Practical use of oil palm nutrient physiological efficiency with regard to nutrient recovery and agronomic efficiencies at different Sumatran sites

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ABSTRACT: The results from seven North and South Sumatra oil palm field fertiliser trials, which were recorded from 1994-2009, were used to study nutrient uptake and efficiencies.. The different trial sites allowed effects of different soil properties and climate (rainfall) on dry matter production and yield to be investigated. Additional information was also assessed from two nursery trials to support the field trial results.

The results showed that the nutrient recovery efficiency (RE), which is defined as palm nutrient uptake per unit of given nutrient is subject to variation in site properties. However, the field and nursery trial results demonstrated that the physiological efficiency (PE), or yield increment per unit of nutrient uptake of oil palm, at a particular age and planting material, remains relatively constant over a range of environments. The increased yield per unit of given fertiliser known as agronomic efficiency (AE) is therefore solely dependent upon the RE for a specific planting material. However, a nursery fertiliser showed variation for dry matter production for the same unit of nutrient uptake. Assuming the current daily field management practices have been developed to meet optimal RE and yield then agronomists are able to assess PE of different oil palm planting materials to screen the most suitable for different environments. From a practical point of view agronomists can predict potential yield based on dry matter production which can be helpful in determining the oil palm fertiliser requirement. PE results can also be used to identify and evaluate problem fields in oil palm plantations.

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1. INTRODUCTION

In South East Asia the cost of fertiliser is usually the most expensive direct plantation cost and is typically 50-60% of the annual budget. It is therefore essential that the maximum returns are gained from this investment by optimizing the fertiliser recommendation and application methods. Fertilisers applied to oil palm fields are subject to a few pathways viz. palm uptake, retained by or loss in the system by means of volatilization, erosion or leaching. It has been observed that under non-limiting agronomic conditions in the field each individual major nutrient (N, P, K and Mg) has a different nutrient recovery percentage.

Once taken up by the palm the nutrients will be utilised to produce additional yields (PE). Previous reports indicated that plant material of annual crops (Epstein and Bloom, 2005) and age of oil palm (Prabowo *et al.,* 2009; 2010) are responsible for the variations in the internal utilization of the recovered nutrients for yield production.

Practical uses of the efficiency information could also assist in daily oil palm field management to identify nutrition and management problem. However, the formulae were developed under Sumatran environments and a single planting material which therefore requires further validation with different palm and site conditions (Prabowo *et al*., 2010).

Jacquemard *et al*., (2002; 2010a; 2010b) studied 489 oil palm progenies and the variation in % leaf nutrient concentrations. They found significant variation between progenies of different genetic origin on nutrient critical levels. Some progenies were lower in their requirements for certain nutrients and therefore there was the potential to select high yielding planting materials which would perform well with low rates of fertiliser. Baihaqi *et al* (2005) reported the results of nursery progeny x fertiliser experiments and concluded that fertiliser recommendations were required for different planting materials as well for the location/environmental conditions. They concluded that fertiliser recommendations should not only be based on the environment (location) but also take into account the genetic origin of planting materials or progenies particularly when a highly homogenous planting material (clones or F_1 hybrids) is planted.

This paper reviews and updates information on oil palm physiological efficiency (PE) with regard to recovery and agronomic efficiencies (RE and AE) based on recent long term field and nursery trial results in Sumatra, Indonesia.

2. METHODS

2.1.NPKMg fertiliser trials on mature oil palm

Results from a series of seven field trials testing different rates of N, P, K and Mg fertilisers on mature oil palms under various Sumatran environments were used for the study. The planting material in the trials was Deli x AVROS. Details of the treatments of each trial are shown in Table 1. Site characteristics (physical, chemical properties and climate) of the trials can be seen in Table 2. All the trials were single replicate NPKMg fertiliser factorial design. The trials had 5x5 to 8x8 palms plots and were installed with 100 cm deep and 50 cm wide trenches surrounding each individual plot. In addition the plots included a double palm row as guards to minimize nutrient poaching effect (BLRS, 1992). Therefore only the central 3x3 to 4x4 palms were recorded which represented the true effects of the treatments given. Data from different recording years were used which provided results over a wide range of palm ages (5 to 17 years old).

Table 1 Planting materials and annual fertiliser treatment rates

Trial	Planting years	Original stands ha^{-1}	Fertiliser rates (kg palm^{-1} annum^{-1})											
			Urea			TSP or RP*			MOP			Kieserite or S.Dolomite*		
			0	1	2	0	1	2	0	1	2	0	1	2
231	1985	128	0	2	4	0	2	4	0	2.5	5	0	1.5	3
232	1985	128	0	2	4	0	2	4	0	2.5	5	0	1.5	3
275	1985	128	0	2	4	0	2	4	0	2	-	0	2	-
277	1985	128	0	2	4	0	2	4	0	2	-	0	2	-
1403	1996	143	0	2	4	-	2*	4*	0	2	4	0	2*	-
1411	1997	143	0	2	4	-	2*	4*	0	2	4	0	2*	-
1413	1995	143	0	2	4	-	2*	4*	0	2	4	0	2*	-

TSP = triple super phosphate; MOP = muriate of potash

Table 2 Site characteristics of seven NPKMg fertiliser trials in Sumatra (1994-2007)

Trial No.	Planting material DxP	Planting year	Original stands (palms ha^{-1})	Soil parent material	0-40 cm Top soil properties (without fertilisers)											Solar radiation (Kwh m^{-2} day^{-1})	Soil moisture content (%)	Annual moisture deficit (mm)
					OM (%)	pH	Exchangeable cations					Total N (%)	Available P Bray-II (ppm)	Hot acid extr. K (meq/ 100 g)	Slope (%)			
							Ca	Mg	K	Al+H	Total							
231	Deli x AVROS 1	1985	128	Rhyolite	5.24	4.6	0.8	0.1	0.1	1.29	2.34	0.25	2.2	0.97	0-3	4.4	97.2	0
232	Deli x AVROS 1	1985	128	Sandstone	3.53	4.5	0.6	0.1	0.1	1.73	2.49	0.16	7.1	0.12	>40	5.2	63.8	34
275	Deli x AVROS 1	1985	128	Rhyolite	3.33	4.9	1.3	0.2	0.1	0.97	2.65	0.19	2.9	4.24	0-3	4.5	14.3	320
277	Deli x AVROS 1	1985	128	Rhyolite	3.29	5	2.1	0.4	0.3	0.65	3.49	0.21	2.6	4.61	0-3	5.1	42.6	188
1403	Deli x AVROS 1	1996	143	Dacite/ claystone	3.56	4.5	1.4	0.5	0.1	4.13	6.17	0.25	4.67	1.34	0-3	4.6	91	1
1411	Deli x AVROS 2	1997	143	Dacite/ claystone	2.58	4.4	0.5	0.4	0.1	1.86	2.83	0.2	2.58	0.26	0-3	4.6	92.3	0
1413	Deli x AVROS 2	1997	143	Dacite/ claystone	4.24	4.4	0.4	0.1	0.1	1.97	2.52	0.24	13.17	0.32	0-3	4.6	92.3	21

Plots with optimum fresh fruit bunch (FFB) yield were determined for each trial. The fertiliser combinations that gave the optimal yield were considered as the best fertiliser rates required for optimal palm growth, nutrient status and yield. Comparisons between the different nutrient rates were then made at non-limiting levels of the other nutrients. This comparison is different from approaches which uses unfertilized or zero fertiliser plots where imbalances and deficiencies of nutrients are likely to have occurred. The conditions may bias or mislead the true response to a single nutrient observed.

Measurements carried out in the field trials included palm growth parameters such as petiole cross section (PCS), annual frond production and trunk height as described by Breure and Verdooren (1995). The field trials applied a non-destructive estimation for dry biomass weight of the above-ground components (leaf, rachis, petiole, trunk, bunch and male inflorescence) using formulae developed by Prabowo *et al*. (2002; 2006). Other records taken from the field trials covered FFB and bunch number data. All the palm components were regularly sampled and analysed for macro nutrient concentrations (N, P, K and Mg).

2.2. Nursery trials

Results from two nursery factorial trials (Table 3) were analysed to investigate nutrient use efficiency in relation to site and planting material. The seedlings were grown and treated for 11-12 months. The objectives of the trials were to investigate the effects of fertiliser rates, pot media type, progenies, watering rates and their interactions on seedling growth and nutrient efficiencies.

Table 3 Treatment description of Trials A and B

% standard	Nutrient (g seedling^{-1})				Watering	Soil
	N	P	K	Mg	(mm a^{-1})	
0%	0	0	0	0	2000	231
50%	30	13	25	5	4000	232
						275
						277
						1403
						1411
						1412
						1413

Trial A

% standard	Nutrient (g seedling^{-1})				Media	Progeny
	N	P	K	Mg		
0%	0	0	0	0	Peat	P1
25%	15	7	12	3	Soil	P2
50%	30	13	25	5		P3
100%	59	26	50	11		P4
						P5
						P6

Trial B

Note: the nutrient rates are cumulative to 52 weeks after seed planting.

Trial A tested nine replicates x two fertiliser rates x eight soils x two watering rates with a single palm plot size. The fertiliser rates tested were 0% and 50% of the standard nursery fertiliser given as straights (urea, triple super phosphate, muriate of potash and kieserite). The fertilisers were weighed in small bags and top-dressed with fertilisers every alternate week following the standard nursery procedure. The soils for the pot media were taken from sites where the field NPKMg trials situated (soil depth 0-40 cm). Rainfall-simulated watering was applied daily at two different rates i.e. 2000 mm and 4000 mm per annum. A single oil palm progeny was used. The trial was established under a plastic shelter to ensure uniform growing conditions and to control water application rates.

Trial B was established in an open area testing two replicates x four fertiliser rates x two media types x six progenies with a plot size of four seedlings. The fertiliser rates tested were 0%, 25%, 50% and 100% of the standard Lonsum nursery fertiliser schedule which is applied as straights (urea, triple super phosphate, muriate of potash and kieserite). The true effect of a single nutrient (e.g. N) could not be separated from the effects of the other nutrients (P, K and Mg) because each fertiliser level contained all nutrients. The application method and timing were similar to that of Trial A. Comparison of the effects of normal top soil and raw peat (fibric stage) as pot media on palm's growth and nutrition was made. Six oil palm progenies of diverse genetic origin were compared.

The trial records included growth measurements and a destructive sampling at the end of the nursery stage for dry biomass and nutrient analysis. The growth parameters measured were petiole cross section (PCS), height, number of fronds and bole diameter. The seedling biomass was separated into different components viz. leaf, rachis, bole and roots. The components were oven-dried and weighed for dry mass. The laboratory analysis covered N, P, K and Mg concentration. The weight of each nutrient was obtained from multiplication of dry mass and the % nutrient concentration. An estimation for frond dry mass from PCS was carried out for Trial B as some progenies had missing values for dry mass. The prediction was significantly correlated with R^2 values ranging 66%-71% (Fig. 3). In this trial frond dry mass and leaf and rachis nutrient concentrations were used for RE, PE and AE computation (Fig. 1). The formulae for the efficiency indices are as defined below (Fairhurst, 1999; Hardter and Fairhurst, 2003; Ciampitti and Vyn, 2012):

$$RE = \Delta nutrient\ uptake / \Delta nutrient\ applied$$

$$PE = \Delta yield / \Delta nutrient\ uptake$$

$$AE = \Delta yield / \Delta nutrient\ applied = RE \times PE$$

$$IE = internal\ efficiency = yield / nutrient\ uptake$$

The increment (Δ) was obtained as a difference of yield or nutrient parameters of different fertiliser rates. The NPKMg fertiliser trials on mature oil palm used fresh fruit bunch (FFB) data as yield. However in the nursery trials the dry mass was used to estimate nutrient efficiencies rather than yield. The data were statistically analysed by a randomized complete block design.

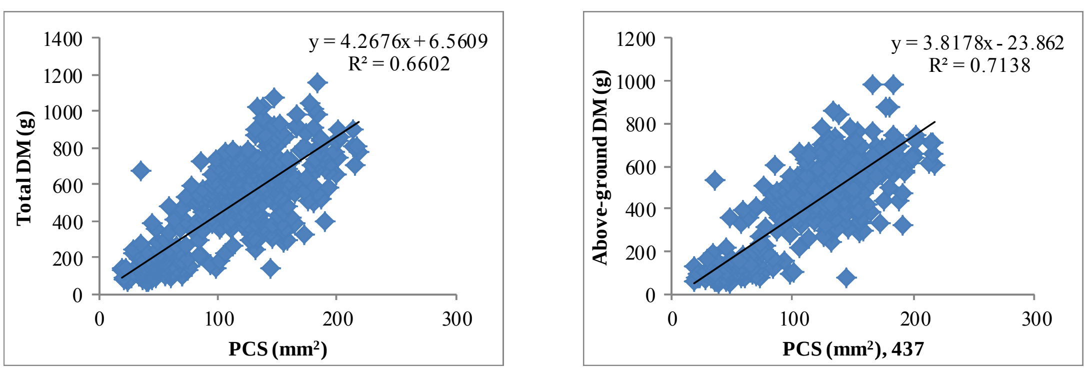


Fig. 1. Prediction of seedling dry mass (DM) (total and above-ground components) from petiole cross section (PCS) at nursery stage (*n*=480)

3. RESULTS

3.1. NPKMg fertiliser trials on mature oil palm

Table 4 shows the amount of annual nutrient applied, total uptake (in frond, trunk, bunch and male inflorescence) and FFB yield at different levels of fertiliser in each trial. The highest fertiliser levels are not necessarily the best fertiliser combinations in terms of maximizing yield. Nutrient uptake varied between trial sites. There was high variation in nutrient uptake for K and Mg where the maximum uptake was four to five times higher respectively than the minimum uptake values.

Table 4 Nutrient application, uptake and FFB yield at optimal levels of other nutrients in seven NPKMg trials in Sumatra

Trial	Treat-ment*	N (kg ha^{-1} a^{-1})		FFB	Treat-ment*	P (kg ha^{-1} a^{-1})		FFB	Treat-ment*	K (kg ha^{-1} a^{-1})		FFB	Treat-ment*	Mg (kg ha^{-1} a^{-1})		FFB
		Applied	Uptake	(kg ha^{-1} a^{-1})		Applied	Uptake	(kg ha^{-1} a^{-1})		Applied	Uptake	(kg ha^{-1} a^{-1})		Applied	Uptake	(kg ha^{-1} a^{-1})
231	0222	0	332	32,120	0022	0	25	25,080	0202	0	141	20,240	0220	0	15	19,850
	1222	96	336	31,090	0122	43	47	28,860	0212	134	338	27,500	0221	28	47	27,910
	2222	193	307	29,320	0222	86	59	32,120	0222	266	432	32,120	0222	55	75	32,120
232	0122	0	258	19,890	2022	0	25	23,860	2102	0	126	17,310	2120	0	24	19,780
	1122	113	324	24,110	2122	50	38	27,010	2112	156	279	23,620	2121	33	50	24,810
	2122	225	361	27,010	2222	100	45	27,400	2122	311	373	27,010	2122	64	61	27,010
275	0110	0	221	18,690	2010	0	25	22,640	2101	0	287	26,980	2110	0	36	28,390
	1110	96	324	26,220	2110	43	44	28,390	2111	107	336	28,390	2111	36	54	25,190
	2110	193	373	28,390	2210	86	49	28,850								
277	0210	0	472	28,250	1010	0	40	28,110	1200	0	436	29,680	1210	0	52	31,290
	1210	108	470	31,290	1110	48	52	30,430	1210	120	526	31,290	1211	41	62	29,230
	2210	216	437	29,380	1210	96	62	31,290								
1403	0120	0	152	29,150					2100	0	195	26,160	2120	0	51	37,320
	1120	128	291	37,320	2120	37	43	37,320	2110	142	419	32,640	2121	34	51	26,640
	2120	256	381	26,750	2220	74	53	36,460	2120	283	545	37,320				
1411	0220	0	268	31,140					2200	0	255	24,150	2220	0	38	32,660
	1220	127	316	32,660	2120	37	28	29,290	2210	141	360	30,360	2221	34	44	28,180
	2220	254	350	25,480	2220	73	35	32,660	2220	281	407	32,660				
1412	0220	0	315	28,200					2200	0	315	28,360	2220	0	37	30,160
	1220	129	356	30,160	2120	37	40	30,030	2210	143	386	28,060	2221	34	46	26,220
	2220	257	365	29,150	2220	74	39	30,160	2220	285	196	30,160				

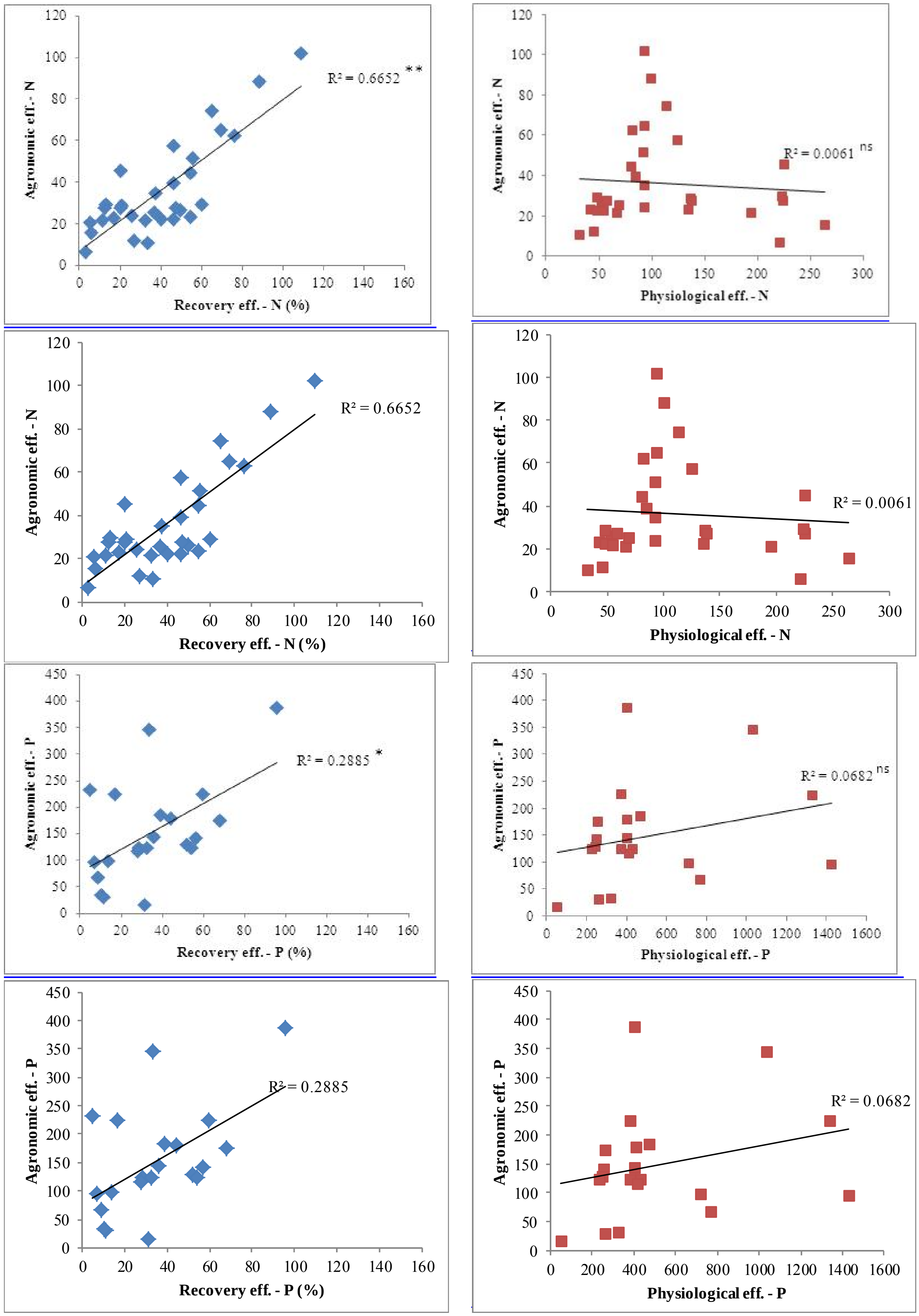
*(Adapted from Tohiruddin et al. 2007). *Treatment level is in the order of N, P, K, Mg fertilisers.*

RE of oil palm in Sumatra ranged from 14% to 147% for the first 1 kg palm^{-1} of added fertiliser nutrient depending on nutrient sources and site properties. The PE ranged from 24 to 503 kg FFB kg^{-1} nutrient uptake. PE of P and Mg were higher than those of N and K despite the lower RE. The calculated AE ranged from 12 to 262 kg FFB kg^{-1} nutrient applied (Table 5).

RE of all nutrients normally decreased with further fertiliser increment due to smaller nutrient uptake at the fertiliser level close to the optimal yield. However the trend did not apply to PE. Despite lower uptake of P and Mg the PE were higher than N and K. Relationships between RE, PE and AE are shown in Fig. 2. The graphs show that AE increased with increases with increased %RE. Meanwhile AE did not vary with PE.

Table 5 Recovery, physiological and agronomic efficiencies (RE, PE and AE) at the optimal fertiliser combinations

Trial	Fertiliser increment	N			P			K			Mg		
		%RE	PE	AE	%RE	PE	AE	%RE	PE	AE	%RE	PE	AE
231	1				53	168	88	147	37	54	66	422	193
232		27	149	32	39	360	132	77	38	29	53	282	129
275		55	65	36	74	346	262	85	24	21	53	143	76
277		62	68	43	52	295	148						
1403		88	102	88				104	52	48	45	153	42
1411		20	157	21				51	60	31	21		
1413		36	109	41				14		24	56	103	37
231	2				28	277	76	71	49	35	53	112	85
232		16	156	24	19	343	48	60	31	19	26	251	56
275		21	69	23	33	377	123						
277		46	48	22	16	503	72						
1403		58	76	49	25			58	57	30			
1411		45	45	12	17			27	66	17			
1413		30	140	34	17			24	32	6			


Agronomic eff. - N
Recovery eff. - N (%)
R² = 0.6652 **
Agronomic eff. - N
Physiological eff. - N
R² = 0.0061 ns
Agronomic eff. - N
Recovery eff. - N (%)
R² = 0.6652
Agronomic eff. - N
Physiological eff. - N
R² = 0.0061
Agronomic eff. - P
Recovery eff. - P (%)
R² = 0.2885 *
Agronomic eff. - P
Physiological eff. - P
R² = 0.0682 ns
Agronomic eff. - P
Recovery eff. - P (%)
R² = 0.2885
Agronomic eff. - P
Physiological eff. - P
R² = 0.0682

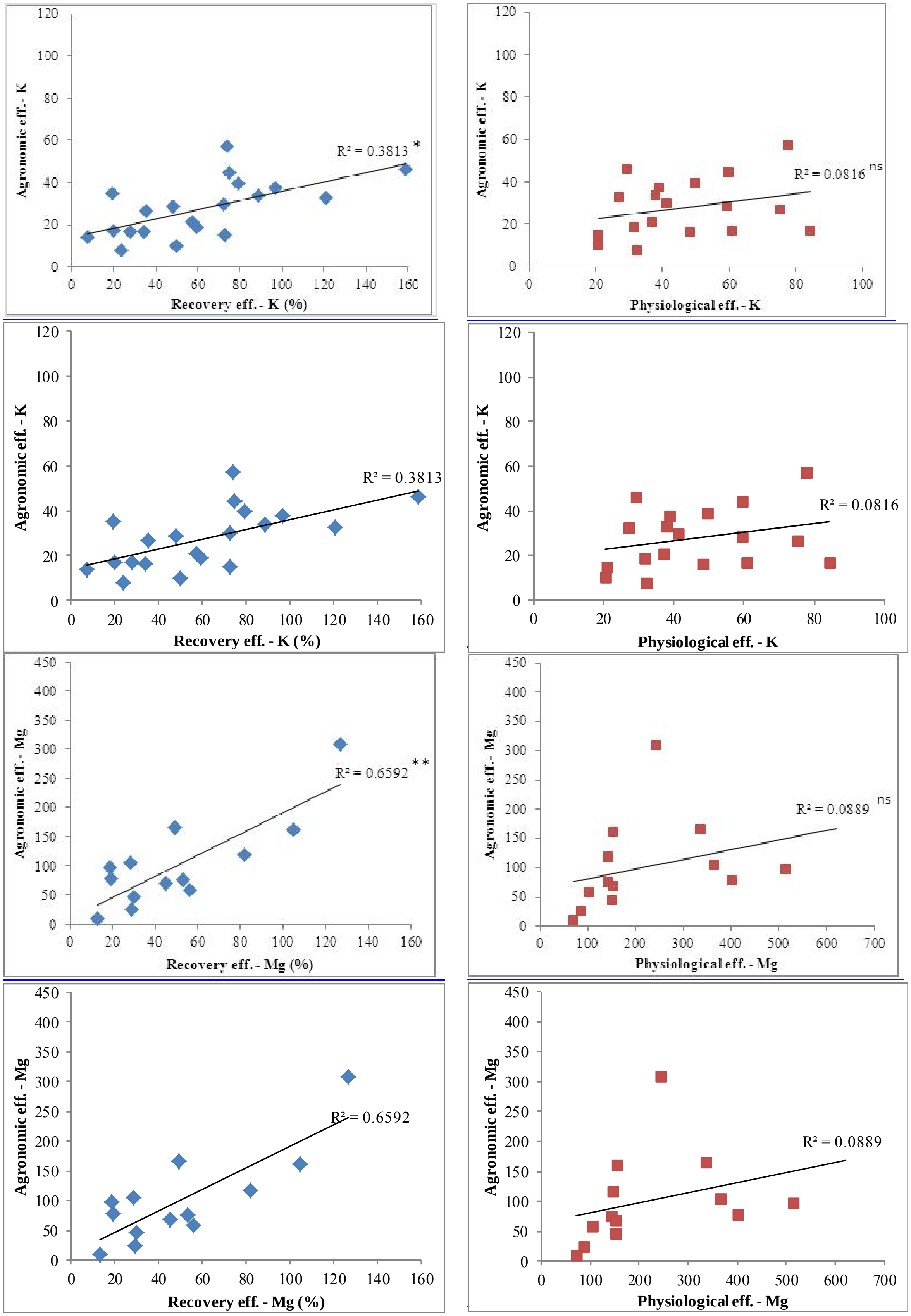


Fig. 2. Relationships between recovery, physiological and agronomic efficiencies (RE, PE and AE) of different nutrients in NPKMg trials on mature oil palm

3.2.Nursery trials

Trial A (Fertiliser x Media x Watering)

RE, PE and AE values for this nursery trial was estimated using total dry mass estimation (Table 6). Similar to the trend in mature oil palm trials (Prabowo *et al*., 2002) RE of the nutrients were higher for N and K relative to those for P and Mg. On the contrary PE of the latter two nutrients were higher due mainly to the small P and Mg uptake increment between fertiliser levels (0% and 50% of the standard nursery fertiliser). AE as a function of PE and RE were similar for each individual nutrients since the seedlings were of a single progeny.

Table 6 Nutrient efficiencies of oil palm seedlings (a single progeny) grown on different soils in the nursery with a non-limiting water (4000 mm rainfall per annum equivalent)

Soil	RE (%)				PE				AE			
	N	P	K	Mg	N	P	K	Mg	N	P	K	Mg
231	44	7	33	19	63	387	76	299	28	28	25	56
232	42	7	40	19	63	371	62	288	27	27	25	55
275	40	6	29	18	55	330	69	238	22	21	20	44
277	42	6	28	18	54	386	75	259	23	23	21	47
1403	42	6	35	12	58	394	64	398	24	24	22	49
1411	43	6	43	18	68	458	62	325	29	29	27	59
1412	48	7	43	15	60	422	61	392	29	28	26	58

In this trial the effect of rainfall rate (2000 and 4000 mm) was analysed for nutrient efficiencies of each individual soils. This site factor was as previously mentioned highly significant (P < 0.05) to seedling nutrient uptake, RE and AE. However, the PE for P, K and Mg in the different sites generally remained statistically non-significant (P>0.05) as indicated by the P values in Table 7.

Table 7 Significance of the effect of rainfall on physiological efficiency (PE) of the major nutrients at individual trial sites

Soil	N	P	K	Mg
231	*	ns	ns	ns
232	**	**	**	**
275	ns	ns	ns	ns
277	*	ns	*	ns
1403	*	ns	*	ns
1411	*	ns	ns	ns
1412	ns	ns	ns	*

*ns= not significant; * P<0.05; ** P<0.01*

Relationships between the three efficiency components are illustrated in Fig. 3. It is obvious that the variation in AE was mainly caused by RE and to a smaller extent, by PE. PE trends in this nursery trial result were different from the NPKMg trial result probably due to two main reasons. Firstly, the nursery trial efficiencies were based on TDM rather than yield. Secondly, nutrient efficiency calculation for the nursery trial used data at average fertiliser and rainfall levels whilst the field trials calculated efficiencies from best fertiliser combinations only.

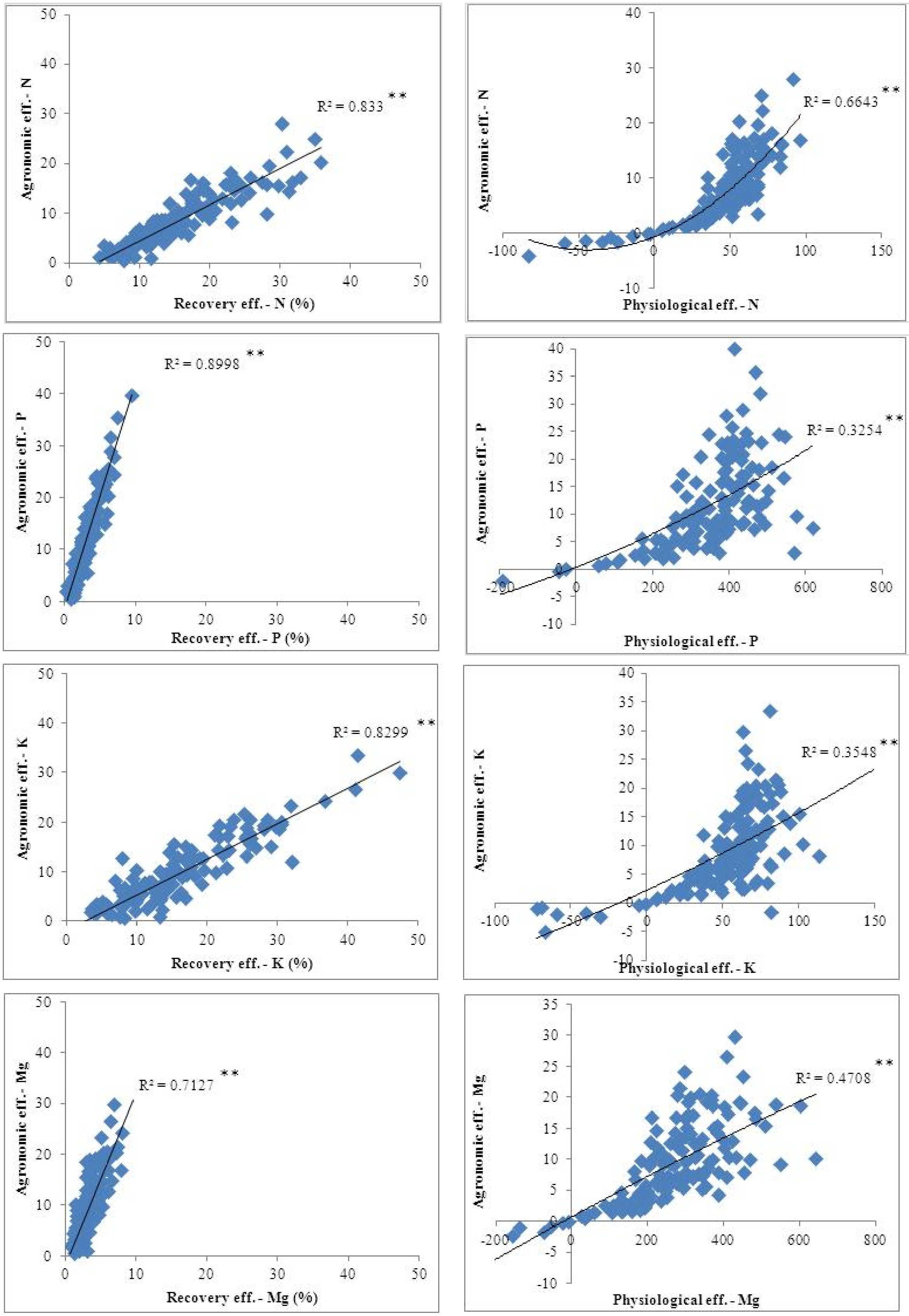


Fig. 3. Relationships between recovery, physiological and agronomic efficiencies (RE, PE and AE) in oil palm nursery trial (Trial A)

Trial B (Fertiliser x Media x Progeny)

Nutrient efficiencies of P and K in the frond component were calculated. Similar to Trial A result, as expected, there were huge effects of media type and fertilisers on nutrient uptake, RE, PE and AE.

The six progenies observed interacted and showed clear grouping with the fertilisers applied (Fig. 4). Progenies 7 and 8 were statistically outstanding for high PEP whilst Progenies 4 and 6 had low PEPs. Two progeny groups were therefore formed with Progenies 1 and 2 between the four progenies. Progeny grouping based on PEK was slightly different. This grouping also applied when the different media (soil and peat) was separated as for K the three factors interacted significantly. Variations in RE and PE were also obvious between progenies. Progenies with high RE were not necessarily high in PE (Table 8). In fertiliser trials variation in the nutrient efficiency indices can provide means of identifying the current problems in the field (e.g. low PE due to poor quality planting material; low RE as a result of nutrient loss) (Hardter and Fairhurst, 2003).

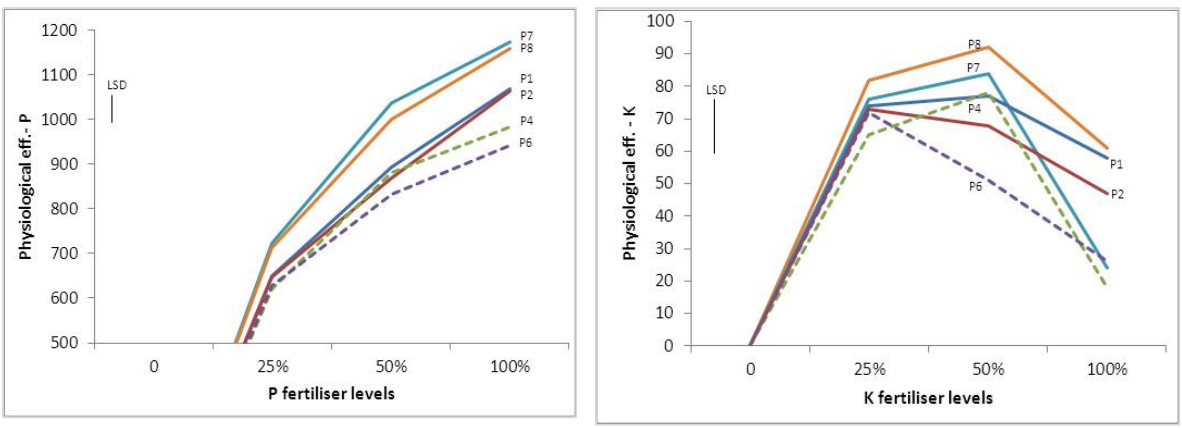


Fig. 4. Progeny x Fertiliser interaction effects on physiological efficiencies of P and K

Table 8 Effects of Progeny*Fertiliser interaction on recovery and physiological efficiency of P (REP, PEP) and K (REK, PEK)

Progeny	Fertiliser increment		
	F_1-F_0	F_2-F_1	F_3-F_2
	Recovery efficiency - P (%)		
P1	3.79	1.90	1.68
P2	4.38	1.59	1.72
P4	4.39	2.18	1.80
P6	4.92	1.73	1.78
P7	4.32	1.97	1.43
P8	4.73	1.60	1.49
LSD	0.65		

Progeny	Fertiliser increment		
	F_1-F_0	F_2-F_1	F_3-F_2
	Physiological efficiency - P		
P1	650	244	175
P2	648	221	195
P4	622	259	102
P6	627	207	108
P7	723	313	135
P8	712	287	159
LSD	67		

*a). Effects of Progeny*Fertiliser interaction on REP (left) and PEP (right)*

Progeny	Fertiliser increment			Progeny	Fertiliser increment		
	F_1-F_0	F_2-F_1	F_3-F_2		F_1-F_0	F_2-F_1	F_3-F_2
	Recovery efficiency - K (%)				Physiological efficiency - K		
P1	30.4	10.7	5.0	P1	74	3	-19
P2	34.8	8.8	5.4	P2	73	-5	-21
P4	38.8	11.9	4.9	P4	65	13	-60
P6	39.1	8.2	4.7	P6	72	-21	-25
P7	37.8	16.8	4.4	P7	76	8	-60
P8	37.5	14.6	5.9	P8	82	10	-31
LSD	4.2			LSD	18		

*b). Effects of Progeny*Fertiliser interaction on REK (left) and PEK (right)*

Note: F_1-F_0 = difference in RE and PE between fertiliser treatment levels 0 and 1

4. DISCUSSION

4.1. Nutrient use efficiency of oil palm

As reported previously by Tohiruddin *et al.* (2007), comparisons of FFB yields of the best fertiliser combinations with the nil fertilisers (0000) indicated that all the trials had different responses to the nutrients applied. The only site that had no response to N fertiliser was Trial 231 on rhyolitic soil with very high rainfall which was associated with the high inherent soil N supply. Responses to P fertiliser were significant in all trial sites. As the soil K reserves vary between the sites responses to K fertiliser also vary considerably. Trials 275 and 277 on rhyolitic soils showed the least responses to K fertiliser due mainly to the illite clay mineral property giving rise to high soil K supply. The remaining trials on soils with kaolinitic properties with low K supply required K fertiliser at high rates to achieve optimal yields. The highest K response was seen in sandstone area of Trial 232 with sloping topography. Furthermore this trial and Trial 231 demonstrated significant responses to Mg fertiliser due to low soil Mg supply associated with the parent material and high rainfall, respectively.

The efficiency of fertiliser nutrient recovery declined as FFB yield increased. Consistently the RE of N and K were higher than P and Mg. RE was highly influenced by limitations in site properties. Daily field practices and nutrient management such as Fertiliser placement (Sweeney, 1997), fertiliser types (Prabowo *et al.,* 2002) or timing of fertiliser application/ season (Goh *et al*., 2003; Dobermann *et al.*, 2004) also contributed to RE variation. Wortmann *et al.* (2011) found significant differences in RE due to different crop management rotations such as maize following after soybean and continuous maize. In contrast, PE of a single oil palm material at a certain age used in the oil palm trials was relatively stable (Tohiruddin *et al*., 2007). Therefore any variation in AE for all nutrients was mainly as a result of varying RE values. Dobermann *et al*. (2004) comparing rice productivity in seven Asia countries found considerable differences between SSNM (site specific nutrient management) and FFP (farmers' fertiliser practice) plots. The SSNM plots yielded 7% higher rice grain yield compared with the farmers' plots. The well-managed plots were 39% higher in AEN which correlated with 41% higher REN relative to the traditional farmers' plots. No significant difference (-4%) in the IEN (internal efficiency of N) was found between the plots compared which suggested the relatively stable PE of the varieties grown over the period (1997-1999). Practical growers may therefore be more interested in managing the AE and RE indices through their nutrient and crop management strategies (Hardter and Fairhurst, 2003).

4.2. Nursery trials

Use of TDM, or above-ground dry mass, of oil palm nursery seedlings, produced similar nutrient efficiencies to those from the field fertiliser trials (Table 9).

Table 9 Comparison of physiological efficiency (PE) values of the major nutrients between mature and nursery oil palms

Trial	PEN	PEP	PEK	PEMg
Field	95	334	66	201
Nursery	58	379	67	309

Results from the nursery trials have indicated that a single progeny had relatively stable PE with non-extreme environmental conditions. Under very different pot media type (peat versus topsoil comparison, for instance) there was very significant variation in PE. The trial result also showed that the main effect of fertiliser strongly affected PE of K (PEK). However in this particular case interactions between treatments (fertiliser, progeny and media type) occurred and the main effect of fertiliser on PEK was misled by the interactions. Fairhurst (1999) suggested that factors such as drought, nutrient interactions or pest and disease could also affect PE. On the other hand RE normally varied and was dependent upon agronomic factors such as fertilization and field management. In turn variation in RE significantly results in AE variation. The nursery trial results strongly confirm previous findings on nutrient efficiency in mature oil palm trials in the field (Tohiruddin *et al*., 2007).

Two progenies tested in nursery trial B had much higher PE values than the other four progenies for phosphate. This result suggests that there may be potential to select planting materials which are able to produce more dry matter (or yield) in response to nutrients and particularly phosphate. Ciampitti and Vyn (2012) compared yields of maize genotypes grown in different countries over two different eras, i.e 1940-1990 and 1991-2011. Yield increased from 7.2 t ha^{-1} (old era) to 9.0 t ha^{-1} (new era) due to increased potential grain yield and N internal efficiency (grain yield/ N uptake) on a per unit basis. It was thought realistic to increase overall maize N RE and N PE simultaneously. However, it was recognized that N RE and the N remobilization efficiency process to achieve yield improvement is a difficult strategy.

4.3.Use of PE-related information

4.3.1. Identification and evaluation of problem fields

Results from these field fertiliser trials showed that correlations between FFB yield and palm tissue (leaf, rachis) nutrient concentration were generally low. However prediction of FFB yield could satisfactorily be made from leaf nutrient weights. Estate data collected during annual sampling of leaf and rachis tissue from leaf sampling unit (LSUs) normally includes some palm growth data such as PCS besides leaf or rachis nutrient concentration. From a series of field NPKMg fertiliser trials in Sumatra, Prabowo et al. (2009, 2010) showed that the available data could be used to estimate weights of the major nutrients in different frond components. The approach did not require additional site information such as rainfall, soil moisture and solar radiation for the yield predictions (R^2 values were 82%, 83%, 73% and 67% for N, P, K and Mg, respectively). The data required represented important palm parameters that were originally influenced by a combination of site factors. The PCS represented a palm's vegetative growth condition. Leaf nutrient concentrations should picture the latest nutrient status (satisfactory, deficient or excessive) of the field. Palm age is required in the equations to indicate the current physiology of the palms in making use of the available nutrient resources. Finally, the FFB yield data was a result of internal and external palm properties which are PE-related as they are a function of leaf nutrient weights, palm age and growth.

FFB yields of commercial oil palm estate fields generally vary with nutrient supply and daily field management practices. Actual yields can be categorised into very good, good and low. Identification of certain low-yielding fields amongst a large number of commercial fields can be determined using the yield prediction equations. Yields were predicted on the basis of N, P, K and Mg status. The lowest predicted yield is considered as the 'expected' yield since it is the most limiting nutrient that determines the yield to be low. The yield data is then plotted on a 1:1 line (Fig. 5 as an example). Yield points below the 1:1 line are problem fields. The average estate yield (e.g. 25 t ha^{-1}) has been shown on Figure 4 to more clearly distinguish between the fields with low and high predicted and actual FFB yields. The field is classified as Group A (nutrition problem) if the yield is lower than the average yield. The next step is field evaluation to check if the low nutrient status was due to insufficient nutrient supply, nutrient imbalance, mistakes in fertiliser rates, method and timing of fertiliser application. Inherent site limitation such as sloping topography, poor soil drainage, sandy soils and very low/ high rainfall can considerably contribute to low yielding.

If the actual yield is between the average and expected yields then it is likely that a field management problem (incomplete harvest/ bunch evacuation, poor in-field road condition/ transportation, bunch security, field supervision, etc) is taking place (Group B). The high expected yield suggests that the fields – as indicated by palm's growth and current nutrient status - have no nutrient problem. Possible explanations for why these fields are not achieving their yield potential could be as a result of poor harvesting, crop evacuation from the field or crop loss between field and factory.

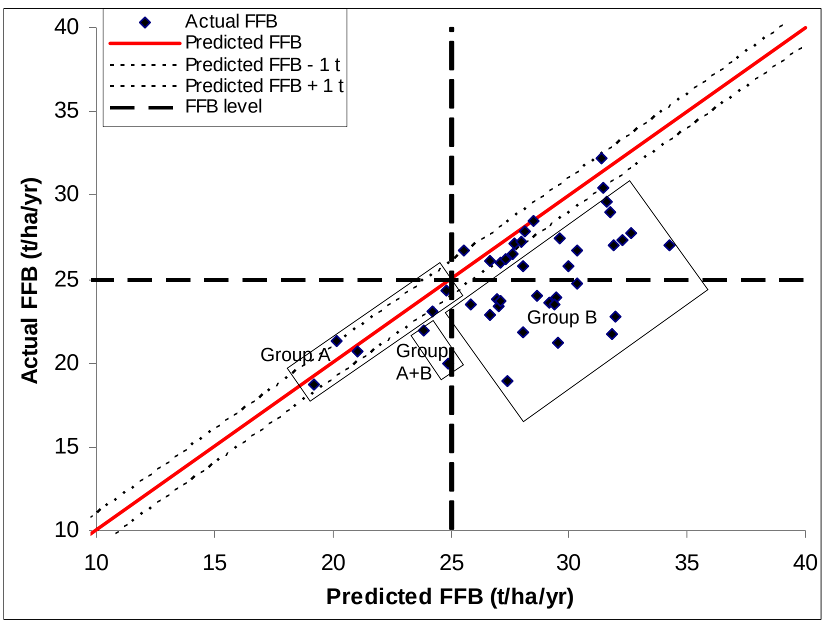


Fig. 5. Implementation of the prediction equations on commercial oil palm fields *(Adapted from Prabowo et al., 2010)*

4.3.2. Fertiliser recommendation

Predictions used to determine recommended fertiliser rates

Oil palm fertiliser recommendation usually relies on foliar diagnosis as a tool to determine if a field is at a certain nutrient status (excessive, satisfactory, deficient). The tool was derived from field NPKMg fertiliser trials that produced a relationship of yield response (to an individual nutrient) and % leaf nutrient levels. Estimation of the fertiliser rates required to correct the current nutritional status of the field also uses this tool (Goh, 2011). However more accurate determination of palm's nutrient requirement should realistically account for the surrounding site factors (physical/ chemical soil properties, palm and weather). BLRS developed a yield response efficiency prediction system to involve site factors into its fertiliser recommendation system. The objective of this yield response prediction is to determine the amount of each fertiliser required to correct the current nutrient status determined by foliar diagnosis from the properties of the location. The last step is an economic analysis that considers a cost-benefit analysis and determination of the most profitable yield to target (Tohiruddin *et al*., 2010).

Following the PE-related equations (Prabowo *et al*., 2009; 2010) it is likely that the foliar diagnosis and response efficiency prediction steps can be short-cut during a fertiliser recommendation process. It is apparent that the latest equations use multi-information which should be more representative for the current palm status. In addition to the leaf nutrient concentration (which mainly generates the foliar diagnosis system), the PE equations also rely on palm growth (PCS), palm age and material. With more relevant data source involved the equations should be able to improve the accuracy of the recommendation.

Application of PE-related equations in fertiliser recommendation system
Sumatran trial results showed that the maximum yield response to N fertiliser depends on leaf N levels and total cations in the leaf and rachis. Likewise, yield response to K fertiliser also correlates with rachis K levels and palm age (Fig. 6). In short a foliar diagnosis step provides a prediction of the expected maximum yield response to applied fertilisers based on tissue nutrient levels.

FFB yield response efficiency prediction step uses information on site properties (soil, palm and weather factors). Following the foliar diagnosis the efficiency prediction is to determine the amount of fertilisers to correct the current nutrient status. Efficiency of FFB yield response to N and K fertilisers are mainly determined by the FFB yield level. In addition other factors also influence the efficiency prediction. Soil TEB (total exchangeable bases), clay content, drainage, slope and palm age are additional determinants for N response efficiency prediction. K efficiency prediction was also affected by soil TEC (total exchangeable cation), silt content, drainage, rainfall, water surplus and number of palm stands (Fig. 7) (Tohiruddin *et al.,* 2010).

High correlations between nutrient weight levels and FFB yield (Fig. 8) provide a possible prediction of the yield from a less complex data source (PE-related equations). With PCS, palm age and nutrient concentration data available the prediction of individual nutrients can be generated. Hence the final step required is to place the predicted FFB yield values based on leaf N and K weights into the yield matrix (Table 10 as an example) for a predicted current FFB yield value (27.0 t). Once the most profitable yield level (28.8 t) is set the additional/ reduced amount of N and K fertilisers can be determined (i.e. +1.5 kg N fertiliser and +1.5 kg K fertiliser) (Prabowo *et al.,* 2010).

Use of the latest PE equations to predict FFB yield offers more convenience since only a few data is required. However it is worth noting that the equations were derived from limited Sumatran conditions (north and south Sumatra) from two Deli x AVROS progenies with different palm ages. Hence use of the equations beyond the trial site properties and planting material needs a thorough evaluation.

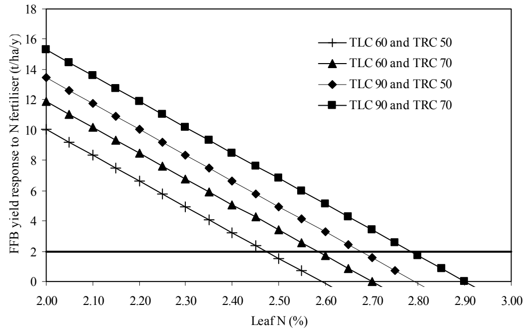


Fig. 6. Predicted maximum yield responses to N and K fertilisers *(adapted from Tohiruddin et al., 2010)*

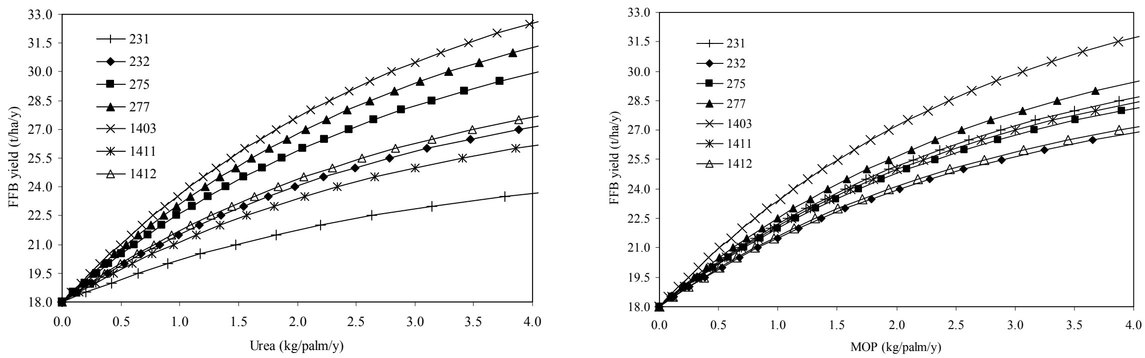


Fig. 7. Predicted FFB yield response efficiency to N and K fertilisers *(adapted from Tohiruddin et al., 2010)*

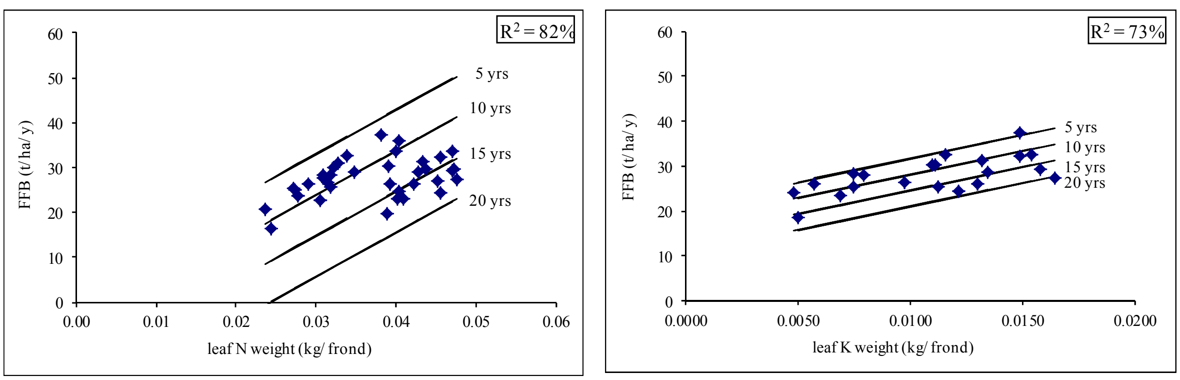


Fig. 8. Predicted FFB yield from N and K status at different palm ages *(adapted from Prabowo et al., 2010)*

Table 10 Predicted FFB yields (tonnes ha^{-1} a^{-1}) for different combinations of N and K fertilisers

MOP (kg/palm/y) across the top; Urea (kg/palm/y) down the left side

Opt.	0.0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	**4.0**	4.5	5.0	**5.5**	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	Opt.
N	16.0	18.5	20.6	22.4	23.8	25.0	26.1	26.9	**27.6**	28.2	28.7	29.2	29.5	29.8	30.0	30.2	30.4	30.6	30.7	30.8	30.9	K
10.0	14.8	18.7	21.5	23.6	25.1	26.2	27.1	27.7	28.2	28.6	28.9	29.1	29.3	29.4	29.6	29.6	29.7	29.8	29.8	29.9	29.9	33.5
9.5	14.9	18.7	21.5	23.6	25.1	26.2	27.1	27.7	28.2	28.6	28.9	29.1	29.3	29.4	29.5	29.6	29.7	29.7	29.8	29.8	29.9	33.4
9.0	14.9	18.8	21.5	23.6	25.1	26.2	27.1	27.7	28.2	28.6	28.8	29.1	29.2	29.4	29.5	29.6	29.7	29.7	29.8	29.8	29.8	33.2
8.5	15.0	18.8	21.6	23.6	25.1	26.2	27.0	27.7	28.2	28.5	28.8	29.0	29.2	29.3	29.5	29.5	29.6	29.7	29.7	29.7	29.8	33.1
8.0	15.1	18.8	21.6	23.6	25.1	26.2	27.0	27.6	28.1	28.5	28.8	29.0	29.2	29.3	29.4	29.5	29.6	29.6	29.7	29.7	29.7	32.9
7.5	15.2	18.9	21.6	23.6	25.1	26.2	27.0	27.6	28.1	28.4	28.7	28.9	29.1	29.2	29.3	29.4	29.5	29.5	29.6	29.6	29.6	32.7
7.0	15.3	19.0	21.6	23.6	25.1	26.1	26.9	27.6	28.0	28.4	28.6	28.8	29.0	29.1	29.2	29.3	29.4	29.4	29.5	29.5	29.6	32.4
6.5	15.4	19.0	21.7	23.6	25.0	26.1	26.9	27.5	27.9	28.3	28.5	**28.8****	28.9	29.0	29.1	29.2	29.3	29.3	29.4	29.4	29.4	32.1
6.0	15.5	19.1	21.7	23.6	25.0	26.0	26.8	27.4	27.8	28.2	28.4	28.6	28.8	28.9	29.0	29.1	29.2	29.2	29.2	29.3	29.3	31.7
5.5	15.7	19.2	21.7	23.6	25.0	26.0	26.7	27.3	27.7	28.0	28.3	28.5	28.6	28.7	28.8	28.9	29.0	29.0	29.1	29.1	29.1	31.2
5.0	15.9	19.3	21.8	23.6	24.9	25.9	26.6	27.1	27.5	27.9	28.1	28.3	28.4	28.5	28.6	28.7	28.8	28.8	28.8	28.9	28.9	30.7
4.5	16.1	19.4	21.8	23.5	24.8	25.7	26.4	26.9	27.3	27.6	27.8	28.0	28.2	28.3	28.3	28.4	28.5	28.5	28.5	28.6	28.6	30.1
4.0	16.3	19.5	21.7	23.4	24.6	25.5	26.2	26.7	**27.0***	27.3	27.5	27.7	27.8	27.9	28.0	28.0	28.1	28.1	28.2	28.2	28.2	**29.4**
3.5	16.5	19.5	21.7	23.3	24.4	25.2	25.9	26.3	26.7	26.9	27.1	27.2	27.4	27.4	27.5	27.6	27.6	27.6	27.7	27.7	27.7	28.5
3.0	16.8	19.6	21.6	23.1	24.1	24.9	25.4	25.8	26.1	26.4	26.5	26.7	26.8	26.8	26.9	26.9	27.0	27.0	27.0	27.0	27.1	27.5
2.5	17.0	19.6	21.4	22.7	23.7	24.4	24.8	25.2	25.5	25.6	25.8	25.9	26.0	26.0	26.1	26.1	26.1	26.1	26.2	26.2	26.2	26.3
2.0	17.2	19.5	21.1	22.3	23.1	23.6	24.0	24.3	24.5	24.7	24.8	24.8	24.9	24.9	25.0	25.0	25.0	25.0	25.0	25.0	25.0	24.8
1.5	17.4	19.3	20.7	21.6	22.2	22.6	22.9	23.1	23.3	23.4	23.4	23.4	23.5	23.5	23.5	23.5	23.5	23.5	23.5	23.5	23.5	23.2
1.0	17.4	18.9	19.9	20.6	21.0	21.3	21.4	21.5	21.6	21.6	21.6	21.6	21.5	21.5	21.5	21.5	21.5	21.4	21.4	21.4	21.4	21.2
0.5	17.3	18.3	18.9	19.2	19.3	19.4	19.3	19.3	19.2	19.1	19.1	19.0	18.9	18.9	18.8	18.8	18.7	18.7	18.7	18.6	18.6	18.8
0.0	16.9	17.2	17.2	17.1	16.9	16.7	16.5	16.2	16.0	15.8	15.7	15.5	15.4	15.3	15.2	15.1	15.0	14.9	14.9	14.8	14.8	16.0

(* Current yield; ** Most profitable yield)

(Adapted from Tohiruddin et al., 2010)

4.3.3. Oil palm planting material screening for specific nutrient requirement and efficiency

A progeny may be internally efficient in utilizing certain nutrients but less efficient in optimizing a specific nutrient. In Trial A, PEN in different soils was significantly affected by variations in the rainfall rates whilst PEP, PEK and PEMg were generally consistent (see Table 7). Breeding for high nutrient-efficient palm material should consider this factor. Another complexity may be present that a certain progeny may be efficient in taking up applied nutrients but could be less efficient in utilizing the resource obtained. Progenies 1 and 4 in Trial A are a good example (Table 8). Although not significantly different but Progeny 4 (P4) tended to take up more P and K applied (as indicated by the %RE) compared with Progeny 1 (P1). However the utilization of the nutrients taken up into dry mass (yield) was more efficient by P1 than P4. Opposite to the example in Trial A, an oil palm clone (ramet) of 12 years old age grown on a Sumatran rhyolitic soil had consistently low leaf Mg level (0.14% in the absence of Mg fertiliser and presence of N, P and K fertilisers) and showed a subtle uniform pinnae yellowing symptom. Application of 3 kg kieserite $palm^{-1}$ a^{-1} over a three year period only slightly increased the Mg level to 0.16% and the symptom still remained but with very good annual FFB yield of 31.3 t ha^{-1} (BLRS, 1997).

Progeny screening based on % leaf nutrient concentration (Jacquemard *et al*., 2002; 2010a; 2010b) may encounter inconsistent results. Foster (2003) suggested that method of leaf sampling including the choice of frond, sampling unit, choice of palms and time of sampling could affect the nutrient analysis results. In addition field trials not well-installed with plot trenching and a double guard palm row are likely to experience serious nutrient poaching (BLRS, 1992). Leaf nutrient concentration of the sampled progeny palms may therefore vary greatly.

5. CONCLUSIONS

Oil palm development of marginal land with poor fertility status should be balanced with good planting material for better internal nutrient utilization for a profitable cropping. A comprehensive knowledge on nutrient use efficiency can then assist in determining a fertiliser recommendation, cost saving, profit optimisation and reduced risk of fertiliser run-off polluting water courses.

Fertiliser trials on mature and nursery oil palms generally demonstrated that RE is influenced by yield levels and site factors (physical/ chemical soil properties and weather). PE on the other hand is relatively more stable under non-extreme site conditions but is very dependent on palm age and can also vary with plant material. Thus AE at a particular yield level and age and plant material is largely dependent on RE (which varies with site factors). AE is affected by PE mainly through its variation with palm age and palm material.

PE and RE-related information is required for various practical uses by the oil palm industry for the following reasons:

1. PE at a particular palm age is largely unaffected by site factors, yield can be fairly accurately predicted from the weight of nutrient uptake alone. This provides a useful tool for checking and explaining commercial oil palm yields. Corrective measures in the fields can then be planned to achieve the target yield.
2. Accurate fertiliser recommendations can be made based on a yield x fertiliser matrix predicted from RE values, in which the current yield position is identified from PE values.
3. Because PE is related to palm materials, this parameter can be used by breeders to select material which most efficiently responds to fertilisers or for sites with known agronomic limitations.

Despite all the possible uses of the PE information a field evaluation is required particularly for uses beyond the trial site properties or when different planting materials and palm ages are in place. Role of daily field management policies – which will vary with companies/ smallholders - on actual FFB yield may be significant and could therefore produce different predictions relative to those by the PE equations. In addition to the nursery trials since 2010 Sumatra Bioscience have established three factorial trials testing Planting materials x N x P x K fertilisers in different agro-climatic sites to see if there is variation in fertiliser requirement with different planting materials and planting material x nutrient interactions.

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