MANAGEMENT OF NUTRIENTS FOR EFFICIENT USE IN SMALLHOLDER OIL PALM PLANTATIONS

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ABSTRACT

In the Ophir nucleus estate smallholder scheme in West Sumatra, smallholders have produced larger yields than the nucleus estate since harvest began due to the use of more intensive management techniques which were extended to farmers through a co-operative management system. Although smallholders work under very different management constraints and opportunities compared to large scale estates, very little work has been done to adapt agronomic techniques developed by the estate sector for use in intensively managed oil palm smallholder plantations.

Mineral fertilizers represent the largest production cost in mature oil palms but a large proportion of total nutrient uptake may be cycled in crop residues. In the Ophir project, fertilizers were applied over weeded circles which represent 20% of the soil surface and pruned fronds were stacked in heaps along alternate inter-rows covering 12% of the soil surface. A further 8% of the soil surface was occupied by harvesting paths used for the transport of fruit bunches and no fertilizer or mulch was applied to the remaining 60% of the soil surface.

The effective rate of nutrient application in both palm circles and the frond stack was large. Soil analysis showed that whilst the concentration of exchangeable K and Mg was increased in soil in the circle zone, the application of urea resulted in reduced soil pH and large losses of Ca due to leaching. The concentration of exchangeable K and Mg was maintained in soil beneath the frond stack where the application of pruned fronds resulted in a marked increase in the concentration of exchangeable Ca and reduced P adsorption. Soil bulk density and soil resistance was increased in the unamended path soil where the concentration of soil exchangeable K
was reduced. The rate of water infiltration into the soil was reduced in the path and circle zones but increased in the frond stack compared with untreated soil,

The results from a pot experiment in which *Pueraria phaseoloides* was grown in soils from the palm circle, frond stack and path zones showed that differences in soil chemical properties found by soil analysis were large enough to produce differences in plant growth and nutrient uptake.

The root length density of tertiary and quaternary roots was found to be larger in amended soil in the circle and frond stack zones and smaller in the unamended soil in the path zone, where soil had been disturbed by the frequent traffic of harvesters and laden wheelbarrows.

Results suggest more efficient nutrient use could be achieved by extending the ameliorative effect of pruned fronds from 20 % to 75 % of the soil surface and, in subsequent years, mineral fertilizer broadcast over the entire soil area.
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Chapter 1

GENERAL INTRODUCTION

1.1 Development of the oil palm industry in Indonesia

Over the past 30 years, the oil palm (Elaeis guineensis Jacq.) industry in Indonesia has expanded rapidly. Oil palm seeds were first brought to Java in 1848 but oil palm plantations were not established until 1911 (Moll, 1987). The estate sector expanded very slowly from 83,000 ha in 1950 to 133,000 ha in 1970, but since then expansion has been rapid with a further 1,645,000 ha planted by 1994. The total area planted is now almost 1.8 M ha (K. Pamin, pers. comm.).

Oil palm requires large-scale processing equipment when grown as a cash-crop (Goldthorpe, 1994). Development of an oil palm smallholder industry was therefore delayed until the establishment of large scale estate projects set up in conjunction with out-grower schemes in which the smallholders sell their produce for processing to the estate-owned factory.

The development of the smallholder sector began with the implementation of the first large scale nucleus estate smallholder oil palm projects in 1979. By 1984, approximately 40,000 ha had been planted but since then the area has expanded rapidly to 565,000 ha by 1994 which represents 32% of the total area planted to oil palm in Indonesia (Figure 1.1).

Smallholder oil palm has largely been restricted to these nucleus estate smallholder schemes, but this is expected to change since there are now a growing number of processing plants keen to accept smallholder produce to augment and improve factory throughput. Thus in future Indonesian farmers will be able to plant up pockets of land with oil palm as
a cash crop provided a processing factory exists within a convenient distance to allow the delivery of fruit bunches.

![Graph showing expansion of the area planted to oil palm in Indonesia.](image)

**Figure 1.1** Expansion of the area planted to oil palm in Indonesia (after K. Pamin, pers. comm.).

Projections indicate that the planted area in Indonesia will continue to expand, reaching 2.5 M ha by the year 2000, 3.9 M ha by 2010 and 5.3 M ha by 2020 when Indonesia, with an annual production of 17 M tonnes of crude palm oil, is expected to have become the largest palm oil producer in the world (Bek-Nielsen, 1995).

All future estate oil palm schemes developed by the private sector are required by the Indonesian government to establish out-grower plantations for smallholders. With the exception of a small number of smallholders who have gained experience in the estate sector, most farmers have little or no knowledge about the crop when they enter an oil palm scheme. The extension services are faced with the task of developing suitable agronomic techniques for smallholder oil palm growers, which may be different from conventional estate practices, and the establishment of organisational structures which the farmers require for activities which
cannot realistically be arranged by each individual farmer. These tasks include fruit transport, road maintenance, fertilizer distribution, and pest and disease control.

The driving force behind the present rapid expansion of oil palm plantations includes the increasing demand for vegetable oil, due to an expanding population with increasing per capita income, and the need for the government of Indonesia to find sustainable, productive farming activities for smallholders as part of their drive to alleviate rural poverty. The present expansion of oil palm is therefore fuelled by both private and public sector investment respectively in estates and smallholders.

1.2 Productivity, energy balance and Life Cycle Assessment (LCA) in oil palm plantations

There are a number of reasons which account for the expansion of oil palm in Indonesia. The oil palm is unsurpassed in its ability to intercept and transform solar energy into vegetable oil (Corley et al., 1971a; Squire and Corley, 1987), and yields more oil per hectare than any other oil crop (Spedding et al., 1981; von Uexkull and Fairhurst, 1991) (Table 1.1).

When compared with coconut (Cocos nucifera), rubber (Hevea brasiliensis) and cocoa (Theobroma cacao), the three other main plantation crops adapted to lowland humid tropical conditions in Indonesia, oil palm has a larger crop growth rate, economic yield, and non-economic harvested residue which may be returned to the field (Corley, 1983; Corley et al., 1971a) (Table 1.2).
Table 1.1 Oil yield of various oil producing crops (taken from Bek-Nielsen, 1977).

<table>
<thead>
<tr>
<th>Crop</th>
<th>Yield t oil ha⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cotton seed</td>
<td>0.19</td>
</tr>
<tr>
<td>Soya bean</td>
<td>0.38</td>
</tr>
<tr>
<td>Peanut</td>
<td>0.87</td>
</tr>
<tr>
<td>Coconut</td>
<td>2.69</td>
</tr>
<tr>
<td>Oil palm*</td>
<td>7.42</td>
</tr>
</tbody>
</table>

* Based on smallholder production in NESP Ophir, West Sumatra (31 t ha⁻¹, 23% mesocarp extraction, 4% kernel extraction, 40% kernel oil extraction).

Table 1.2 Comparison of growth parameters in oil palm, coconut, rubber, and cocoa (adapted from Corley, 1983).

<table>
<thead>
<tr>
<th>Crop</th>
<th>Crop growth rate t ha⁻¹ yr⁻¹</th>
<th>Economic yield</th>
<th>Harvested residue</th>
<th>Biomass recycled in leaves</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil palm</td>
<td>29</td>
<td>5</td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td>Coconut</td>
<td>24</td>
<td>2.5</td>
<td>5</td>
<td>no data</td>
</tr>
<tr>
<td>Cocoa</td>
<td>20</td>
<td>2</td>
<td>2</td>
<td>no data</td>
</tr>
<tr>
<td>Rubber</td>
<td>26</td>
<td>2</td>
<td>0.3</td>
<td>6</td>
</tr>
</tbody>
</table>

The agricultural efficiency of oil production from oil palms may be assessed by calculating the ratio of energy required in terms of production inputs (fertilizer, workers, transport, agrochemicals) to the energy contained in the economic product. In terms of energy requirement, oil palm mills are self-sufficient since the energy required for steam and power generation is balanced by energy produced from the combustion of fibre and kernel shells (Wood and Corley, 1993). Fertilizers accounted for 76% of the total energy requirement of 19 Gj to produce 20 t ha⁻¹ fruit bunches which had
an energy value of 180 Gj and the energy output:input ratio of 9.5 for oil palm was larger than for oilseed rape, soya bean, wheat and rice but smaller than for shifting cultivation systems which produce only a small energy yield in terms of Gj ha$^{-1}$ (Wood and Corley, 1993). The oil palm’s large oil yield and efficient energy balance help to explain why palm oil accounts for 22 % of world vegetable oil production from only 2 % of the land planted to oil crops (Mielke, 1994).

Oil palm is a nutritionally demanding crop, and large quantities of mineral fertilizer are required to sustain economic yields (Chew et al., 1994; Ng, 1977; von Uexkull and Fairhurst, 1991). In this respect, Indonesia is disadvantaged in having only small deposits of phosphate for either direct application as rock phosphate or as a raw material for the manufacture of triple super phosphate, and no reserves of potash. The national N-fertilizer requirement is met and even exceeded by the manufacture of urea using energy from locally produced natural gas, but both P and K fertilizers must be imported, using foreign exchange, to meet the increasing demand from the oil palm sector.

In future, as part of a strategy to promote sustainable and productive agriculture, stringent efforts will be required in Indonesia to ensure that large amounts of nutrients imported for the oil palm industry are effectively recycled in the cropping system, nutrient losses due to exported crop materials are carefully balanced with the import of nutrients in mineral fertilizers, and losses due to leaching and erosion are minimised.

Life Cycle Assessment (LCA) has been used to measure the impact of a product throughout its life cycle on the environment (Knaut, 1993). More efficient oil palm waste management and nutrient cycling in oil palm plantations may improve the environmental profile of palm oil in the world vegetable oil market (Teoh and Chia, 1993) and reduce the cost of production. The interest shown by vegetable oil product manufacturers in
LCA (Knaut, 1994) underlines the importance of efficient nutrient management in oil palm cultivation if oil palm products and the production system are to be promoted on world markets as ecologically acceptable and environmentally responsible.

1.3 The effect of field management on the soil under oil palm

An important feature of oil palm cultivation is the imposition of rigid spatial patterns in terms of the management of soil and plant materials, from the onset of land preparation for new plantings, and aspects of the methods used for oil palm establishment and maintenance which contribute to the development of soil spatial heterogeneity are reported and discussed in the following three sections.

1.3.1 Soil management during the establishment of oil palm plantations

On flat and undulating land, prior to land clearing, arterial roads are marked out approximately 2.5 km apart. Perpendicular to these main roads, minor roads are marked in at 200 m intervals to form a grid of palm blocks each of approximately 50 ha. After the survey is completed, the land is cleared of the native vegetation, and it is at this early stage that a rigid system of management is imposed to handle soil and plant residues.

Prior to planting, forest or old oil palm trees are felled and wind-rowed to allow oil palm planting in cleared avenues (Plate 1.1). When the vegetation is burnt, nutrients in the standing biomass are concentrated in the future palm inter-rows. If the vegetation is not burnt, the soil in the inter-
row line is protected from the erosive force of rainfall, to which the palm line is exposed until a legume cover crop canopy is established.

On poorly-drained, clay soil grass lands, raised bunds may be constructed prior to oil palm planting (Plate 1.2). Off-set disc harrows are used to move the top soil into the marked palm planting line so that the palms are planted into soil lying above the water table. This protects the palms during early vegetative growth when they are particularly sensitive to water logging.

On steeply sloping land, terraces 4-5 m wide may be constructed along the contour of alternate planting lines, and top soil is removed to the outer edge of the terrace, leaving exposed sub-soil on the inside edge of the terrace.

These three examples show that even before planting, important soil spatial heterogeneity may have developed in bands perpendicular to the planting row as a result of land preparation.
Plate 1.1 In this replanted oil palm field, oil palm seedlings have been planted between lines of wind-rowed palm trunks.

Plate 1.2 Top soil has been removed to the planting line to form raised bunds to prevent water logging in young palms.
1.3.2 Field management in immature palm plantations

Oil palms and the legume cover crop are normally planted simultaneously and as soon as possible following land clearing and preparation. The most commonly used legume cover crop is made up of a mixture of species which includes *Pueraria phaseoloides* and *Calopogonium caeruleum* (Chee and Devendra, 1981). The timing of these operations is critical since the normally thin, fragile and nutrient-rich top soil is exposed to the erosive effects of rainfall (planting is timed to coincide with the rainy season) until ground covers become established, and nutrients lost through poor management at this stage may have to be replaced later in the form of mineral fertilizers.

Plate 1.3 Legume cover crop growth one month after planting in a field of oil palms established on an old rice field in Guadalcanal, Solomon Islands

The cover plants grow outwards from the planting points spaced 2 m apart and generally form a thick blanket cover over the soil after about three months. A small basal application of 25-50 kg ha$^{-1}$ P fertilizer is
usually provided at planting to stimulate early and vigorous legume cover crop growth. However, weeded circles are cleared around the base of each palm at this stage and kept weed free throughout the life of the plantation (Corley et al., 1976). For the first two years, monthly weeding operations may be required to prevent the inter-row legume cover crop from climbing up the newly planted palms, to facilitate fertilizer application, and to minimise competition between the inter-row vegetation and the newly planted palms. In the first year, circles with a 1 m radius are established, but by the end of the first year following planting, fronds may already droop into the legume cover crop and the width of palm circles must be increased to 1.5 - 2.0 m to prevent the legume cover crop climbing and smothering the young palms (Hartley, 1977).

A large biomass accumulates in the legume cover crop (Agamathu and Broughton, 1985). The total dry weight including roots of *P. phaseoloides* grown on a Selangor series soil in a commercial oil palm plantation in Malaysia was measured 12 months after planting (Han and Chew, 1982). In addition to the 5.5 t ha\(^{-1}\) dry matter in plant parts (leaf, stem and roots), more than 5 t ha\(^{-1}\) leaf litter had accumulated beneath the cover crop, and the growing and standing biomass contained 16, 129, and 31 kg ha\(^{-1}\) of P, K and Mg. Although similar amounts of P, K, and Mg accumulated in the litter and standing biomass of grass covers in this experiment, the N-content of grass covers was much smaller than that of the legume covers.

Estimates of N-accumulation in legume cover crops in plantations are rather consistent at 150 kg ha\(^{-1}\) yr\(^{-1}\) (Giller and Wilson, 1991), and *P. phaseoloides* was estimated to fix 60 to 80% of the N accumulated (Zaharah et al., 1986). In terms of nutrient supply, the legume cover crop makes a net contribution of 90 to 120 kg N ha\(^{-1}\) yr\(^{-1}\) during the three to four year period prior to canopy closure when the legume cover crop is shaded out. However, the legume cover crop may help to concentrate other
nutrients (P, K, Mg, Ca) in the surface soil horizon by scavenging for nutrients deeper in the soil profile, and some of the nutrients in mineral fertilizers applied to boost early legume cover crop growth are probably cycled through the cover crop and deposited at the soil surface.

The full benefit of legume cover crops also includes the conservation of nutrients present in the fragile soil surface horizon and released from the burnt standing biomass which might otherwise be lost through erosion when the soil is left uncovered following land clearing. The litter provided by the legume cover crop also fuels soil faunal activity which can improve soil structure by creating stable soil aggregates. Improved soil structure imparted by the development of stable aggregates may help to explain the increased infiltration rates (and presumably reduced surface run off and soil loss) under legume cover crop measured by Soong and Yap (1976). The legume cover crop also modulates diurnal soil temperature fluctuations which are much larger when the soil surface is exposed following land clearing compared with soil insulated by vegetative or litter cover.

However, the benefits from the legume cover crop N accumulation and nutrient cycling are restricted to soil in the inter-row area since the soil in weeded circles is kept free of the legume cover crop vegetation. Thus newly planted oil palms, with roots extending 1-2 m from the palm bole may not derive any immediate benefit from soil which has been ameliorated by the legume cover crop in the inter-row space. During the immature phase, mineral fertilizers are applied around the base of the palm in the weeded circle.

The oil palm canopy closes as the palms grow in height and frond length increases. The species composition in the inter-row gradually changes as *P. phaseoloides* dies out and the more shade tolerant *C. caeruleum* persists. The permanent inter-row vegetation will depend on the weeding techniques employed, and where light penetration is rapidly
reduced in high density stands with moderate pruning, all the legume covers will disappear to be succeeded by ferns (e.g. Nephrolepis biserrata), and grasses (e.g. Paspalum conjugatum, Axonopus compressus) which are usually kept slashed to a height of about 0.5 m.

During the first three years of growth, frond retention is of the utmost importance for satisfactory vegetative growth and very little of the nutrients taken up by the palms is returned to the soil. Small amounts of nutrients may be returned to the soil in female flowers if ablation is practised and there may be some removal of nutrients from the leaf canopy due to through-fall.

A network of paths is installed during the immature period, first between every fourth row, but later between every second row, to allow access by workers and management staff.

1.3.3 Field management in mature palm plantations

Two to three years after planting, the farmers begin to harvest and prune regularly as the canopy begins to close. Ripe fruit bunches are removed by cutting the penduncle with either a chisel or a sickle attached to a pole. At first, it may be advantageous to harvest fruit bunches without removing subtending fronds in order to maintain a large leaf area to service the assimilate requirement for vegetative and reproductive growth. However, even if frond removal is delayed for one or two years, eventually subtending fronds are cut at the base of the petiole and removed with each ripe bunch.

About 20-24 fronds are pruned each year, and male flowers removed during harvest and pruning operations are stacked in alternate inter-rows. The dry weight of pruned fronds was found to be about 10.4 t dry matter ha⁻¹ yr⁻¹ in 8 to 15 year old palms in Malaysia (Ng et al., 1968), and the amount of nutrients returned to soil beneath the frond stack was about 108 kg N, 10 kg P, 139 kg K, and 17 kg Mg ha⁻¹ yr⁻¹ (Chan et al., 1980).
At this stage, there is less encroachment of cover crops on palms and the frequency of circle weeding required is reduced due to the overhead shade provided by palms. However, clean weeded circles are now essential to facilitate the collection of oil-rich detached fruits (approximately 40% oil extraction rate) which scatter over the circle area when the harvested bunch (approximately 22% oil extraction rate) falls to the ground. Larger circles are required under older palms since the loose fruits from ripe bunches scatter over a wide area when bunches fall from the 10-12 m high palm crowns at harvest.

Paths are established in rows alternating with the "frond stack" rows to allow access to the farmer/labourer for the removal of fruit to the roadside in wheel barrows. In comparison with the undisturbed frond stack, the path and to a lesser extent the circle are subject to frequent traffic which is likely to cause compaction and soil disturbance. Circles and paths frequently become drainage channels after heavy rain, carrying water and sometimes fertilizers from the field into the drainage system.

From planting onwards, mineral fertilizers are applied in the weeded palm circle. In the first few years after planting there may be good reason to apply fertilizer close to the tree where, at first, there is a greater concentration of oil palm roots.

Thus, at an early stage in the establishment of an oil palm plantation, four contrasting zones emerge in which the soil under oil palm receives clearly different treatments. These may be described as the palm circle, the inter-row harvesting path, the frond stack, and the remaining part of inter-row area usually covered by ferns and grasses. These four zones are illustrated in Plates 1.4, 1.5, and 1.6 and the scale diagram in Figure 1.2. The circle and frond stack represent, respectively 20 % and 12% of the total surface area which means that with respect to the effects on soil properties,
the rate of application of fertilizer and fronds over these zones is in fact much larger than indicated by the *per hectare* rates usually given.

![Diagram of oil palms, palm circles, harvesting paths and frond stacks](image)

**Figure 1.2** Layout of oil palms, palm circles, harvesting paths and frond stacks in Kelompok 2, Ophir Project.
Plate 1.4  Palm circle in a 13 year old smallholder old palm plantation (Kelompok 2, NESP Ophir)

Plate 1.5  Harvest path avenue in a 13 year old smallholder old palm plantation (Kelompok 2, NESP Ophir)
1.4 Nutrient cycling in palm fronds, empty bunches, bunch ash and palm oil mill effluent

Tinker (1976) distinguished between three types of nutrient demand by oil palm:

a. nutrients removed in fruit bunches.

b. nutrients taken up and immobilized in palms but not returned to the soil.

c. nutrients recycled to the soil in pruned fronds and male inflorescences.

Unless the nutrients removed from the system are replaced, soil reserves may become depleted which results in soil degradation. There may be a large requirement for fertilizer during the immature growth period.
following planting since 47, 5, 98, 12, and 12 kg ha\(^{-1}\) yr\(^{-1}\) respectively of N, P, K, Mg, and Ca was found to be immobilized in the crown, trunk and roots in oil palms planted on marine clay soils in West Malaysia in the three years following planting (Ng et al., 1968). Nutrients are removed permanently in fruit bunches unless a proportion is returned in palm oil mill effluent (POME) and empty bunches, and nutrients accumulate in the incremental trunk growth but are returned to the soil at replanting.

Nutrient removal and immobilization in an oil palm plantation in Malaysia (148 palms ha\(^{-1}\), 25 t ha\(^{-1}\) fruit bunches) was measured by Ng and Thamboo (1967) and their results are presented in Table 1.3.

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>P</th>
<th>K</th>
<th>Mg</th>
<th>Ca</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vegetative growth</td>
<td>41</td>
<td>3</td>
<td>56</td>
<td>12</td>
<td>14</td>
</tr>
<tr>
<td>Pruned fronds</td>
<td>67</td>
<td>9</td>
<td>86</td>
<td>22</td>
<td>62</td>
</tr>
<tr>
<td>Fruit bunches</td>
<td>73</td>
<td>12</td>
<td>193</td>
<td>21</td>
<td>20</td>
</tr>
<tr>
<td>Male inflorescences</td>
<td>11</td>
<td>2</td>
<td>16</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>192</td>
<td>26</td>
<td>251</td>
<td>62</td>
<td>100</td>
</tr>
</tbody>
</table>

In mature oil palms, with established crowns, the amount of fertilizers required annually to replace nutrients removed from the system may be calculated from the sum of the nutrients immobilized in vegetative growth and removed in fruit bunches. Non-destructive methods may be used to estimate trunk biomass production, by measuring trunk girth and incremental growth (Corley and Breure, 1981) and trunk nutrient concentration may be measured in cores extracted from the trunk. Trunk nutrient content together with the amount of nutrients removed in fruit
bunches gives a good estimate of the total annual amount of nutrients removed from the soil.

A large proportion of the nutrients removed in fruit bunches is contained in the empty fruit bunches and palm oil mill effluent (POME) which are the main residues produced which remain after oil extraction in a palm oil mill. Formerly, empty bunches were incinerated by auto-combustion in specially built incinerators at the palm oil mill. The N and S contained in empty fruit bunches is lost during incineration, but the alkaline bunch ash produced contains about 33% K (Turner and Gillbanks, 1974) and may be applied to palms as a substitute for KCl. This is particularly useful for the amelioration of acid sulphate soils. Alternatively, empty fruit bunches may be used as boiler fuel after pressing to reduce the water content from 60 to about 40%. More recently, with the advent of clean air legislation, Malaysian producers have developed techniques to use EFB as a nutrient rich mulch.

The nutrient content of empty fruit bunches was measured by Gurmit et al., (1990) and the amount of nutrients contained in empty bunches as a proportion of nutrients contained in fruit bunches which may be returned to the field is shown in Table 1.4.

**Table 1.4** Amount of nutrients contained in empty bunches produced from 25 t ha\(^{-1}\) fruit bunches (after Gurmit, *et al.*, 1990).

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>P</th>
<th>K</th>
<th>Mg</th>
<th>Ca</th>
</tr>
</thead>
<tbody>
<tr>
<td>kg ha(^{-1})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% dry matter</td>
<td>0.80</td>
<td>0.094</td>
<td>2.41</td>
<td>0.18</td>
<td>0.18</td>
</tr>
<tr>
<td>2.0 t ha(^{-1}) empty bunches*</td>
<td>16</td>
<td>1.9</td>
<td>48</td>
<td>3.6</td>
<td>3.6</td>
</tr>
<tr>
<td>% removed in fruit bunches</td>
<td>22</td>
<td>16</td>
<td>25</td>
<td>17</td>
<td>18</td>
</tr>
</tbody>
</table>

* Empty bunches represent 8% of fruit bunches
A number of different techniques have been developed to use empty fruit bunches as a nutrient rich mulch. The material may be applied selectively to ameliorate particularly poor or damaged soils in an estate, and in areas prone to prolonged dry seasons empty bunches have been used effectively as a mulch to improve moisture availability in the soil immediately surrounding newly planted palms.

In Papua New Guinea, specialised machines have been developed which apply a carpet of empty bunches along the palm inter-rows. In Malaysia, empty fruit bunches applied at 75 t ha\(^{-1}\) together with an application of 0.75 kg and 1.0 kg palm\(^{-1}\) of urea and rock phosphate respectively, was found to be sufficient to meet the nutrient requirement of palms for 12-18 months (Gurmit et al., 1990). Apart from their nutrient content, other benefits reported due to the application of empty bunches to the soil include reduced erosion due to improved infiltration and reduced run off, improved conservation of soil moisture, and better vegetative palm growth and yield of fruit bunches (Chan et al., 1980).

Nutrients are also contained in the palm oil mill effluent (POME) which is produced at the mill during fruit processing. A yield of 30 t ha\(^{-1}\) produces approximately 15 t POME with a dry weight of about 1 t. Before direct application in the field, the high biological oxygen demand of POME (30,000 µg g\(^{-1}\)) must first be reduced by anaerobic digestion in ponds (Chan et al., 1980). However, during the digestion process, most of the nutrients contained in the POME accumulate at the bottom of the pond as a sludge which is periodically removed and may be returned to the field. Small quantities of nutrients are also contained in fibre and shells but these wastes are used respectively as a mulch in oil palm nurseries and as an all-weather road surfacing material.

Clearly, capital investment is required in handling facilities before large scale recycling of empty fruit bunches and POME can take place. For
empty fruit bunch cycling, large hoppers are required at the factory in
addition to equipment for transporting the material to the field. For the land
application of POME, specialised pumping equipment and tankers are
required. For the estate sector, decisions on a recycling strategy will
depend on favourable cost-benefit analyses but for smallholders, the
recycling of factory wastes will depend first on their contractual agreement
with the palm oil mill.

In a nucleus estate smallholder scheme in Papua New Guinea, after
investing in the necessary equipment, an estate company applied all the
empty bunches from the mill to its own plantations, which represented a
large transfer of nutrients from the smallholders' fields to the estate
company, whilst in Indonesia, nucleus estate companies commonly
incinerate empty fruit bunches and use the bunch ash as a substitute for
KCl on their estates. For smallholders, there are many organisational and
contractual issues which must be addressed before recycling takes place
on a large scale. The extent to which these issues will be resolved will
depend on future trends in mineral fertilizer costs, the implementation of
environmental protection legislation and how far smallholders are able to
organise their plantations to handle the materials.

The organic matter in pruned fronds, male flowers, empty bunches,
oil palm trunks and palm oil mill effluent (POME) provide opportunities for
the recycling of nutrients and may also contribute to improved soil physical
and chemical properties, and any reduction in nutrients lost through
leaching and erosion will contribute to savings in imported mineral
fertilizers.
1.5 Preparation of fertilizer recommendations for mature oil palm plantations

The preparation of fertilizer recommendations for mature oil palms requires the integration of a large number of factors, some of which are shown in Figure 1.3. Computer programmes are now widely used to store and process the large amounts of information which accrue in oil palm plantation projects and are used in the preparation of fertilizer recommendations. An example of a field record sheet from a smallholder project in Indonesia is presented in the Appendix 2.

**Figure 1.3** Some factors considered in the preparation of fertilizer recommendations for mature oil palms

1.5.1 The use of soil analysis for the preparation of fertilizer recommendations

Routine soil analysis is of limited use for the preparation of fertilizer programmes but is essential for site characterization which is required to assess the applicability of the results of fertilizer experiments carried out in other locations. The results of soil analysis carried out at regular intervals
throughout the life of a plantation revealed important temporal changes in soil properties (Dufour and Olvin, 1985; Kowal and Tinker, 1959) and may be helpful by prompting corrective action involving adjustments to the amount and type of fertilizer applied. Soil analysis may also reveal significant variability in soil properties in large plantations of 5-10,000 ha, but the sampling procedure must allow for spatial micro-variability in soil properties found in mature oil palm plantations (Foster and Dolmat, 1986; Kang, 1977; Teoh and Chew, 1985). Knowledge of soil parent material and soil texture have been the basis for the distinction made in Malaysia between the heavily fertilized "inland" soils and the more fertile "coastal clay" soils.

Oil palm is not susceptible to the high Al saturation which often accompanies low soil pH, but high Al saturation may result in a large P sorption capacity. On soils with low pH, rock phosphate and dolomite may be more effective and cheaper sources of Mg and P than respectively triple super phosphate and kieserite. A minimum requirement for soil exchangeable K of 0.15 cmol(+) kg\(^{-1}\) was proposed by Boyer (1972) and also by Ollagnier et al., (1970) and has gained widespread acceptance. However, leaf analysis may reveal K deficiency in oil palms when the amount of exchangeable K is larger than 0.15 cmol(+) kg\(^{-1}\) due to the presence of a large concentration of soil exchangeable Mg which suppresses K uptake (Turner and Gillbanks, 1974). For this reason, a critical ratio for soil exchangeable Mg:K of 2 was proposed by Tinker and Ziboh (1959), and other workers found a requirement of 1.5-2 for the percentage saturation of K which also predicted response to K fertilizer (Ochs, 1965; Tinker and Ziboh, 1959). Tentative minimal soil solution concentrations of \(0.7 \times 10^{-4}\) for potassium, \(3 \times 10^{-6}\) for phosphorus, and \(1.5 \times 10^{-5}\) for Mg for oil palms grown on a moist sandy loam soil were proposed by Tinker (1974) based on total nutrient demand and length of fine feeder
roots, but the measurement of nutrient concentration in the soil solution was considered too variable and difficult to measure to be applicable for field work. Soil analysis was considered unsatisfactory for estimating the availability of soil P and N for oil palms (Tinker, 1976), but more recently a minimum requirement of 15 µg g⁻¹ P (extracted with the Bray II method) was proposed by Caliman et al., (1994) based on an analysis of a network of fertilizer trials.

Thus soil analysis may provide important background information but is not usually the main criterion for the preparation of fertilizer recommendations for the reasons mentioned above and also because of the opportunities offered by leaf analysis which provides more useful information on how rapidly a soil can supply nutrients and water to palm roots than the concentration of nutrients in the soil.

1.5.2 The use of field inspection, leaf production and leaf analysis for the preparation of fertilizer recommendations

The oil palm presents very distinctive symptoms for N, K, Mg and B, (von Uexkull and Fairhurst, 1991) and a thorough inspection of the leaf canopy is required both to corroborate the results of leaf analysis and for the detection of nutrient deficiencies. Important indications of nutrient availability may be derived from an appraisal of ground cover vegetation since legume cover plants show clear deficiency symptoms for K, Mg, and P, and other plants such as Melastoma malabathricum, Imperata cylindrica and Dicanopteris linearis may become dominant where the soil has been eroded.

The measurement of vegetative dry matter production was suggested as a reliable indicator of gross nutrient deficiency by Corley and Mok, (1972) who proposed the comparison of measurements of leaf
characteristics such as petiole cross section (which is related to leaf dry weight) with "standard curves" relating leaf dry weight to palm age. This method has not been adopted on a wide scale, but could be conveniently combined with routine leaf sampling with little additional work to provide useful information on palm vegetative growth. The importance of measurements of vegetative dry matter production is illustrated by fertilizer experiments conducted in an oil palm plantation in West New Britain, Papua New Guinea where the application of fertilizer resulted in increased vegetative dry matter production but no increase in yield (Breure, 1982).

Leaf analysis is a potentially useful technique for detecting nutrient requirements and is conveniently carried out in oil palms because the leaf phyllotaxis allows the selection of tissue of the same physiological age. Since the pioneering work of Chapman and Gray (1949), the laminae from pinnae removed from the mid point of the 17th fully opened frond has been adopted as the standard reference tissue for leaf analysis in mature palms. In comparisons between fertilizer treatments, frond 17 showed the greatest difference in the concentration of N, P, and K, and yield was more closely correlated with nutrient concentration in frond 17 than physiologically younger leaves. Various shortcomings associated with the use of frond 17 as the reference tissue were highlighted by Foster, (1976) and palm nutritional status was found to be more closely related to rachis K concentration than lamina K concentration in oil palm fertilizer experiments carried out on a K deficient soil in Malaysia (Teoh and Chew, 1988). However, frond 17 remains the standard tissue for leaf analysis in oil palm cultivation.

Leaf nutrient concentrations vary according to leaf rank (Prevot and Peyre de Montbreton, 1958) and the time of sample collection, due to diurnal changes in leaf nutrient concentration. Seasonal variation in nutrient concentration was found to be associated with the effect of water
deficits on palm nutrient uptake (Ollagnier et al., 1987) and possibly the rate of soil organic matter mineralization (Foster, 1976). Significant correlation between leaf nutrient concentration and palm age, particularly for leaf K concentration was reported by Ochs and Olivin (1976), and further complications arise due to differences in the physiological age of frond 17 between similar aged plantations with different leaf production rates.

Differences in leaf nutrient concentration due to the factors mentioned above underline the importance of strict adherence to guidelines for leaf sampling and the difficulties involved in the interpretation of the results of leaf analysis. "Critical" leaf nutrient concentrations were proposed by Ochs and Olivin (1976), (see Table 1.5) who considered these values to have wide applicability, but the dangers of reliance on such critical values was argued by Green (1972) who found that foliar analysis did not provide a reliable guide to fertilizer requirements, based on an analysis of the results of several fertilizer experiments, except in the case of quite severe nutrient deficiency.

Table 1.5  Critical concentration of N, P, K, Mg and Ca in frond 17 taken from mature oil palms (after Ochs and Olivin, 1976)

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>P</th>
<th>K</th>
<th>Mg</th>
<th>Ca</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frond 17</td>
<td>2.50</td>
<td>0.15</td>
<td>1.00</td>
<td>0.24</td>
<td>0.6</td>
</tr>
</tbody>
</table>
1.5.3 The use of fertilizer experiments to estimate nutrient responses in oil palm

Field experiments are required to estimate the amount of fertilizer required to achieve maximum economic yield (Hartley, 1977). Response curves and interactions between nutrients may be derived from factorial experiments in which N, P, K, and Mg are applied at up to five different rates and yield (bunch number and bunch weight) and leaf nutrient content measured. Either plots of 49 palms (7 x 7) are used in which yield from the centre 25 palms are recorded or isolation trenches are installed to avoid the poaching of nutrient between treatments (Green, 1976). But such experiments are costly to implement and the results are only directly applicable in areas with soil and climatic conditions similar to the experimental site (Ochs and Olivin, 1976). Oil palm experiments are further complicated by the time between floral initiation and bunch production of about 44 months, which means that past water deficits may mask nutrient responses, and yield must be recorded for four to five years before the full yield response is obtained (Green, 1976). Even then results may be distorted since periods of large yield impose stress on the palm and result in smaller yields two or three years later (Corley, 1977). Response to fertilizer has been shown to depend on the amount of inter-palm competition (Breure, 1982; Ng, 1972) which may explain the poor response to fertilizer in experiments carried out in high density mature oil palm plantations. Response to all the major nutrients have been reported and response depended on local soil and climate conditions and there have been significant interactions between K and N and between K and Mg (Green, 1976; Ochs and Olivin, 1976).

However, complex experiments are beyond the scope of most estate companies and are obviously impossible to implement in smallholder
plantations. Ideally, fertilizer recommendations are based on an appraisal of the results of relevant fertilizer experiments, leaf and soil analysis results, production data and a thorough inspection of each field of 40-50 ha. At present, however, a small team of agronomists at the National Oil Palm Research station in Indonesia is responsible for the leaf analysis, field inspections, and the preparation of fertilizer recommendations for all state owned plantations and government sponsored small holder schemes amounting to about 1 M ha or 20,000 individual fields.

1.6 Management factors affecting nutrient use efficiency

Agronomists are also concerned with the effect of fertilizer placement, the timing and frequency of application and the type of fertilizer used on yield response, and the effect of empty bunch application and frond placement on fertilizer response, and these aspects have also been included in some field experiments which are discussed in the following sections.

1.6.1 Frequency and timing of fertilizer application

The most suitable frequency of fertilizer application depends on the nutrient's susceptibility to leaching, the soil's capacity for nutrient retention, and local patterns of rainfall distribution and intensity. Because the NO$_3^-$ produced from the mineralization of fertilizer N is highly susceptible to leaching, more frequent application may be required than for P fertilizers which are comparatively immobile in the soil. Frequency of K and Mg application should be related to soil properties, in particular the clay content and mineralogy and the cation exchange capacity.
On a sandy soil in Malaysia, the yield response to P, applied as rock phosphate was greater when applied annually compared to once in four years, but frequency of application had no effect on leaf P content (Foong and Syed, 1995). Larger yields were obtained when N, P, and K were applied three times a year compared to once a year on a Rengam soil (sandy clay) with small cation exchange capacity (<10 cmol(+) kg⁻¹) (Foster and Dolmat, 1986) but on Serdang (silty clay loam) and Munchong (clay) soils with a small cation exchange capacity there was no advantage from increased frequency of application, provided fertilizers were applied during periods of low rainfall (Teoh and Chew, 1985).

Although humid tropical climates with annual rainfall of 2000 - 2,500 mm imply the loss of large amounts of nutrients through leaching, the large evaporative demand of oil palms large suggests that leaching losses may in fact be small (Chang and Chow, 1985). Nutrients lost by leaching represented between 2 - 5 % of the nutrient content of fertilizers applied to a clay loam soil in a lysimeter planted with oil palms and legume cover crop where annual rainfall was 1,800 - 3,000 mm. Losses were different for each nutrient, increasing in the order P<N=K<Mg, and the largest losses occurred during periods when monthly rainfall exceeded 200 mm (Foong, 1993). In contrast, on an acid sand soil in Nigeria where annual rainfall was 2,000 mm, 34, 18, 172, and 60 % respectively of the fertilizer N, K, Ca, and Mg were leached from the soil in an experiment in which lysimeters were installed 150 cm below the palm circle. These two experiments illustrate the larger amounts of nutrients which may be lost through leaching on coarse textured sandy soils (probably with small cation exchange capacity) compared to clay soils.

Nutrients may also be lost in surface wash and erosion. About 11, 3, 5, 6 and 5 % of the fertilizer N, P, K, Mg and Ca added to the soil was lost from the field in run-off water, but losses were smaller from the soil
protected by dead fronds in the frond stack than the exposed soil in the harvest path (Maene et al., 1979).

1.6.2 Placement of fertilizer in oil palm plantations

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

In fertilizer experiments carried out in Malaysia, yield was larger when P was applied in the harvest path avenue compared to the frond stack and circle, and when K was applied in the frond stack compared to the circle (Foster and Dolmat, 1986). In contrast, Teoh and Chew (1985) and Yeow et al., (1982) found no difference in yield between different placement strategies. Of particular interest is the increased response to fertilizer in experiments carried out in Malaysia when palm fronds were broadcast over the inter-rows compared to the placement of fronds in alternate palm rows, and when fertilizer was applied together with an application of 3.5 t ha\(^{-1}\) empty bunches (Chan et al., 1993).

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

1.7 Summary and conclusions

The rapid expansion of oil palm plantings in Indonesia is related to the oil palm's biological efficiency as an oil producing crop and the increasing demand for vegetable oil in Southeast Asia. The crop is well adapted to cultivation by both the estate and small holder sectors, and the smallholder sector now represents more than 30 % of the total area planted.

A large part of the total annual biomass produced by oil palms is recycled in pruned fronds, and there is considerable scope for the recycling of residues produced in the oil extraction process. N₂-fixation may provide a net contribution of up to 120 kg ha⁻¹ yr⁻¹ in the immature phase following establishment. These aspects have attracted the attention of the vegetable oil processing sector which has attempted to exploit the positive ecological and environmental aspects of the production system in the promotion of products derived from palm oil.

Fertilizers and pruned fronds are placed in spatially discrete zones covering respectively 20 % and 12 % of the total land area under the canopy, and methods used in the establishment phase result in changes to the soil between palm rows and inter-palm avenues.

The preparation of fertilizer recommendations requires an integrated approach involving an assessment of nutrient removal, based on production records, and nutrient immobilization, which may be achieved using non-destructive techniques. Soil analysis provides important information required for an assessment of the applicability of the results of fertilizer experiments which are expensive, complicated to design, and must be run for up to five years before useful results are obtained. The results of
soil analysis may be used to predict the likelihood of P, K, and Mg deficiency.

Leaf analysis is relatively uncomplicated to carry out, but the interpretation of results is complicated by the number of factors which have been shown to affect leaf nutrient concentrations. However, when combined with a thorough inspection of the palm canopy for leaf deficiency symptoms, which are easy to detect in oil palm, leaf analysis remains a cornerstone in the estimation of fertilizer requirements.

However, the limited capacity of the institutions responsible for the preparation of fertilizer recommendations for state owned and smallholder plantations remains a serious deficiency in the Indonesian oil palm industry which is rapidly approaching a position of pre-eminence in the world.
Chapter 2

THE NUCLEUS ESTATE SMALLHOLDER PROJECT
(NESP) OPHIR OIL PALM SCHEME

2.1 Oil palm cultivation in West Sumatra and the NESP Ophir project

During the 1970's, as part of the national smallholder oil palm development drive, the government of Indonesia started the rehabilitation of the formerly Dutch owned oil palm estate located on the western slopes of the Gunung Talamau volcano which lies almost directly on the equator in West Sumatra.

The Nucleus Estate Smallholder Participation (NESP) Ophir project lies almost exactly on the equator 99° 50' to 100° E of Greenwich in the north-west of the Province of West Sumatra in the District of Pasaman. The project site ranges in altitude from 50 m a.s.l. on the coastal plain to 400 m a.s.l. in the foothills of the Talamau volcano. Most of the land is gently sloping (1 - 3%) but slopes increase to 10% in the eastern border area. A number of small rivers run down the slope from the volcano in a westerly direction towards the Indian Ocean. Kelompok (i.e. farmer group) 2, the farmers' field chosen for the investigations carried out in this study lies on the flat coastal plain at an altitude of about 50 m a.s.l.

2.1.1 Climate in the NESP Ophir project

Because growth and productivity are affected by temperature, which decreases with increasing altitude, oil palms are normally not cultivated at altitudes of more than 500 metres above sea level. Indonesia possesses
very large areas of soils under forest, logged forest and anthropic savannah with suitable climate and soil conditions for oil palm cultivation.

In the project feasibility documents, soil and climatic conditions were considered almost perfectly suited to oil palm cultivation. The mean annual rainfall of 3228 mm is well distributed throughout the year with small seasonal peaks in March to April and October to December (see Figure 2.1). The mean monthly rainfall has always exceeded 151 mm which means for oil palm, with an evaporative demand of 5 - 5.5 mm day\(^{-1}\) (Foong, 1993) water deficits are unlikely to occur.

![Figure 2.1](image)

**Figure 2.1** Mean monthly rainfall and number of raindays in the Ophir Project (after Purba and Lubis, 1993).

Oil palms indicate moisture stress by presenting un-opened fronds but this has never been observed in the Ophir plantation. Solar radiation recorded at the Sukamenanti meteorological station at 180 m a.s.l., 10 km from the project site, was estimated at 4.3 mean daily sunshine hours. Sunshine hours are measured in Indonesia from 08.00 to 16.00 hrs. which
means that these records may have underestimated the true amount. Furthermore, the amount of sunshine is likely to be larger at the project site where rainfall is slightly lower. Daytime temperatures range from 26 to 38 °C with a mean of 31 °C, which are normal for oil palm cultivation. Night time temperatures were 19 °C minimum and 24 °C maximum.

2.1.2 Soils in the NESP Ophir project

The soils in the project area were derived from basic volcanic ash from eruptions in the Holocene period. Under the USDA Soil Taxonomy, the soils have been classified as Hydric or Typic Dystrandepts (Delveaux and Peeters, 1992) taking account of their relative infertility (base saturation between depths of 25-75 cm less than 50%) and Andic properties (i.e. the presence of allophane). However, in the revised Keys to Soil Taxonomy (Soil Survey Staff, 1990), the Ophir soils come under the new order of Andisols and the great group Melanudands, reflecting their dark or melanic surface horizon, the lack of seasonality in rainfall or udic moisture regime, and the presence of andic properties.

A comprehensive soil survey was carried out by the Dutch over the entire project district to investigate the suitability of the area for oil palm cultivation (Sieverts, 1938). The survey report remarked on the soil's large organic matter content but small exchangeable K concentration. Although the available P content was small, serious P deficiency was considered unlikely since the soils physical properties favoured extensive root development. Soil analysis was also carried out in 1975 as part of the feasibility study of the present project (Rosenquist and Anderson, 1975), and a summary of the results is presented in Table 2.1
Table 2.1 Soil chemical properties in the Ophir plantation site measured in 1975 (after Rosenquist and Anderson, 1975)

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>pH</th>
<th>C</th>
<th>N</th>
<th>C/N</th>
<th>P Bray</th>
<th>K</th>
<th>Na</th>
<th>Ca</th>
<th>Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-20</td>
<td>5.7</td>
<td>7.9</td>
<td>0.69</td>
<td>11.4</td>
<td>7.7</td>
<td>0.48</td>
<td>0.07</td>
<td>2.24</td>
<td>0.55</td>
</tr>
<tr>
<td>20-40</td>
<td>5.8</td>
<td>4.5</td>
<td>0.43</td>
<td>10.6</td>
<td>7.9</td>
<td>0.34</td>
<td>0.07</td>
<td>1.15</td>
<td>0.18</td>
</tr>
<tr>
<td>40-60</td>
<td>6.0</td>
<td>1.9</td>
<td>0.19</td>
<td>10.0</td>
<td>9.3</td>
<td>0.25</td>
<td>0.08</td>
<td>1.08</td>
<td>0.15</td>
</tr>
</tbody>
</table>

In addition, a catena of 12 soil pits was prepared in 1991 along a transect stretching from the western boundary of the project up the slope of the extinct volcano to the eastern perimeter of the project. Soil horizons in each pit were identified and assessed for colour using Munsell soil colour charts, consistency and drainage. Each horizon was sampled and the soil physical and chemical properties were analysed by the Institut National de la Recherche Agronomique (INRA) and the Université Catholique de Louvain (Delveaux and Peeters, 1992). The concentration of Ca, Mg, and K was smaller and soil pH lower (particularly in the soil surface horizon) in the soil catena study compared with the results of the project feasibility study (Table 2.2) and the soil texture was a sandy loam (Table 2.3).

Table 2.2 Soil chemical properties from a soil profile close to Kelompok 2, NESP Ophir (Pit No. 4) (after Delveaux and Peeters, 1992)

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>pH</th>
<th>Ca</th>
<th>Na</th>
<th>Mg</th>
<th>K</th>
<th>Al</th>
<th>ECEC</th>
<th>Al sat</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-24</td>
<td>4.7</td>
<td>2.0</td>
<td>0.05</td>
<td>0.25</td>
<td>0.07</td>
<td>0.9</td>
<td>7.7</td>
<td>12</td>
</tr>
<tr>
<td>24-50</td>
<td>5.2</td>
<td>0.4</td>
<td>0.05</td>
<td>0.10</td>
<td>0.05</td>
<td>0.2</td>
<td>7.2</td>
<td>3</td>
</tr>
<tr>
<td>50-80</td>
<td>6.1</td>
<td>1.2</td>
<td>0.04</td>
<td>0.16</td>
<td>0.05</td>
<td>0.1</td>
<td>8.1</td>
<td>1</td>
</tr>
<tr>
<td>&gt;80</td>
<td>5.6</td>
<td>0.5</td>
<td>0.03</td>
<td>0.14</td>
<td>0.03</td>
<td>0.2</td>
<td>6.2</td>
<td>3</td>
</tr>
</tbody>
</table>
Table 2.3 Soil particle size analysis from a soil profile close to Kelompok 2, NESP Ophir (Pit No. 4) (after Delveaux and Peeters, 1992)

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>&lt;2</th>
<th>2-20</th>
<th>20-50</th>
<th>50-200</th>
<th>&gt;200</th>
<th>Allophane</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-24</td>
<td>18.6</td>
<td>36.5</td>
<td>16.5</td>
<td>11.5</td>
<td>16.9</td>
<td>12.3</td>
</tr>
<tr>
<td>24-50</td>
<td>7.1</td>
<td>16.0</td>
<td>20.9</td>
<td>26.2</td>
<td>29.8</td>
<td>-</td>
</tr>
<tr>
<td>50-80</td>
<td>2.9</td>
<td>6.2</td>
<td>7.8</td>
<td>21.2</td>
<td>61.9</td>
<td>22.8</td>
</tr>
<tr>
<td>&gt;80 cm</td>
<td>4.3</td>
<td>18.8</td>
<td>8.8</td>
<td>14.9</td>
<td>53.2</td>
<td>-</td>
</tr>
</tbody>
</table>

A diagnostic characteristic of Andisols is the presence of allophane, a primary weathering product of volcanic ash. Soil mineralogical analysis of 12 soils sampled from the catena stretching up the slope of the Ophir volcano confirmed the presence of 11-24% allophane in the 0-2 mm soil mineral fraction, with a tendency for concentration to increase with depth. The other minerals identified were halloysite, kaolinite, gibbsite, and small amounts of chlorite. Allophane interacts with soil organic acids to form stable particles (Buol et al., 1973) which are protected from attack by microorganisms (Wada, 1985). These particles account for the almost black A horizons found in Andisols (Tan, 1993). The presence of allophane also gives Andisols their characteristic fluffiness and smeary thixotropic consistency (Fitzpatrick, 1986), and high porosity.

In addition to increasing water retention, allophane also contributes to bulk density values of less than 0.83 g cm\(^{-3}\) which are characteristic for these soils. Allophane has a variable or pH-dependent charge which is reported to adsorb large amounts of P (Wada, 1985).
2.2 Development of the NESP Ophir project

A total of 6,000 ha oil palm was planted by the State Plantation Company PTP VI between 1981 - 1985, of which 4,800 was divided into 2 ha plots which were subsequently settled by small-holder farmers. The remaining 1,200 ha became the nucleus estate which was subsequently expanded to over 5,000 ha. Smallholders have been cultivating oil palms within the framework of the NESP Ophir since 1985, and spectacular yields have been achieved and sustained over a period of eight years since harvesting began (Figure 2.2).

![Figure 2.2](image)

**Figure 2.2** Yield of fruit bunches in the nucleus estate and the smallholder plantation Sawit Perentis (mean of 26 farmers' fields) in the NESP Ophir project (1981/82 planting)

Yearly fluctuations in yield were similar in the nucleus estate and smallholder plantations, but the yield of fruit bunches was larger in all years, and particularly in the first seven years in the smallholder plantation compared with the nucleus estate. Since soil and climate conditions, and planting material on the two sites were very similar, the difference in yield
probably resulted from better standards of management in the smallholder's plantation. This provides clear evidence that a properly organised smallholder plantation was able to produce larger yields than its partner nucleus estate, and some of the possible reasons for this are given in section 2.5 below.

2.3 Fruit bunch yield and nutrient removal in fruit bunches in Kelompok 2, Sawit Perentis

Compared with the estimated fruit bunch yield for Class 1 land in Indonesia, yields were very large in the ten years of production (Figure 2.3a) and the cumulative yield of fruit bunches after 10 years of harvest was more than 270 t ha\(^{-1}\) (2.3b). There was a large increase in yield in the second year of production due to increased bunch size and bunch number (Figure 2.3c, 2.3e), but in the following year yield surprisingly decreased due to a sharp decrease in the number of bunches. In between 1987 and 1993, yield increased slightly from 27.2 to 31.0 t ha\(^{-1}\) and during this period, bunch weight increased but the rate of increase became gradually smaller (Figure 2.3d). The number of bunches produced decreased between 1987 and 1991 but there was little change in bunch number in the following two years (Figure 2.3f). Yield decreased in 1994 due to a reduction in the number of bunches produced.
Figure 2.3  Annual and cumulative fruit bunch yield, bunch weight bunch number and yearly change in bunch weight and bunch number in Sawit Perentis, NESP Ophir (mean of 24 farmers fields).

2.4  Leaf analysis in Sawit Perentis, planted in 1981.

There was a general decrease in leaf N and P concentration between 1986 and 1994, but the amounts were above the critical
concentrations proposed by Ochs and Olivin (1976) (Figure 2.4a, 2.4b). Leaf K concentration increased from 1986 until the critical concentration of 1% was reached in 1990 but since then leaf K concentration decreased until 1993 when there was a small increase (Figure 2.4c). Leaf Ca concentration followed a similar pattern to leaf K concentration (Figure 2.4e). Leaf Mg was smaller than the critical concentration in all years since 1986 since when there has been a general decrease in leaf Mg concentration.

Pronounced Mg deficiency became evident in 1988 when leaf Mg concentration was well below the "critical" leaf Mg concentration given by Ochs and Olivin (1976) (Figure 2.4d). The application of Mg was increased and kieserite substituted for dolomite in 1989. As a result, leaf Mg deficiency symptoms disappeared with the appearance of new leaves. However, whilst there was a slight increase in 1991, leaf Mg concentration continued to decrease. Magnesium deficiency was not anticipated in the project feasibility study due to the large amount of soil exchangeable Mg (Table 2.1). This example illustrates the difficulty of predicting nutrient responses from soil analysis and underlines the difficulty involved in correct interpretation of the results of leaf analysis.
Figure 2.4 Concentration of N, P, K, Mg and Ca in frond 17, Sawit Perentis (mean of 24 farmers' fields).

2.5 A comparison of management techniques adopted by oil palm estates and smallholders.

Standardised methods for field management in estates of 10-20,000 ha are an essential feature of successful plantation organisation, and every effort is made to achieve a high degree of orderliness and homogeneity amongst
the 1000 ha "divisions" which are sub-divided into 50 ha "fields" and constitute an estate.

For example, on a well run estate of 5,000 ha, each of the 700,000 trees is recorded in an inventory and tree health and productivity is marked on isometric maps. About 10% of trees are monitored at regular intervals for the incidence of pest and disease and leaf nutrient deficiency symptoms. The goal of plantation management is to apply a standardized field management policy with strict attention to detail over, in this case, an area of 50 km².

However, agronomic objectives may be constrained and compromised by the need to devise maintenance methods which are easy to implement by unskilled labour, and to supervise in the field. In contrast, the smallholder farmer with a 2 ha plot containing about 240 trees is working under very different constraints but is in pursuit of similar economic goals.

For example, the conventional approach of applying mineral fertilizers in the weeded circle and pruned fronds in a stack every alternate row represents a compromise between the application of sound agronomic principles and the need to devise systems which are easy to supervise in large scale plantations. When dealing with a large work-force, it has been found necessary to design methods to check that each tree has received, for example the correct amount of fertilizer properly applied. The main reason, therefore, why fertilizer is still generally applied in the weeded circle is because the material is highly visible and "proper" application (quantity applied and spreading technique) is easy to check. The same logic may be applied to other aspects of field upkeep, including pest and disease control, weeding, and pruning.

The smallholders' economic and social setting is of course very different to that of a large estate. When rubber was adapted and
incorporated into the farming systems in West Sumatra by indigenous farmers, the agronomic methods employed and organisational set up were adjusted and tailored to the farmer's state of knowledge and the social and economic conditions prevailing when planting began. It is therefore not surprising that the rubber farming system which evolved under smallholder management contrasts in almost every respect with estate sector rubber plantations in terms of the maintenance and establishment methods used.

The adoption of technology by smallholders in the developing and more formal smallholder oil palm industry is very different. First, farmers who often come from outside the region move into oil palm smallholdings established through government initiatives which are planted and yielding fruit. Second, housing and a small area for food production are included in the package the farmer receives as part of a loan agreement. At the same time, at least in the beginning, the farmers are expected to follow the nucleus estate field maintenance methods, particularly during the period of loan repayment. Thus, extension workers together with the participating but inexperienced farmers must set up a viable organisational structure at a time when the farmers' knowledge of oil palm cultivation is virtually non-existent.

Each 50 ha field in the NESP Ophir project is under the collective management of 25 farmers who elect a leader to represent the farmer group at the primary co-operative responsible for servicing the needs of the 20 member farmer groups. At the group level, small incentives, based on the number of bunches produced per week and amounting to perhaps 10% of total proceeds, are paid to individual farmers based on individual plot productivity. However, the largest part of the total proceeds for the farmer group is divided equally between individual members. In this way, both individual incentives encourage competition between farmers (who all maintain their plots individually) but, at the group level, cross checks are
built into the system to develop peer pressure towards farmers who either neglect their plots or fail to come up to the group standard for maintenance. In addition, each farmer group sets up mutually agreed penalties for negligent work. Fines are imposed on farmers who fail to collect fruit or apply fertilizers for which a programme has been agreed at annual general meetings. Eventually, extension services, manned exclusively by farmers or farmers' sons are provided by the primary co-operative, and paid from the farmers' revenue.

The organisational set up is explained and described here because not only is it the major factor responsible for the very high standards of field maintenance and large yields which prevail in the project, but it also shows that a system exists through which modified and improved techniques could be introduced.

A recurring theme throughout the period during which technical assistance was provided to the NESP Ophir project was to re-think the conventional "estate" field maintenance techniques for harvesting, pest and disease control as well as nutrient management and to develop modified approaches which more suited to the very different circumstances of the smallholder oil palm grower. This was a major challenge for the project since, at the outset, the farmers' organisation was issued copies of the state-owned nucleus estate field management techniques manual and expected to adopt and apply them in entirety.

It should also be mentioned at this point that in contrast to rubber there is no published information on the adaptation of management techniques developed in the estate sector for use in smallholder oil palm plantations, in spite of the large area planted to smallholder oil palm. If the government of Indonesia's objective to set up self-reliant smallholder plantations is to be reached, much more work will be required in future to
refine and modify estate management techniques specifically for use by smallholders.

The primary management unit in estate agriculture is the "division", a planted area of more than 1000 ha, whilst in the small holder plantation the primary management unit is the 50 ha farmer group. With a relatively small individual plot size (2 ha) farmers can only increase profitability by the use of intensive management techniques to improved palm productivity and increase the efficiency of input use. Three examples of technological improvements introduced by the farmers organisation with a direct effect on nutrient use efficiency are cited to illustrate this.

The cost of mineral fertilizer accounts for 50-70% of mature field upkeep costs in Malaysia (Ng, 1977). The cost of fertilizer has increased in recent years partly due to the government's policy to progressively remove subsidies on TSP, KCl and urea (see Figure 2.5). In the Ophir project, fertilizer costs represent 84% of the total cost of production inputs and services provided by the farmers' organisation to the member farmers. Fertilizer recommendations are provided to the farmers' organisation separately for each 50 ha field based on leaf analysis, canopy inspection and tree census to the nearest ±0.25 kg tree⁻¹.

However, fertilizer applied to individual trees was measured in handfuls in the smallholder plantation which meant that carefully calculated fertilizer recommendations were not implemented accurately. Calibrated cups for each fertilizer type were designed, manufactured and introduced by the farmers' organisation in all farmer groups to add precision to the implementation of fertilizer recommendations.
Figure 2.5  Fertilizer and fresh fruit bunch prices in the NESP Ophir project.

Pruning is motivated by the grower's desire to view the production and ripening of bunches and by the labourer's wish to reduce the burden of his work (Hartley, 1977). The smallholder, as both owner and labourer, gains both from reducing the labour required for harvest and from the yield of fruit. To obtain the maximum yield, young palms should be pruned as little as possible. However, in the first three years of production, when trees produce a large number of small bunches, removal of the subtending frond at harvest means that the most productive trees are continuously over pruned, affecting production in subsequent years. To avoid this, special narrow harvesting chisels were designed and introduced and farmers were trained to harvest bunches in young trees without removing the subtending frond.

Some 15% of the yield of a vacant point is compensated by the production of the six surrounding trees (Bachy, 1965). Therefore, a significant increase in yield results from the removal of unproductive trees. The farmer's organisation co-ordinated surveys in which the productivity of
trees was monitored over a two year period and subsequently all unproductive trees were poisoned out.

These three examples are given to illustrate positive aspects of the intensive management techniques practised by smallholders, but problems were also encountered when, for example, over zealous weeding resulted in increased surface run-off and soil erosion in the first three years following the onset of harvesting. Bare ground conditions disturb the biological equilibrium between the population of important oil palm pests and their predators (Mariau et al., 1991) and this resulted in pest outbreaks which required control with pesticides.

In developing an appropriate strategy for field management, a key issue for the farmers' organisation was to harness and direct the farmers' commitment to intensive management to produce large yields by maximising the efficiency of nutrient use without disturbing and damaging the soil and oil palm ecosystem. In this study, the focus is on the effect of applying "estate" maintenance methods of fertilizer and frond placement on soil properties and oil palm root distribution and to propose alternative methods for improved nutrient use efficiency.

2.6 Conclusions

The suitability of climate and soil in the Ophir project site for oil palm production was confirmed by the very large yields sustained in the smallholder plantation. However, yields in the nucleus estate were smaller at 188 t ha\(^{-1}\) compared with 267 t ha\(^{-1}\) in the smallholder plantation in the first ten years of production. The larger yields produced in the smallholder plantation may be explained by the attention paid to aspects of oil palm field management such as fruit collection, fertilizer application and pruning, and the effect of the removal of unproductive trees upon inter-palm competition.
This underlines the value and importance of a properly organised farmers co-operative able to implement sound agronomic techniques over a large plantation area owned by thousands of farmers.

A comparison of the results of soil analysis carried out before the present project with the results of soil analysis carried out in 1991 suggests that after six years of large fruit bunch yields, the concentration of K, Ca and Mg was reduced and soil pH lowered.

2.7 Aspects of present nutrient management strategy which require investigation

Five main questions arise in terms of the efficient use of added and recycled nutrients.

1. Is the application of mineral fertilizer over 20 % of the total surface area the most agronomically efficient method of application?

2. Could the ameliorative effect of dead fronds be extended over more than 12 % of the total surface area?

3. What are the long term effects of the application of large quantities of organic matter and mineral fertilizer on soil properties?

4. What could be proposed to smallholders to improve nutrient use efficiency and conserve and improve soil properties?

5. What are the implications of the build up of soil fertility gradients on fertilizer management at replanting?
3.1 Study site

The study is based on investigations carried out in Kelompok 2, a 48 ha field of oil palms in Sawit Perentis, one of four 1,000 ha smallholder plantations in the Nucleus Estate Smallholder Participation (NESP) Ophir project in West Sumatra planted with Dura x Pisifera oil palm seedlings in March 1982. This field had been under the collective management of 24 smallholder farmers since the harvest of fruit bunches began in 1985.

The palms were planted in a triangular arrangement with 9.8 m between palms giving an inter-row spacing of 8.5 m and a planting density of 126 palms ha\(^{-1}\). Soil and palm samples were taken over a two year period between 1993-1995.

Fruit bunches were cut at weekly intervals and the total number and weight of bunches recorded. Cut bunches were transported by wheel barrow from the field to the road side along weed-free paths of between 1 to 1.5 m width which were maintained in each alternate inter-row. Fronds cut at harvest or during biennial pruning rounds were placed in lines between alternate lines of palms to form a stack about 2 m in width.

All mineral fertilizers have been applied within the weeded palm circle since planting. Weeds in the inter-row area not covered by fronds or kept weed free (palm circle and path) were regularly slashed to about 0.5 m height and the weeds left in situ.
3.2 Oil palm biomass sampling

To assess nutrient immobilisation and cycling in a mature oil palm stand, estimates of dry matter production in the different parts of the oil palm are required. The amount of nutrients contained in the palm crown and cabbage is assumed to be constant in a mature stand, but it is necessary to quantify the nutrients immobilised in incremental trunk growth and recycled in cut fronds and fruit bunches to allow accurate description of nutrient cycling.

Non-destructive methods are most convenient as they do not require the removal and drying of large amounts of material, and avoid large scale damage to palms in farmers' fields.

Annual root dry matter production or root turnover is difficult to estimate and the production of male inflorescences is not usually recorded in the plantation. Although the total amount of dry matter produced annually by these two parts may be appreciable, they amount to less than 4% of the total annual vegetative dry matter production and, in investigations into annual nutrient cycling in mature stands, may be ignored.

The methods used in this study are based on those described by Corley and Breure, (1981), Corley et al., (1971b) and Breure and Powell (1987).

3.2.1 Oil palm leaves

The dry weight of individual fronds can be estimated from the close correlation between petiole cross section, measured at the point of insertion of the first true pinnae, and frond dry weight (Corley et al., 1971b).

To test this relationship under local conditions nine fronds from randomly selected trees were removed as close to the oil palm trunk as
possible. The petiole cross section was estimated from the product of the width and depth of the petiole at the same point and the sun-dried frond weight recorded. The following regression equation was then computed.

\[ W = 0.352 + 0.184P, R^2 = 0.911 \]

where

- \( W \) = Frond weight (kg)
- \( P \) = Petiole cross section (depth x width) (cm²)

The regression equation given by Corley et al., (1971b) gives a slightly smaller frond mass per cm² petiole cross section, probably because fronds used to determine the relationship were oven-dried before weighing.

The rate of frond production was estimated by marking the youngest fully opened frond with blue paint to produce a conspicuous mark. After one year, the position of the previously marked leaf in relation to the current first fully opened frond was recorded. Frond production was then calculated knowing that 8 leaves are produced in each parastichy.

Annual dry matter production in fronds was then estimated as:

\[ F = N \times W \times D \]

where

- \( F \) = Dry weight of fronds (kg ha⁻¹ yr⁻¹)
- \( N \) = Number of fronds (fronds palm⁻¹ yr⁻¹)
- \( W \) = Dry weight of palm fronds (kg frond⁻¹)
- \( D \) = Palm planted density (palms ha⁻¹)

Oil palms are characterised by a (8+13) phyllotaxis with eight leaves produced in each parastichy (Hartley, 1977). To measure the changes in leaf nutrient concentration with increasing frond age, fronds 1, 9, 17, 25 and 33 were removed from a selected healthy and productive tree.

Ten upper and lower storey pinnae were detached from the frond rachis with a sharp knife at the point on the rachis where the mid-rib runs to
a point. The lamina were stripped from the mid-rib on each pinnae leaf, wiped with cotton wool moistened with bottled drinking water and stored in a paper bag. The rachis from which the pinnae were detached was stored and, together with the pinnae samples, dried in an oven at 60 °C for 24 hours. It was not possible to replicate this measurement since it would have resulted in intolerably large amounts of damage to the farmers' palms.

To estimate the nutrients contained in freshly-cut fronds removed at harvest, five fronds were randomly selected from the frond stack adjacent to different productive trees. Pinnae, rachis and petiole samples were taken from each frond and oven dried at 60 °C and stored prior to analysis in the laboratory.

3.2.2 Oil palm trunk

Trunk incremental height was estimated by first measuring the distance from the ground to the base of frond 41. A second measurement was then taken one year later to the base of the current frond 41 and incremental growth calculated from the difference.

Trunk diameter was measured at a height of 1.5 m from ground level. First, petiole bases were removed from opposite sides of the trunk at a height of 1 m. Trunk diameter was then measured using a pair of large wooden callipers.

The weight of dry matter per unit volume of trunk has been shown to depend on palm age (Corley et al., 1971b) as follows

\[ S = 0.083 + 0.0076Y \]

where

\[ \begin{align*}
S & = \text{weight of dry matter per unit volume (kg m}^{-3}\text{)} \\
Y & = \text{age of palm stand (years)}
\end{align*} \]

Trunk vegetative dry matter can then be estimated as follows:
\[ T = \frac{\pi d^2 h}{4} \times S \times D \]

where

- \( T \) = trunk dry matter increment (kg ha\(^{-1}\) yr\(^{-1}\))
- \( d \) = trunk diameter (m)
- \( h \) = trunk height increment (m yr\(^{-1}\))
- \( S \) = specific weight of trunk (kg m\(^{-3}\))
- \( D \) = palm planted density (palms ha\(^{-1}\))

Trunk core samples for nutrient content analysis were taken at 1 m height increments starting at 0.5 m above the soil surface. Using a brace and bit, a 2.5 cm diameter core 10 cm in length was drilled out of the trunk at each height. Samples were oven dried at 60 °C for 24 hours and weighed.

### 3.2.3 Oil palm fruit bunches

Fruit production data was derived from records kept by the farmers’ organisation using data from the oil palm mill where fresh fruit bunches were weighed over the weigh bridge at weekly intervals. Bunch dry weight is influenced by the fruit to bunch ratio but under normal field conditions this factor may be ignored and bunch dry weight estimated as 53 % of fresh fruit bunch weight (Corley et al., 1971b).

### 3.2.4 Root biomass

After completing root length measurements (see 3.5), roots samples were dried to constant weight in an oven at 60 °C before weighing to measure dry matter content. Samples were ignited in a muffle furnace to estimate and correct for the extent to which roots were contaminated with soil.
3.2.5 Litter biomass in the frond stack

The composition and quantity of the standing litter biomass was estimated for the frond stack by isolating 1 m sections of the frond stack. Two lines were drawn perpendicular to the frond stack 1 m apart. The fronds were removed from this section in increments of 20 cm and separated into pinnae and rachis parts. The fresh weight of the component parts was then recorded and the samples sun-dried to constant weight and the weight recorded.

3.3 Soil chemical analysis

3.3.1 Sampling method

Datum palms had been marked in all fields in the project and are used for leaf analysis, pest and disease surveys and routine soil sampling. The nearest healthy palm was selected on a regular pattern, every tenth tree in every tenth row which gives a sampling density of 1.2 points ha\(^{-1}\) with a planting density of 126 palms ha\(^{-1}\).

The field was divided into 13 sections, each of which contained 4-5 datum palms. A sample of approximately 0.5 kg was taken from each of the three zones (circle, path and frond stack) at two depths (0-20 cm, 20-40 cm). In each section, the samples from each zone and depth were bulked and thoroughly mixed to produce a composite sample. Coarse material and small stones were removed by passing the samples through a 2 mm sieve before analysis.
3.3.2 Analytical methods

3.3.2.1 Cation exchange capacity and soil base cations

Because volcanic soils contain large amounts of variable-charge clay material, the cation exchange capacity and exchangeable cations were determined at soil pH by leaching with ammonium chloride, a neutral salt which does not alter the soil pH (Wada, 1985). 25 g air dry soil was mixed with 50 ml 1 M ammonium chloride and left overnight. Samples were then filtered using a 5.5 cm Buchner funnel and Whatman's No. 2 filter paper, washed through with 1 M ammonium chloride until 200-225 ml of filtrate was collected. The filtrate was transferred to a 250 ml volumetric flask and made up to volume with 1M ammonium chloride. The solution was then filtered into polythene bottles and Ca and Mg determined in the filtrate by atomic absorption spectrophotometry (Pye Unicam SP9) and K and Na by flame photometry (Corning Flamephotometer 410).

The soil remaining on the filter paper was washed with 25 ml 0.25M ammonium chloride followed by approximately 125 ml 96% ethanol to remove excess NH$_4^+$. The filtrate was discarded and the soil left to dry. The soil and filter paper were then transferred to a 250 ml wide necked conical flask. Exactly 100 ml of 2M KCl was added and the flasks shaken on an orbital shaker for 1 hour at 150 r.p.m. After filtering through Whatman's No. 2 filter paper into polythene bottles, having rejected the first portion of the filtrate, NH$_4^+$ was determined using a modified Berthelot reaction with a Burkard SFA2 and the CEC calculated.
3.3.2.2 Soil phosphorus

Total P was measured by digesting air dried soil samples in concentrated H$_2$SO$_4$ and 30 % H$_2$O$_2$ (Anderson and Ingram, 1993). Selenium powder was added as a catalyst and lithium sulphate to raise the boiling point. Approximately 0.2 g of soil was weighed exactly into a 75 ml digestion tube. 4.4 ml of the digestion mixture was added to the digestion tubes and the samples digested at 150 °C for 1.5 hours and 4.5 hours at 350 °C. After the digestion was complete, the samples were allowed to cool and made up to 75 ml with de ionised water. The samples were thoroughly mixed and then allowed to stand until all the digested soil material had settled. Clear supernatant was poured off and the P in solution determined using an automated molybdenum blue method with a Burkard SFA2 system.

Organic P was estimated from the difference between acid extracted P from un-ignited and ignited soil (Anderson and Ingram, 1993). Approximately 1 g (± 0.1 g) of air-dried soil was weighed exactly and placed in a porcelain crucible. The sample was ignited in a muffle furnace by first slowly heating to 550 °C over 2 hours and ashing at that temperature for one hour. After cooling, the soil was transferred to a 50 ml conical flask.

A second sample of 1 g of air dried soil was weighed exactly and transferred directly to a 50 ml conical flask. 50 ml 1M H$_2$SO$_4$ was added to each flask and the samples shaken for 14 hours on an orbital shaker set at 150 r.p.m. The soil extractions were then filtered through Whatman's 542 filter paper and P was determined in the extracts using an automated molybdenum blue method using a Burkard SFA2 system.

Organic P was calculated as follows:

\[
\text{Organic P (mg kg}^{-1}\text{)} = P \text{ ignited} - P \text{ unignited}
\]

56
Available P was determined using the Bray I method, as described by (Bray and Kurtz, 1945), which is designed to remove easily acid soluble P forms (largely calcium phosphates) and a portion of the aluminium and iron phosphates. 7 ml of the extracting solution (NH₄F/HCl) was added to 1 g air dry soil in a PVC tube. The tubes were shaken for 1 minute and filtered through Whatman's No. 42 paper. After adding 5 ml distilled water to 2 ml of the filtrate, 2 ml of ammonium paramolybdate solution and 1 ml stannous chloride were added and mixed. The absorbance at 660 nm was measured using a spectrophotometer and the amount of P present calculated.

Soil phosphorus isotherms were prepared using the method of Fox and Kamprath (1970). Three grammes of air-dry soil was placed in a conical flask. 30 mls of a 0.01M CaCl₂ solution containing different concentrations of Ca(H₂PO₄)₂ was added to each of ten samples from the 0-20 cm depth of each soil zone. The following concentrations (mg P l⁻¹) were used: 0, 50, 100, 200, 400, 800, 1400, 2400, 3200. Three replicates were prepared for each concentration. Each sample was shaken daily for 1 hour for 7 days. P in solution was then determined as described above.

3.3.2.3 pH and exchangeable acidity

Soil pH was determined in water (1:2.5) using a pH meter. 25 ml distilled water was added to 10 ml air dried soil and the pH was determined 30 seconds after stirring thoroughly with a glass rod.

Exchangeable acidity was determined using the method described by (Anderson and Ingram, 1993). 25 ml 1M KCl was added to 10 g air dry soil. The mixture was then stirred and filtered through a Buchner funnel with 5 successive aliquots of 1M KCl after waiting for 30 minutes. The filtrate was titrated to a permanent pink end point with 0.1M NaOH using 5 drops of phenolphthalein as an indicator.
3.3.2.4 Soil carbon and nitrogen

Carbon and nitrogen were determined using a Roboprep automatic CN analyser (Europa Scientific) coupled to a Micromass 622 mass spectrometer. Air-dried soil samples were passed through a 2 mm sieve and finely ground in a roller mill. Approximately 3 mg soil was weighed exactly into a tin capsule. The sample and capsule were ignited in the RoboPrep and C and N determined by mass spectrometry.

3.4 Soil physical properties

3.4.1 Soil bulk density

Soil bulk density was measured using the method described by Anderson and Ingram (1993). After removing 1-2 cm of surface soil, and levelling the spot, a 5 cm diameter tube of known volume was driven into the soil surface. Soil was then excavated from around the tube, and the soil cut beneath the tube. Excess soil was trimmed from the tube ends. The soil was dried for two days at 105 °C and weighed. Bulk density was then calculated as follows:

\[
\text{Bulk density (g cm}^{-3}\text{)} = \frac{\text{total dry weight} - \text{weight of tube}}{\text{volume of tube}}
\]

3.4.2 Soil infiltration rate

Soil water infiltration rate was measured in the circle, path and frond stack using the "double ring" method described by Landon (1991). The surface litter was removed from an area 1.5 m². The area was pre-wetted by soaking for a few hours using an earth bund to contain the water. Two concentric metal cylinders (inner 60 cm, outer 60 cm diameter) were driven
5-15 cm into the wet soil so that the smaller ring was centred within the larger one. Pieces of cut-to-size sacking were laid out inside the rings. Both cylinders were filled to 15 cm and the time and the distance from the top of the ring to the water surface recorded. Refilling in both the outer and inner rings was carried out to maintain an equal height of water in both the cylinders of about 15 cm. Water levels were recorded at 1, 5, 10, 20, 30, 45, 60, 90, 120 and 240 minutes. Instantaneous infiltration rate (cm hr\(^{-1}\)) and cumulative infiltration rate (cm hr\(^{-1}\)) were then calculated.

3.4.3 Soil resistance

Soil resistance was measured in the circle, path and frond stack using an EL 516-010 penetrometer. Approximately 10 cm\(^2\) of the soil surface was cleared of debris. The penetrometer was driven vertically into the soil to achieve a penetration rate of 13 mm s\(^{-1}\) by applying steady downward pressure to the apparatus. Three readings were taken 15 cm apart to make sure that individual penetrations did not interfere with each other. An appropriate needle was selected to give a reading between 20 and 75 on the penetrometer scale. The penetrometer resistance of the soil was calculated by dividing the average penetrometer reading by the area of the end of the needle.

3.5 Plant analysis

*Pueraria phaseoloides* samples were analysed for N, P, K, Mg, and Ca content after digesting oven dried plant samples in concentrated H\(_2\)SO\(_4\) and 30 % H\(_2\)O\(_2\) (100 vol H\(_2\)O\(_2\) 350 ml, concentrated H\(_2\)SO\(_4\) 420 ml, selenium powder 0.42 g, lithium sulphate monohydrate 14.0 g). Selenium
powder was added as a catalyst and lithium sulphate to raise the boiling point.

Approximately 0.2 g of plant material was weighed exactly into 75 ml digestion tubes. 4.4 ml of the digestion mixture was added to the digestion tubes and the samples digested at 150 °C for 1.5 hours and 4.5 hours at 350 °C. The cool digest was transferred to a 100 ml volumetric flask, made up to the mark with water and mixed. The digests were then filtered through Whatman's number 541 filter paper into a plastic bottle. Ca and Mg were determined by atomic absorption spectrophotometry, K by flame photometry, and N and P colourimetrically using a Burkard SFA2 system in which P was determined using an automated molybdenum blue method and N using a modified Berthelot reaction.

Oil palm leaf, trunk, root, and litter samples were analysed for P, K, Mg and Ca content after digestion in nitric and perchloric acid. Approximately 0.25 g of plant material was exactly weighed into a 75 ml boiling tube. 5 ml of mixed acids (85 % HNO₃, 15 % KClO₄) was added and the tubes left to pre-digest overnight. The following day, tubes were digested at 60 °C for 1 hour, 100 °C for 1 hour, 120 °C for 1 hour, 190 °C for 2 hours, and allowed to cool slowly to 25 °C. After cooling 15 ml 25 % HCl was added (to give a final concentration of 5% HCl), heated at 80 °C for 30 minutes and made up to almost 75 ml. After cooling the tubes were made up to exactly 75 ml, filtered through Whatman's 541 filter paper into plastic bottles. Ca and Mg were determined by atomic absorption spectrophotometry, K by flame photometry, and P by using an automated molybdenum blue method using a Burkard SFA2 system. Because N cannot be determined in nitric acid digestions, plant N content was determined by mass spectrometry using a Roboprep.
3.6 Oil palm roots

3.6.1 Sample extraction

Samples with a volume of 541 cm$^3$ soil were extracted with an 83 mm diameter soil corer in successive increments of 10 cm. In order to avoid tearing and breaking thick primary roots, the cutting edge was serrated and filed to produce a very sharp edge. The corer was hammered into the stoneless soil with a mallet. The length of the hole was measured after extraction of four increments of 10 cm to confirm that 10 cm length cores had in fact been removed and no compaction of the soil underneath had occurred. Samples were labelled and stored in polythene bags.

3.6.2 Root separation

Samples were pre-soaked for 24 hours by adding 1 litre of soap solution (25 g l$^{-1}$ Rinso®) to the polythene bags. The samples were then gently washed over two 2 mm box sieves placed one on top of the other. Live roots were separated from dead roots and collected from both boxes and stored in paper bags in the refrigerator.

3.6.3 Root length measurement

Root samples were taken from the refrigerator and spread over a glass plate covering a laminated 32 cm by 32 cm printed 1 cm grid. Both vertical and horizontal intersections were counted and total root length calculated according to the method described by Newman (1966) based on Buffon’s needle problem. Root length was calculated:
\[ L = N \frac{D}{4} \]

where

- \( L \) = root length (cm)
- \( N \) = number of intersections
- \( D \) = Grid dimension (1 cm)

The method was tested using exactly measured pieces of string of various thicknesses and the estimated length was ±5 % of the actual length.

### 3.6.4 Measurement of 1, 2, 3 and 4 root length

Roots were separated into primary (> 6 mm), secondary (2 - 4 mm), tertiary (0.7 - 1.2 mm) and quaternary (< 0.3 mm) roots, using the categories described by (Tinker, 1976). Each root fragment was sorted by comparing its diameter with guide bars printed on a laminated sheet which defined the size limits of each root category (see Appendix 1). Tinker's system makes separation easier than the system given by (Hartley, 1977) since the root diameter categories do not overlap, forcing the separation of root fragments into one of the four categories. Root length of primary, secondary, and tertiary roots was measured by wheeling a planimeter along side root pieces for each category to give a total length for each root diameter category. Quaternary roots were too fine to count by this method, so an estimate was made by subtracting the total length of manually counted primary, secondary and tertiary roots from the total root length calculated using the grid intersection method.
3.6.5 Inspection of roots for mycorrhizal infection and soil for the presence of mycorrhizal spores

Root fragments were separated from soil as described in section 3.5.2 but without the use of Rinso®. Root fragments were stored in alcohol and brought to Wye College for analysis. Short lengths (1-2 cm) of tertiary and quaternary roots were placed in test tubes and 20 ml of 10 % KOH was added. Prolonged heating in KOH was required to de-stain the roots which were very dark coloured and the tubes were heated at 55 °C overnight in an oven. Root fragments were removed from the oven, washed in water and bleached in H₂O₂ for 10 minutes, rinsed three times in water, acidified for 5 minutes in 2 % HCl and stained for 10 - 30 minutes in a 1 % solution of Trypan blue in lactic acid. Root fragments were examined under a high power light microscope for the presence of infection points, arbuscules and vesicles.

Moist soil taken from the circle, path and frond stack zones was washed through 710, 250, 106, and 63 µM sieve. The residue collected on the 106 and 63 µM sieves was decanted into 50 ml water which was then poured into a Petri dish. The residue was then observed under a binocular microscope for the presence of mycorrhizal spores.
Chapter 4

NUTRIENTS ADDED, CYCLED AND IMMOBILIZED IN THE OPHIR OIL PALM PLANTATION

4.1 Introduction

This chapter provides details of the annual amounts of nutrients applied to oil palms in mineral fertilizers, removed from the plantation in fruit bunches, immobilized in the growing oil palm trunk, and cycled in palm fronds. The amount of nutrients contained in pruned frond residues in the frond stack and palm roots in soil in the three zones is also presented. This information was used in the interpretation of differences in soil chemical properties between the three zones (Chapter 6) and provided the basis for the construction of a nutrient balance sheet for the farming system.

The oil palm may be conveniently divided into six component parts which are the roots, trunk, crown, fronds, and male and female inflorescences. The amount of dry matter and nutrients in the crown, contained in the spear (un-opened fronds) and cabbage, was found to reach a steady state five years from planting in Malaysian oil palms (Ng et al., 1968). The amount of root dry matter per palm increased up to the ninth year following planting but thereafter was rather constant (Ng et al., 1968) and the annual increase in root dry matter was found to be less than 5% of the total dry matter incorporated in above-ground parts in Malaysian oil palms (Corley et al., 1971a). An estimate of root turnover is required to calculate the amount of nutrients returned to the soil in dead roots but this was beyond the scope of the present work. Male flowers constitute less than 3% of total above ground dry matter (Corley and Breure, 1981) and the
amount of dry matter and nutrients cycled in male flowers was not investigated in this work.

For the purpose of estimating annual nutrient budgets and cycling, the important components are incremental trunk growth, which represents a cumulative sink for nutrients until replanting, frond production, which represents an important vehicle for nutrient cycling, and fruit bunch yield which represents the main source of nutrient removal, but part of the nutrients removed may be recycled in empty bunches.

4.2 Materials and methods

Details of the materials and methods used for the estimation of biomass production and the analysis of plant material are given in Chapter 3.

Since the onset of harvest, meticulous records of fertilizer inputs, yield, and leaf analysis data for the Ophir project have been kept by the farmers' co-operative in a bespoke data-base programme. A record sheet for Kelompok 2 from the data base programme is attached in Appendix 2. The amounts of nutrients added in mineral fertilizer and removed in fruit bunches were calculated from these records using published information on the nutrient content of fertilizers and fruit bunches.

Fertilizer and pruned fronds were applied to the soil in discrete areas and this means that effective application rates are larger than per hectare rates. The area occupied by palm circles was about 2030 m$^2$ ha$^{-1}$, the inter-row path 880 m$^2$ ha$^{-1}$ and the frond stack 1180 m$^2$ ha$^{-1}$ (see Figure 1.2).
4.3 Results

4.3.1 Nutrients added in mineral fertilizer

In the Ophir plantation, the recommended annual rates of K, Mg and N fertilizers were applied in two doses, and P fertilizer was applied once. Since harvest began, N and K were applied respectively as urea and KCl (Table 4.1). TSP was used for a number of years due to the effect of government subsidy. Mg was applied as dolomite until the appearance of pronounced Mg leaf deficiency symptoms in 1988 when kieserite was substituted for dolomite.

Table 4.1 Amount and source of nutrients applied to oil palms in Kelompok 2, NESP Ophir.

<table>
<thead>
<tr>
<th>Source</th>
<th>Urea</th>
<th>TSP</th>
<th>RP</th>
<th>KCI</th>
<th>Kieserite</th>
<th>Dolomite</th>
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</thead>
<tbody>
<tr>
<td>Nutrient</td>
<td>N</td>
<td>P</td>
<td>K</td>
<td>Mg</td>
<td>Ca</td>
<td></td>
</tr>
<tr>
<td>Year</td>
<td>kg ha⁻¹ yr⁻¹</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>1985</td>
<td>88</td>
<td>13</td>
<td>176</td>
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<td>25</td>
<td>113</td>
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<td>1987</td>
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<td>25</td>
<td>139</td>
<td>10</td>
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<td>13</td>
<td>189</td>
<td>10</td>
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<td>151</td>
<td>25</td>
<td>176</td>
<td>13</td>
<td>9</td>
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<tr>
<td>1990</td>
<td>113</td>
<td>25</td>
<td>126</td>
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<td>1991</td>
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<td>1994</td>
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<td>25</td>
<td>8</td>
<td>139</td>
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<td>34</td>
</tr>
</tbody>
</table>
4.3.2 Fruit bunch yield and nutrient removal in fruit bunches in Kelompok 2

The nutrient content of fruit bunches was found to be 2.9 N, 0.46 P, 3.7 K, 0.82 Mg, and 0.77 Ca kg⁻¹ fruit bunch (fresh weight) in an oil palm plantation in Malaysia (Ng and Thamboo, 1967). These concentrations were used to calculate the removal of nutrients in fruit bunches in Kelompok 2 (Table 4.2).

**Table 4.2** Yield of fruit bunches and nutrient removal in Kelompok 2, NESP Ophir (planted 1982, 126 palms ha⁻¹).

<table>
<thead>
<tr>
<th>Year</th>
<th>t ha⁻¹</th>
<th>Nutrient removal (kg ha⁻¹ yr⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>N</td>
</tr>
<tr>
<td>1985</td>
<td>11.9</td>
<td>35</td>
</tr>
<tr>
<td>1986</td>
<td>29.0</td>
<td>84</td>
</tr>
<tr>
<td>1987</td>
<td>27.2</td>
<td>79</td>
</tr>
<tr>
<td>1988</td>
<td>27.6</td>
<td>80</td>
</tr>
<tr>
<td>1989</td>
<td>28.7</td>
<td>83</td>
</tr>
<tr>
<td>1990</td>
<td>27.6</td>
<td>80</td>
</tr>
<tr>
<td>1991</td>
<td>27.9</td>
<td>81</td>
</tr>
<tr>
<td>1992</td>
<td>30.5</td>
<td>88</td>
</tr>
<tr>
<td>1993</td>
<td>31</td>
<td>90</td>
</tr>
<tr>
<td>1994</td>
<td>28.2</td>
<td>82</td>
</tr>
</tbody>
</table>

The dry matter contained in empty fruit bunches was found to represent approximately 8% of the weight of fruit bunches (Chan *et al.*, 1980) and contained 0.8% N, 0.094% P, 2.41% K, 0.18% Mg, and 0.18% Ca (Gurmit *et al.*, 1990). Thus, the yield of 31 t ha⁻¹ fruit bunches recorded in 1993 would have produced about 2.5 t dry matter of empty bunches containing 20 kg N, 2 kg P, 60 kg K, 5 kg Mg, and 5 kg Ca. Whilst
the potential for recycling N, P, Mg and Ca was rather small in comparison to the amount removed in fruit bunches, the scope for recycling K is obviously large, and the 60 kg K contained in empty bunches represents 36 % of the K added in fertilizer and more than 50 % of the amount removed in fruit bunches.

4.3.3 Crop growth rate and dry matter production

Height increment, frond production and petiole cross section were measured in 1993 and the results have been used to calculate vegetative dry matter production and crop growth rate.

The mean annual height increment of palms in Kelompok 2 was 0.62 m (SE = 0.220, n=42) and the mean trunk diameter was 0.57 m (SE = 0.087, n= 42). Using the relationship between palm age and trunk density found by Corley et al., (1971b), trunk density was about 159 kg dry matter m$^{-3}$. This gave an annual increase in trunk dry matter of 25 kg palm$^{-1}$ yr$^{-1}$ or 3150 kg ha$^{-1}$ yr$^{-1}$.

Mean annual frond production was 22 frond palm$^{-1}$ yr$^{-1}$ (SE = 1.8, n=42). Frond dry weight was estimated using the method developed by Corley and Breure (1981) which makes use of the close relationship between frond dry weight and the cross sectional area of the frond petiole at the point of insertion of the first true pinnae. This relationship was tested for palm fronds in Kelompok 2 where 96 % of the variation in frond weight was accounted for by the linear regression model (Figure 4.1).

From the relationship given in Figure 4.1 mean frond dry weight was calculated as 4.9 kg frond$^{-1}$ (SE = 0.11, n=42). Total dry matter recycled in pruned fronds was calculated from the product of mean frond weight and the mean annual frond production per palm at 108 kg palm$^{-1}$ or 13.6 t ha$^{-1}$ yr$^{-1}$, and the weight of frond pinnae was 38% of total frond weight.
Figure 4.1 Relationship between petiole cross section and dry weight in palm fronds in Kelompok 2 (n=9)

Bunch dry weight was found to be about 53% of bunch fresh weight (Corley and Breure, 1981) and thus the fruit bunch yield in 1993 of 31.0 t ha\(^{-1}\) represented about 16.4 t dry matter ha\(^{-1}\). Total vegetative dry matter increment (trunk incremental growth + annual frond production) and crop growth rate (vegetative growth + bunch dry weight) are given in Table 4.3.

Table 4.3 Trunk incremental growth, annual frond production, vegetative dry matter production, bunch dry matter production and crop growth rate in Kelompok 2, 1993

<table>
<thead>
<tr>
<th></th>
<th>t ha(^{-1}) yr(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trunk incremental growth</td>
<td>3.15</td>
</tr>
<tr>
<td>Annual frond production</td>
<td>13.6</td>
</tr>
<tr>
<td>Total vegetative dry matter increment</td>
<td>16.75</td>
</tr>
<tr>
<td>Bunch dry weight</td>
<td>16.40</td>
</tr>
<tr>
<td>Crop growth rate</td>
<td>33.15</td>
</tr>
</tbody>
</table>
4.3.4 Nutrient immobilization in incremental trunk growth

The concentration of N was similar at all heights measured in the trunk (Figure 4.2a). The trunk P concentration decreased from a point 0.5 m from the soil surface to 1.5 m in height but from this point trunk P concentration increased consistently to a height of 6.5 m (Figure 4.2b). The concentration of K and Ca increased between 1.5 m and 3.5 m from the soil surface but decreased from that point to a height of 6.5 m (Figure 4.2c).

Trunk Mg concentration was similar at all heights sampled up to a distance of 5 m from the soil surface and from that point decreased slightly to a height of 6.5 m (Figure 4.2d).

The annual immobilization of nutrients in trunk biomass was calculated from the mean nutrient concentration measured in the trunk at 6 m from the soil surface and the incremental trunk biomass calculated above and appears in Table 4.4.
Figure 4.2  Nutrient concentration in palm trunks measured at 1 m height increments in Kelompok 2 (n=7).

Table 4.4 Annual immobilization of N, P, K, Mg, and Ca in ten year old palm trunks in Kelompok 2, NESP Ophir.

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>P</th>
<th>K</th>
<th>Mg</th>
<th>Ca</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentration (%)</td>
<td>0.645</td>
<td>0.054</td>
<td>0.376</td>
<td>0.164</td>
<td>0.322</td>
</tr>
<tr>
<td>kg palm(^{-1}) yr(^{-1})</td>
<td>0.16</td>
<td>0.013</td>
<td>0.094</td>
<td>0.041</td>
<td>0.081</td>
</tr>
<tr>
<td>kg ha(^{-1}) yr(^{-1})</td>
<td>20</td>
<td>1.6</td>
<td>12</td>
<td>5.2</td>
<td>10</td>
</tr>
</tbody>
</table>
4.3.5 Nutrients contained in palm fronds

4.3.5.1 Nutrient content of fronds in the palm crown

The concentration of N, K, and Mg in frond pinnae decreased with increasing leaf age (Figure 4.3a, 4.3c, 4.3d). Pinnae P concentration was larger in frond 9 compared with frond 1, but both pinnae and rachis P concentration decreased from frond 9 to frond 33 (Figure 4.3b). Pinnae and rachis Ca concentration increased with increased frond age (Figure 4.3e).

The concentration of N, P, Mg and Ca was larger in pinnae compared with rachis tissue but the concentration of K in leaf pinnae was smaller compared with leaf rachis tissue in frond 9, 17, 25 and 33. Such differences between pinnae and rachis nutrient concentration were also found in Malaysian oil palms by Ng et al., (1968).

The larger concentration of N, P, and Mg in frond pinnae compared with frond rachis tissue is explained by the function of these elements in biochemical processes and the larger amount of photosynthetic activity in frond pinnae. Nitrogen is an essential constituent of nucleic acids and the proteins found in enzymes which catalyse all physiological functions. Phosphorus is also required for the synthesis of nucleic acids, but is also required in all energy transfer reactions involving adenosine diphosphate and triphosphate. Magnesium activates enzymes involved in important cell metabolic processes including the synthesis of fatty acids and is an essential constituent in the chlorophyll molecule. In addition to its role as an enzyme activator, calcium is an important component of the middle lamella of plant cell walls.

Potassium is important in the activation of enzymes involved in synthesis reactions and the regulation of stomatal opening closing but also
in the maintenance of leaf turgor which may explain the larger K concentration found in the rachis which provides support to leave pinnae.

Figure 4.3 Concentrations of N, P, K, Mg, and Ca in pinnae and rachis in fronds 1, 9, 17, 25 and 33 in Kelompok 2.
4.3.5.2 Nutrient content of freshly pruned fronds and the amount of nutrients contained in the frond stack

The total amount of nutrients contained in pruned fronds was calculated from the nutrient concentration of freshly pruned fronds and the estimated annual frond dry matter production (Table 4.5). A large amount of N, K and Ca, and small amounts of P and Mg were recycled to the frond stack in pruned fronds.

Table 4.5 Amount of N, P, K, Mg, Ca contained in pruned fronds added to soil in the frond stack (13.6 t dry matter ha⁻¹, 8.4 t rachis, 5.2 t pinnae) (figures in brackets are standard errors of means, n=5).

<table>
<thead>
<tr>
<th></th>
<th>Rachis</th>
<th>Pinnae</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%</td>
<td>kg ha⁻¹</td>
<td>%</td>
</tr>
<tr>
<td>N</td>
<td>0.41 (0.073)</td>
<td>34</td>
<td>1.74 (0.069)</td>
</tr>
<tr>
<td>P</td>
<td>0.043 (0.01)</td>
<td>4</td>
<td>0.110 (0.007)</td>
</tr>
<tr>
<td>K</td>
<td>1.27 (0.067)</td>
<td>107</td>
<td>0.77 (0.31)</td>
</tr>
<tr>
<td>Mg</td>
<td>0.102 (0.033)</td>
<td>9</td>
<td>0.112 (0.023)</td>
</tr>
<tr>
<td>Ca</td>
<td>0.712 (0.039)</td>
<td>60</td>
<td>1.072 (0.139)</td>
</tr>
</tbody>
</table>

4.3.5.3 Nutrients contained in pruned frond residues in the frond stack

The concentration of N, P, Mg, and Ca in pruned frond residues was similar at all heights within the frond stack (Figure 4.4), but there was a striking decrease in the concentration of K in pinnae and rachis between freshly added pruned fronds at the surface of the frond stack and partly decomposed fronds near the soil surface. Differences between pinnae and rachis nutrient concentration were similar to the results of leaf analysis for
fronds 1 - 33 (Figure 4.3) where leaf N, P, Mg, and Ca concentrations were larger in pinnae and the concentration of K was smaller in pinnae compared to rachis tissue.
Figure 4.4 Concentration of N, P, K, Mg and Ca in pinnae and rachis in pruned fronds in the frond stack at four distances from the soil surface (bars represent standard errors of means, n=3).
Frond pinnae as a proportion of total dry weight was larger in frond residues in the frond stack compared with frond 17, particularly in partially decomposed residues at the bottom of the frond stack (Table 4.6). A larger proportion of total N, P, Mg, and Ca was contained in frond pinnae but the reverse was found for K (Figure 4.5).

When the frond stack was dismantled, the vascular tissue inside fronds lying closest to the soil surface was found to have decomposed leaving hollow petioles and rachis parts. Thus part of the dry matter contained in pruned fronds had already decomposed before the pruned fronds reached the soil surface. This helps to explain the results shown in Table 4.6 in which the amount of dry matter in the frond stack was smaller in the base compared with the surface of the frond stack.

Table 4.6 Rachis and pinnae dry matter contained in the frond stack at four heights above the soil surface in Kelompok 2 (n=3).

<table>
<thead>
<tr>
<th>Distance from soil surface</th>
<th>Rachis</th>
<th>Pinnae</th>
<th>Total</th>
<th>% Pinnae</th>
</tr>
</thead>
<tbody>
<tr>
<td>60-80 cm</td>
<td>390</td>
<td>440</td>
<td>830</td>
<td>53</td>
</tr>
<tr>
<td>40-60 cm</td>
<td>230</td>
<td>430</td>
<td>660</td>
<td>65</td>
</tr>
<tr>
<td>20-40 cm</td>
<td>190</td>
<td>290</td>
<td>480</td>
<td>60</td>
</tr>
<tr>
<td>0-20 cm</td>
<td>130</td>
<td>190</td>
<td>320</td>
<td>59</td>
</tr>
<tr>
<td>Total</td>
<td>940</td>
<td>1350</td>
<td>2290</td>
<td>58</td>
</tr>
</tbody>
</table>

Between 17 - 22 % of the N, P, Mg, and Ca but only 6 % of the K added to the frond stack in pruned fronds was contained in decomposing pruned frond residues (Table 4.7). The rapid release of K from decomposing fronds is underlined by the large difference between the K concentration in freshly pruned fronds and frond residues at the base of the
frond stack, and the smaller proportion of added K contained in the frond stack residues.

Figure 4.5 Amount of nutrients contained in pinnae and rachis residues in the frond stack, estimated from the nutrient concentration and the amount of dry matter contained in pinnae and rachis frond parts.

Table 4.7 Total amount of nutrients contained in pruned fronds in the frond stack in alternate inter-rows in Kelompok 2.

<table>
<thead>
<tr>
<th>Distance from soil surface</th>
<th>N</th>
<th>P</th>
<th>K</th>
<th>Mg</th>
<th>Ca</th>
</tr>
</thead>
<tbody>
<tr>
<td>60-80 cm</td>
<td>9.2</td>
<td>0.64</td>
<td>5.5</td>
<td>0.9</td>
<td>7.6</td>
</tr>
<tr>
<td>40-60 cm</td>
<td>8.6</td>
<td>0.54</td>
<td>1.6</td>
<td>0.79</td>
<td>5.5</td>
</tr>
<tr>
<td>20-40 cm</td>
<td>5.4</td>
<td>0.31</td>
<td>0.7</td>
<td>0.59</td>
<td>4.3</td>
</tr>
<tr>
<td>0-20 cm</td>
<td>4.9</td>
<td>0.24</td>
<td>0.8</td>
<td>0.42</td>
<td>3.1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>28.1</td>
<td>1.73</td>
<td>8.6</td>
<td>2.7</td>
<td>20.5</td>
</tr>
</tbody>
</table>
4.3.6 Concentration and amount of nutrients contained in roots extracted from soil in the circle, path and frond stack zones.

The concentration of N in root fragments increased in the order path < circle < frond stack ($P<0.05$) (Figure 4.6a), but there were no significant differences between the soil zones in root P concentration (Figure 4.6b). Root K concentration was larger and Mg smaller in roots taken from soil in the path compared with the frond stack and circle zones ($P<0.05$) (Figure 4.6c, 4.6d), and Ca concentration was larger in roots extracted from soil in the frond stack compared with the circle and path zones ($P<0.001$) (Figure 4.6e).

The dry weight of roots extracted from soil in the circle path and frond stack zones (Figure 6.1) and the root nutrient concentrations given above have been used to calculate the amount of nutrients contained in roots in the soil in the three zones (Table 4.8).

Table 4.8 Root dry matter content and the amount of N, P, K, Mg, and Ca contained in palm roots in the circle, path, and frond stack in Kelompok 2 (0-40 cm soil depth).

<table>
<thead>
<tr>
<th></th>
<th>Circle</th>
<th>Path</th>
<th>Frond stack</th>
</tr>
</thead>
<tbody>
<tr>
<td>Root dry matter</td>
<td>980</td>
<td>620</td>
<td>720</td>
</tr>
<tr>
<td>N</td>
<td>5.35</td>
<td>3.31</td>
<td>5.11</td>
</tr>
<tr>
<td>P</td>
<td>0.36</td>
<td>0.22</td>
<td>0.26</td>
</tr>
<tr>
<td>K</td>
<td>2.95</td>
<td>2.70</td>
<td>1.58</td>
</tr>
<tr>
<td>Mg</td>
<td>1.04</td>
<td>0.58</td>
<td>0.84</td>
</tr>
<tr>
<td>Ca</td>
<td>1.63</td>
<td>1.18</td>
<td>1.63</td>
</tr>
</tbody>
</table>
Figure 4.6 Concentration of N, P, K, Mg and Ca in roots extracted soil from the circle, path and frond stack zones in Kelompok 2 (bars represent standard errors of the means, n=20)

The root dry matter content of soil and root nutrient concentration in the path zone was taken to represent the amount of root dry matter present in the soil excluding the circle and frond stack zones. Thus, the total amount of root dry matter in the soil was calculated to be about 7 t ha$^{-1}$ and
contained approximately 45 kg N, 3 kg P, 19 kg K, 8 kg Mg, and 14 kg Ca ha$^{-1}$.

4.4 Discussion

The part of the soil surface amended with nutrients contained in fertilizers and pruned fronds was 30% of the total field surface area (Figure 1.2). This resulted in large effective nutrient application rates in both the circle and frond stack (Table 4.9). The effective application rate of N was slightly larger in the frond stack compared with the circle zone, but the effective P application rate was larger in the weeded circle. The rate of K and Mg applied in palm circles and the frond stack was similar, but the effective Ca application rate was three times larger to soil in the frond stack compared with the circle.

Table 4.9 Amount of N, P, K, Mg and Ca added to soil in the circle, path and frond stack soil zones in Kelompok 2 in 1992.

<table>
<thead>
<tr>
<th></th>
<th>Circle</th>
<th>Path</th>
<th>Frond stack</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>151 kg ha$^{-1}$</td>
<td>740 kg ha$^{-1}$</td>
<td>0 kg ha$^{-1}$</td>
</tr>
<tr>
<td>P</td>
<td>25 kg ha$^{-1}$</td>
<td>120 kg ha$^{-1}$</td>
<td>0 kg ha$^{-1}$</td>
</tr>
<tr>
<td>K</td>
<td>164 kg ha$^{-1}$</td>
<td>810 kg ha$^{-1}$</td>
<td>0 kg ha$^{-1}$</td>
</tr>
<tr>
<td>Mg</td>
<td>25 kg ha$^{-1}$</td>
<td>120 kg ha$^{-1}$</td>
<td>0 kg ha$^{-1}$</td>
</tr>
<tr>
<td>Ca</td>
<td>25 kg ha$^{-1}$</td>
<td>120 kg ha$^{-1}$</td>
<td>0 kg ha$^{-1}$</td>
</tr>
</tbody>
</table>

* Application rate per field hectare

** Effective application rate

When Mg and P were applied as dolomite and rock phosphate receptively, as for example in 1982 (see Table 4.1), a larger amount of Ca
was supplied to soil in the circle, but the effective application rate was still small by comparison with the effective application rate in the frond stack zone. The effective application rate of organic matter in the frond stack was very large at about 115 t ha\textsuperscript{-1} yr\textsuperscript{-1}, and there are probably few cropping systems found in the tropics where such large application rates of fertilizer (particularly of urea and KCl) and crop residues have been maintained over long periods. The effect of these additions on soil physical and chemical properties is the subject of Chapter 5.

It can be shown that 20 % N, 15 % P, 50 % K, 20 % Mg, and 25 % of Ca applied as fertilizer was contained in empty bunches, and this underlines the potential savings in fertilizer which can be achieved when the provision of facilities at the palm oil mill and contractual arrangements between the nucleus estate and smallholders provide mechanisms to ensure that the nutrients contained in empty bunches are returned to the farmers' fields.

Leaf production decreases and frond dry weight increases with increased palm age (Corley and Gray, 1976). Mean annual leaf production and leaf dry weight in Kelompok 2 were similar to those measured by Corley and Gray (1976) for oil palms grown on a latosol in West Malaysia where leaf production was 18-24 leaves palm\textsuperscript{-1} yr\textsuperscript{-1} and frond weight was between 3-4.5 kg frond\textsuperscript{-1} in eight year old palms. Trunk incremental growth in Kelompok 2 was at the upper end of the range reported by Corley of 0.35-0.75 m yr\textsuperscript{-1} but more rapid growth of palms planted on volcanic soils has been reported and resulted in the requirement for replanting after only 15 years of harvest according to Hartley (1977). Total annual dry matter production was similar to the upper end of a range of 27-33 t ha\textsuperscript{-1} yr\textsuperscript{-1} for oil palms in West Malaysia (Corley et al., 1971a) but this was not surprising given the larger trunk incremental growth and fruit bunch production in the Ophir project.
The concentrations of N, P, and Mg in trunk, pinnae, rachis, and root tissue were similar to the results of tissue analysis obtained for oil palms grown in Malaysia (Ng et al., 1968). However, the concentration of Ca was larger and K strikingly smaller in frond pinnae, trunk tissue, and roots compared to the Malaysian palms.

The amount of N, P, K, and Mg immobilized in trunk tissue was small compared with the amount removed in fruit bunches and cycled in pruned fronds (Table 4.4, 4.2, 4.5). Pinnae represented almost 60 % of the 2.3 t ha\(^{-1}\) dry matter contained in decomposing pruned fronds in the frond stack (Table 4.6) whilst pinnae represented only 38 % of the total dry weight of freshly pruned fronds. This suggests that the rate of decomposition was slower for pinnae compared with rachis tissue even though the C:N ratio was wider in rachis and petiole parts which also appeared to be more heavily lignified than frond pinnae. The fast decomposition of the vascular tissue contained within frond rachis and petiole tissue may explain this apparent anomaly. The amount of dry matter contained in the frond stack represented about 17 % of the total annual addition of 13.6 t dry matter contained in pruned fronds. The amounts of dry matter contained in the frond stack showed that in spite of the large quantities of organic matter added to the soil, the decomposition of pruned fronds proceeded at a faster rate than the rate of addition. There is no published information on the rate of frond decomposition and simple litter bag studies would be most useful in this regard.

The dearth of information on the role of roots as an organic input to the soil was stressed by Sanchez et al., (1989). Knowledge of root turnover rate is required before an estimate of the addition of nutrients to the soil in dead roots can be made. The total amount of nutrients immobilized in oil palm roots measured in this study was small. 1° and 2° roots were dark and heavily lignified and the C:N ratio of all roots was high at about 80:1.
Thus root turnover may result in a pool of nutrients contained in recalcitrant organic residues which decompose slowly. Even if the root turnover was large, the amount of nutrients contained in the yearly deposition of dead roots would probably be small. However, the amount of root dry matter and root nutrient concentration was smaller in the path zone compared to the frond stack and circle and therefore the deposition of nutrients in dead root material was probably smallest in the path zone.

4.5 Conclusions

The annual amounts of nutrients immobilized in palm trunks, cycled in pruned fronds, and removed in fruit bunches is given in Table 4.10, and the balance between nutrient addition to the soil in fertilizer and removal in bunches and trunk immobilization is presented in Figure 4.7.

Table 4.10 Amount of nutrients removed in fruit bunches, recycled in pruned fronds and immobilized in palm trunks in Kelompok 2 (1992).

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>P</th>
<th>K</th>
<th>Mg</th>
<th>Ca</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kg ha(^{-1}) yr(^{-1})</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trunk</td>
<td>20</td>
<td>2</td>
<td>12</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>Fronds</td>
<td>125</td>
<td>10</td>
<td>147</td>
<td>15</td>
<td>116</td>
</tr>
<tr>
<td>Bunches</td>
<td>88</td>
<td>14</td>
<td>112</td>
<td>25</td>
<td>23</td>
</tr>
<tr>
<td>Total</td>
<td>233</td>
<td>26</td>
<td>271</td>
<td>45</td>
<td>149</td>
</tr>
</tbody>
</table>

The amount of N, P, and K applied in fertilizer was generally sufficient to replace crop removal and immobilization over the period of ten years since harvest began (Figure 4.7a, 4.7b). However, insufficient Mg was applied to replace the amount removed from the soil, and a positive balance for Ca
was only maintained when P and Mg were applied respectively as rock phosphate and dolomite (Figure 4.7d, and see Table 4.1).

Figure 4.7 Differences between the amounts of N, P, K, Mg and Ca added to the soil in fertilizers and removed in fruit bunches and immobilized in palm trunks in Kelompok 2.

A number of assumptions were made in order to estimate the amounts of nutrients removed, immobilized and cycled in the oil palm system. The amount of mineral fertilizer applied in the field, and the weight of bunches removed has been carefully monitored by the farmers' organisation since harvest began in 1985. However, whilst the amount of nutrients added to the system may be accurately estimated from the nutrient content of the fertilizers, the estimation of nutrients removed and recycled relied on published information on the nutrient content of fruit bunches and
empty bunches. The concentration of Ca was larger and K smaller in fronds, trunk and roots compared with results obtained in Malaysia, and thus the removal of K and Ca may have been respectively over- and under-estimated in this work.

Whilst the linear relationship between frond petiole cross section and frond dry weight found by Corley and Breure, (1981) was also evident in this work, the equation constants were slightly different. The equation constants for the relationship between trunk density and palm age may also be different under Indonesian conditions, particularly since the rate of trunk growth was larger in the Ophir project compared to growth rates under Malaysian conditions.
Chapter 5

THE LONG TERM EFFECTS OF NUTRIENT MANAGEMENT AND CYCLING ON THE SPATIAL DISTRIBUTION OF NUTRIENTS AND SOIL PHYSICAL PROPERTIES

5.1 Introduction

In contrast to the frond stack avenue and palm circles the path inter-row, which provides access to harvesters for the removal of fruit bunches, was not mulched or fertilized. Thus in mature oil palm plantations it is likely that crop residue and fertilizer additions have marked effects on the physical and chemical properties of the underlying soil. Detailed soil analysis carried out in the plantation site investigated here prior to the establishment of oil palms (Rosenquist and Anderson, 1975) also allowed an assessment of the changes in soil properties resulting after eight years of oil palm production.

In undisturbed soils, spatial variability in soil properties may result from differences in, for example, weathering, lithology and erosion (Wilding and Drees, 1978). In cultivated soils, management practices may also result in soil spatial variability, and differences in soil properties over short horizontal distances due to management practices have been reported to account for uneven crop growth (Moormann and Kang, 1978).

The beneficial effects of trees on soil which underpin any assessment of trees as soil improvers were described by Young (1989), but quantitative information is required to validate these statements. The importance of understanding the changes to soil properties under tree crops was underlined in an assessment of "Tree Crops as Soil Improvers in the Humid Tropics?" by Sanchez et al., (1985), and the need for investigations into the effect of soil and crop management practices on the
spatial variability of soils was emphasized by Dobermann and George (1994).

There have been a number of reports detailing spatial and temporal changes to soil properties in oil palm and rubber plantations.

A high degree of micro variability in soil chemical properties between randomly selected 13 m² plots was found in an Ultisol planted to oil palms in Southern Nigeria and was considered large enough to be taken into account in the design of field trials (Ogunkunle, 1986) but no discussion of the probable causes was reported.

In a bush fallow system in Nigeria, the effect of wild unfertilized palms on soil heterogeneity was investigated (Kang, 1977). In this unfertilized system, oil palm fronds, male flowers and fruit bunches accumulated at the base of the palm trees where organic carbon, total nitrogen, extractable P, and exchangeable base concentration were larger and soil bulk density smaller close to the palm bole compared with 2-3 m from the palms. These positive effects on soil properties resulted in improved maize growth over two crop cycles when the land was cleared for annual crop production. In this instance, the oil palm had concentrated nutrients in its immediate vicinity which may increase its competitive advantage in a mixed stand of vegetation.

Total soil N concentration was larger and available P, total organic C and base cation concentration smaller in a 20 year old oil palm plantation compared with soil under adjacent bush fallow vegetation in Southern Nigeria (Aisueni, 1987), but the amount, if any, of fertilizer applied to the oil palms was not given.

In an oil palm plantation in Nigeria, the larger amount of organic C but smaller amount of exchangeable K detected in soil close to the palms compared with soil mid-way between palms was attributed to differential deposition of cut fronds, spatial differences in root density and differences in
the distribution of rainfall under the palm canopy (Kowal and Tinker, 1959). After ten years under oil palm, the concentration of Ca, Mg and particularly K in the soil as a whole was reduced, and there was an accumulation of bases, except for K, in the 15-45 cm depth. Apparently palms were not fertilized in this experiment which ran from 1941-1956.

The acidifying effect of nitrogenous fertilizers such as sulphate of ammonia on soil under rubber was examined by Pushparajah et al., (1975). Significantly, fertilizer applications were considered in terms of the rate (in kg) per effective area since, in all cases, fertilizer was applied within a strip in the inter-row, which represented one third of the total land area. K fertilizers had a limited and transitory effect on the amount of acid extractable K, except in soils with 2:1 lattice layer clays which fix K in the inter-lattice space. The concentration of exchangeable K increased in the 20-40 cm depth, indicating the movement of applied K through the profile. P fertilizers increased the total and readily soluble amounts of P, and rock phosphate increased soil pH.

Soil nutrient concentration was measured at intervals for eighteen years in a rubber plantation in Southern Nigeria. Soil exchangeable K, Ca and Mg concentration decreased with increasing age of the rubber plantation because the amount of nutrients supplied in fertilizer was insufficient to correct the imbalance between nutrients immobilized in the rubber and nutrients returned to the soil in leaf litter (Aweto, 1987). In Papua New Guinea, the application of large amounts of fertilizer in palm circles resulted in lower soil pH and increased soil exchangeable K concentration in oil palms planted on Andisols in West New Britain (Breure and Rosenquist, 1977).

In a fertilizer placement experiment in Malaysia soil chemical properties in the three zones described in this work were investigated (Foster and Dolmat, 1986). The concentration of exchangeable K and Mg,
and available P was much larger in the soil beneath the circle than either the frond stack or path. However, the exchangeable Ca concentration in the frond stack soil was twice the amount in the circle soil.

The above mentioned work shows that in unfertilized palms, depletion and enrichment of the soil depends upon the placement of cycled nutrients contained in pruned fronds and the distribution of oil palm roots. In fertilized palms, both mineral fertilizer and pruned fronds have a direct effect on soil properties in their respective zones of application.

Fertilizers are applied to increase economic yield, but may also result in increased vegetative dry matter production. This may result in a greater amount of nutrients immobilized in the trunk and a greater amount recycled in a larger yield of pruned fronds which affect only the limited area of soil over which they are applied. Efficient nutrient management therefore requires careful management not only of fertilizer inputs but also of crop residues once the nutrients added in mineral fertilizer become part of the oil palm nutrient cycle.

In a replanted oil palm plantation on a sandy ferralitic soil in the Ivory Coast, soil compaction which occurred in the circle and inter-row area during the previous crop cycle resulted in poor cover crop growth and oil palm root development (Caliman et al., 1990b) and reduced yield (Dufour and Olivin, 1985) in the replanted palms. Sub-soiling and the use of deep rooted legume shrubs such as Flemingia congesta were advocated as ameliorative measures. Soil compaction in the harvesting path was attributed to the use of mechanized fruit transport in oil palm fields in Malaysia (Mokhtaruddin et al., 1992). Thus in addition to the effect of fertilizers and organic residues on soil chemical properties, the frequent traffic of harvesters and wheel barrows in the harvesting path may result in changes to soil physical properties.
5.2 The influence of Andisol soil properties on the effects of fertilizer and organic residue application

The modification of soil properties under oil palm cultivation is influenced not only by nutrient addition, cycling and removal, but also by the soil type. For example, soils with a large buffering capacity, in terms of nutrient content and soil pH will be proportionately less affected by the addition of mulch and fertilizer. A brief discussion of important properties of the Andisol soil order is given here in terms of the way their physical and chemical characteristics determine the way organic matter and fertilizer additions change soil properties.

Andisols have a number of distinctive properties which help to explain why they are often considered some of the most fertile and productive soils in SE Asia, although their geographical extent is small (Sanchez, 1976). For many years, Andisols have been successfully cultivated for industrial crops, in particular for the famous Deli tobacco wrappers in North Sumatra, and for vegetable and high quality tea production in Java (Tan, 1964). Excellent oil palm yields were also reported from oil palm plantations on Andisols in West New Britain, Papua New Guinea (Breure and Rosenquist, 1977).

Perhaps the most distinctive feature of Andisols is the presence of a dark, almost black or melanic surface epipedon due to the accumulation of soil organic matter (SOM). Humic and fulvic acids react with hydrous oxides of Al and Fe and with allophane to form complexes which are very resistant to microbial degradation and constitute very stable silt- and sand-sized particles (Wada, 1980). Mineralization of SOM was almost three times slower in allophanic Andisols compared to non-allophanic soils, due to the formation of stable and resistant aggregates (Broadbent et al., 1964; Fox, 1980). The toxic effect of Al on the soil microbial population or the physical
protection afforded to the SOM complex by the presence of Al were suggested to account for the slow mineralization rates and stability of SOM in Andisols (Goh, 1980; Tate and Theng, 1980). However, increased respiration in Andisols after P application was reported by Munevar and Wollum (1977) who suggested P deficiency as the reason for slow microbial decomposition of SOM in Andisols. Clearly, where the mineralization rate is slow, the release of nutrients, particularly P and N is retarded and the large SOM content in acid, P-deficient Andisols may be regarded as a large nutrient reserve only sparingly available for plant growth and crop production.

A second property of Andisols is their ability to adsorb very large quantities of Phosphorus. Allophane, with its large surface area was shown to be important in P adsorption in Andisols by Mizota (1977), but other workers have reported the importance of Al-bound humus (Wada and Gunjigake, 1979). The amount of ammonium oxalate extractable Al was also shown to be correlated with P retention (Alvarado and Buol, 1985), and a significant correlation between P-adsorption and humus content and a reduction in P adsorption after treating the soil with H₂O₂ was found by Wada (1980).

The presence of allophane is a diagnostic feature of Andisols. Allophane is an X-ray amorphous clay mineral allophane which has a large specific surface area and variable charge properties. Variable charge in Andisols is also imparted by the presence of sesquioxides and SOM. Liming increases the total amount of negative charge in a variable charge soil (Parfitt, 1980) which may increase the soil's ability to retain cations against leaching.

The large SOM content imparts very low bulk density, typically below 0.85 g cm⁻³, which is a further diagnostic property of Andisols and
contributes to their large water storage capacity and total pore volume (Warkentin and Maeda, 1980).

5.3 Materials and methods

In the work described here, spatial patterns in soil properties in the circle, path and frond stack, due to the removal, addition and cycling of nutrients and organic matter were assessed by making a comparison of soil physical and chemical properties in the three zones which have received clearly contrasting treatments in terms of nutrient additions and physical disturbance. An indication of changes in soil properties since the palms were planted was gained from comparisons with measurements of soil chemical properties made as part of the project feasibility study carried out in 1975 by Rosenquist and Anderson (1975). The means of five measurements for soil chemical properties were presented in his report.

Details of the soil sampling and soil chemical and physical analysis methods are given in Chapter 3.

The sampling system violated the requirement for randomization needed for comparisons between zones and depths using standard error differences of means following analysis of variance. Instead, differences in soil properties between the soil zones were compared by performing sets of selected orthogonal contrasts between the soil zones on measurements of soil physical and chemical properties and on differences in soil physical and chemical properties between the two soil depths using the Genstat 5 statistical package (Payne, 1987).

P sorption isotherm isotherms were fitted to data using the Freundlich equation cited by Warren (1992) using the SigmaPlot 4.7 graph system (Kuo and Fox, 1993).
5.4 Results

5.4.1 Soil physical properties

5.4.1.1 Soil bulk density

Bulk density of the soil under the path zone was larger than the soil in the circle and frond stack zones ($P<0.001$) (Figure 5.1). The difference between bulk density in the frond stack soil compared to the circle soil was only significant at $P<0.1$.

![Figure 5.1 Soil bulk density measured in the circle, path and frond stack soil zones (bars represent standard errors of the means, n=5)](image)

5.4.1.2 Infiltration

The accumulated infiltration rate was an order of magnitude larger in the grass covered inter-row and frond stack zones compared with the circle and path zones (Figure 5.2, 5.3). There were no significant differences
between the infiltration rates in the circle and path soil zones and or between the frond stack and grass covered inter-row zones.

Figure 5.2 Accumulated (closed circles) and instantaneous (open circles) water intake measured in the circle (a), path (b), frond stack (c), and grass covered (d) soil zones (means of four measurements).
Figure 5.3 Mean infiltration rate after 4 hours in the circle, path, frond stack and grass covered inter-row soil zones (bars represent standard errors of the means, n=4)

5.4.1.3 Soil resistance

Soil resistance, measured with a penetrometer was orders of magnitude smaller in the frond stack compared with the path and circle soil zones (Figure 5.4).

In a transect across the path and frond stack inter-rows, soil resistance was very small in the centre section of the frond stack covering a distance of 2.5 m, and large in the path inter-row space (Figure 5.5). Soil resistance increased moving from the palm bole towards the centre of palm circles.
**Figure 5.4** Soil resistance measured using a penetrometer in the frond stack side and path side of the circle (Circle s and Circle p), the path and the frond stack (bars represent standard errors of the means, n=7).

**Figure 5.5** Soil resistance measurements in a transect across the circle, path and frond stack soil zones in Kelompok 2, NESP Ophir (means of three readings).
5.4.2 Soil chemical properties

5.4.2.1 Soil pH, exchangeable Al, and Al saturation

Compared to the soil in the path and the frond stack, the soil in the circle at both depths investigated was more acid with lower pH, a larger concentration of exchangeable Al, and higher Al saturation. The differences between mean soil pH readings for the three zones were small but highly significant ($P<0.001$) (Figure 5.6). At both depths, the soil was more acid in the circle zone where the exchangeable Al concentration (Figure 5.7a) and saturation (Figure 5.7b) were significantly larger than the soil in the other two zones ($P<0.05$).

5.4.2.2 Cation exchange capacity and base saturation

There were no significant differences between the three soil zones in cation exchange capacity measured at soil pH in the 0-20 cm soil depth, but large and significant differences were apparent in the samples from the 20-40 cm depth where CEC in the circle was smaller than the frond stack and path ($P<0.05$) (Figure 5.8a). CEC was significantly larger in the 20-40 cm compared to the 0-20 cm depth in both the path and frond stack ($P<0.05$) but in the circle, there was no significant difference in CEC between the two depths.

The pattern was very different when the effective cation exchange capacity (i.e. the sum of exchangeable cations and 1 M KCl extractable Al) was compared (Figure 5.8b). At both depths sampled, the ECEC was significantly larger in the soil beneath the frond stack than the soil in the other two zones ($P<0.001$), and in all three soil zones, ECEC was larger in the 0-20 cm compared with the 20-40 cm depth.
Figure 5.6 Comparison of soil pH (1:2.5 H₂O) measurements in the circle, path and frond stack soil zones at two depths (bars represent standard errors of the means, n=13). The dashed line shows the soil pH measured in the project feasibility study in 1975.

Figure 5.7 Exchangeable aluminium concentration (a) and aluminium saturation (b) in the circle, path and frond stack soil zones at two depths (bars represent standard errors of the means, n=13).
Figure 5.8 Cation exchange capacity measured at soil pH in NH$_4$Cl (a) and effective cation exchange capacity (b) measured in the circle, path and frond stack soil zones at two depths (bars represent standard errors of the means, n=13).

5.4.2.3 Exchangeable base cations

In the 0-20 cm depth, the amount of exchangeable K was larger in soil from the circle zone compared to the path and frond stack soils ($P<0.05$), and larger in soil from the frond stack than the path zone ($P<0.1$) (Figure 5.9a). The concentration of exchangeable K was significantly larger in the 20-40 cm compared with the 0-20 cm depth in the frond stack, but in the circle soil K concentration was larger in the 0-20 cm depth ($P<0.05$).

Exchangeable Na concentration was significantly larger in the circle zone at the 0-20 cm depth compared to the other soil zones irrespective of depth (Figure 5.9b).

The amount of exchangeable Mg was smaller in soil from the path zone ($P<0.001$) at both depths compared with the circle and frond stack soil zones (Figure 5.9c). There were no significant differences in the Mg
concentration between the circle and frond stack zones at either depth. Exchangeable Mg concentration was larger in the 20-40 cm depth in the frond stack but smaller in the two other zones compared to the 0-20 cm depth.

Very large and significant differences were found in the concentration of exchangeable Ca which increased in the order circle<frond stack in the 0-20 cm depth ($P<0.001$) (Figure 5.9d). In the circle, exchangeable Ca concentration was larger in the 20-40 cm depth than the 0-20 cm depth whilst in the frond stack, the reverse trend was observed.
Figure 5.9 Exchangeable K (a), Na (b), Mg (c), and Ca (d) concentration in soil from the circle, path and frond stack zones at two depths (bars represent standard errors of the means, n=13). The dashed lines shows cation concentration measured in the project feasibility study in 1975.
5.4.2.4 Soil phosphorus

The total and organic soil P concentration was larger in the circle soil zone in the 0-20 cm depth compared with the 20-40 cm depth and the path and frond stack zones \( (P<0.05) \) but there was no significant difference in the amount of total P and organic P between the path and the frond stack at either depth (Figure 5.10a and 5.10b).

The amount of organic P as percent total P was larger in the circle zone in the 0-20 cm depth compared with the 20-40 cm depth and with the path and frond stack soil zones.

There were no significant differences between the soil zones in the amount of P extracted by Bray's solution in the 0-20 cm depth (Figure 5.10d). In the 20-40 cm depth, available P concentration was smaller in the path compared with the frond stack and circle soil zones \( (P<0.05) \). In all zones, available P concentration was smaller in the 20-40 cm compared with the 0-20 cm depth.

P sorption isotherms showed no differences between the soils from the circle and path soil zones, but there was a marked reduction in P sorption capacity in the soil from beneath the frond stack (Figure 5.11).
Figure 5.10 Total P (a), organic P (b), organic P as a% of total P (c), and available P (d) in the circle, path and frond stack soil zones at two depths (bars represent standard errors of the means, n=5). The dashed line shows amount of available P measured in the project feasibility study in 1975.
Figure 5.11 P sorption isotherms for soil in the circle, path and frond stack (0-20 cm depth) fitted with curves using the Freundlich equation (each point represents the mean of three measurements).

5.4.2.5 Soil carbon and nitrogen

Differences in the amount of soil organic C between the zones were small. The amount of organic carbon was larger in the soil beneath the frond stack compared to the path and circle \((P<0.001)\) and smaller in the soil from the path zone compared to the circle at both depths \((P<0.001)\) (Figure 5.12a).

Total N concentration was larger in the frond stack than the circle and path at both depths \((P<0.001)\) but there was no significant difference between the circle and path zones (Figure 5.12b). In the 20-40 cm depth, soil N increased in the order stack>circle>path \((P<0.05)\).
Figure 5.12 Comparison of the amount of soil organic carbon (a) and total N (b) in soil from the circle, path and frond stack zones at two depths (bars represent standard errors of the means, n=13)

5.5 Discussion

5.5.1 Soil physical properties

The larger bulk density in the path soil zone may be attributed to the frequent passage of heavily laden wheelbarrows along the same line in the harvesting path. Compaction in the path will have gradually increased over the eight year period from the start of harvest since the effect of wheelbarrow traffic occurs at each weekly harvesting event. The mean bulk density value of 0.85 g cm$^{-3}$ in the path soil zone is similar to typical values given for andisols (e.g. Warkentin and Maeda, 1980) but bulk density was considerably smaller in the circle and frond stack soil zones at 0.69 and
0.60 g cm\(^{-3}\) respectively (Figure 5.2). In spite of the traffic of harvesters and the effect of 25-30 kg fruit bunches and 15-20 kg fronds falling from a height of 6-7 m onto the soil surface in the circle, soil bulk density was only slightly larger in the palm circle compared with the frond stack zone where the soil surface was not disturbed at all.

The loose and fluffy structure of soil in the 0-20 cm depth in the frond stack zone made the extraction of uncompacted soil cores difficult and thus bulk density may have been overestimated in the frond stack zone. However, penetrometer readings showed that soil resistance was almost an order of magnitude smaller in the frond stack zone compared with the path and circle zones (Figure 5.3).

Cumulative infiltration was larger in the frond stack and the grass covered inter-row than both the circle and path where slower infiltration rates may be attributed to soil compaction mentioned above (Figure 5.3). In the frond stack soil, fast infiltration rates may be attributed not only to the lack of soil compaction in this zone but also to the effect of the annual deposition of large quantities of organic matter on soil structure and increased soil faunal activity. The cumulative infiltration rate in the grass covered inter-row area, which has not been compacted and does not receive dead fronds probably represents the conditions which prevailed prior to oil palm planting.

Infiltration rates in all zones are sufficient to allow infiltration of recorded peaks in rainfall intensity and therefore, since the site is almost flat, the amount of surface run-off, which would distribute fertilizers applied over the soil surface in the circle over a wider area, was probably small. However, due to the comparatively large infiltration rate in soil beneath the frond stack, the loss of nutrients released from fronds during mineralization by leaching in the frond stack may be large unless there is a large and active root system in this zone. For oil palms planted on sloping land, on
soils with slow water infiltration rates, frond stack avenues positioned across the slope may be an important means of reducing surface run-off by increasing the rate of water infiltration. In Chapter 6, root length density was similar in the frond stack compared to the circle zone (Figure 6.1b) which suggests efficient capture of nutrients carried into soil in surface run off in the frond stack zone.

The improved water infiltration rates found under the frond stack underline the importance of pruned frond placement in the control of soil erosion, particularly on sloping land suggested by Quencez (1986) and Maene et al., (1979). However in Kelompok 2 the ameliorative effect of pruned fronds on soil physical properties was restricted to a 2 m band in alternate inter-rows in Kelompok 2. Without any additional work, pruned fronds could be spread over a larger area leaving only a narrow strip to provide access for harvesting, and thus the ameliorative effect of pruned fronds would be extended to a greater portion of the total soil surface. Alternatively, the location of path and frond stack zones could be periodically alternated in order that the respective beneficial and degradative effects of the frond stack and path zones are evenly distributed.

5.5.2 The effect of soil bulk density on soil nutrient reserves.

Differences in bulk density between the three zones must be taken into account when comparing total nutrient reserves in the three zones. The importance of taking into account differences in soil bulk density when comparing nutrient concentrations in different soils was emphasised by Harrison (1987) who compared the concentration of soil organic phosphorus in different soils.
Reserves of available nutrients in the 0-20 cm soil depth, after adjusting for differences in bulk density, are compared with effective nutrient application rates in fertilizer and pruned fronds in soil from the circle, path and frond stack zones in Figure 5.13. After correcting for bulk density, differences between the zones in soil total N were small, in spite of the large amounts of N added to the soil in the circle and frond stack respectively as urea and pruned fronds (Figure 5.13a). The soil available P reserve was largest in the circle zone where large amounts of P fertilizer had been added to the soil, but the available P reserve was larger in the unamended but compacted soil from the path compared with the soil in the frond stack which had been amended with pruned fronds (Figure 5.13b). However, the larger bulk density in the path soil compared to the circle and frond stack soils means that the potential for P adsorption per volume of soil is even greater in the path soil than is implied by the P sorption isotherms in Figure 5.11.

Reserves of exchangeable K and Mg were larger in the fertilizer amended circle and mulched frond stack zones, and the difference in the reserves of exchangeable K between amended and unamended soil was particularly striking (Figure 5.13c, 5.13d). The largest reserve of exchangeable Ca was found in soil from the frond stack where the addition of Ca was, in most years, five times the rate added to soil in the circle (Figure 5.13e). However, the reserves of exchangeable Ca were larger in soil from the path zone compared with the circle which suggests that Ca had been lost from the soil in the circle zone to plant uptake or leaching (Figure 5.13e).
Figure 5.13 Effective nutrient application rate and soil nutrient reserves (adjusted for bulk density) in the circle, path and frond stack soil zones (0-20 cm).
5.5.3 Effect of the addition of fertilizers and pruned fronds on soil acidity, cation concentration and cation exchange capacity

The most striking features of soil chemical properties in soil in palm circles was lowered pH, increased Al saturation, and reduced exchangeable Ca concentration all of which are indicative of strong leaching. Oil palm is not susceptible to the phytotoxic effects of high Al saturation, but since Al plays an important role in the sorption of P, acidification may result in reduced efficiency of P use.

The acidifying effect of plant roots depends on the overall balance between cation and anion absorption, in particular on the proportion of the applied N taken up as and NH$_4^+$ and NO$_3^-$ ions and the quantity of base cations absorbed. Changes in soil pH, Al saturation and CEC in the circle zone therefore represent the net effect of the fertilizers applied and the uptake of nutrients by the crop and losses from leaching.

The effective rate of N applied as urea in palm circles was very large at about 740 kg ha$^{-1}$ yr$^{-1}$. All N-fertilizers which contain ammonium contribute to a lowering of soil pH following nitrification under aerobic soil conditions according to the following equations (Wild, 1993):

\[ NH_4^+ + 4O \rightarrow 2H^+ + NO_3^- + H_2O \]

In the absence of a crop, the proton equivalence of 28 kg N applied as urea is 2 kg according to the following equations:

\[ CO(NH_2)_2 + 2H_2O \rightarrow (NH_4)_2CO_3 \]

\[ (NH_4)_2CO_3 + 8O \rightarrow 2HNO_3 + H_2CO_3 + 2H_2O \]

The proton equivalence of 151 kg N ha$^{-1}$ added in urea fertilizer to palm circles would thus have been 11 kg H$^+$ ha$^{-1}$ yr$^{-1}$ in the absence of oil
palms. However, effective proton equivalence was probably smaller since part of the total N uptake in Kelompok 2 of about 233 kg ha$^{-1}$ yr$^{-1}$ (see Table 4.10) was likely absorbed in the form of NO$_3^-$ from soil in the circle zone.

The protons produced from acidification may have displaced base cations from exchange sites which are then carried away in leached water together with the NO$_3^-$ produced in the nitrification process but not absorbed. In addition, when K and Mg, supplied respectively as KCl and kieserite are absorbed by the crop, the Cl$^-$ and SO$_4^{2-}$ ions which are not absorbed may also be leached, carrying away base cations and for this reason an application of 1.1 kg CaCO$_3$ is required to neutralize the acidity which develops from an application of 1 kg K as KCl (Rowell, 1973).

In the circle, exchangeable Ca concentration was larger in the 20-40 cm depth compared with the 0-20 cm depth, whilst in the frond stack soil Ca concentration was larger in the 0-20 cm depth, which suggests the movement of Ca downwards through the soil profile in the circle zone and the accumulation of Ca at the soil surface in the frond stack zone (Figure 5.9d). The loss of Ca from soil in the 0-20 cm depth in the circle is also suggested by the reduced Ca concentration in the 0-20 cm depth and increased Ca concentration in the 20-40 cm depth since 1975 (Figure 5.9d) and the smaller amount of exchangeable Ca found in the circle soil compared to the un-amended path soil.

Several workers have investigated the extent of nutrient losses from leaching under oil palm. Palm evaporative water demand was measured under Malaysian conditions by Chang and Chow (1985) who argued that only small amounts of nutrients would be leached in view of the large amount of water transpired. This view was supported by Foong (1993) who reported the loss of 2.4 % N, 1.6 % P, 2.7 % K and 15 % Mg applied as fertilizer in a lysimeter filled with clay loam soil planted to oil palm. These are small amounts, particularly for N which is very mobile in the soil. The
amount of Ca leached from the soil was not reported but may have been large due to the displacement of Ca at exchange sites by added K and Mg. Leaching losses were found to decrease with increasing palm age, presumably due to the expansion of the palm's root system.

The amount of Al extractable with 1 M KCl is usually small in Andisols unless large quantities of acid-forming fertilizer have been applied to the soil (Soil Survey Staff, 1975). Al saturation was larger in the soil from the 0-20 cm depth in the circle zone (Figure 5.7b) where soil pH was lower than the path and frond stack zones (Figure 5.6). The relationship between Al saturation and soil pH for each soil zone and depth is shown in Figure 5.14.

![Graph showing relationship between soil pH and aluminium saturation](image)

**Figure 5.14** Relationship between soil pH and aluminium saturation in the circle (a), path (b) and frond stack (c) soil at two depths (n=13).

In soil from the 0-20 cm depth in the circle where exchangeable Al occupied 70% of exchange sites points are clustered together and the relationship between pH and Al saturation was indistinct. In the soil from the
20-40 cm depth in the circle zone and in both depths in soil from the path and frond stack zones, pH decreased with increasing Al saturation.

The acidifying effect of urea and KCl fertilizer on soil may have been balanced by the liming effect of dolomite and rock phosphate which were used to supply Mg and P in some years (see Table 4.1), but the application of N, K, and Mg respectively as urea, KCl and kieserite probably accounts for the lower pH, small Ca concentration and large Al saturation found in the soil in the circle zone.

Andisols have variable charge properties and negative charge has been found to increase by up to 50% when soil pH was increased from pH 5 to 6 (Parfitt, 1980). Several studies have shown an increase in soil CEC following the application of P fertilizer. The CEC of the soil surface horizon of an Oxisol was increased significantly and the leaching of applied Ca, Mg, and K reduced with increasing super phosphate application to the soil (Gillman and Fox, 1980) and CEC was increased by 0.7 cmol(+) kg\(^{-1}\) due to the application of 600 kg ha\(^{-1}\) triple super phosphate to the soil (Sanchez, 1976). An increase in soil CEC in proportion to the amount of P adsorbed by the soil was shown by Schalscha et al., (1974). However, the possible beneficial effects of added fertilizer P on CEC were probably insufficient to counteract the acidifying effect of urea N on the soil from the circle zone. Whilst soil pH was lower in soil from the circle zone compared to the path and frond stack, no significant correlation was found between cation exchange capacity and soil pH in the three soil zones.

The addition of pruned fronds at an effective rate of about 115 t ha\(^{-1}\) maintained the concentration of K and Mg in soil beneath the frond stack at amounts similar to those found in the fertilized circle soil. However, in contrast to the circle soil, where Ca concentration had probably been reduced due to leaching, and the unamended path soil, the concentration of exchangeable Ca was very large in the soil beneath the frond stack at
about 6 cmol(+) kg\(^{-1}\), due to the larger amount of Ca added to the frond stack in pruned fronds compared with the amount added to the circle in fertilizer. The larger concentration of soil exchangeable Na in soil in the 0-20 cm depth in the circle may be attributed to the application of KCl fertilizer contaminated with Na salts. The importance of the nutrients contained in pruned fronds to the maintenance of soil fertility was shown by Tajudin and Yeoh (1985) who reported a large reduction in yield when pruned fronds were removed from the field.

The larger ECEC found in soil from the frond stack may be explained by the exchange sites on SOM which was larger in concentration in the frond stack soil compared with soil from the other two zones (Figure 5.12a). When measured by leaching with a neutral salt (ammonium chloride) soil CEC was similar in the three soil zones from the 0-20 cm depth. However, soil CEC was larger in the 20-40 cm depth compared with the 0-20 cm depth in the frond stack and path zones but not in the circle zone. One possible explanation for this is the larger concentration of allophane at lower depths in the soil profile (see Table 2.3) which may have resulted in a larger CEC, particularly when accompanied by higher soil pH as was found in the frond stack and path soil zones (Figure 5.6).

The uptake of each nutrient depends not only on its concentration in the soil but also on antagonistic and synergistic effects between nutrients on uptake. If the minimum exchangeable K requirement of 0.15 cmol(+) kg\(^{-1}\) proposed by Boyer (1972) is accepted, K was deficient in the path soil (Figure 5.9). However, the ratio of exchangeable K to cation exchange capacity has been considered a better measure of K availability than soil exchangeable K since the ratio takes into account the amount of other cations present. A response to K fertilizer was considered likely when the ratio was below 0.015, and the supply of soil K was considered marginal when the ratio was 0.02 (Tinker and Ziboh, 1959). Using this criterion, K
was clearly deficient in soil in the path zone and the supply was marginal in the frond stack and circle soils (Table 5.1). Minimal magnesium to potassium and calcium to potassium ratios for oil palm of 2:1 and 5:1 respectively were proposed by Boyer (1972). The "critical" Mg:K ratio has been met in all zones, but in the circle, the Ca:K ratio is below optimal. These examples show that the different nutrient treatments imposed upon the circle, path and frond stack soil zones have resulted in changes in both the concentration and the balance between cations in the soil and thus the three zones contrast strongly in terms of the availability of K, Ca, and Mg for palm uptake.

Table 5.1 Ratio between cations in soil from the circle, path and frond stack

<table>
<thead>
<tr>
<th></th>
<th>Circle 0-20</th>
<th>Circle 20-40</th>
<th>Path 0-20</th>
<th>Path 20-40</th>
<th>Stack 0-20</th>
<th>Stack 20-40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ca:Mg</td>
<td>1.2</td>
<td>2.6</td>
<td>7.2</td>
<td>11.3</td>
<td>7.7</td>
<td>8.7</td>
</tr>
<tr>
<td>K:ECEC</td>
<td>0.020</td>
<td>0.022</td>
<td>0.005</td>
<td>0.019</td>
<td>0.014</td>
<td>0.016</td>
</tr>
<tr>
<td>Ca:K</td>
<td>1</td>
<td>3</td>
<td>7</td>
<td>11</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>Mg:K</td>
<td>3</td>
<td>6</td>
<td>7</td>
<td>3</td>
<td>5</td>
<td>4</td>
</tr>
</tbody>
</table>

5.5.4 Soil phosphorus

Large amounts of P fertilizer have been applied over the palm circle and this has increased the total P and organic P content in the circle soil zone compared with the soils under the path and frond stack, which received similar additions of P in pruned fronds. The larger amount of organic P in the circle soil compared to the frond stack and path soils may be explained by the active role of OM complexed by Al and Fe oxides and hydrous oxides which have adsorbed some of the P applied in fertilizer.
Past P additions were reported to reduce P sorption in soils (Fox, 1980) but in this work, the amount of P adsorbed was similar in the P fertilized circle soil and the unamended path soil. P sorption is commonly very large in Andisols (Fox, 1974) and was shown to depend on the presence of Al and Fe humus complexes in A1 horizons, and on the amorphous clay mineral allophane in B horizons (Wada and Gunjigake, 1979). P sorption by Al and Fe humus complexes was proportional to the P concentration but P sorption by allophane was found to depend on soil pH (Gunjigake and Wada, 1981).

In all three soil zones, the amount of P adsorbed was large, and the Standard Phosphorus Requirement, calculated using the method described by Warren (1992), was 1760, 1690, and 1290 mg kg\(^{-1}\) respectively in soil from the circle, path, and frond stack. The amount of P adsorbed was not larger in the more acid circle zone soil compared to the soil in the path zone as might be expected if allophane was the main adsorbing surface and exchangeable Al increased the amount of P adsorbed, and this suggests that the Al and Fe humus complex accounted for most of the P sorption in these two zones. The difference in P sorption between soil from the path and circle zones and the frond stack may be explained by the presence of organic anions produced from the decomposition of organic residues which compete with P for sites of adsorption (Le Mare et al., 1987).

5.5.5 Organic C and total N concentration

Very large amounts of organic matter have been added to the soil in the frond stack zone over the eight year period since harvesting and frond removal began. The effective application rate of about 115 t dry matter ha\(^{-1}\) yr\(^{-1}\) resulted in significantly larger organic C and total N concentrations in the soil beneath the frond stack compared with soil in the path and circle.
zones. The larger organic C and total N content in soil from the frond stack but the similar C:N ratio in all three soil zones is shown in Figure 5.15. However, the differences in organic C concentration and the amount of total N were small and, when differences in bulk density between the soil zones were taken into account, the soil carbon and total N content was similar in the three zones.

**Figure 5.15** Carbon to nitrogen ratio in soil from the circle, path, and frond stack zones in the 0-20 cm depth (a) and the 20-40 cm depth (b) (n=13).

In an experiment to compare the mineralization of soil organic matter and added grass residues in volcanic soils, the protective effect of allophane was not conferred on fresh plant materials added by simple physical mixing. Soil respiration was increased when pH was increased and the mineralization of added Sudan grass was similar in volcanic and non-volcanic soils, but the mineralization of soil organic matter was slower (Broadbent *et al*., 1964). Thus it appears that soil organic matter in volcanic soils mineralises slowly (which explains the large SOM content of Andisols) but the degradation of added residues proceeds at similar rates in volcanic and non-volcanic soils.
Organic matter content in the soil may be said to be in a state of dynamic equilibrium between the process of degradation and accumulation (Cresser et al., 1993). The turnover time of organic C in the frond stack may be calculated from the relationship between the soil organic C content and the addition of C in dead fronds.

\[
\text{Turnover (steady state)} = \frac{\text{soil organic carbon (kg ha}^{-1}\text{)}}{\text{organic carbon input (kg ha}^{-1}\text{ yr}^{-1}\text{)}}
\]

In the frond stack, large amounts of organic carbon were added to a soil already containing a very large concentration of organic C and the turnover rate was calculated to be 2.7 years for the frond stack land area (0-40 cm soil depth). The organic carbon content of the soil in the frond stack had been maintained but not increased by the addition of pruned fronds compared to the unmulched circle and path where the amount of organic C appears to have decreased since the establishment of oil palms by comparison with the soil analysis reported before the plantation was established (Figure 5.13).

The amount of litter in the frond stack appears to reach a steady state in mature oil palm plantations after three to four years of harvest, and in the ten year old palms in Kelompok 2, was about 2.29 t ha\(^{-1}\), compared to the rate of addition of 13.6 t ha\(^{-1}\) yr\(^{-1}\). The loose, friable and moist soil conditions and the protection from diurnal temperature fluctuations afforded by the mulch layer combine to constitute an environment which may be conducive to the rapid breakdown of the pruned fronds added in the frond stack zone. No estimates of the soil microfauna or microbial activity were made, but when the frond stack was dismantled, there was clearly an abundance of soil macrofauna (earthworms, earwigs) and partially decayed dead fronds were covered in a layer of fungal mycelium. In other studies, the soil respiration rate in the frond stack was found to be larger than the path and circle zones presumably due to the increased supply of substrates for
microbial decomposition (Anon, 1992). The relatively fast breakdown of
death fronds in the frond stack zones provides a constant and continuous
release of N, P, K Mg and Ca for palm uptake.

Part of the N contained in urea fertilizer may have been lost from the
soil surface by volatilization, particularly when applied urea was not
washed into the soil by rainfall. Volatilization was indicated at times by the
strong smell of ammonia which prevailed in the field following applications
of urea fertilizer.

5.5.6 Changes in soil chemical properties since 1975

Comparison of soil properties in the circle, path and frond stack with the
results of the soil survey carried out in the feasibility study (Rosenquist and
Anderson, 1975) provides an indication of enrichment and depletion of soil
nutrient reserves over the eight years since crop removal and fertilizer
application began.

In all zones, pH and the amount of exchangeable K were reduced
compared to the 1975 survey (Figure 5.6 and 5.9a). The exchangeable Mg
concentration had increased in the circle and frond stack soil zones at both
depths whilst in the path, Mg concentration was smaller in the 0-20 cm and
larger in the 20-40 cm depth (Figure 5.9c).

The exchangeable Ca concentration in the path was larger in both
the 0-20 and the 20-40 cm depth compared to the 1975 survey, whereas in
the circle, Ca concentration was smaller in the 0-20 cm depth and larger in
the 20-40 cm depth (Figure 5.9d). In the frond stack, Ca concentrations
were double those found in 1975. Exchangeable Na concentration was
larger in the circle 0-20 cm depth but slightly reduced in the other two zones
(Figure 5.9b).
The amount of organic C and total N in the 0-20 cm depth was smaller in the circle and path but the amount in the 20-40 cm depth in all zones was larger (Figure 5.12a and 5.12b). In the frond stack soil, the amount of organic C was similar in the 0-20 cm but larger in the 20-40 cm depth, due to the addition of pruned fronds.

In Figure 4.7c, it was shown that the amount of K applied was generally more than the amount of K removed in oil palm vegetative and reproductive growth. However, since soil exchangeable K was reduced even in the soil zones where large amounts were added in pruned fronds and fertilizer, this suggests that part of the K added may have been lost in leaching.

The balance between Mg added in fertilizer and removed in the crop was negative for most years (Figure 4.7d) and oil palms presented acute Mg deficiency symptoms until kieserite was substituted for dolomite and the rate of Mg application was increased, but nevertheless, the amount of soil exchangeable Mg was apparently increased except in the path zone in the 0-20 cm depth.

5.6 Conclusion

The spatially stratified system of fertilizer and crop residue management imposed under oil palm has resulted in the development of significant and pronounced gradients in soil physical and chemical properties under oil palm.

Measurements of soil bulk density, soil resistance and water infiltration rates have shown distinctive differences between the soil zones in Kelompok 2. The degradation of soil physical properties in the path-interrow sandy ferralitic soils planted to oil palms in the Ivory Coast found by Caliman et al., (1987) and Dufour and Olivin (1985) was sufficiently
pronounced to require the application of ameliorative measures to restore soil structure (Caliman et al., 1990a). In the path zone, soil bulk density and soil resistance was increased, and water infiltration rate reduced due to the repeated passage of wheel barrows and harvesters. Corrective measures may also be required to avoid reduced palm growth in replanted palms planted in the path inter-row compared to the frond stack avenue if the same avenues are used for access and fruit transport in the remaining ten years before replanting takes place. The very fast infiltration rate in the frond stack, due to the effect of organic matter on soil physical properties, may result in the loss of nutrients released during the decomposition of pruned fronds.

The addition of fertilizers to the palm circle partly balanced the loss of K and Mg from the soil but may have increased the loss of Ca through leaching. The loss of Ca was probably balanced by the addition of Ca when Mg and P were applied as dolomite and rock phosphate respectively, but not when kieserite and TSP were used. In the frond stack, exchangeable Ca concentration was increased due to the large quantities of Ca contained in pruned fronds.

Whilst the amount of available P was similar in the frond stack and circle soils, the reduced P adsorption found in soil in the frond stack suggests that P fertilizer might be more efficiently used if applied over the frond stack instead of in palm circles, particularly if root length density was similar in both these soil zones.

A comparison of nutrient concentration in soils may be misleading if there are large differences in bulk density between the soils. The addition of large amounts of organic matter to the soil may result in increased soil nutrient concentration, but also reduced soil bulk density, and thus only small changes in the amount of nutrient per volume of soil.
6.1 Introduction

Tree crops are considered to cycle nutrients more efficiently than annual crops for a number of reasons which have been thoroughly reviewed by Nair (1993) and Young (1989). Important advantages of perennial tree crops which contrast with annual crops include the presence of roots throughout the year which provides capacity for the capture of nutrients released from the mineralization of soil organic matter and organic residues. The roots of trees may also ramify the soil to a greater depth than annual crops and this provides potential for the recovery of leached nutrients, particularly nitrate and base cations which may otherwise be lost in drainage water.

Such characteristics are particularly important when trees grown in "low external input" systems rely on native soil nutrient reserves which must be used and recycled with minimal losses. In these systems, there is a requirement for a large network of roots exploring a large portion of the soil volume to the greatest possible depth. However, whilst large root densities may be required to extract available soil nutrients, plants are confronted with diminishing returns on dry matter invested in additional roots (de Willigen and van Noordwijk, 1991). For example, the relationship between uptake and root density is not linear, and the rate of nutrient uptake increases only to the point where depletion zones of individual roots overlap and result in inter-root competition for nutrients present on the soil (Marschner, 1986).
Many studies show a proliferation of roots where the concentration of nutrients in the soil, particularly of N and P, is greater (e.g. Coutts and Philipson, 1977). Furthermore, a small portion of the total root system of a plant was considered capable of supplying the nutrients and water required for plant growth, provided that portion was abundantly supplied with nutrients and water (Mengel and Kirkby, 1987). Thus, areas in the soil where roots have proliferated due to improved nutrient supply may be the zones where nutrient recovery from fertilizers and organic residues is more efficient. In such a situation, a ubiquitous root system may in fact represent a wasteful allocation of assimilates to root dry matter production.

In an oil palm plantation, differences were found in the concentration of nutrients and soil physical properties in the circle, path and frond stack soil zones (Chapter 5) due to the spatial distribution of fertilizers and organic residues (Chapter 4). In this Chapter, the palm root system is assessed in terms of its ability to capture nutrients in the circle, path and frond stack soil zones. Some characteristics of oil palm root systems with regard to nutrient use efficiency are discussed in the following section before the presentation and discussion of the results of this investigation.

6.2 General characteristics of oil palm roots

6.2.1 Root morphology

Oil palm roots are usually separated into four orders according to root diameter, described as primaries, secondaries, tertiaries and quaternaries ($1^\circ$, $2^\circ$, $3^\circ$, $4^\circ$) (Wood, 1986). Different classification systems have been described, but the one given by Tinker (1976) was considered of greatest utility because the categories do not overlap and this facilitates the separation of root fragments extracted in cores. A diagram of the template
used to distinguish between root categories in this study is presented in Appendix 1.

Primary roots about 6-10 mm in diameter are adventitious and may be traced to the palm bole at the base of the trunk. They spread either horizontally or descend at various angles into the soil. The 1° roots provide both the main arterial network for the transfer of water and nutrients from the soil to the palm and secure anchorage.

Descending primaries had fewer branches but secondary roots, 2-4 mm in diameter, branched at right angles mainly ascending but also descending from the horizontal primary roots and gave rise to tertiary roots 0.7-1.2 mm in diameter. The tips of 1°, 2°, and 3° roots were un-lignified and measured 3-4 cm, 5-6 cm, and 2-3 cm respectively in length (Hartley, 1977). Un-lignified quaternary roots 0.1-0.3 mm in diameter and 1-3 cm in length arise on the tertiary roots (Tan, 1983).

6.2.2 Distribution of oil palm roots in the soil

Palm roots were shown to extend as far as the edge of the palm canopy during the immature phase (Tan, 1979) but in eleven year old palms, primary roots were found to extend 19 m from the palm bole in a study of root systems in oil palm plantations in Malaysia (Lambourne, 1935).

The vertical extent of the root system was restricted to a depth of less than 1 m by the water table (Lambourne, 1935) but on free draining sandy soils roots extended to a greater depth (Purvis, 1956). The vertical extent of root penetration may be influenced by other soil physical properties which may be characteristic of the soil or the result of palm and soil management, and these reasons may help to explain the variation in the extent of vertical root development between different sites reported by Tinker (1976).
The positive tropism of oil palm roots towards areas with better water and nutrient supply led to a concentration of roots under the frond stack in the palm inter line (Bachy, 1964; Tailliez, 1971) and at the edge of palm circles root length density was larger where there had been an accumulation of organic debris (Purvis, 1956). The quantity of roots in the harvesting path was reported to be small (Hartley, 1977).

Root distribution was measured in concentric rings around the base of nine year old palms (Tan, 1976). At all ages, root density (given in mg dry root l⁻¹ soil) decreased with increasing distance from the palm. Root density had increased in the sites examined furthest from the palm bole in older palms. On the basis of these findings the application of fertilizers in progressively larger circles as the root system expands outwards from the palm base with increased palm age was recommended.

Root distribution was investigated in six year old palm stands in West Africa by digging inspection trenches at right angles to the palm row across the palm inter-row, and between palms within the palm row (Bachy, 1964). A larger concentration of fine roots (measured in g root l⁻¹ soil) was found in a superficial layer of soil and plant debris which had built up in the inter-row between palms compared with the soil within the line of palms which had been kept clear of weeds.

In a 12 year old palm stand in Ivory Coast root concentration was measured in the soil between palms (Frémond and Orgias, 1952). Surprisingly, in spite of the age of the palms, the inter-row space was still covered with a mixture of legume cover crops (P. phaseoloides and Centrosema pubescens). The largest density of secondary and tertiary roots was found between 2 - 4 m from the palm base which was recommended as the most suitable zone for the application of mineral fertilizer.

The weight of primary, secondary, tertiary, and quaternary roots was measured in transects perpendicular to palm rows across the frond stack in
a field of 7 year old palms in Columbia (Tailliez, 1971). Although fertilizers had been applied in palm circles since planting root density (given in g root m^{-2}) was smaller in the soil adjacent to the palm compared with the frond stack zone where there was a conspicuous proliferation of fine feeder roots. The largest concentration of roots was found in the circle 1 m from the palm bole and outside the edge of the weeded circle in a 14 year old palm field in Nigeria, due perhaps to the accumulation of weed mulch which had been removed from the circle (Purvis, 1956).

From these studies it can be seen that whilst the root system continues to expand horizontally from the palm bole for at least ten years, there may be areas of more intensive root proliferation where nutrient supply has been increased, particularly where organic residues, particularly palm fronds, have accumulated.

### 6.3 Methods used for root analysis

The use of soil augers for the extraction of volumetric soil-root samples was considered difficult in stony soils and compaction may result in differences in the volume of soil extracted with increased depth of sampling (Bohm, 1979). Neither of these problems was encountered in work carried out in this study. The Andisols in the experimental site were almost completely free of stones and this allowed the recovery of undisturbed cores in which oil palm roots were severed from the surrounding soil without tearing or distortion when a root auger of 8.5 cm diameter with a sharp cutting edge was driven into the soil with a large mallet. Measurements of holes from which successive cores of 10 cm length had been extracted showed that the soil had not been compacted due to the sampling procedure and thus the soil volume extracted by the corer was representative of field conditions.
The separation of root fragments from the soil was time consuming due to the difficulty of dispersing the fine textured clayey soil in water. In oil palm root studies conducted in Malaysia, elutriation time was reduced by soaking root cores in 5% Calgon® solution overnight, but root length was not affected by the extraction procedure (Goh and Samsudin, 1993a). In this study, root separation was made easier when soil cores were soaked overnight in a solution of commercial washing detergent (Rinso®).

In studies carried out in Malaysia, total root length was estimated by the relationship between the dry weight and length of root fragments. Roots were first separated into three classes according to root diameter before calculating the relationship between total root length and root mass for each root category. Total root length was then calculated from the sum of the length of each root diameter category (Goh and Samsudin, 1993b). In the work described here, total root length was estimated using the grid intersection method described by (Anderson and Ingram, 1993) based on the model of (Tennant, 1975). The root length of primary, secondary, and tertiary roots was measured directly using a high quality planimeter and the length of quaternary roots was calculated by difference. The more laborious methods used in this investigation, compared with the methods described by Goh may be justified in view of the very scanty information published in the literature on root length for oil palm.

Core samples from ten locations in concentric rings around trees were collected in a study of the spatial distribution of roots of single orchard trees by Weller (1971) but the aim of experiments reported here was to compare root distribution in soil zones which had received different nutrient treatments. Replicated root samples were taken from the soil in the circle (on each side of the palm adjacent to the frond stack and path) and from the path and the frond stack soil zones, and a transect of unreplicated core
samples was taken at 0.5 m intervals between palms across the path and frond stack soil zones (Figure 1.2).

At each sampling point, cores were extracted from four depths each of 10 cm which allowed comparisons between root distribution and soil chemical properties which were measured in the soil at 0-20 and 20-40 cm depths in the circle, path and frond stack zones (Chapter 5). Two sub-samples were taken at each sampling point and the mean was used to calculate overall means for the seven replicates which have been presented in the results. The sampling system violated the requirement for randomization needed for comparisons between zones and depths using standard error differences of means following analysis of variance. Instead, differences in root distribution between the soil zones were compared by performing orthogonal contrasts between the soil zones using the summary statistics of root length density per unit land area (L_A, cm cm⁻²) and the slope and intercept of the linear relationship between the log of root length density (L_V, cm cm⁻³) and soil depth.

A number of different root parameters may be measured to describe the root system in crop plants. Root mass is rather simple to measure but gives a poor indication of potential uptake since old and thick roots may make a large contribution to root mass but contribute little to total root length and therefore play a minor role in nutrient uptake (Bohm, 1979).

Root length density, L_V, was considered to have more influence on soil water uptake (Taylor and Klepper, 1973) and the depletion of soil nutrients by roots (Nye and Tinker, 1969). L_A allows the calculation of Root Area Index which is analogous to Leaf Area Index (Mengel and Kirkby, 1987) and may be used to compare root density in different parts of the soil under oil palm. Specific root length density may be used to compare the root length provided by a given amount of dry matter and represents a measure of efficiency of the investment of assimilate in root growth by
plants. Large specific root length density implies a larger amount of root length provided per gramme of root dry matter. \( L_V, L_A, \) and specific root length are defined in the following equations:

\[
L_V \ (\text{cm cm}^{-3}) = \frac{\text{Root length (cm)}}{\text{Soil volume (cm}^3\text{)}}
\]

\[
L_A \ (\text{cm cm}^{-2}) = \frac{\text{Total root length(cm)}}{\text{Soil surface(cm}^2\text{)}}
\]

\[
\text{Specific root length (cm g}^{-1}) = \frac{\text{Root length (cm)}}{\text{Root mass (g)}}
\]

6.4 Results

The preparation of profile walls for the examination of root distribution was attempted but abandoned because it was very difficult to disperse the soil surrounding the palm roots. However, in a trench dug between palms across the path and frond stack inter rows, an examination of the soil profile revealed the presence of a sharply defined boundary between the top soil and a continuous layer of weathered volcanic ash at a depth of between 70-80 cm. Small amounts of roots were found in the soil at a depth of 70-80 cm, and some primary roots extended into the very compact subsoil.

6.4.1 Root mass, root length density \((L_A)\), and specific root length per unit area of land surface.

The weight of oven dry roots in the soil in the three zones increased in concentration in the order path<frond stack<circle \((P<0.05)\) (Figure 6.1a). There was no significant difference between the amount of roots in the circle soil on the path side of the palm compared with the frond stack side.
The total length of primary, secondary, tertiary and quaternary roots was smaller in the path zone compared to the circle and frond stack zones ($P<0.001$) (Figure 6.1b). Root length was smaller in the frond stack compared with the two areas measured in the palm circles ($P<0.1$) and there was no significant difference between root length in the two circle soil zones (Figure 6.1d).

Specific root length was smaller in the path zone compared with the circle and frond stack soil zones ($P<0.05$), and larger in the frond stack than the two sites measured in the palm circle ($P<0.1$). There was no difference between the specific root length in the circle on the path side compared with the circle on the frond stack inter-row side of palms.

### 6.4.2 Root length density ($L_A$) of primary, secondary, and tertiary roots in the circle, path, and frond stack soil zones.

The length of primary roots was smaller in the frond stack soil zone compared with the circle and path soil zones ($P<0.05$) but there was no difference between the length of primary roots in the circle compared with the path (Figure 6.2a). The amount of secondary roots increased in the order path<frond stack<circle ($P<0.05$) (Figure 6.2b). The length of secondary roots in the circle was almost twice the amount in the path soil zone but there was no significant difference in the amount of secondary roots between the two sides of the circle soil zone. The length of tertiary roots was smaller in the path soil zone compared with the circle and frond stack ($P<0.001$), and larger in the frond stack compared to the circle soil zone ($P<0.1$) (Figure 6.2c). The length of quaternary roots was smaller in the path soil zone compared with the circle and frond stack zones.
and the length of quaternary roots was smaller in the frond stack compared with the circle soil zone \((P<0.05)\) (Figure 6.2d).

In the transect of root measurements crossing the frond stack and path avenues, less variability in root length density was found in the frond stack avenue compared with the path avenue (Figure 6.5). There was a marked increase in root length density over the 2 m distance from the base of palms to the point which describes the perimeter of the weeded circle in both transects. Root length density decreased between the point which describes the perimeter of the circle and the centre of the harvesting path, but there was no discernible pattern of increase or decrease in root length density in the transect across the frond stack avenue. Specific root length was notably small in the centre of the path avenue soil for a distance of 1.5 m. Since root mass was similar in the frond stack and path soil zones, the smaller specific root length found under the path indicates a preponderance of coarse roots (Figure 6.3).
Figure 6.1 Total root mass (a), total root length (b), and specific root length (c) in the circle, path and frond stack soil zones (bars represent standard errors of the means, n=7). Circle s and Circle p represent the frond stack and path sides of the oil palm circle respectively.
Figure 6.2  Length of primary (a), secondary (b), tertiary (c), and quaternary (d) roots in the circle, path and frond stack soil zones (Bars represent standard errors of the means, n=7). Circle s and Circle p represent the frond stack and path sides of the oil palm circle respectively.
Figure 6.3 Measurements of root length (a), root mass (b), and specific root length (c) from a transect across the path and frond stack zones at four depths.
6.4.3 Root length density ($L_v$) of primary, secondary, and tertiary roots in the circle, path, and frond stack soil zones.

Total root length density ($L_v$) decreased with increasing soil depth from 0 to 40 cm (Figure 6.4b) and specific root length density decreased from 0 to 30 cm soil depth (Figure 6.4c), but there was no clearly discernible trend in root mass (Figure 6.4a). There was a close linear relationship between root length density ($L_v$) and root mass in the 0-10 cm depth where the proportion of primary and secondary roots in relation to total root mass was small compared to the other depths sampled (Figure 6.5). In the 10-20, 20-30, and 30-40 cm depths investigated, where primary roots contributed a large proportion of total dry root weight but only a small amount of root length, there was no clear relationship between the dry weight of roots and root length.

The root length density of primary roots increased from the soil surface to a depth of 30 cm in all zones (Figure 6.6a). The difference between root length density of primary roots in the 20-30 and 30-40 cm depths was small in all zones except in the path soil, where root length density of 1° roots was less in the 30-40 cm compared with the 20-30 cm depth.

The root length density of secondary roots was similar in all four depths measured but the amount in the path was smaller than in the other soil zones (Figure 6.6b). Root length density of 3°, and 4° roots was smaller beneath the path zone at all depths measured (Figure 6.6c, 6.6d).

In all the soil zones, the root length density of tertiary and quaternary roots decreased from 0 to 40 cm depth and there was a close linear relationship between the log of root length density and soil depth (Figure 6.7a, 6.7b). There was no significant difference in the slope of the
regression curves for $3^\circ$ and $4^\circ$ roots between the four zones sampled. The
intercept was smaller in the path compared with the frond stack and circle
zones for tertiary roots ($P<0.001$). For quaternary roots, the intercept was
significantly smaller in the path compared with the frond stack and circle
zones ($P<0.05$), and smaller in the frond stack compared with the circle
zones ($P<0.05$).

In the transect across the path and frond stack avenues, a tendency
for root length density to increase over the 2 m distance from the palms to
the point which describes the perimeter of the circle was found in the 0-10,
10-20, and 20-30 cm depths, but in the 30-40 cm depth, the reverse was
found (Figure 6.8).

Root length density was larger in the soil under the frond stack
avenue compared with the path zone, and the difference was particularly
pronounced in the 30-40 cm depth (Figure 6.8). A zone of small root length
density was evident in the soil immediately beneath the path between 10-
40 cm where root length density was smaller than 0.5 cm cm$^{-3}$, whilst in
most of the cores extracted from the soil beneath the frond stack, root length
density was larger than 0.5 cm cm$^{-3}$ (Figure 6.9).
Figure 6.4  Total root mass (a), root length density (b) and specific root length (c) in the circle, path and frond stack soil zones at four depths (bars represent standard errors of the means, n=7). Circle (stack) and Circle (path) represent the frond stack and path sides of the oil palm circle respectively.
Figure 6.5 Relationship between root dry weight and root length in the 0-10 cm depth in the circle, path and frond stack zones (n=7). Circle (stack) and Circle (path) represent the frond stack and path sides of the oil palm circle respectively.
Figure 6.6  Root length density of 1° (a), 2° (b), 3° (c) and 4° (d) roots in the circle, path and frond stack soil zones at four depths (bars represent standard errors of the means, n=7). Circle (stack) and Circle (path) represent the frond stack and path sides of the oil palm circle respectively.
Figure 6.7  Relationship between root length density (L_v) and soil depth in the circle, path, and frond stack soil zones (each point represents the mean of seven measurements). Circle (stack) and Circle (path) represent the frond stack and path sides of the oil palm circle respectively.
Figure 6.8 Root length density ($L_v$) and in soils from a transect across the path and frond stack zones at four depths.
**Figure 6.9** Transect of root length density measurements across the path and frond stack inter-rows.
6.4.4 Infection of roots with vesicular arbuscular mycorrhiza

Large amounts of fungal hyphae were detected on and within the tertiary and quaternary roots inspected, but arbuscules and vesicles were not found in any of the root fragments examined. There were no differences between root fragments from the three soil zones in the amount of hyphal infection sites detected and there was an abundance of mycorrhiza spores present in soil from the three zones.

6.5 Discussion

In all the soil zones examined, root length density was larger in the Ophir site compared with the root length densities reported by Gray (1969) for oil palms planted on a coastal clay in Malaysia (Table 6.1). This may be explained by the excellent physical properties of Andisols which are likely to be more conducive to root development than coastal clay soils in Malaysia. The comparatively large root length density found in the Ophir site may be an important factor in the very large yields of fruit bunches.

Split root experiments have shown that mineral nutrient supply, particularly of N and P may have strong effect on the growth, morphology and distribution of roots in the soil profile and thus root distribution may be modified by the placement of fertilizers (Marschner, 1986). In the site investigated in this work the frond stack and circle zones have received large amounts of N and P compared with the unfertilized and un-mulched path soil zone (Chapter 4). Compared with the frond stack and circle zones the root length density of 3° and 4° roots was smaller in the path zone where the concentration of exchangeable K and Mg was smaller in both the 0-20 and 20-40 cm depths compared to the soil in the frond stack and circle
soil zones and the concentration of readily available P was smaller in the 20-40 cm depth in the path zone compared with the frond stack and circle at the same depth.

**Table 6.1** Comparison of root parameters in a Malaysian coastal clay soil (after Gray, 1969) with root parameters in the Ophir plantation in the circle, path and frond stack zones.

<table>
<thead>
<tr>
<th>Soil</th>
<th>Root mass (mg cm(^{-2}))</th>
<th>Root length density (cm cm(^{-2}))</th>
<th>Specific root length (cm g(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Malaysia</td>
<td>50</td>
<td>0.5 0.4 1.4 3.9</td>
<td>6.2 126</td>
</tr>
<tr>
<td>Circle</td>
<td>98</td>
<td>0.8 2.9 8.8 25.9</td>
<td>38.4 391</td>
</tr>
<tr>
<td>Path</td>
<td>62</td>
<td>0.6 1.7 3.4 9.8</td>
<td>15.5 250</td>
</tr>
<tr>
<td>Frond stack</td>
<td>72</td>
<td>0.3 2.3 10.7 19.7</td>
<td>33.0 458</td>
</tr>
</tbody>
</table>

Root length density of \(3^0\) and \(4^0\) roots was similar in the frond stack avenue and the circle soil zone which suggests that the potential for root growth in the path zone has been inhibited by both the smaller concentration of nutrients and the soil compaction which has resulted from the traffic of harvesters and laden wheel barrows.

Extrapolation of the linear curves fitted to the relationship between the log of root length density and soil depth (Figure 6.7) suggest that \(3^0\) and \(4^0\) roots penetrate to a depth of approximately 40 cm, but in the circle and frond stack soil zones, roots may penetrate to a much greater depth of between 60 to 65 cm below the soil surface which describes the boundary between the melanic epipedon of soil and the weathered volcanic ash lying beneath.
6.5.1 Comparison of the effect of soil physical and chemical properties on the uptake of nutrients by root interception

The proportion of total nutrient uptake by root interception depends on the amount of available nutrients in the soil, the root volume as a percentage of the total soil volume, and the proportion of the soil volume occupied by pores (which is related to bulk density) (Marschner, 1986). The absorption of soil nutrients by root interception may also be enhanced by a larger amount of new root growth but since roots usually occupy only 1% of the soil volume, nutrient interception by roots accounts for a small proportion of the total uptake of N, P and K (Tisdale et al., 1993). Root interception of nutrients may be enhanced due to the mutualistic symbiosis between mycorrhiza and crop root systems. Fungal hyphae of vesicular arbuscular mycorrhiza extend into the soil surrounding roots and increase the surface available for nutrient absorption. Oil palm roots were reported to be heavily colonized by vesicular arbuscular mycorrhiza under natural conditions, but the degree of infection and thus the contribution to total nutrient uptake in crop plants depends on the amount of P, K, and N present in the soil (Sieverding, 1991). However, whilst there was an abundance of mycorrhiza spores present in the soil, there was no conclusive evidence of mycorrhizal infection of roots in any of the soil zones. Although no clear vesicles could be seen the abundant presence of intercellular hyphae indicated that the root infection was symbiotic rather than pathogenic. It would be necessary to conduct inoculated experiments under axenic conditions using inocula from these roots to clarify whether the lack of vesicles and arbuscules is a common characteristic of mycorrhizal infection of oil palm roots. The large amounts of P applied to soil in the frond stack and circle might have been expected to reduce root mycorrhiza infection, but even in the unamended
path soil, where the concentration of P was small there was no conclusive evidence of mycorrhiza infection.

In the path zone, soil bulk density was larger and therefore pore volume smaller, and soil resistance was larger than the soil in the frond stack zone (Figure 5.1, 5.4). Thus root elongation was comparatively less favoured by the soil in the path zone compared to the frond stack. The concentration of exchangeable K and Mg was smaller in the path compared with the soil in the circle and frond stack soils (Figure 5.9), and the percentage of the soil volume occupied by 3° and 4° roots was smaller in the path compared with the circle and frond stack soils (Figure 6.10). Root elongation was probably favoured in the frond stack where bulk density was smaller than the path and circle soils (Figure 5.1).

6.5.2 Comparison of the effect of soil physical and chemical properties on the uptake of nutrients by mass flow

Mass flow occurs when nutrients dissolved in water are transported in the convective flow of water to roots to meet the loss of transpiration from the crop canopy (Tisdale et al., 1993). The process is described in the following equation:

\[
J = V_t \times C_i
\]

where \( J \) is the mass flow (mg cm\(^{-1}\) s\(^{-1}\)), \( V_t \) is the rate of water flux into the root (cm\(^3\) cm\(^{-1}\) s\(^{-1}\)), and \( C_i \) is the concentration of ions in solution (mg l\(^{-1}\)).

The rate of nutrient transfer by mass flow depends on the concentration of ions in solution and the rate of water flux into the root. Calculations have indicated that the transfer of Ca and Mg to the root surface by mass flow is greater than the rate of uptake by the crop, and
leads to increased concentration of Ca and Mg at the root surface (Gregory, 1988). In the Ophir plantation, water deficits, which reduce the transpirational flow of water through palms and result in an accumulation of un-opened fronds in the palm crown, have not occurred.

The evaporative demand of oil palm was estimated to be between 5-6 mm day⁻¹ (Foong, 1993). This amounts to a total transpiration requirement of about 2000 mm year⁻¹, but rainfall has always been in excess of this amount in the Ophir project. The proportion of water absorbed in the frond stack, where the soil was found to have lower bulk density and therefore a larger amount of pore space compared with the path and circle soil zones, may have been greater when compared with the other two zones.

The smaller concentration of Ca in the circle soil compared with the frond stack and path soils indicates that less Ca would have been absorbed by mass flow from the soil in the circle compared with the frond stack soil. The soil in the frond stack was continually supplied with nutrients from the decomposing palm fronds, whilst in the circle, nutrients were applied in large quantities several times per year.

6.5.3 Comparison of the effect of soil physical and chemical properties on the uptake of K and P by diffusion

For most crops, when the amount of P and K taken up in absorbed water is calculated from the product of the soil nutrient concentration and the amount of water absorbed, it is clear that the quantity supplied is less than the amount absorbed by the crop (Gregory, 1988; Marschner, 1986). Oil palms absorb about 20 x10⁶ l water yr⁻¹. If sufficient P is supplied to maintain solution concentration of 0.2 mg l⁻¹, the annual uptake would be 4 kg ha⁻¹ yr⁻¹ which is smaller than the total uptake of P which was 38 kg ha⁻¹.
yr\(^{-1}\) for oil palms planted on coastal clays in Malaysia (Ng et al., 1968). Such calculations highlight the importance of diffusion in the uptake of P but the same principles apply to the uptake of K. The diffusion process in soil is described in the following equation (Marschner, 1986):

\[
D_s = D_o \times \theta_v \times f \times \frac{dC_i}{dC}
\]

where \(D_s\) is the effective diffusion coefficient (m\(^2\) s\(^{-1}\)), \(D_o\) is the diffusion coefficient in water (m\(^2\) s\(^{-1}\)), \(\theta_v\) is the soil volumetric content (m\(^3\) m\(^{-3}\)), \(f\) is the impedance or tortuosity factor, and \(dC_i/dC\) is the reciprocal of the soil buffer capacity for the ion concerned. Diffusion of ions from the soil to the root surface is increased by increased nutrient concentration, increased volumetric water content (\(Q\)) and a larger value for \(dC_i/dC\).

Sorption isotherms presented in Chapter 5 showed that P was less strongly buffered in the soil beneath the frond stack compared to the soil in the circle and path zones (Figure 5.12) and the concentration of exchangeable K was larger in the circle and frond stack zones compared to the path (Figure 5.10). This suggests a larger value for \(dC_i/dC\) for P in the frond stack compared with the circle and path zones and a larger value of \(dC_i/dC\) for K in the frond stack and circle zones compared with the path soil zone.

Bulk density was smaller in the frond stack which implies a larger total pore space. The relationship between bulk density and volumetric water content depends on the pore characteristics since water drains more freely from macro-pores compared with micro-pores. Volumetric water content was not measured in this work, but a larger value for \(Q\) in the frond stack compared with the path and circle zones may be implied by the lower soil bulk density in the frond stack soil.

According to Marschner (1986) the relationship between nutrient uptake and root length density is linear up to the point where the depletion
zones surrounding roots overlap which results in inter-root competition. The
distance between 3° and 4° roots was smaller in the frond stack and circle
compared with the path zone (Figure 6.11) which suggests larger uptake of
P and K in the frond stack and circle soil zones compared with the path.

The relationship between root length density, root mass and specific
root length density is presented in Figure 6.12. At each of the four depths in
which root properties were measured, specific root length density was
similar in the soil zones but root length density was smaller in the path
compared with the frond stack and circle. In each soil zone, specific root
length was smaller at greater depth in the soil.

Theoretical consideration of the effect of differences in root length
density, nutrient concentration, and soil physical properties between the
circle, path and frond stack soil on nutrient uptake discussed above suggest
that palms derived a larger proportion of their nutrient requirements from the
circle and frond stack soil compared with the path. The root length density in
the circle and frond stack zones may have been increased by the large
quantities of N and P applied respectively as fertilizer and pruned fronds
and this situation may be expected to prevail in oil palm plantations where
similar nutrient management systems are practised.
Figure 6.10 Soil volume occupied by 1° (a), 2° (b), 3° (c), and 4° (d) roots (cm⁻³ cm⁻³) in the circle, path, and frond stack soil zones and four depths. Circle (stack) and Circle (path) represent the frond stack and path sides of the oil palm circle respectively.
Figure 6.11  Distance between fine roots ($3^\circ$ and $4^\circ$) in the circle, path, and frond stack soil zones. Circle (stack) and Circle (path) represent the frond stack and path sides of the oil palm circle respectively.

Figure 6.12  Relationship between root length density and root mass for the circle, path, and frond stack soil zones at four depths. Lines represent specific root length density (mean of seven measurements). Circle (stack) and Circle (path) represent the frond stack and path sides of the oil palm circle respectively.
Spatial differences in root density in the soil under oil palms have prompted investigations into the effect of different fertilizer placement strategies on nutrient use efficiency. The extent to which palms scavenge for nutrients was demonstrated in experiments carried out in Malaysia (Zaharah et al., 1989). In different treatments, labelled $^{32}\text{P}$ was applied in palm circles and the frond stack. $^{32}\text{P}$ applied in the frond was absorbed by palms up to 36 m or 4 palms distant from the palm to which fertilizer had been applied. In the circle treatment, $^{32}\text{P}$ was detected in all the palms surrounding palms to which fertilizer was applied even when the surrounding palms were isolated from the treated palm by a 65 cm deep trench.

In a study on the effect of fertilizer placement on oil palm yield, Foster and Dolmat (1986) compared yield and oil palm leaf nutrient content in palms when fertiliser was applied over the circle, the path and frond stack. He concluded that optimum fertiliser placement depended on palm age, frequency of application and solubility of the nutrient applied. It was also argued that since N is absorbed by mass flow, fertilizer should be placed in the weeded circle of young palms where root density is greatest to allow maximum uptake by roots and reduce the amount lost by leaching. He also proposed that since P moves through the soil mainly by diffusion, P fertilizer should be applied where root density is greatest and the soil remains moist for the longest period.

No difference was found in yield between treatments receiving fertilizer in the circle compared to fertilizer broadcast between palms in a fertilizer experiment on mature palms in which yield and uptake was measured for five years (Teoh and Chew, 1985), and in a review of ten experiments investigating the effect of fertilizer placement on oil palm yield,
Yeow et al., (1982) concluded that placement was not critical. There was no difference in yield when fertilizer was applied to half the palms in the field, and palms in experimental plots not isolated by trenches scavenged nutrients from adjacent palm plots to which fertilizers had been applied. Both these effects were attributed to the encroachment of roots from palm to palm. This also implies that root samples taken from positions intermediate between palms are likely to contain some roots from all of the neighbouring palms.

6.6 Conclusions

A major deficiency in past root studies in oil palm is the presentation of root mass which does not give a good indication of root length, unless root fragments are first separated into different categories and for each category a relationship is established between root mass and root length density.

The measurement of the length of 1°, 2°, 3°, and 4° roots, extracted from soil cores, using the grid intersection method was considered effective and efficient particularly when elaborate equipment is not available at field sites. A high quality planimeter was useful for the rapid assessment of the length of primary, secondary and tertiary roots.

The placement of pruned fronds in alternate inter-row and mineral fertilizer in weeded palm circle resulted in large root length density in the frond stack and circle soil zones compared with the path zone. Root development may have been restricted in the path zone by the small amount of nutrients and the large bulk density and soil resistance.

In spite of apparent differences in root density there was no advantage from any particular strategy of fertilizer placement in a number of field experiments, but there may be advantages to be gained from the application of fertilizer and pruned fronds in spatial patterns which prevent
the development of large differences in root density, and this aspect is discussed in Chapter 8.
Whilst soil chemical analysis provided an indication of the comparative availability of nutrients in the soil in the three zones (Chapter 5), pot experiments may provide a better indication of the availability of nutrients for plant uptake. It would have been ideal to conduct fertilizer response experiments with oil palm but this was not feasible in the UK. It was hoped to conduct experiments on clonal oil palm material ready for transplanting in Indonesia but eventually this also proved unmanageable.

Cover plants, such as *Pueraria phaseoloides* are convenient for experimental work because they are easy and quick to establish. Experiments which investigated the nutrition of *P. phaseoloides* improved understanding of rubber nutrition (Watson, 1989) partly because the legume showed clear leaf deficiency symptoms when grown on soils deficient in N, P, K, Mg and Ca. In addition, “critical” leaf nutrient concentrations and nutrient deficiency symptoms for different cover crop species have been reported and described in the literature (Shorrocks, 1964).

Differences in the growth and nutrient uptake of *P. phaseoloides* between plants grown in soil from the circle, path and frond stack zones and in response to the amendment of soil exchangeable K, Mg and Ca do not necessarily reflect the comparative availability of nutrients to oil palms, but
may help to corroborate the differences in soil properties found in soil analysis reported in Chapter 5.

Two pot experiments were carried out to investigate the effect of differences found in soil chemical properties between in the circle, path and frond stack zones on the growth and nutrient uptake of *P. phaseoloides*.

### 7.2 Materials and methods

*P. phaseoloides* was grown in soil taken from beneath the circle, path and frond stack zones in Kelompok 2, NESP Ophir. Soil samples from each soil zone and depth used for soil analysis in Chapter 5 was bulked and thoroughly mixed to provide material for the experiments which were carried out in a heated glass house (18-22 °C) at Wye College between April and August 1992.

Ninety 7 cm pots were filled with 200 g air-dried soil. Nine scarified seeds were sown directly in each pot and the three most vigorous plants selected three weeks after sowing. All pots were inoculated with *Bradyrhizobium* strain CIAT 3918 from CIAT, Colombia which was grown in a yeast-mannitol broth, diluted and watered over the germinated plants.

Experiment 1 was designed to explore the main effects of soil zone and soil depth and possible interactions between soil zone and soil depth on dry matter production and nutrient uptake in *P. phaseoloides*.

In Experiment 2 the growth and nutrient uptake of *P. phaseoloides* was compared in soil from the 0-20 cm depth from the three soil zones with five rates of nutrient amendment. Three stock solutions containing CaCl₂, MgSO₄, and KCl respectively were prepared and different amounts added to the soil to give the following treatments. Soil in the control plots was not amended. In the *Rate 1* treatment, the amount of exchangeable Ca, Mg and K was adjusted to 7.0, 0.9, 0.3 cmol(+) kg⁻¹ respectively. In the *Rate 2* treatment, Ca, Mg, and K were adjusted to 14.0, 1.8, and 0.6 cmol(+) kg⁻¹.
respectively, and in the K only and Mg only treatments, the amounts of exchangeable K and Mg in the soil were adjusted to the same amounts in the Rate 1 treatment. Details of the treatments are given in Table 7.1. Magnesium sulphate and potassium chloride were used to supply respectively Mg and K since they were the standard fertilizers used to supply these nutrients in the Ophir oil palm plantation. Calcium chloride was used as the source of Ca to avoid the liming effect which would accompany an application of calcium carbonate. All pots received 20 mg P g\(^{-1}\) soil, applied as NaH\(_2\)PO\(_4\)-2H\(_2\)O in solution.

Pots were watered daily, adjusted to 70% of the pot free draining capacity at weekly intervals, and the plants were harvested after exactly eight weeks. Leaf material was removed by cutting the stems at the soil surface which were then dried in an oven at 85 °C overnight and weighed. The tops were milled in a hammer mill using a 10 mesh sieve prior to analysis. Roots were first separated from the soil by gently washing root pieces over a 2 mm sieve and then inspected for the presence of nodules before they were dried and weighed.

Table 7.1 Calculated concentrations of Ca, Mg, and K in the soil from three zones following the application of nutrient solutions to pots in the glass-house experiment.

<table>
<thead>
<tr>
<th>Fertilizer used</th>
<th>CaCl(_2)</th>
<th>MgSO(_4)-7H(_2)O</th>
<th>KCl</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment</td>
<td>(cmol (+) kg(^{-1}))</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>not adjusted</td>
<td>not adjusted</td>
<td>not adjusted</td>
</tr>
<tr>
<td>Rate 1</td>
<td>7.0</td>
<td>0.9</td>
<td>0.3</td>
</tr>
<tr>
<td>Rate 2</td>
<td>14.0</td>
<td>1.8</td>
<td>0.6</td>
</tr>
<tr>
<td>K only</td>
<td>not adjusted</td>
<td>not adjusted</td>
<td>0.3</td>
</tr>
<tr>
<td>Mg only</td>
<td>not adjusted</td>
<td>0.9</td>
<td>not adjusted</td>
</tr>
</tbody>
</table>
A randomised complete block design with five replicates was adopted for each experiment and the treatments were randomly assigned to positions within each block on the glass-house bench.

7.3 Results

7.3.1 Qualitative assessment

In the first month, growth of *P. phaseoloides* in soil taken from the path was poor, but growth and appearance improved in the second month. Pronounced deficiency symptoms (probably of K and Mg) were observed in plants grown in soil from the 0-20 cm depth in the palm circle irrespective of nutrient treatment, and symptoms became progressively more pronounced in the second month.

**Plate 7.1** Growth of *Pueraria phaseoloides* in soil from the 0-20 cm depth in the circle, path and frond stack zones (Experiment 1).
In contrast to the circle and frond stack, where the effect of nutrient treatments on plant appearance was rather small, *P. phaseoloides* grown in soil from under the path was noticeably more vigorous under the K only and particularly the Mg only treatments compared with the control.

7.3.2 **Comparison of the growth and nutrient uptake of *P. phaseoloides* in soil taken from two depths in the circle, path and frond stack (Experiment 1)**

There was no significant interaction between the soil zone and soil depth in the amount of root and shoot dry matter produced by *P. phaseoloides*. The amounts of shoot and root dry matter produced were smaller in plants grown in soil from under the path zone compared with the frond stack and circle zones (*P*<0.05) (Figure 7.1a, 7.1b), and the amounts of shoot and root dry matter were smaller in plants grown in soil from the 20-40 cm depth compared with the 0-20 cm soil depth (*P*<0.05) (Figure 7.1a, 7.1b). There were no significant differences between root and shoot dry matter produced by plants grown in soil from the circle and frond stack zones.

Examination of plant roots when the experiment was terminated revealed that plants were not nodulated. The interaction between soil zone and soil depth was significant for shoot N concentration (*P*<0.05). In plants grown in soil from the 0-20 cm depth, shoot N concentration increased in the order circle<path<frond stack (*P*<0.05) (Figure 7.2a). In the circle and path soil zones, there was no significant difference between shoot N concentration in *P. phaseoloides* grown in the 0-20 cm soil depth compared with the 20-40 cm soil depth, but in the frond stack soil zone, shoot N concentration was larger in plants grown in soil from the 0-20 cm compared with the 20-40 cm soil depth (*P*<0.001) (Figure 7.2a).
Figure 7.1 Comparison of root dry matter, shoot dry matter and total dry matter production of *P. phaseoloides* grown in a pot trial in three soil zones at two depths (bars represent the standard error of the difference between means, n=5)

The interaction between soil zone and soil depth was significant for total N uptake (*P*<0.001). In the 0-20 cm soil depth, total N uptake in *P. phaseoloides* grown in soil from the frond stack was twice the amount in plants grown in soil from the circle and path zones (*P*<0.001) (Figure 7.2b). Total N uptake was larger in plants grown in the 0-20 cm compared with the 20-40 cm depths in the frond stack soil (*P*<0.001), but not in the circle and
path soils. Total N uptake was larger in plants grown in soil from the 20-40 cm depth in the frond stack compared with the total N uptake in plants grown in the 0-20 cm and 20-40 cm depths in the circle and path soil zones ($P<0.05$).

There was a significant interaction between soil zone and soil depth for shoot P concentration ($P<0.05$). In plants grown in soil from the 0-20 cm depth, shoot P concentration increased in the order stack=path<circle ($P<0.05$) (Figure 7.2c), but in plants grown in the 20-40 cm depth there was no significant difference in shoot P concentration among the three soil zones. There was no significant difference in shoot P concentration between the 0-20 cm and the 20-40 cm depths in plants grown in soil from the path zone, but shoot P concentration was significantly larger in plants grown in soil from 0-20 cm depth from the frond stack zone ($P<0.05$), and twice the concentration in the 20-40 cm soil depth in plants grown in soil from the circle soil zone.

There was a significant interaction between soil zone and depth for total P uptake ($P<0.05$) which increased in the order path<frond stack<circle soil zone in plants grown in soil from the 0-20 cm depth ($P<0.001$) (Figure 7.2d). Differences between soil zones in total P uptake in plants grown in soil from the 20-40 cm depth were not significant. In plants grown in soil from the circle and frond stack, total P uptake was larger in the 0-20 cm depth ($P<0.001$) but no difference in total P uptake was found between plants grown in the 0-20 cm and 20-40 cm depths in soil from the path zone.

The interaction between soil zone and soil depth was not significant for shoot K concentration or total K uptake. Shoot K concentration and total K uptake were smaller in the plants grown in soil from the path zone compared the frond stack and circle soil zones ($P<0.001$), and smaller in plants grown in the 20-40 cm compared with the 0-20 cm depth ($P<0.05$) (Figure 7.2e, 7.2f).
A significant interaction was found between soil depth and soil zone for shoot Mg concentration \((P<0.001)\). Shoot Mg concentration increased in the order frond stack<path<circle soil zone in plants grown in the 0-20 cm soil depth \((P<0.05)\) (Figure 7.2g). In the 20-40 cm soil depth, there was no difference between shoot Mg concentration in plants grown in the circle and frond stack soil zones, but shoot Mg concentration was smaller in plants grown in the path soil compared to the frond stack and circle soils \((P<0.05)\). There was no significant difference in shoot Mg concentration between plants grown in the two soil depths in the frond stack soil, but in the circle and path soil zones, shoot Mg concentration was larger in the 0-20 cm soil depth \((P<0.001)\) (Figure 7.2g).

The interaction between soil depth and soil zone was significant for total shoot Mg uptake \((P<0.05)\) which increased in the order path=frond stack<circle soil zone in plants grown in soil from the 0-20 cm depth \((P<0.05)\) (Figure 7.2h). Total Mg uptake was larger in plants grown in the 0-20 cm compared with the 20-40 cm soil depth in the circle and path soil zones \((P<0.001)\) but not in the frond stack soil zone.

The interaction between soil zone and soil depth was not significant for shoot Ca concentration which increased in the order circle<frond stack<path \((P<0.001)\) (Figure 7.2i). Shoot Ca concentration was larger in the 20-40 cm soil depth \((P<0.05)\). Total Ca uptake increased in the order circle<path=frond stack \((P<0.05)\) but there was no significant difference in total Ca uptake between the two soil depths (Figure 7.2j).
Figure 7.2 Shoot nutrient concentration and total nutrient uptake of *P. phaseoloides* grown in soil from the circle, path and frond stack zones from two depths (bars represent the standard errors of the differences between means, n=5).
7.3.3 Comparison of the growth and nutrient uptake of *P. phaseoloides* in soil taken from the 0-20 cm depth in the circle, path and frond stack in response to K, Mg and Ca (Experiment 2)

The interaction between soil zone and nutrient treatment was significant for the amount of root dry matter produced by *P. phaseoloides* (*P*<0.05). Compared with the control, the amount of root dry matter produced with the *Rate 1* addition was significantly increased in plants grown in path soil but not in frond stack soil, and reduced in the circle soil (*P*<0.05) (Table 7.2a). With the *K only* and *Mg only* treatments the amount of root dry matter was increased compared to the control in plants grown in soil from the path and frond stack but not in soil from the circle zone. The yield of root dry matter was larger with the *Mg only* compared with the *K only* treatment in plants grown in soil from the path and frond stack zones (*P*<0.05). There was no significant difference in the amount of root dry matter produced in plants grown in soil from the path between the *K only* and *Rate 1* treatments. There was a large and significant reduction in root dry matter production with the *Rate 2* treatment in plants grown in soil from the circle zone (*P*<0.05).

The interaction between soil zone and nutrient treatment was not significant for shoot dry matter production (Table 7.2b). The amount of shoot dry matter produced by *P. phaseoloides* was larger in plants grown in the frond stack soil compared with the circle and path soils (*P*<0.001).

The interaction between soil zone and nutrient treatment was significant for shoot N concentration (*P*<0.001). Shoot N concentration was increased in plants grown in soil from the circle in the *Rate 2* treatment (*P*<0.001) (Table 7.3a). Compared with the control, shoot N concentration was increased in plants grown in soil from the path zone with *K only*
but with \textit{K only} and \textit{Mg only} shoot N concentration was reduced in plants grown in soil from the frond stack zone ($P<0.001$).

The interaction between soil zone and nutrient treatment was significant for total N uptake ($P<0.001$). In plants grown in soil from the circle zone, there was no significant difference between the nutrient addition treatments in total N uptake (Figure 7.3a). Compared with the control, the total N uptake in plants grown in soil from the path was increased with Rate 1 ($P<0.05$), and with \textit{K only} and \textit{Mg only} ($P<0.001$), and total N uptake was significantly larger with \textit{Mg only} compared with the Rate 1 treatment ($P<0.001$). In the plants grown in soil from the frond stack, total N uptake was reduced compared with the control with the \textit{K only} and \textit{Mg only} treatments ($P<0.001$).

There was a significant interaction between soil zone and nutrient treatment for shoot P concentration ($P<0.05$). Compared with the control there was a significant increase in shoot P concentration at Rate 2 in plants grown in soil from the circle and path zones but not in the frond stack zone ($P<0.001$) (Table 7.3b).

The interaction between soil zone and nutrient treatment was significant for shoot K concentration ($P<0.05$). In plants grown in soil from the circle, shoot K concentration increased in the order control=\textit{K only}=\textit{Mg only}<Rate 1<Rate 2 ($P<0.05$) (Table 7.3c). In plants grown in soil from the path zone, shoot K concentration was increased at Rate 1, Rate 2, and \textit{K only} ($P<0.001$), but no significant difference was found between shoot K concentration in plants at \textit{K only} and Rate 1. In plants grown in soil from the frond stack, there was no significant response to the nutrient treatments. There was no significant difference in shoot K concentration between the control and \textit{Mg only} in the three soil zones.

The interaction between soil zone and nutrient treatment was significant in total K uptake ($P<0.05$). In the circle, there was no difference
between the nutrient treatments on total K uptake (Figure 7.3b). In the path total K uptake was increased with the Rate 1, Rate 2, and K only treatments ($P<0.001$) and with Mg only ($P<0.05$) compared to the control. In plants grown in soil from the frond stack, total K uptake was increased with Mg only ($P<0.001$).

The interaction between soil zone and nutrient treatments was not significant for shoot Mg concentration. Compared with the control, shoot Mg concentration was increased with the Rate 2 and Mg only treatments in all three soils ($P<0.001$) (Table 7.3d).

The interaction between soil zone and nutrient treatment was significant for total Mg uptake ($P<0.05$). In plants grown in soil from the circle, total Mg uptake was increased with Mg only (Figure 7.3c). In plants grown in soil from the path, total Mg uptake was increased with Rate 1, Rate 2, and Mg only, and total Mg uptake was larger with Mg only compared with Rate 1 and Rate 2 ($P<0.05$). In plants grown in soil from the frond stack, total Mg uptake was increased with the Rate 2 and Mg only treatments compared with the control ($P<0.05$).

The interaction between soil zone and nutrient treatment was significant for shoot Ca concentration ($P<0.001$) (Table 7.3e). In plants grown in soil from the circle, shoot Ca concentration was more than twice the concentration found in the control with Rate 1, and more than three times the control with the Rate 2 treatment ($P<0.001$), but the K only and Mg only treatments had no effect on shoot Ca concentration. In plants grown in soil from the path, shoot Ca concentration was increased at Rate 2 treatment but reduced at Mg only compared with the control ($P<0.001$).

The interaction between soil zone and nutrient treatment was significant for total Ca uptake (Figure 7.3d). Compared to the control, total Ca uptake was increased in plants grown in soil from the circle and path
with the *Rate 1* and *Rate 2* treatments (*P*<0.05) but not in plants grown in soil from the frond stack.

**Table 7.2** Root (a) and shoot (b) dry matter produced by *P. phaseoloides* grown in soil from the circle, path, and frond stack under five nutrient treatments (figures in italics are standard errors of the differences between means, n=5).

a) Root dry matter

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>Rate 1</th>
<th>Rate 2</th>
<th>K only</th>
<th>Mg only</th>
<th>Mean</th>
<th>±0.011***</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circle</td>
<td>0.23</td>
<td>0.19</td>
<td>0.11</td>
<td>0.20</td>
<td>0.23</td>
<td>0.19</td>
<td></td>
</tr>
<tr>
<td>Path</td>
<td>0.18</td>
<td>0.25</td>
<td>0.14</td>
<td>0.24</td>
<td>0.30</td>
<td>0.22</td>
<td>±0.011***</td>
</tr>
<tr>
<td>Frd. stack</td>
<td>0.23</td>
<td>0.23</td>
<td>0.19</td>
<td>0.28</td>
<td>0.30</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>0.22</td>
<td>0.22</td>
<td>0.15</td>
<td>0.24</td>
<td>0.28</td>
<td>±0.025***</td>
<td>±0.014***</td>
</tr>
</tbody>
</table>

b) Shoot dry matter

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>Rate 1</th>
<th>Rate 2</th>
<th>K only</th>
<th>Mg only</th>
<th>Mean</th>
<th>±0.016***</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circle</td>
<td>0.27</td>
<td>0.24</td>
<td>0.17</td>
<td>0.29</td>
<td>0.28</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>Path</td>
<td>0.21</td>
<td>0.27</td>
<td>0.21</td>
<td>0.26</td>
<td>0.33</td>
<td>0.26</td>
<td>±0.016***</td>
</tr>
<tr>
<td>Frd. stack</td>
<td>0.29</td>
<td>0.32</td>
<td>0.27</td>
<td>0.34</td>
<td>0.39</td>
<td>0.32</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>0.26</td>
<td>0.28</td>
<td>0.22</td>
<td>0.29</td>
<td>0.33</td>
<td>±0.035</td>
<td>±0.020***</td>
</tr>
</tbody>
</table>
Table 7.3 Shoot N (a), P (b), K (c), Mg (d) and Ca (e) concentration in *P. phaseoloides* grown in soil from the circle, path, and frond stack under five nutrient treatments (figures in italics are standard errors of the differences between means, n=5).

### a) Nitrogen

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>Rate 1</th>
<th>Rate 2</th>
<th>K only</th>
<th>Mg only</th>
<th>Mean</th>
<th>Std Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circle</td>
<td>1.79</td>
<td>2.14</td>
<td>2.52</td>
<td>1.95</td>
<td>1.82</td>
<td>2.04</td>
<td>±0.096***</td>
</tr>
<tr>
<td>Path</td>
<td>2.67</td>
<td>3.35</td>
<td>2.62</td>
<td>2.98</td>
<td>2.61</td>
<td>2.57</td>
<td>±0.124***</td>
</tr>
<tr>
<td>Frd. stack</td>
<td>3.45</td>
<td>3.21</td>
<td>3.13</td>
<td>2.23</td>
<td>1.99</td>
<td>2.80</td>
<td>±0.124***</td>
</tr>
<tr>
<td>Mean</td>
<td>2.50</td>
<td>2.57</td>
<td>2.76</td>
<td>2.39</td>
<td>2.14</td>
<td>±0.22***</td>
<td>±0.124***</td>
</tr>
</tbody>
</table>

### b) Phosphorus

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>Rate 1</th>
<th>Rate 2</th>
<th>K only</th>
<th>Mg only</th>
<th>Mean</th>
<th>Std Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circle</td>
<td>0.15</td>
<td>0.18</td>
<td>0.22</td>
<td>0.12</td>
<td>0.12</td>
<td>0.16</td>
<td>±0.010**</td>
</tr>
<tr>
<td>Path</td>
<td>0.09</td>
<td>0.11</td>
<td>0.15</td>
<td>0.10</td>
<td>0.11</td>
<td>0.11</td>
<td>±0.124***</td>
</tr>
<tr>
<td>Frd. stack</td>
<td>0.10</td>
<td>0.08</td>
<td>0.09</td>
<td>0.10</td>
<td>0.13</td>
<td>0.10</td>
<td>±0.124***</td>
</tr>
<tr>
<td>Mean</td>
<td>0.11</td>
<td>0.12</td>
<td>0.16</td>
<td>0.11</td>
<td>0.12</td>
<td>±0.022**</td>
<td>±0.124***</td>
</tr>
</tbody>
</table>

### c) Potassium

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>Rate 1</th>
<th>Rate 2</th>
<th>K only</th>
<th>Mg only</th>
<th>Mean</th>
<th>Std Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circle</td>
<td>1.25</td>
<td>1.50</td>
<td>1.65</td>
<td>1.35</td>
<td>1.19</td>
<td>1.39</td>
<td>±0.039***</td>
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<tr>
<td>Path</td>
<td>0.87</td>
<td>1.30</td>
<td>1.44</td>
<td>1.30</td>
<td>0.83</td>
<td>1.14</td>
<td>±0.124***</td>
</tr>
<tr>
<td>Frd. stack</td>
<td>1.21</td>
<td>1.35</td>
<td>1.32</td>
<td>1.31</td>
<td>1.22</td>
<td>1.28</td>
<td>±0.088**</td>
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<tr>
<td>Mean</td>
<td>1.11</td>
<td>1.39</td>
<td>1.47</td>
<td>1.32</td>
<td>1.08</td>
<td>±0.088**</td>
<td>±0.124***</td>
</tr>
</tbody>
</table>

169
d) Magnesium

<table>
<thead>
<tr>
<th></th>
<th>Shoot Magnesium %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control</td>
</tr>
<tr>
<td>Circle</td>
<td>0.31</td>
</tr>
<tr>
<td>Path</td>
<td>0.24</td>
</tr>
<tr>
<td>Frd. stack</td>
<td>0.20</td>
</tr>
<tr>
<td>Mean</td>
<td>0.25</td>
</tr>
</tbody>
</table>

e) Calcium

<table>
<thead>
<tr>
<th></th>
<th>Shoot Ca concentration %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control</td>
</tr>
<tr>
<td>Circle</td>
<td>1.67</td>
</tr>
<tr>
<td>Path</td>
<td>3.25</td>
</tr>
<tr>
<td>Frd. stack</td>
<td>2.63</td>
</tr>
<tr>
<td>Mean</td>
<td>2.52</td>
</tr>
</tbody>
</table>
7.4 Discussion

In the pot experiments, the total amount of biomass was small in all treatments due to the short duration of the experiment. Differences in dry matter production and total nutrient uptake would probably have been larger if the experiment had been continued for an additional month. However, large differences found in shoot nutrient concentration and total uptake of *P. phaseoloides* were closely related to the differences in soil nutrient content discussed in Chapter 5. In plants grown in soil from the
unfertilized and un-mulched path zone the amount of dry matter produced by *P. phaseoloides* was small compared with plants grown in soil from the mulched frond stack and fertilized circle zones where dry matter production was similar.

Compared with the "critical nutrient concentrations" reported by Shorrocks (1964), the shoot concentration of N was deficient in plants grown in the circle and path zones, but not in the frond stack (Table 7.4). *P. phaseoloides* was expected to nodulate in the pot experiments and thus no N limitation was anticipated. Shoot P concentration was small compared with the critical concentration in all shoot samples. Shoot K concentration was smaller than the critical value in all plants except those grown in soil from the circle zone when soil exchangeable K, Mg, and Ca was amended at *Rate 1* and *Rate 2*. Shoot Mg concentration was deficient in all shoot samples except in plants grown in soil from the circle when the amount of exchangeable Mg was increased with the *Mg only* addition.

**Table 7.4** Comparison of shoot nutrient concentrations in *P. phaseoloides* grown in unamended soil from the three zones (0-20 cm depth) compared with "critical" concentrations (after Shorrocks, 1964).

<table>
<thead>
<tr>
<th>Shoot nutrient content</th>
<th>Nutrient concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N %</td>
</tr>
<tr>
<td>Healthy</td>
<td>≥3.5</td>
</tr>
<tr>
<td>Moderate deficiency</td>
<td></td>
</tr>
<tr>
<td>Severe deficiency</td>
<td></td>
</tr>
<tr>
<td>Circle soil (0-20 cm depth)</td>
<td>1.8</td>
</tr>
<tr>
<td>Path soil (0-20 cm depth)</td>
<td>2.3</td>
</tr>
<tr>
<td>Frond stack soil (0-20 cm depth)</td>
<td>3.5</td>
</tr>
</tbody>
</table>
N-fixation has been reported to contribute 60-80% of plant N uptake in *P. phaseoloides* (Zaharah et al., 1986). Although soil was inoculated with *Bradyrhizobium*, no nodules were found on the *P. phaseoloides* plants grown in the pot experiments. A large concentration of nitrate in the soil may inhibit nodulation, but this was unlikely to have inhibited nodulation in the pot experiments since the shoot N concentration in all the plants grown in pots was small compared to the shoot concentration reported for healthy *P. phaseoloides* leaves reported by Shorrocks (1964). Shoot N concentration and uptake in plants grown in the experiments reported here may therefore provide an indication of the availability of soil N for plant uptake.

Large amounts of fertilizer N were applied to the soil in palm circles (Table 4.1), but the residual effect of fertilizer N on shoot N concentration and uptake in *P. phaseoloides* was small by comparison with plants grown in soil from the frond stack soil where the larger shoot N concentration total uptake may be explained by the mineralization of pruned frond residues when soil was re-wetted at the start of the experiment. A smaller amount of total soil N was found in soil from the circle and path compared with the frond stack (Figure 5.12b).

The comparatively slow rate of organic matter mineralization in Andisols was explained by the effect of allophane which protects soil organic matter from degradation, although this protective effect was not considered to extend to added residues which were found to breakdown at a rate similar to non-volcanic soils (Broadbent *et al*., 1964). Thus, in soil from the frond stack, a pool of readily decomposable organic matter exists which provided *P. phaseoloides* grown in pots with a larger supply of nitrogen compared with soil from the path and frond stack, where shoot N concentration and total N uptake was smaller. There was no difference in shoot N concentration or total shoot N uptake between plants grown in soil from beneath the circle and soil from the path zone and this is further
evidence for the absence of residual fertilizer N in soil from beneath the circle.

*P. phaseoloides* is tolerant of low soil pH and has been successfully established without liming in oil palm plantations planted on very acid soils. However, growth of *P. phaseoloides* was reported to respond to fertilizer P (Watson, 1989), and the application 60-120 kg ha$^{-1}$ in four instalments in the first year of cover crop establishment was recommended by Hartley (1977).

The P sorption isotherms presented in Chapter 5 showed a marked reduction in P sorption capacity in the soil from the frond stack compared with soil from the path and circle zones (Figure 5.11). There was no significant difference between the soil zones in the amount of available P in soil from the 0-20 cm depth, but in the 20-40 cm depth, available P concentration was smaller in the path zone compared with the circle and stack zones. In soil from the 0-20 cm depth, total and organic P concentration was larger in the circle soil compared with the frond stack and path soil zones (Figure 5.10).

The P added to all treatments (20 mg P g$^{-1}$ soil) was larger than the standard P requirement of 1760, 1690, 1290 mg kg$^{-1}$ respectively in the circle, path and frond stack, and the objective was to remove P as a factor limiting plant growth. However, large differences in P uptake were found between the zones. Total P uptake increased in the order path<frond stack<circle in plants grown in soil from the 0-20 cm depth.

The preparation of soil for pot experiments disturbed soil structure and caused the break up of soil aggregates which may have increased the surface area of soil particles exposed to the soil solution. The release of residual P fertilizer from adsorption sites may therefore account for the larger amount of P taken up by *P. phaseoloides* grown in soil from the 0-20 cm depth in the circle soil compared with plants grown in soil from the same
depth in the path and frond stack soil zones. The larger total P uptake found in plants grown in soil from the 0-20 cm depth in the frond stack compared with the path may be explained by the increased supply of P in the frond stack soil due to the mineralization of pruned frond residues and the smaller amount of added P adsorbed by the soil. In soil from the 0-20 cm depth, the smallest total P uptake occurred in soil from the path where the soil was not amended with either fertilizer or pruned fronds in the field.

The large differences between the three soil zones in total P uptake by *P. phaseoloides* in the 0-20 cm soil depth contrast with P uptake in soil from the 20-40 cm depth where no difference in total P uptake was found between the soil zones was found in spite of significant differences between the soil zones in the amount of available P in the soil.

The concentration of exchangeable K was smaller in the soil from beneath the path compared with soil from beneath the frond stack and circle zones (Figure 5.9a) and shoot K concentration and total K uptake was smaller in plants grown in soil from the path compared with the circle and frond stack zones (Figure 7.2c). Caution must be exercised when comparing nutrient uptake and soil nutrient concentration since in each soil zone the availability of soil K was influenced not only by the amount of exchangeable K but also the balance between the concentration of K and other cations and the relationship between exchangeable K concentration and total K uptake may have been masked by differences between the three zones in the supply of N and P. However, there was a close relationship between K uptake and the amount of exchangeable K in the soil (Figure 7.4).
The results of both the pot experiment and soil analysis suggest that the amount of K available for palm uptake was smaller in the path soil compared with the frond stack and circle soils. However, differences in both soil exchangeable K and total K uptake by *P. phaseoloides* between plants grown in soil from the circle and frond stack were small.

Total Mg uptake was greatest in plants grown in soil from the circle zone where the concentration of exchangeable Mg was larger than the soil in the path zone. Total Mg uptake was similar in plants grown in soil from the path and frond stack zones even though the concentration of exchangeable Mg was larger in soil from the frond stack compared with the path. Large applications of Ca may induce Mg deficiency in crop plants (Marschner, 1986). The amount of exchangeable Ca was greatest in soil from the frond stack where antagonism between Ca and Mg may have reduced total Mg uptake. The addition of Mg only had no effect on shoot K concentration in plants grown in soil from the three zones, but the concentration of shoot Mg and total Mg uptake was increased with the K only treatment in plants grown in soil from beneath the frond stack which suggests that plant Mg uptake was limited by the amount of available K in...
the soil in the frond stack zone. Total Ca uptake increased with increasing exchangeable Ca concentration in the soil (Figure 7.5).

![Figure 7.5 Relationship between soil exchangeable Ca and total Ca uptake by *P. phaseoloides* grown in soil from two depths in the circle, path and frond stack.](image)

The response to the amendment of soil exchangeable K, Ca, and Mg in terms of nutrient uptake by *P. phaseoloides* was different in the three zones which suggests that plants grown in each soil zone had different fertilizer requirements. Plant uptake of N, K, and Mg was not increased by any of the nutrient treatments in plants grown in soil from the circle zone, but Ca uptake was increased when the amount of exchangeable Ca, Mg and K was increased at *Rate 1* and *Rate 2*. The response was probably due to the added Ca since there was no increase in Ca uptake when K and Mg were supplied alone, and the result is consistent with the small amount of exchangeable Ca found in the 0-20 cm depth in the circle soil.

In plants grown in the 0-20 cm depth from the path zone, N uptake was increased by the addition of either K or Mg. K uptake was increased when Ca, Mg and K were added at *Rate 1*, but the addition of K alone resulted in a similar response. There was a greater increase in Mg uptake with the *Mg only* treatment compared with *Rate 1* where Ca, Mg and K were
added together which indicated a large response to the amendment of soil Mg.

7.5 Conclusions

The pot experiments showed that dry matter production and the total uptake of P and K was smaller in plants grown in soil from the path zone compared with the circle and frond stack zones. Whilst dry matter production was similar in plants grown in soil from the frond stack and circle zones, there were large differences in shoot nutrient concentration and total uptake.

The larger shoot N concentration and total N uptake in plants grown in soil from the frond stack compared with the circle and path zones was consistent with the larger concentration of total N found in the soil from the frond stack (Figure 5.12b). The residual effect of a smaller amount of N supplied to the soil in pruned fronds appeared to be larger than that from a similar amount of N applied to the circle soil in urea (see Table 4.9).

Total P uptake was larger in plants grown in soil from the circle zone, where the amount of P applied to the soil was similar to the rate of P applied in pruned frond residues to the soil in the frond stack (Table 4.9), and the concentration of total P was larger than the other zones (Figure 5.10a). The larger uptake of P by *P. phaseoloides* grown in soil from the frond stack compared to the path zone was probably due to the addition of P in pruned frond residues and the reduced P sorption in soil in the frond stack zone. The comparative immobility of P in the soil was underlined by the small differences between the zones in shoot P concentration and total P uptake in plants grown in soil from the 20-40 cm depth.

The comparatively small amount of K taken up by plants grown in soil from the path zone, and the increased uptake of K when soil was amended with K showed that the concentration of exchangeable K in the soil of 0.054
cmol(+) kg\(^{-1}\) (Figure 5.9a) was insufficient for normal plant growth. Whilst the amount of exchangeable K in the circle soil was larger than the amount in the frond stack (Table 5.9a), total K uptake and the response to the addition of K were similar in plants grown in soil from the frond stack and circle zones.

Although soil exchangeable Mg was smaller in soil from the path compared with soil from the frond stack (Figure 5.9c), total Mg uptake was similar (Figure 7.2h). This may be explained by the very large concentration of Ca in soil from the frond stack zone (Figure 5.9d) which may have suppressed Mg uptake, since Mg uptake was increased when the amount of exchangeable Mg (and the ratio of exchangeable Mg to Ca) was increased.

The application of mineral fertilizer and mulch in spatially discrete zones resulted in significant differences between the soil zones both in plant growth and response to nutrient amendment. The results of the pot experiment are in broad agreement with the results of soil chemical analysis and help to explain the comparatively small amount of fine feeder roots found in the path soil zone and the similar amounts of roots found in the circle and frond stack zones (Figure 6.1b).
Chapter 8

GENERAL DISCUSSION

8.1 Nutrient removal, immobilization and cycling in the Ophir project

The research detailed in this thesis has shown that in a well organized and intensively managed smallholder oil palm project in West Sumatra, the large yields of fruit bunches maintained over ten years resulted in the removal of large quantities of all nutrients, but particularly K (Chapters 2 and 4). Due to the absence of contractual arrangements between the farmers and the state-owned nucleus estate in the Ophir project, and the lack of facilities at the oil palm mill, the great potential for recycling nutrients contained in empty fruit bunches has been foregone. Empty bunches could be transported in trucks which at present return unladen to the field after delivering fresh fruit bunches to the processing mill. Thus, whilst additional costs would be incurred to spread empty bunches in the field, no additional transport equipment would be required. With clean air legislation in prospect in Indonesia, there may soon be legal as well as economic and ecological reasons for the recycling of empty bunches to farmers' fields which would allow reductions in the amounts of all mineral fertilizers but particularly KCl required. The return of all fruit bunches would reduce the requirement for KCl by nearly 40 %, and result in a large saving of foreign exchange for the Indonesian government by reducing the requirement for imported potash by up to 500,000 t yr\(^{-1}\) when the area planted to oil palm reaches 2.5 M ha by the year 2000.

The removal of nutrients contained in fruit bunches was roughly balanced by the addition of fertilizer for N, P, K but not for Mg (Figure 8.1,
8.2, 8.3), and the balance between the removal and addition of Ca depended on the type of Mg and P fertilizers used due to differences in the amount of Ca they contained (Figure 4.1). Since the removal of government subsidies on TSP, farmers have reverted to using rock phosphate, imported from Christmas Island as the source of P fertilizer, and because Mg deficiency has now been corrected following the application of kieserite, part of future maintenance Mg requirements could be met with locally mined dolomite instead of imported kieserite. Thus, the present net removal of Ca may in future be corrected.

The amounts of nutrients immobilized annually in palm trunks were small (Figure 8.1, 8.2, 8.3), but the amount of nutrients contained in palm trunks when the field is replanted after 20 - 25 years production will be large at about 400 kg N, 40 kg P, 240 kg K, 100 kg Mg, and 200 kg Ca ha\(^{-1}\). Palm trunks are aligned along the former planting line and decompose quickly over the following 2 - 3 years resulting in the amelioration of soil properties in the avenues between but not within the lines of newly planted palms.

By contrast, the amounts of nutrients cycled in the 22 or so fronds removed from each palm during harvesting was large, and the 13.6 t ha\(^{-1}\) dry matter contained in pruned fronds resulted in an exceptionally large application rate of 115 t dry matter ha\(^{-1}\) over the area occupied by the frond stack. The amounts of P, K, and Mg returned to soil in the frond stack zone is shown in Figure 8.1, 8.2 and 8.3 respectively.
Figure 8.1 Phosphorus addition, uptake, removal and cycling in oil palms. Δ values represent annual changes in amounts. Other values are amounts of available P (Bray II) in soil in the circle, path and frond stack zones converted for bulk density or the amount of P in the frond stack. Quantities are proportionately represented by area in the figure. All values are in kg ha⁻¹.
### Table: External and Within field potassium budget

<table>
<thead>
<tr>
<th>External</th>
<th>Within field</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch wastes</td>
<td>Bunches</td>
</tr>
<tr>
<td>Δ55 kg</td>
<td>Δ115 kg</td>
</tr>
<tr>
<td>Δ60 kg</td>
<td>Δ12 kg</td>
</tr>
<tr>
<td>Empty bunches</td>
<td>Empty bunches</td>
</tr>
<tr>
<td>Fertilizer</td>
<td>Fertilizer</td>
</tr>
<tr>
<td>Δ164 kg</td>
<td>Δ274 kg</td>
</tr>
</tbody>
</table>

### Figure 8.2 Potassium addition, uptake, removal and cycling in oil palms.

Δ values represent annual changes in amounts. Other values are amounts of exchangeable K in soil in the circle, path and frond stack zones converted for bulk density or amount of K in the frond stack. Quantities are proportionately represented by area in the figure. All values are in kg ha⁻¹.
**Figure 8.3**. Magnesium addition, uptake, removal and cycling in oil palms. Δ values represent annual changes in amounts. Other values are amounts of exchangeable Mg in soil in the circle, path and frond stack zones converted for bulk density or the amount of Mg in the frond stack. Quantities are proportionately represented by area in the figure. All values are in kg ha\(^{-1}\).
Chew and Pushparajah (1995) showed that the soil under oil palm in Malaysia is the most heavily fertilized in the tropics, but application rates expressed as kg ha\(^{-1}\) tend to underestimate the localized effect of fertilizer on soil since only 20 % of the soil surface, located in the weeded palm circle, is affected. This research has shown that the effective application rate of N, P, K, and Mg contained in pruned fronds to soil in the frond stack was similar to that in fertilized palm circles.

8.2 Changes to soil physical and chemical properties in the circle, path and frond stack zones

Different nutrient treatments applied to the soil in the three soil zones over a ten year period had resulted in large differences in soil physical and chemical properties between soil in the frond stack, circle and path zones. These differences must be considered in terms of the net effect of nutrient addition in crop residues and fertilizer, removal by the crop, and losses in leaching and surface run-off.

Differences in the amount of nutrients contained in soil the three zones were large enough to result in significant differences in the growth and nutrient uptake of *Pueraria phaseoloides* grown in pot experiments (Section 7.4). Exchangeable Ca concentration was increased in the frond stack soil and reduced in the circle soil where Ca had been leached. The P sorption capacity was reduced in the frond stack soil due to the effect of added pruned fronds, and the amount of exchangeable K in soil in the path was small by comparison with the amount contained in the frond stack and circle and was almost certainly insufficient to sustain large yields of fruit bunches (Section 5.5.3). Differences in soil total N content were small but highly significant and the larger total N content in soil from the frond stack resulted in a larger total uptake of N by un-nodulated *P. phaseoloides*
plants grown in pot experiments compared with plants grown in the circle and path soils.

In tropical soils with small and variable charge, a reduction in CEC results in a decrease in the soil's potential to retain cations against leaching. The application of urea, KCl and kieserite at large effective rates in palm circles resulted in lower soil pH, decreased CEC, and the leaching of soil exchangeable Ca, whilst in the frond stack zone the soil CEC was increased, particularly at the 20-40 cm depth, and soil exchangeable Ca increased due to the application of pruned fronds.

Soil physical properties were also shown to have been modified by the management system. The soil in the path has become compacted due to the traffic of laden wheelbarrows. The water infiltration rate of soil in the frond stack was maintained and possibly increased due to the addition of large amounts of organic matter, whilst in the circle and path zones, water infiltration rates were slower compared with untreated soil.

8.3 The effect of differences in root distribution on nutrient capture in the three soil zones

A comparison of the root distribution in the three soil zones showed that whilst the rate of decrease of root length density with increased soil depth was similar in all three soil zones, root length density, particularly of tertiary and quaternary roots was found to be smaller in the path zone compared to the frond stack and circle zones (Chapter 6). The proportion of the total length of tertiary and quaternary roots contained in the circle, path and frond stack zones was 34, 48, and 18 % respectively whilst the three zones occupy respectively 20, 68, and 12 % of the soil surface (Figure 1.2). The
8.4 Alternative strategies for the management of fertilizers and pruned fronds

Past experiments which compared the effect of fertilizer placement in palm circles, broadcast in the palm inter-rows, or applied over the frond stack on fruit bunch production have shown conflicting and often inconclusive results (Foster and Dolmat, 1986; Teoh and Chew, 1985; Yeow et al., 1982; Zaharah et al., 1989) and this may be explained partly by differences in root length density which had probably developed within the soil volume before the experiments were carried out. However, experiments conducted in Malaysian oil palm estates have shown increased response to applied nutrients when fertilizers and pruned fronds were broadcast over the palm inter-row space compared with the application of fertilizer and pruned fronds in spatially separate zones (Chan et al., 1993). The results presented here provide a framework for understanding these results and predicting future, more appropriate fertilizer management strategies.

In the Ophir project, the farmers' organisation provides the necessary framework to test alternative methods for the placement of fertilizer and pruned fronds, but farmers are unlikely to adopt several changes to management practice introduced simultaneously. With these opportunities and constraints in mind, the following alternative management practices are proposed for evaluation in the smallholder project.

In a step-wise approach to the modification of nutrient management, frond placement should first be altered in one of two ways. The simplest system involves alternating the position of the harvesting path and frond stack so that the degradative effect of traffic on soil physical properties is
periodically ameliorated by the addition of pruned fronds. A small investment in labour of perhaps 3 - 4 man days ha\(^{-1}\) would be required to re-arrange pruned fronds to allow the passage of wheel barrows. In this way, costly soil rehabilitation works found necessary in other plantations to restore soil structure in harvesting paths (e.g. Caliman et al., 1990a) might be avoided.

Alternatively, pruned fronds should be spread over the entire inter-row space excluding palm circles and the harvesting path and thus the ameliorative effect of pruned fronds would be extended from 12 % to 75 % of the soil surface (see Figure 8.4). This would reduce the effective application rate of nutrients contained in pruned fronds to about 170 kg N, 13 kg P, 195 kg K, 20 kg Mg, and 154 kg Ca ha\(^{-1}\). In the following and subsequent years it is proposed that fertilizers should be broadcast over the entire soil area.
Small plots are not practical for the implementation of oil palm experiments due to problems of nutrient poaching between treatments. Yield and leaf analysis is at present carried out for each 50 ha farmer group, and therefore the alternative nutrient management system could be compared using farmers' fields as treatment plots. In addition to the measurement of yield (t ha\(^{-1}\), bunch palm\(^{-1}\), kg bunch\(^{-1}\)) and leaf nutrient concentrations, which are routinely carried out in each field in the project, measurements of vegetative growth (leaf production, leaf dry weight) and root length density could be used to compare the effect of the different treatments on palm growth.

Leaching tube experiments to compare the amount of N released from unamended soil and soil amended with pruned fronds would help to quantify the how much decomposable organic matter accumulates in the
soil under the frond stack, and litter bag studies would allow comparisons of the rate of nutrient release from petiole, rachis, and pinnae parts of palm fronds which vary in nutrient (and probably lignin) content.

Since the present strategy of fertilizer and pruned frond placement is widely practised in the industry, differences between the three zones could be measured in plantations where palms are established on less favourable soils, or subject to drought stress since, under such conditions, the ameliorative effect of organic residues on soil physical and chemical properties might be expected to be larger.

8.5 Conclusions

The following conclusions are made with respect to the five main nutrient management questions posed in Chapter 2.

1. The application of all fertilizers to 20 % of the soil surface in the palm circle surface increased the supply of nutrients to about 34 % of the total length of tertiary and quaternary roots. Nutrient supply was increased to 18 % of the total root length in soil the frond stack zone but the remaining 48 % of fine feeder roots relied on the supply of nutrients contained in unamended soil.

2. The ameliorative effect of pruned fronds on soil physical and chemical properties found in soil beneath the frond stack could be extended to 75 % of the soil surface and should be combined with fertilizer broadcast over the mulched avenues to take advantage of the interactions between mulch and fertilizer application on bunch yield reported by Chan et al., (1993).
3. The concentration of soil exchangeable K and Mg was increased by the application of fertilizer and pruned fronds applied respectively in soil beneath palm circles and frond stacks. Soil pH was decreased, and exchangeable Ca leached from soil in the circle zone, whilst the concentration of exchangeable Ca was increased in soil beneath the frond stack where the soil P sorption capacity was reduced by the addition of pruned fronds.

4. Experiments to measure the effect of proposed alternative strategies for pruned frond and mineral fertilizer placement on palm yield and vegetative growth could be implemented in farmers' fields in the Ophir project with little additional cost over the current management practice.

5. The degradation of soil physical and chemical properties in the path zone may result in reduced vegetative growth and increased time to maturity in palms planted in the path compared with the frond stack avenue. Alternating the position of harvesting paths and frond stacks is a possible strategy to avoid soil degradation in the harvesting path.

In the coming years I hope to be able to use these results to contribute to improved nutrient management in smallholder tree crop farming systems from my new base in Singapore.
References


Anon (1992) *Palm Oil Research Institute of Malaysia Annual Research Report.* PORIM.


Appendix 1. Root classification system used to separate primary, secondary, tertiary and quaternary roots from root samples

Primary roots

- 10 mm
- 6 mm

Secondary roots

- 4 mm
- 2 mm

Tertiary roots

- 1.2 mm
- 0.7 mm

Quaternary roots

<0.3 mm
## Appendix 2. Field record sheet for Kelompok 2, NESP Ophir

### Form 2

<table>
<thead>
<tr>
<th>PTP VI Ophir</th>
<th>Afd PL-I</th>
<th>Block 2</th>
<th>Immerate perd.: 35</th>
<th>Land Class : 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plot size : 48.0 ha</td>
<td>Altitude : 40 m</td>
<td>First harvest: 01.01.85</td>
<td>Previous crop: Ladang</td>
<td></td>
</tr>
<tr>
<td>Tree density: 126 tree/ha</td>
<td>Date planted: 01.03.82</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil type : Hapludand</td>
<td>Topography : Datar</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### PRODUCTION

<table>
<thead>
<tr>
<th>Year t/ha kg/t t/p</th>
<th>LEAF ANALYSIS</th>
<th>----ppm----</th>
<th>TLB - % of TLB- Crit</th>
<th>----FERTILIZER DOSES (kg/palm/year)----</th>
<th>gr</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N %</td>
<td>P %</td>
<td>K %</td>
<td>Mg %</td>
<td>Ca %</td>
</tr>
<tr>
<td>1985 11.9 5.2 18</td>
<td>2.58</td>
<td>0.183</td>
<td>0.96</td>
<td>0.24</td>
<td>0.90</td>
</tr>
<tr>
<td>1986 29.0 9.5 24</td>
<td>2.72</td>
<td>0.176</td>
<td>0.82</td>
<td>0.19</td>
<td>0.46</td>
</tr>
<tr>
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<td>2.66</td>
<td>0.174</td>
<td>0.78</td>
<td>0.16</td>
<td>0.72</td>
</tr>
<tr>
<td>1988 27.6 15.7 14</td>
<td>2.27</td>
<td>0.180</td>
<td>0.93</td>
<td>0.17</td>
<td>0.72</td>
</tr>
<tr>
<td>1989 28.7 19.2 12</td>
<td>2.59</td>
<td>0.154</td>
<td>1.07</td>
<td>0.14</td>
<td>0.65</td>
</tr>
<tr>
<td>1990 27.6 22.4 10</td>
<td>2.60</td>
<td>0.176</td>
<td>1.10</td>
<td>0.18</td>
<td>0.72</td>
</tr>
<tr>
<td>1991 27.9 24.5 9</td>
<td>2.55</td>
<td>0.162</td>
<td>0.94</td>
<td>0.21</td>
<td>0.70</td>
</tr>
<tr>
<td>1992 30.5 25.4 10</td>
<td>2.32</td>
<td>0.150</td>
<td>0.72</td>
<td>0.14</td>
<td>0.53</td>
</tr>
<tr>
<td>1993 31.0 26.5 9</td>
<td>2.52</td>
<td>0.162</td>
<td>0.70</td>
<td>0.14</td>
<td>0.46</td>
</tr>
<tr>
<td>1994 28.2 26.9 8</td>
<td>2.46</td>
<td>0.149</td>
<td>0.86</td>
<td>0.16</td>
<td>0.66</td>
</tr>
</tbody>
</table>

### Leaf nutrient levels:

- Optimum leaf levels:
- TLB = Total Leaf Bases
- Crit P = Critical Level

<table>
<thead>
<tr>
<th>t/ha kg/b b/p</th>
<th>Leaf nutrient levels:</th>
<th>Optimum leaf levels:</th>
<th>TLB = Total Leaf Bases</th>
<th>Crit P = Critical Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tot: 269.6</td>
<td>N %</td>
<td>P %</td>
<td>K %</td>
<td>Mg %</td>
</tr>
<tr>
<td>Max: 31.0 26.9 24</td>
<td>2.72</td>
<td>0.183</td>
<td>1.10</td>
<td>0.24</td>
</tr>
<tr>
<td>Min: 11.9 5.2 8</td>
<td>2.27</td>
<td>0.149</td>
<td>0.70</td>
<td>0.14</td>
</tr>
<tr>
<td>Ave: 27.0 18.8 13</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Report date: 11.03.96