Managing Soil Environment & Its Major Impact on Oil Palm Nutrition & Productivity in Malaysia

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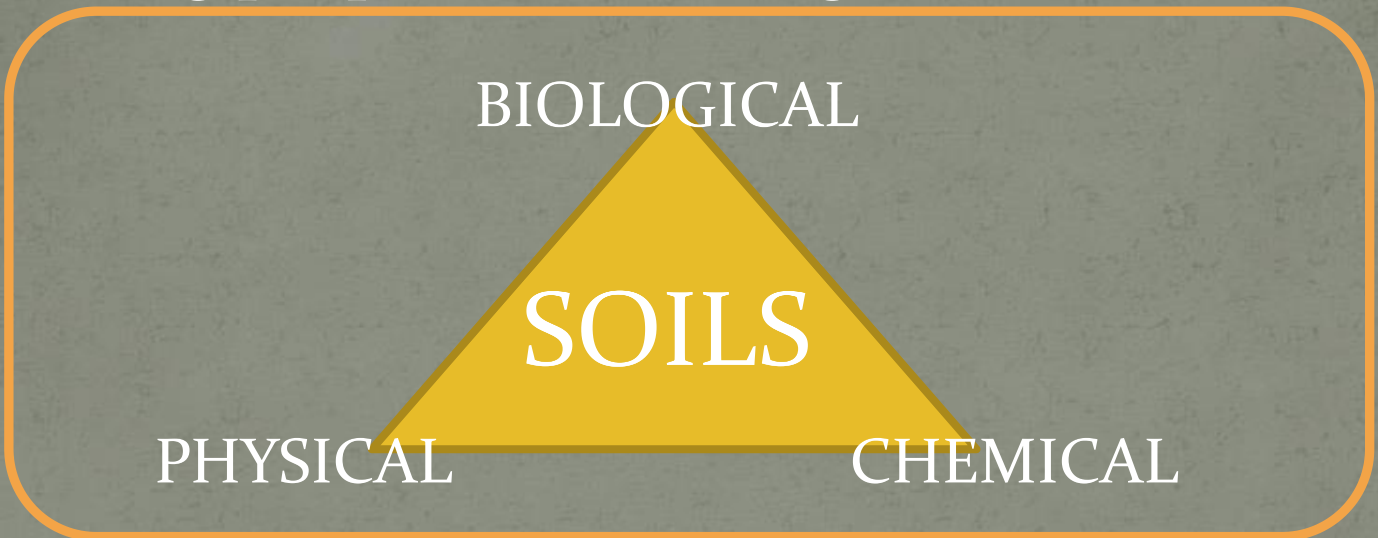
INTRODUCTION

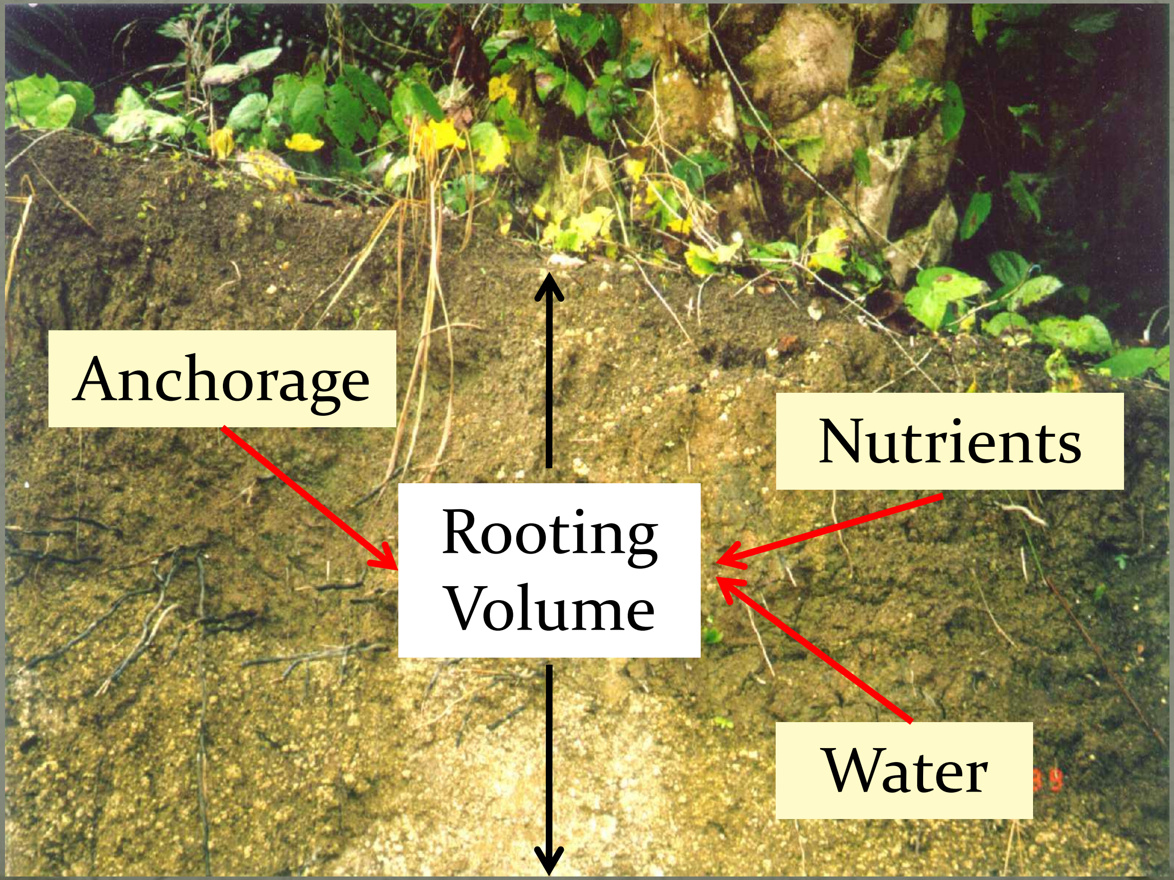
- Plantation tree crops are now cultivated on a *diversified range of soils and landforms*, with increasing proportion of marginal soils.



Evidences showed that inputs required to obtain the site yield potential *do not necessarily endanger the environment, cause soil degradation nor reduce quality of the products*.

PRINCIPLES OF SOIL MANAGEMENT

- To maintain and improve soil fertility
- To synchronise soil productivity, with and without enhancement, with crop requirements for high sustainable growth and yields throughout the economic life span of the trees.



SOIL REQUIREMENTS OF PLANTATION TREE CROPS

- First approach is to match the crop requirements with soil properties, with or without amendments.
- *Water* and *nutrients* need to be *supplied by SOILS* to sustain growth and yield of plantation tree crops ~ *affected by rooting activity.*
- *Rooting activity* is influenced by many soil properties such as *terrain*, *soil depth*, *stoniness*, *texture*, *structure*, *consistence*, *permeability*, *drainage* and *nutrients*.

PHYSICAL CHARACTERISTICS

TERRAIN

- Vertical & horizontal dimension of the land surface.
- Pen. Malaysia - cultivation @ max. slope $\leq 20^{\circ}$ or 36%
- Sabah & Sarawak - cultivation @ max. slope $\leq 25^{\circ}$ or 46.6%
- Main problem caused by steep topography:
  - High risks on erosion, landslides & run-off losses of nutrients
  - Poor water balance due to excessive run-off
  - Need to terrace = planting on less fertile sub-soil
  - Difficulty in harvesting and field maintenance operations with probably poorer crop recover

SOIL DEPTH & STONINESS

- *Soil volume* is the function of *soil depth x stoniness*. Primary requirement for *root development*.
- Main effects of shallow effective soil volume:

➢ Limited root room for adequate amount of roots

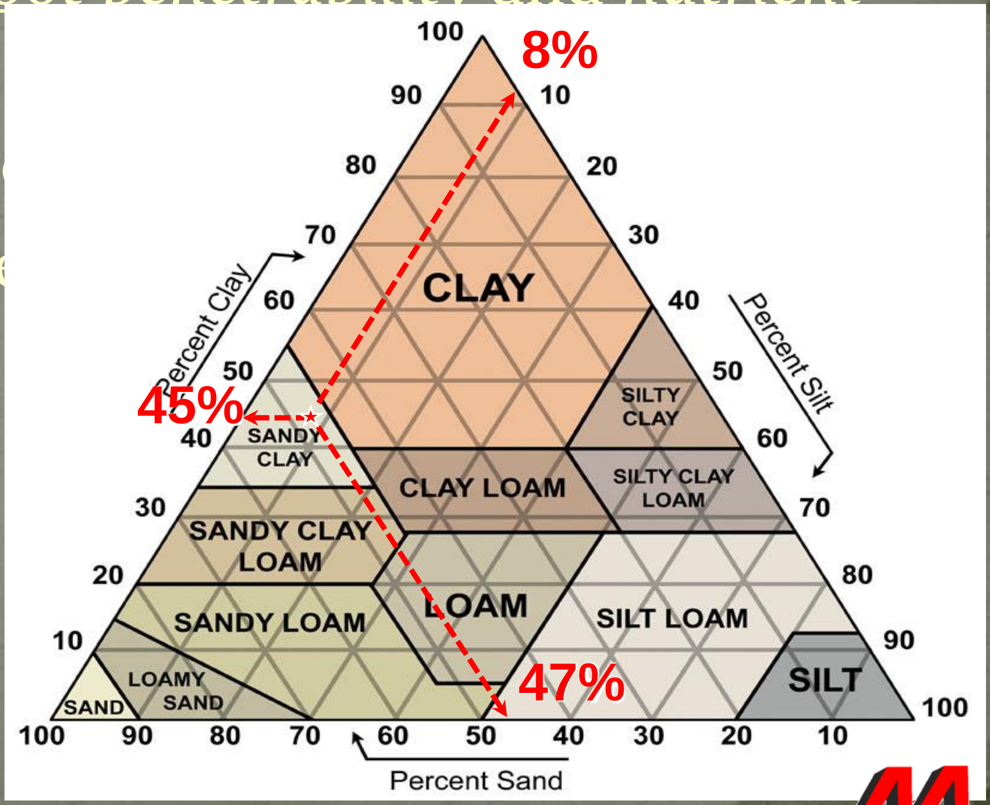
➢ Weak anchorage

➢ Low available of soil moisture

➢ Low soil nutrient supply

TEXTURE, STRUCTURE & CONSISTENCY

- These 3 physical parameters are closely related & determine *soil aeration (porosity)*, *water holding capacity*, *permeability*, *root penetrability* and *nutrient retention capacity*.
- Soil texture = propotion
  ➔ significantly influence



PERMEABILITY& DRAINAGE

- Permeability = property of the soil to transmit water & air and closely related to soil physical properties
- Poor permeability causes:
  - Perched water table such as in podzols, Batu Anam series
  - Imperfect drainage even in hilly soils such as Batu Anam series
  - Poor rooting activity and its consequences

PERMEABILITY & DRAINAGE

- On flood plains or valley floor, high water table can be common & excessively high water table can give rise to:
  - Inadequate soil aeration
  - Poor anchorage and lodging
  - Canopies turn chlorotic and become small resulting in poor photosynthesis

CHEMICAL CHARACTERISTICS

NUTRIENT STATUS

- Nutrient, being one of the two most limiting factors to crop productivity, must be correctly assessed to afford proper fertiliser management practices.
- Over- or under-application of fertilisers can have disastrous effects:
  - Poor crop productivity due to lack of fertiliser or imbalance
  - Lower profit due to excess fertilisation
  - Soil acidification and degradation, and
  - Environmental pollution due to excessive leaching and run-off losses

FERTILISER APPLICATION

- Required for high yields of oil palm
- Supply nutrients

Various Fertiliser Trial Data (summary of various trials)

Trial period	Site	Soils	FFB Yield (t/ha/yr)		Average response
			Max	Control	
1970s - 1980s	Inland	Bungor	31.8	8.6	269 %
	Coastal	Selangor	35.1 - 36.1	30.0 - 34.0	11 %
	Riverine	Koyah	32.7	21.1	55 %
1980s – 1990s	Inland	Rengam	34.4 - 38.5	12.1 - 23.8	103 %
	Coastal	Carey	28.8	27.1	6 %
	Riverine	Buran	41.5	25.4	63 %

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SOIL REQUIREMENTS OF PLANTATION TREE CROPS

- The major soil management requirements:
  a) Soil and water conservation management
  b) Soil fertility management
  c) Soil acidity management
  d) Soil organic matter management
  e) Soil water management (drainage & irrigation)
  f) Soil microbe management
- Main objectives of soil and water conservation are to <u>prevent soil degradation</u> & <u>environmental pollution</u>, and thereby <u>obtain maximum sustained level of production</u> from a given area of land.

SOIL & WATER CONSERVATION PRACTICES

TERRACING

- *Planting terraces* = constructed mainly to facilitate harvesting, crop evacuation and maintenance operation apart from conserving soil and water

- *Conservation terraces* = constructed on long slope of less than 8° or short rolling to around 12 ° in order to cut the length of slope.

SOIL & WATER CONSERVATION PRACTICES

ESTABLISHMENT OF LEGUMES

Establish full coverage of legumes as rapid as possible after land clearing to minimise soil erosion and land degradation.

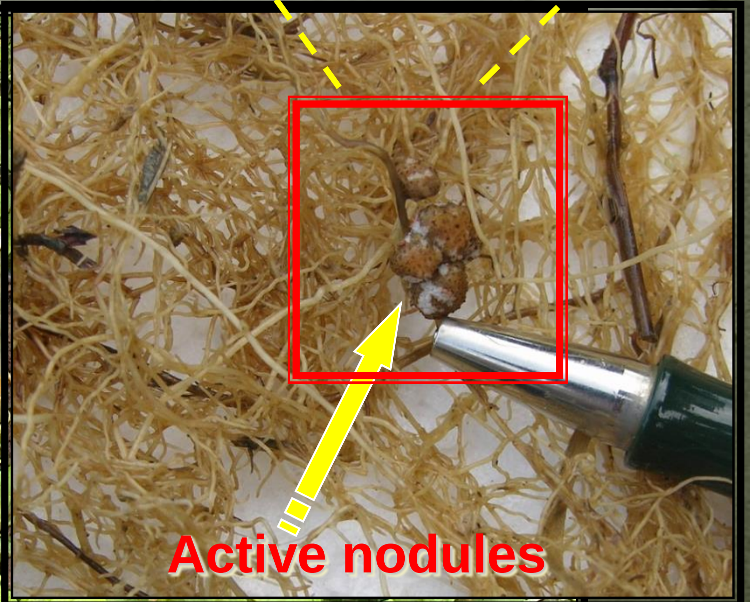
EFFECTS OF LEGUMES

Dry Weight (t ha^{-1}) of shoot and litter of MB at different periods

Ref.	6th Month			12th Month			21st Month		
	Shoot	Litter	∑	Shoot	Litter	∑	Shoot	Litter	∑
Ng *et al*. (2006)	1.51	0.05	1.56	2.28	0.13	2.41	7.80	9.17	17.0

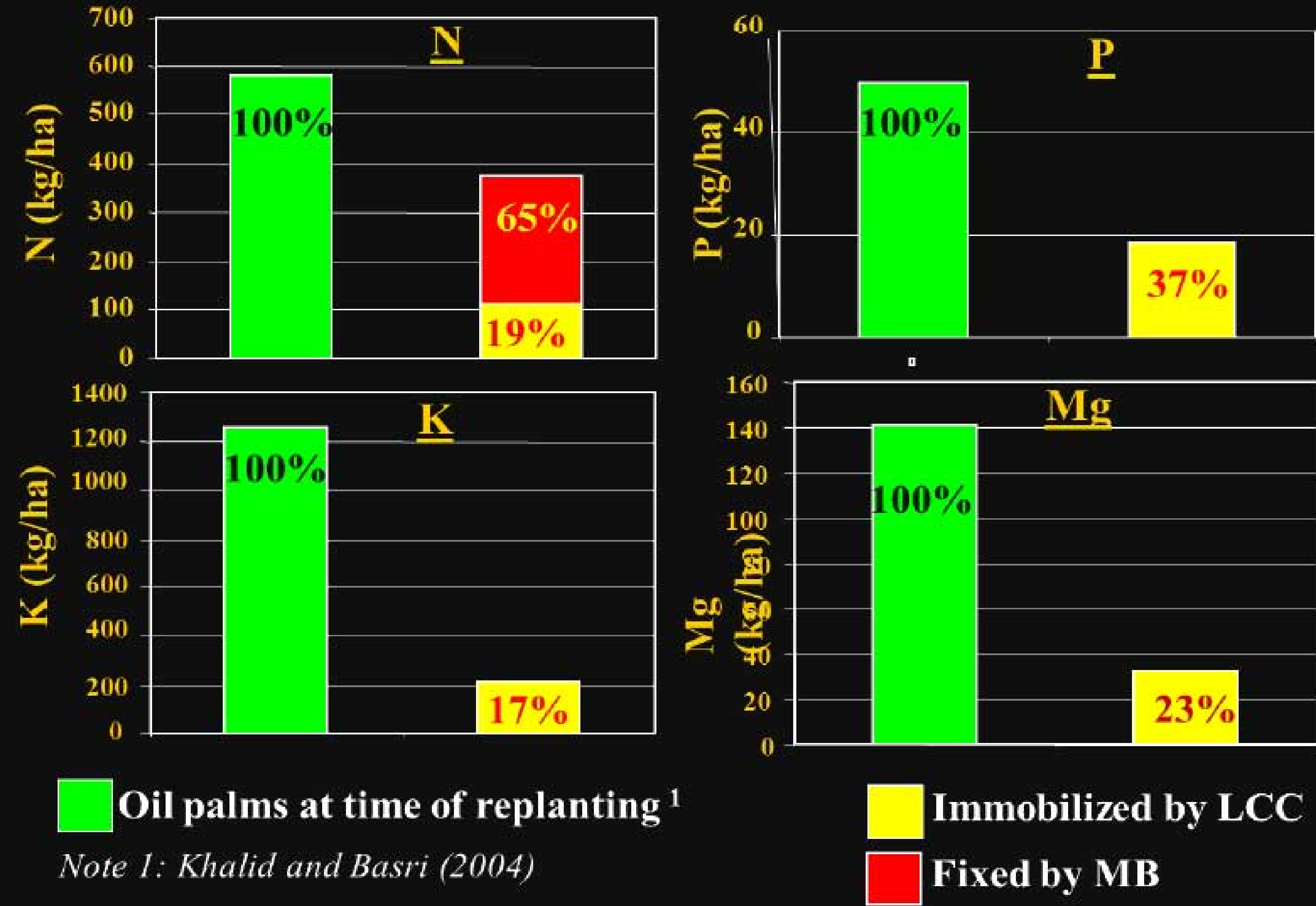
EFFECTS OF LEGUMES

- **Mixed legumes (PJ + MB + CC)**
  - ✓ **Quick coverage**
  - ✓ **Shade tolerant (MB + CC)**
  - ✓ **Able to fix Nitrogen from atmosphere**
  - ✓ **High production of dry matter/org. carbon**



EFFECTS OF LEGUMES

Nutrients available in oil palms at time of replanting and nutrients immobilized by legumes



Note 1: Khalid and Basri (2004)

SOIL & WATER CONSERVATION PRACTICES

- **Maintaining Ground Vegetation**

  - Natural covers which are not competitive for nutrients & water can be used to reduce soil erosion & run-off losses; they should be encouraged to gradually succeed the legumes as the latter dieback due to shading effect

SOIL & WATER CONSERVATION PRACTICES

- **Frond Stacking**

- Stack pruned fronds across the slope and cover as much ground area as possible to help in reducing run-off and erosion losses substantially.

- In terraced area, pruned fronds placed across the terrace width at regular intervals will assist to break the flow of run-off water.

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SOIL & WATER CONSERVATION PRACTICES

- **Mulching with Empty Fruit Bunch (EFB)**

  - Minimise erosion and run-off losses of the bare soil

  - Reduce soil moisture evaporation loss during the dry month

  - Supply nutrients to the planted seedlings or palms

  - Improve soil conditions

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SOIL & WATER CONSERVATION PRACTICES

Normal EFB vs Pressed EFB (Kluang Region)

Type of EFB	Total N (%)	Total P (%)	Total K (%)	Total Mg (%)	Moisture (%)	n
Normal EFB	0.70	0.08	2.47	0.17	63.5	40
Pressed EFB	0.65	0.07	1.70	0.11	53.7	40

→> 30% reduction in Total K concentration in Pressed EFB……

Source: AAR (unpublished)

SOIL & WATER CONSERVATION PRACTICES

Release Time for 50% of Nutrient in EFB

Reference	Nutrient Release	Total N	Total P	Total K	Total Mg	Dry Weight
Caliman *et al*. (1994)	Time (Days)	205	85	25	115	40

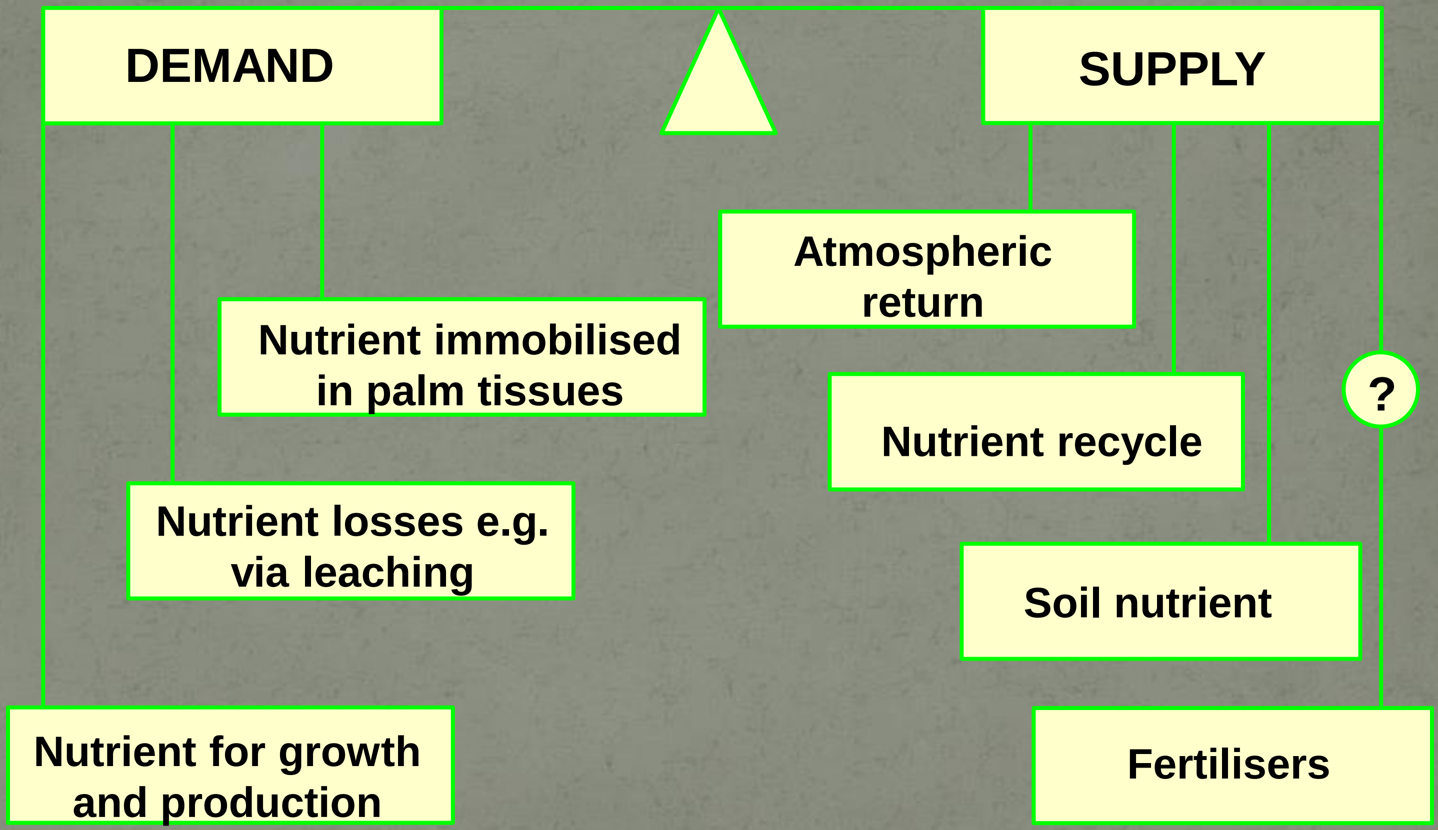
→ EFB should be applied into the field as soon as they leave mill to avoid major losses through leaching (especially K)

SOILS FERTILITY MANAGEMENT

- Soil fertility depends on four groups of factors:
  - Inherent characteristics of the soil profile
  - Plant species growing on it
  - The local weather conditions
  - The recent agricultural operations
- Large variations in soil fertility occur within and between soil series
- This agrees with the varied responses of plantation tree crops to fertilisation on the same soil series, where yield responses for oil palms ranged from 0 to 250%, for cocoa from 0 to 47% and for rubber from 0 to 39%.
- This realisation has caused scientists to develop schemes or methods to measure or assess soil fertility quantitatively or qualitatively.

NUTRIENT REQUIREMENT

- The nutrient requirements of plantation tree crops are usually calculated based on the nutrient balance and dynamic concept:



- Soil and Foliar analysis is also used as a supplementary tool for the diagnosis of nutrient requirements

SOIL ACIDITY MANAGEMENT

- Involves two major issues: *soils with low pH* and *soils acidified by our management practices* such as manuring and terracing
- Soil acidification is a natural process of soil formation e.g. leaching of nutrients & pollutants
- Generally regarded as soil degradation which can occur through fertilisation with acidifying fertilisers such as ammonium sulphate (AS)

SOIL ACIDITY MANAGEMENT

- *Oil palm is quite tolerant to low pH.*
- *Soil pH between 4.0 to 4.8 have no effect on max. yields* of oil palm but decrease linearly when pH lower than 3.5

- Application of OM & liming are known to increase soil pH
- Fertiliser management particularly application method

SOIL ORGANIC MATTER (SOM) MANAGEMENT

- SOM is the dominant controlling driver for soil physical process, soil chemical reactions, and soil biological activities.
- Management and conservation of SOM:
  - Minimize loss of OM at planting or replanting e.g. return above ground biomass to the soils
  - Build up OM e.g. from legumes or vegetated ground covers
  - Maintain organic residues from palm and vegetation
  - Return organic by-products from palm oil mill

SOIL WATER MANAGEMENT

- Water management practices include

  a) drainage

  b) irrigation

- ***Water conservation measures*** should be aimed primarily at ***maintaining maximum use of rainfall on the plantations.***

- ***Irrigation***, despite giving good yield responses, should only be implemented if the following conditions can be met:

  a) regular severe moisture stress is limiting growth and yield,

  b) adequate water with salinity less than 1000 µmhos cm $^{-1}$ can be ensured during dry season,

  c) the irrigation system is easy to maintain, and

  d) an economical system of irrigation is possible.

SOILS WATER MANAGEMENT

- Primary aim of *DRAINAGE* for plantation tree crops is to *maintain water table at 75 cm and not less than 50 cm from ground surface* at most times.
- A good *outlet* with sufficient capacity for water discharge is vital.
- In sandy podzols, perched water table may occur due to poor percolation of water. *Scupper or aeration drains* which preferably break through the hard-pan (spodic horizon) are required to *remove the stagnant water* before planting.
- In compacted soil with poor infiltration rate, aeration drains have been found to be beneficial.

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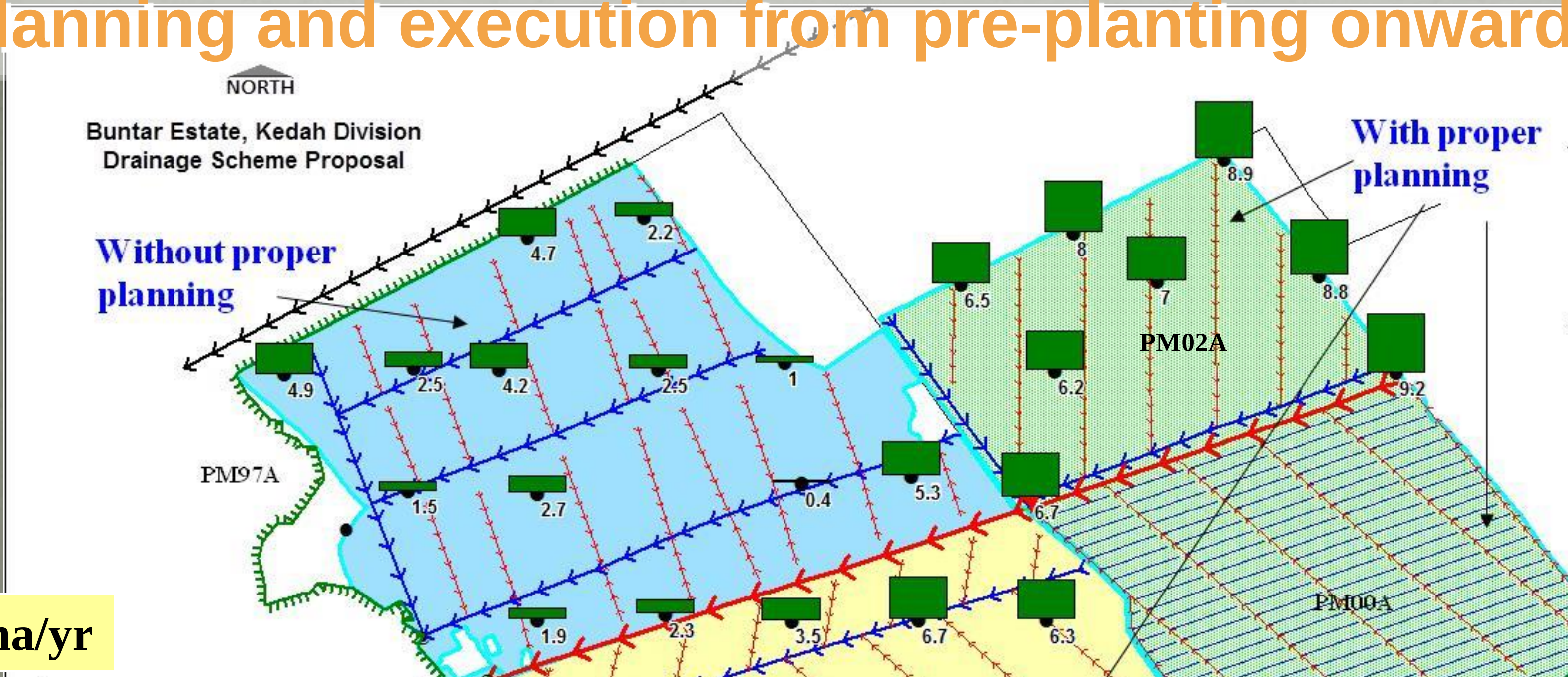
DRAINAGE

- Effect of poor drainage vs
- Good drainage

IMPORTANCE OF DRAINAGE

- ✓ Pre-requisite for growing oil palms if planted on wet soils
- ✓ Planning and execution from pre-planting onwards.



FFB t/ha/yr

Blk	Ha	Yr4	Yr5	Yr6	Yr7	Yr8	Yr9	Yr10	Yr11	Total	Avg/yr
97A	116	19.3	25.6	22.5	27.3	25.2	30.8	35.3	31.2	217.2	27.2
00A	79	22.7	30.2	31.5	30.5	30.6	32.2	33.3	33.1	244.1	30.5
01A	84	24	27.7	25.3	31	29.9	29.5	29.8	27.6	224.8	28.1
02A	50	29.4	27.6	32.2	35.9	34.2	40.5	37.2	36.2	273.2	34.2

BIOLOGICAL CHARACTERISTICS

SOIL ORGANISM / MICROORGANISM

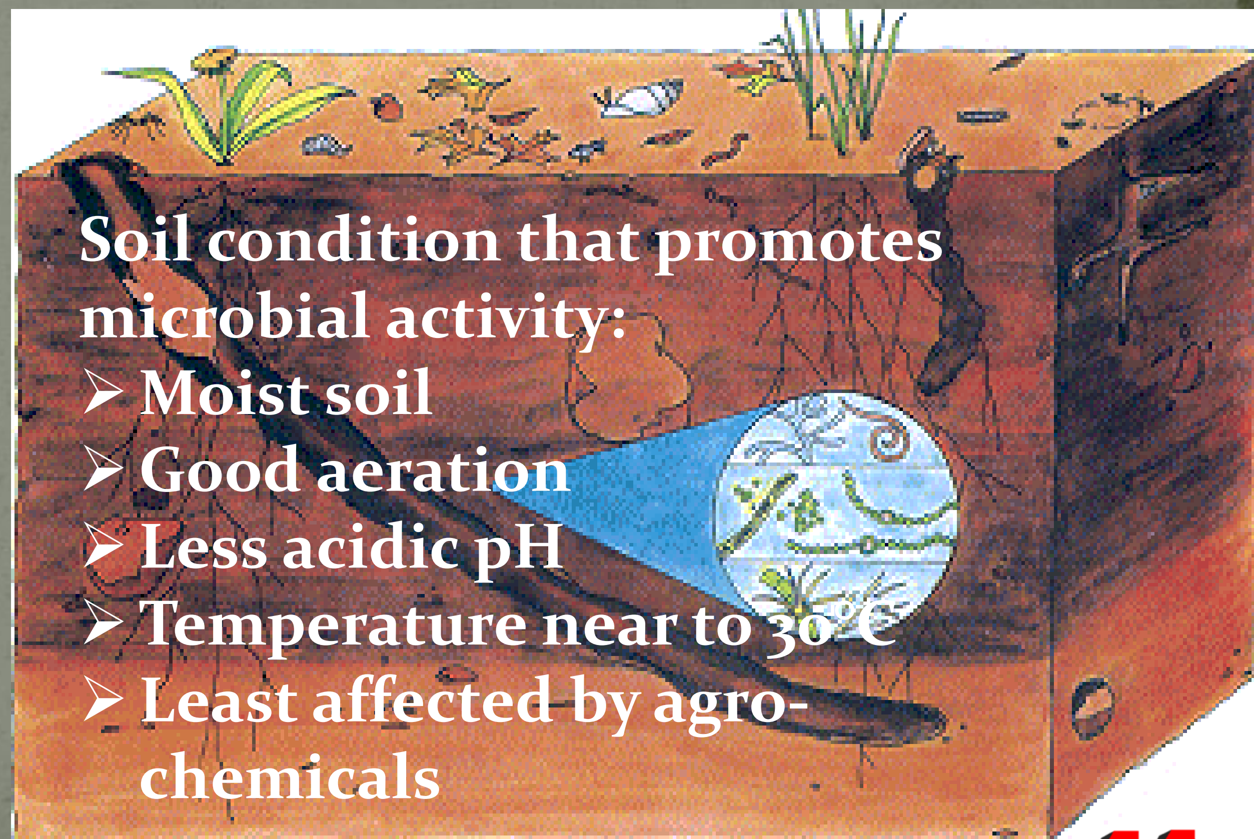
- Earthworms, beetles, snails, termites, centipedes…
- Microbes i.e. bacteria, fungi etc.
- Fungi (and bacteria) important as decomposer of SOM

Mycorrhiza:

- Symbiosis with plant (“fungus roots”)
- Increase water , P & micronutrients uptake
- Better growth?

Bacteria:

- Nitrogen fixation
- P-solubilizers



Soil condition that promotes microbial activity:

- **Moist soil**
- **Good aeration**
- **Less acidic pH**
- **Temperature near to 30°C**
- **Least affected by agro-chemicals**

Image adopted from: http://www.sccdistrict.com/ … .htm

SOIL MICROBE MANAGEMENT

- ***Soil Microbe*** → key roles in *Nutrients Cycling*

  → Turnover of carbon (C) and Nitrogen (N), Phosphorous (P) and Sulphur (S) mineralisation

  → Associate with plant disease suppression
- Complex inter-linkages between biological, chemical and physical soil components.
- Land management practices e.g. SOM management impacts soil microbe diversity & population

SOIL MICROBE MANAGEMENT

- *Good agricultural practices* minimise the losses of biodiversity yet achieve goal of attaining maximum yields.

→Recycling of palm oil mill by-products (EFB or POME) & pruned fronds

→Legumes cultivation during planting or replanting

→ Maintain vegetated ground covers (add variation to monocropping)

→ Fertilizer management (types, placement & rates)

→ Other operations e.g. soil compaction, usage of fungicides etc.

SOIL MICROBE MANAGEMENT

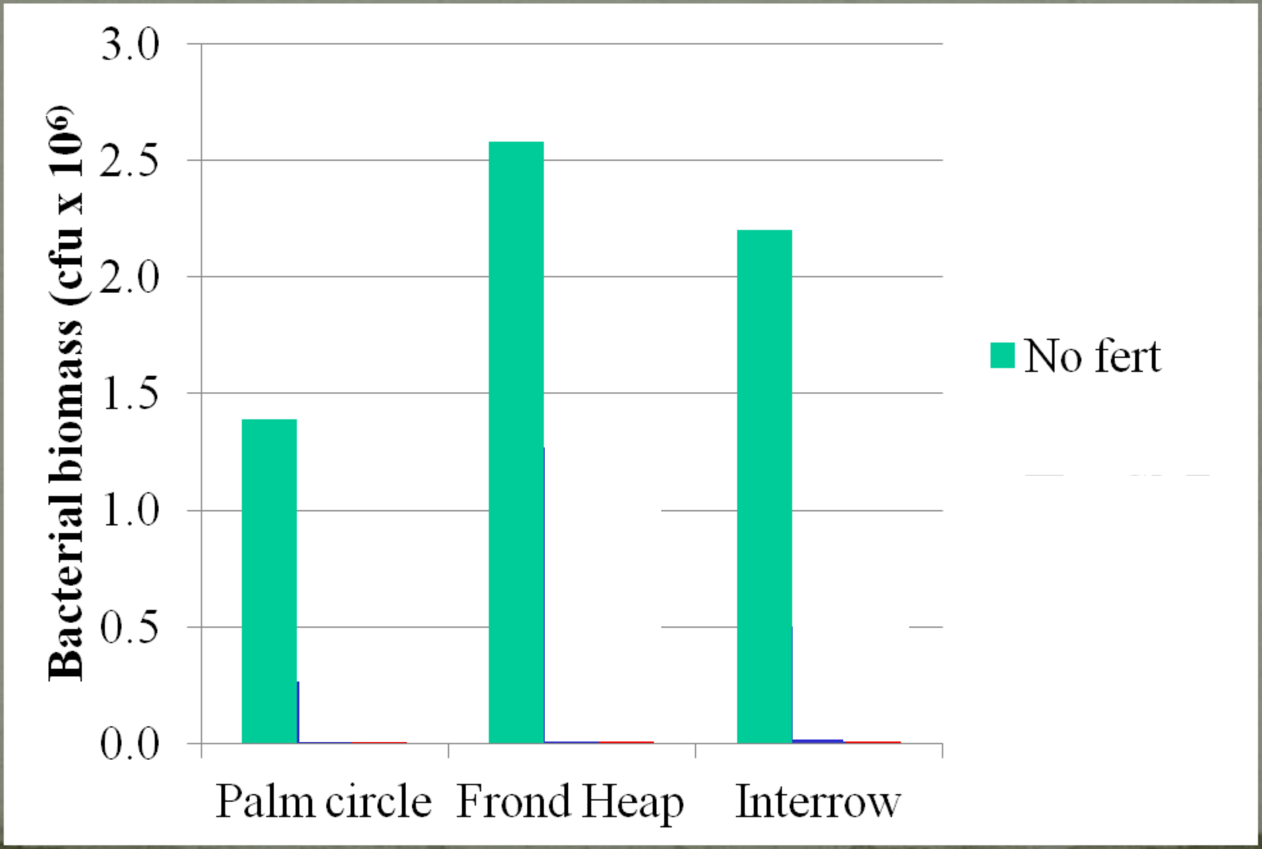
- Increase in soil microbial biomass
- Above effect on palm growth and yield being investigated

Treatments		Bacterial biomass (cfu x 10^6)					
		Palm circle		Frond heap		Inter-palm	
T1	Control	1.39	A	2.58	A	2.20	B
T2	Inorganic fert	0.263	A	1.27	A	0.499	A
T7	Inorganic + pH amend	0.357	A	1.47	A	0.579	A
T3	EFB @ 40t/ha/yr	3.71	B	9.77	B	31.95	C
T4	EFB@ 20t/ha/yr + POME	4.12	B	9.34	B	27.88	C
T5	Organic mulch 1, N=T3	3.83	B	9.83	B	27.14	C
T6	Organic mulch 2, N=T3	3.60	B	8.35	B	28.26	C

SOIL MICROBE MANAGEMENT

We knew that fertiliser application:

- ✓ Required to sustain high yields of oil palm
- ✓ Supply nutrients
- ✓ What happens to soil microbes?

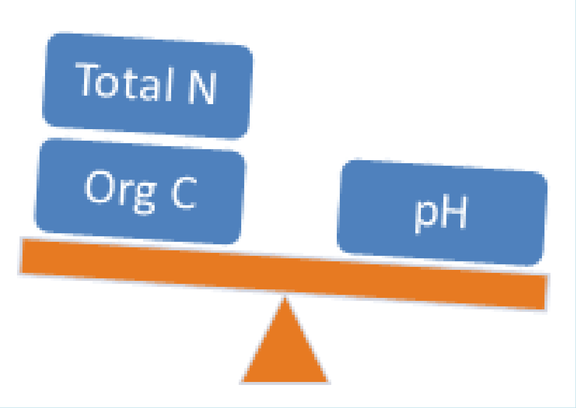


SOIL MICROBE MANAGEMENT

INCREASE ORGANIC MATTER CONTENT TO INCREASE C AND N CONTENT

- EFB MULCHING
- FROND STACKING
- BENEFICIAL FERNS & SOFT GRASSES
- LEGUMES

CHEMICAL COMPONENT



BIOLOGICAL COMPONENT

MEASURES TO AVOID ACIDIFICATION

- BROADCASTING FERTILIZERS
- TIMELY SPACING OF FERTILIZERS
- N FERTILISERS WITH LESS ACIDIFYING EFFECT
- MAINTAIN WATER TABLE IN ACID SULPHATE SOILS
- LIMING

RESEARCH

MANAGING PROBLEM SOILS

- “Plantation” Definition = Unsuitable soils for cultivation in their natural states but upon proper soil management and amendments, they can be converted for plantation tree crops with yield performances, at times, matching those on suitable soils.

- Problem soils = Soils which require special or specific attention, thought and methods to successfully manage them; they are not necessary the same as fragile soils.

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MANAGING PROBLEM SOILS

- Seven groups of problem soils:
  a) Deep peat
  b) Shallow acid sulfate soils
  c) Saline soils
  d) Shallow lateritic soils
  e) Podzols or spodosols
  f) Sandy soils (quartzipsamments)
  g) Ultra-basic and limestone derived soils

MANAGING DEEP PEAT

- Contains excessive amount of water
- Poor aeration
- Low in bulk density ~0.1 g cm^{-3}
- May undergo irreversible drying & extensive subsidence upon drainage
- Imbalanced nutritional medium for plant growth
- Acidic (pH < 3.5) – hyperacidity

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MANAGING DEEP PEAT

1. Remove excessive water in the peat swamp before felling and clearing operation by drainage (prevent over-draining to avoid rapid shrinkage & irreversible drying)
2. Construction of perimeter bund/road, perimeter drains, field drains to keep water levels at 50 to 75 cm from the surface at most times with stops, weirs, water gates depending on type of peat and local climate
3. Compaction of the low bulk density soils @ IR & planting rows to achieve bulk density of $\geq$0.2 g cm^{-3} min. $\geq$ 30 cm
4. Periodic flushing of the acidic and excessive storm water during the rainy season
5. Maintaining good ground vegetation e.g. legumes, light grasses, ferns etc. to avoid irreversible drying

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MANAGING DEEP PEAT

- Consolidation increases the bulk density, reduces the incidences of leaning and fallen palms, improves micro-pores, decreases water cavity, accelerates water capillary flow from the water table to the upper peat profile, and improves FFB yield.
- Deep acid peat provides interesting nutritional complexes to agronomists ~ state of decomposition, physical & chemical properties of the peat etc.

 - Mineralisation of peat releases N and P into soils

 - Deficient in potassium (K) & micronutrients e.g. Cu, Zn, B

 - Liming? Improved mineralisation rate, increased soil pH and a better cationic-anionic balance in the plant system

Managing Shallow Acid Sulfate Soils

- Waterlogged in nature and must be drained before cultivation
- Draining beyond pyrite layer generates excessive acidity

$FeS_2 + 8O \rightarrow Fe^{2+} + 2SO_4$

$Fe^{2+} \rightarrow Fe^{3+}$
(accelerated by Thiobacillus ferrooxidans)

$Fe^{3+} + FeS_2 \rightarrow 2Fe^{2+} + (S...SO_4^{2-})$

Managing Shallow Acid Sulfate Soils

- Liming was ineffective but creating "anaerobic condition" i.e. maintained water level to stop oxidation
- Drainage management - water table maintained between 45 to 60 cm from soil surface
- Periodic flushing – remove acidity (min. 2 to 3 times per year)
- Application of bunch ash or boiler ash could be very effective

MANAGING SALINE SOILS

- Saline soils occur by the sea or around river mouths and are constantly inundated by sea or brackish water.
- Plantation tree crops are not salt tolerant and hence cannot be grown on saline soils before ameliorations.

MANAGING SALINE SOILS

- Following conditions is required before reclamation:

a) Materials for “bunding” is available
b) If (a) is unavailable, then the “n” value of the soils should be less than 0.7
c) Most of the land boundary should not be on erosional surface
d) The land should preferably be higher than the sea or river level at low tides
e) Rainfalls should be sufficient (> 1700 mm yr-1) to allow flushing and leaching of salts
f) Land area must be sufficiently large to dilute the cost of reclamation and maintenance to economic level

MANAGING SALINE SOILS

- *Preventing further intrusion of sea or brackish water* of more than 1000 µmhos cm^{-1} into the land is central to reclamation of saline soils.
- Construction of *BUND*.
- Upon completion of bund construction, a DRAINAGE NETWORKS comprising main and collection drains must be laid down to reduce the water table and allow for subsequent flushing of the drains.
- Sufficient WATER GATES and WATER PUMPS to remove the water trapped in the land.

➔ Bund maintenance to prevent seepage and leakage, and sound water management is necessary to ensure successful reclamation of saline soils for oil palms

MANAGING SHALLOW LATERITIC SOILS

- Oil palms grown on shallow lateritic soils can come into bearing two years later compared to deep soils.
- Slower root development of oil palm in lateritic soils due to impediments with consequent poorer growth rate and lower partitioning of biomass to reproductive organs.
- Low effective soil volume, poor nutrient status and water holding capacity.
- Types and compactness of the laterites also play a major role on the degree of severity of limitations to oil palms.


Malacca


BINTANG

Palms on lateritic soils – poor growth and vigour

MANAGING SHALLOW LATERITIC SOILS

- Main approaches ➔ improve soil fertility and implement soil and water management.

a) Maintain ground vegetation e.g. legumes during immaturity to early maturity phase and light grasses and ferns (*Nephrolepis biserrata*) in later years.

b) Spread the pruned fronds as broadly as possible e.g. L-shape frond stacking.

c) Terraces must have sufficient back-slope and regular stops along the terraces to trap soil and water.

d) Mulching with empty fruit bunches (EFB) if available.

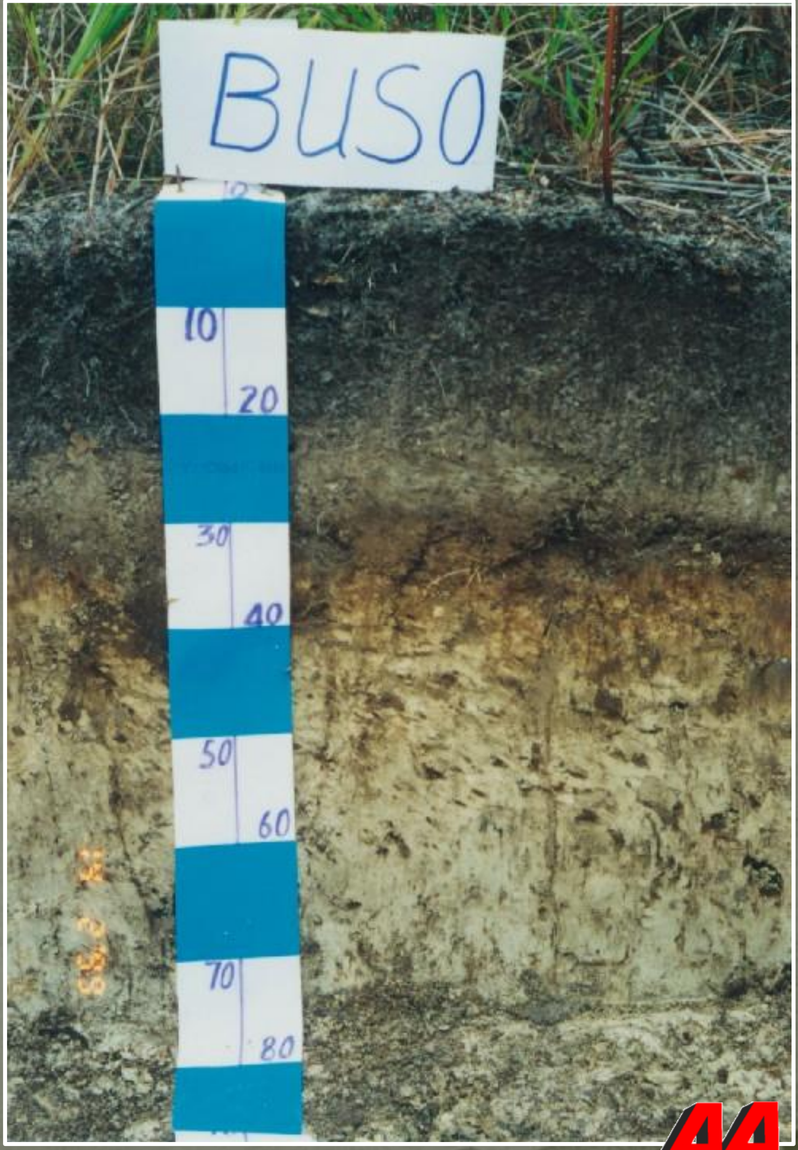
e) Apply palm oil mill by-products e.g. decanter cake and belt-pressed cake if available.

MANAGING SHALLOW LATERITIC SOILS

- Increase the planting density to between 148 and 160 palms ha^{-1} and extend ablation by 3 to 6 months for maximum leaf area index and better yields.
- Irrigation should only be conducted if it is economically viable, easy to maintain and a ready source of water during the dry season is available

MANAGING PODZOLS or SPODOSOLS

- Podzols generally occur within BRIS (Beach Ridges Interspersed with Swales) soils although they have been found on moderate hills in East Malaysia.
- Major constraints: perched water table, low nutrient status and CEC and poor moisture retention capacity.



MANAGING PODZOLS or SPODOSOLS

- First priority = remove the stagnant water on the soil surface by digging scupper drains with lower depths breaking the hard spodic horizons.
- Conditions reverted to the other extreme of likely severe moisture stress due to excessive drainage and low moisture retention capacity.

➔ Water conservation practices similar to those described for lateritic soils must be improved immediately.

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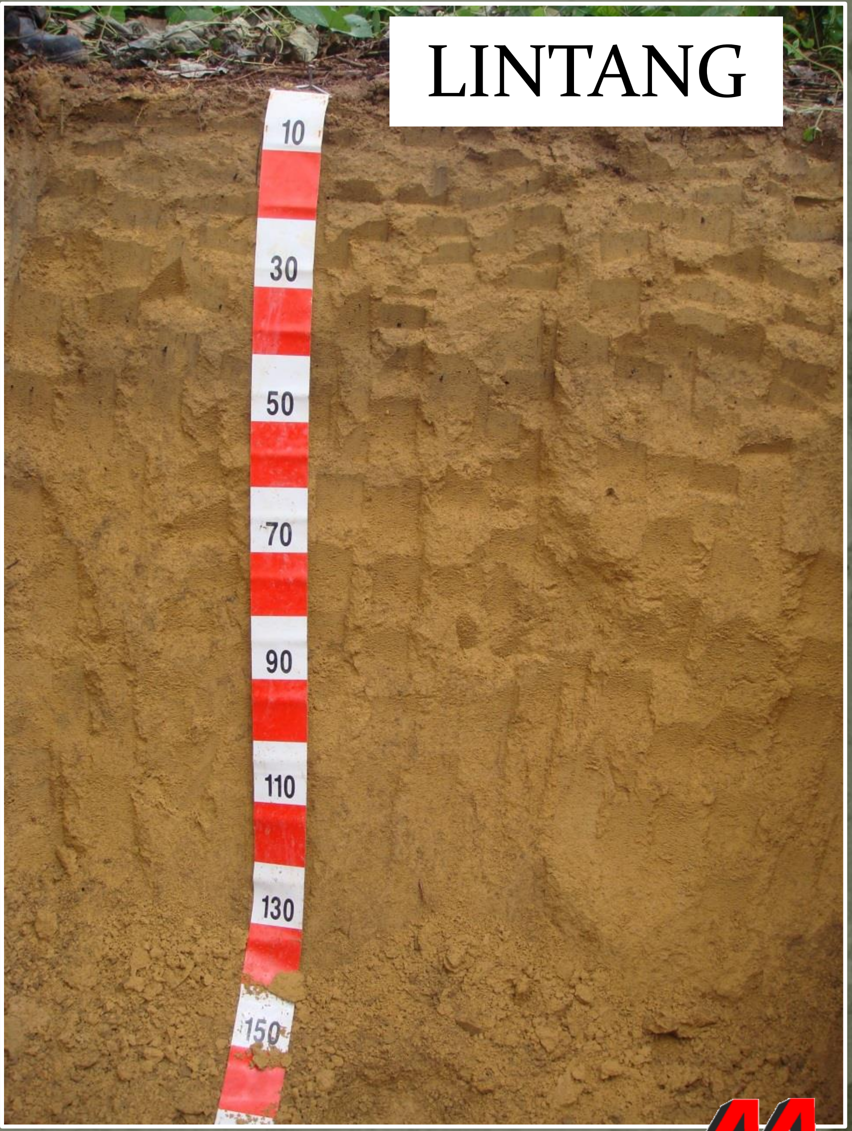
MANAGING VERY SANDY SOILS

- Known to occur extensively besides mining or ex-mining areas and flat river basins.
- Major constraints: low nutrient status and CEC and poor moisture retention capacity.
- Management procedures for oil palms on these sandy soils are similar to those on podzols except that scupper drains are not dug.



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MANAGING HIGH pH SOILS

- Rapid & extensive expansion of oil palm → soils with high pH of above 6.0, which are generally derived from ultrabasic rocks, limestone or coral limestone.
- Major limitations posed by these soils to oil palm are mainly associated with plant nutrition, steep terrain and shallow, stony soils.
- Unique soil properties where Ca and/or Mg predominate the exchangeable cations coupled with relatively low K.
- Due to the preferential and "forced" excessive uptake of Ca and Mg, the cation composition in the palm will become imbalance.

→ Severe K deficiency resulting in poor growth and production if not corrected.

MANAGING HIGH pH SOILS

- Oil palms planted on ultrabasic soils also frequent suffered from N and P deficiency as the soils are normally low in total N and total P.
- Normally used rock phosphate (RP) will not be soluble in high pH soils. Need to switch to the use of water soluble P fertilizer source.
- Micronutrient deficiencies such as manganese (Mn), iron (Fe), zinc (Zn) and boron (B) are also common although they tend to occur sporadically especially during period of dry weather.

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MANAGING HIGH pH SOILS

- Proper nutrient management

→ water soluble P, application of micronutrients (salts or chelated), apply organic by-products e.g. EFB, decanter cake etc.

- Acidify the soils with fertilizer management e.g. using ammonium sulfate, triple superphosphate etc.
- Improve rooting activity with application of organic by-products etc.

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CONCLUSIONS

- Proper understanding of soils and crops has allowed us to exploit marginal soils successfully in Malaysia.
- Upon correction or alleviation of the soil constraints, the oil palm performances can generally match those on better soil types.
- More than one soil management approaches are usually required and these must be implemented correctly and interactively. Among others, correct timing implementation is also essential to ensure success.

CONCLUSIONS

- It must be cautioned that cultivation of oil palms on marginal soils entails higher cost, more intensive inputs, good managerial skill and exposes the planters to higher risk and poorer competitiveness.
- It is therefore advisable to regard planting on marginal soils as a last resort rather than an opportunity for development and business.

CONCLUSIONS

- The concept of good soil management is nothing new and best exemplified by the following quotation from Sanskrit, the classical, literary language developed from about 1500 B.C. by the Hindus in Northern India (Johnson, 1995).

"Upon this handful of soil our survival depends. Husband it and it will grow our food, our fuel and our shelter and surround us with beauty. Abuse it and the soil will collapse and die taking man with it"

THANK YOU

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Selangor, Malaysia

Abstract

In the early years of oil palm expansion in Malaysia, extensive use of soil information was common especially to select suitable lands for oil palm, understand the dynamic mechanism of soil water and nutrients, which are commonly the most limiting agronomic factors to oil palm growth and production in Malaysia, and formulate manuring (fertilizer) recommendations for oil palm. Furthermore, oil palm is mainly rain-fed and therefore, almost all its needs apart from carbon dioxide for photosynthesis are derived from the soils. While good soil management is essential and probably the key reason for the continuous and successful cultivation of oil palms on the same piece of land for nearly a century or into the fourth generation of cropping, poor soil management can have dire consequences. For example, without manure, the mean fresh fruit bunch yield of oil palms was 32 t ha^{-1} yr^{-1} on Selangor series soil compared to just 15 t ha^{-1} yr^{-1} on Rengam series soil but with manure similar oil palm yields were obtained from both soil types. With the expansion of oil palm, many new soil series/types are regularly added to oil palm cultivation, which may not have been covered by past experiences or may pose major challenges. In fact, it can readily be envisaged that this will present a more complex situation for soil management and probably dictate a better one to ensure competitiveness and economic viability of oil palm cultivation. Therefore, this paper re-visited our earlier works with updates on soil management with the objectives of providing a general discussion of the principles of soil management, soil requirements of oil palm, and soil management requirements with emphasis on soil organic matter and soil microbe management for oil palm before elucidating the specific soil management practices to improve problem or marginal soils for oil palm cultivation.

Introduction

Since 1990s, there is a discernible lack of interest in soils by both agronomists and Planters in the industry (Goh and Chew, 1994) despite the emphasis placed on soils in the principles and criteria of the Roundtable on Sustainable Palm Oil (RSPO). This situation differs sharply from the early years of oil palm expansion in Malaysia where extensive use of soil information was common especially to select suitable lands for oil palm, understand the dynamic mechanism of soil water and nutrients, which are commonly the most limiting agronomic factors to oil palm growth and production in Malaysia, and formulate fertilizer recommendations for oil palm. Furthermore, oil palm is mainly rain-fed and therefore, almost all its needs apart from carbon dioxide for photosynthesis are derived from the soils. Goh and Chew (1994) further surmised that although the reason for this is unclear, it might stem from our experience of similar high fresh fruit bunch (FFB) yields in different soil types (Goh *et al*., 1994) and the present immediate problems in the oil palm industry which are not directly linked to soils. Moreover, many if not all local universities have de-emphasized soil science in their agricultural courses which is probably a major contributor to the lack of knowledge and its implementation in oil palm cultivation.

Good soil management is essential and probably the key reason for the continuous and successful cultivation of oil palms on the same piece of land for nearly a century or into the fourth generation of cropping. However, poor soil management will have dire consequences. For example, Goh and Chew (1994) showed that without fertilization, the mean fresh fruit bunch (FFB) yield of oil palms was 32 t ha^{-1} yr^{-1} on Selangor series soil compared to just 15 t ha^{-1} yr^{-1} on Rengam series soil. However, with fertilization similar oil palm yields were obtained from both soil types. With the rapid expansion of oil palm, many new soil series/types are regularly added to oil palm cultivation, which may not have been covered by past experiences or may pose major challenges. In fact, it can readily be envisaged that the increasing use of marginal land will present a more complex situation for soil management and probably dictate a better one to ensure competitiveness and economic viability of oil palm cultivation. This will also demand a correct identification of the types of soil limitations present and assessment of the degree of severity of each limitation in order to determine the most appropriate soil management practices required to fully exploit the yield potentials of the crop.

No agricultural system will be sustainable if it is not economically viable both for the farmer and the society of which he is a part (Johnston, 1995). Therefore, the importance of high early yields and sustainable yields from the economic stand point is obvious. Oil palm being a perennial is subjected to large fluctuations in yields and prices of inputs and outputs. Coupled with the large investments and fixed costs involved in the industry, the maximum economic yield is usually at or near the site yield potential (Goh et al., 1994a). There is now evidence to show that the inputs required to obtain the site yield potential do not necessarily endanger the environment, cause soil degradation nor reduce quality of the products (Chew et al., 1999).

The oil palm productivity is essentially an interplay between the palm's insatiable demand for resources to satisfy its growth and production, and the soil environment in its vicinity, which involves many factors. As expounded by Hew and Ng (1968) on oil palm nutrition and quoting them "such a situation can only be adequately resolved by comprehensive field experimentation on various soil types, repeated under different environmental conditions which unfortunately would necessitate a large number of trials and take a considerable time to complete" and/or extensive field management experiences on similar soil types and environment to understand and manipulate the soil properties to the benefits of oil palm and close the information gap.

In 1995, the first author presented a lecture in two parts entitled "Managing soils for plantation tree crops I. General soil management and II. Managing problem soils in Malaysia" at a course on "Soil Survey and Managing Tropical Soils" organized by the Malaysian Society of Soil Science and Param Agricultural Soil Survey. Much of the materials presented then is still relevant today and for this paper. Similarly, a few of our past papers cover the same subject matter e.g. Goh (1997) and Goh and Teo (2011). They are therefore reproduced verbatim for the benefits of most readers who are probably a new generation of agronomists and planters. Nevertheless, relevant updates are provided especially on the impact of soil microbiology and pH on soil fertility and oil palm nutrition and productivity. The primary objectives of this paper are to provide a general discussion of the principles of soil management, soil requirements of oil palm, and soil management requirements for oil palm before elucidating the specific soil management practices to improve problem or marginal soils for oil palm cultivation.

Part 1: General soil management

Principles of soil management

Tropical environments provide unique conditions for the high yields of numerous crops, only if the right combinations of management, inputs and other factors influencing outputs per unit area and unit time are utilised (Pretty and Sanders, 1985). Soil management is one of the principal components of the above in the worldwide race between food production and distribution, and population growth. Hence, it is not new and probably exists in tandem with the commencement of agriculture as recorded in writing dating back to 2500 B.C.

For many years, the main purposes of soil management are to maintain and improve soil fertility and synchronise soil productivity with and without enhancement, with crop requirements for high sustainable growth and yields. Therefore, we create soil conditions which are conducive to crop productivity such as

a) good anchorage for crops,
b) ensure sufficient soil volume for rooting activity, and
c) supply adequate essential nutrients and water throughout each and every crop cycle.

These basic principles have served us well as shown by the present agricultural production which is in surplus worldwide although food distribution can be a problem.

Food surpluses have brought along not only low prices and cheap food policies which often favour politics (Johnston, 1995) and agricultural produce of developed countries but also concern for environmental pollution, soil degradation and non-sustainable agriculture. With increasing population and decreasing amount of land per capita, these threats can be real if our soils are ineptly managed because farmers are forced to opt for cheaper management options to remain competitive or afloat. Thus, the present principles of soil management should encompass efforts to prevent such detrimental occurrences rather than a simple shift in paradigm to primarily tackle them. This is because the existence of mankind depends on the soils to provide an adequate supply of food and agricultural venture is a business concern.

We shall show that our present knowledge of oil palm and soils has allowed us to manage them in a sustainable manner and to do so in an environmentally acceptable way. This is probably central to our success in continuous cultivation of oil palm on the same land at profitable level for many years. However, we must take cognizance of the changing scenarios in and demands on the oil palm industry such as the risk of environmental degradation and unsubstantiated concerns camouflaged as scientific facts commonly taking precedent over crop productivity, and similarly for impacts of soil management on factors commonly regarded as associated with climate change, conservation of biodiversity and minimizing water and carbon footprints. Closer to home, issues involving labour shortage and effective plantation management put further unwanted pressure on soil management. Most of them can be overcome or alleviated through proper utilization of soil knowledge and appropriate implementation of site-specific soil management.

Soil property requirements of oil palm

The first approach in good soil management is to attempt to match the crop requirements with soil properties, with or without amendments. Water and nutrients are probably the most limiting agronomic factors to growth and yield of plantation tree crops (Goh and Chew, 1994). This is because tropical environments usually provide sufficient and uniform sunshine for crop production. It is well known that the above limiting agronomic components are available to rain-fed plants via the soils. However, to tap into water and nutrients efficiently, the plants need to have good rooting activity.

Rooting activity is influenced by many soil properties such as terrain, soil depths, stoniness, texture, structure, consistence, permeability, drainage and nutrients. These properties generally act in an interactive manner and an understanding of this dynamics is necessary to elevate the yield curve. Therefore correct identification of the types of soil limitations present is vital to soil management.

We also need to assess the severity of the identified soil properties which are limiting yield performances. Overcoming or alleviating them should upgrade the yield performances. It also enables proper formulation and implementation of specific soil management practices in each field in order to maximise return, avoid soil degradation and prevent environmental pollution.

The soil properties and their criteria for assessment of severity of their limitations for oil palm are provided in Appendix 1 and briefly discussed below.

Terrain

Under Peninsular Malaysian land law, it is unlawful to cultivate land with slopes more than 20° or 36%. These lands are classified as steepland and are usually marked in gray without identifying the soil series within them. Such landforms are commonly found in Sarawak and Sabah also but they are classified as steepland only if the slopes exceed 25°. Steepland may occur in the plantations but they are usually left unplanted, planted with forestry trees or if the area is very small, may be planted with plantation tree crops.

The main problems caused by steep topography are:

a) high risks on erosion, landslides and run-off losses of nutrients,
b) poor water balance due to excessive run-off,
c) the need to terrace implies the planting on less fertile sub-soil, which is commonly devoid of organic matter and generally firmer consistence,
d) generally lower planting density which is below the optimal for oil palm
e) poorer uniformity of planting pattern and palm growth
f) difficulty in harvesting and field maintenance operations with probably poorer crop recovery
g) often, economically impractical to implement known corrective measures to improve oil palm growth, nutrition and yields such as empty fruit bunch (EFB) mulching

Therefore, poor tree performances are not uncommon on steep slopes. However, the effect of slope seems to be less detrimental if the soils are fertile, such as with Kobovan Family soil in Sabah which is derived from basic volcanic parent materials.

Soil depth and stoniness

Adequate soil volume is a prime requirement for root development. Soil volume is a function of soil depth and stoniness. In plantation, effective soil depth is measured with an Edelman auger to an impenetrable layer within 90 cm depth while an increase in the degree of stoniness will correspond to a decrease in rooting activity.

The main effects of shallow effective soil volume are:

a) limited root room for adequate amount of roots,
b) weak anchorage,
c) low available soil moisture,
d) poor micro-porosity
e) low exploitable soil nutrients

In Sabah, stoniness is a less important factor because most rock fragments are loosely formed, partly weathered and mainly only stone sizes and sparse. Therefore, it does not form a continuous barrier to root penetration, development and activity unlike lateritic soils found in West Malaysia.

Under permanent moisture stress conditions as induced by poor rooting volume, the inflorescence abortion rate will increase and inflorescence differentiation will tend towards maleness in oil palm.

Texture, structure and consistency

These three soil physical parameters are closely related. They determined soil aeration (porosity), water holding capacity, permeability (infiltration), root penetrability and nutrient retention capacity. Unfavourable soil physical conditions inhibit root growth and function, leading to poor plant growth even under liberal applications of fertilisers (Soong and Lau, 1977).

Soil texture can significantly influence our management decisions. For example, in loamy soil to sandy loam soils such as Lintang series, with high percolation and low nutrient and water retention capacity, we will need more frequent manuring and mulching to improve crop productivity and reduce environmental pollution. On the other hand, tillage should be avoided on heavy soils such as Briah series to avoid soil compaction which degrades the soils and reduces crop productivity (Cheong and Ng, 1974).

Apart from soils with firm to very firm consistence such as Durian and Batu Anam series soils, further soil compaction can be caused by logging activities or use of heavy machineries. The hard pan left behind is difficult to break and establishment of oil palm is often slow. Aeration drains to remove surface water from ponding and improve water infiltration rate may be necessary for better palm growth and productivity.

The permeability of soils to water depends more on the structure with pore spaces than texture itself (Table 1). The implementation of poor permeability on crop growth is discussed in the next section.

Structure also influences soil aerations, which if restricted can cause:

a) inhibited root development
b) impaired respiration of root system leading to reduced water and nutrient absorption
c) inhibited beneficial microbial activities.

Total porosity may differ only slightly between soils of different structure and texture (Table 2) but air-filled porosity (non-capillary pores) is generally better for sandy soils or soils with good structure and friable consistence such as Munchong and Serdang series. Experience indicates that crop growth can be severely limited if air-filled porosity falls to 2% of the total porosity (Soong and Lau, 1977). Soils with good structure are also less erosive and less prone to landslides. The latter is common in Sabah where the soils are generally younger and have weaker structures.

Permeability and drainage

Permeability is generally associated with internal soil drainage and it is closely related to soil physical properties as mentioned earlier. Poor permeability can cause

a) perched water table such as in podzols
b) imperfect drainage even in hilly soils such as Batu Anam series,
c) poor rooting activity and its consequences as described earlier.

On flood plains and valley floors, high water table can be a common feature as in most Gleysols or Aquepts. Excessively high water table can give rise to:

a) inadequate soil aeration which hampers root respiration and causes poor nutrient and water uptake,
b) poor anchorage and lodging due to poor root development,
c) canopy turns chlorotic resulting in poor photosynthesis
d) stronger effect of moisture stress during drought periods as a result of poor root development and shallow rooting depth.

Generally, oil palm is less influenced by poor permeability and drainage compared to cocoa and rubber.

Nutrient status

Malaysian soils have highly heterogeneous inherent soil nutrient status (Goh et al, 1998). For example, Selangor series soils and young soil derived from basic volcanic rocks tend to have higher soil fertility compared to sandy or highly weathered soils such as Lintang and Munchong series, respectively. Moreover, soils in Sabah generally have high inherent Mg content compared to West Malaysian soils (Goh et al, 1998). However, Mg is continuously exported from oil palm plantation through fresh fruit bunches (FFB) and therefore, close monitoring of soil Mg status with interventional Mg input is essential to prevent its depletion to below the critical Mg level.

Nutrients, being one of the two most limiting factors to crop productivity, must be correctly assessed to afford proper fertiliser management practices. Over- or under-application of fertilisers can have disastrous effects such as

a) poor crop productivity due to lack of fertiliser or imbalance,
b) less in profit due to excess fertilisation,
c) soil acidification and degradation,
d) environmental pollution due to excessive leaching and run-off losses.

Apart from acid sulphate and very high pH (alkaline) soils, serious to very serious limitations on soil pH do not occur for oil palms. Further discourse is provided in Part 2 of this paper.

Other soil limitations

The other soil limitations are generally associated with particular type of soils. These limitations are high salinity or conductivity in saline soils (Bakau series), sulphidic layer in acid sulphate soils, ultra high soil pH in limestone derived soils and ultra-basic soils, and peat. These will be discussed in detail in the second half of this paper.

Soil management requirements for oil palm

After going through the soil properties and their limitations, we can broadly summarise the major soil management requirements into:

a) soil and water conservation management,
b) soil nutrient management,
c) soil acidity management,
d) soil water management,

as described by Cheong and Goh (1988). Soil and water conservation management also includes the amelioration and improvement of soil physical properties. Apart from the above four soil management requirements, it is essential to include soil organic matter management and soil microbe management in the oil palm plantations. These six soil management methods are not independent of each other and must be taken together to capitalize on their intricacies and interlinks for maximum benefits to the oil palm. In fact, soil fertility management is all about understanding the above relationships and strategizing and harmonizing the various soil management approaches into a single, unified and comprehensive soil management where only positive interactions must be implemented whilst avoiding practices that could cause intractable conditions and negative returns.

Soil and water conservation management

Erosion and run-off commences with the dispersion or breakdown of soil particles in the topsoil from the impact of rain. The dispersed soil particles and the usually more compact sub-soil slow down infiltration of the rain water into the soil. This accelerates and increases run-off which occurs when the rate of rainfall exceeds infiltration rate of water into the soil. Loss of topsoil not only reduces soil fertility but also means lower water-holding capacity of the soil.

In Malaysia, soil erosion under oil palms on slopes of 4 to 7° was measured at 6 to 13 t ha^{-1} yr^{-1} (Maene et al., 1979; Lim, 1990) compared to jungle area at 0.31 t ha^{-1} yr^{-1} (Maene and Sulaiman, 1980). Similar results were obtained by later researchers who found soil erosion rates in the first 3 years of replanting were between 2.3 and 5.4 t ha^{-1} yr^{-1} under bare ground conditions (Arif et al., 2007). Factors which affect the rate of soil loss are rainfall, rate of run-off, soil types, slope, plant cover and presence or absence of conservation measures.

The main objectives of soil and water conservation are to obtain the maximum sustained level of production from a given area of land by preventing soil degradation and environmental pollution. Therefore, soil conservation practices usually aim at the primary causal factors and areas. For example, reducing or protecting bare areas or exposed soil and reducing the rate of run-off. Timing in implementation of soil conservation measures is also important in plantation tree crops, as the highest risk of erosion usually occurs in specific period such as during planting or replanting and monsoon season.

Soil conservation practices should be considered in the following situations also:

a) strongly sloping or rolling areas and steeper (8° or more), particularly where slopes are long,
b) highly erodible soils especially in areas with slopes about 6^o. Such soils are usually sandy, with weak structure and low in organic matter such as Malau series and Kapilit Family soils,
c) areas with poor crop canopies and bare soil or sparse ground cover conditions,
d) areas with high and frequent intense rainfalls of more than 25 mm hr^{-1},
e) shallow soils (less than 50 cm) and compacted soils areas.

Lim et al. (1994) suggested that soil and water conservation measures such as terracing should be implemented on slopes of 3° or more but this has not been adopted by most plantation companies.

The following soil conservation practices should be considered for application in appropriate situations, depending on the specific erosion risks posed in the areas.

Terracing

Generally, there are two kinds of terraces; planting terraces and conservation terraces. The former is constructed mainly to facilitate harvesting, crop evacuation and maintenance operation apart from conserving soil and water. Planting terraces should slope inwards and there should be a vertical drop of about 50 cm between the lip and the rear of the terrace to trap run-off water. Regular stops along the terraces are also necessary for the same purpose.

The dimensions of terraces depend on the crops, planting density, slopes and whether future mechanisation will be implemented. In general, the terraces for oil palms should exceed 3.5 metre wide and preferably 4 metres for future mechanization and the horizontal distance between two adjoining terraces (6.5 to 9.5 metres) will depend on the planting distance along the terrace and planting density.

Long slopes which are less than 10° or short rolling to hilly slopes may require conservation terraces instead. They should be cut at approximately 30m intervals, primarily to reduce the length of slope. If platforms are made, they should be about 1.5m x 1.5m or larger for oil palms. However, they should be restricted to areas where terracing is impractical.

Establishment of leguminous cover crops

In oil palms, it is important to establish the legumes to reach full ground coverage as rapidly as possible after land preparation where threats of erosion and land degradation are most real. Ling et al (1979) showed that soil loss on a 10° gradient Munchong series can be 8 folds higher on bare soil compared to legumes or natural covers (Table 3). This is even more essential where the effective soil depth is already shallow. Furthermore, Ling et al (1979) reported that soil loss was reduced from 9.0 t ha^{-1} yr^{-1} at 0-30% ground coverage to 0.1 t ha^{-1} yr^{-1} at 90-100% ground coverage (Table 4). Similar marked reductions in run-off losses were also obtained. Moreover, the other beneficial effects of legumes on soil fertility, soil physical properties and soil biological activities are well-known.

Maintaining ground vegetation

Table 3 shows that natural covers which are not competitive for nutrients and water can be used to reduce soil erosion and run-off losses. This will improve soil moisture balance compared to bare soil conditions.

Good maintenance of ground covers is especially important in oil palm where legume covers are not established.

Frond stacking

In mature oil palms there is an additional opportunity to correctly stack the pruned fronds across the slope and cover as much ground area as possible to help in reducing the run-off and erosion losses substantially. This was demonstrated by Maene et al. (1979) on Durian series with mature oil palms on 5 to 9% slopes (Table 5). In terraced areas, pruned fronds placed across the terrace width at regular intervals will also assist to break the flow of run-off water.

Mulching with empty fruit bunches (EFB)

Wherever EFB is available, it can be suitably used for mulching especially in new plantings. The mulch will:

a) minimise erosion and run-off losses of the bare soil,
b) reduce soil moisture evaporation loss during the dry months (Lim and Messchalck, 1979),
c) supply nutrients to the planted seedlings,
d) improve soil conditions.

Fresh EFB can contain high soluble salts and must be applied as soon as possible to the oil palm which can withstand high conductivity to minimize soluble salts from being washed or leached off by rain before application.

Silt pits

In some areas, soil erosion and run-off may be very severe even with the construction of soil conservation and planting terraces. For such special areas, the digging of silt pits may be helpful as shown by Lim et al. (1994). However, yield response to silt pitting has not been established.

Soil nutrient management

Law and Tan (1973) and Goh et al. (1998) had clearly shown that large variations in soil fertility occurred within and between soil series in Malaysia. These variations also occurred spatially at macro- and micro-scales (Goh et al., 1996) thus demanding site-specific management approach to maximise efficiency. This is in agreement with the varied responses of plantation tree crops to fertilisations, where yield responses for oil palms ranged from 0 to 250%. Moreover, seasonal variation in soil nutrient contents is known but there are few data to quantify them in Malaysia. Also, with the high soil heterogeneity, the representativeness of the soil samples for the field where they are taken is often low. Therefore, soil analysis can only give a rough indication of the likelihood of a nutrient deficiency in plants, and one would not look to this technique in the first instance to decide on fertilizer rates in an existing plantation (Corley and Tinker, 2016). These authors further contended that nutrient is absorbed by a root from the soil solution via mass flow or diffusion and the nutrient equilibrium in soil solution is dynamic and varies widely depending on the desorption step, the diffusion/convection step or the actual uptake step. This complex process has to be condensed by soil analysis into a single value, and it is hardly surprising that it often fails (Corley and Tinker, 2016).

The realisation of above difficulties has caused scientists to develop schemes or methods to measure or assess soil fertility quantitatively or qualitatively. One of the schemes is called fertility capability classification system (FCC) but this is seldom applied in oil palm plantation. Instead, the assessment of soil fertility generally takes the format of single nutrients approach as shown in Appendix 2. The soil physical and biological properties are not included because they are generally handled separately.

Although one commonly uses extreme or large values in soil analysis to have a better probability of being correct, the major objectives of interpreting soil analytical data remain as follows:

a) to improve or maintain soil fertility
b) to recommend lime and fertilisers to the field
c) to diagnose the soil limitations
d) to provide a prognosis of the soil nutrient supply

that will produce maximum economic returns and sustainability of farming system without endangering the environment.

Soil diagnostic approach

The effectiveness and reliability of the interpretation should be judged by the accuracy of the recommendation in achieving the above objective rather than how it is reached. In soil diagnosis approach, some common philosophies used in soil test interpretation (Goh, 1997) are:

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

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

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

d) Over-fertilisation philosophy
This is derived from the fact that response curves are steeper below the economic optimum application than above (see Figure 1). Therefore, increasing the recommended fertiliser rate beyond that indicated by the experimental data to compensate for the fact that losses to the grower from using too little fertiliser are greater than those from adding more fertiliser than is needed. This philosophy also ensures that if the season is a good one, the economic returns will not be sacrificed for lack of nutrients.

Interestingly, these philosophies do not work in most situations on an individual basis. However, when they are used together or in combinations, they can form a sound scientific technique to interpret soil analytical data for manuring recommendations.

In fact, the early fertilizer recommendation system for oil palm was largely based on soil analysis results and nutrient balance approach (Goh and Teo, 2011). The underlying premise is that the soil can continuously supply a proportion of nutrients to the palms with negligible depletion of soil nutrients. Thus, it makes the assumption that the soil nutrients taken up by the palms can be replenished by soil weathering processes and biological activities. However, the soil nutrient supply differs substantially depending on its fertility status. For example, the fertile Selangor series soil can supply 1376 g potassium (K) palm^{-1} yr^{-1} which is equivalent to the amount of K in fresh fruit bunches (FFB) of 268 kg/palm/year (Table 6). On the other hand, the highly weathered Munchong series soil can only supply 302 g K palm^{-1} yr^{-1} or equivalent to 70 kg FFB palm^{-1} yr^{-1}.

It is also well-recognized that soil fertility is affected not only by soil nutrient content but also texture, structure, consistency, terrain, moisture status and mineralogy. This is shown in Table 6 where Briah series soil has higher K content but supplies lower amount of K to the palms compared with Selangor series soil probably due to its silty clay texture which has high K buffering capacity, firmer consistence and poorer soil structure (Goh et al., 1994b). It is not the purpose of this paper to discuss this subject in detail but the principles were illustrated by Hew and Ng (1968) when they drew up a tentative fertilizer schedule for oil palm (Table 7).

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

To avoid excessive application of fertilizer or mining of soil nutrients especially phosphorous (P), K and magnesium (Mg), a general classification table for soil nutrients is usually drawn up (Appendix 2).

The interpretation of the above soil nutrient classification, in particular for nitrogen (N), P, K and Mg, is explained in Table 8.

Apart from single soil nutrient classification, soil nutrient ratios have also been used to diagnose or provide a rough indication of the likelihood of a nutrient deficiency in the oil palm. For example, soil exchangeable Mg/K has to be above two to avoid magnesium deficiency on acid soils in West Africa (Tinker and Ziboh, 1959; Tinker and Smilde, 1963) and a variety of other soils in other parts of the world (Dubos et al., 1999; Goh et al., 1999) although it did not fit some Malaysian soils such as Rengam series (Corley and Tinker, 2016). Tinker (1964) further found that the activity ratio equation $\frac{K}{\sqrt{Ca + Mg + \sqrt[3]{Al}}}$ was a good guide to potassium status on acid sands soils of West Africa. This equation works well for Malaysian soils also e.g. Hew and Khoo (1970) showed that oil palm on acid sulphate soils responded well to bunch ash (K) but not limestone dust due to its high soil Ca despite the very low soil pH.

Inclusive of the aforementioned, the actual fertilizer rate for each nutrient status will also depend on the nutrients, palm age, soil types, terrain, soil moisture status and expected nutrient losses. Soil nutrient analysis is therefore rather subjective and probably unreliable, and those using it usually fall back to fertilizer response trials and experiences for further guidance.

Soil prognostic approach

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

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

The variables required by the set of equations are shown in Table 9. They can be separated into variable site characteristics and permanent site characteristics. The former (X1 to X8) are factors which control the FFB yields without N or K fertilizer inputs (i.e. dependent on soil N and K only) whereas the latter (X2, X8, X9 to X14) are factors which determine the efficiency of the response (FFB/kg nutrient applied) and probably, fertilizer recovery (Corley and Tinker, 2016).

The detailed equations and step by step procedures to compute the yield response curves of oil palm to N and K fertilizer inputs on alluvial and sedentary soils in West Malaysia are provided in Goh and Teo (2011), and will not be reiterated here. Suffice to say, Foster (2003) himself cautioned that this method is applicable within the environments where the trial data were collected i.e. in West Malaysia. Also, it only provides a first approximation of the initial fertilizer rates for the site. The fertilizer rates should be monitored and fine-tuned by leaf analysis results. Nevertheless, it gives a good insight into the major soil factors and environment influencing oil palm nutrition and productivity, which have been deliberated earlier.

Nutrient requirements

This part of the paper will cover only the fertiliser management of soil fertility since the other aspects have been dealt with.

The nutrient requirements of plantation tree crops are usually calculated based on the nutrient balance concept (Chew et al., 1994; Kee et al., 1994). This involves the equating of factors of nutrient removal against those of nutrient supply (Figure 2). Therefore, the fertiliser requirements will depend, apart from the crop removal, also on the inherent soil nutrient status. Foliar analysis is also used as a supplementary tool for the diagnosis of nutrient requirements.

Therefore, the key steps of an effective fertiliser management programme are:

a) determination of growth and yield targets,
b) assessment of the action required;

    i) What nutrients are needed?
    ii) What rates of nutrients are needed?
    iii) How best to achieve the most efficient and cost effective application of fertilisers to meet nutrient requirements?
    iv) What types of fertiliser to apply?
    v) Where to apply the fertiliser?
    vi) How often should we apply the fertiliser?
    vii) When to apply the fertiliser?

c) Assessment of the results and further action required,
d) Computation of the economics of the results.

Detailed description of the above is provided by Chew et al. (1994) and interested readers should refer to the paper. We shall instead discuss the fertiliser application technique in plantation tree crops which is one of the key factors in determining an efficient and environment friendly approach to soil fertility management.

Fertiliser application techniques

The higher the fertiliser efficiency the lower is the risk of manuring on the environment. This simple relationship demands that we maximise or attain satisfactory efficiency of the fertiliser applied. Proper application methods are essential to achieve this, especially in areas where the soils are prone to high run-off and leaching losses and to combat these, we generally rely on frequency, timing and placement of applied fertilisers.

Frequency of application

Foong (1993) using field lysimeter reported that after the first four years, low leaching losses in Munchong series soil were recorded for all nutrients except Mg (Table 10). However, Chang and Zakaria (1986) working on the sandier Serdang series recorded leaching losses of

10.4% for N and 5.1% for K with 2352 mm of rain per year. This apparent correlation between nutrient loss via leaching with soil texture was also illustrated by Pushparajah et al. (1973) in laboratory trials.

These results suggest that higher frequency with smaller dressings of soluble fertiliser is advocated for sandy soils such as Holyrood and Malau series. Similarly, higher frequency is recommended for steeper terrain where the risk of run-off losses is greater. The actual frequency of fertiliser application also depends on crop requirements, tree age, ground conditions, types of fertilisers and rainfalls. For example, higher frequency of application is provided to immature trees compared to mature trees and only a round of water insoluble phosphate rock a year compared to more frequent applications for soluble fertilisers such as ammonium sulphate.

Time of application

Although we are in the humid tropics, the rainfall patterns differ considerably between locations. On-going studies (Chew et al., 1994) show that high rainfalls prior to fertiliser application resulted in substantial nutrient loss, especially in high fertiliser concentration areas (Table 11).

The general guideline is to avoid fertiliser applications during:

a) period with high rainfall months of more than 250 mm month^{-1},
b) months with high rainfall days of more than 16 days month^{-1},
c) months with high rainfall intensity of more than 25 mm day^{-1}.

Placement of fertiliser

Fertilisers should be applied in areas with anticipated active root development and maximum feeder root distribution, which vary according to plant age and species. Therefore, fertilisers are applied close to the tree base in the initial years and gradually extended to the tree avenues when the canopy has overlapped and good root development is found there. In hilly terraced areas with mature trees, the fertilisers should be applied broadcast in the terrace itself and between the trees. In areas with platforms, the fertilisers should logically be placed around them.

Application of palm oil mill by-products

The palm oil mill produces substantial amounts of by-products such as EFB and anaerobic sludge. The applications of these by-products are encouraged because they return the organic matter and nutrients to the soil and hence, help to maintain soil fertility without causing environmental pollution.

Empty fruit bunches (EFB)

Gurmit et al. (1982) reported that 1 tonne of EFB contains 15.3 kg of ammonium sulphate, 2.5 kg of Christmas Island rock phosphate (CRIP), 18.8 kg of muriate of potash and 4.7 kg of kieserite. Hence, in mature oil palms, 40 t ha^{-1} of EFB are generally applied in the interrows to supply sufficient nutrients for a year. Supplementary fertiliser applications such as CIRP may be required to balance the nutrient requirements of oil palms.

Apart from being a source of nutrients, EFB also improves the soil physical properties and reduces soil water evaporation (Lim and Messchalck, 1979). Therefore, preference for EFB application should be given to problem soil areas such as the sandy podzols and shallow Malacca series.

Anaerobic sludge

The application of anaerobic sludge would also help to partly relieve moisture stress in soils susceptible to moisture deficits, in view of the considerable amount of water in the sludge. The usual recommended rate of application for mature oil palms is 450 l palm^{-1} yr^{-1}. The fertiliser equivalents according to the nutrient composition of 3.6g N, 2.4g K, 1.2g P and 1.5g Mg per litre (Lim, 1984) are 7.6 kg palm^{-1} of ammonium sulphate, 1.6 kg palm^{-1} of CIRP, 2.1 kg palm^{-1} of muriate of potash and 2.6 kg palm^{-1} of kieserite.

Supplementary fertiliser applications may again be required to ensure balance nutrition. The application areas of anaerobic sludge should also be in the palm avenues.

Other organic by-products

Apart from the above, decanter cake and belt-pressed cake are excellent sources of N for oil palm. The application of about 100 kg palm^{-1} yr^{-1} of these products will supply approximately 1.07 kg N palm^{-1} yr^{-1} and 1.12 kg N palm^{-1} yr^{-1}, respectively. Belt-pressed cake also contains relatively high amount of P and with 100 kg palm^{-1} yr^{-1} will provide 0.83 kg P_2O_5 palm^{-1} yr^{-1}, which is adequate for the growth and production of oil palm.

Soil acidity (pH) management

This aspect involves two major issues: one, soils with low pH and two, soils acidified by our management practices such as manuring and terracing. It also involves the crop species since cocoa is sensitive to low pH and high Al saturation while oil palm and rubber are much more tolerant to them.

Excluding acid sulphate soils which will be discussed in part two of this lecture, soils of pH less than 4.0 or Al saturation more than 70% might need liming although oil palm is known to be tolerant to soil pH. Lee et al. (2013) reported that oil palm seedlings showed Al toxicity symptoms when the Al^{3+} concentration in the soil solution was 4 mM. The lower leaves showed marginal chlorosis and root tips thickened and turned brown with no new development of fine roots. Both photosynthesis and nutrient uptake were also markedly reduced. The pH was 2.78 and using H^+ to induce the same pH did not cause leaf toxicity symptoms although fine root development was restricted. However, the oil palm tolerance to Al toxicity depends on its parentage with Dumpy Avros materials being more tolerant compared with Nigerian and Avros materials (Cristancho et al., 2011).

Soil acidification is generally a natural process of soil formation such as leaching of nutrients, nutrient uptake by plants and pollutants. However, soil acidification which is generally regarded as soil degradation can occur through fertilisation with acidifying fertilisers such as ammonium sulphate as shown.

$$(NH_4)_2SO_4 + 8O \dashrightarrow 2NO_3 + H_2SO_4 + 2H_2O$$

Kee et al. (1993) showed that this process occurs in oil palm agroecosystem where soil pH decreased from 4.2 to 3.8 after 7 years of NK applications (Table 12). Further reduction occurred a month after fresh application of NK fertilisers. However, K uptake did not seem to be influenced by such low pH (Kee et al., 1993). Although further trial is necessary to ascertain this, some plantation sector has taken the precaution to avoid soil acidification by applying NK fertilisers in the avenues of fully mature oil palms.

In general, based on over 25,000 soil samples taken from 1960s to 2009, we found that pH between 4.0 and 4.8 have no effect on maximum yields of oil palm. However, the maximum yields attainable decreased linearly when pH was lower than 3.5. Between pH 3.5 and 4.0, there was a discernible decline in maximum yield achievable although the differences seemed small. At pH 4.0, aluminium (Al) saturation is generally below 70%, which indicates the high tolerance of oil palm to Al. EFB mulching and liming are known to increase soil pH and might be used if the degree of acidification is found to be detrimental. However, the liming rate in Peninsular Malaysia depends on the initial soil Al saturation as illustrated by the general relationship (Foster et al., 1980):

$$dA/dL = -4.49 - 0.356\,A$$

where A = Al saturation (%) and L = liming rate (t ha^{-1})

It is assumed that the liming potential of ground magnesium limestone (GML) and calcium carbonate is similar for Malaysian soils.

Soil organic matter management

Soil organic matter is the paramount ingredient in soils because it is the dominant controlling driver of soil physical processes, soil chemical reactions and soil biological activities; the three key components of soil fertility triangle. In adequate amount, it ensures that the essential conditions for fertile soils are met i.e. a balance composition of nutrients, water and oxygen which are the critical needs of oil palm. Soil organic matter is also the main determinant of cation exchange capacity (CEC), buffering capacity for nutrients and pH, water holding capacity for water retention and food source for soil microbes and fauna, and it makes the soils more friable for ease of root penetration: all factors for better soil productivity or conditions for palm growth and production.

Traditionally, the composition of soil organic matter may be distinguished into living organisms (microbial biomass), identifiable dead tissue (detritus or litter) and nonliving, non-tissue (humus) matters. Brady and Weil (1999) further separated the latter component into humic and non-humic substances. The non-humic substance refers to the group of compounds e.g. polysaccharides that are mainly produced by microbial action and less resistant to decomposition. Among the humic substance, humin which is insoluble in NaOH has the highest molecular weight, is highly condensed and forms complexes with clay and probably silt particles. Humic acid, which is insoluble in strong acid of pH 1.0, and fluvic acid which is soluble, constitute the other two components of humic substances. All three groups of humic substances are relatively stable in soils and depending on the environment have half-life varying from 10 years to centuries (Brady and Weil, 1999).

These chemical division of humic substances although seems interesting, has little relevance to ecological processes. A more useful concept is to separate the soil organic matter into three functional fractions: active, slow and passive (Figure 3) as described by Brady and Weil (1999). The active fraction comprises materials with relatively high C:N ratio (> 15) and short half-lives where they are metabolized easily within a few months to less than 2 years. These materials probably include the living biomass, some of the fine particulate detritus (litters), polysaccharides and non-humic substances. The passive fraction consists of very stable substances which decompose very slowly and remain in the soils for hundreds to thousands of years. This fraction probably includes humus, humin and much of humic acids. The slow fraction which is an intermediate between the active and passive fraction and probably comprises mainly very fine divided plant tissues high in lignin, and other slowly decomposable and chemically resistant components.

Of the three major pools of soil organic matter or compounds, those in the active fraction are probably the most important in cultivated fields being directly involved in soil aggregate stability, mineralisation processes particularly N, P and C, and other soil properties attributed to soil organic matter. The active fraction is probably a very small pool in the soils and any very small changes in it will often cause pronounced alterations in soil properties and dynamic processes (Brady and Weil, 1999). The breakdown of slow fraction of soil organic matter will contribute to the active fraction whereas the roles of passive fraction in cultivated crops are probably more restricted to the discrimination of fertile and non-fertile soils based on their quantity, C cycle and sequestration, and cation exchange and water-holding capacity. Therefore, the management and conservation of soil organic matter in oil palm plantations is mainly geared towards the active and slow fractions of soil organic matter as follows:

a) Minimize loss of organic matter at planting or replanting i.e. returns above ground biomass to the soils
b) Build-up organic matter e.g. from legumes and vegetated ground
c) Maintain organic residues from palms and vegetation
d) Returns organic by-products from palm oil mills
e) Organic and bio-fertilizers

Minimise loss of organic matter at planting

Briefly, in the past and before the mid-1990s, fire is used to clear the land of the remnant trees after logging (logged-over, degraded land) of the previous crops when developing or replanting the land to oil palm. This practice of controlled fires was carried out by professionals with a prescribed set of procedures from felling, stacking and drying the trees and they were ignited when the weather including wind direction was optimal to have a good burnt and reduce smokes and particulate pollution to local level. It is a common perception that this practice will devastate soil organic C but studies showed otherwise e.g. Anon. (1989) reported that the initial decline in soil organic C from felling to planting the oil palm and cover crops was quickly replenished as the cover crops grew and produced substantial leaf litters particularly when they eventually shaded out and died (Figure 4). The decomposing leaf litter contributed to the soil organic C as evidenced by the escalated quantity in 1985, 3 years after planting the oil palm. In fact, if soil samples were taken to 60 cm soil depth, the soil organic C (%) under the oil palm were higher than those under forest in Sungai Tekam experimental basin in Pahang, West Malaysia (Figure 4). Khasanah et al. (2015) concluded from her study of 155 plots in 20 oil palm plantations across the major production areas of

Indonesia that the soil C stock of oil palm cultivation taken over 30 cm depth was neutral on mineral soils regardless of their previous land use i.e. forest or non-forest (Table 13).

With zero-burnt planting and replanting, the above and below ground biomass of forest trees and crops (oil palm, cocoa, rubber, coconut etc) will contribute substantial necromass to the soil organic C pools. van Noordwijk et al. (Unpublished) showed that about 12 t C ha^{-1} of necromass were returned to the soils when the degraded, logged-over forests were converted to oil palm plantations. This result also implied that most of the above ground biomass of forest was exported ex-site prior to land use change. Similarly, there is about 70 t C ha^{-1} of oil palm biomass at replanting and with zero-burnt replant will increase the soil organic C by an average of 7.7% in the interrow area (Ng et al., 2011). Khalid et al. (2000) corroborated this result by showing that chipping and shredding the biomass of the previous oil palm stands at replanting compared with complete removal of the biomass would increase the soil organic C in the top 30 cm by 12.8% at 18 months after treatment. Pulverization of the chipped and shredded biomass was even more effective because it increased the soil organic C by 24%.

Build-up soil organic matter

Apart from preserving the organic biomass at planting, the most effective way to build-up soil organic matter in highly degraded, infertile tropical soils from external vegetation is by establishing good and thick leguminous cover crops in the shortest possible time after land clearing. The conventional mixed of leguminous cover crops e.g. *Pueraria phaseoloides* and *Centrosema pubescens* when fully developed will improve soil organic C by 2.3 to 12.8% at 22 to 28 months after planting (Table 14). However, planting the fast growing and aggressive *Mucuna bracteata* will raise the soil organic C substantially by 110%. Nevertheless, most plantation management has difficulty in keeping this legume at bay and from smothering the immature oil palm. A better option is to mix it with traditionally grown leguminous cover crops at a low density of one *Mucuna bracteata* plant per oil palm i.e. same density as oil palm. This mixture of leguminous cover crops has been shown to be superior in terms of management, oil palm yields and improvement of soil properties.

In the absence of leguminous cover crops, light grasses and/or *Nephrolepis bisserata* should be maintained as the dominant vegetation in the plantations. This is because they can improve soil organic C in the top 15 cm by about 10.5% compared with bare ground (Table 14).

Maintain organic residues in the plantations

The oil palm has the highest carbon assimilation among the C3 crops and being a perennial, it therefore continuously contributes carbon to the soils via pruned fronds, dead roots (root turnover), frond butts, male inflorescences and other debris. These organic litters must be properly managed to maximize their conversion to soil organic C instead of being physically loss or decomposed into carbon dioxide.

Oil palm fronds pruned during harvesting and periodic upkeep are normally stacked between the palms where they decompose and build up soil organic matter. However, they should not be stacked too thick because the breakdown leaf litter must be mixed with the soils for it to become soil organic C. This mechanism is usually through fauna activity and rainfall. The frond stack should also be spread wide and against the contour for best effect. The carbon in pruned fronds is approximately equal to that generated for canopy growth because all fronds will eventually be recycled, which average approximately 4.25 t C ha^{-1} yr^{-1} (Henson, 2009).

In fact, soil organic C under the frond stack is usually 5 to 10% higher than the interrow areas (Table 13).

The root turnover is relatively rapid in oil palm and it can provide about 1.08 t C ha^{-1} yr^{-1} to the soils (Henson, 2009). Roots especially the primary and secondary roots have high lignin and low N contents resulting in C:N ratio exceeding 100. Thus, they decayed slowly and contribute to both active and slow fractions of the soil organic C pool.

The frond butt can account for about 11% of the standing biomass of oil palm (Henson et al., 2012). By the 14^{th} year after planting, it contains about 12 t C ha^{-1} and may slowly fell off the trunk until they are replanted. The drop off frond butts should be swept from the palm circles into the interrow areas or frond heap for them to decompose naturally.

The male inflorescences and other debris are small C sources probably less than 0.3 t C ha^{-1} yr^{-1}. They are usually removed from the palm circle during the raking process. Currently, there is no report on their role in the formation of soil organic C.

Returns organic by-products from palm oil mills

The palm oil mill produces a number of organic by-products when processing the fresh fruit bunches to palm oil. These by-products, namely, empty fruit bunches (EFB), palm oil mill effluent (POME), decanter cake and belt-pressed effluent cake, are regularly applied in the fields and they raise the site yield potentials between 0 and nearly 30% in Malaysia. Apart from this, they also improve the soil organic C content. For example, EFB applied at 40 t ha^{-1} yr^{-1} will supply 6.3 t C ha^{-1} yr^{-1} to the soils. Recomputing the data of Rosenani et al. (2011) showed that 2.09% of EFB applied at 22 t ha^{-1} yr^{-1} were converted to soil organic C over 10 years. When the rate of EFB application was doubled, the rate of soil carbon sequestration was 3.02% of applied EFB. Upon the application of EFB, the soil organic C content increased over that treated with chemical fertilizer with the greatest effect at the soil surface and generally following a decreasing effect with soil depth (Table 15).

Many workers have also reported that the application of palm oil mill effluent (POME) increases soil organic carbon within the vicinity of the applied areas. For example, Liwang et al. (2006) found that soil organic C increased within 60 cm from the point of application and down to at least 120 cm depth. Re-computation of their data showed that about 4.61% of the carbon in POME was converted to soil organic carbon over the period of study (4 years). Assuming all the EFB and POME were returned to the fields, this will contribute a substantial amount of C (7.45 t C ha^{-1} yr^{-1}) to the field with 3 to 4.6 % being converted to soil organic C.

The application of compost, decanter cake and belt-pressed effluent cake should have similar positive effect on the soil organic C since they are basically derived from EFB and/or POME.

Organic and bio-fertilizers

Recently, organic and bio-fertilizers have been actively promoted for oil palm although they have been used for decades now particularly among the smallholders. Unlike the utilization of by-products from palm oil mills which are applied in large quantity exceeding 10 t ha^{-1} yr^{-1}, the inputs of organic and bio-fertilizers are considerably lower in the kg ha^{-1} yr^{-1} scale due to economic reasons. Hence, these products may contribute insignificant amount of C to the soil organic C pool.

Currently, there is only a trickle of reports on well conducted, scientific investigations on the impact of organic and bio-fertilizers on oil palm yields and soil properties, particularly on soil organic C. Khalid et al. (2015) showed that soil organic C in the weeded circle in the top 15 cm was raised from 0.76% to 0.93% (22.4% increase) when organic fertilizer containing 70% organic materials, 20% mineral fertilizer and 10% zeolite was applied at 592 kg ha^{-1} yr^{-1} for 4 years. There was negative response to vegetative growth parameters and no difference in FFB yields in the first 3 years of treatments. However, in the fourth year before the trial was closed, FFB yield in plots treated with organic fertilizer jumped to 29.09 t ha^{-1} yr^{-1} compared with 25.48 t ha^{-1} yr^{-1} in chemical fertilizer plots. Application of bio-fertilizer (5:5:5) at 2.66 t ha^{-1} yr^{-1} could not meet the K requirement of oil palm with consequent lower FFB yield at the 4^{th} year of treatments despite improving the soil organic C to 0.94%. These results also indicated that the constituents of the bio-fertilizer were probably in the light C fraction, which decomposed rapidly and contributing to the active C pool only. Variable results from negative to positive effects of organic and bio-fertilizers on oil palm production have also been reported by others. These organic and bio-fertilizers seem to act slower than chemical fertilizers. We shall not delve further into this subject in this section of the paper but suffice to say, further research on organic and bio-fertilizers for oil palm is still urgently needed particularly on partial substitution of chemical fertilizers, and their long-term impacts on soil fertility, microbial activity, and pest and diseases of oil palm.

Soil water management

Water management practices include drainage and irrigation of the land, and soil moisture conservation practices. Adequate soil moisture is required for good growth and yield of plantation tree crops. Hence, moderate responses to irrigation have been reported for oil palm in Malaysia (Kee and Chew 1993, Lim et al., 1994). Later work e.g. Lee et al. (2007) showed higher oil palm yield response to irrigation exceeding 30% but much of this work was non-replicated although conducted on a relatively large scale. However, excessive water such as high water table can reduce crop productivity substantially (Lim et al., 1994).

Soil moisture conservation measures or irrigation will be beneficial in the following areas:

a) inadequate rainfall of less than 1700 mm per year,
b) poor rainfall distribution pattern,
c) somewhat excessively to excessively drained soils,
d) very shallow soil or soil causing restricted rooting.

As irrigation is frequently impossible or economically unfeasible due to unavailability of water and high capital costs of installation, water conservation measures should be aimed primarily at maintaining maximum use of rainfalls on the plantations. This includes minimising run-off and erosion, and maintaining or improving infiltration of water into the soil. Therefore, soil and water conservation practices are complementary to a large extent.

Irrigation, despite giving good yield responses, should only be implemented if the following conditions can be met:

a) regular severe moisture stress is limiting growth and yield,

b) adequate water with salinity less than 1000 mhos cm^{-1} can be ensured during dry season,
c) the irrigation system is easy to maintain,
d) an economic system of irrigation is possible.

The other extreme of water management is when excess water occurs in the area. Proper drainage systems are essential to prevent prolonged flooding which is detrimental to crop production.

The primary aim of drainage for plantation tree crops is to maintain the water table at 75 cm and not less than 50 cm from ground surface at most times. The optimal depth of water table depends on soil types, peat types, climate particularly the rainfall quantity and distribution and cultural practices e.g. the degree of compaction in peat to elicit optimal rooting activity for best oil palm growth and production. To achieve this, a good outlet with sufficient capacity for the water discharge requirements is vital. Otherwise the excess water could still be contained within the planted area. The direction of field and main drains should be in line with the flow direction of the water. The intensity and dimension of drains depend largely on the expected amount of water to remove during the wet months. Cheong and Ng (1974) proposed higher intensity of field drains for clayey soils compared to sandy soils. The water level in the drains may be controlled using water gates, weirs and stops.

In sandy podzols, perched water table may occur due to poor percolation of water. Scupper drains which break through the hard-pan (spodic horizon) are required to remove the stagnant water before planting. Similarly, in compacted soil with poor infiltration rate, aeration drains have been found to be beneficial.

The drainage requirements of peat, acid sulphate and peat soils are discussed in Part 2 of this paper.

Soil microbe management: Preserving soil microbial diversity and its implications on soil ecosystem processes and agro-management practices

Soil microbes are often reiterated to play key roles in global ecosystem processes, such as nutrient cycling while there are bountiful reports published over the years documenting the impact of land-management practices on microbial dynamics (Bender et al., 2016). Microbial processes associated with nutrient cycling in soil include C turnover, and N, P and S mineralisation amongst others. Soil microbial diversity has also drawn much attention associated with plant disease suppression (Bonilla et al., 2012) and even more recently reported to influence weed establishment by either facilitating or limiting their invasion (Inderjit and Chill, 2015). Various abiotic and biotic factors influence soil microbial dynamics, with the decomposition of organic matter commonly being reiterated as a dominant factor. Though various studies have reported that inputs of organic matter enhance microbial dynamics, their responses vary with numerous reports associating C:N ratio with substrate quality affecting microbial diversity and its rate of decomposition. Briefly, low-quality organic matter substrate (i.e. high C:N) generally favours fungi while high-quality substrates (low C/N) favours bacteria.

It may be objected though that the primary function of agricultural land use is not the preservation and support of biological biodiversity, but instead the production of food and raw materials. Agro-management practices irrespective of the cropping system have been investigated to achieve the right balance for sustaining maximum yields and hence shaping cultivation methods and the cropping landscape. Irrespectively, agronomists and agriculturists have factored in the pros and cons of various practices and through research are establishing good agricultural practices that minimise the losses of biodiversity yet achieve their goal of attaining maximum yields, especially in the last decade or so when environmental awareness has grown. With the oil palm ecosystem, good agricultural practices include utilisation of necromasses (i.e. frond heaps and EFB) and legume cultivation at the time of replanting. Beneficial plants and ferns are often advocated. These practices not only return organic matter back to the soils (which drive microbial dynamics) but add variation to the oil palm monocropping system, contrasting to most other monocropping systems for edible oil production.

The oil palm ecosystem can generally be categorised into microsites, comprising palm circles (PC) (bare ground conditions) and frond heaps (FH). Other microsites exist including interpalm (IR) areas (with soft grasses though this may vary with estates as often weeds are also common) and furthermore, vary with the different planting phases when leguminous cover crops dominate ground vegetation during the immature and young mature years before they are phased out due to light reduction. From our on-going works, these microsites create microhabitats resulting in niche microbial diversity (Figure 5). Importantly, the availability of organic matter and its subsequent decomposition and rate limiting processes appear to shape the niches in microbial diversity in the oil palm landscape. Estimations of diazotrophs (non-symbiotic N2-fixers) and P solubilizers in soil samples in different microsites are summarised in Table 16. Despite their variation, their numbers reveal that the oil palm ecosystem is not void of beneficial microbes and furthermore highlight their elevated responses in the presence of organic matter. Microbial activities also increased in microsites with organic matter inputs (Table 16).

The degree of variation, however, is further influenced by the prevailing soil physicochemical properties (i.e. clay content, pH) (Mahamooth et al., 2014), though other factors are also to be factored in, i.e. plant diversity (via their exudates and litter quantity and abundances) and available moisture. Soils below frond heaps exhibited greater variation compared with palm circles comprising bare ground conditions, which showed surprisingly minimal variation. Frond heaps overall exhibited higher microbial abundances (including beneficial microbes) which correlated with the increase in soil microbial activity. We also observed higher fungal abundances in palm circles while interrows were dominated by bacteria. Copitotrophic (Fermicutes, Actinobacteria, Bacteroides and β-proteobacteria):oligotrophic (Acidobacteria and α-proteobacteria) ratios also vary between the two sites, attributed primarily to differences in organic matter inputs, i.e. frond heaps. Irrespectively, both microsites are not void of either group of microbes. The differences in microbial diversity may have an immediate effect on the distribution of PGPR (beneficial microbes), BCAs (biocontrol agents) as well as pathogens. We have attributed their microbial distribution patterns between the two microsites primarily to the availability of organic matter and moisture.

It is evident by the abundance of microbial-based research that further considerations are required to preserve soil microbial diversity. Their interlinked and inter-dependence on crop growth warrants further research and due considerations to be factored in. Evidently, research on oil palm is still in its infancy and warrants further exploration albeit we are gathering evidence on the effects of agro-management practices on microbial dynamics, the need to correlate ecosystem processes with microbial diversity and abundance remains. More importantly, sufficient evidence is still lacking on the responses of symbiotic/beneficial microbial interactions on oil palm growth (including palm productivity), as most studies investigating the effects of biofertilizers with oil palm were ascertained under nursery conditions. Inferring from nursery trial responses, biofertilizers are now commonly recommended for field application. The responses in terms of growth benefits to field cultivated oil palms and their FFB yields remains to be addressed. The use of biofertilizers (though comes with good prospects) may vary in their responses to boost soil fertility and plant responses attributed to the prevailing abiotic and biotic factors that are likely to vary between different soils and geographical locations. It is also well documented that the survival of microbes (endogenous or exogenous via biofertilizers) are dependent on the availability of C and N to sustain microbes. With the limited research findings available, it is evident that organic matter preservation and additional inputs help drive microbial diversity within the oil palm ecosystem. Our current assessment concurs with various studies that soil biological activity is interlinked with soil physical and chemical properties and hence resulting in variation in microbial diversity and their abundances. These factors should all be considered in assessing whether a biofertilizer product can universally adapt to all agro-climatic conditions cultivated with oil palm or limited to specific conditions. With an average 25-year economic lifespan and various commercial planting materials (with different lineages) available to planters, one should also address whether microbial-plant responses are age and lineage-dependent.

Inferring from our literature review and on-going research, agro-management plays an important role in preserving microbial diversity in any agriculture landscape. Table 17 summarises some of the key agro-management considerations that can impair or enhance microbial (biological) activities and their subsequent effects on soil dynamics (soil physicochemical properties). Evidently, organic matter inputs drive microbial diversity and thus far, the oil palm industry is utilising palm necromasses to enhance soil quality. Emphasis should also be placed in preserving beneficial plants and maintaining weeds within a manageable standard to increase agrobiodiversity unless sufficient evidence arises that associates a particular weed to enhance pathogen levels. Fertilizers too have an important role. While the oil palm relies on high fertilizer rates, understanding the chemistry of fertilizers and their fate in soils can help minimise the possibility of soil acidification (often attributed to ammonium-N based fertilizers). Other considerations such as broadcasting them over a wider area as opposed to concentrating it say over frond heaps only may help to buffer the reduction in microbial dynamics. Agro-chemicals, e.g. herbicides are also known to exert changes in diversity particularly if applied as blanket spraying which leads to losses in ground vegetation. The cascading effect of vegetation loss will likely have detrimental effects on preservation of microbial dynamics. Unlike other cropping systems, field cultivated oil palms do not rely on the usage of fungicides, which are more potent towards fungi. Its usage and subsequent effect on fungal populations will result in a cascading effect affecting the microbial food-web chain.

In summary, with the complex inter-linkages between biological, chemical and physical soil components, it is evident that agro-management practices can impact soil dynamics irrespective of whether it directly targets a soil component, e.g. the effects of soil compaction along the harvester’s path which does not only affect the soil physical component but has a cascading effect altering both the chemical and biological component. While microbial activity is gaining interest, ascertaining their interrelations in soil and effect on palm growth is paramount. Knowledge of their beneficial or detrimental effects should be considered a tool for the betterment of agro-management strategies rather than a hindrance. With the advances in agriculture sciences and incorporation of omic technologies, we are now in a capable position to address some of the pertinent issues relating to the oil palm ecosystem and its management.

Part 2: Managing problem soils in Malaysia

Introduction

The first part of this paper elucidates the general principles of soil management, interprets soil requirements and implements proper soil management practices for plantation tree crops. We shall now discuss how we can combine them interactively to manage problem soils for oil palm.

The term "problem soils" appeared many times in literature but it has not been well-defined yet. Longman dictionary describes the word "problem" as "a difficulty that needs attention and thought". Therefore, problem soils may be defined as soils which require special or specific attention, thought and methods to successfully manage them. Within the plantation industry, the conceptual idea of problem soils is probably "unsuitable soils for cultivation in their natural states but upon proper soil management and amendments, they can be converted for plantation tree crops with yield performances, at times, matching those on suitable soils". This statement underscores the crucial role of soil management and that problem soils are not necessarily fragile soils or unsuitable soils for oil palm cultivation.

Based on this concept, there are probably seven groups of problem soils, namely,

a) deep peat
b) shallow acid sulfate soils
c) saline soils
d) shallow lateritic soils
e) podzols or spodosols,
f) sandy soils (quartzipsamments), and
g) ultra-basic and limestone derived soils

Each group of soils requires its own specific soil management practices. With the present lack of labour, cost of management and price of produce, oil palm is the primary tree crop grown on these soils.

There is a growing and discernible pressure from some quarters to utilise problem soils for oil palms despite the much more effort, time, difficulty and cost to do so which reduce competitiveness. This might stem from the reports of high yields on these soils but more so, from the lack of large scale experience to manage them for oil palms or for political gains. Our own experiences generally indicate that it is probably inadvisable to have more than a quarter of problem soils in any one plantation for long-term viability. Nevertheless, it is still critical to manage these soils correctly from economic standpoint, environmental consideration and maintaining competitiveness.

Managing deep peat

There are 2.4 million hectares of peat in Malaysia, with 1.5 million hectares occurring in Sarawak alone. Oil palms are cultivated on peat on a large scale since the mid-fifties. However, major problems were encountered especially on deep, fibrous and woody peat particularly those located in peat dome and it was not until the eighties that oil palms are successful grown on it.

The problems with deep peat lie in its physical and chemical characteristics. Peat, in its natural state, contains excessive amount of water due to its low physiography and water holding capacity of 20 to 30 times its own weight. Consequently, aeration is poor and bulk density is very low at less than 0.1 g cm^{-3}. Upon drainage, peat will undergo irreversible drying and extensive subsidence of 3.6 cm yr^{-1} in the early years of development before slowing down to less than 1.5 cm yr^{-1}. Apart from this, peat provides an imbalance nutritional medium for plant growth (Table 18). Although it has high total N content, it also has high C:N ratio, rendering a slow availability of N to the plant. Moreover, it has low K, Cu, Zn and B and high acidity of pH less than 4.0 (Gurmit et al., 1987).

Bearing this in mind, United Plantations Berhad (UPB) has developed various novel methods to alleviate the problems and allow successful cultivation of oil palms on deep peat. Therefore, this part of the paper is extensively drawn from the excellent papers written by Gurmit et al. (1987) and Melling et al. (2011). Later papers describing the successful cultivation of oil palms on peat especially from 2nd generation oil palm on deep peat where FFB yields exceeded 30 t ha^{-1} yr^{-1} was based on the above papers with adaptation to local environments.

The first problem confronting a planter when developing peat for oil palm is to remove the excessive water in the peat swamp before felling and clearing operation can be initiated. This is done by constructing a perimeter drain, the dimensions of which depend on the size of area to be cleared and distance from a river outlet, using an excavator. Due consideration should be given out to prevent over-draining the area as this will result in rapid shrinkage of the peat and irreversible drying of the top layer, which adversely affects establishment and growth of oil palms. Hence, the drainage system must take into consideration the whole peat basin and not just the concession area alone.

Perimeter bund is commonly required and it is constructed from excavated soil materials of the perimeter drains or nearby soils. There should be an excess berm of at least 5 m wide between the perimeter bund and drain for future maintenance work. The perimeter bund should be at least 1.5 m wide, leveled and compacted to allow supervision by motorbike or truck. For stability, the bottom width of the bund should be at least twice that of the top width although it would depend on the height. In general, the higher the bund, the wider the base. The bund should be at least 50 cm higher than the highest flood level in the past 30 years, if possible. Also, the depth of the bund should be about 1 m deeper than the main drain which connects to it to facilitate drainage and water control.

Basically, the internal field drainage system consists of a network of field, collection and main drains (Figure 6), the usual dimensions of which are:

Type of drain	Drain spacing	Width (m)		Depth (m)
		Top	Bottom	
Field	1:4 palm rows	1.0 - 1.2	0.5 - 0.8	0.9 - 1.2
Collection	300 m	1.8 – 3.0	0.8 – 2.0	1.2 – 2.0
Main	1000 m	3.0 - 6.0	1.2 – 2.5	1.8 – 3.0

The intensity of drains depends on the rainfall, topography of the field, planting density and types of peat but the primary objective is to keep the water levels at 50 to 75 cm from the surface at most times. In Riau, Indonesia where rainfall is much lower than Sarawak, Malaysia with many of their peat basin overlying acid sulphate soils, the optimal water table in the field is between 40 and 60 cm from the peat surface. We also wish to point out that this is usually 10 to about 30 cm above the water depth measured in the drains depending on the rainfall season. The optimal water level is achieved through a series of stops, weirs and water gates. Periodic flushing of the acidic and excessive storm water during the rainy season is also carried out.

The low bulk density and subsidence earlier present obstacles to road construction and planting. Field and main roads are now created using spoils from roadside drains, levelled and compacted by bulldozer and then lined with laterite and mining ballasts. In Sarawak, the underlying sand is commonly used as surface materials for roads. Before planting, the harvesting path and planting rows are mechanically consolidated by running an excavator 2 to 3 times over them. This operation should be carried out during the drier period and the water table is temporarily lowered to a meter or more to allow proper compaction to take place. The completed operation leaves a 9.5 to 11.5 m wide area free of timber and compacted to a depth of 40 to 50 cm (Figure 7). Consolidation increases the bulk density from 0.11 to at least 0.20 g cm^{-3}, reduces the incidences of leaning and fallen palms by at least half, improves micro-pores, decreases water cavity, accelerates water capillary flow from the water table to the upper peat profile, and improves FFB yield by more than 25%. Planting density is also increased to 160 palms ha^{-1} to attain optimum leaf area index of 6.0 by the 10^{th} year for peak FFB production on this poor growing medium.

The irreversible drying of the top layer is prevented by maintaining satisfactory water-level of 50 to 70 cm from the peat surface, and good ground vegetation of legumes (where feasible to establish), light grasses and low density of *Nephrolepis biserrata*. Moreover, blanket spraying may increase the risk of fire and affect the predator-pest balance.

Deep acid peat provides interesting nutritional complexes to agronomists. While total N content can be high (1.3 to 1.5%), its availability is initially low due to high C:N ratio (Table 18). Upon drainage (Table 19) and liming, the peat will mineralize leading to a decline in C:N ratio and enhancing N availability. Thus, the priority is to provide high N rate (up to 1.2 kg urea $palm^{-1}$ yr^{-1}) in the initial immature phase and subsequently reduce it during the mature phase (0.5 to 1.25 kg urea $palm^{-1}$ yr^{-1}). This approach was supported by the work of Gurmit et al. (1987) which showed good FFB response to N in the first 4 years of harvests only (Table 20). However, in fibrous and woody peat with relatively low rainfall, higher rate of N up to 3 kg urea $palm^{-1}$ yr^{-1} may be required to maintain adequate N in the canopy for maximum FFB yields. This approach needs to be closely monitored as excessive N can cause premature frond desiccation and negative yield response.

The mineralisation of peat also releases P to the system, which contains low Al and Fe for fixation. Therefore, only low P rates of 0.5 to 1.0 kg phosphate rock $palm^{-1}$ yr^{-1} are generally provided. Excessive P application can leads to lower yield and Cu imbalance (Cheong and Ng, 1980). Together with excessive N uptake, it can also cause leaf chlorosis and premature frond desiccation which was speculated to be caused by the accentuated accumulation of free amino acids, amines and organic acids (Cheong and Ng, 1980). On the other hand, potassium is very deficient in peat and hence, high rate of Muriate of potash up to 6.0 kg $palm^{-1}$ yr^{-1} is recommended. EFB mulching where practical and economical can also be applied because apart from supplying K, it also improves soil pH and rooting activity of the oil palms on peat.

Although good response to liming has been obtained for 1st generation oil palms on deep peat, the effect is unlikely to be due to Ca. It is most probably a result of improved mineralisation rate, increased soil pH and a better cationic-anionic balance in the plant system (Cheong and Ng, 1980).

Peat is also deficient in Cu, Zn and B. Early dressings with these micronutrients are essential to avoid mid-crown chlorosis, peat yellow and stump leaves respectively. Often, structural deformities of the canopy and white-stripe can be alleviated by temporarily withholding the application of N while increasing the rates of K and B to the oil palms. However, excessive B application must be avoided as it can be phytotoxic and can adversely affect the uptake of Cu (Gurmit et al., 1987).

Draining the peat swamp increases acidity as shown in Table 19. This is alleviated by periodic flushing of the drain water, especially during rainstorms, and liming. Maintenance of correct water levels is also important since hyperacidity seems to occur only during prolonged dry spell. Although the symptoms of hyperacidity were similar to premature lower frond desiccation, the likely primary causes are probably different. Nevertheless, we cannot discount the possibility that both maladies act together or in consort.

Proper soil and water management of oil palms on deep peat has resulted in FFB production closely mirroring that on good mineral soils (Figure 8). However, we must caution that the problems with planting oil palms on deep peat escalated exponentially with the areas of peat, particularly in relation to the amount of good mineral soils in the plantation. We should also be aware that there is currently a continuous and concerted effort by various quarters who lobby aggressively against the cultivation of oil palm on peat regardless of peat depth on the ground of deforestation and excessive carbon dioxide emission which purportedly accelerates global warming. This negative call for action ignores other valid reasons for development inter alia local and national socio-economic advancement and must be urgently addressed by the plantation industry via landscape planning and multi-stakeholder decision making if oil palm trade particularly in developed countries is not curtailed, fairly or otherwise.

Managing shallow acid sulfate soils

Acid sulfate soils are estimated to cover an area of about 110,000 ha in Peninsular Malaysia with at least 20,000 ha under oil palms (Poon and Bloomfield, 1977). These soils are characterised by very low pH values (< 3.5) and the presence of yellowish jarosite ($KFe_3(SO_4)_2(OH)_6$) mottles (Shamshuddin and Auxtero, 1991).

The problems with acid sulfate soils are:

a) they tend to be waterlogged in their natural state and must be drained before cultivation, and
b) draining beyond the pyrite layer will generate excessive acidity which is detrimental to palm growth.

The latter is due to the oxidation of pyrite to form sulphuric acid as shown overleaf:

$FeS_2 + 8O \text{-------->} Fe^{2+} + 2SO_4$ (1)

$Fe^{2+} \text{------------->} Fe^{3+}$ (accelerated by Thiobacillus ferrooxidans) (2)

$Fe^{3+} + FeS_2 \text{------>} 2Fe^{2+} + (S......SO_4^{2-})$ (3)

This oxidation also causes breakdown of clay minerals which releases Al, Mn and K into the soil solutions (Shamshuddin and Auxtero, 1991). The drop in pH to below 3.0 is not uncommon and the oil palms will suffer hyperacidity symptoms and poor yields. Toh and Poon (1982) further classified acid sulfate soils into 3 categories based on oil palm performances. Their severe category has acid layer at 0 to 60 cm while current soil classification in Malaysia tags it at 0 to 50 cm for shallow acid sulfate soils, such as Linau and Sedu series.

Hew and Khoo (1970) found that liming was generally ineffective to control acidity in acid sulfate soils. Poon and Bloomfield (1977) then showed that by creating anaerobic conditions, the reaction in equation (1) will not proceed and thus, preventing the generation of acidity. Since inadequate drainage will give rise to flooded conditions which also adversely affect palm performance, a balance has to be struck between over and under drainage.

This balance is achieved through a network of field, collection and main drains similar to those found in peat swamp as described earlier but their objective differs. The prime requirement in the management of acid sulfate soils is that the water-table should be maintained above the pyritic layer for as long as possible. This is again carried out using stops, weirs and water gates, their numbers are largely determined by the depth to pyritic layer and slope of the land. Normally, the water-table is maintained between 45 to 60 cm from the soil surface, hence, the depth of field drains should not exceed 75 cm. Otherwise, there is a risk of accelerated oxidation of the pyritic layer during dry weather conditions (Poon, 1983).

Another important aspect in the management of shallow acid sulfate soils is to provide for periodic flushing of the drains to remove the accumulated toxic polyvalent ions such as Al^{3+} and the extremely acidic water (Poon, 1983). Therefore, during the wet season, all the water retention blocks and water gates are opened to allow flushing. One to two flushings during the wet season are usually adequate. Before the end of the wet season, the blocks and water gates are again closed to allow fresh water to build up to the required level.

The other aspects of management of acid sulfate soils are similar to those of coastal non-acid sulfate soils except for the oil palm nutrition. The success in using water control to manage oil palms on shallow acid sulfate soils is best illustrated by Figure 9.

In terms of oil palm nutrition, we need to take cognition of the impact of drainage and flushing on soil properties. Firstly, during the flushing process, apart from the removal of Al^{3+}, K^{+} is more susceptible compared with the divalent Ca^{2+} and Mg^{2+} from being flushed out or leached beyond the rooting zone. Thus, the amount of K and/or $\frac{K}{\sqrt{Ca + Mg + \sqrt[3]{Al}}}$ may be sub-optimal and positive K response can be obtained e.g. Hew and Khoo (1970) showed strong oil palm yield response to bunch ash and MOP in Sedu series soils.

Secondly, the hydromorphic nature of acid sulphate soils increases the availability of phosphate rock (PR) to the palms. They also have lower P sorption capacity. Therefore, low P response can be expected on this soil type. In fact, excessive input of PR may have deleterious effect on growth and yield of oil palm although the reason for this is still uncertain.

Thirdly, the acidity of the soils changes with time and regular soil tests should be made to determine the optimal depth of water table in relation to soil acidity at each soil depth and local weather. It is not uncommon for the Kranji series and Sedu series soils to quickly develop into the better soil types such as Jawa series.

It should be noted that with proper management of acid sulphate soils in the 1st generation oil palm planting and at replanting, the yield performances of 2nd or 3rd generation oil palm plantings commonly exceeded the previous generation with reports of FFB yields over 20 t ha^{-1} yr^{-1} in the first year of harvesting and over 30 t ha^{-1} yr^{-1} during the peak yielding period (Xavier et al., 2011).

Managing saline soils

Saline soils occur by the sea or around river mouths and are constantly inundated by sea or brackish water. Consequently, they have a young A/C profile with conductivity commonly above 10,000 µmhos cm^{-1}. In potential acid sulfate soils such as Bakau series, they may contain high water soluble sulfate exceeding 0.35%. Saline soils generally occur in low rainfall region in Malaysia.

Our plantation tree crops are not salt tolerant and hence cannot be grown on saline soils before ameliorations. Despite this, a number of large plantation companies in Malaysia, such as K.L. Kepong Bhd., Sime Darby Bhd. and Golden Hope Plantation Bhd., have successfully grown oil palms on it. However, before reclamation work proceeds, we have to ensure that at least the following conditions prevail at the site.

a) materials for bunding are available,
b) if (a) is unavailable, then the “n” value of the soils should be less than 0.7
c) most of the land boundary should not be erosional surface,
d) the land should preferably be higher than the sea or river level at low tides,
e) rainfalls should be sufficient (> 1700 mm yr-1) to allow flushing and leaching of salts,
f) land area must be sufficiently large to dilute the cost of reclamation and maintenance to economic level

Preventing further intrusion of sea or brackish water of more than 1000 µmhos cm^{-1} into the land is central to reclamation of saline soils. This is accomplished by constructing a bund around the periphery of the land. The bund should be at least 3 feet above the highest tide level. Consideration must be given to the river and its tributaries in the land in deciding the course of the bund. The soil strength of the bund has to be considerably improved if it faces the erosional surface of the river. In fact, under such condition, it is not uncommon to set back the bund by about 30 m.

Upon completion of bund construction, a drainage network comprising main and collection drains must be laid down to reduce the water table and allow for subsequent flushing of the drains. There must be sufficient water gates and water pumps to remove the water trapped in the land. The periodic flushings usually continue for two to four years before the conductivity drops below 2000 µmhos cm^{-1} within the top 45 cm to allow successful planting of oil palms but best growth is obtained when it drops below 1000 µmhos cm^{-1} in the top 75 cm.

Once the above is achieved, field drains are then constructed to lower the water table to between 50 and 70 cm from the soil surface, and eventually to below 70 cm depending on the soil salinity and palm age. Planting of oil palms and other cultural practices resemble those of coastal soils. However, boron application is generally unnecessary.

Bund maintenance to prevent seepage and leakage, and sound water management is necessary to ensure successful reclamation of saline soils for oil palms. An example of yield profile of oil palms on saline soils with mean annual rainfalls of 1822 mm is shown in Figure 10. The mean FFB yields were low due to two periods of distinct dry season per year although occasionally they may exceed 24 t ha^{-1} yr^{-1}. With the current high yielding planting materials, higher FFB yields should be expected if there is sufficient rainfall or water source for optimal water management. It must be cautioned that since 2004 developing mangrove swamp (mainly saline soils) to oil palm is prohibited under the Malaysian law.

Managing shallow lateritic soils

Shallow lateritic soils such as Malacca and Gajah Mati series, and their associated soils occupy 0.6 million hectares in Peninsular Malaysia (Law and Selvadurai, 1968). Early experiences indicated that oil palms grown on shallow lateritic soils came into bearing two years later and three times less compared to deep soils (Tan and Thong, 1977; Pang et al., 1977). Increasing the fertiliser rates only partially alleviate the constraint and raise yield by 84% (Tayeb et al., 1990). They also showed that productivity seems to improve with palm age. This might be partially attributed to the slower root development of oil palm in lateritic soils due to impediments with consequent poorer growth rate and lower partitioning of biomass to reproductive organs.

These results show that the main problems with shallow lateritic soils are low effective soil volume, poor nutrient status and water holding capacity. These detriments further hinder root development, which aggravates oil palm growth and production. It has to be mentioned that the types and compactness of the laterites also play a major role on the degree of severity of limitations to oil palms. For example, the less compact and subangular laterites of Jitra series pose only moderate limitation to oil palms compared to very serious limitation in Malacca series despite both being shallow lateritic soils.

The main approaches to obtain satisfactory oil palms on shallow lateritic soils are to improve soil fertility and implement soil and water management adroitly. Improvement in soil fertility is necessary to increase nutrient uptake per unit soil volume. Since most lateritic soils are well weathered with low CEC and high P fixing capacity, it is necessary to maintain high and balanced rates of manuring as well as frequent applications to the palms. It is also essential to apply very large quantity of phosphate rocks to ensure sufficient P for good rooting activity.

The primary aims of soil and water management here are to reduce run-off and soil erosion, and build-up organic matter in the soil. These are achieved by:

a) maintain desirable ground vegetation such as legumes during immaturity to early maturity phase and light grasses and *Nephrolepis biserrata* in later years,

b) spread the pruned fronds as broadly as possible. In flat areas, L-shaped frond stacking should be carried out while in terraced areas, they should be staked on the terraced lips and between the palms along the terraces,
c) terraces must have sufficient back-slope and regular stops along the terraces to trap soil and water,
d) mulching with empty fruit bunches (EFB) or Ecomat if available,
e) apply by-products e.g. decanter cake and belt-pressed cake if available.

Irrigation should only be conducted if it is economically viable, easy to maintain and a ready source of water during the dry season is available as mentioned in Part I of this paper.

It is also advisable to increase the planting density to between 148 and 160 palms ha^{-1} and extend ablation by 3 to 6 months for maximum leaf area index and better yields. The higher planting density is also needed in areas with high endemic Ganoderma disease in order to maintain sufficient stands for satisfactory yields in later years particularly from 14 years old palms and older.

Proper implementation of soil fertility, and soil and water managements had raised the oil palm yields on lateritic soils. Yields on commercial scale are shown in Figure 11.

Managing podzols or Spodosols

Podzols generally occur within BRIS (Beach Ridges Interspersed with Swales) soils although they have been found on moderate hills in East Malaysia. The total extent of these soils in Peninsular Malaysia alone has been estimated at 162,000 ha (Choo, 1991). Majority of these soils are used for tobacco, vegetables, cashew nut trees and star-fruit trees. Of late, some of these soils which occur in the plantations have been cultivated with oil palms.

The major constraints in Podzols are perched water table, low nutrient status and CEC and poor moisture retention capacity. Some podzols may not have perched water table and these soils resemble quartzipsamments, which are discussed later.

The obvious first priority is to remove the stagnant water on the soil surface. This is easily accomplished by digging scupper drains with lower depths breaking the hard spodic horizons. The intensity of drains is usually 1 in 8 palm rows although this varies with sites. The top width of the drain is 60 cm and the bottom width is 30 cm to allow for gentler slope, therefore easier maintenance.

Upon surface drainage, the conditions reverted to the other extreme of likely severe moisture stress due to excessive drainage and low moisture retention capacity. Hence, water conservation practices similar to those described for lateritic soils earlier must be improved immediately. The EFB mulching rate should be increased to 60 to 80 t ha^{-1} yr^{-1} and this is continued for at least 5 years before a lower rate is adopted. Similarly, other by-products such as decanter cake and/or belt pressed cake should be applied if available.

The poor nutrient status and retention capacity pose a dilemma of high total fertiliser input but low rate at each application. This is generally solved by using compound or mixture fertilisers supplemented with straight fertilisers. The total fertiliser applications may reach 7 to 9 rounds a year and this should minimise leaching losses. The frequency of fertilizer application can be reduced substantially with compact fertilizers. Despite the sandy soils with anticipated low P fixing capacity, high phosphate rock is still recommended to ensure good root development and activity. Very high rate of ground magnesium limestone (GML) is also necessary to build-up the soil Mg status and prevent Mg deficiency.

Good ground vegetation is also important in reducing the surface soil temperature, which helps to reduce soil water evaporation and improve microbiological activity. The leaf litter return also binds the soil particles for better structure and aggregation.

Just like for shallow lateritic soils, the planting density should be increased to at least 148 palms per ha and ablation extended to maximize palm growth before bringing it to maturity.

Our experiences with planting oil palms on Podzols with satisfactory rainfall with more than 2000 mm yr^{-1} has been encouraging as shown in Figure 12.

Managing sandy soils (quartzipsamments)

The extent of quartzipsamments in Malaysia has not been reported. However, they are known to occur extensively besides mining or ex-mining areas and flat river basins. Some of these soils are classified as Sg. Buloh, Subang, Nangka, Lintang and Jambu series. The major limitations of these soils mirror those of podzols except that perched water table does not exist.

The management procedures for oil palms on these sandy soils are similar to those on podzols except that scupper drains are not dug. Our experience with plantings on these soils has been fortunate because they occur in high rainfall regions of Central Perak and Southern Kedah. Their yield performances are shown in Figure 12 also.

Managing high pH soils

With the rapid and extensive expansion of oil palm in Malaysia, it is inevitable that soils with high pH above 6.0, which are generally derived from ultrabasic rocks, limestone or coral limestone, are encountered sporadically in the plantations although at times in relatively large areas such as in Sahabat complex in Lahad Datu, Sabah. However, the extent of limestone and ultrabasic derived soils in Malaysia has not been well documented even on reconnaissance scale. Nevertheless, a number of soil series derived from these high pH rocks have been established in Malaysia, such as Langkawi series, Tingkayu series and Semporna series. The major limitations posed by these soils to oil palm are mainly associated with plant nutrition, steep terrain and shallow, stony soils.

The difficulty in maintaining optimal nutrition of oil palms planted on ultrabasic and limestone derived soils is caused by their unique soil properties where Ca and/or Mg predominate the exchangeable cations coupled with relatively low K (Table 21). While Ca is almost always the dominant cation in the solid and liquid phases of limestone derived soils, Mg can be dominant in ultrabasic derived soils. Both cations severely depress K uptake by oil palm following Tinker (1964)'s activity ratio equation $\frac{K}{\sqrt{Ca+Mg}}$ (there is no exchangeable Al in these soils because of the high pH and therefore, it can be ignored) as presented earlier, and due to the preferential and "forced" excessive uptake of Ca and Mg, the cation composition in the palm will become imbalance (Foster, 2003) with dire consequence of severe K deficiency resulting in poor growth and production if not corrected. In soils with high Ca but very low Mg such as in limestone derived soils e.g. Semporna series Mg deficiency symptoms may be manifested in the oil palms particularly during dry weather (Lee and Rosaman, 2011). Application of excessive N rate can also induced Mg deficiency symptoms in oil palm due to the remobilization of Mg from the older to younger fronds (Goh et al., 1999).

The oil palm also frequently suffers from N and P deficiencies. These soils have low organic C and total N with extremely low C:N ratio indicating very stable organic matter. Therefore, their mineralisation rate is generally low (Kitayama et al., 1998) resulting in low soil N and P supply to the oil palm. Apart from this, N volatilization losses from applied N even in the ammonium (NH_4^+) form are likely to be high based on laboratory experiments. As for phosphate, the high soil pH will render the use of phosphate rock ineffective due to the very slow P dissolution rate. The more expensive soluble P sources such as diammonium phosphate and triple super phosphate are usually applied until the soil pH declines to below 6 and preferably 5.5 before reactive phosphate rock can be used economically to supply P to the oil palm.

Micronutrient deficiencies such as manganese (Mn), iron (Fe), zinc (Zn) and boron (B) are also common although they tend to occur sporadically especially during period of dry weather. Although soil and foliar applications of appropriate micronutrients, chelated or otherwise, are effective in overcoming the above nutrient deficiencies, they are expensive and require repeated treatments. A better solution is to apply organic by-products e.g. decanter cake and EFB to supply these micronutrients and/or build-up the palm micronutrients to a relatively high status when they are young and maintain their recycling via pruned fronds. The leakage of micronutrients through the export of FFB and soil loss processes is anticipated to be low.

Apart from the above nutrient management and strategy, it is important to acidify the soils and improve the rooting activity of the oil palm. To achieve the former objective, ammonium sulphate is usually used and applied in the palm circle only. Similarly, triple superphosphate may be applied instead of diammonium phosphate and reactive phosphate rock to acidify the soils. Some attempts have been made to lower soil pH with sulphur but results were inconsistent and uneconomical. The process of soil acidification is slow in these high pH soils probably due to their high buffering capacity. Nevertheless, over a decade or so, the pH dropped by 1 to 1.5 units to about pH 5.7, which is suitable for oil palm. To improve the rooting activity, the best approach seems to be the application of organic by-products e.g. EFB at rates between 60 and 80 t ha^{-1} yr^{-1}. Unfortunately, its implementation is usually difficult due to the steep, rugged terrain and therefore, lower EFB rates, decanter cake and other organic materials such as chicken dung are applied, if available.

Soils derived from ultrabasic rocks in Malaysia are known to contain relatively high amount of heavy metals such as chromium (Cr), arsenic (As), etc. However, the uptake of these heavy metals by oil palm has not been reported to the best of our knowledge. Nevertheless, little, if any, heavy metals is expected in crude or refined palm oil since the latter is filtered through bleaching earth which should effectively adsorb them.

Most of the high pH soils derived from limestone and ultrabasic rocks occur on steep terrain and karst formation. Those found on flat to rolling terrains generally have pH below 5.8 and moderate to deep soil profiles, which do not pose major limitations to oil palm. The challenges in managing oil palm on hilly to steep terrain have been described by Ng and Goh (2011) and will not be elaborated here. Suffice to say that the planting density in these soils on steep terrain such as in Sabah is extremely low, at about 90 to 115 oil palms per hectare. This limits the site yield potential of oil palm further which seldom exceeds 24 t FFB ha^{-1} yr^{-1} during the peak yielding period (Figure 13). The impact of shallow, stony soils in reducing rooting activity, nutrient availability and moisture retention capacity of the soils are similar to those found in shallow, lateritic soils. Thus, the management practices to alleviate the constraints of these latter soils as discussed earlier are also applicable for high soil pH soils with stony and shallow soil depth.

The yield profiles of oil palm on high soil pH soils on commercial scale are illustrated in Figure 13. The oil palms on limestone derived soils (Figure 13a) showed pronounced yield decline in dry periods whereas those on ultrabasic derived soils (Figure 13b) showed linear yield decline 15 years after planting due to difficulty in harvesting tall palms in steep terrain and the low planting density.

Conclusions

Cultivation of oil palm is still expanding in Southeast Asia, particularly in East Malaysia and Indonesia. A diversified range of soils is used with increasing proportion of marginal soils. It is vital that good soil management is implemented to ensure high sustainable production for economic viability and maintain or improve soil fertility. There is also a growing concern on soil degradation and environmental pollution with high input agriculture but these can be avoided in most instances with good soil management.

The first approach in soil management is to identify the soil constraints to crop production and assess their degree of severity. In the humid tropics, these detriments are closely related to nutrients and water which are the most limiting factors to crop productivity. Both are available via the soil to the plants, particularly those with good rooting activity.

The rooting activity of plants is influenced by many soil properties such as terrain, texture, structure, consistency, permeability, drainage and inherent nutrients. They require interactive management approach to achieve the basic objectives of crop productivity and maintenance of soil fertility and to do so in an environmentally acceptable way. These soil management approaches encompass soil and water conservation management, soil nutrient management, soil organic matter management, soil acidity management, soil water management and soil microbe management.

We also need proper understanding of both soils and crops to manage marginal soils successfully in Malaysia. Upon corrections or alleviation of the soil constraints, the oil palm performances can generally match those on better soil types. More than one soil management approaches are usually required and these must be implemented correctly and interactively. Among others, good timing is also essential to ensure success.

It must be cautioned that cultivation of oil palms on marginal soils entails, inter alia, higher cost, difficult inputs, and good managerial skill, and exposes the planters to higher risk and poorer competitiveness. It is therefore advisable to regard planting on marginal soils as a last resort rather than an opportunity for development and business.

In managing problem or non-problem soils, there are no great secrets, sophisticated practices or silver bullets though. Perseverance and hard work in implementing tedious, laborious at times but tractable measures passionately and ingenuity in developing science-based and proven, practical solutions to alleviate difficulties as they continuously arise are epitome of good soil management. In fact, the concept of good soil management is nothing new and best exemplified by the following quotation from Sanskrit, the classical, literary language developed from about 1500 B.C. by the Hindus in Northern India (Johnson, 1995).

"Upon this handful of soil our survival depends. Husband it and it will grow our food, our fuel and our shelter and surround us with beauty. Abuse it and the soil will collapse and die taking man with it".

This transcendent adage, which has evolved through time, still poignantly encapsulates a major concern today; so when will man learn to ensure plentiful food and beauty for the generations to come, if it is not now.

The younger generations of agronomists have the unenviable, daunting and arduous task of continuously striving for practical solutions and management system for oil palm in order to stay competitive and ahead of other vegetable oil crops. Thus, the first author hopes that this long discourse but a snapshot on soil management for optimal oil palm nutrition, growth and yield will provide the needed impetus and spur them on.

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Figure 1: Relative yields of oil palm in relation to its build-up and maintenance nutrient requirements

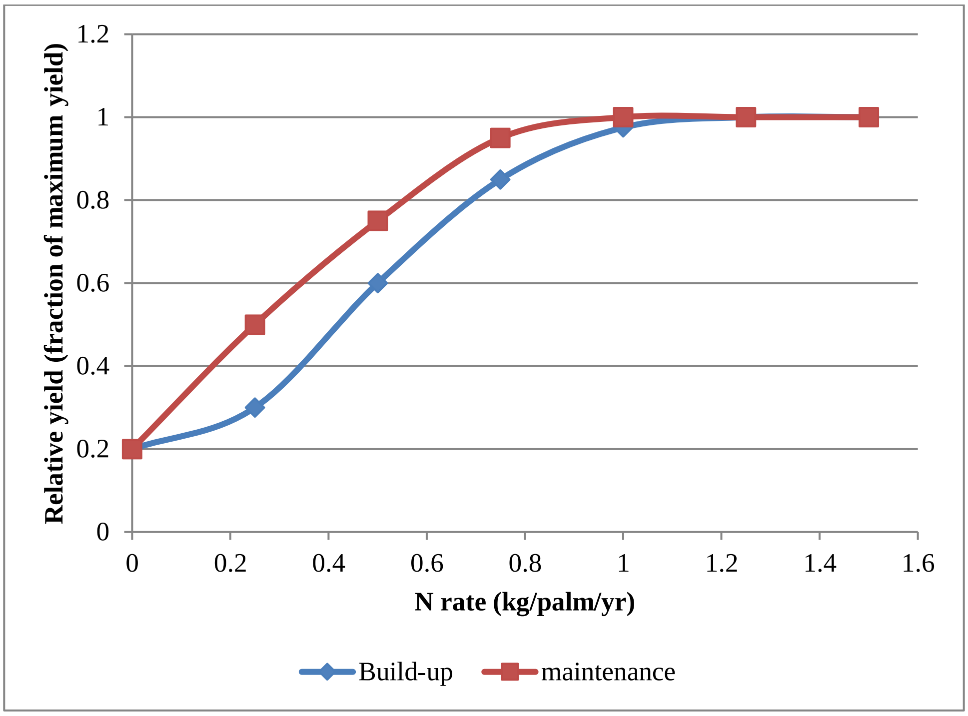


Figure 2: The major components of nutrient demand and supply in oil palm plantation and its nutrient cycling

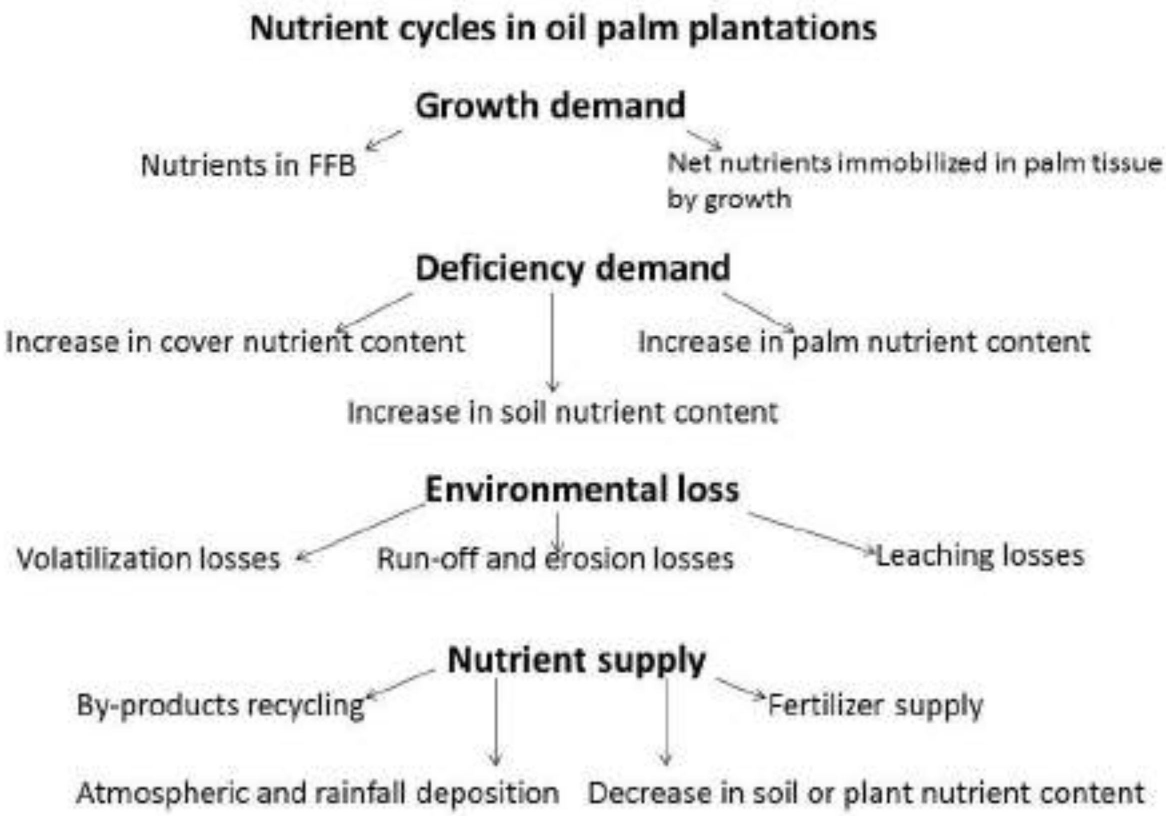
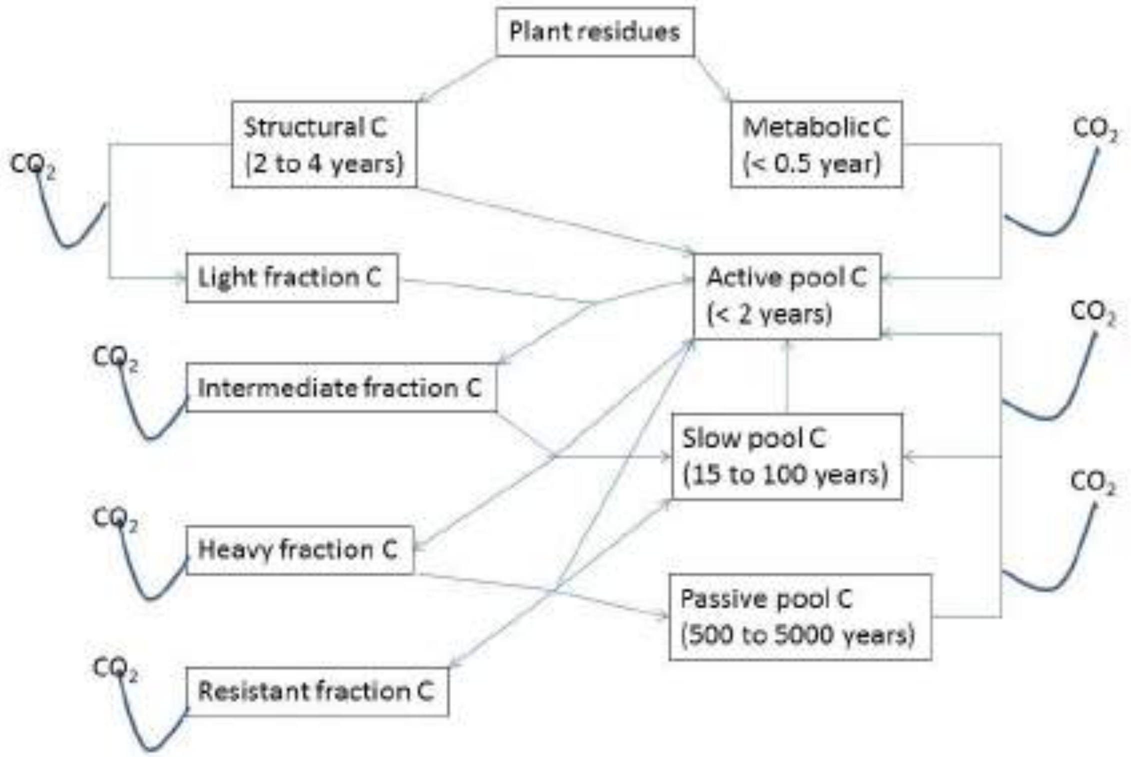
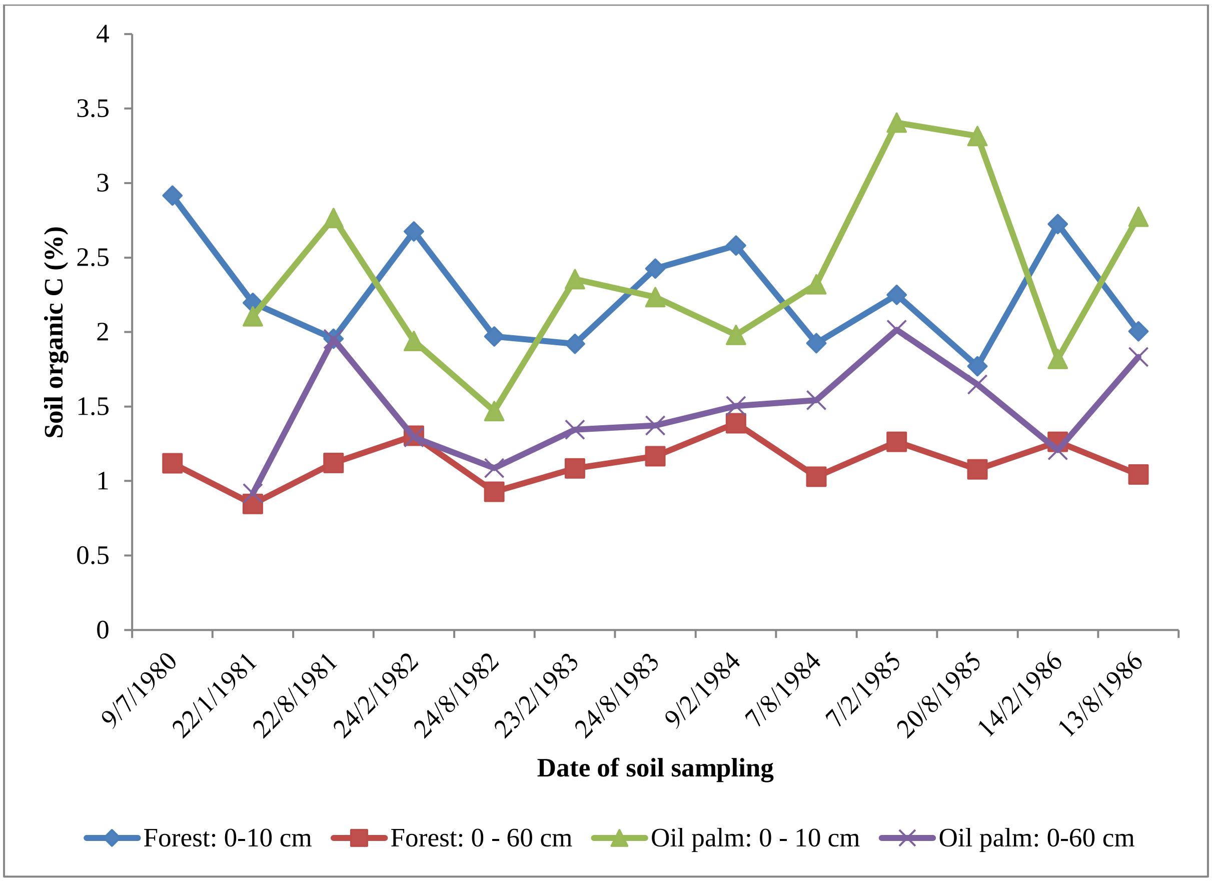


Figure 3: Flow diagram of the breakdown of plant residues into various fractions and types of soil organic C



Note: The figures in bracket are estimates of the number of years for each C pool to decompose. The dynamic mechanisms of C flow from one fraction and pool to another will generate carbon dioxide. In oil palm, the estimates of the C flow rates have not been deciphered yet. Similarly, the proportion of plant residues, C fractions and C pools have not been ascertain for most major soil types under oil palm.

Figure 4: Effect of forest clearance and subsequent establishment of leguminous cover crops and oil palm on soil organic C (%) in 0 to 10 cm and 0 to 60 cm soil depths in the Sungai Tekam experimental basin in Pahang, West Malaysia.



Source: Re-plotted from data from Anon (1989). The leguminuos cover crops were established in April 1981 and the oil palm planted in August 1982.

Figure 5: Representation of bacterial species richness (A) and taxonomic composition (B) (phyla) in soils sampled from palm circles (PC) and frond heaps (FH). Bacterial diversity was ascertained via 16S rDNA MiSeq metasequencing analysis.

Figure 5A

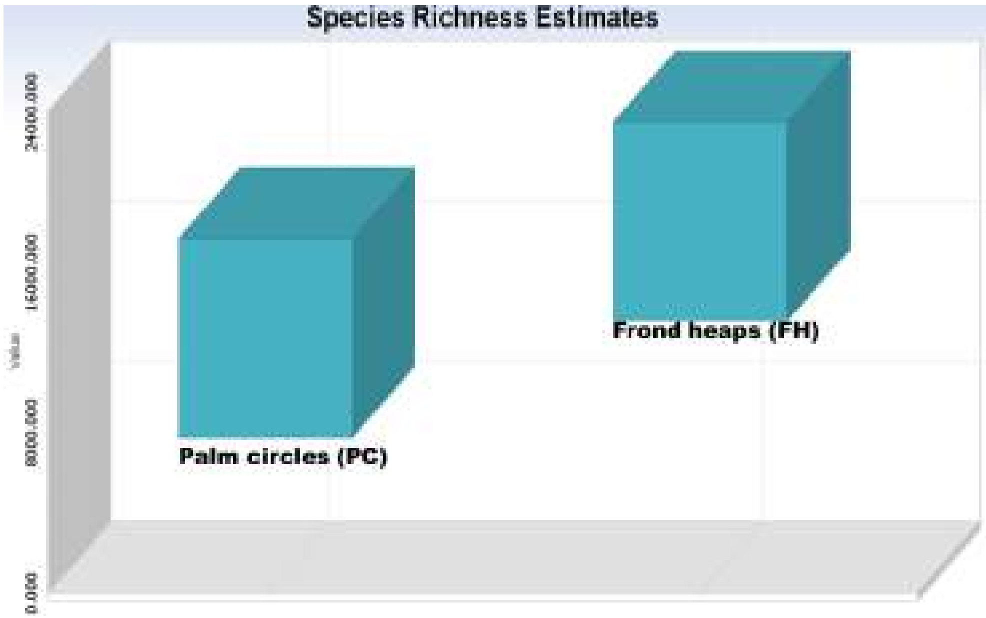


Figure 5B

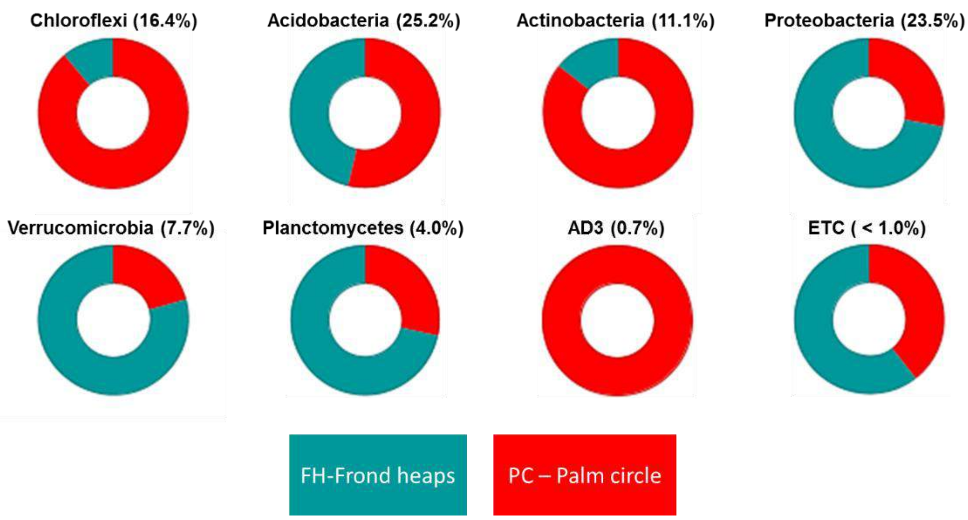
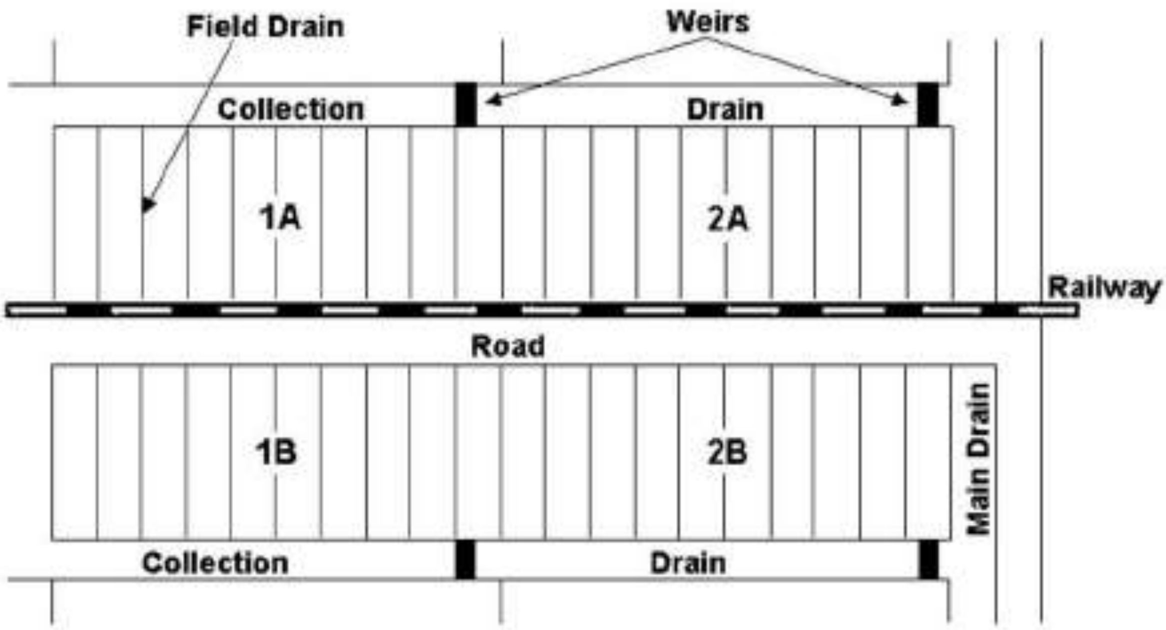
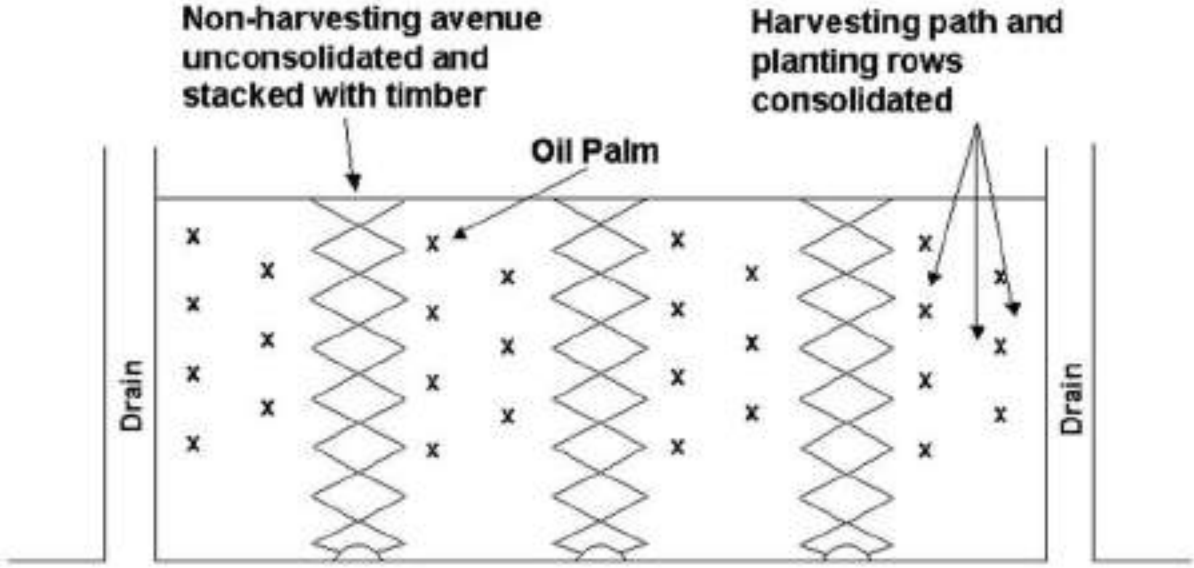


Figure 6: Layout plan of the drainage system in peat swamp



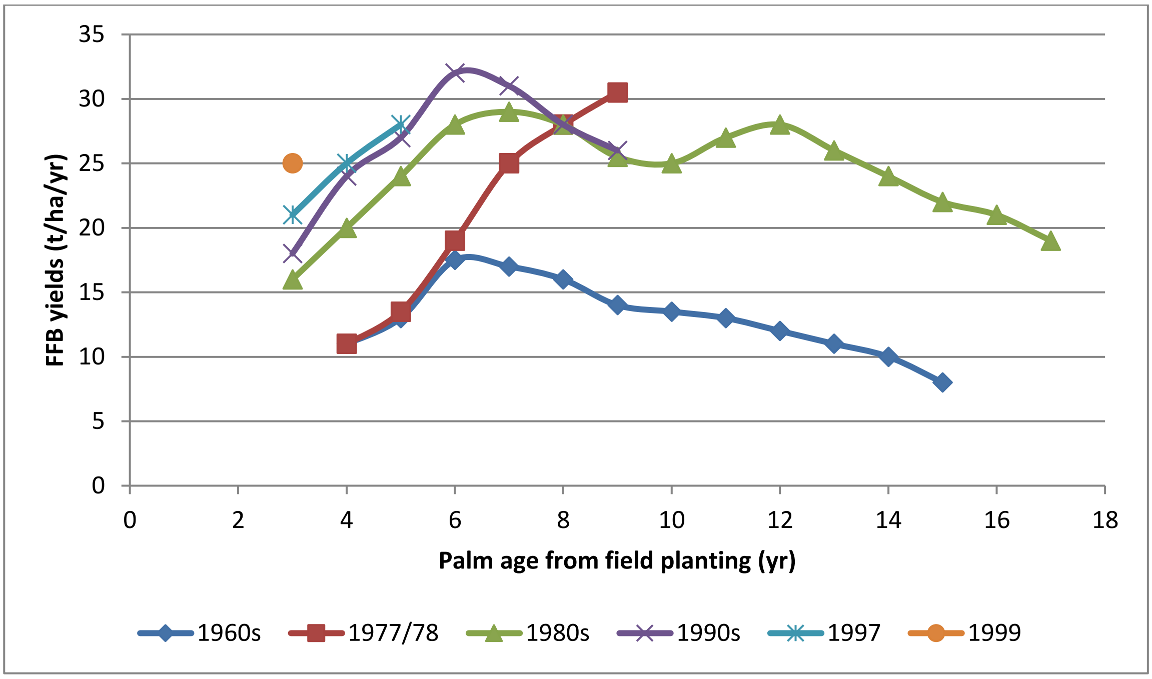
Source: Gurmit et al., 1987

Figure 7: System of consolidation of harvesting paths and planting rows in peat swamp



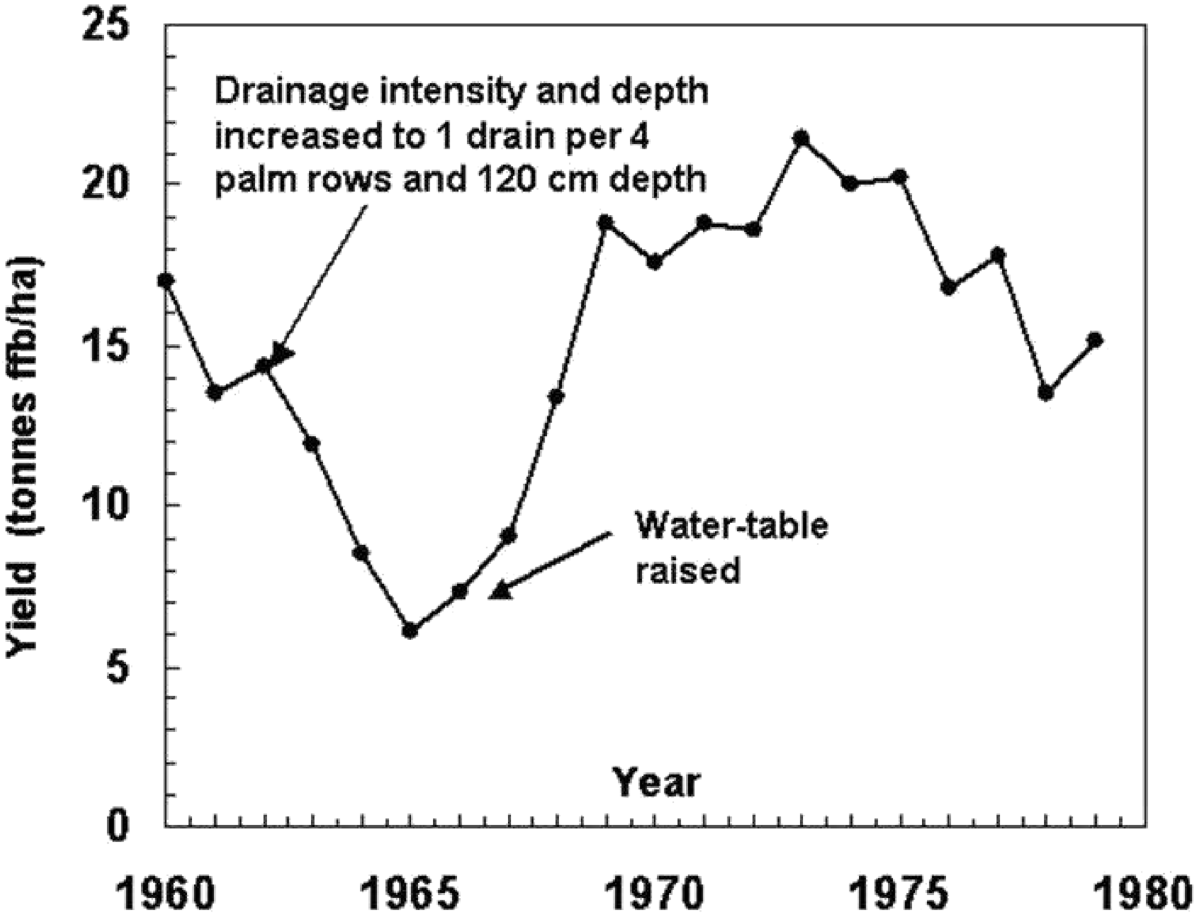
Source: Gurmit et al., 1987

Figure 8: FFB yields of oil palm on deep peat in United Plantations Bhd. from 1960s to 1990s



Note: The years shown in the graph refer to the year of planting. The 1960s and 1970s planting were from ex-jungle, the 1980s planting may include replanted fields and the 1990s plantings were replants.
Source: Gurmit et al. (1987); Gurmit (2004).

Figure 9: Effect of increased drainage and subsequent raising of water table on yield of oil palms on severe acid sulphate soils



Source: Toh and Poon, 1982

Figure 10: Yield performances of oil palms on saline soils

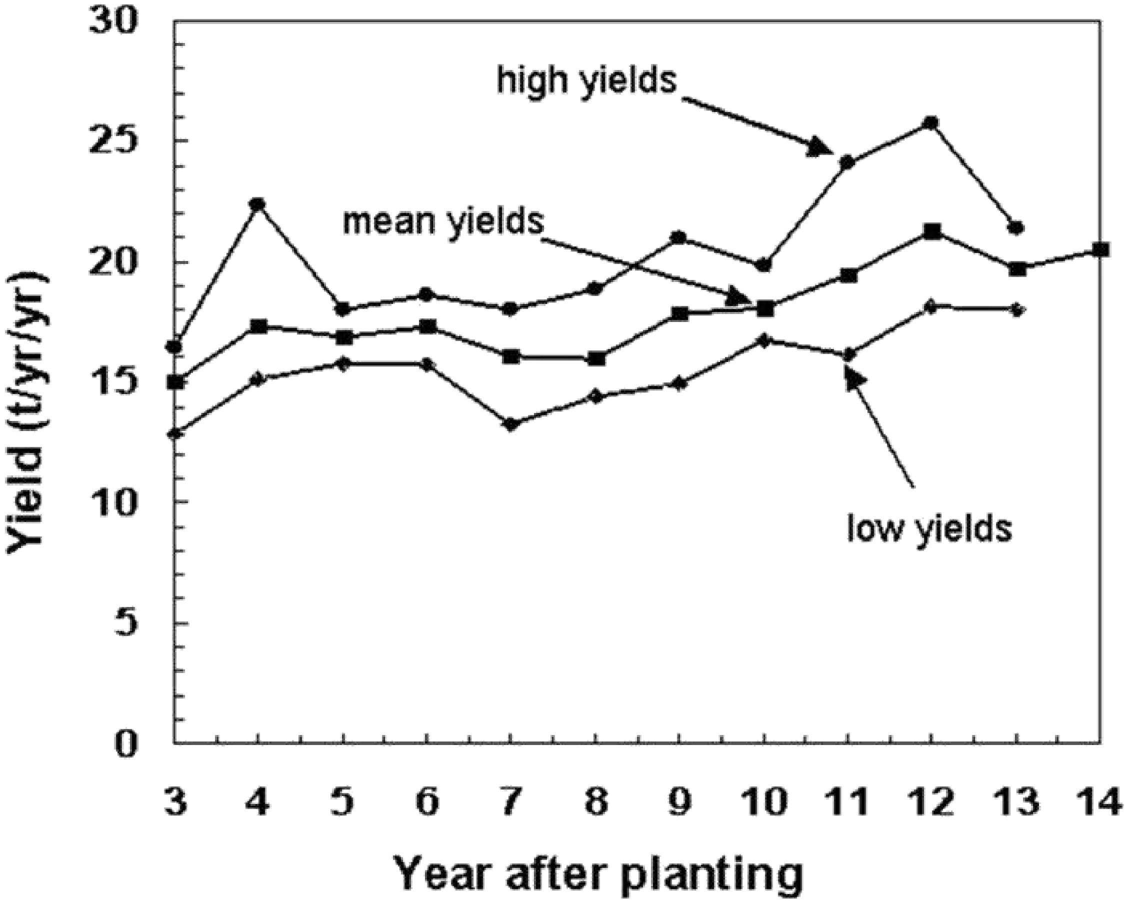
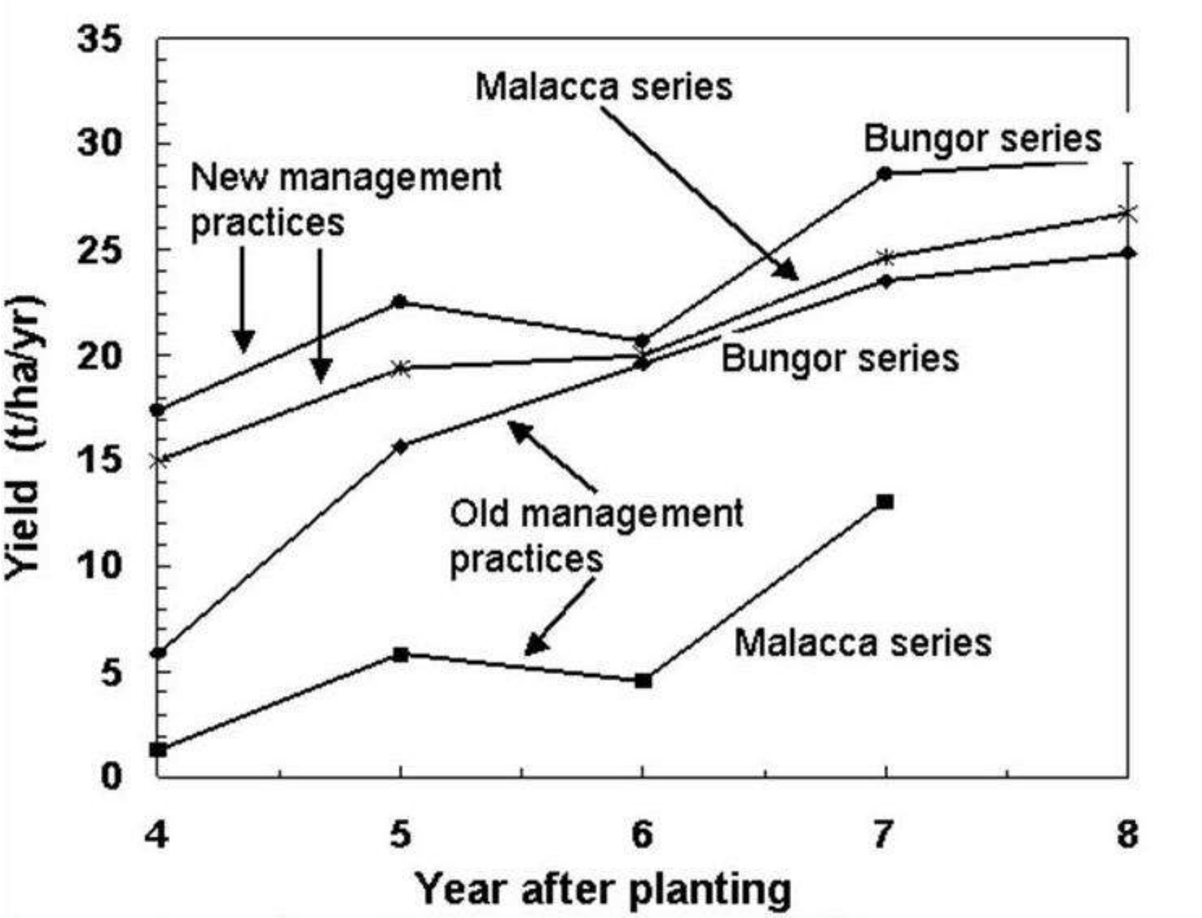


Figure 11: Comparison of yield performances of oil palms on Malacca and Bungor series soils



Source: Pang et al., 1977 and Goh et al., 1994

Figure 12: Yield performances of oil palms on podzols and sandy soil

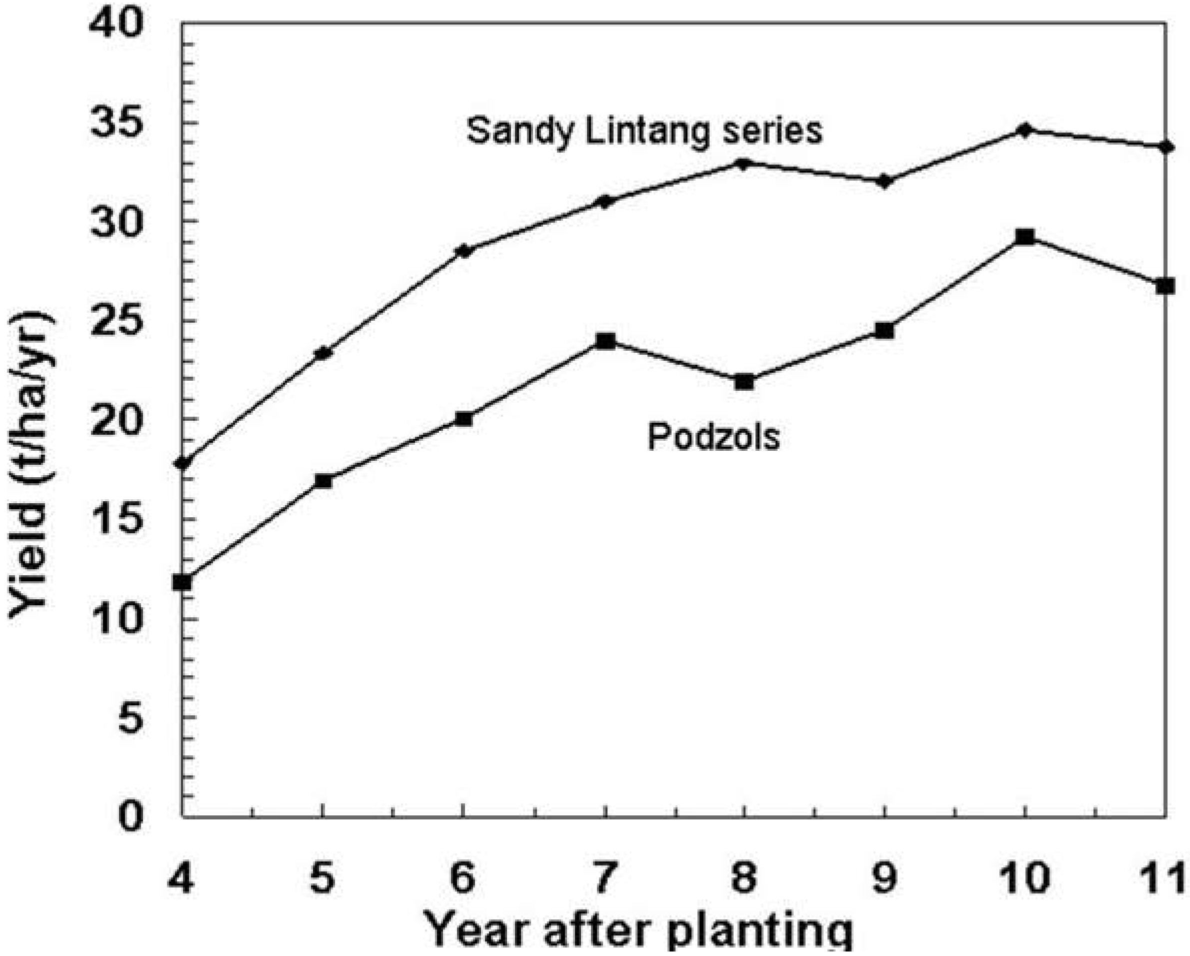
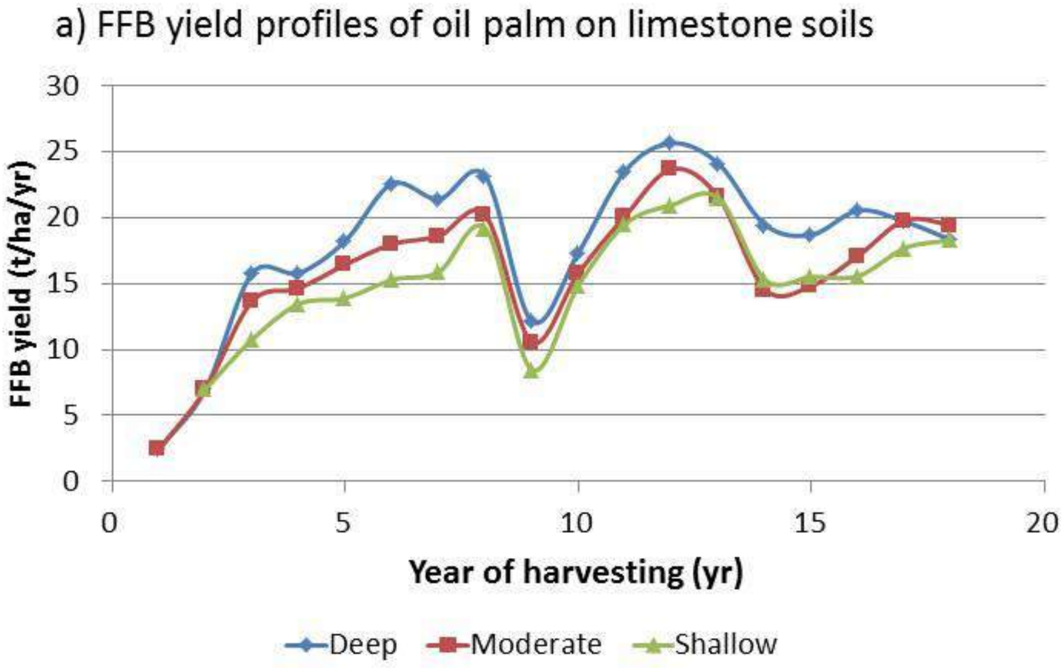
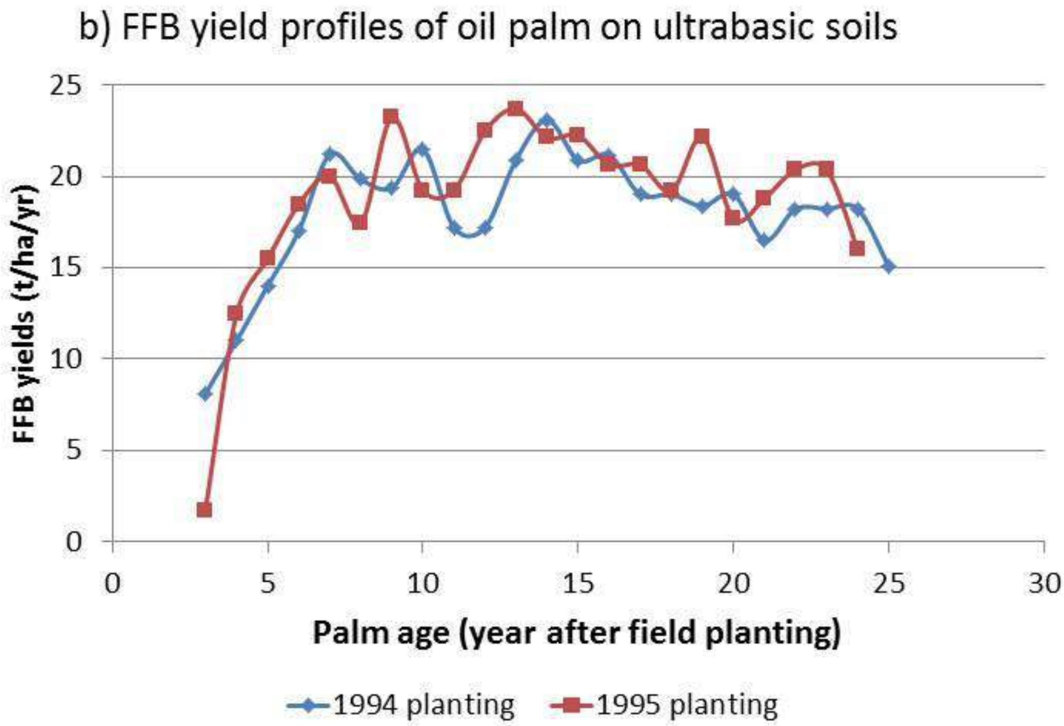


Figure 13: Yield performances of oil palms on limestone and ultrabasic derived soils.





Note: Figure 13a is plotted from data in Lee and Rosman (2011). The planting densities of oil palms in Figure 13b were 94 and 112 palms ha^{-1} for 1994 and 1995 plantings, respectively because of the steep terrain.

Table 1: Infiltration rate of water at different depths in different Peninsular Malaysian soils.

Soil series	Infiltration rate (cm hr-1)			
	0 - 15 cm	15 - 30 cm	30 - 45 cm	45 - 60 cm
Sungai Buloh	115	55	30	23
Serdang	26	31	27	15
Durian	18	0.08	0.08	0.10

Source : Soong and Lau (1977).

Table 2: Total and air-filled porosities of some Peninsular Malaysian soils under rubber.

Soil series	Porosity (%)	
	Total	Air-filled
Langkawi	55 - 58	19 - 27
Holyrood	51 - 53	31 - 35
Lunas	51 - 53	24 - 27
Sitiawan	57 - 59	5 - 17
Sogomana	51 - 55	6 - 21
Serdang	50 - 52	24 - 30
Segamat	61 - 62	8 - 16
Malacca	58 - 60	10 - 14
Jerangau	57 - 58	6 - 10
Senai	58 - 63	2 - 19
Harimau	53 - 55	15 - 21
Masai	55 - 59	7 - 13
Rengam	53 - 56	12 - 20
Durian	63 - 65	19 - 27

Source : Soong and Lau (1977).

Table 3: Effect of ground vegetation on run-off and soil loss on Munchong series soil.

Vegetation	Rainfall (mm)	Run-off (mm)	Run-off (% rainfall)	Soil loss ($t\ ha^{-1}\ yr^{-1}$)
Bare soil	1854	236	15	79
Legumes	1854	70	5	11
Natural cover	1854	61	3	10

Source : Ling *et al.* (1979)

Table 4: Effect of percent ground coverage by vegetation on run-off and soil loss on Munchong series soil.

Vegetation	Ground cover					
	0 - 30 %			90 - 100 %		
	Rainfall (mm)	Run-off (mm)	Soil loss ($t\ ha^{-1}\ yr^{-1}$)	Rainfall (mm)	Run-off (mm)	Soil loss ($t\ ha^{-1}\ yr^{-1}$)
Bare soil	269	57	13.5	287	64	11.3
Legumes	269	47	9.0	287	3	0.1

Source : Ling *et al.*, (1979)

Table 5: Mean nutrient losses through runoff water.

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

Source : Maene *et al.*, (1979)

Table 6: Soil K supply to oil palm without manuring

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

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

Table 7: Fertilizer schedule (kg/palm/year) for oil palm replant at 8 years after planting on different soil groups with legume covers

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

Source: Hew and Ng (1968)

Table 8: Interpretation of soil nutrient status for fertilizer recommendations

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

Table 9: Variable and permanent site characteristics that affect the yield responses to N and K fertilizers in West Malaysia

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

Table 10: Leaching losses of nutrients measured in oil palm by lysimeter study.

Palm age (yr)	Leaching losses (% of applied nutrient)			
	N	P	K	Mg
1 - 4	16.6 (10.9 - 26.5)	1.8 (neg. - 5.8	9.7 (3.4 - 19.5)	69.8 (8.4 - 169.4)
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)

Note : ( ) = range
Source : Foong, S.F. (1993)

Table 11: Effect of fertilisers and rainfalls on run-off and soil losses on Rengam series soil.

Antecedent weather	Fertiliser application	Period	Rain days	Rainfall (mm)	Nutrient losses (kg ha^{-1})											
					Via run-off losses						Via soil sediment losses					
					N			K			N			K		
					N0 K0	N1 K1	N2 K2	N0 K0	N1 K1	N2 K2	N0 K0	N1 K1	N2 K2	N0 K0	N1 K1	N2 K2
Wet	Before	1/4-19/4	7	499	0.06	0.09	0.07	0.64	1.08	0.75	1.25	0.99	1.11	0.06	0.04	0.03
	After	20/4-30/4	5	109	0.08	0.26	1.11	0.74	3.02	7.34	1.06	0.68	0.97	0.06	0.03	0.06
"Dry"	Before	6/9-23/9	6	224	0.07	0.07	0.15	0.07	0.09	0.21	0.22	0.29	0.34	0.01	0.01	0.05
	After	24/9-5/10	5	130	0.93	1.04	2.29	1.40	3.31	5.55	0.36	0.39	0.46	0.05	0.09	0.09

Source: Recomputed from Chew et al. (1994)

Table 12: Effect of NK fertiliser on the soil acidity of Musang series soils.

Treatment	Site	Depth (cm)	
		0 - 15	15 - 30
Without NK fertiliser	Palm circle	4.15	4.07
	Interrow	4.49	4.37
	Frond heap	4.48	4.36
With NK fertiliser	Palm circle	3.35	3.43
	Interrow	4.27	4.14
	Frond heap	4.38	4.33
SE for treatment		0.07	0.05
SE for site		0.04	0.04
SE for interaction		0.06	0.04

Source : After Kee *et al.* (1995)

Table 13: Soil carbon stock of mineral soils in the top 30 cm of soil at different plantation/company managements, soil types, initial land covers, soil depths and management zones

Factor	Particular	Soil organic C (%)	Time-averaged C stock (Mg C ha^{-1})
Plantation management	Nucleus	1.72 ± 0.75	51.60 ± 17.14
	Plasma	1.60 ± 0.81	50.00 ± 22.02
	Independent	1.76 ± 0.63	56.13 ± 20.42
Soil type	Inceptisol	1.58 ± 0.80	45.53 ± 16.93
	Ultisol	1.69 ± 0.55	53.45 ± 15.20
	Others	1.91 ± 1.08	56.04 ± 27.04
Initial land cover	Forest	1.72 ± 0.70	53.63 ± 15.98
	Other than forest	1.63 ± 0.78	49.86 ± 20.94
Soil depth	0 – 5 cm	2.92 ± 1.37	
	5 – 15 cm	1.87 ± 0.88	
	15 – 30 cm	1.14 ± 0.54	
Management zone	Weeded circle	1.71 ± 0.77	52.12 ± 20.80
	Interrow	1.69 ± 0.75	51.99 ± 19.47
	Frond stack	1.80 ± 0.87	54.77 ± 21.72
	Harvest path	1.46 ± 0.70	43.08 ± 17.28

Source: Khasanah et al. (2015)

Table 14: Effect of legume cover crops on soil organic C in oil palm plantation

Legumes	Soil organic C (%)		% difference in soil organic C
	Legume	Natural vegetation	
[1]Pure legume covers – Bungor series	1.16	1.09	6.4
[1]Mixed legume covers – Bungor series	1.23	1.09	12.8
[2]Mixed legume covers – Durian series	0.98	0.88	2.3
[3]Pure Mucuna bracteata cover – mineral soils	2.61	1.24	110.4
[4]Pure legume covers – mineral soils	1.54	1.43	7.7

Note: 1) and 2) Soil samples in top 15 cm taken at 22 – 33 months after legume covers planting (Tan and Ng, 1982). 3) Soil samples in top 30 cm taken at 3 years after legume cover planting (Chiu et al., 2001). 4) Soil samples in top 15 cm taken at 28 months after legume cover planting (Agamuthu and Broughton, 1985). The authors also showed that bare ground had 1.28% organic C which was 10.5% lower than the natural vegetation. In 1), 2) and 4), the legume covers were mainly *Pueraria phaseoloides* and *Centrosema pubescens*.

Table 15: Soil organic carbon (SOC) in response to long term response to long-term empty fruit bunch (EFB) application

Soil depth (cm)	SOC (%) from 10 years application of:			SOC increase over chemical fertilisers:	
	Chemical fertilisers	EFB at 22.2 t ha^{-1}	EFB at 44.4 t ha^{-1}	EFB at 22.2 t ha^{-1}	EFB at 44.4 t ha^{-1}
0-20	1.50	2.50	2.75	1.00	1.25
20-40	0.92	1.08	1.67	0.16	0.75
40-60	0.67	0.67	1.08	0.00	0.41
60-80	0.33	0.50	1.00	0.17	0.67
80-100	0.25	0.33	0.95	0.08	0.70

Source: Rosenani et al. (2011)

Table 16: Estimations of microbial abundances (A) and microbial activity (B) in soils sampled from different oil palm microsites

[A]

Microsites	Heterotrophs	N-fixing	P-solubilisers
Bareground	$8.77(x10^{6})$	$9.08(x10^{1})$	$2.20(x10^{3})$
Frond heaps	$3.13(x10^{7})$	$2.26(x10^{3})$	$3.20(x10^{3})$
EFB	$7.65(x10^{7})$	$1.92(x10^{3})$	$6.20(x10^{4})$
Legumes	$4.01(x10^{7})$	$6.21(x10^{3})$	$7.80(x10^{4})$

[B]

Soil enzyme	Microbial Indicator	Frond Heaps vs. PC	EFB vs. PC
Soil Dehydrogenase activity (µg/g dry soil/h)	C cycling	319%	688.6%
Soil microbial respiration (µg CO_2-C/g dry soil/h)	C cycling	300%	650%
Soil phosphatase (*p-NP* released µmoles/g/soil/hr)	P-cycling	183%	427%
Microbial C (µg C/g/soil)	Microbial biomass	153%	ND
Microbial N (µg N/g/soil)	Microbial biomass	136%	ND

Table 17: The effects of agro-management practices on soil biological processes and their consequence towards soil fertility

Management options	Soil biological processes influenced	Change to soil chemical fertility	Change to soil physical fertility
Effects of organic matter, e.g. necromasses (including EFB mulching)	Microbial populations enhanced. Initially, may cause immobilisation of soil nutrients due to high C:N of organic residues. Soil faunal groups may increase or decrease depending on residue quantity and quality	Increased availability of nutrients especially N, S, and P.	Improve soil structure through aggregation and water holding capacity
Effects of preserving beneficial plants (increasing in agrobiodiversity) in a monocropping landscape	Contributes to organic matter inputs. Variation in litter quality, plant exudate composition can affect microbial diversity. Weeds can also interact with pathogen management (either limiting or enhancing the pathogen) (Wisler and Norris, 2005)		
Effect of fertilizers	High N inhibits N_2 fixation. Nitrifier populations increased with NH_4^+ fertilizer. Some faunal groups increased	Decreased availability of nutrients derived from soil biological processes.	
	Fertilizers namely ammonium-based can contribute to soil acidification. Soil acidification can affect microbial populations, e.g. limits Rhizobium survival and persistence. Reduction in bacterial growth.	Soil acidification may also lead to a reduction in soil CEC.	Severe acidification can cause non reversible clay mineral dissolution and structural deterioration
	Some beneficial foil fauna also killed. Potential to lose beneficial species.	Nutrient supply altered depending on the shift in the food web.	
Effects of soil compaction (Silva *et al.*, 2011)	Reduction in biopores and macropore connectivity, lower O_2 concentration and lower macroporosity may cause a reduction in aerobic microbial activity and may favour N losses by denitrification	Decreased availability of nutrients derived from soil biological processes.	Increase in soil density leading to altered pore size and distribution, lower O_2 and CO_2 diffusion rates. Anaerobic microsites may occur

Modified from Abbott and Murphy (2007)

Table 18: Sample chemical analysis of peat from Jalan Kebun Peat Research Station, West Selangor, Malaysia.

Soil properties	Forest Type						
	Mixed Peat Swamp[1]	Mixed Peat Swamp[2]		Alan[2]		Padang Alan[2]	
Sampling depth (cm)	0 – 45	0-25	25-50	0-25	25-50	0-25	25-50
Soil pH	3.5	3.37	3.29	3.40	3.31	3.33	3.25
Pyrophosphate solubility index (PSI)	-	18.04	22.07	11.11	11.24	11.64	10.33
Loss of ignition (%)	90.4	96.45	95.93	97.32	97.94	96.52	96.67
Total C (%)	56.5	57.47	60.35	56.42	58.39	55.48	58.10
Total N (%)	1.4	1.94	1.60	1.90	1.69	1.83	1.69
C:N ratio	39.9	29.70	37.72	29.65	34.63	30.27	34.38
CEC ($cmol_c\ kg^{-1}$)	145	37.95	39.21	34.36	33.28	36.03	34.34
Base saturation (BS)	7.9	13.72	6.83	13.76	7.44	7.92	4.47
Available P (ppm)	-	157.79	52.71	125.42	30.52	95.17	30.56
Exch K ($cmol_c\ kg^{-1}$)	0.28	0.38	0.12	0.73	0.32	0.52	0.21
Exch Ca ($cmol_c\ kg^{-1}$)	7.4	1.47	0.75	0.82	0.57	0.72	0.57
Exch Mg ($cmol_c\ kg^{-1}$)	1.7	2.82	1.37	2.50	0.88	1.15	0.33
Exch Na ($cmol_c\ kg^{-1}$)	-	0.50	0.45	0.69	0.70	0.47	0.42
Extractable Fe (ppm)	3446	15.02	11.06	11.74	12.96	6.10	6.10
Extractable Mn (ppm)	25	4.21	0.62	1.77	0.52	3.10	0.77
Extractable Cu (ppm)	-	3.19	4.13	1.77	2.77	3.13	2.19
Extractable Zn (ppm)	-	8.65	8.86	6.54	8.02	7.54	7.49
Extractable B (ppm)	-	0.95	0.85	0.93	1.01	1.11	1.30
Total P (ppm)	560	347.38	129.35	306.96	120.63	272.60	79.90
Total K (ppm)	260	55.33	19.94	116.81	73.06	68.05	30.50
Total Ca (ppm)	1250	319.21	184.29	360.15	104.46	119.54	80.94
Total Mg (ppm)	1290	266.13	91.00	232.10	44.17	60.69	1.56
Total Fe (ppm)	-	529.39	204.21	219.88	209.48	37.44	13.52
Total Mn (ppm)	-	0.00	0.00	0.04	0.88	1.15	0.00
Total Cu (ppm)	-	25.33	28.58	14.79	20.23	26.33	14.60
Total Zn (ppm)	-	36.38	34.69	31.50	33.40	33.23	30.81
Total B (ppm)	-	20.00	21.90	16.60	20.90	17.48	26.94

Source: 1) Joseph et al., 1974 and 2) Melling et al. (2011)

Table 19: Chemical properties of undrained and drained peat, and different kinds of organic soil materials

Items	pH (H20)	Exc. Acidity		C.E.C. at pH			Ash	Total Analysis				C	N	C/N
		H	A1	3.9	7.0	8.2		Ca	Mg	K	P			
		cmol (+) kg						% (w/w)						
Undrained	4.0	17.1	4.5	26.4	118.7	161.8	5.0	0.05	0.02	0.01	0.059	35.4	0.98	36
Drained	3.8	20.9	4.2	33.2	139.0	160.1	5.6	0.11	0.04	0.02	0.051	28.1	1.41	20
Fibric	4.2	16.4	4.7	26.0	110.0	152.9	4.3	0.05	0.02	0.01	0.058	34.4	0.80	43
Hemic	4.0	22.0	3.3	32.9	134.0	162.6	3.1	0.09	0.04	0.01	0.061	28.8	0.88	33
Sapric	3.6	19.7	4.7	32.3	145.3	169.9	9.2	0.12	0.06	0.02	0.064	25.6	1.65	17

Source: Peli, M. and Shamsuddin, J. (1994)

Table 20: Effect of nitrogen on FFB production

Treatment	FFB yield (kg/palm)			
	Mean of 1st 3 years	4th year	5th year	6th year
N1	148	152	174	199
N2	161	163	184	205
Var. Test	6.9*	6.8*	ns	ns
% Increase	8.8	7.2	5.7	3.0

Ref : * = Significant at 5%   ns = Not significant

Source: Gurmit et al. (1987)

Table 21: Soil properties of some major ultrabasic and limestone derived soils

Parent rock	Serpentinite										Limestone[1]	
Soil series	Tingkayu - moderately deep				Tingkayu - moderately deep to deep						Semporna	Dent
Horizon	A	Bt1	Bt2	BC	AB	Bt1	Bt2	BC1	BC2	C	N/A	N/A
Depth (cm)	0 - 6	6 - 24	24 - 55	> 55	0 - 8	8 - 36	36 - 58	58 - 72	72 - 111	> 111	N/A	N/A
pH	7.1	6.5	6.3	6.6	7.2	6.8	6.5	6.5	6.6	6.7	6.8	7.5
Clay (%)	22	36	44	55	28	30	25	25	34	35	26	37
Silt (%)	24	24	22	21	28	24	17	19	32	33	11	37
Fine sand (%)	42	32	23	17	28	23	12	20	29	21	62	22
Coarse sand (%)	11	8	10	7	15	23	46	36	6	10		
Exchangeable K (m.e. %)	0.23	0.39	0.38	0.42	0.41	0.36	0.21	0.2	0.31	0.3	0.3	0.1
Exchangeable Ca (m.e.%)	14.11	11.78	11.91	16.21	28.72	19.61	5.1	5.15	3.28	5.45	15.9	40.6
Exchangeable Mg (m.e.%)	9.06	14.19	22.88	28.14	7.22	13.12	16.62	37.13	24.97	24.57	1.7	1.2
CEC (m.e.%)	20.48	24.08	24.96	35.48	26.91	29.07	23.53	34.03	23.09	25.28	15.5	15.5
Base saturation (%)	114	109	141	126	135	141	93	125	124	120	115	270
Total P (ppm)	139	78	65	42	469	189	124	774	87	302	328	525
Bray 2-P (ppm)	5.4	2.5	2.2	2.4	38.4	3.5	2.8	19.9	1.4	2.3	47	< 1
Organic C (%)	1.26	0.48	0.39	0.35	2.96	1.04	0.29	0.19	0.14	0.15	0.81	3.73
Total N (%)	0.15	0.08	0.08	0.07	0.3	0.13	0.06	0.05	0.05	0.06	0.09	0.31
C:N ratio	8	6	5	5	10	8	5	4	3	3	9	12

Note: 1) Data from Lee and Rosman (2011). N/A denotes not available.

Appendix 1: Criteria for assessment of severity of soil limitations in oil palm

Soil properties	Desirable range	Minor limitation	Serious limitation	Very serious limitation
Terrain (°)	0 – 12	12 - 16	16 - 24	> 24
Effective soil depth (cm)	> 90	60 - 90	30 - 60	< 30
Stoniness (%)	0 – 5	5 - 20	20 - 40	> 40
Consistence	friable-moderately firm	firm	very firm - loose	compact
Texture	sandy clay loam, clay loam or heavier	loam, sandy loam	loamy sand	sand
Structure	well developed	moderately developed	very weak or massive	structureless
Nutrient status	low fertiliser requirements	moderate fertiliser requirements	high fertiliser requirements	very high fertiliser requirements
Permeability (drainage)	Moderately well to well drained	imperfectly drained	poorly or excessively drained	very poorly drained
Water table (depth in cm)	75 – 90	60 - 75	30 - 60	< 30
Soil pH	> 4.0	3.5 - 4.0	3.0 - 3.5	< 3.5
Conductivity (mhos/cm)	< 1000	1000 - 1500	1500 - 2500	> 2500
Sulphidic layer (depth in cm)	> 90	60 - 90	30 - 60	< 30
Peat (depth in cm)	< 30	30 - 100	100 - 150	> 150

Appendix 2: Classification of some nutrient status for oil palm

Nutrient	Nutrient status				
	Very low	Low	Moderate	High	Very high
pH	< 3.5	3.5 - 4.0	4.0 - 4.8	4.8 - 5.5	> 5.5
Organic C (%)	< 0.8	0.8 - 1.2	1.2 - 1.5	1.5 - 2.5	> 2.5
Total N (%)	< 0.08	0.08 - 0.12	0.12 -0.15	0.15 - 0.25	> 0.25
Total P (µg g^{-1})	< 120	120 - 200	200 - 250	250 - 400	> 400
Available P (µg g^{-1})	< 8	8 - 15	15 - 20	20 - 25	> 25
Exchangeable K (cmol kg^{-1})	< 0.08	0.08 - 0.20	0.20 - 0.25	0.25 -0.30	> 0.30
Exchangeable Mg (cmol kg^{-1})	< 0.08	0.08 - 0.20	0.20 -0.25	0.25 -0.30	> 0.30
CEC (cmol kg^{-1})	< 6	6 - 12	12 - 18	18 - 24	> 24

After Goh and Chew (1997) with updates