usually the largest variable cost item in oil palm production. The yield potential of oil palm has increased greatly over the past 30 years following the introduction of tenera planting materials, but improvements in oil palm nutrition, however, are required to exploit the site yield potential of these new planting materials (Goh *et al*., 1994), particularly since much of the recent expansion in the area planted to oil palm has occurred on poor fertility status soils.

In order to draw up an appropriate and balanced fertilizer program, the potential needs of the crop at projected levels of growth and yield must be determined (Foster, this volume). Recycling palm residues is also an essential component of efficient nutrient management (Redshaw, this volume). Furthermore, assumptions have to be made with regard to differences in fertilizer recovery efficiency for each nutrient and nutrient source. These assumptions generally involve an estimate of the amount or proportion of nutrient loss after application. This chapter is therefore concerned with the events following the application of fertilizer to palms. Nutrient loss pathways (e.g. surface runoff, leaching), are discussed and the appropriate methods of application (i.e. frequency and placement of fertilizers) are proposed to minimize nutrient losses and maximize the returns from fertilizer use.

NUTRIENT LOSSES

Soil indigenous and fertilizer nutrients that are not taken up by the palm or adsorbed onto soil particles are dissolved and lost through surface runoff, volatilization, denitrification, or leaching. Adsorbed nutrients may also be lost in eroded soil and sediments.

Losses are more pronounced at particular phases in the life of an oil palm plantation. The potential for nutrient losses is probably greatest immediately after land-clearing when the soil surface is exposed to erosion and uncontrolled surface runoff losses before legume cover plants (LCP) have been established. Losses can be great when large amounts of nutrients such as potassium (K) are released when the standing biomass (e.g. fronds, trunks) is burned during plantation development.

The other period when the risk of nutrient losses is high occurs when ground vegetation is sparse due to poor light penetration through the closed oil palm canopy (Breure, this volume). At canopy closure, the LCP dies off and a large amount of nitrogen (N) is released from the decomposing LCP biomass. Unless palm growth is vigorous, losses of mineralized N due to leaching are likely to be large.

Nutrient losses are more pronounced in areas of the plantation where steep topography and inadequate soil conservation measures result in erosion and uncontrolled surface wash. Clearly, a proper assessment must take account of these temporal and spatial aspects of the potential for nutrient losses.

Leaching losses are more prevalent in coarse-textured soils in high rainfall areas where large fertilizer application rates are required but fertilizer recovery efficiency is poor. Nitrogen may be lost to the atmosphere due to volatilization but, as we shall see, N fertilizers differ in their susceptibility to volatilization losses, which are also affected by the field conditions when the fertilizers are applied.

LAND-CLEARING AND PREPARATION

Oil palm is planted on a variety of land types:

- Logged primary or secondary forest land.
- Land abandoned to *alang-alang* (*Imperata cylindrica*) after a period under slash-and-burn agriculture.
- Land replanted from plantation crops (e.g. rubber, cocoa, oil palm).

Proper land-clearing techniques are required in order to conserve indigenous soil nutrient supplies and the nutrients returned to the soil in the cleared biomass (Gillbanks, this volume). In the past, when tropical rainforest was converted to oil palm, the felled trees and the organic residues of the previous vegetation were often burned to make field operations (i.e. lining, planting, drainage) easier and thus reduce labor costs, but large amounts of N and sulfur (S) were lost to the atmosphere in the process.

In an experiment to measure the effects of burning biomass on soil properties in Benin, West Africa on acid sand, soil chemical properties and yield were measured at 20 years (Trial A) and 10 years (Trial B) after planting (Sly and Tinker, 1962). In Trial A, there was a significant increase in soil exchangeable K in the burnt treatment (Table 1) but in Trial B, exchangeable Ca and Na, organic carbon and total N were larger in the unburnt treatment (Table 1).

In the first four years of production, yield was larger in the burnt treatment (Trial A) but there were no significant differences in yield when averaged over 11 years of production. The authors concluded that the burning of felled forest under typical Nigerian conditions was not detrimental to later growth and yield of oil palms, and has definite practical advantages in implementing field work (Sly and Tinker, 1962).

Foong (1984) measured soil chemical properties of a virgin Munchong (Typic Hapludox) soil at intervals after land-clearing and LCP establishment (Table 2). Six months after land-clearing, there was a discernible increase in soil pH due to the liming effect of the ash from the burnt vegetation. This seemed to be a temporary effect, as soil pH decreased to 3.9–4.0 thereafter. Total phosphorus (P) content also decreased after

Table 1. Effects of burning felled vegetation on oil palm yield and soil chemical properties (0–15 cm depth) in Nigeria at 20 years (Trial A) and 10 years (Trial B) after planting (Sly and Tinker, 1962). [denotes mean of 11 years (Trial A) and 6 years (Trial B); ** denotes significant difference (P<0.05).]*

Trial	Treatment	Bunch yield ($t\ ha^{-1}$)		K	Na	Mg	Ca	CEC	Org. C	Total N
		Years 1 - 4	Adult Years*	cmol kg^{-1}					%	
A	Burnt	4.86	9.95	0.045**	0.070**	0.68	3.15	6.04	1.10	0.095
	Unburnt	5.24	9.73	0.038**	0.039**	0.63	3.82	6.27	1.20	0.100
B	Burnt	4.96**	6.55	0.070	0.048	0.69	2.18**	5.87	1.18**	0.098**
	Unburnt	4.36**	6.50	0.073	0.056	0.83	2.75**	6.15	1.24**	0.106**

Table 2. Changes in chemical properties of topsoil (0–15 cm) in Malaysia at intervals after land-clearing and legume cover plant establishment (Foong, 1984).

Status (stage of land cultivation)	Month	pH	Organic C	Total N	Total P	Available P	K	Ca	Mg
			%		mg kg^{-1}		cmol kg^{-1}		
Virgin soil	0	4.1	16.3	1.7	165	6.0	1.7	2.1	2.5
After clearing	6	4.3	15.4	1.7	140	7.0	1.8	2.2	2.1
6 months after planting LCP	18	3.9	15.3	1.4	170	10.0	2.0	1.8	1.9
13 months after planting LCP	25	4.0	14.7	1.3	155	6.0	1.6	2.1	1.5
36 months after planting LCP	48	3.9	14.0	1.4	155	5.0	2.0	4.0	2.4
50 months after planting LCP	62	3.9	18.3	1.8	179	8.0	1.6	3.6	2.7

LCP = legume cover plants

land-clearing but was increased substantially after planting LCP, due to the application of phosphate rock during the establishment of legume cover plants (LCP). Organic carbon (C) and total N also decreased at first, but were replenished by the LCP at 62 months after land-clearing when the LCP was shaded out by the oil palm canopy. There were small changes in soil available P and exchangeable K over the period monitored, but there was an increase in soil Ca and Mg. Thus, with proper LCP establishment, soil chemical properties could be maintained or even improved at this site during the first five years after planting (YAP).

In recent years, burning has been prohibited by legislation in Malaysia and Indonesia in response to concerns about environmental pollution and zero-burn land-clearing techniques were developed (Mohd. Hashim *et al*., 1993). Zero-burn replanting techniques may contribute to improved soil physical and chemical properties because the large quantity of biomass and nutrients contained in palm trunks and fronds is conserved and returned to the soil (Goh and Härdter, this volume; Redshaw, this volume). Felled trunks and fronds should be chipped and spread over the soil surface to provide mulch, reduce localized nutrient build-up, and minimize potential leaching losses.

Although zero-burn replanting techniques are currently the norm in the oil palm industry, it should be pointed out that pest control measures may be exacerbated due to an increase in the population of *Oryctes* beetles and rats. Thus, whilst zero burn land clearing results in reduced smoke emissions and improved soil properties it amy also result in an increase in pesticide use.

It should be remembered that the cost of replenishing soil fertility is almost always larger than the cost of implementing proper land clearing, land preparation and soil erosion control techniques that contribute to the conservation of indigenous nutrient supplies. Mechanical clearing and burning can result in increased surface runoff, topsoil erosion, leaching, N-volatilization, and P-sorption (von Uexküll, 1986). Soil damage during site preparation may be so severe that LCP establishment is greatly impaired, and this must be avoided.

RUNOFF AND TOPSOIL EROSION

Surface runoff water is the amount of water contained in rainfall and runoff received from higher elevations that does not infiltrate the soil. Runoff is greater where the soil structure has been damaged due to compaction, which causes a reduction in the soil water infiltration rate. In a study in West Sumatra on 10-year-old oil palms, significant spatial variability was found when soil water infiltration rates in the soil beneath the palm circle, path and frond stack were compared. Infiltration rate increased in the order *path* < *circle* < *frond stack*. The larger infiltration rate in the frond stack was attributed to the effect of pruned fronds on soil structure. The smaller infiltration rate in the circle and path was related to soil compaction due to wheelbarrow and human traffic (Fairhurst, 1996).

In a simulation study of in-field transport of fruit bunches and fertilizers, Tan and Ooi (2002) showed that infiltration rate in the mechanization path could be reduced to zero after 24 runs by a 2.3 t mini-tractor grabber carrying a 1 t load. Thus, the use of low ground pressure vehicles for infield transport is strongly advocated to reduce soil compaction.

Soil erosion occurs when soil cover is poor and particles of soil are detached by raindrops and carried offsite. Preventive strategies include the installation of erosion bunds (on slightly sloping land), palm platforms (on sloping land), and contour terraces (on steeply sloping land) (Gillbanks, this volume). Nutrient loss due to erosion are greater on steep slopes are where rainfall intensity is greater, but losses can be reduced by improving soil cover and installing soil conservation structures (Kee and Chew, 1996). It is therefore very important to practice selective weeding in mature oil palm plantations to preserve groundcover and reduce the amount of nutrients lost in surface runoff and eroded soil. When properly arranged in the inter-rows, pruned fronds are an important means to reduce run-off and erosion and thus should not be removed from the field for other purposes (Redshaw, this volume).

The amount of nutrients lost due to runoff and topsoil erosion may be large (Maene *et al*., 1979) (Table 3) and are usually greater than losses due to leaching. Losses of N and boron (B) in runoff water were greater than 10% of the amount applied as fertilizer, but losses were smaller for the nutrients K, magnesium (Mg) and P (Table 3). This was probably due to the greater solubility of N and B fertilizers and the adsorption of K, Mg and P on soil complex. Losses from surface runoff were larger in the uncovered soil in the harvest path, compared to the interrows, where pruned fronds provide soil cover (Table 3) and improve soil structure and the rate of water infiltration (Fairhurst, 1996).

Other studies indicate that the amount of fertilizer nutrients lost due to surface runoff could be related to the amount and intensity of rainfall immediately after fertilizer application. Kee and Chew (1996) found that N concentrations in runoff water collected after the first rain event following fertilizer application in the wet month of October were 89 mg kg^{-1} for Rate 1 at 65 kg N ha^{-1} and 135

Table 3. Nutrient losses in surface runoff water on a Durian Series soil (Typic Hapludult) in Malaysia (Maene et al., 1979).

Fertilizer placement	Nutrient losses (% of applied fertilizer)					
	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
Fertilizer nutrients applied (kg ha^{-1})	90.2	52.0	205.9	32.8	78.9	2.4

mg kg^{-1} for Rate 2 at 130 kg N ha^{-1}, compared to 4 mg kg^{-1} in the control plot.

During the dry period when there was no rain for five days after fertilizer application, however, the N concentrations in the runoff water collected after the first rain event were much lower at 30 mg kg^{-1} (Rate 2), and <5 mg kg^{-1} (Rate 1 and the control plot). The drier soil surface appeared to result in an increase in the infiltration rate and thus a greater proportion of applied fertilizer was washed into the soil. Similar trends were observed for P, K and Mg fertilizers.

Phosphorus is more likely to be lost due to sheet erosion as it is less soluble than other nutrients and is held strongly on soil particles (particularly in highly weathered inland and upland soils). Sheet erosion also results in the loss of organic matter that forms an important part of the cation exchange capacity in highly weathered tropical soils. Steeply sloping inland and upland soils are more vulnerable to sheet erosion, and thus the effect of erosion on soil fertility in these soils is more pronounced. The subsoil in highly weathered soils is characterized by low cation exchange capacity (CEC) and the presence of small concentrations of plant available K, P, and Mg. The subsoil is thus a less-favorable environment for root growth and root activity, particularly if the concentrations of Al^{3+}, H^{+} and Mn^{2+} are large due to low soil pH. For these reasons, the concentration of oil palm feeder roots is greatest in the upper 30 cm of soil (Ng, *et al*., on botany, this volume). Cover plants are very difficult to establish on areas affected by sheet erosion, and usually soil P must first be replenished before a full LCP canopy can be established. The importance of LCP in soil conservation is illustrated by Ling *et al*. (1974) in an experiment in Malaysia where runoff and soil loss decreased from 22% under bare soil conditions to 1% where soil surface was covered with LCP (Figure 1).

To summarize, measures to minimize nutrient losses due to surface runoff and soil erosion include the following:

- Maintain adequate groundcover by selective weeding, so that harvesting is not obstructed and competition from weeds is minimized,
- Implement contour planting with properly designed terraces and platforms on steep land,
- Align cut fronds along the contour,
- Mulch with empty fruit bunches,
- Avoid fertilizer application when heavy rainfall is likely to occur, and

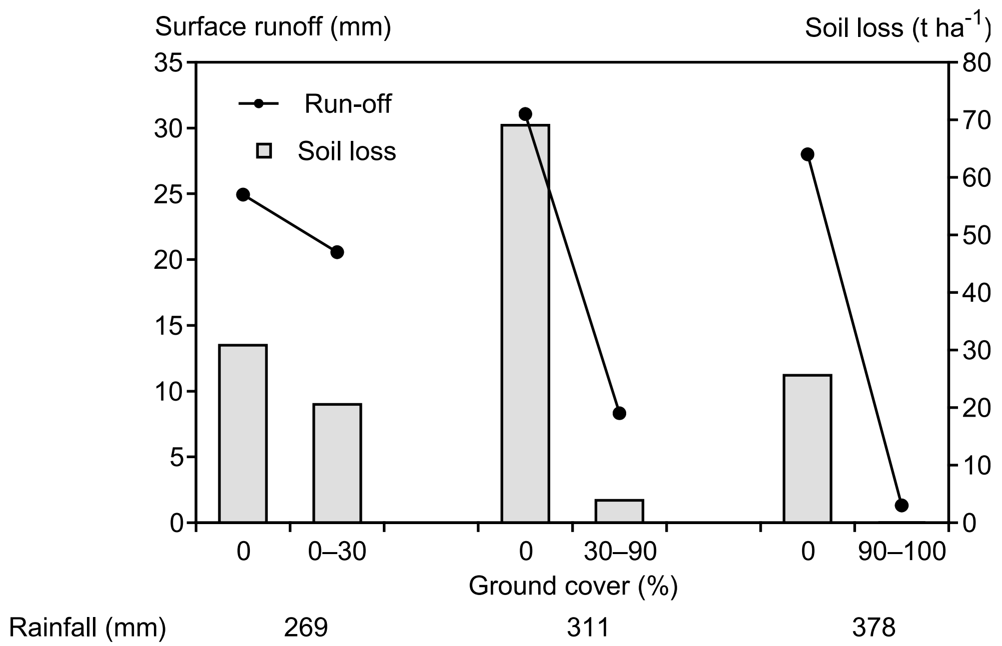


Figure 1. Effect of groundcover and rainfall on surface runoff water and soil loss from a Munchong Series soil (Typic Hapludox) in Malaysia (Ling et al., 1974).

- Install contour soil bunds.

LEACHING

Leaching losses occur when nutrients are dissolved into the drainage water as it percolates through the soil profile. Leaching is particularly problematic on coarse-textured soils in the humid tropics where rainfall exceeds evapo-transpiration. Other factors that affect nutrient losses by leaching include soil pore size, rainfall intensity, the initial water content of the soil, and the amount and timing of fertilizer application. The cations Ca^{2+}, Mg^{2+}, and K^{+} and the anions NO_3^- and Cl^- are most prone to leaching (Foong, 1993) (Table 4). Leaching losses are generally larger in older palms, probably because larger amounts of fertilizer have been applied.

In a catchment study in the same plantation where Foong (1993) conducted an experiment on leaching losses, the exceptionally large Mg losses were attributed to the excessive application of kieserite and the application of N and K fertilizers that displaced Mg from cation exchange sites into the soil solution. Losses of P were very small, due to its comparative immobility in the soil (Chang *et al*., 1994).

In a study on nutrient leaching on Orlu and Algba series (Rhodic Paleudult) soils in Nigeria, Omoti *et al*. (1983) distinguished between nutrients originating from the soil indigenous supply and nutrients added in mineral fertilizers by using fertilized and unfertilized lysimeters installed 60 cm below the soil surface. Losses of NH_4-N and K were small in young palms in the absence of fertilizer, but for all nutrients, leaching losses from fertilizer were smaller in the older palms compared with the young palms (Table 5).

Table 4. Loss of nutrients by leaching measured by lysimeter in mature oil palm on a Munchong series (Typic Hapludox) (Foong, 1993).

Palm age (years)	Leaching losses (% of applied fertilizer)							
	N		P		K		Mg	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range
5 - 8	1.2	0.5 - 2.7	1.6	1.4 - 1.7	2.5	0.9 - 3.7	11.5	5.2 - 28.8
9 - 14	3.0	1.6 - 5.8	1.5	0.8 - 2.7	2.9	1.4 - 4.4	15.5	8.3 - 23.7

Table 5. Loss of indigenous and fertilizer nutrients from a Rhodic Paleudult soil in central southern Nigeria (1923 mm annual rainfall) (after Omoti et al., 1983).

	NH_4-N	NO_3-N	K	Ca	Mg	SO_4-S	Cl
	kg ha^{-1}						
4-year-old palms							
Loss from native pool	5	18	2	115	22	37	37
Loss from fertilizer	10	16	24	125	26	20	61
Total loss	15	34	26	140	48	57	98
22-year-old palms							
Loss from native pool	5	34	21	89	23	59	22
Loss from fertilizer	4	3	8	27	7	7	48
Total loss	9	37	29	116	30	66	70

This outcome is to be expected since the older palms have better root system to absorb applied and indigenous soil nutrients, a larger demand for nutrients, and a higher transpiration rate with a consequent lower water balance for leaching.

Losses of NO_3-N, K and SO_4-S all were greater in the unfertilized soil in older palms compared with young palms, presumably because of nutrient accumulation in the soils due to fertilization prior to the measurements (Table 5).

Calcium was leached in the greatest quantity followed by Cl, SO_4-S, and Mg. As could be expected, losses of NO_3-N were greater than of NH_4-N. It appears that Ca was the main carrier for the anions in these soils, probably due to the relatively low K rate applied during the experiment.

Clearly, there is a wide difference between nutrients in terms of their susceptibility to leaching. Nutrient losses may be large, particularly where organic matter status of the soil is low, in coarse-textured soils, and in areas with high rainfall.

To summarize, measures to minimize nutrient losses due to leaching include the following:

- Implement balanced nutrition (nutrients supplied according to crop demand).
- Split large application rates into a number of smaller doses (particularly for N, K, and Mg).
- Spread fertilizers evenly to maximize contact with the root system.
- Avoid fertilizer application during periods of heavy rainfall (by using statistical techniques or expert systems to predict the occurrence of dry periods).
- Apply empty bunches and cut fronds to increase soil organic status and cation exchange capacity.
- Increase the soil pH through liming to increase soil cation exchange capacity in variable charge soils.

NITROGEN VOLATILIZATION

Nitrogen is lost to the atmosphere by volatilization when moisture (from the soil or air) is just sufficient to dissolve urea applied to the soil surface but insufficient to wash urea and its decomposition product (ammonium bicarbonate) into the soil. Losses occur because the ammonium bicarbonate is hydrolyzed to ammonium hydroxide and carbon dioxide.

$$CO(NH_2)_2 + 2H^+ + 2H_2O \xrightarrow{\text{(urease)}} 2NH_3 + 2H^+ + H_2CO_3$$

This process causes an increase in soil pH in the vicinity of the applied urea that favors rapid liberation of ammonia gas into the atmosphere (volatilization). A simple procedure to assess the likely occurrence of volatilization losses from urea was proposed by Ng *et al*. (1983) based on factors that affect the rate of urea volatilization (Table 6). For example, high clay and silt content tends to increase the

Table 6. Parameters for assessing the potential for N losses by volatilization from surface-applied urea (Ng et al., 1983).

Probability of NH_3-N losses	Clay + silt content	Soil moisture	Soil surface structure	Weeded circle radius	Shade	Days between fertilizer application and rainfall
	%	% WHC		cm		
High	<35	<45	Hard	160	Open	>4
Moderate	35 - 65	45 - 65	Firm to friable	160 - 200	Shaded	3 - 4
Low	>65	65 - 85	Friable	200 - 240	Well-shaded	1 - 2

WHC = water-holding capacity

fixation of NH_4-N to the soil complex, which reduces the amount of volatilization. Similarly, urea applied on moist soils will dissolve and percolate into the soil resulting in smaller volatilization losses. Conditions that promote the rapid downward movement of urea or its decomposition products into the soils will reduce volatilization losses.

Ammonium sulfate (AS) is a more suitable N source in sites wher the probability of NH_3-N losses from urea is great.

In addition to these factors, high soil pH, temperature, and wind speed increases volatilization losses. Urea should be stored carefully since volatilization losses also increase when compacted lumps (formed in bags stored under damp conditions) are applied to the soil.

In experiments carried out on N-deficient coastal clay soils in Malaysia, Zakaria *et al*. (1989) showed that the average relative efficiency of urea was 80–85% of ammonium sulfate. Yield response was greater with urea in three of 12 experiments but under adverse conditions, more than 70% of the N contained in urea was lost within one week of application.

Provided the conditions for low probability of NH_3 losses are met (Table 6), however, volatilization losses are tolerably small and urea can be considered a highly concentrated and economic N source for oil palm. Volatilization losses can also be reduced by applying a mixture of urea soluble Ca or Mg sources, e.g. kieserite (1:0.1 to 1:0.5 N:Mg) (Fenn *et al*., 1981; von Rheinbaben, 1987).

To summarize, measures to minimize nutrient losses due to volatilization include the following:

- Apply N (urea) only during months when moderate rainfall immediately following application is assured (i.e. months with between 150–250 mm rainfall).
- Cover the N fertilizer with soil after application.
- Split larger N fertilizer requirements into a number of small doses.
- Use S-coated urea.
- Use urea/kieserite mixtures.

NUTRIENT FIXATION

Nutrients are said to be 'fixed' when they are converted from a form readily-available for plant uptake into a form unavailable or very slowly-available for uptake due to reactions with soil particles.

Both K and N are affected by 'fixation', which occurs on coastal clay soils containing lattice layer clays (e.g. montmorillonite, illite). Phosphorus fixation occurs mainly on highly weathered 'upland' or 'inland' soils containing large concentrations of Fe and Al oxides (termed sesquioxides) that form insoluble complexes with applied P. Soluble P fertilizers (e.g. triple superphosphate (TSP), diammonium phosphate (DAP), watersoluble P in NPK compounds) are particularly susceptible to fixation when applied to acid upland and inland soils. Reactive phosphate rock is a more suitable P fertilizer source for use on upland and inland soils, but not on the slightly acid-neutral soils where there is insufficient acidity for P dissolution. In acid soils, reactions between the soil and the phosphate rock result in a continuous release of P for plant uptake.

A large application of phosphate rock may be required to saturate part of the soil's P-fixation capacity such that sufficient P is available for plant uptake. In a pot experiment with four soil types (i.e. two Ultisols and two Oxisols) in Malaysia 80–98% of the P applied was not available for plant uptake due to fixation when 250–500 mg P kg^{-1} soil was applied (Zaharah, 1979). At larger application rates, however, a larger proportion of P applied is available for plant uptake (Figure 2). This has been confirmed in field experiments with mature palms where P uptake increased by >300% when the P fertilizer application rate was doubled, compared with the control (Goh and Chew, 1995).

In experiments carried out in Malaysia, the response to rock phosphate was small in coastal clay soils (where soil pH was higher) compared with acid, P-fixing inland soils (Zakaria *et al*., 1991) (Figure 3). The lower yield responses to P in coastal soils can be

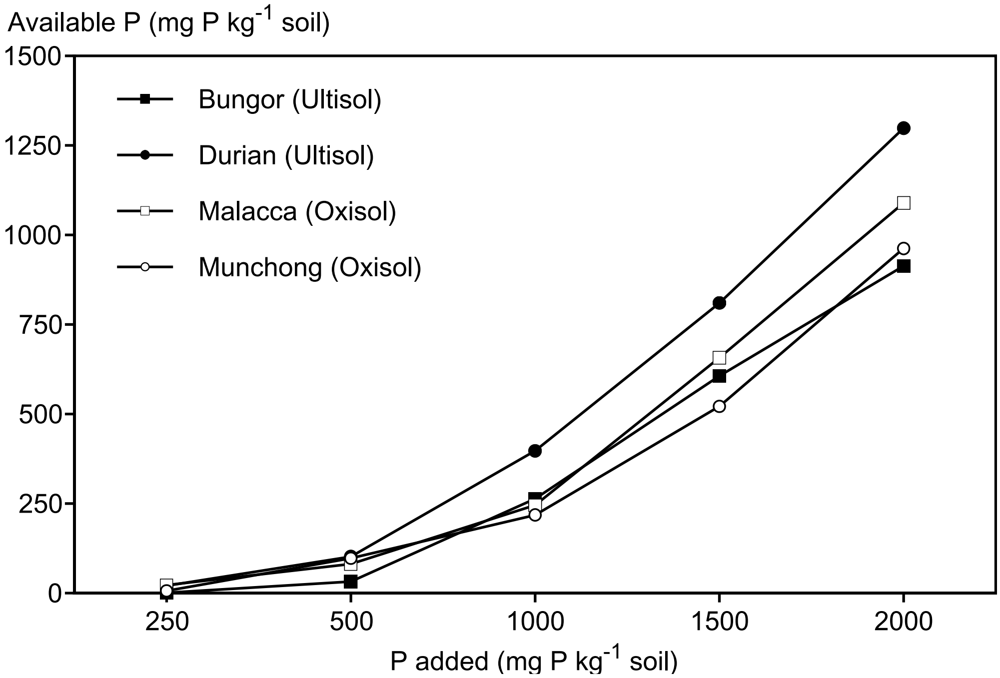


Figure 2. Amounts of P adsorbed by soils at different levels of P added (Zaharah, 1979).

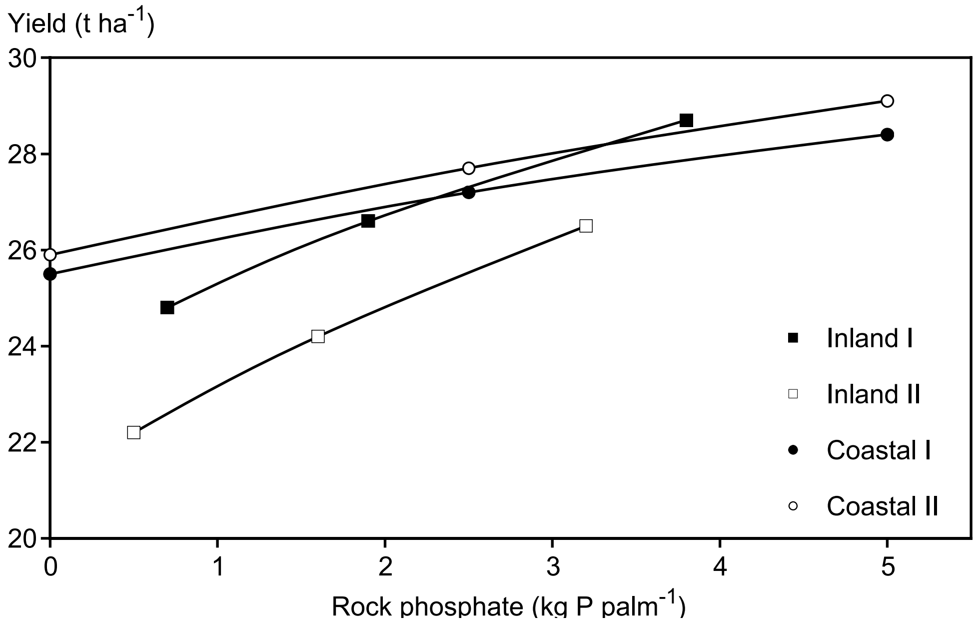


Figure 3. Effect of rock phosphate on bunch yield on inland and coastal soils in Malaysia over two periods (Zakaria et al., 1991). [I and II refer to Period I (first 4 years of P treatment) and Period II (next 4 years of P treatment) respectively.]

partially attributed to less P-fixation and hydromorphic effects (which reduce Fe^{3+}-P to more plant availabel Fe^{2+}-P). Yield responses to P in both the coastal and inland soils were similar in Period I (first 4 years of P treatments) and Period II (next 4 years of P treatments). In Period II in the inland soils, however, the absolute yields were lower, probably due to palm etiolation caused by the relatively high density of 148–161 palms ha^{-1}.

To summarize, measures to minimize P-fixation include the following:

- Minimize contact of water-soluble P-fertilizer with soil (P should be applied in bands, over frond stacks, or to the outer rim of the weeded circle).
- Apply empty bunches as a soil mulch.
- Establish LCP to increase P-cycling.
- Apply lime to very acid soils (pH<4).
- Apply large amounts of reactive phosphate rock to replenish soil P stocks in degraded soils.

MAXIMIZING FERTILIZER USE EFFICIENCY

I Assessment of nutrient use efficiency

Three basic questions must be answered in all assessments of fertilizer use efficiency:

- How much of the nutrients applied are taken up by the crop?
- How much *additional* yield is obtained for each *additional* unit of nutrient uptake?
- To what extent can the crop benefit from the nutrients not recovered by the crop during the period of assessment?

There are five indices that can be used to assess nutrient use efficiency.

Partial factor productivity (*PFP*)

PFP answers the question: How much yield is produced for each kg of fertilizer nutrient (FN) applied?

PFP_{FN} = kg bunch kg^{-1} fertilizer nutrient (*FN*) applied:

$$PFP_{FN} = BY_{+FN} \;/\; FN \qquad (1)$$

where BY_{+FN} is the bunch yield (kg ha^{-1}) and *FN* is the amount of fertilizer nutrient applied (kg ha^{-1}).

Because *BY* at a given level of *FN* represents the sum of yield without fertilizer inputs ($BY_{0\,FN}$) plus the increase in yield from applied fertilizer (ΔBY_{+FN}),

$$PFP_{FN} = (BY_{0\,FN} + \Delta BY_{+FN}) \;/\; FN \qquad (2)$$

or

$$PFP_{FN} = (BY_{0\,FN} \;/\; FN) + (\Delta BY_{+FN} \;/\; FN) \qquad (3)$$

and by substitution with equation (5):

$$PFP_{FN} = (BY_{0\,FN} \;/\; FN) + AE_{FN} \qquad (4)$$

where AE_{+FN} is the agronomic efficiency of applied fertilizer nutrients (see below).

Equation 4 shows that PFP_{FN} can be increased by increasing the uptake and use of indigenous soil-N resources (measured as $BY_{0\,FN}$) and increasing the efficiency of applied fertilizer nutrient use (AE_{FN}).

Agronomic efficiency (*AE*)

AE answers the question: How much additional yield is produced for each kg of fertilizer nutrient (FN) applied?

AE_{FN} = kg bunch yield increase kg^{-1} *FN* applied (often-used synonym: nutrient use efficiency):

$$AE_{FN} = (BY_{+FN} - BY_{0\,FN}) \;/\; FN \qquad (5)$$

where BY_{+FN} is the bunch yield in a treatment with fertilizer nutrient application; $BY_{0\,FN}$ is the bunch yield in a treatment without fertilizer nutrient (*FN*) application; and *FN* is the amount of fertilizer nutrient applied, all in kg ha^{-1}.

AE_{FN} represents the product of the efficiency of nutrient recovery from applied nutrient sources (= recovery efficiency, RE_{FN}) and the efficiency with which the plant uses each unit of nutrient acquired (= physiological efficiency, PE_{FN}):

$$AE_{FN} = PE_{FN} \times RE_{FN} \qquad (6)$$

Both RE_{FN} and PE_{FN} thus contribute to AE_{FN}, and each can be improved by crop and soil management practices, including general crop management practices and those specific to nutrient management, e.g. a more balanced N:P:K ratio or improved splitting and timing of nutrient applications (see Table 8 and 9).

Because $AE_{FN} = PE_{FN} \times RE_{FN}$, it is necessary to quantify the relative contribution of each component to explain measured differences in agronomic efficiency that result from different nutrient or crop management strategies.

Recovery efficiency (*RE*)

RE answers the question: How much of the nutrient applied was recovered and taken up by the crop?

RE_{FN} = kg fertilizer nutrient taken up kg^{-1} fertilizer nutrient applied:

$$RE_{FN} = (UN_{+FN} - UN_{0\,FN}) / FN \quad (7)$$

where UN_{+FN} is the total palm uptake of fertilizer nutrient measured in aboveground biomass in plots that receive applied fertilizer nutrient at the rate of *FN* (kg ha^{-1}); and $UN_{0\,FN}$ is the total nutrient uptake without the addition of fertilizer nutrient .

RE_{FN} is obtained by the 'nutrient difference' method based on measured differences in plant nutrient uptake in treatment plots with and without applied nutrient (Equation 7). Recovery efficiency of applied nutrient is estimated more accurately when two treatments with a *small* difference in the application rate are compared:

$$RE_{FN} = (UN_{FN2} - UN_{FN1}) / (FN_{FN2} - FN_{FN1}) \quad (8)$$

where RE_{FN} is the recovery efficiency (kg nutrient uptake kg^{-1} nutrient applied); *UN* is the total nutrient uptake in bunches, fronds and trunk (kg ha^{-1}); and *FN* is the amount of fertilizer nutrient added (kg ha^{-1}) in two different nutrient treatments (*FN2* and *FN1*) e.g. *FN2* receiving a larger nutrient rate than *FN1*.

RE_{FN} is affected by agronomic practises and rainfall (Table 8)

Physiological efficiency (*PE*)

PE answers the question: How much additional yield do I produce for each additional kg of nutrient uptake?

PE_{FN} = kg bunch yield increase kg^{-1} fertilizer *FN* taken up:

$$PE_{FN} = (BY_{+FN} - BY_{0\,FN}) / (UN_{+FN} - UN_{0\,FN}) \quad (9)$$

where BY_{+FN} is the bunch yield in a treatment with fertilizer nutrient (*FN*) application (kg ha^{-1}); $BY_{0\,FN}$ is the bunch yield in a treatment without fertilizer nutrient (*FN*) application; and *UN* is the total uptake of fertilizer nutrient (kg ha^{-1}) in the two treatments.

PE_{FN} represents the ability of a plant to transform a given amount of acquired fertilizer nutrient into economic yield (oil or bunches) and largely depends on genotypic characteristics such as the bunch index and internal nutrient use efficiency, which is also affected by general crop and nutrient management (Table 8).

Internal efficiency (*IE*)

IE answers the question: How much yield is produced per kg fertilizer nutrient (FN) taken up from both fertilizer and indigenous (soil) nutrient sources?

IE_{FN} = kg bunch kg^{-1} *FN* taken up:

$$IE_{FN} = BY / UN \quad (10)$$

where *BY* is the bunch yield (kg ha^{-1}), and *UN* is the total uptake of fertilizer nutrient (kg ha^{-1}).

This definition of IE_{FN} includes *FN* taken up from indigenous and fertilizer sources. IE_{FN} largely depends on genotype, harvest index, interactions with other nutrients and other factors that affect flowering and bunch formation.

II Implementation of nutrient use efficiency assessment in oil palm fertilizer experiments

In annual crops, destructive sampling methods can be used to measure nutrient uptake in fertilized and unfertilized plots in each crop season and fertilizer nutrient use efficiency can then be calculated by difference (Dobermann and Fairhurst, 2002). The relative ease with which this can be carried out explains why in grain crops, measurement of nutrient use efficiency is standard practice when analyzing data from field fertilizer experiments. Destructive sampling cannot be used in oil palm fertilizer experiments, however, because it is costly and precludes the possibility of further measurements in the experiment. For this reason, Fairhurst (1996) and Fairhurst (1999) devised a non-destructive approach to measure nutrient uptake, based on standard methods for estimating above ground biomass production in trunk, leaf, bunches (Corley *et al*., 1971, Appendix 6) combined with tissue analysis. Nutrient uptake is calculated from the nutrient concentration and the amount of biomass produced (kg ha^{-1} yr^{-1}) respectively in the trunk, leaves, and bunches, and nutrient use efficiency is measured by comparing nutrient uptake in different treatments in fertilizer experiments.

Differences in nutrient use efficiency between plantations, blocks, single palms or fertilizer sources are explained by a range of factors (Table 8). The goal of a good field management is to maximize uptake by identifying possible limiting factors and implementing remidial measures.

These methods were used to assess nutrient use efficiency in six fertilizer trials at Bah Lias Research Station (BLRS) (Prabowo *et al*., 2002). Preliminary results from one year of measurements indicate recovery efficiencies of 19–36% (N), 7–29% (P), 29–70% (K) and 10–60% (Mg) (Table 7). Large differences in RE were measured for different fertilizer sources of P and Mg fertilizer and *RE* was much greater when these nutrients were supplied in soluble forms respectively as TSP and kieserite (Table 7).

In almost all cases, *RE* was greater for each nutrient when other nutrients were supplied in non-limiting amounts. *RE* was smaller in Trial 231 where high rainfall resulted in large fertilizer nutrient losses in surface water runoff and eroded soil (Prabowo *et al*., 2002). In Trial 231 *RE* was >100% for K where yield was less than 23 t ha^{-1}. This suggests that palms were able to use soil indigenous K more efficiently after K deficiency had been corrected.

The separation of *AE* into its components of *RE* and *PE* provides the means to identify problems in fertilizer response experiments. For example it may be possible to achieve large values for *RE* but low values for *PE* result in low values for *AE*. Field management factors can be separated into those affecting *RE* and *PE* (Table 8). For example, *RE* may be large in a fertilizer treatment but a low value for *PE* is caused by inter palm competition and the genetic characteristics of the planting material.

SOURCE OF FERTILIZER

A wide range of fertilizer products is available on the market. The choice of fertilizer depends on the following factors:

- Nutrients required.
- Availability of fertilizers.
- Physical and chemical properties (nutrient concentration, availability) of fertilizers.
- Cost ($ kg^{-1} N, P, K, Mg, B, and Cu).
- Soil characteristics (pH, clay content and type, texture).
- Terrain (e.g. flat, sloping, hilly).
- Palm age and condition.
- Climate.
- Availability of labor.

In general, the water soluble fertilizers are used for immature palms, correction of nutrient deficiencies, and aerial application. Water insoluble fertilizers (e.g. dolomite, rock phosphate) are used on acid soils to provide a sustained slow release of nutrients, to counter the acidifying effect of urea and SOA, and to build up soil fertility. The common fertilizers used in oil palm are listed by Goh and Härdter (this volume) and a comprehensive account is given by Chew *et al*. (1994).

Table 7. Recovery of nutrients from mineral fertilizers in five fertilizer experiments in North Sumatra, Indonesia (after Prabowo et al., 2002).

Fertilizer increment	Fertilizer nutrient recovery efficiency (%)				
	Trial 231	Trial 232	Trial 275	Trial 277	Trial 1403*
N_1-N_0	24.0	18.8	36.0	23.7	26.7
P_1-P_0	20.8	16.2	29.0	25.6	7.2
K_1-K_0	69.5	57.9	48.0	38.1	37.6
Mg_1-Mg_0	60.0	21.9	20.0	9.7	6.7

* *RP and dolomite used instead of TSP and kieserite.*

Table 8. Examples of factors affecting and physiological efficiency (PE) and recovery efficiency (RE) of fertilizer nutrients in oil palm.

Factor	Cause of poor efficiency	Remedial measures
Physiological efficiency		
Planting material	Poor quality planting material.	Use certified seed. Proper nursery culling.
Density	Inter-palm competition on response to applied nutrients.	Fit density to soil type and climatic conditions. Thin over-crowded palms.
Pruning	Over- and under-pruning.	Retain two subtending fronds (≤ 8 years after planting) and one subtending frond thereafter.
Harvesting	Incomplete recovery of fruit bunches and loose fruit.	Improve harvesting (mechanization, supervision and in-field access).
Nutrient interactions	Reduced response to one nutrient due to deficiency of another.	Balanced fertilizer use.
Drought	Impaired stomata function due to K deficiency.	Apply K fertilizer.
	Poor nutrient uptake.	Apply empty fruit bunches; irrigate.
Pests	Canopy damage caused by nettle caterpillars and bag worms.	Pre-emptive control measures (regular patrols, prompt follow-up).
Recovery efficiency		
Reduced uptake	Uneven fertilizer spreading.	Introduce mechanized spreading.
	Untimely application.	Prompt fertilizer application.
	Uneven distribution of fertilizer nutrients between palms.	Use calibrated cups for manual fertilizer application.
	Loss of NH_4-N fertilizer due to volatilization.	Do not apply ammonia-N fertilizer during very hot or wet weather.
	N deficiency induced by anaerobic soil conditions.	Install field drains, check drain outlets.
Rainfall	Fertilizer nutrients lost in surface runoff.	Install trenches to catch runoff.
Erosion	Loss of fertilizer nutrients contained in eroded soil.	Install soil erosion control measures (platforms, terraces).
Compaction	Impaired root development across palm interrows.	Use low ground pressure vehicles for in-field mechanization.
Nutrient source	Poor quality fertilizers.	Routine analysis of fertilizers, change fertilizer material type.
	Poor recovery of nutrients from un-reactive rock phosphate.	Use reactive rock phosphates.

FERTILIZER QUALITY AND COST

Generic fertilizer products (e.g. urea, SOA, TSP, potassium chloride, kieserite) should conform to statutory quality parameters stated in fertilizer tender documents and contracts.

For example, in Malaysia it has become a common practice for the buyer and seller to refer to the SIRIM (Standard and Industrial Research Institute of Malaysia) standards as guidelines, and specifications for fertilizer quality and testing methods. In general, the quality of fertilizers should meet the following specifications (Razman *et al*., 1999):

- Nutrient content and concentration.
- Nutrient chemical composition.
- Moisture content.
- Particle size.
- Physical condition (e.g. free flowing).
- Solubility and/or availability.
- Packaging details.

At least one sample from each fertilizer consignment should be sent to a reputable laboratory for analysis to confirm that it conforms to specifications (Appendix 8). Equally important is the quality of fertilizer bags, which should be waterproof, and manufactured from woven polypropylene with a polyethylene inner liner (Razman *et al*., 1999). Fertilizers should be stacked properly in a dry storage area and used promptly because fertilizers become caked after long periods in storage and space must be available for the next fertilizer consignment.

When comparing the cost of fertilizers, consider the following:

- Cost per kg nutrient, not cost per bag.
- Transport costs to destination.
- Quality of fertilizer (e.g. additional costs incurred to break up caked fertilizer).
- Availability of nutrients (e.g. phosphate rock and dolomite are only available for uptake after reaction in the soil).
- Application costs (e.g. application cost for kieserite is less coslty than dolomite on per kg nutrient basis).
- Number of application rounds required (fertilizers with a large nutrient content [e.g. urea] or containing more than one nutrient [e.g. DAP] will reduce the number of applications requried).

Thus, some seemingly expensive fertilizer may be less costly when all the factors are considered.

APPLICATION METHODS

Once the amount required and source of each fertilizer nutrient has been determined (Foster, this volume), a strategy for the placement, and frequency and timing of application must be considered.

I Strategies for the placement of fertilizer

It is axiomatic that fertilizers should be placed where they can most readily be absorbed by feeding roots of the crop. The proportion of the soil volume exploited by the oil palm increases with palm age (Ng *et al*., 1968; Ruer, 1967) but the rate of expansion depended on soil type (Tan, 1976). Palms absorbed labeled 32P applied over 30 m from the point of application, even when the palms were separated by a 65 cm deep trench (Zaharah *et al*., 1989). Physical disturbance of the soil in the path inter-row due to mechanized fruit collection also affected root growth in this zone (Mokhtaruddin *et al*., 1992) and the quantity of roots was increased by more than 20% following sub-soiling of compacted palm inter-rows (Caliman *et al*., 1990b).

Based on cursory investigations in the field, it is sometimes asserted that there are generally more active feeder roots in the soil beneath the frond stack compared with soil from beneath the weeded circle. In a detailed study in West Sumatra on palms 10 YAP, however, no difference was found in feeder root length density between these two zones but root length density was smaller in soil beneath the harvesting path, where the soil was more compacted than the other two zones due to frequent wheelbarrow traffic (Fairhurst, 1996) (Figure 4). In the soil beneath the area where fertilizer had been applied, root length density was greater, suggesting that roots proliferate where the concentration of nutrients is greatest (Figure 5). Other workers reported the positive

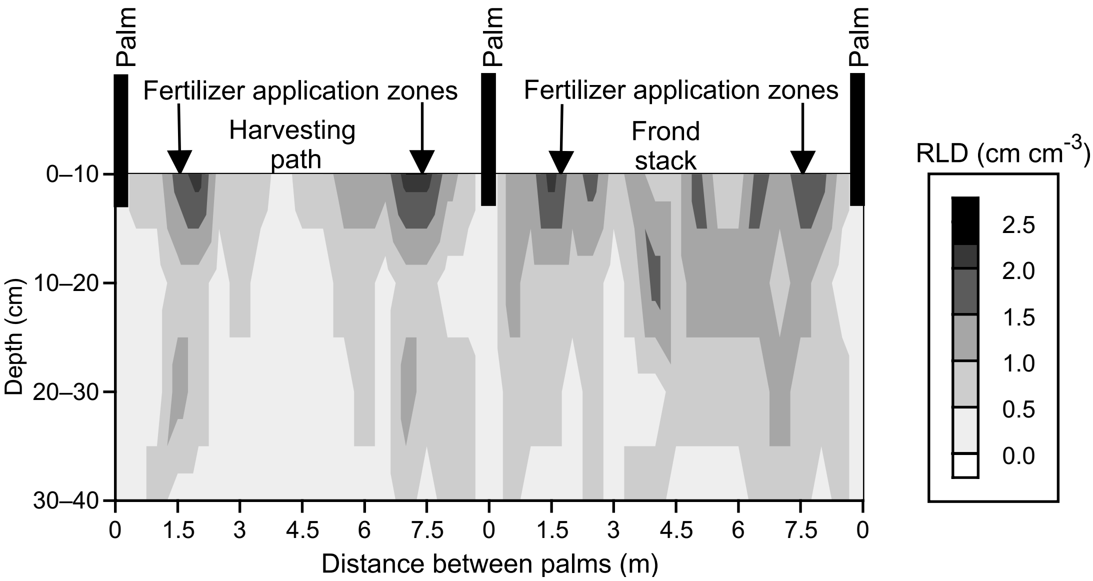


Figure 4. Contour map showing root length density (RLD) in a transect between three palms across the harvest path and frond stack interrows in a field of palms in West Sumatra 10 years after field planting (Fairhurst, 1996).

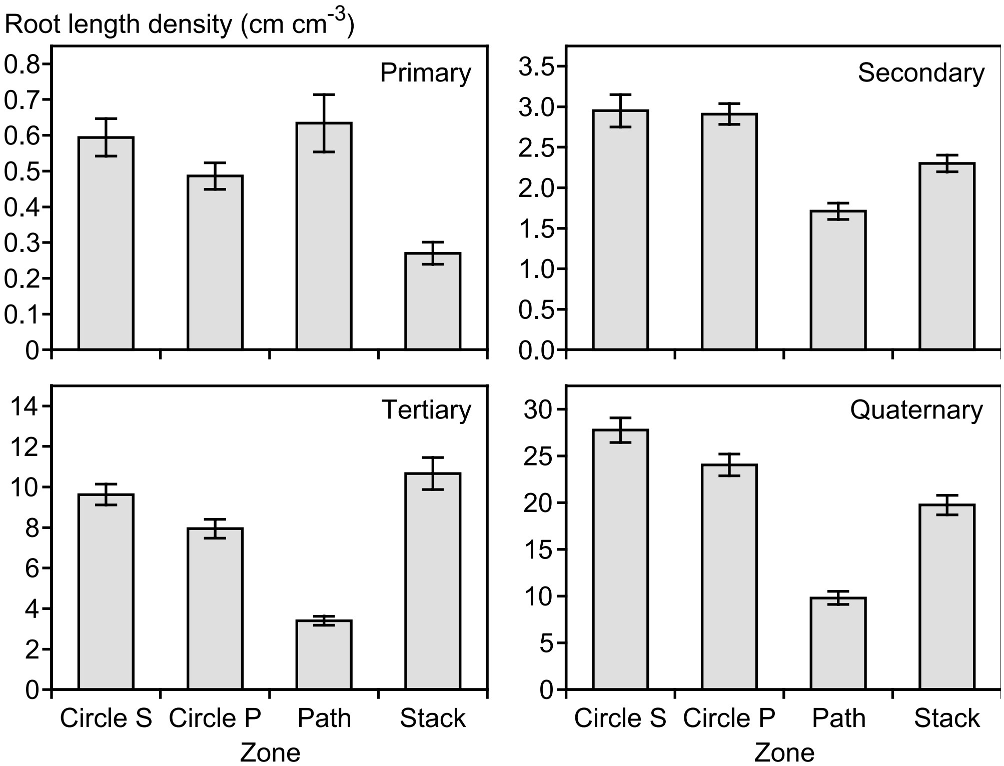


Figure 5. Root length density of primary, secondary, tertiary and quaternary roots in the circle facing the front stack (Circle S) and harvest path (Circle P), and frond stack in a field of palms in West Sumatra 10 years after field planting (Fairhurst, 1996). [Bars represent standard error of the means, n=7)

tropism of oil palm roots towards areas with better water and nutrient supply, with a greater concentration of roots in soil beneath the frond stack in the palm inter line (Bachy, 1964; Tailliez, 1971), and at the edge of palm circles where there had been an accumulation of organic debris (Purvis, 1956). The quantity of roots in soil beneath the harvesting path was reported to be small (Hartley, 1977).

Fertilizer application rates may be very large, particularly when the rate is calculated based on the area of soil over which the fertilizer is applied. Palm circles occupy only 20% of the soil surface area under oil palm and thus, for example, 1.5 kg palm^{-1} urea applied over the weeded circle is equivalent to an application of 1,000 kg ha^{-1}.

From an agronomic point of view the application of fertilizers over the weeded circle would, at first, appear to be unsatisfactory because

- the root system in mature palms extends far beyond the boundary of the weeded circle (Ng, *et al*., on botany, this volume),
- the soil beneath the circle may have insufficient cation exchange capacity to store the large amount K and Mg applied but not immediately taken up by the palm, resulting in increased leaching losses,
- the application of large amounts of a particular cation (e.g. K) may result in the displacement and leaching of another cation (e.g. Ca), and
- the application of large quantities of urea and sulfate of ammonia may cause soil acidification (and a consequent reduction in cation exchange capacity in variable charge soils).

Some arguments can be made in favor of fertilizer placement over the frond stack:

- Soil P fixation is reduced due to the effect of organic residues on soil properties.
- There may be a greater proportion of fine feeder roots (tertiary and quaternary roots) in soil beneath the frond stack.
- Surface wash of fertilizers may be reduced by the protective layer of pruned fronds lying on the soil surface.

The infiltration rate in soil beneath the frond stack is more rapid, however, and this may result in greater losses of K and Mg fertilizers due to leaching. Since the water infiltration rate in the soil in the weeded circle is often reduced due to compaction, however, fertilizers applied over the weeded circle may be washed out and distributed over the surrounding area. Clearly, the selection of a suitable placement strategy must take into account the nature of the fertilizer material, the particular nutrient applied and the age of the palms.

There are three reasons why there was, in the past, a tendency to apply fertilizers over the circle:

- First, some of the N supplied in fertilizers applied over the inter-row will be taken up by ground cover vegetation and lost when slashed ground vegetation decomposes on the soil surface,
- Second, N volatilization losses are greater when urea is applied over decomposing organic debris where urease activity is greater, and
- Third, it is much easier for the manager to verify that fertilizers have actually been applied and spread properly when they are applied over the weeded circle.

We will now review some past experiments that investigated the effect of fertilizer placement on nutrient use efficiency. Fertilizer placement studies have generally produced inconclusive results despite large yield responses to fertilizer in a number of experiments (Table 9). In fertilizer experiments carried out in Malaysia, yield was larger when P was applied in the harvest path avenue compared to the frond stack and circle, and when K was applied in the frond stack compared to the circle (Foster and Dolmat, 1986). In contrast, Teoh and Chew (1985) and Yeow *et al*., (1982) found no difference in yield between different placement strategies. Of particular interest is the increased response to fertilizer in experiments carried out in Malaysia when palm fronds were broadcast over the inter-rows compared to the placement of fronds in alternate palm rows, and when fertilizer was applied together with an application of 3.5 t ha^{-1} empty bunches (Chan *et al*., 1993). To summarize, fertilizer

Table 9. Effect of fertilizer placement on bunch yield in Malaysia.

Nutrient	Soil series	Soil taxonomy	Control	Weeded circle		Alternate avenues	Frond stack
				Within	Outside		
					t ha^{-1}		
N	Briah[1]	Tropaquent	15.3	23.1	24.3	-	-
	Rengam[2]	Paleudult	-	22.5	21.7	-	21.6
	Durian[3]	Tropudult	24.0	29.5	29.7	-	-
P	Rengam[2]	Paleudult	-	21.2	22.6	-	21.4
K	Rengam[2]	Paleudult		21.4	21.7	-	22.7
	Durian[3]	Tropudult	27.4	27.7	28.1	-	-
	Prang[3]	Acroorthox	36.2	37.2	37.1	-	-
	Seremban[4]	Tropudult	26.6	27.2	27.7	-	-
NK	Munchong[5]	Hapludox	21.2	25.9	24.7	-	-
	Serdang[5]	Paleudult	15.1	19.9	19.6	-	-
NPK	Selangor[1]	Tropaquept	29.2	-	32.0	32.1	-
	Selangor[1]	Tropaquept	-	31.1	-	31.6	-
	Carey[1]	Tropaquept	-	29.6	-	29.9	-

[1]Yeow et al. (1981); [2]Foster and Tayeb (1986); [3]Chan et al. (1994); [4]Chan et al. (1993).

application over clean weeded palm circles, over the outside edge of the weeded circle, or over the frond stack gave similar yield responses in mature oil palms planted on coastal soils, NPK fertilizer could be applied in alternate avenues in the oil palm plantations without reducing efficiency.

Foster and Tayeb (1986) measured the effect of different fertilizer placement strategies on yield of palms 7–9 and 10–11 YAP (Figure 6). Very similar results were obtained for both age groups:

- With one application of N per year, yield was greater when N fertilizer was applied over the weeded circle, but when N was supplied in three applications, there was no difference between the placement strategies.
- Phosphorus was most effective when broadcast over the avenue, while K was most effective when broadcast over frond stack (Figure 6).

Goh *et al*. (1996) measured K uptake indirectly in an experiment with palms 16 YAP on a Rengam Series soil (Typic Paleudult). Two 1-m^2 plots were marked within each microsite, i.e. palm circle, interrow, frond stack and harvest path. At each micro site, one plot was isolated by a trench (0.3 m wide x 0.9 m deep) and K uptake was estimated from total K contents in the 1-m^2 plots by difference. The plots were allowed to settle for a year before K fertilizer treatment (500 kg K ha^{-1}) was applied. In the fertilized plots, K uptake was greatest in the palm circle, followed by the inter-row, frond stack and harvest path, where uptake was probably affected by soil compaction (Table 10). In unfertilized plots, K uptake was greatest in the palm circle where the concentration of exchangeable K (0.22 cmol kg^{-1}) was the smallest of the areas sampled.

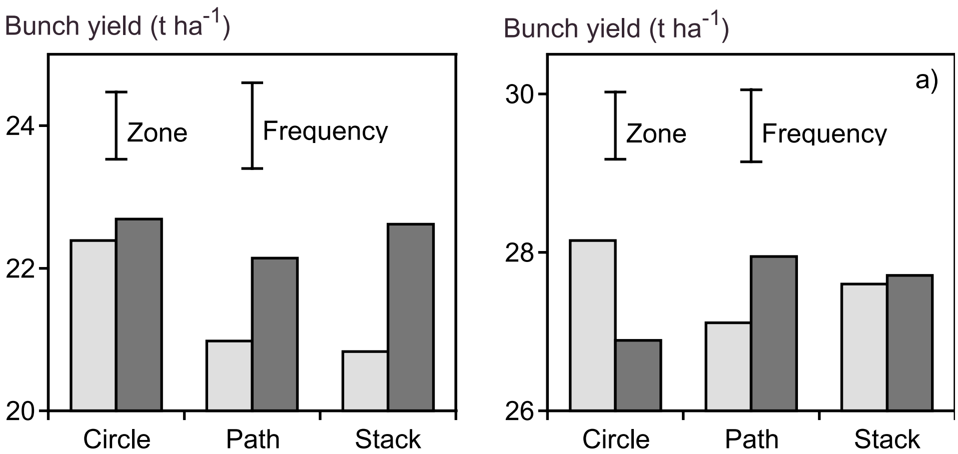
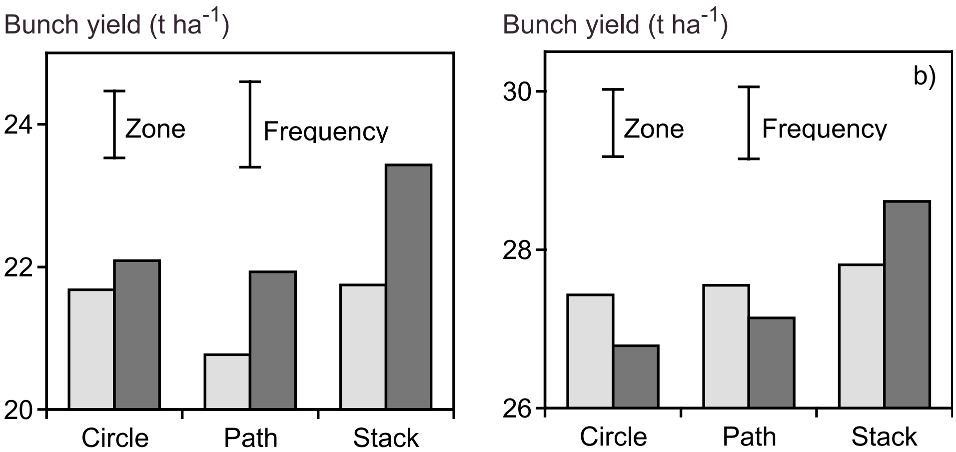


Figure 6a. Effects of different fertilizer N placement strategies on bunch yield in oil palm at 7–9 and 10–11 years after field planting (Foster and Tayeb, 1986).



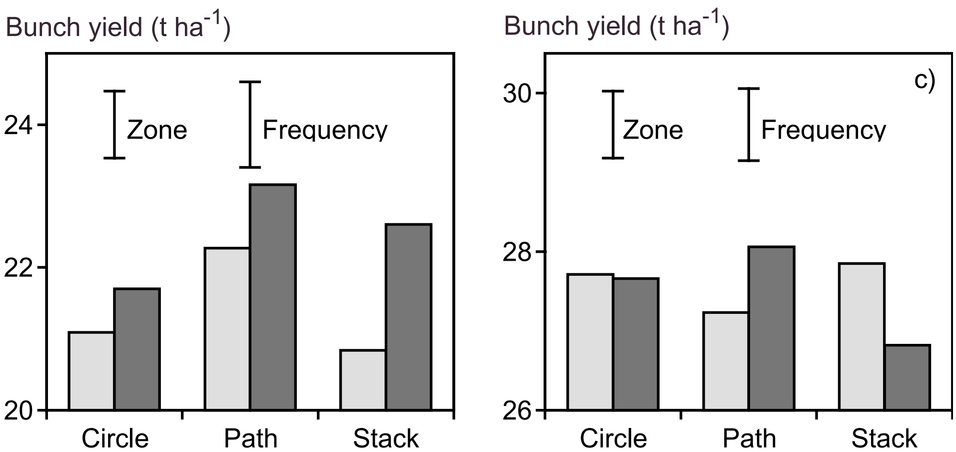


Figure 6c. Effects of different fertilizer K placement strategies on bunch yield in oil palm at 7–9 and 10–11 years after field planting (Foster and Tayeb, 1986).

Table 10. Effect of frequency of fertilizer application on oil palm yield in Malaysia.

Nutrient	Soil series	Soil taxonomy	Frequency of application						
			F_0	F_1	F_2	F_3	F_4	F_5	F_6
			Yield (t FFB ha^{-1})						
N	Rengam[1]	Paleudult	22.0	-	-	24.5	-	25.0	-
K	Rengam[1]	Paleudult	22.0	-	-	23.9	-	24.5	-
	Seremban[2]	Tropudult	26.6	-	-	-	-	27.3	27.6
	Durian[3]	Tropudult	27.4	-	-	-	-	27.8	28.0
	Prang[3]	Acrorthox	36.2	-	-	-	37.5	37.5	36.8
P	Rengam[1]	Paleudult	22.0	-	-	24.5	-	25.0	-
	Jerengau[4]	Hapludult	10.4	-	13.3	14.9	-	-	-
	Holyrood[5]	Hapludult	-	18.6	20.5	21.2	-	-	-
NK	Munchong[6]	Hapludult	13.5	-	18.7	19.6	18.4	-	-

F_0 = no fertilizer; F_1 = 1 round in 4 years; F_2 = 1 round in 2 years; F_3 = 1 round yr^{-1}; F_4 = 2 rounds yr^{-1}; F_5 = 3 rounds yr^{-1}; F_6 = 6 rounds yr^{-1}.

[1]Foster and Tayeb (1986); [2]Chan et al. (1993); [3]Chan et al. (1994); [4]Chan (1982); [5]Foong and Sofi (1995); [6]Teoh and Chew (1985).

In addition to nutrients supplied in fertilizer, small quantities of nutrients may be added in rainfall. Annual rainfall of 2,000 mm in Malaysia contained about 5 kg K ha^{-1} yr^{-1} but a substantial amount of K was leached from the canopy resulting in the addition of 36 kg ha^{-1} yr^{-1} to the soil in through-fall (Goh *et al*., 1994).

One reason for the inconclusive results in past investigations on the effect of fertilizer placement is that gradients in root distribution may already have been established at the start of each experiment. Thus, when treatments to compare broadcast fertilizer with application in weeded circles are installed in a field of palms where root gradients are already pronounced, nutrient uptake is likely to be less efficient in areas of the field that have not received fertilizer or pruned fronds in the past, such as the harvest path, and where root development is poor. Ideally experiments on fertilizer placement should be established in fields of young palms so that both uptake efficiency and the effect of nutrients on root development are taken into account.

Broadcasting fertilizers over the entire soil surface under mature palms has also been advocated because it results in an overall buildup of soil fertility (and probably more uniform root distribution), avoids excessive nutrient buildup (and acidification) in the palm circle, and reduces leaching losses of K and Mg in the palm circle. Clearly, fertilizer placement is not an issue in plantations that have changed to mechanical fertilizer application due a shortage of labor for manual application. Fertilizer use efficiency may increase where fertilizers are broadcast due to more even root distribution.

Fertilizer placement strategies for mature palms must take into account the characteristics of each fertilizer, oil palm root development and palm age (Table 11. Placement strategies should also be adjusted to take into account soil properties, weed management (some companies prefer bare-ground conditions or sparse vegetation favoring fertilizer application in the palm circle), and rainfall distribution.

It is recommended that bunch ash is applied around the weeded circle to palms 4–7 YAP, and outside the weeded circle in palms >7 YAP.

Table 11. Recommendations for fertilizer placement by manual application for oil palm.

Fertilizer	Palm age (years from field planting)			
	0 - 3	4 - 6	7 - 10	>10
N (urea, SOA, CAN)	Weeded circle	Weeded circle	Weeded circle	Outside circle
P (rock phosphate)	Weeded circle	Around circle	Around circle	Outside circle
K (KCl)	Weeded circle	Weeded circle	Around circle	Outside circle
Mg (kieserite)	Weeded circle	Weeded circle	Around circle	Around circle
Mg (dolomite)	-	Around circle	Outside circle	Outside circle
B (Borate)	Weeded circle	Weeded circle	Weeded circle	Weeded circle

II Frequency and timing of fertilizer application

Hew and Ng (1968) showed that uptake efficiency was increased with more frequent applications of fertilizer and designed a schedule for fertilizer application according to tree age and fertilizer source.

The frequency of fertilizer application is constrained by

- the time it takes to apply a single application of fertilizer in a management unit,
- the number of fertilizers that must be applied in a year, and
- the requirement for a period of two months without fertilizer application prior to leaf sampling.

Thus, there is potential for ten fertilizer applications in a year assuming one application can be completed within a month in a single management unit of 1,000 ha. The most suitable frequency for fertilizer application depends on:

- the nutrient's susceptibility to leaching,
- the soil's capacity for nutrient retention, and
- local patterns of rainfall distribution and intensity.

Because NO_3^- produced from the mineralization of N-fertilizer is highly susceptible to leaching, more frequent applications may be required for N fertilizers than for P fertilizers, which are comparatively immobile in the soil. Frequency of K and Mg application should be related to soil clay content and mineralogy, and the soil's cation exchange capacity.

On a sandy soil in Malaysia, the yield response to P, applied as rock phosphate was greater when applied annually compared to once in four years, but frequency of application had no effect on leaf P content (Foong and Sofi, 1995) (Table 12). Larger yields were obtained when N, P, and K were applied three times a year compared to once a year on a Rengam soil (sandy clay texture) with small cation exchange capacity (<10 cmol kg-1) (Foster and tayeb, 1986) but on Serdang (silty clay loam texture) and Munchong (clay texture) soils with a small cation exchange capacity there was no advantage from increased frequency of application of NK fertilizer, provided fertilizers were applied during periods of low rainfall (Teoh and Chew, 1985) (Table 12). Results from other fertilizer frequency experiments on mature oil palms are more equivocal (Chan *et al*., 1993; Chan *et al*., 1994) (Table 12). The general trends showed that N, K, and NK fertilizers could be applied once a year for optimum yield, while the less-soluble phosphate rock could be applied in alternate years. It should be noted, however, that these experiments used soluble fertilizers on heavy textured sandy-clay to heavy-clay soils and may not be applicable to light-textured soils.

Although humid tropical climates with annual rainfall of 2000 - 2,500 mm imply the loss of large amounts of nutrients through leaching, the large evaporative demand of oil palms suggests that leaching losses may in

Table 12. Estimated K uptake by oil palm from different soil zones on a Rengam Series (Typic Paleudult) soil in Malaysia (Goh et al., 1996).

Fertilizer placement	Estimated uptake (g K m^{-3} soil)		
	6-month period		12-month period*
	Fertilized	Unfertilized	
Palm circle	187	110	183
Harvesting path	0	10	29
Interrow	160	10	-24
Frond heap	50	-39	62

* *Uptake of K over 12 months prior to fertilizer applicaiton.*

fact be small (Chang and Chow, 1985). Nutrients lost by leaching represented between 2–5 % of the nutrient content of fertilizers applied to a clay loam soil in a lysimeter planted with oil palms and legume cover crop where annual rainfall was 1,800–3,000 mm. Losses were different for each nutrient, increasing in the order P<N=K<Mg, and the largest losses occurred during periods when monthly rainfall exceeded 200 mm (Foong, 1993). In contrast, on an acid sand soil in Nigeria where annual rainfall was 2,000 mm, 34, 18, 172, and 60 % respectively of the fertilizer N, K, Ca, and Mg were leached from the soil in an experiment in which lysimeters were installed 150 cm below the palm circle. These two experiments illustrate the larger amounts of nutrients, which may be lost through leaching on coarse textured sandy soils (probably with small cation exchange capacity) compared to clay soils.

To summarize, whilst there is no empirical proof that increasing the frequency of application always increases uptake efficiency, it is common practice to apply N and K fertilizers 2–3 times per year to reduce the risk of nutrient losses, and kieserite and rock phosphate once per year. Application frequency is usually increased in very young palms where, for practical reasons, the use of compound and mixed fertilizers (mixtures) supplemented with straight fertilizers is common. Fertilizers are spread much more evenly with mechanical application when compared with manual application and it may be possible to decrease the frequency and increase the application rate at each dose without adversely affecting uptake efficiency.

It is clear that applying very large amounts of fertilizer to any crop at one time may result in large losses due to leaching, surface runoff and erosion. The planter must therefore attempt to synchronize the supply of mineral fertilizer nutrients with palm demand. Unlike annual crops, the demand for nutrients in oil palm is continuous and in the end, the optimal frequency is a compromise between meeting nutrient demand, and supplying these nutrients without incurring excessive labor costs or organizational difficulties.

III Timing of fertilizer application

Very little has been published on the effect of the timing of fertilizer application on fertilizer use efficiency (Teoh and Chew, 1980). Runoff losses, however, can exceed 45% of rainfall during months with high rainfall (November–December). Unlike other crops, where fertilizer application must be timed according to particular phases of vegetative and generative growth, the oil palm produces bunches throughout the year and thus requires a continuous supply of nutrients. The importance of timing is thus mainly related to the use of N fertilizers that are susceptible to loss by volatilization (Thompson, 2003). It may be possible to improve the timing of N fertilizer application by taking into account rainfall patterns and distribution and for this purpose each plantation should install a rain gauge (mm $month^{-1}$) and a pluviometer (rainfall distribution during each day). To optimize recovery efficiency of N from urea, applications should always be followed by light rain and urea should never be applied to dry soil.

To summarize, fertilizer application should be avoided during months with a high probability of rainfall exceeding 250 mm month^{-1} and months with >15 rain-days. Losses of soluble P, K, and Mg fertilizers from runoff are smaller if applied in dry months (<100 mm month^{-1}) in Malaysia.

NUTRIENT BALANCE

Nutrient balance calculations are useful for determining whether there is a net removal or addition of nutrients to the soil:

- Nutrient removal is calculated from the bunch yield and nutrient content.
- Nutrient immobilization is calculated from trunk incremental growth and its nutrient content.
- Nutrient addition is calculated from the amount of fertilizer nutrients added and the amount nutrients recycled in palm oil mill effluent (POME), empty bunches, and bunch ash.

Foster (this volume) provides a detailed discussion on the use of nutrient balance to determine fertilizer requirements of oil palm.

If net nutrient removal is not balanced by the addition of mineral fertilizers, the system will not be sustainable in the long term. For example, a negative nutrient balance may not affect yield in the short term on coastal clay soils with large nutrient reserves, but a negative balance on a sandy soil with small nutrient reserves will result in a rapid reduction in yield as soil nutrient reserves are depleted.

A change in the source of one fertilizer nutrient may affect the nutrient balance of others. This was confirmed in an oil palm plantation in West Sumatra, where the nutrient balance for Ca was positive and Mg negative when dolomite was used as the Mg fertilizer. After kieserite was substituted for dolomite (to overcome acute Mg deficiency), however, the balance for Ca became negative (Figure 7) (Fairhurst, 1996).

SITE-SPECIFIC NUTRIENT MANAGEMENT TECHNIQUES

Proper fertilizer management is required not only to achieve large yields and profits, but also for the sustainability of a plantation in the long term. The fertilizer requirements on a particular plantation depends on the inter-relationship of a large number of factors that include the following:

- Nutrient supply to sustain the target biomass production and bunch yield.
- Maximum contribution from biological N2 fixation (Giller, this volume) and recycled crop residue (Redshaw, this volume).

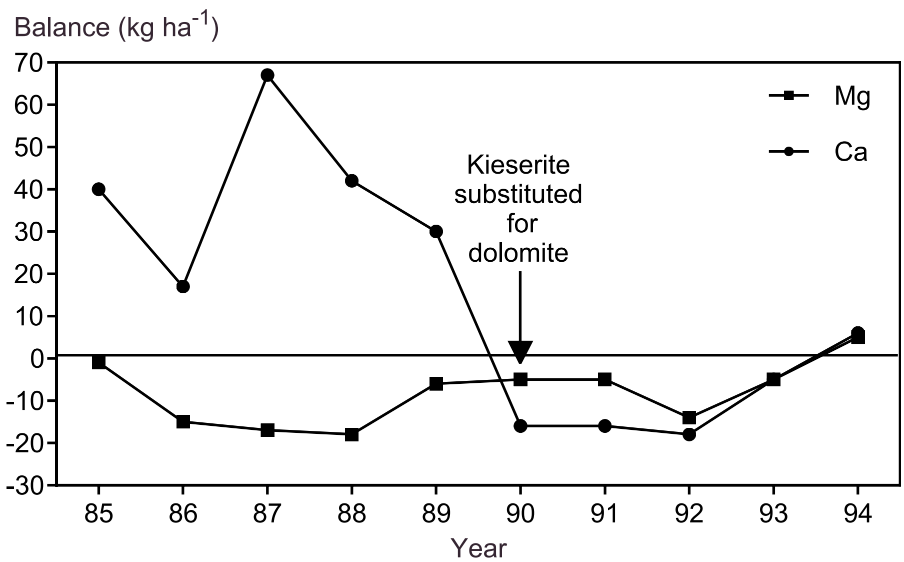


Figure 7. Effect of fertilizer source on the nutrient balance for Ca and Mg over a 10-year period in an oil palm plantation in West Sumatra (Fairhurst, 1996).

- Soil conditions, including soil chemical, physical and microbiological properties (Paramananthem, this volume).
- Climate, including rainfall intensity, frequency and total amount (Paramananthem, this volume).
- Nutrient sources, placement, frequency and timing of application.
- Management policies, such as weed control, harvesting and removal of fruit bunches (Goh and Härdter, this volume; Gillbanks, this volume).
- Field history, for monitoring changes in nutrient balances (Fairhurst, this volume).
- Soil and plant nutrient analysis (Foster, this volume).

These factors are site-specific and time-dependent, and plantations should be divided into leaf sampling units where soil, topography, and drainage conditions are comparatively uniform (Appendix 1). With the advent of field mechanization, computer and electronic tools (e.g. Geographical Information Systems [GIS], Global Positioning Systems [GPS]), and tool controls for accurate application of fertilizers, it may be possible to achieve site-specific management at a scale of 1 ha (Tey *et al*., 2000). A very important step in site-specific management is to first collate all available agronomic data for each year and planted field in a database system that allows for rapid data analysis, reporting and mapping (Fairhurst *et al*., 2000).

The following aspects that relate to site-specific nutrient management deserve special attention (Ng, 1977; von Uexküll and Fairhurst, 1991):

- Maintain a proper balance between macronutrients (e.g. between N and K).
- Consider the micronutrient needs of oil palm (e.g. B, Cu, Fe, and Zn) particularly on organic soils.
- Identify and correct nutrient deficiencies through frequent visual monitoring and plant analysis.
- Identify problem soils (e.g. acid sulfate soils, deep peat) early on during field preparations, and implement ameliorative measures promptly.
- To maximize yield potential in young palms, avoid rapid depletion of soil nutrient reserves during the immature growth phase. In most cases, it is economical to capitalize soil fertility during the immature growth period, to provide a buffer supply during periods when nutrient demand is great. This is particularly important for K as the young palms coming into production have very small K reserves in storage tissue. Potassium exhaustion must be avoided and supplies for the second to fourth years should exceed the amount of nutrients required based on calculated nutrient uptake.
- Make full use of high yield potential areas (i.e. favorable climate, no dry periods, high solar radiation) by applying fertilizer in excess of the amount calculated for uptake to allow for nutrients lost through volatilization, runoff, erosion, leaching, and fixation.
- Under intensive cropping, soils in the tropics can undergo rapid changes in fertility. It is therefore essential to continue monitoring changes in soil fertility (through regular soil and leaf analysis) and vegetative growth measurements in order to improve and maintain large yields.
- Further fine-tuning of fertilizer recommendations (based on plant analysis) is required since there is a long recovery period before yields are restored in palms that have been depleted of nutrients and carbohydrate reserves.
- Fertilizer affects yields up to four years from the time of application. Do not reduce fertilizer applications when palm oil prices are low as this may result in poor yields when prices have recovered. Omission of fertilizers is particularly harmful to young palms that may, as a result, never reach their genetic yield potential.

Important points for practical planters

1. Fertilizers are usually the largest variable cost item in oil palm production and therefore, should be used at the highest possible recovery efficiency by minimizing soil (nutrient) losses.

2. The major soil loss processes or pathways are runoff and topsoil erosion, leaching, N volatilization and nutrient fixation.

3. Apart from mitigating practices such as soil conservation terraces and stop bunds along terraces, planters should adhere to the following sound practices:
   - Select the best, cost-effective fertilizer source.
   - Apply fertilizers under suitable climatic and ground conditions.
   - Broadcast fertilizers evenly and widely into areas with maximum root length to increase root 'safety net' and reduce leaching losses.
   - Ensure that every palm receives its quota of fertilizer by good supervision.
   - Split the fertilizer application if necessary.

4. Planters should also ensure the following:
   - A dry storage area for the fertilizers.
   - Adequate storage capacity for the fertilizers.
   - Fertilizers should be delivered to the plantations just in time for application.
   - Fertilizers should not be stored for more than 3 months to avoid fertilizer caking and occupying fertilizer store.
   - Fertilizers from every consignment should be sampled and sent to a reliable laboratory for analysis to ensure that they meet an agreed standards between seller and buyer, e.g. SIRIM standards.

5. Planters should be aware of site-specific nutrient management practices including the use of a good relational database with map facility.

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