STUDY OF NITROGEN LOSS PATHWAYS IN OIL PALM (*Elaeis guineensis* Jacq.) GROWING AGRO-ECOSYSTEMS ON VOLCANIC ASH SOILS IN PAPUA NEW GUINEA

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Abstract

Oil palm is the largest national crop produced in Papua New Guinea. It is grown on over 80,000 ha of young volcanic soils in five Provinces, employs over 12,000 workers and uses >12,000 tonnes of fertiliser to offset nitrogen deficiency which is the most limiting factor to production. Oil palms strip out 160 – 200 kg N ha^{-1} yr^{-1} from the soil. Nitrogen fertilisers account for 60-70 % of all variable production costs but 40-60 % of applied fertiliser cannot be accounted for. Few studies have investigated the amounts of nitrogen lost via leaching, denitrification, volatilisation or as surface runoff in tropical soils and none have been done in Papua New Guinea. Oil palm soils typically have extremely high infiltrabilities (80-8,500 mm hr^{-1}) and receive high annual rainfall which throughfall makes spatially non-uniform.

The objective of this study was to assess and quantify nitrogen losses and suggest strategies that might assist in reducing them and their impact on the environment. The modest facilities available at the two research sites, West New Britain (Dami) and Oro (Sangara) Provinces, meant that no analytical work could be done on-site, so simple but appropriate methods were used to evaluate losses, with samples collected, preserved and sent off-shore for analysis. Large four-palm plots were used to evaluate runoff; a gas trap was used to collect evolved nitrous oxide, and lysimeters, suction cups and finally an *in situ* destructive soil sampling procedure were all used to assess leaching losses and the rate of nitrification of ammonium fertiliser.

Results suggest that under the extreme total annual rainfall at Dami (3,500-4,000 mm) and to a lesser extent at Sangara (2,500-3,000 mm), leaching is the dominant loss pathway, with the rate of loss depending, to some extent, on the rate of nitrate formation and the retentivity of the soil for ammonium, but mainly on the rate at which drainage water is generated.

A leaching model was developed that indicated that the average residence time of nitrogen fertiliser in the root zone (0-50 cm) varied from 21 days in February, at Dami, to 190 days in May, at Sangara.

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Finally, I dedicate this thesis to the Papua New Guinea Oil Palm Industry.

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List of abbreviations and symbols

AMC	Ammonium chloride
AMN	Ammonium nitrate
Br^-	Bromide ion
BZ	Between zone
CDE	Convection dispersion equation model
Cl^-	Chloride ion
CLT	Convective lognormal transfer function model
DAP	Diammonium phosphate
FP	Frond pile
FT	Frond tip
HP	Harvest path
K	Kina (PNG currency, 1 kina = NZ$0.47
LAI	Leaf area index
N	Nitrogen
NBPOL	New Britain Palm Oil Limited
NH_4^+-N	Ammonium nitrogen
NI	New Ireland
NO_3^--N	Nitrate nitrogen
NZ	New Zealand
OPIC	Oil Palm Industry Corporation
OPRS	Oil Palm Research Station (NBPOL)
pdf	Probability density function
PNG	Papua New Guinea
PNG OPRA	Papua New Guinea Oil Palm Research Association
SOA	Sulphate of ammonium
WC	Weeded circle
WFPS	Water-filled pore space
WNB	West New Britain

List of Symbols

Symbol	Description	Dimensions
a	Exponential decay constant	T^{-1}
C	Normalised ammonium N concentration	-
C	Capillary rise	L
C_o	Normalised concentration of ammonium N when $t = 0$	-
C_s	Solute concentration in soil solution	$M L^{-3}$
C_{tot}	Total solute concentration	$M L^{-3}$
C	Average solute concentration	$M L^{-3}$
D	Dispersion coefficient	$L^2 T^{-1}$
D	Surplus water	L
E	Evaporation	L
E_{ff}	Effective evaporation	L
E_r	Reference crop evaporation	$L T^{-1}$
f	Porosity	-
I	Added water or throughfall	L
I	Water input to the soil	L
I_c	Calibrated throughfall	L
I_m	Leaching water	L
I_r	Interception	L
J_w	Soil water flux	$L^3 L^{-2} T^{-1}$
M	Fertiliser applied onto soil surface	$M L^{-2}$
M_s	Mass of soil solid	M
M_w	Mass of water	M
n	Sunshine hours	T
ρ_b	Soil bulk density	$M L^{-3}$
ρ_s	Soil particle density	$M L^{-3}$
P	Precipitation	L
θ	Volumetric water content – theta	$L^3 L^{-3}$
θ_{FC}	Volumetric water content at field capacity	$L^3 L^{-3}$
θ_{PWP}	Volumetric water content at permanent wilting point	$L^3 L^{-3}$

Symbol	Description	Dimensions
θ_{SP}	Volumetric water content at stress point	$L^3\ L^{-3}$
q_s	Solute flux density (mass of solute carried across a unit cross-sectional area per unit time)	$M\ L^{-2}\ T^{-1}$
q_w	Darcy flux density (volume of water flowing across a unit cross sectional area per unit time)	$L^3\ L^{-2}\ T^{-1}$
R	Retardation factor	-
R	Surface runoff	L
S	Deep drainage	L
S_f	Stemflow	L
t	Time	T
$t_{1/2}$	Half life	T
T	Throughfall	L
μ	Mean	-
u_z	Wind speed at height z	$L\ T^{-1}$
V	Average speed of solute (non-adsorbed) down through a profile	$L\ T^{-1}$
V	Mean water velocity	$L\ T^{-1}$
V_t	Volume of soil	L^3
V_w	Volume of water	L^3
w	Gravimetric water content	$M\ M^{-1}$
W	Equivalent depth of soil water	L
W_n	Soil water storage in the root zone, relative to field capacity, on day n	L
W_R	Readily available water	L
W_T	Total plant available water	L
z	Soil depth	L
Z	Height above sea level	L
Z	Depth of soil in lysimeter	L
Z_m	Leaching depth	L

Chapter 1

General information

1.1 Background

Oil palm is Papua New Guinea's largest export crop and is emerging as the largest contributor to sustainable rural development (Orrell, pers comm., 2003). Currently there are 80,000 ha of oil palm plantations and smallholder blocks located within the tropical lowlands of Papua New Guinea (PNG). The industry directly employs over 12,000 Papua New Guineans and that makes it by far the country's largest private sector employer. Oil palm also supports over 11,000 smallholder families.

Nitrogen (N) deficiency is the single most important yield-limiting factor for oil palm production in PNG (PNGOPRA Annual Report, 2005). For both smallholder blocks and plantations, fertiliser inputs comprise 60 to 70 % of crop production costs. Most of the fertilisers used are nitrogenous, generally either sulphate of ammonia (SOA) or ammonium chloride (AMC). Smallholders tend to use solely N whilst >50 % of fertilisers used on plantations are nitrogenous. The use of N fertilisers on most of the oil palm soils in PNG is essential for increasing productivity and maintaining acceptable yields.

Long-term field trials conducted by PNGOPRA on different soil types and under different environmental conditions have shown variability in the patterns and magnitude of responses of oil palm to the application of N fertiliser. Reasons for these locality differences are not known but probably relate to the age of palms, soil organic matter contents, factors affecting N cycling and/or the efficiency of recovery of applied N fertiliser. However, to date, no studies have been carried out to identify the major N loss processes or the quantities of N that could be lost. Nor have there been any studies into management strategies that could be adopted to minimise losses and enhance the efficiency of use of these increasingly expensive imported fertilisers.

Most of the oil palm in PNG is grown on coarse-textured, free-draining soils that are formed on ash, alluvium or colluvium of recent volcanic origin. Characteristically these soils have high infiltration rates, high hydraulic conductivities and high erodibilities. However these same oil palm producing areas experience very high annual rainfalls with very high intensity events. This type of environment, whilst highly conducive to oil palm growth and productivity, can lead to significant losses of N from both native (soil) and added (fertiliser) sources. Losses are suspected to be high due to the combined effects of leaching, surface run-off and denitrification and could amount to >50 % of the amount of N fertiliser applied annually; a loss that would be of significant economic and environmental concern.

Based on the size of the oil palm industry and the magnitude of the N deficiency problem, this research addresses what is probably the PNG oil palm industry's most important plant nutrition problem.

The research for this thesis was part of a project funded by a grant from European Union (STABEX 4.22) to the Papua New Guinea Oil Palm Research Association (PNGOPRA) in collaboration with Massey University (NZ). All field experiments were done in PNG while all laboratory analyses and preliminary studies were done at Massey University. Funds were also provided by ACIAR to purchase soil water monitoring equipment (Sentek Diviner 2000®).

1.2 Objectives

This study aimed to provide fundamental information about the processes that cause losses of N, and suggest remedial steps that might be taken, to allow better use and recovery of N fertilisers under the various soil and climatic conditions encountered within the oil palm growing areas of PNG. Specific objectives were:

- To provide an overview of N fertiliser use on oil palm in PNG
- To characterise areas under the palms
- To develop a water balance for an oil palm system
- To determine the nitrification rates of N fertilisers in the oil palm soils
- To quantify and identify major N loss processes (leaching, runoff and denitrification)
- To develop a residence time model
- To suggest management strategies for minimising losses and improving the efficiency of use of N fertilisers on oil palm.

One expected outcome from this study was the development of a model that could be used to explore fertiliser management strategies to minimise N losses from any given oil palm system and to prioritise research initiatives without the need to conduct expensive trials to gain this insight.

1.3 Thesis outline

The research topic is broad covering soil biology, chemistry, physics, hydrology and general crop husbandry sciences. The basic structure of the thesis is shown in Schematic 1.1.

Schematic 1.1 Thesis outline

Chapter 2	General N use is discussed with current practices in PNG and other oil palm areas mostly from experience in Malaysia. The N balance is explored.
Chapter 3	Provides a description of the experimental sites, characterises the different management zones under palms and describes the main climatic factors at the two sites, Dami and Sangara.
Chapter 4	Examines rainfall and its redistribution by the oil palm canopy, evaporation, deep drainage and surface runoff and develops a water balance model for later use.
Chapter 5	*In situ* measurement of nitrification rates under oil palms systems.
Chapter 6	Field measurement of N_2O (denitrification).
Chapter 7	Measurement of N losses via surface runoff.
Chapter 8	An investigation of the leaching of N for different rainfall events and creation of simple models using information from Chapters 4 and 5. A residence time model is also developed to predict how long fertilisers remain within the oil palm root system.
Chapter 9	Summarises all the main findings from the various experiments and explores the use of the model developed in Chapter 8, to suggest practical management strategies for minimising leaching losses.

A published paper produced from this study is appended.

Nelson, P. N., Banabas, M., Scotter, D. R., and Webb, M. J. (2006). Using soil water depletion to measure spatial distribution of root activity in oil palm (*Elaeis guineensis* Jacq.) plantations. *Plant and Soil,* 286(1-2), 109 - 121

1.4 References

Orrell, I. (2003) Pers. Comm..

Papua New Guinea Oil Palm Research Association (PNGOPRA) Annual Report, 2005, Dami West New Britain Province, Papua New Guinea. p 290

Chapter 2

N requirements, balance and fertiliser use

N is a limiting nutrient to crop production but it is also a nutrient that is easily lost from the soil in a variety of ways and forms (Alexander, 1991). The management of fertiliser applications, and other agronomic practices in PNG oil palm plantations, contributes to the losses that are not only of agronomic importance but also of environmental concern. The management of fertiliser applications varies between different plantation companies, between plantations and between the smallholders. Actual fertiliser management practices have evolved over time from both research trials and experience within the oil palm industry, together with experience gained from other cropping systems.

2.1 Functions of N

N is a constituent of important organic compounds in plants including amino acids, proteins, nucleic acids, chlorophyll and growth regulators (Corley, 1976). Enzymes, which are proteins, play a major role in all biochemical processes in plants which in turn affect all physiological functions e.g. photosynthesis and production and distribution of carbohydrates to different plant parts (Goh and Hardter, 2003). Agronomically, N has four very important physiological functions (Below, 2002):

- Establishment of photosynthetic capacity – increasing the number and size of leaves
- Maintenance of photosynthetic capacity – duration of fronds remaining photosynthetically active
- Establishment of sink capacity – increase in the number of bunches and bunch sizes
- Maintenance of functional sinks throughout seed development

Because of the effects of N on the above-mentioned functions, growth and fresh fruit bunches (FFB) yield of oil palm are also affected. Corley and Mok (1972) found that N fertilisers increased leaf area index (LAI) and the net assimilation rates of palms which resulted in increased FFB yields.

Generally, an N deficient palm will have yellow leaves, stunted growth and low FFB yields (Goh and Hardter, 2003). N deficiency in palms can be due to N unavailability in soils, low OM, sandy nature of the soils, competition from weeds such as *Imperata* spp and *Mikania*, poorly-drained soils and transplanting shock in young newly planted palms. Visible N deficiency symptoms are common in many smallholder blocks in PNG as shown in Plate 2.1.

Plate 2.1 Palms in a smallholder block in the Popondetta Plains showing N-deficient (yellow) palms and well fertilised (green) palms

2.2 N requirement of oil palm

Of all the tropical tree crops, oil palm strips the most N out of the system via product removal (162 kg N ha^{-1} yr^{-1}) (Table 2.1). In terms of the removal of other nutrients, N is second only to that of K (217 kg N ha^{-1} yr^{-1}). Assuming an extraction ratio of 25 %, 2.5 tonnes of oil per ha is equivalent to 10 tonnes of FFB ha^{-1} yr^{-1} which is probably a typical yield for oil palms in Nigeria (Table 2.2). FFB yields in Malaysia and PNG, however are much higher than those in Africa and therefore there is an even higher demand for N than that suggested by Mengel and Kirkby (1987).

Table 2.1 Nutrient removal by plantation crop products

Crop	Yield (ha^{-1} yr^{-1})	Nutrient removed (kg ha^{-1} yr^{-1})				
		N	P	K	Mg	Ca
Oil palm	2.5 tonnes of oil	162	30	217	38	36
Sugar cane	88 tonnes of cane	45	25	121	-	-
Coconuts	1.4 tonnes of dry copra	62	17	56	6	12
Bananas	45 tonnes of fruit	78	22	224	-	-
Rubber	1.1 tonnes of dry rubber	7	1	4	-	-
Coffee	1 tonne of made coffee	38	8	50	-	-
Tea	1.3 tonnes of dried leaves	60	5	30	6	3

Source: Mengel and Kirkby (1987).

Tinker (1976) recognised three types of nutrient demand by oil palm; (a) nutrient removed from the oil palm system in FFB, (b) nutrient taken up by the palms and immobilised into plant tissues, and (c) nutrient released into the soil pool from pruned fronds, male inflorescences and other dead oil palm tissues. Demand types (a) and (b) (Table 2.2) represent long-term nutrient depletion from soil reserves while (a) + (b) + (c) represents the immediate rate of supply which the soil needs to provide. The three types of demand for Nigeria (a low yield environment) and Malaysia (a high yield environment) are contrasted in Table 2.2. N demand in PNG will be more like that for Malaysia due to similar growing conditions in the two countries. Differences in demand between PNG and Malaysia will most likely be due to differences in planting densities and other management factors. Planting densities in PNG are usually between 120 and 148 palms/ha. The total N demand for average mature palms in PNG, is likely to be in the range 1.2 – 1.5 kg N palm^{-1} yr^{-1}.

Table 2.2 N distribution (kg palm^{-1} yr^{-1}) in oil palm trees in Nigeria and Malaysia

Distribution component	**Nigeria**	**Malaysia**
Average FFB yield (t ha^{-1})	9.6	24
(a) Bunch removal (kg palm^{-1} yr^{-1})	0.20	0.49
(b) Immobilised in palms (kg palm^{-1} yr^{-1})	0.18	0.27
(c) Nutrient turnover in fronds, male inflorescence etc. (kg palm^{-1} yr^{-1})	0.63	0.53
Mean total nutrient uptake (kg palm^{-1} yr^{-1})	1.01	1.29
Total uptake for 148 palms ha^{-1} (in PNG)	149	191

Source: Tinker (1976).

2.3 N balance

For high FFB yields, soils have to be capable of providing at least 191 kg N ha^{-1} yr^{-1}. The N balance for oil palm comprises three parts; a) N circulating within the system, b) N input from outside the system and c), N leaving the system as illustrated in Figure 2.1. Each component of this N balance is discussed below.

2.3.1 N recycling within the system

From Table 2.2, 0.53 kg N palm^{-1} yr^{-1} is circulating in pruned fronds and male inflorescences. Therefore this amount of N that is turning over annually ranges from 64 kg to 78 kg N ha^{-1} yr^{-1} (mean = 71 kg N ha^{-1} yr^{-1}) for densities of 120 to 148 palms per ha. Kee and Chew (1997) reported that turnover from fronds within a Malaysian plantation was 82 kg N ha^{-1} yr^{-1}, which is close to the calculated mean value. Therefore if 156 - 191 kg N (for densities of 120 and 148 palms ha^{-1}) is the total required and 63-78 kg N is recycled to the soil, 92 – 113 kg (mean = 102 kg) has to be provided from other sources.

2.3.2 N input into oil palm

The major external N input into oil palm in PNG, and in most other oil palm growing countries, is as inorganic fertiliser. In PNG, fertiliser application rates normally range from 0.42 to 0.82 kg N palm^{-1} yr^{-1} (56-106 kg N ha^{-1} yr^{-1}, mean = 80 kg N ha^{-1} yr^{-1}) while in Malaysia, normal rates are even higher. According to Foster (2003), for Rengam soil series in Malaysia, optimum N rates range from 0.42 to 1.47 kg N palm^{-1} yr^{-1} for mature palms. However, rates are lower than 0.42 kg N palm^{-1} yr^{-1} for palms less than 3 years of age in both plantations and smallholder blocks in PNG. Plantations also spread empty fruit bunches (EFB), a mill waste, onto some of their blocks at a rate of 32 tonnes EFB ha^{-1} yr^{-1} fresh weight. EFB contain 0.65 – 0.94 % N (average = 0.8 %) and contribute on average about 13 kg N ha^{-1} yr^{-1}.

Another important input is from atmospheric N that is fixed into ammonium (NH_4^+-N) by both symbiotic and non-symbiotic soil microorganisms. The NH_4^+ is then changed into organic forms in plants and microorganisms. Agamuthu and Broughton (1985) conducted an experiment in Malaysia using a combination of various cover crops and found that about 150 kg N ha^{-1} yr^{-1} was biologically fixed over a period of 3 years during the immature establishment phase. The contribution from legume cover crops is probably useful during the immature phase while the oil palm canopies are open and maybe for a year or two after the canopy has closed. At maturity (7-8 years of age), the oil palm canopy is usually fully-closed and the cover crops are shaded out, hence contributions from the legume cover crops are probably not important until the replant. However if it is assumed that the average life span of a plantation is 18 years before replanting, and if N fixed by the legume cover crops during the first 3 years is spread throughout the life span of the plantation, then the N provided from N fixation will be about 25 kg N ha^{-1} yr^{-1} ((150 kg N ha^{-1} yr^{-1} x 3 years)/18 years).

In the soils, around 60 kg N ha^{-1} yr^{-1} is mineralised from the soil organic matter.

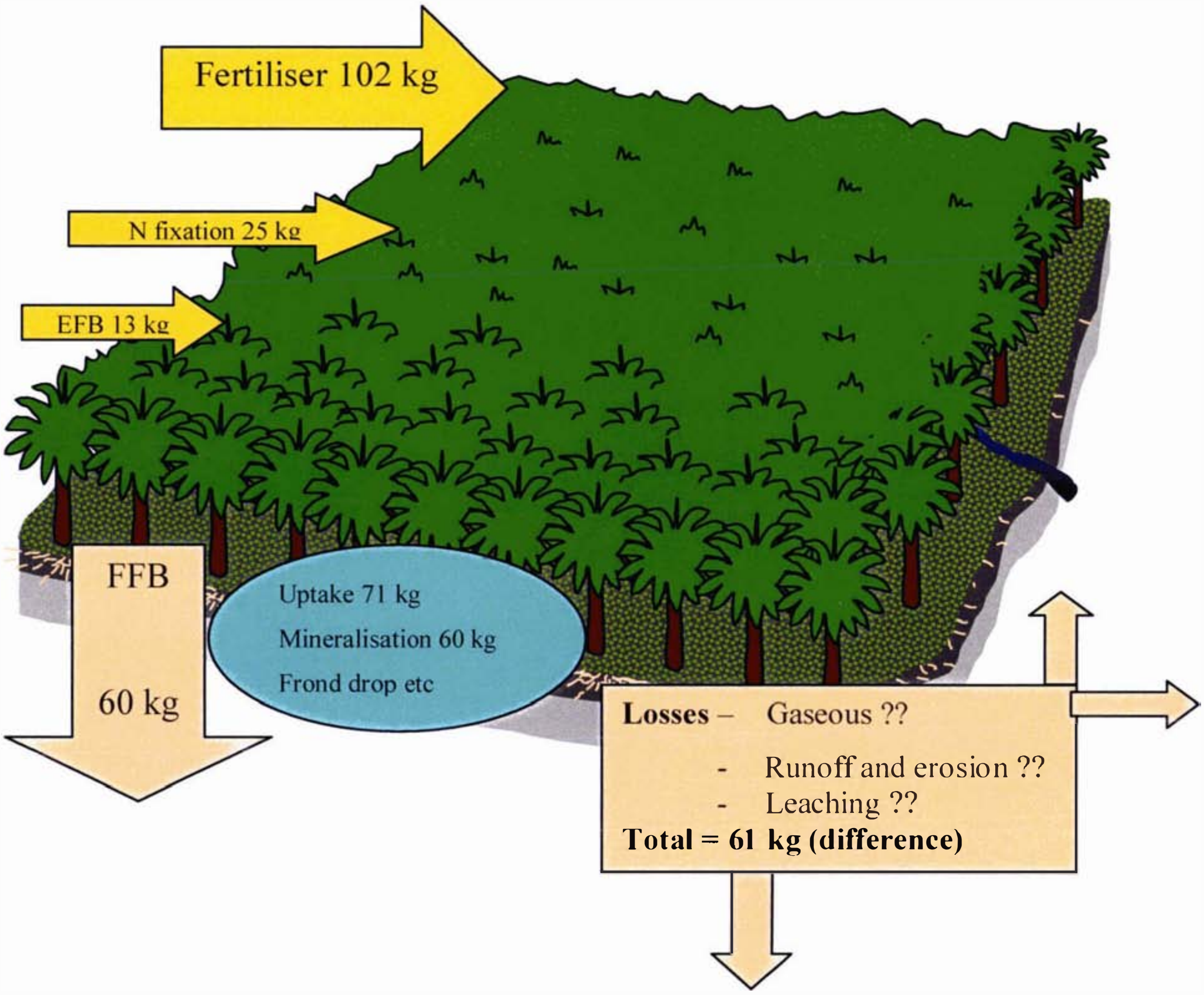

Figure 2.1 N balance in an oil palm system in PNG in kg ha^{-1} yr^{-1} (data from Tinker (1976), Agamuthu and Broughton (1985) and Kee and Chew (1997)

2.3.3 N output from oil palm system

Oil palm annual yield varies for different geographic and climatic conditions e.g. from 10 tonnes FFB ha^{-1} yr^{-1} in Nigeria to 24 tonnes FFB ha^{-1} yr^{-1} in Malaysia (Table 2.2). In PNG the average yield ranges from 15 tonnes in smallholders' blocks to 26 tonnes FFB ha^{-1} yr^{-1} in the plantations. However, the best areas in both plantations and smallholder blocks can produce up to 30 to 40 tonnes FFB ha^{-1} yr^{-1}.

From Table 2.2, 0.49 kg N palm^{-1} yr^{-1} is removed from the system in FFB. With a density of palms of 148 per ha and a yield of 24 tonnes FFB ha^{-1} yr^{-1}, this amounts to annual removal of 73 kg N ha^{-1}, or 3 kg N for every tonne of FFB removed from the field. So in PNG, for the smallholder blocks with an average FFB yield of 15 tonnes, 45 kg N ha^{-1} yr^{-1} will be removed while in a plantation with an average FFB yield of 26 tonnes ha^{-1}, 78 kg N ha^{-1} yr^{-1} will be removed in FFB. Taking an average of these two systems, about 60 kg N ha^{-1} yr^{-1} is removed with FFB but this figure can be higher (90 – 120 kg N ha^{-1} yr^{-1}) in areas where yields reach 30 to 40 tonnes FFB ha^{-1} yr^{-1}.

The difference between what goes into the system and what comes out is the unaccounted for N. This includes N that is lost in gaseous form via denitrification, or as soluble forms in surface runoff and leaching, or as particulate form in eroded sediments. The combined losses, being the difference between inputs and outputs, were estimated for three common scenarios in PNG assuming a constant 60 kg N ha^{-1} yr^{-1} being removed in FFB products as;

a) where N fertiliser and EFB are added to a field with N contributions from legume cover crops
   (100 + 13 + 25) – 60 = 78 kg N ha^{-1} yr^{-1}
b) where N fertiliser added to a field that has received N contributions from legume cover crops but no EFB added (this scenario represents many smallholder blocks and a large proportion of plantations)
   (100 + 25) – 60 = 65 kg N ha^{-1} yr^{-1}
c) where N fertiliser added but no N from legume cover crops and no EFB added.
   100 – 60 = 40 kg N ha^{-1} yr^{-1}

Therefore unaccounted-for losses range from 40 to 78 kg N ha^{-1} yr^{-1}.

This loss of N is of both economic and environmental concern. In monetary terms the loss is;

- equivalent to 3,200 – 6,240 tonnes of N over 80,000 ha of mature oil palms in PNG
- equivalent to 12,800 – 24,960 tonnes of AMC fertiliser (assuming 25% N content in AMC)
- equivalent to 25.3 – 49.4 million kina loss yr^{-1} assuming that 1 tonne of AMC costs 1,980 kina.

The amount lost in monetary terms is even larger if administrative and application costs are also taken into account.

In terms of the environmental consequences, Keeney (1982) listed the effects that N can have on the environment and on human health as shown in Table 2.3.

Table 2.3 Effects of N losses from soil on the environment

Effect	**Causative agents**
Stratosphere ozone depletion	Nitrous oxide from nitrification and denitrification.
Global warming	Nitrous oxide from nitrification and denitrification.
Methemoglobinemia in infants	Excess nitrate and NO_2^--N in water and food.
Eutrophication	Inorganic and organic N in surface water

Source: Keeney (1982).

Due to rapid N cycling, tropical soils are thought to be a major source of N gases (N_2O, NO and NO_2) which normally occur in trace amounts in the atmosphere (Mosier *et al.*, 2004). According to these authors, N_2O concentrations have increased from 275 ppbv in 1900 to about 317 ppbv at present, an increase of 0.7 ppbv per year. Nitrous oxide is about 200 times more potent in causing earth warming than carbon dioxide and it has been estimated that an increase of 0.2 – 0.3 % would contribute to about 5 % of the increase in greenhouse warming. This has important implications for changes in weather patterns on earth. The increase in N_2O also depletes the ozone layer which can result in more UV radiation reaching the earth's surface and possibly causing an increase in the incidence of skin cancer and other related health problems.

Leaching of nitrate from a soil can build up the nitrate concentration in the ground waters to levels that can cause water to become unsafe for drinking. When water of high nitrate concentration is consumed, nitrate changes to nitrite which can then oxidise the iron of the haemoglobin in the blood and affect the O_2 carrying capacity of red blood cells. Especially in babies, this can lead to methemoglobinanemia (blue baby syndrome) (Keeney, 1982). The critical limits set by the WHO and EEC are 10.2 and 11.3 mg L^{-1} of NO_3^--N, respectively (Owens, 1994).

Nitrate that ends up as runoff in waterways can cause excessive growth of water plants and lead to eutrophication. Pierzynski *et al.* (2005) (page 141) defined eutrophication as....“an increase in nutrient status of natural waters that causes accelerated growth of algae and water plants, depletion of dissolved oxygen, increased turbidity and general degradation of water quality”. The concentration of dissolved N that can cause eutrophication (0.5 – 1 mg N L^{-1}) is lower than the acceptable maximum concentration for drinking.

2.4 N fertiliser trials in PNG

Since the formation of PNGOPRA in 1980, a large number of N fertiliser trials have been established across the country in the main oil palm growing provinces. The trials had N alone as a treatment or in various rates and combinations with other nutrients such as P, K and Mg. The N rates ranged from 0 to 2.5 kg N $palm^{-1}$ yr^{-1}. The fertiliser types used in the trials included ammonium chloride (AMC), sulphate of ammonia (SOA), urea, diammonium phosphate (DAP) and ammonium nitrate (AMN). The different N rates used in the different trials reflect the different soil types in the different oil palm growing areas. Nitrogen rates for the initial trials were chosen on the basis of experience gained in other oil palm trials (mostly in Malaysia and Indonesia), however for subsequent trials, rates were determined from trials already in place. The trials were established to; a) determine the optimum N rate for the plantations and smallholder blocks, b) determine the optimum N rate in combination with other nutrients (mainly for plantations) and c) determine the best source and rate of N for any particular environment.

Significant and consistent responses to N fertiliser were found in Trials 305 and 306 in Oro Province (Banabas, 2003a, 2003b; Wilkie and Foster, 1990) and at Navo in WNB (PNGOPRA 2003 Annual Report) (Table 2.4). Fresh fruit bunch (FFB) yield responses ranged from 5 – 8 tonnes ha^{-1} yr^{-1}. Leaf N contents and LAI were also significantly increased by N fertilisers. In Hoskins, Kapiura and Bialla, there were no consistent responses to N fertilisers though there were occasional results of inconsistent responses in some years (PNGOPRA Annual Report 1990, 1991).

Responses to N fertilisers across the country vary and appear to reflect differences in soil C and N contents. In an early trial at Hoskins, Breure and Rosenquist (1977) found no response in FFB yields or leaf nutrient contents to N fertiliser applied as urea. Long-term fertiliser trials conducted by PNGOPRA on different soil types and under different environmental conditions in PNG have shown variable response patterns and magnitudes of response to N fertilisers. However, N still appears to be the major limiting nutrient to oil palm production in PNG.

Table 2.4 FFB yield, leaflet N content, and LAI responses to N fertilisers and some soil characteristics of selected trials in WNB and Oro Provinces

Province	Location	Trial	N rate (g N palm^{-1} yr^{-1})	FFB yield (t ha^{-1} yr^{-1})	Leaf N (% DM) #	LAI	Soil Properties		
							Depth (cm)	Total N (%)	C (%)
WNB	Navo	204	0	**14.4**	**1.92**		0 – 10	0.33	4.29
			780	**19.2**	**2.16**		10 – 55	0.16	2.73
			1560	**20.5 *****	**2.29*****				
WNB	Hargy	201	0	21.4	**2.24**		0 – 10	0.52	5.70
			630	20.4	**2.29**		10 – 20	0.44	4.32
			1260	20.9	**2.35*****		20 – 30	0.29	2.94
WNB	Kapiura	402	0	21.7	2.37		0 – 10	0.58	5.54
			780	22.0	2.36		10 – 20	0.27	2.38
			1560	22.2	2.36		20 – 30	0.11	0.89
WNB	Hoskins	107	0	25.4	**2.35**	**6.25**	0 – 10	0.38	3.73
			420	26.5	**2.45**	**6.54**	10 – 20	0.11	0.99
			840	26.2	**2.47*****	**6.51***	20 – 30	0.06	0.37
Oro	Popondetta	305	0	**18.5**	**1.82**	**5.45**	0 – 20	0.21	2.02
			420	**23.8**	**1.96**	**6.04**	40 – 60	0.06	0.54
			840	**26.3*****	**2.09*****	**6.06*****			
Oro	Popondetta	306	0	**16.1**	**1.86**	**5.59**	0 – 10	0.18	2.34
			630	**23.8**	**2.06**	**6.33**	10 – 20	0.12	1.39
			1260	**24.4*****	**2.18*****	**6.49*****	20 – 30	0.03	0.50

Source: PNGOPRA Annual Reports (1982-2005)
* = significance at $p < 0.05$
*** = significance at $p < 0.001$# = Frond 17

2.5 N fertiliser trials in other oil palm producing countries

Tampubolon *et al.* (1990) reviewed eight fertiliser trials in Indonesia, three of which were on volcanic soils. Urea was applied at three rates in factorial combination with P, K and Mg. The trials all showed significant and consistent increases in FFB yield (3 – 7 t ha^{-1} yr^{-1}) to N however responses only occurred 3-4 years after fertiliser addition.

In reviewing N response trials in Malaysia, Chew and Pushparajah (1995) found some FFB yield responses to N fertilisers, but again large responses were only seen in the presence of K, P and sometimes Mg fertilisers. Zakaria *et al.* (1989) summarised the results of 18 fertiliser trials conducted during 1983-89 in Peninsular Malaysia, Sabah and Sarawak, all in Malaysia. Three rates of N, 0.4, 0.8 and 1.2 kg N $palm^{-1}$ yr^{-1} were used and high rates of P, K and Mg fertilisers were applied to ensure that they were not limiting. Of these 18 trials, three did not show any responses to N while the rest showed responses. However the mean yield response was only three tonnes FFB ha^{-1} yr^{-1} and there was no effect on leaf N content. The results of trials in Malaysia suggest that N alone is probably not a major limiting nutrient but higher yields are obtained when N is combined with other nutrients, especially K.

Responses to N fertilisers in African oil palm growing countries are rare (Ollagnier and Ochs, 1981) with yields being more affected by soil erosion and competition from weeds.

2.6 N fertiliser use on oil palm in PNG

2.6.1 General

Of the fertiliser types used in PNG, on volcanic ash soils, 50 to 90 % for plantations, and almost 100 % for smallholder blocks, contain N (Table 2.5). However for non-volcanic soils, such as those at Poliamba in New Ireland Province, N fertilisers account for only 40 % of the fertiliser types used. These soils are formed from raised coral beds (Bleeker, 1987) which are deficient in K and so K fertilisers dominate the fertiliser mixes. Comparisons cannot be made with amounts or types of fertiliser used in the other agricultural industries in PNG, such as coffee, cocoa, tea and sugar, because comparable data are not available. But oil palm is a significant user of N fertiliser (>12,000 tonnes) each year.

The amount and type of fertilisers ordered by any single company or the Oil Palm Industry Corporation (OPIC), which is the smallholders' extension body, varies from year to year for the following reasons.

a) Increase in fertiliser rates from < 250 g N palm^{-1} yr^{-1} for immature palms (1-3 years old) to 750 -800 g N palm^{-1} yr^{-1} for mature palms (4+ years old)
b) Change in fertiliser application rates according to leaf monitoring to meet the optimum range of 2.3 – 2.5 % N
c) Increase in the total area of oil palm plantings such as the inclusion of mini estates i.e. the landowners, through the government, lease their land to the plantation companies to grow oil palm
d) Reduction in fertiliser applied to mature palms in the year prior to poisoning for the replant
e) Change in commodity price of oil palm and exchange rate having an effect on plantations' and smallholders' income and ability to purchase fertilisers

All these factors contribute to the total amount of fertiliser required for a particular year, but still N-containing fertiliser is the major fertiliser applied to both the plantation and smallholder blocks in PNG.

Table 2.5 Tonnage of N fertilisers used by major plantations and smallholders in relation to other fertilisers used (1997 to 2005)

Year	Plantation companies								Smallholders			
	NBPOL	%	Hargy	%	Higaturu	%	Poliamba	%	Hoskins	%	Popondetta	%
1997	ND		705 AMC 235 SOA	94	ND		ND		ND		ND	
1998	ND		1000 AMC	89	ND		ND		ND		ND	
1999	ND		1200 AMC 90 SOA	81	ND		ND		ND		ND	
2000	ND		1675 AMC 121 SOA	74	ND		1100 SOA	37	ND		ND	
2001	4978 AMC 2821 SOA	77	1500 AMC	88	ND		1250 SOA	34	1354 AMC	100	ND	
2002	9521 AMC	79			ND		1050 AMN	29	1445 AMC	100	ND	
2003	8442 AMN	73	2193 AMC	72	ND		800 AMN	30	1615 AMC	100	ND	
2004	7122 AMN	64	4208 AMC 14 SOA	83	2494 AMN	60	215 AMN 968 AMC	35	2092 AMC	100	3000 SOA	100
2005	5482 AMN	54	2205 AMC 14 SOA	73	1311 UREA	38			2200 AMC	100	1848 SOA	100

Information source: Plantations and Oil Palm Industry Corporation.
ND = no data available

2.6.2 Forms of N

The main types of N fertiliser used on plantations and smallholder blocks are SOA, AMC, AMN and urea as shown in Table 2.6. In addition to inorganic fertilisers, EFB which is a mill waste, is also applied to some blocks. However, EFB is mostly added to provide a source of N and K and to provide mulch between adjacent palms in a row.

One of the main factors governing the choice of N fertiliser is cost. Fertilisers and related costs constitute a significant proportion (50 – 70 %) of the field upkeep budget and 25 % of total production costs (Goh and Hardter, 2003). Because of the high cost, plantation companies choose the cheapest N fertiliser based on cost per unit N. The prices in 2006 of different types of N fertiliser (and cost per kg N), provided by Farmset Ltd (PNG) which is a major fertiliser supplying company in PNG, are presented in Table 2.6. AMN is the cheapest N fertiliser however it is not readily available due to restrictions on its use and therefore urea is usually the next cheapest option, at 3.79 Kina per kg N. Urea however has the problem of volatilisation in the warm tropical climate. AMC and SOA are expensive assuming Cl and S to be of no value.

Table 2.6 Common N fertilisers and cost (kina/kg N) in 2006

N fertiliser type	Cost per tonne (Kina)	N content (%)	Cost (kina/kg N)
Ammonium Sulphate (SOA)	1525	21	7.26
Ammonium chloride (AMC)	1980	26	7.62
Ammonium nitrate (AMN)	875	36	2.43
Urea	1742	46	3.79

One Kina = NZ$ 0.47

In most cases for smallholder blocks, a standard fertiliser application is used for logistical reasons. To change a fertiliser type and rate recommendation could easily lead to confusion amongst growers. Smallholders in West New Britain (WNB) and Oro Provinces are supplied with only AMC or SOA respectively.

In addition to choosing fertiliser type on the basis of cost per kg N, the choice also depends on other nutrient requirements e.g. on the soils on the Popondetta plains in Oro Province, soils are sandy and the S content is very low (Bleeker, 1987). Here the recommended fertiliser type is SOA or another fertiliser combination such as urea plus elemental S. For WNB, the major limiting nutrients are N and Mg. So AMC and kieserite is preferred. However more recently, a switch has been made to AMN plus kieserite because AMN is a cheaper N source.

Studies done to date in PNG and in Malaysia have shown that there is no difference in effectiveness of different forms of N for oil palm. Field experiments aimed at evaluating different N sources (AMC, AMN, DAP, SOA and Urea) in West New Britain (WNB) and Oro Provinces did not show any advantage from any of the different N forms (PNGOPRA Annual Reports 2000 and 2003). Zakaria *et al.* (1989) reported on 18 field experiments designed to evaluate urea as a source of N in Malaysia. Comparisons were made between two granular sizes, 2.9 and 7 mm, of urea and urea plus SOA. The differences between treatments were less than 1 t FFB ha^{-1} and were not statistically significant.

2.6.3 Fertiliser recommendations

Fertiliser recommendations vary with different climatic conditions, soil types, age of the palms and planting materials. Foster (2003) summarised the four main methods for determining the fertiliser requirements of oil palm as follows;

a) Relating results of field trials to soil and environmental conditions at the experimental site, then translating these findings to other sites that have similar environments e.g. this method is usually used for initial fertiliser recommendations for areas that have yet to have field trials
b) Use of soil analysis data from unfertilised areas in the plantations and relating them to target values obtained from yield response curves. This approach is not very practical because of the large variability in soil properties under the palms

c) Using frond analysis to assess the nutritional status of the palms. This method is based on establishing a relationship between yield and leaf nutrient content. However, results from using this method are affected by the supply of other nutrients

d) A combination of leaf (frond) analysis to assess the extent of a deficiency and site properties to assess the amount of fertiliser required to correct any deficiency. Site factors affect the efficiency of recovery of applied fertiliser so need to be taken into account when determining how much fertiliser is required.

Of the above four methods, c) is most commonly used in the plantation industry and recommendations are made for specific areas as follows:

The plantation is divided into management units called “leaf sampling units” (LSU) (Fairhurst and Hardter, 2003). These units are created on the basis of common soil and landscape features and year of planting. Each LSU is usually 1,000 to 1,500 ha depending on the uniformity of soil properties and the age of palms. Fertiliser application rates for individual LSUs are assessed using leaf tissue analysis done during the previous year. Other background information required includes; year of planting, previous leaf analysis, FFB yield, yield response data from fertiliser trials, expected FFB yield, rainfall data and previous land use.

For immature palms (<3 years of age), fertiliser is split into 4 – 5 applications per year, applied around the drip circle. The amounts applied, at each application, range from 50 to 70 g N palm^{-1}. The objective in splitting is to meet palm requirements but not burn young growing oil palm roots and to minimise the risk of leaching and surface runoff losses if there is an extreme rainfall event soon after fertiliser application. The number of applications per year is normally reduced to 2 – 3 as palms mature (>3 years) and the rates increased from 520 to 850 g N palm^{-1} yr^{-1}.

Smallholders apply fertiliser twice per year at 50 – 60 % of plantation rates. The smallholder fertiliser application rates are lower than the plantation rates because not all smallholders harvest regularly and also because of the high costs of fertilisers. When

FFB prices are high, growers can afford to buy fertilisers but when prices drop fertilisers are not applied.

For smallholders, within each province, a standard fertiliser application rate is usually recommended irrespective of the different soil types or level of production. However in 2002, in Oro Province, fertiliser recommendations were made on the basis of soil type and standard of management. It was recommended that better managers apply 0.84 kg N palm^{-1} yr^{-1} while 0.63 kg N palm^{-1} yr^{-1} was recommended for the average and below average growers.

Different containers are used for measuring and spreading fertilisers around the palms. They include empty cans, bleach containers, plastic containers, coconut shells or old rubber cups. Fertilisers are issued to smallholders on the basis of the number of bags required to cover their blocks and they are advised that a bag covers so many palms. For the plantations, fertiliser bags are dropped off on the roadside according to the number of palms that the bags should cover. Fertilisers are then spread to cover the required number of rows per fertiliser bag depending on the recommended application rate. Plantations often calibrate their containers for the different rates and fertiliser types being applied.

Foster and Goh (1977) and Teoh and Chew (1984) reported that the frequency of fertiliser application and yield responses were negatively correlated. These two studies show that increasing the number of applications appears to be detrimental to yield of oil palm and where rates are low, it is probably best to apply in one or two doses each year.

2.6.4 Timing of fertiliser applications

The first application of fertiliser to both the plantations and smallholder blocks is normally applied after the wet season starts tailing off to avoid losses that could accompany heavy rains. Fertiliser is also applied at this time because this is after the peak crop so labour is available for upkeep work. The remaining two applications are then spread out during the rest of the year depending on when new stocks of fertilisers arrive. Quite often fertiliser is applied 1- 3 days after it rains. In many cases the plantations have no choice but to apply fertiliser and hope for the best.

2.6.5 Fertiliser placement

In Malaysia, fertiliser is applied within the weeded circle (WC) on the basis that this is the area where the highest rooting density occurs so that most of the uptake will occur from this zone. However studies have shown that this is not necessarily the case especially for mature palms. Foster and Dolmat (1986) compared the effectiveness of fertiliser placement in the WC, frond pile (FP) and the harvest path (HP) on a mature oil palm plantation. They found no significant differences in yield for placement in any of the three zones. Also there was no difference in leaf N contents obtained for fertiliser placed or broadcast onto any zone. They suggested that for palms greater than 5 years of age, the roots are everywhere and it does not really matter where fertilisers are placed. However for immature palms it is recommended to apply fertilisers within the WC where root density is high.

Yeow *et al*. (1981) reported on a comprehensive study that examined various ways of placing fertiliser under palms in six large scale trials in Malaysia. They found no effect of fertiliser applied in the WC on yield as compared to applications to the other areas. There was also no difference in yield between the different percentages (25-100 %) of palms receiving fertilisers. They concluded that fertiliser placement does not affect FFB yield for mature palms and suggested costs could be reduced by fertilising only alternate rows of palms instead of applying fertiliser to every row.

For mature palms, PNGOPRA recommends fertiliser be scattered thinly onto the frond pile and frond tip area. This recommendation is based on the understanding that most of the oil palm feeding roots are found in these areas and there is a reduced chance that the fertilisers will be washed away by surface water runoff. However, in practice, placement of fertilisers varies for the different plantations and for the different smallholder blocks in PNG. At Milne Bay, it is common practice to apply fertiliser onto the frond piles only, whereas at Sangara, fertiliser is applied in the between zone (BZ) (between frond tip (FT) and WC) with some onto the edge of WC and in the FP next to the palms. The same is done at Dami, in WNB. On the whole, for mature palms, the commonest areas that receive fertilisers are the FP and BZ zones.

Evenness of the spread of fertilisers on the ground depends on how soon they are applied onto the plantations and blocks. Because of their crystal-like properties, AMC and SOA are spread evenly on the ground. For some of the smallholders who do not apply their fertilisers immediately after delivery, the fertilisers form into huge lumps that are difficult to spread. Many growers apply fertilisers only to palms next to their residential areas and roadsides. Palms further away from the residential areas, near the back of the blocks, do not get fertilised and therefore the spread and rates of fertiliser applied are uneven as seen in Plate 2.2

Plate 2.2 A smallholding block showing uneven fertiliser applications Palms furthest from the road and the village are yellow showing N deficiency symptoms

2.7 Summary

- N is an important plant nutrient in biochemical processes and affects very important physiological processes such as photosynthesis which in turn affects growth and yield of palm.
- no response to N on very old soils e.g. Africa
- Responses secondary to K in Malaysia

- Consistent N responses were found on sandy clay volcanic soils at Popondetta (Oro Province – PNG) and Sumatra –Indonesia, but inconsistent N responses on very young sandy volcanic or pumice, soils at Hoskins, Kapiura and Bialla
- FFB and growth responses vary between and within different countries and appear to be explained by differences in soil C and N contents.
- Oil palm strips more N (160 – 200 kg N ha^{-1} yr^{-1}) out of a soil via product removal than all other tropical crops
- Total annual N demands for mature palms is 1.2 – 1.5 kg palm^{-1}
- On average N fixation adds around 25 kg N ha^{-1} yr^{-1} (averaged over 18 years)
- Annually per hectare, it is estimated that 100 – 130 kg N is added as fertiliser, 45 – 78 kg N (40 – 60 % of added fertiliser) is removed with FFB and 40 – 78 kg N (40 – 60% of added fertiliser) is unaccounted for. Fertiliser and its management cost makes up 50 – 70% of field upkeep costs. More than 70 % of fertiliser types used in the PNG oil palm industry and are N types
- Unaccounted for losses of N are equivalent to a loss of up to 25 million kina/year to PNG
- No differences in responses from different N fertiliser types, or fertiliser placements in the different areas under palms. Most studies done were from the perspective of yield and N uptake and none looked at where and how losses of N occurred.

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Chapter 3

General background information

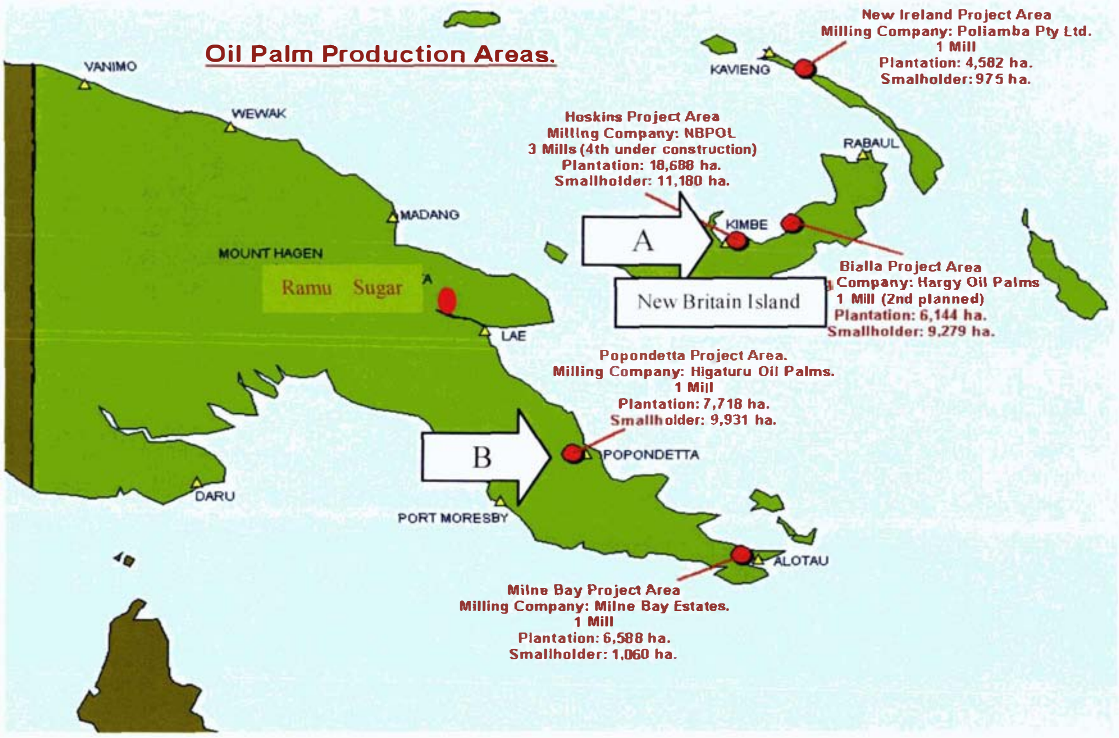
This chapter provides general background information on the sites, soils and climates for the different experimental areas used in this study;

a) Location of experimental sites and soil descriptions using information from the literature and field work
b) Characterisation of areas under the palms using field measurements and information from the plantations
c) Soil chemical characterisation of the different zones under the palms determined from soil sampling and the laboratory analysis at Massey University
d) Climate data for representative oil palm producing areas in PNG using data from PNGOPRA and various weather stations within the plantations with special emphasis on the two experimental sites.

3.1 Soils and site descriptions

3.1.1 Experimental sites

The experiments were carried out at two sites in PNG. The first site was at Dami (long 150 deg 5" lat 5 deg 6" alt 19 m asl) in WNB Province which is on New Britain Island. The second site was at Sangara (long 148 deg 12" lat 8 deg 44" and alt 130 m.a.s.l) in Oro Province on the mainland (Figure 3.1). These two provinces are major oil palm growing areas and together they produce about 70 % of the total oil palm crop in PNG.



A = Dami, B = Sangara and (●) = oil palm growing areas

Figure 3.1 Map of Papua New Guinea oil palm growing areas showing the two experimental sites

At Dami, the experimental site was within 1.5 km of the PNGOPRA/OPRS Office while at Sangara the site was within 100 m of the PNGOPRA office.

3.1.1.1 Dami

3.1.1.1.1 Soils and landforms

Soils at Dami are classified as Typic Udivitrands (Soil Survey Staff, 1999). The topography on the coastal alluvial plain is flat to slightly undulating.

Soil parent materials in the Hoskins area are derived from 11 volcanoes in the Cape Hoskins area. The oldest recorded ash from Mt. Galilo is about 2,500 years old (Bleeker and Parfitt, 1974) and the latest is from the still active Mt. Pago which erupted in 1914 - 1918 (Blake and Ewart, 1974). In between these two eruptions there have been other eruptions which have resulted in a number of buried horizons in the soils. The soil parent materials are either direct ash deposits, colluvium or alluvium (Hartley *et al.*, 1967; Zijsvelt, 1977; Zijsvelt and Torlach, 1975).

3.1.1.1.2 Soil description

A soil pit was dug down to 2 m depth and the soil profile is shown in Plate 3.1 and described in Appendix A1.1.

The soils at the surface (0-10 cm) are dark brown (10YR 2/2), changing to light olive-brown (2.5Y 5/4) at 33-60 cm and back to dark yellow-brown (10YR 5/8) at 178-200 cm. The structure changes from moderately to strongly-developed at the surface layer and changes to weak or structureless with depth. However at the lowest depths (163 – 200 cm) the structure changes back again to weakly-developed. The texture changes from sandy loam at the surface to sandy gravely loam and coarse sandy loam reverting to sandy loam again at the lowest depth. Common throughout the area is a hard sand/gravel/pumice band at 30 – 50 cm depth and in most of the layers there is a high proportion of pumice. Also common throughout the area is the presence of a coarse structureless gravelly pumice layer at around 80 – 140 cm depth. At the lowest depth (178 – 200 cm), the soil materials are mostly pumice, sand and gravel.

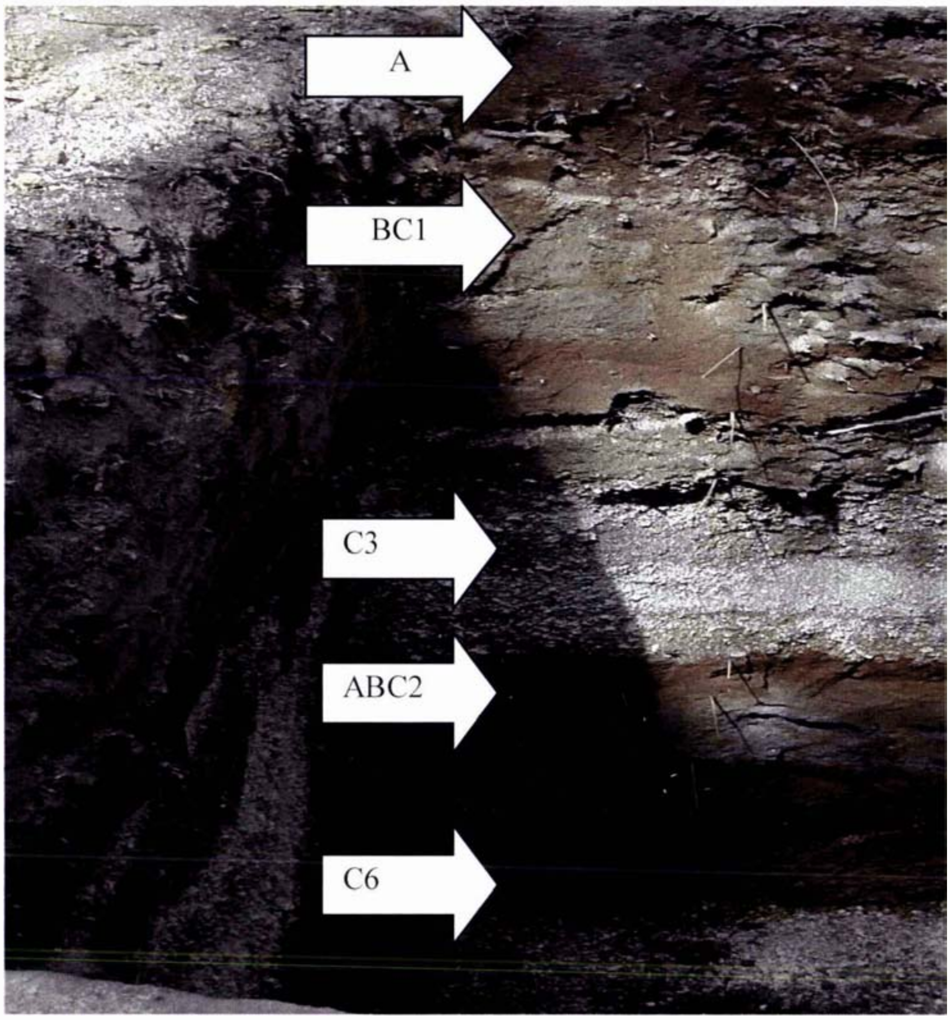


Plate 3.1 A 200 cm soil profile at Dami showing the major horizons – more details in Appendix A1.1

3.1.1.1.3 Soil mineralogy and chemistry

Soil parent materials are dacitic to andesitic in the Hoskins area. Banabas (1998) investigated the mineralogy of oil palm growing soils from the Hoskins area (which includes Dami) and reported that the volcanic ash soils appear to be relatively young as judged by the presence of high to very high levels of volcanic glass minerals in the sand, silt and clay fractions.

Top soils at Dami are generally slightly acidic (pH 6.0) with low to very low CEC (<13 cmole (+) kg^{-1}) with base saturation ranging from 64 to 90 %. Olsen P (Blakemore *et al.*, 1987) values are generally very low, (2.5-9.7 mg kg^{-1}) with low to medium phosphate retention values (range 26 to 67 %, mean = 52 %) in the top 20 cm. The pH in NaF ranges from 8 to 10, indicating the presence of allophane in the soils.

3.1.1.2 Sangara

Soils at Sangara fall into the Higaturu soil family which is a Typic Hapludand (Soil Survey Staff, 1999). Landform, climate, vegetation and soils of Oro Province were described in the 1960's by the CSIRO (Haantjens *et al.*, 1964). Soil surveys were undertaken by Bleeker (1987) and Land Use Section of the PNG Department of Agriculture (1996).

3.1.1.2.1 Landform

Haantjens *et al.* (1964) identified 30 land systems in the province and assigned soil groups to them. The Higaturu soil family was included in the Higatura Land System which also included some Ohita and Sangara soil families. They recognised two main landforms; volcanic plains and outwash plains. Higaturu soils are found on the volcanic plains, mostly south - west of the Ambogo River.

The volcanic plain is mostly flat to gently undulating terrain, dissected by narrow valleys. The plain is subdivided into six landform units; dissected terraces, upper terraces, middle terraces, lower terraces, flood plains and gullies. Higaturu soil family is mostly found on the middle and upper terraces though it can also be found on the lower terraces (Bleeker, 1987).

3.1.1.2.2 Soil description

A soil pit was dug down to 200 cm depth and soil profile is shown in Appendix A1.2. A photograph of an exposed soil profile is shown in Plate 3.2.

Soils on the volcanic ash plains are moderately-weathered with generally well-developed dark topsoil (0-30 cm) (Bleeker, 1987). Haantjens (1964) described the Higaturu soils as yellow brown ash soils formed from moderately to slightly-weathered volcanic ash materials. Higaturu soils in general have moderately-developed fine to medium subangular blocky structures. The black A1 (10YR 2/1) horizon merges into a very dark brown (10YR 4/3), very dark grey (10YR 3/2) or very dark greyish brown transition B horizon at 30 – 120 cm and light yellowish brown (2.5 Y 6/2) C horizon at 145 – 200 cm. Texture changes from sandy clay loam (in A1) to fine sandy clay with a significantly higher clay content, firm but brittle consistency in the B horizon; texture becoming sandier/coarser at 145 – 200 cm.

Plate 3.2 An exposed side of a gulley showing the soil horizons at Sangara

3.1.1.2.3 Soil mineralogy and chemistry

Higaturu soils are derived from Mt. Lamington volcanic ash materials from the last eruption in 1951 (Haantjens *et al.*, 1964 and Bleeker, 1987). The volcanic parent materials are dacitic i.e. having high Si to Al ratio with generally high levels of feldspars and hornblende (Banabas, 1998). The sand, silt and clay fractions have very high levels of unweathered volcanic glass minerals as well as plant opals. Allophane and ferrihydrite (both variable charge minerals) contents are very low being less than 0.8 and 0.5 % respectively (Banabas, 1998).

Soils are slightly acidic with very low to low CEC content (3 - 14 cmole (+) kg^{-1}) and medium to very high base saturation (40 to 100 %) (Bleeker, 1987). Exchangeable Ca and Mg values range from medium to high while exchangeable K ranges from low to medium. Olsen P (Blakemore *et al.*, 1987) values are generally very low (<10 mg kg^{-1}) and the soils have low to medium P retention values (mean of 30 % in the top 20 cm). Organic matter, total and available N levels are low and decrease with depth.

3.2 Characterisation of zones

3.2.1 Spacing and age of palms

Oil palms in the plantation and smallholder blocks are usually planted in a triangular pattern but at various spacings to suit the soils and climate factors at the sites. This results in various densities from 110 – 143 palms ha^{-1} at both Sangara and Dami. The palms in the experimental sites are replanted 2nd generation palms. During the replant, the palms from the 1st generation were cleared mechanically and placed in every 3rd row which over time became frond piles.

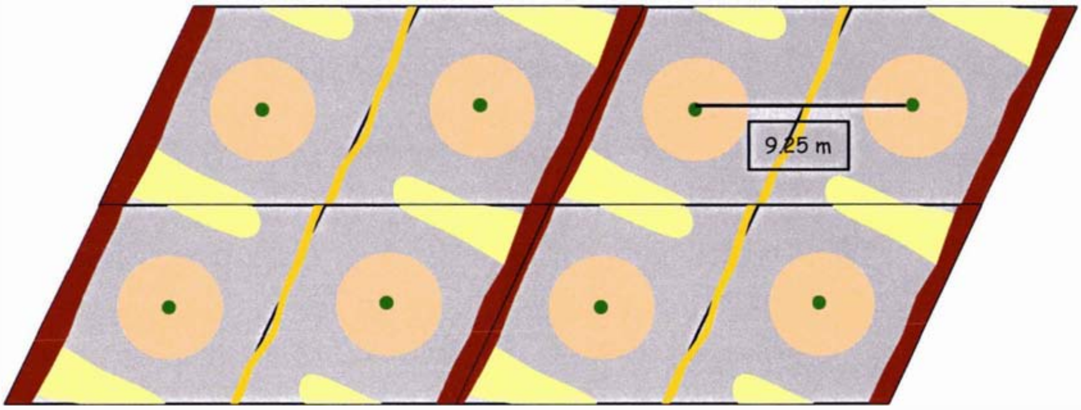
The palms at Dami are Dura type, used for seed production. They were planted in 1989 at a spacing of 9.8 m between palms to achieve a density of 120 palms ha^{-1}. During replanting, the palm rows were not realigned and therefore palm rows, harvest path and frond piles remained as they were for the first planting. The experiments were done under 15 – 17 year-old palms.

At Sangara, the palms were planted in 1996 at a spacing of 9.25 m between palms to achieve a density of 135 palms ha^{-1}. The palms at Sangara are commercial palms typical of those in plantations and smallholder blocks. However the palm rows were realigned at the replant and therefore new palm rows were created. Experiments at Sangara were done under 7 – 9 year old palms.

3.2.2 Zone characterisation and % of area covered

The area under the oil palms was divided into five zones as described below and shown in Figure 3.2.

In oil palm plantations, every 2nd row between palms is a clear path referred to as the harvest path (HP). Here the harvested oil palm bunches are wheel-barrowed or trucked out to the road sides for collection. Plantation workers also use the HP to access the plantation and to carry out agronomic practices such as fertilising, weeding, pruning and to do pest and disease scouting. The path widths range from about 0.5 m in some smallholder blocks to 2.5 m in some plantations that use machinery for in-field bunch collection and fertiliser application. For a typical plantation, the harvest path occupies about 3 % of the area (Figure 3.2). Fertiliser is not applied to this zone and it is usually kept weed-free by manual slashing, use of herbicides, or mowing by tractor in some plantations (Plate 3.3).



frond pile (7-8 %)🟥, frond tip (6 %) 🟨 , between zones (73 %)⬜ ,
weeded circle (10 %) 🟧 harvest path (3 %)🟨 and trunk (0.5 %)🟩

Figure 3.2 Schematic showing palm planting arrangement and different management zones

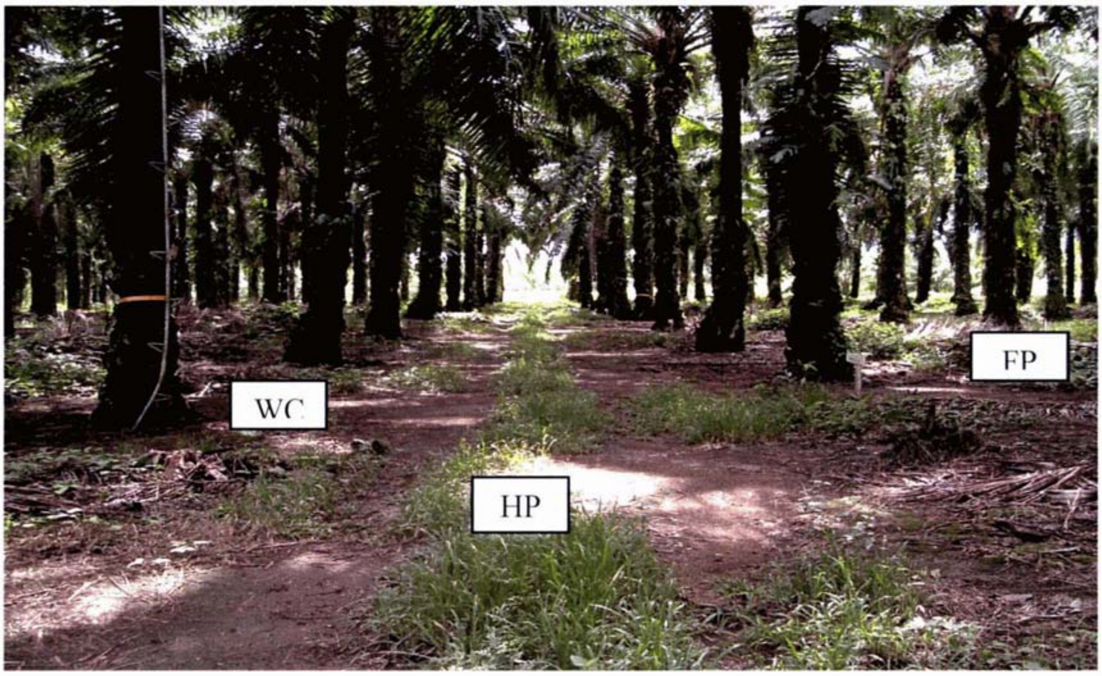


Plate 3.3 Rows of oil palm at Dami showing WC, HP and FP

Every other row between palms is where fronds that are pruned during harvesting, and normal pruning upkeep are placed. This is referred to as the frond pile zone (FP). Fronds from palms on either side of the pile are placed in this zone. The width of a FP ranges from 1.0 m in newly-planted palms to 2.5 m in mature palms and the FP occupies about 7-8 % of the total area. Part of this zone next to the palms receives fertiliser during fertiliser application. In many well-kept plantations, legume cover crops, ferns and other under-storey vegetation are allowed to grow in this zone.

In plantations, the area between adjacent palms in the same row is an area that receives frond tips. During pruning and removal of fronds that occurs during harvesting, the frond bases with spikes are cut off and placed in the FP in such a way that the spikes do not injure the workers. The top ends of the fronds which have leaflets and no spikes are referred to as frond tips and these are placed perpendicular to the FP with the end of the tips next to the HP. Over time this practice forms a mat that covers the area between the palms and protects the soil from erosion during rain events. In some plantations empty fruit bunches are also placed in the FT zone. In plantations, the FT zone occupies about 6 % of the total area. In the FP and FT, and some parts of the BZ zones, legume cover crops and under-storey vegetation are encouraged to grow for soil conservation purposes and to provide nectar for beneficial insects. Some of the FT area receives fertiliser during applications. In smallholder blocks, frond tips are not separated so there is no FT zone.

The cleared area around oil palm trunks is referred to as the weeded circle (WC) zone. This area has a radius ranging from 1.9 to 3 m and occupies about 10 % of the total area. This area is cleared, either manually or by spraying with herbicides, to allow labour to harvest and remove the oil palm bunches. This is also the area where fertiliser spreaders stand and spread fertilisers onto other zones but not onto the WC itself. Whilst the palms are still young (1-2 years from planting), fertilisers are usually applied close to the trunk, but as the palms mature fertilisers are spread further away from the WC zone.

The other area, not covered above between the weeded circle and FT zones, is referred to as the BZ (between zone) zone. This is a very important zone because this is usually the area that receives most of the fertiliser. This area makes up about 73 % of the total area.

3.3 Soil chemical characteristics of the different zones

3.3.1 Introduction

The different zones receive different crop husbandry practices (as discussed in 3.2) that impact on the biological, chemical and physical properties of the soils.

Soil sampling and analysis (for pH, total C and total N) were done to chemically characterise the different zones at the Dami and Sangara sites.

3.3.2 Methods and materials

Soil sampling was done in the early stages of the research before the BZ was recognised as a separate zone. Soil samples were taken from the FP, FT, WC and HP zones. Soil samples were bulked from five "locations" along a single path at both Dami and Sangara. Each location was two palms apart. At each location, the soils were taken from five points within each of the four zones, at 0 –20 cm, 20 – 40 cm and 40 – 60 cm depths. To take the samples, a 60 cm deep soil pit was dug and soil samples were taken from the side of the pit. Soil samples were later bulked for each depth within each zone. Soils were air-dried at room temperature and sent to Massey University for analysis. C and N analysis was done on the 0 – 20 cm depth samples for all zones but for the 20-40 cm and 40 – 60 cm depths, analysis was done only on the FP samples. It was assumed that there would not be any major difference between total C and N contents, at depth, between the different zones.

Soil pH was measured for all zones and all the depths according to the method of Blakemore *et al.* (1987); 10 g of air dry soil (<2 mm) and 25 ml water was stirred vigorously with a glass rod and then left to stand overnight. The pH was determined the next morning with a PHM83 Autocal Radiometer pH.

Soil total C and N were determined by Landcare Research using methods described by Blakemore *et al.* (1987) with a LECO CNS - 2000 analyser and combustion in ultrapure oxygen at 105 C. Carbon dioxide produced was measured with an infrared detector and N with a thermal conductivity detector. Both detectors were calibrated using an EDTA standard.

3.3.3 Results and discussion

3.3.3.1 Soil pH

Subsoil (20-40 and 40-60 cm) pH at Dami ranged from 5.3 to 6.3 and was lowest in the FT and WC zones (Table 3.1). At Sangara, subsoil pH was within the relatively narrow range 6.2 – 6.6. These subsoil pH values of 6.0 – 6.5 are similar to values reported for volcanic ash soils such as the Egmont black loam in NZ (Soil Bureau Bulletin 26 (3), 1968) and Hanaipoe soils in Hawaii (Loganathan and Swindale, 1969).

At both sites, soil pH at the 0–20 cm depth was lower than in the subsoil, with the notable exception of FP at Dami, where the topsoil pH was almost the same as that of the subsoil. Lower surface soil pH values are somewhat “classical” presumably reflecting the accumulation of organic matter and the pH depressing effect of long-term N fertiliser use. However on this basis, FP soil (0-20 cm) at Dami could be expected to have a lower soil pH than at Sangara on the basis of longer term fertiliser use and greater organic matter accumulation. However this was not the case and in fact the pH at Dami was constant with depth. One possible explanation for the relatively high pH at Dami (FP, 0-20 cm) could be the complexation of Al by organic ligands (Haynes and Mokolobate, 2001). Another explanation could that the uptake of cations and charge balancing by negatively charged organates in the fronds have acid neutralising potential (Hedley, 2006. pers. comm.). During decomposition of fronds in the FP, these organates are released and they probably prevent the soil pH from declining as compared to the situation in other zones (WC and HP) which do not receive pruned fronds.

3.3.3.2 Soil total C and N

At both sites, total C and N at 0 – 20 cm depth are higher in the FP than in the other zones and depths (Table 3.1). The addition of pruned fronds over time has obviously resulted in higher C and N contents in the FP zones compared with the other three zones. Also the higher total C and N content (0 – 20 cm) at Dami compared to Sangara is probably due to continuous placement of pruned fronds onto the FP at Dami over two generations of palms. At both sites, total C and N contents in the FP decreased markedly with depth which suggests that the influence of the addition of prunings on soil organic matter seems to be limited to the top 20 cm of soil.

Table 3.1 Soil pH (H_2O), total C (%) and total N (%) contents at different depths and zones at Dami and Sangara

Site	Depth (cm)	pH $_{(H2O)}$				Total C (%)				Total N (%)			
		Zones				Zones				Zones			
		FP	FT	WC	HP	FP	FT	WC	HP	FP	FT	WC	HP
Dami	0 – 20	6.2	4.6	4.9	5.5	6.19	3.81	3.24	2.27	0.55	0.40	0.33	0.24
	20– 40	6.1	5.4	5.3	6.0	1.41				0.14			
	40– 60	6.3	5.6	5.9	6.3	0.25				0.03			
Sangara	0 – 20	5.3	5.5	4.7	5.6	2.85	2.32	2.11	2.41	0.24	0.20	0.20	0.23
	20– 40	6.2	6.2	6.2	6.5	0.74				0.07			
	40– 60	6.4	6.2	6.2	6.6	0.52				0.05			

3.3.4 Summary

- Five main zones recognised within an oil palm plantation occupying the following % areas: HP (3 %), FP (7-8 %), FT (6 %), WC (10 %) and BZ (73 %)
- There are major differences in soil chemical characteristics of the various zones that appear to be a function of plantation management practices
- There is evidence that soils need to be studied in relation to zones because of the obvious differences in soil chemical properties.

- Top soil pH ranges from 4.6 – 6.2 and subsoil pH from 5.4 to 6.6 and tend to be lower at Dami except in the FP soils where the alkalinity of the frond residues appears to neutralise the normal acidifying process
- Organic C and N are higher in top soils and higher at Dami than at Sangara.
- Effects of prunings on total C and N contents are especially evident at Dami where the additions to FP have occurred for the longest time.
- Soil chemical differences could have an effect on biological reactions particularly the rate of nitrification of soil and fertiliser ammonium
- Ammonium that leaches to greater than 20 cm depth might be expected to nitrify at a slower rate in the subsoil than in the topsoil due to a smaller supply of substrates and likely associated impact on microbial activity.
- Soils at Dami are derived from dacitic to andesitic volcanic ash with a hard sand/gravel/pumice band at 30 – 50 cm depth. They are mainly free-draining
- Soils at Sangara are mainly developed from dacitic volcanic ash with a more clayey subsoil that could impact on the drainage characteristics.

3.4 General climate of oil palm growing areas in PNG

3.4.1 Introduction

Oil palm in PNG is grown in five provinces that have very different climates. This section provides a summary of the climate in the main oil palm growing areas, with special emphasis on the two experimental sites, Dami and Sangara. Four major weather features affect the physiological ability of oil palm to produce high yields; viz rainfall, solar radiation, temperature and wind (Uexkull von and Fairhurst, 1991). These same factors also affect the water balance under palms by determining the flux of water into and out of the oil palm system. These fluxes, in turn, affect the amount of N lost via surface runoff and leaching. Biological processes are also affected and this has implications for the NO_3^--N generation system and rates of denitrification.

3.4.2 Climate data

Climate data from a number of sites is shown in Table 3.2. Rainfall is recorded in nearly all oil palm growing areas on a daily basis. The values are later summarized to provide monthly information. Standard manual rainfall gauges are normally located next to plantation offices. All data summarized and reported here were collected from plantations throughout the PNG oil palm growing areas.

Full weather data were collected from three sites; Dami in WNB, Sangara in Oro and Ramu Sugar in Morobe Province (shown for comparison). Data were collected at Dami by OPRS (NBPOL), at Sangara by PNGOPRA, and at Ramu Sugar by Ramu Sugar plantation. At these three stations, rainfall, minimum and maximum temperatures, wet and dry bulb temperatures, cloud cover, sunshine hours and wind direction were recorded. Wind run and pan evaporation were recorded at Dami and Ramu Sugar only. Weather measurements were made at 7 am, 10 am, 2 pm and 4 pm at Dami, 7 am, 10 am and 4 pm at Ramu Sugar, and at 10 am and 4 pm at Sangara every day. Sunshine hours were also recorded at five other sites (Table 3.2).

Table 3.2 Summary of years of data available for rainfall, rain days and sunshine hours for various sites in PNG

Province	Company	Site	Years of available data		
			Rainfall	Rain days	Sunshine hours
WNB	NBPOL	Dami *	1980-2005	1970-1990	1980-2005
		Kumbango	1997-2005		
		Garu	1997-2005		
		Numundo	1979-2005		
		Navarai	1996-2005		
		Haella	1990-2005		
		Daliavu	2001-2005		
		Sapuri	2001-2005		
		Kapiura	1997-2003		
	Hargy Oil Palms	Bialla	1989-2005		1990-2005
		Navo	1989-2005		1989-2005
New Ireland	Pacrim Plantations	Lakurumau	1990-2005		1999-2004
		Maramakas	2002-2005		
Oro	Pacrim Plantations	Sangara *	1976-2005	1981-1990	1977-2005
		Ambogo	1986-2005		
		Embi	1990-2005		
		Mamba	1990-2005		2000-2005
Milne Bay	Pacrim Plantations	Giligili	1988-2005		
		Kwea	1986-2005		
		Waigani	1987-2005		
		Bomata	1986-2005		1988-2005
		Padipadi	2000-2005		
		Marawatte	1999-2005		
Morobe	Ramu Sugar	Ramu Sugar*	1979-2005	1979-2005	1979-2005

* Sites with full weather data measurements

3.4.3 Rainfall

Ideally oil palm requires rainfall of between 2,500 – 3,500 mm yr^{-1}, distributed fairly evenly with not less than 120 mm/month (Uexkull von and Fairhurst, 1991). Mean annual rainfall in most of PNG is between 2,000 and 4,000 mm (McAlpine *et al.*, 1983). The oil palm growing provinces in PNG have mean annual rainfalls ranging from 1,913 mm at Ramu Sugar to nearly 4,000 mm at Bialla and Mamba (Figure 3.3). Within a province the mean annual rainfall varies for the different plantations e.g. in WNB it ranges from 3,327 mm at Hoskins to 4,451 at Bialla, and from 2,164 mm at Ambogo to 3950 mm at Mamba (Oro Province). Mean annual rainfall for the two experimental sites are 3,657 mm at Dami (1980 – 2005) and 2,398 mm at Sangara (1976 – 2005) (see Appendix A1.3 for monthly rainfall summary for all sites).

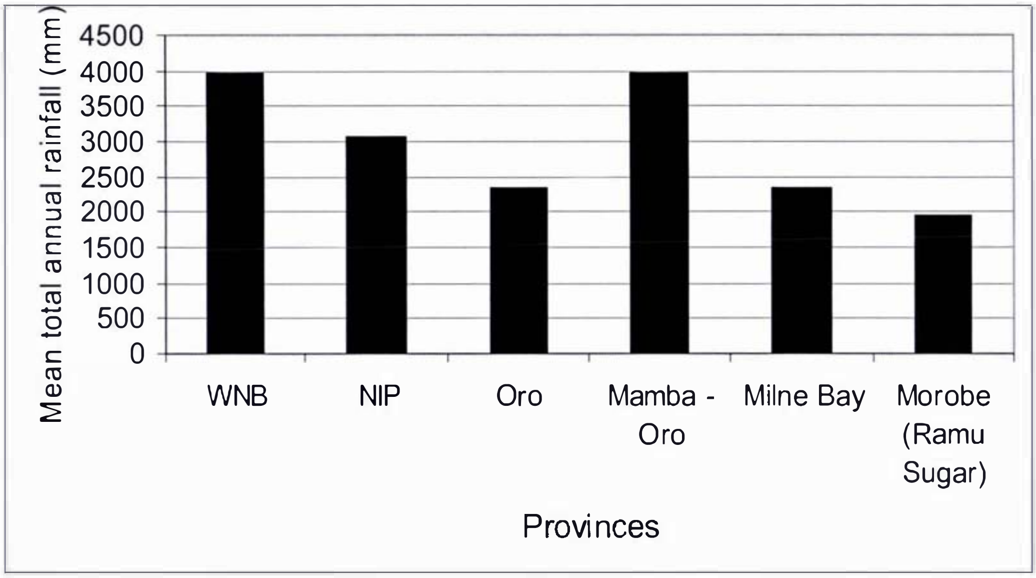


Figure 3.3 Mean annual rainfalls (mm) in oil palm growing provinces in PNG

The rainfall at Dami and at Sangara is different in both the total amounts received and in the monthly distribution. At Dami, 50 – 70 % of the total annual rainfall is received in December - April which is the high rainfall period, while the rest is spread out over the remaining seven months (Figure 3.4). At Sangara, the high rainfall months are from October to April and the low rainfall months are from May to September (Figure 3.4). The other plantations in WNB and Poliamba in NI Provinces have a similar rainfall pattern to Dami, while those in Oro Province are similar to Sangara (Appendix A1.3 Climate data summary). Ramu Sugar also has a similar pattern to Sangara, but with lower amounts. McAlpine *et al.* (1983) grouped the rainfall seasons in PNG into two major types, the north-west season and the south–east season. Dami and Sangara are both in the north-west monsoon season.

The implications of the monthly rainfall distribution to the water balance, to nutrient losses and to fertiliser management practices are discussed later (Chapters 4, 7, 8 and 9).

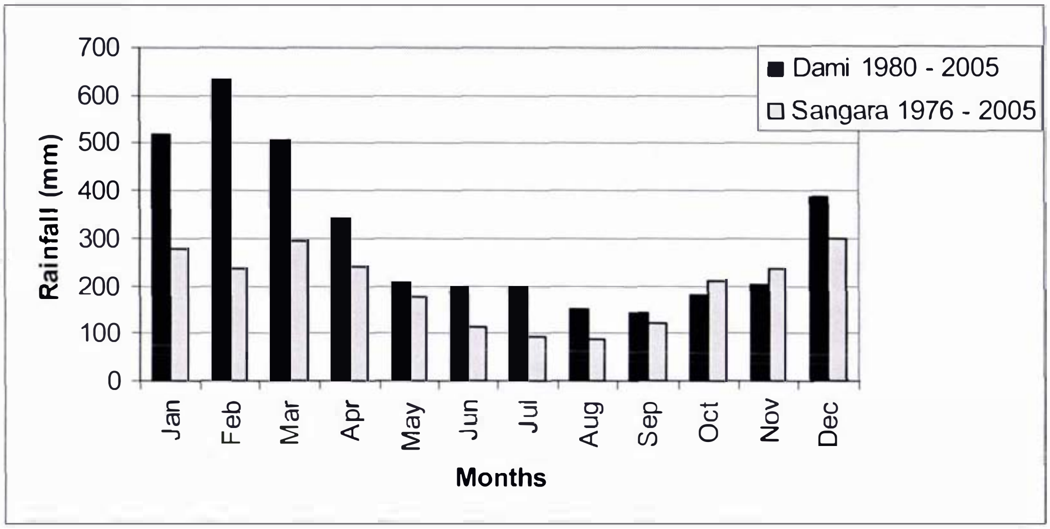


Figure 3.4 Mean monthly rainfall distribution at Dami and Sangara

At both experimental sites the number of rain days defined as days with equal to or greater than 1 mm of rainfall follows a similar trend to the monthly rainfall distribution, with Dami having a slightly higher number of rain days than Sangara during the rainy months (Figure 3.5). For both sites, the lowest number of rain days in a month is 10 and this occurs during the low rainfall month of July. The highest number of rain days, 25, occurs in Jan-March which are also high rainfall months. The mean number of rain days in a year is 227 at Dami and 202 at Sangara.

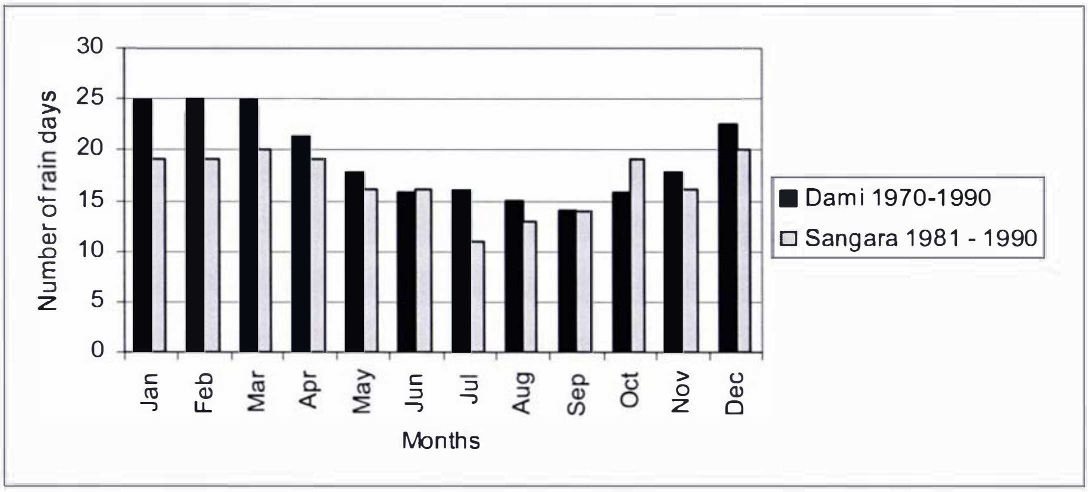


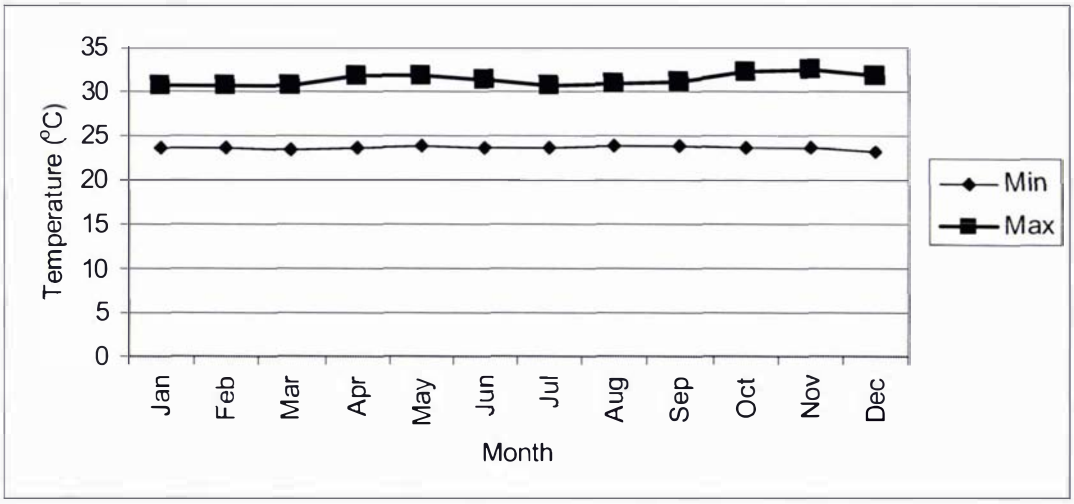
Figure 3.5 Mean number of rain days per month at Dami and Sangara

Rainfall intensity is defined as the amount of rainfall recorded per unit-time. McAlpine *et al.*, (1983) analysed daily rainfall data for 15 years from a representative number of stations across PNG. Three general conclusions resulted from this analysis. Firstly, rainfalls >100 mm day^{-1} commonly occurred on the mainland-coastal and island regions which cover all major oil palm growing areas. Secondly, rainfall >150 mm day^{-1} occurred at all coastal stations on average once every 1 to 3 years. Thirdly, most frequent heavy rainfalls (>150 mm day^{-1}) occurred in the southeast monsoon areas that do not currently grow oil palm.

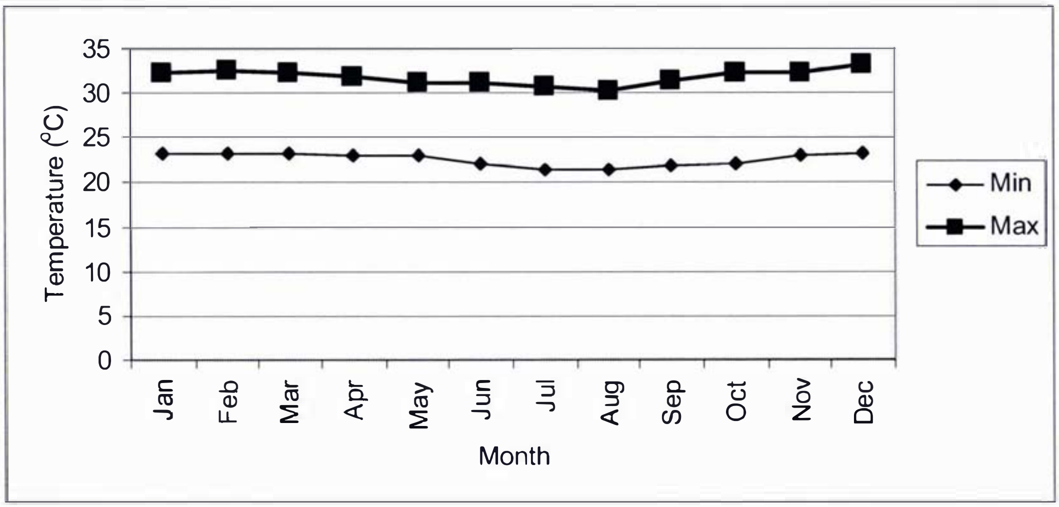
In the coastal lowland areas that experience the north-west monsoon season, short term intensities (lasting for less than 6 minutes) can reach 140 mm hr^{-1} every 2 years and up to 180 mm hr^{-1} with a 10 year return period. For 1 hour duration, the rates fall to 75 mm hr^{-1}. However in the southeast monsoon areas, 6 minute short-term intensities of 170 mm hr^{-1} occur with a 2-year return period, and 200 mm hr^{-1} occur once every 10 years, and the decline for 1 hour duration is less than at other stations. The highest daily rainfall recorded between 1993 and 2005 was 188 mm in April 2005 at Dami and 133 mm in January 2005 at Sangara.

3.4.4 Air temperature

The air temperature in PNG shows little seasonal variation because of its location close to the equator and being exposed to the ocean (McAlpine *et al.*, 1983). However there are temporal and altitudinal variations. Since most of the oil palm growing areas in PNG are in the lowlands, there is little altitude effect except for Mamba which is located at 350 - 400 m above sea level. The average daily minimum screen temperature at Dami and Sangara ranges between 22 °C and 23 °C while the average daily maximum is 32 °C and these values remain relatively constant throughout the year (Figures 3.6 (a) and (b)). The temperature occasionally gets down to 15 °C at Sangara, and up to 38 °C at Dami. McAlpine *et al.* (1983) report that for the lowlands, the minimum temperature typically ranges from 20 °C – 24 °C and the maximum from 28 °C – 32 °C.



(a) Dami



(b). Sangara

Figure 3.6 Mean daily minimum and maximum temperatures (°C) for each month at Dami and Sangara

3.4.5 Sunshine hours

The average number of bright sunshine hours per day in PNG shows some seasonal variation (McAlpine *et al.*, 1983). In the oil palm areas mean daily sunshine hours range from 3.5 to 5.8 hours per day (Figure 3.7). At Dami and Sangara, mean daily sunshine hours are lowest during the high rainfall months from December to March. The sunshine hours are also low in June-July and this could be due to location of PNG being in the southern hemisphere with a slightly "short day" winter effect.

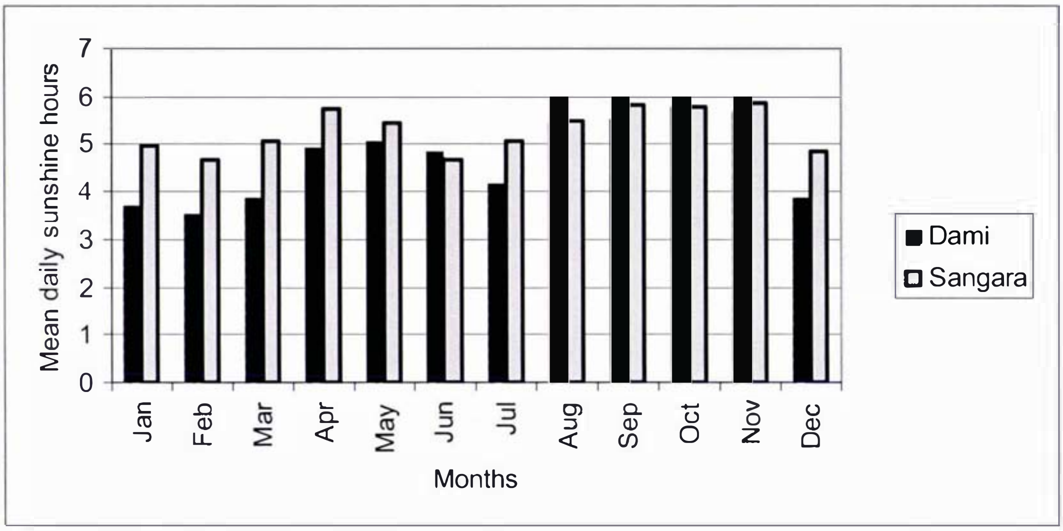


Figure 3.7 Mean daily sunshine hours distribution for each month at Dami and Sangara

3.4.6 Wind run

Wind run is measured only at Dami (anaenometer height = 4 m) and Ramu Sugar (anaenometer height = 2 m). Daily wind run data for 2003, 2004 and 2005 was used to determine the mean daily run per month for the 3 years, at each site. The mean daily wind run shows a clear trend, increasing from December to a high in August and then declining for the rest of the year, at both Dami and Ramu Sugar (Figure 3.8).

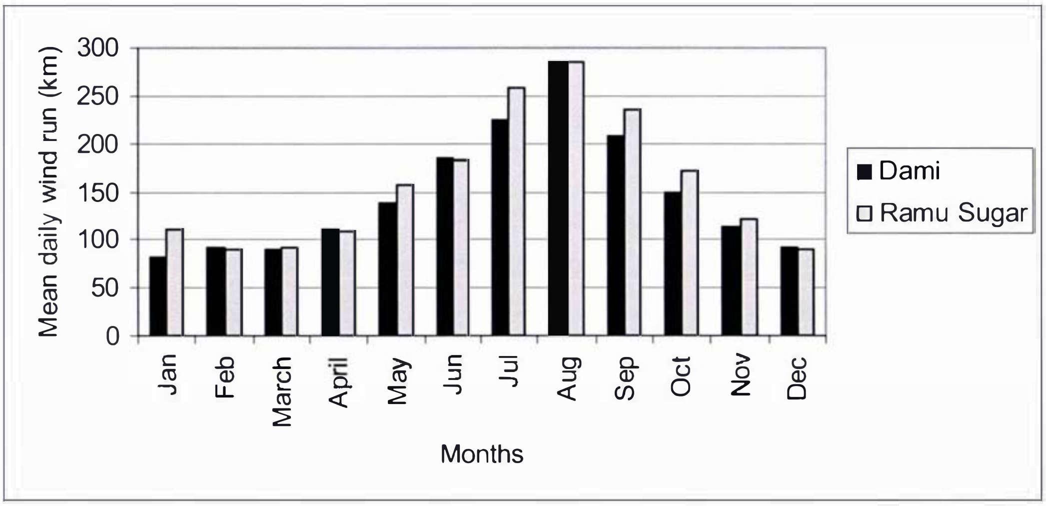


Figure 3.8 Mean daily wind run (km) for each month for 2003-2005 at Dami and Ramu Sugar

3.4.7 Evapotranspiration (E_r)

One of the components of the water balance is the return of water into the atmosphere. Evaporation is the process whereby energy, mostly from solar radiation, converts liquid water to vapour which moves away from the evaporating surface (Allen *et al.*, 1998). Evaporation occurs from soil surfaces, from vegetation, from intercepted water, and from water bodies such as lakes, rivers and ponded water in crop fields. Evaporation occurring from plant leaves through the stomata is called transpiration. Transpiration from leaves, of water taken up by roots, is the major contributor to water loss via the crop. For a growing crop in a particular environment, evaporation is usually referred to as evapotranspiration. Allen *et al.* (1998) defined a standard reference crop evapotranspiration (E_r) which can be adjusted with various coefficients for different crop growth stages and agro-ecological conditions. To quote Scotter and Heng (2003)….. "Allen *et al.* use the "big leaf" approach to obtained E_r and assume that the hypothetical reference crop has a height of 0.12 m, a surface resistance of 70 s/m, and an albedo of 0.23. The surface resistance indicates how readily water vapour escapes from the crop, while the albedo is the fraction of incoming solar radiation reflected by the crop. The reference crop fits the description of a short green crop, completely shading the ground, of uniform height, and never short of water, referred to in Penman's (1956) definition of potential evapotranspiration".

E_r is measured in mm per unit time, and the required data for calculating it include solar radiation (or sunshine hours), air temperature, air humidity and wind speed. Details of how E_r is calculated from the available weather data will be given later (4.2.4).

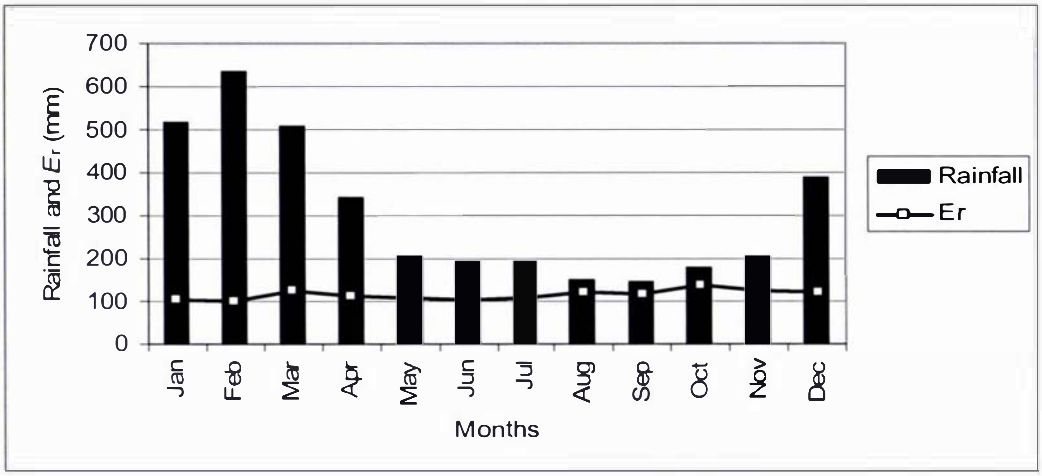
Reference crop evapotranspiration (E_r) was calculated (Table 3.3) for Dami, Sangara and Ramu Sugar, (which have nearly all the required climatic information), using average monthly parameter values. It is assumed in Table 3.3 that actual evaporation equals the reference crop evaporation, so the crop is never short of water. Ramu Sugar has the highest amount (80 %) of rainfall lost as E_r followed by Sangara (60 %) and then Dami (40 %). Water that is not evaporated is referred to here as surplus water, which includes deep drainage and surface runoff. Dami has by far the greatest surplus water, followed by Sangara and then Ramu Sugar. These processes are discussed later in 4.2.4.3.

Table 3.3 Mean annual rainfall, E_r (mm) and surplus water (mm) for Dami, Sangara and Ramu Sugar

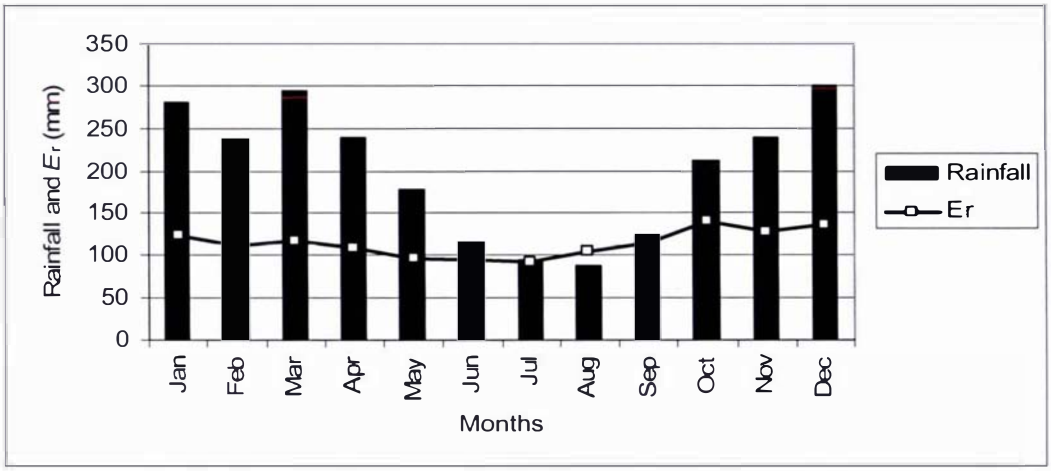
Site	Mean annual rainfall (mm)	Mean annual E_r (mm) (2003-05)	Surplus water (mm)
Dami	3657	1380 (40)	2280
Sangara	2398	1368 (60)	1030
Ramu Sugar	1913	1514 (80)	400

Percentage of mean annual rainfall shown in brackets.

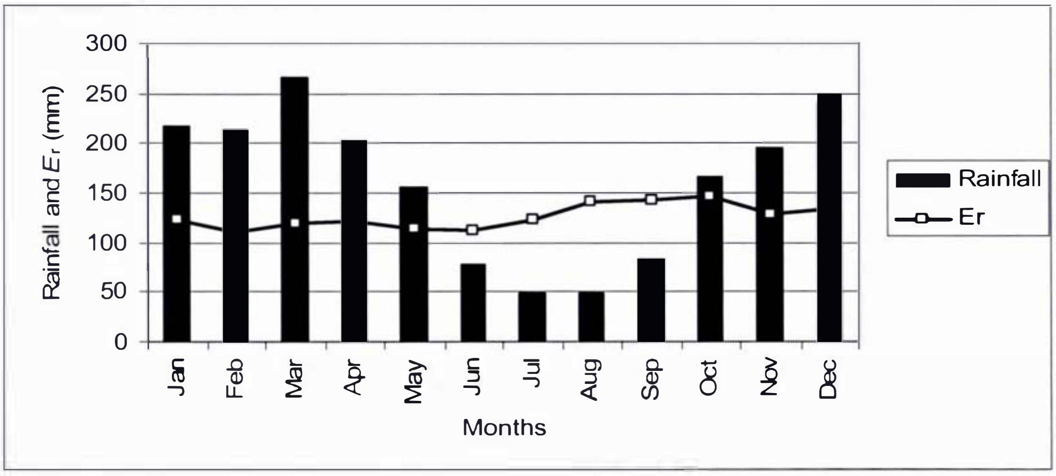
The monthly mean E_r for Dami is relatively constant throughout the year, whereas at Sangara, there is a small trough in the middle of the year and at Ramu Sugar there is a slight increase after July (Figure 3.9 (a), (b) and (c)). Monthly E_r values for the three sites range from 92 mm to 147 mm, with an average of 115 mm/month at Dami, 114 mm/month Sangara and 126 mm/month at Ramu Sugar. Palms will be stressed when all the readily available water within the rooting zone is extracted. Mature palms at Dami are unlikely to ever be water-stressed because a) the average monthly rainfall input is always higher than E_r (Figure 3.9 (a)), b) the palms are deep rooting (Appendix A2.2) and c) the soils have a high water holding (4.2.1.2.3) capacity. At Sangara, palms are more likely to be stressed on occasions due to a lower rainfall and a lower soil water holding capacity. At Ramu Sugar there is quite a large water deficit from June to September in an average year, and irrigation may be warranted.



(a) Dami



(b) Sangara



(c) Ramu Sugar

Figure 3.9 Monthly mean E_r (mm) and rainfall (mm) at Dami, Sangara and Ramu Sugar

3.4.8 Summary

- In terms of climate, PNG oil palm growing areas are highly suitable for oil palm production with mean annual rainfalls ranging from 2,300 mm to 4,000 mm per year.
- There is a clear "wetter-drier" rainfall pattern in WNB, NI, Oro and Ramu Sugar in Morobe Provinces, but not in Milne Bay Province.
- The mean number of rain days in a month ranges from 10 to 25 days.
- Mean daily sunshine hours are relatively constant throughout the year ranging from 4 to 6 hours.
- Mean daily minimum and maximum temperatures are relatively constant throughout the year, typically being about 23 ^{o}C and 32 ^{o}C respectively.
- There is clear annual pattern for wind run at Dami or Ramu Sugar; the wind run being highest in August, and lowest in December to March.
- E_r at Dami and Sangara is about 1,370 mm/year, and at Ramu Sugar, it is about 1,500 mm/year.

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Chapter 4

Hydrology

N losses via leaching, surface runoff and denitrification are directly associated with factors affecting the soil water balance (Chang and Zakaria, 1986; Aulakh *et al.*, 1992). Losses by leaching and surface water runoff usually occur when rainfall is greater than evapotranspiration after the soil has reached field capacity. Denitrification mostly occurs when the soil water content is high enough to create anaerobic conditions. By these three processes, N is lost in dissolved, particulate or gaseous forms. This review examines the various components of the water balance under oil palm and their contribution to N losses from the system.

4.1.1 The overall soil water balance

Water is continually recycled from the soil into the atmosphere and back to the soil (Kee *et al.*, 2000). Determining the soil water balance of an oil palm agro–ecosystem involves defining the fluxes of water into and out of the system, and associated changes in water storage over time. The water balance of an area (or a volume) is based on the principle of conservation of matter, which states that water is neither created nor destroyed but is stored, and can be transported from one point to the other, or transformed from one state to another (Hillel, 1998). Over any time period, the amount of rainfall received less the amount of water lost equals the change in the amount stored within the system. Water is lost through evapotranspiration, deep drainage and surface runoff (McAlpine *et al.*, 1983).

The soil water balance for any period and area can therefore be expressed as follows:

$$D = P - E + C - \Delta W \qquad [4.1]$$

Where

D = surplus water (mm), includes deep drainage and surface runoff

P = rainfall (mm)

E = evaporation (mm)

C = capillary flow (mm) up into the zone of interest in soils with high water table

ΔW = change in storage (mm)

A change in one of the components of the soil water balance affects the other components, and the resultant change determines in part the amount of nutrients lost from the soil via the various loss processes. According to Bristow *et al.* (1988), the soil water balance is affected by several factors including;

a) climatic factors - rainfall amount and intensity, solar radiation, temperature, wind and atmospheric vapour pressure
b) landscape characteristics - topography, soil type and subsurface pedological features
c) plant factors – age of crop, leaf area index, understorey vegetation, water stress and stomatal conductance
d) soil properties – storage and transport capabilities
e) management practices – use of machinery and other agronomic practices such as weed control and cover crop management.

In the next sections, the components of the water balance are discussed along with some of the above factors that affect these components and implications for N loss in oil palm systems.

4.1.1.1 Rainfall

Rainfall is the main source of water input into unirrigated cropping systems. Hartley (1988) summarised mean annual rainfall and monthly rainfall distribution for all major oil palm growing regions in the world. The annual rainfall figures ranged from 1,600 mm to 3,700 mm in Asia, 1,200 mm to 3,500 mm in Africa and 1,600 mm to 3,400 mm in Central and South America. In each of these regions, there were areas that had three to six months with less than 120 mm/month of rainfall. The Sangara site (and Milne Bay and Ramu Sugar) is near the middle of this range of annual rainfall but Dami (and Bialla) lie beyond the extreme wet end of the range. Dami may qualify as one of the wettest areas that oil palm is grown in. Amounts and distribution of rainfall for the different oil palm growing areas in PNG are discussed in 3.4.3. The minimum average monthly rainfall at Dami was 158 mm, and 107 mm at Sangara, while the maximum was 440 mm at Dami and 317 mm at Sangara, however very low amounts of less than 50 mm/month were recorded at both sites during the 1997 *El Nino* event.

4.1.2 Rainfall redistribution under oil palm canopy

At the plantation scale, rainfall (*P*) above the oil palm canopy is relatively uniform, however, as soon as it touches the oil palm canopy, it becomes unevenly redistributed, and is usually reduced in quantity as it moves to the ground. According to Crockford and Richardson (2000) redistributed rainfall reaching the soil surface can be partitioned into three fractions;

a) the amount that stays on the vegetation and is evaporated during and after the rain event, known as **interception** (I_r)
b) the amount that is intercepted by the plant but flows down to the soil surface via the trunk or stem known as **stemflow** (S_f)
c) the amount that either contacts the plant canopy and then drips from it or falls straight through the canopy to the soil surface, known as **throughfall** (*T*).

Mathematically, this can be expressed as;

$$P = I_r + S_f + T \qquad [4.2]$$

The extent of redistribution will be affected by 1) crop characteristics such as LAI and canopy structure, presence of epiphytes and buds on the stem, hydrophobicity of plant leaves and other parts and 2) climatic factors including amount, intensity, and duration of rainfall, wind speed, air temperature and vapour pressure during and after rain events.

Rainfall redistribution studies have been done for various reasons, some of which include;

a) assessing soil water balance (Domingo *et al*., 1994; Gash and Morton, 1978)
b) investigating nutrient cycling in forests (Parker, 1983)
c) assessing changes in soil properties around tree trunks (Gersper and Holowaychuk, 1970)

d) determining deep drainage and leaching of nutrients and agrochemical products (fertilisers and pesticides) to ground water (Parkin and Codling, 1990; Taniguchi *et al.*, 1996).

Such unevenly redistributed rainfall reaching the soil surface can be further modified by local ponding and redistribution, all of which affect the water flux into a soil. Local ponding can occur depending on soil infiltrability, plant litter and microtopography.

Redistribution studies have covered annual crops such as corn (Parkin and Codling, 1990), tree crops such as cocoa and citrus (Alva *et al.*, 1999; Li *et al.*, 1997; Opakunle, 1991) and agroforestry and coniferous forests (Schroth *et al.*, 1999; Taniguchi *et al.*, 1996).

Because of the range of crops and different reasons for studying rainfall redistribution, there is no one standard method for measuring it. For oil palm, there does not appear to have been any specific study done on the redistribution of rainfall and resultant nutrient losses.

4.1.2.1 Throughfall

As already mentioned, throughfall is defined as that part of the rainfall that reaches the soil surface directly or by dripping from the canopy (Lee, 1980).

Kee *et al.* (2000) found that 70 – 78 % of rainfall would reach the soil surface as throughfall in oil palm in Malaysia (see Table 4.1). The range of throughfall values found in oil palm stands was similar to that found for forests. Fahey *et al.* (2001) and Rowe (1979) reported throughfall of 67 and 77 % of gross rainfall for Douglas fir-radiata pine, and beech-podocarp-hardwood forest, respectively. Fahey *et al.* (2001) found a strong positive relationship between the size of rainfall event and throughfall. However, for oil palm there is a dearth of information on the amount and distribution of throughfall with distance from the trunk. Such information could have important implications for nutrient leaching. The percentage of rainfall (*P*) appearing as throughfall is likely to be somewhat site specific.

Table 4.1 Rainfall partitioning under oil palm canopy in Malaysia

Reference	Age (years) Ŧ	Location	Percentage of rainfall as		
			Stemflow	Throughfall	Interception *
UPM – Belgium JSRP, 1979	13	Gormali Est. Johor	13	70	17
And 1980	14		13	70	17
Squire, 1984	8	PORIM, Kluang, Johor	11	78	11
AAR (unpublished)	15	Balau Est. Selangor	11	72	17

Source; Kee *et al.* (2000)
* Estimated by difference between rainfall and the sum of throughfall and stemflow
Ŧ All palms planted at 148 per ha

4.1.2.2 Stemflow

Stemflow water is that part of the rainwater that is collected by the canopy, channelled to the stem and flows down the stem to reach the soil surface (Lee, 1980). Stemflow has a very important part to play in the soil water balance, because it is concentrated in a localized area of soil. In particular it can result in increased leaching of nutrients from the soil, and can also trigger surface runoff that can lead to the loss of nutrients in soluble or particulate forms.

Levia and Frost (2003) reviewed the literature on stemflow in various agro-ecosystems and showed that stemflow ranged from 0.6 to 45 % of rainfall. The main reason for the wide range in % values relates to the different canopy structures. Lee (1980) suggested mean stemflow for most forest trees of only 1 – 5 % of rainfall. Rowe (1979) reported stemflow of 1.5 % of rainfall for beech-podocarp-hardwood forest trees in New Zealand. For cocoa trees, Opankule (1991) reported stemflow of 1.8 % of rainfall. Kee *at al.* (2000) estimated mean stemflow for various oil palm plantations in Malaysia at 11 – 13 % of rainfall (Table 4.1).

It is generally found that oil palms tend to have quite large amounts of stemflow compared to other tree crops. Schroth *et al.* (1999) compared peach palm in a monoculture system with mixed tree crop systems comprising a number of tree crop species. They found that the monoculture had 20 % of rainfall as stemflow, compared to the mixed tree crop system that had only 3.4 %. They attributed the difference to the different canopy structures of the two systems. The palm canopy is such that it diverts a lot of intercepted water towards the trunk, resulting in more stemflow.

With annual crops, such as corn and sorghum, 49 % of rainfall appeared as stemflow at a rainfall intensity of 64 mm hr^{-1} (Bui and Box, 1992). Quinn and Laflen (1983) in a study looking at redistributed rainfall under corn, also reported stem flow of 49 % for a 12 week old crop, but this reduced to 16 % for a senesced canopy. The results suggest that the acutely-angled leaves channel a lot of intercepted water to the stem. This may have some relevance to oil palm, in terms of differences in redistributed rainfall during low and high crop seasons. During the low crop season palms go through a male phase and the fronds are generally at an acute angle, and this can result in increased stem flow. However during the high crop season, the heavy oil palm bunches pull the fronds down and the angles, between the fronds and the trunk are less acute, and therefore less rain may appear as stemflow.

Because of the high concentration of stem flow around the trunks, Gomez *et al.* (2002) and Schroth *et al.* (1999) have argued that fertilisers should be placed some distance from the trunks to avoid excessive leaching.

4.1.2.3 Interception

Interception is defined as the amount of rainfall held up and evaporating from the aerial parts of plants. The aerial parts of oil palm include the canopy (fronds), cabbage (the distal end of the trunk from which bunches and fronds grow), bunches, male inflorescence, stembuds and epiphytes growing on the palms. The amount of interception depends on the LAI (which depends on the number of leaves, the size of leaves and the density of the stands), and the presence and type of epiphytes. Interception is hard to measure directly, so it is usually calculated as the difference between rainfall and the sum of throughfall and stemflow. Kee *et al.* (2000) found that between 11 and 17 % of gross rainfall was intercepted by the aerial portions of the palm (Table 4.1). They cited Chang and Rao (1983), who reported that most of the intercepted rainwater was held up in the cabbage, bunches and frond buds (bases) and also retained on the trunk, with only a very small fraction being retained by the frond pinnae. Oil palm interception values appear to be generally lower than those found for other systems e.g. Fahey *et al.* (2001) and Rowe (1979) reported mean values ranging from 20% to 29 % for temperate forests and Opakunle (1991) reported interception of 24 % for cocoa. Water retained in the aerial parts of oil palm is either evaporated into the atmosphere or used by epiphytes and living organisms on the palms, and thus eventually is transpired into the atmosphere.

4.1.2.4 Conclusions from the review

- For oil palm in Malaysia a total of 83 – 89 % of total rainfall reaches the soil surface as stemflow and throughfall. However there appears to be a total lack of information on the pattern and variability of redistributed rainfall under the oil palm canopy.
- There appear to have been no studies done on the distribution of rainwater between throughfall and stemflow and impact on the nutrient and water dynamics under oil palm systems. A better understanding of this may lead to the development of management options to minimize leaching losses and enhance nutrient uptake.

- The Dami site may qualify as one of the wettest areas growing oil palm
- Rainfall above an oil palm canopy is relatively uniform but as soon as it touches the canopy it becomes unevenly redistributed
- Interception can account for up to 17 % of the rainfall
- Up to 78 % of rainfall can reach the soil surface as throughfall and is site specific
- Stemflow can be substantial, up to 13 % of rainfall.

4.1.3 Soil surface water runoff

Because of the high spatial variability of soil infiltrability, the generation of surface runoff water is also likely to be highly variable. Ponding and surface runoff will be generated in those parts of the field that have an infiltrability less than the rate at which water arrives.

Maena *et al.* (1979) reported on a trial that was carried out in Malaysia during a dry year to determine surface runoff under oil palm. The trial had four 5 m x 30 m plots, replicated four times. One plot contained a row of palms, one contained only the harvest path, one contained only the frond piles, and one contained all three of the above mentioned zones. Runoff was measured from the plots from December 1976 to November 1977 during which a total rainfall of 1,426 mm was measured with the monthly rainfall ranging from 23 to 281 mm. The proportion of total annual rainfall appearing as runoff was 20 % from the palm rows, 31 % from the harvest path, 3 % from frond piles and 18 % from the plot that covered all areas (Table 4.2). So, most of the runoff came from the palm rows and harvest paths. A review by Kee *et al.* (2000) of surface runoff studies done under oil palm in Malaysia, summarized in Table 4.2, shows that with the exception of frond piles, surface runoff measured under the palms ranged from 20 % to 49 % of rainfall with the highest value of 49 % recorded during the wet months, as expected. On the other hand, only 3 % runoff occurred in the frond piles.

Although some studies have looked at rainfall during the high rainfall months, none have developed any relationship between rainfall and other soil water balance components that might be used to predict runoff throughout the year. A significant amount of runoff (about half) occurs during the wet months and this could have a major effect on nutrient losses in the Malaysian and PNG systems.

Table 4.2 Surface runoff (% of rainfall) under oil palm in various plantations in Malaysia

Reference	Location	Soil/Slope	Palm age (years)	Mean annual rainfall (mm)	% Runoff	Notes
Kee and Chew (1996)	Lepan Kabu	Musang 7-7.5°	18	2748	28	148 palms ha^{-1}
	Balau	Rengam 6.9–7.1 °	14	2523	25	148 palms ha^{-1}
	Sri Kunak	Batang 5.2–6.2 °	13	1979	23	120 palms ha^{-1}
Maena et al. (1979)	Gomali Estate	Durian 3–4° (148 palms ha^{-1})	11	1426 (dry year)	20 31 3 18	Palm rows HP FP Mean
UPM – Belgium JSRP,	Gomali Estate	Durian 3-4° (148 palms ha^{-1})	12	2171	30	Mean
(1979 and 1980)			13	571 (4 wet months)	49	Mean

Source: Kee *et al.*, (2000)

Note the Malaysian studies were done on non-volcanic soils. Cattan *et al.* (2006) conducted a surface runoff experiment in a banana plantation over two crop cycles in Guadeloupe on an Umbric Andosol which had 2,500 – 4,500 mm annual rainfall, on a 12 % slope. The mean runoff coefficient for this volcanic soil ranged from 5 to 11 % which is much lower than the values reported for oil palm in Malaysia (Table 4.2). It would be reasonable to propose that surface runoff is probably much lower on the young volcanic ash soils of PNG than was found in the Malaysian studies, even though the PNG soils receive higher rainfall.

4.1.4 Soil water

4.1.4.1 Soil water content

Water is a very important factor because it affects most of the processes occurring in soils, such as; nutrient movement within and below the rooting zone, nutrient movement to plant roots, evapotranspiration rates, and soil biological processes such as mineralisation, nitrification and denitrification. Soil water content can be expressed in various ways (Hillel, 1998);

a) gravimetric water content (w) which is the mass of water (M_w) in a soil sample divided by the mass of solid soil (M_s). M_s and M_w are found by oven drying soils at 105 °C

$$w = M_w / M_s \qquad [4.3]$$

b) volumetric water content (θ) which is the volume of water (V_w) in a volume of soil (V_t)

$$\theta = V_w / V_t \qquad [4.4]$$

c) equivalent depth of water. Water inputs (rainfall and irrigation) and outputs (drainage, surface runoff water and evaporation) are measured in depth units, usually in mm. Each 1 mm depth of water is equivalent to 1 mm^3 of water per mm^2 of soil surface. Therefore the equivalent depth of water (W) in a soil profile from the surface to a specified depth (z_1) is the volume of water present per unit surface area. If θ is uniform with depth,

$$W = \theta z_1 \qquad [4.5]$$

However if θ changes with depth then the soil profile is treated as a number of layers with variable water contents θ_n and thicknesses Δz_n so

$$W = \sum_{n=1}^{m} \theta_n \, \Delta z_n \qquad [4.6]$$

4.1.4.2 Readily and total available soil water contents

As soil that has been thoroughly wet by heavy rainfall (or irrigation) loses its excess water, the larger soil pores (macro-pores) empty first as gravity pulls the soil water downwards. As the large pores are emptying and θ decreases, the pressure potential decreases (becomes more negative) because capillary and adsorption forces hold onto the remaining water in the smaller pores. The relationship between water content and force holding the remaining water is called the soil water retentivity curve, that plots pressure potential as a function of water content. The retentivity curves reflect the soil pore size distribution (at the wet end) and the specific surface of a soil (at the dry end). The relationship between soil pressure potential and soil water content is not unique but depends on the wetting history of the soil. This is called hysteresis. From the draining retentivity curves, macro-porosity (and so how well drained and aerated a soil is), field capacity, stress point, wilting point and both readily and total available water holding capacities of a soil can be estimated.

The total plant-available soil water (W_T) is all that water held between field capacity (θ_{FC}) and permanent wilting point (θ_{PWP}). Field capacity is rather loosely defined as θ in the soil 2 – 3 days after thorough wetting, when the excess water has redistributed and/ or drained out, the macro-pores have emptied, and the drainage rate has become very slow, or negligible. When this occurs, the pressure potential is often about -10 kPa (- 1.0 m). At permanent wilting point, soil water is tightly held by the soil solid phase, after the plants have withdrawn all the "available" water. At this point, plants cannot withdraw any more water, and the pressure potential is about -1,500 kPa. The total available water is thus:

$$W_{\mathrm{T}} = \sum_{n=1}^{m} (\theta_{\mathrm{FC,n}} - \theta_{PWP,n}) \Delta z_n \qquad [4.7]$$

Or assuming a uniform soil,

$$W_{\mathrm{T}} = (\theta_{\mathrm{FC}} - \theta_{\mathrm{PWP}}) z_{\mathrm{r}} \qquad [4.8]$$

where z_r is the effective rooting depth of interest.

Readily-available water (W_{R}) refers to the amount of water a plant can take up for growth and transpiration before it is affected by water stress (Scotter, 1977). W_{R} is the amount of water held between field capacity and stress point (θ_{SP}) (often estimated as the water content at a pressure potential at about -100 kPa), and is given by;

$$W_{\mathrm{R}} = \sum_{n=1}^{m} (\theta_{\mathrm{FC},n} - \theta_{\mathrm{SP,n}}) \Delta z_{n''} \qquad [4.9]$$

or in a uniform soil where z_r is the effective rooting depth,

$$W_{\mathrm{R}} = (\theta_{\mathrm{FC}} - \theta_{\mathrm{SP}}) z_r \qquad [4.10]$$

The soil above a coarse-textured sand, gravel and/or pumice horizon usually has a higher field capacity than a similar soil without such a horizon. The hydraulic conductivity reduces rapidly with decreasing pressure potential in the coarse horizon and this also reduces the amount of water sucked out of the finer-textured layer above. Clothier *et al.* (1977) showed that the amount of water stored in layered soils increases with an increase in the size of the particles in the coarser layer below but decreases with height above the layer.

Chang and Chow (1985) reported W_{R} for Malaysian soils of 120 – 208 mm in the top 1 m of soil. In NZ, Gradwell (1976) found W_{R} of from 103 to 175 mm, with a mean of 123 mm, in the top 76 cm of volcanic ash-derived soils, generally higher than for other non-volcanic soils.

Waringa (PNGOPRA Annual Report, 1985) conducted a study to determine the W_T and water balance of oil palm soils at five sites in WNB and eight sites in Oro. The study suggested that at Dami for a rooting depth of 120 cm, there was 175 mm of W_T while at Arehe (Oro), a site on same soil type as Sangara, there was 364 mm for a rooting depth of 130 cm. No other studies have been done on oil palm growing soils in PNG to determine water holding capacity which is obviously important in the water balance and availability for crop uptake.

4.1.5 Evapotranspiration

One of the very important components of the water balance is the return of water to the atmosphere which takes place through the process of evapotranspiration which is the combination of direct evaporation from soil and transpiration from leaves. Evaporation results in a change of state of water from liquid to vapour. Transpiration occurs by evaporation through leaf stomata (Brooks *et al.*, 2003). The process is usually measured in mm per unit time and 1 mm day^{-1} will equate to 10 m^3 ha^{-1} day^{-1} water loss.

For evaporation to occur, all three of the following conditions have to be met (Brooks *et al.*, 2003);

b) there has to be a flow of energy to the evapotranspiring surface
c) there has to be a flow of water in liquid form to the surface and
d) there has to be a flow of water vapour away from the surface.

Factors affecting evaporation, according to Allen *et al.* (1998) include;

a) Weather factors; radiation, air temperature, humidity and wind speed
b) Crop factors; type, variety, age and differences in height, resistance to transpiration and reflectance
c) Management and environment factors; low fertility, the presence of an impermeable soil layer at depth, pests and diseases (all of which can lead to poor crop growth and reduced evapotranspiration).

Reported evaporation rates for oil palm in Malaysia range from 2.5 mm to 10 mm per day. Foong (1991) reported 3.5 mm day^{-1} from irrigated palms, increasing to 10 mm day^{-1} in very dry months in 1997 which was an *El Nino* year. Kee *et al.* (2000) reported evaporation from immature palms of 4.3 mm day^{-1} decreasing to 2.5 mm day^{-1} during the dry months. A typical value of 4 mm day^{-1} would produce an evapotranspiration loss of around 1,500 mm per year from an oil palm system. This means that areas that have less than 1,500 mm of rainfall, or have uneven monthly rainfall distributions at higher total annual rainfall, may have water stressed-palms at certain times.

4.1.6 The water balance summary

A summary of an oil palm water balance by Kee *et al.* (2000) in Malaysia showed 40 – 65 % of rainfall being lost as evaporation and 11 – 28 % as deep drainage (Table 4.3).

Table 4.3 Percentage of rainfall as evaporation (mean 5 years 1992 – 1996)

Site	**Rainfall (mm)**	**Evaporation (%)**	**Runoff (%)**	**Deep drainage (%)**
Sri Kunak Estate	2060	65	22	13
Balau Estate	2527	60	30	11
Lepan Kabu	2648	40	32	28

Source: Kee *et al.*, (2000)

4.1.7 Findings from the review

- In Malaysia surface runoff amounted to 3 % of the total rainfall in the FP zone and 31 % from the HP but these figures were achieved on non-volcanic soils
- There has not been any research done on the water balance components in the oil palm growing areas in PNG, despite its relevance to nutrient losses.
- Studies done in other countries are of limited application to PNG, due to the different soil and climatic conditions.
- There is a lack of understanding of the water dynamics under the palm and this study addresses some of these issues, relating mostly to N loss.

4.2 Field research

4.2.1 Bulk density, water retention and infiltrability.

a) Bulk density

Soil bulk density (ρ_b) is measured as the dry weight of a unit volume of soil. In oil palm plantations, increased ρ_b can occur as a result of a range of management practices including;

a) use of machinery to remove crops
b) use of machinery to spread fertilisers
c) falling bunches causing compaction in the weeded circle zone and
d) foot traffic during harvesting and fertiliser operations.

Increased ρ_b means a reduction in porosity that affects the infiltrability and aeration of soil, root growth and activity and soil microbial activities. All these can affect soil productivity.

b) Water retentivity curves

Water retentivity curves provide useful information about the pore size distribution and plant-available water holding capacity of a soil (Loveday, 1974). The volume and pore size distribution varies with soil type due to differences in texture and structure. Such differences can have major effects on soil permeability and water storage capacity. The capacity to store water is very important because it determines the availability of water to crops during periods of low rainfall (Hillel, 1998).

c) Infiltrability

The process by which water enters the soil (usually flowing downwards) is called infiltration. The volume of water moving through an area of soil per unit time is referred to as the infiltration rate, and is commonly measured in mm per hour. The maximum infiltration rate that a soil can sustain is sometimes called the infiltrability (Hillel, 1998). It is measured by ponding water on the soil surface and observing the rate at which it soaks in. The infiltrability relative to the rate at which water is supplied to the soil surface, i.e. rainfall intensity, determines whether all the added water infiltrates or some of it ends up as surface runoff water. Water entering the soil recharges the crop rooting zone and provides water for root uptake and transpiration. Infiltrating water is also the medium for transporting nutrients down to the roots. But these nutrients can also move out of the rooting zone in which case they may contaminate the ground water (Rose, 2004). Surface runoff water can result in soil erosion and loss of plant nutrients from the system. An understanding of infiltration rates, and of the related soil physical properties such as ρ_b and water retentivity, in the oil palm system is important for efficient soil, water and nutrient management.

The studies of the basic soil physical properties were done with the following aims;

1) To determine ρ_b and water retention characteristics of the soils at both experimental sites
2) To determine the infiltrability of different zones within the plantations at both experimental sites.

4.2.1.1 Methods and materials

4.2.1.1.1 Bulk density

Bulk densities were determined at each of the sites and for each pedologically-distinct horizon. Soil pits were dug down to 1.5 m and 2.0 m depths at Dami and at Sangara, respectively. The reason for only digging down to 1.5 m depth at Dami was to economise on the number of samples since there were at least 9 soil horizons identified in the 1.5 m depth. Soil samples were taken from the same soil pits as those used for water retention measurements, however they were not collected at the exact same time. At Dami, ρ_b measurements were determined only once and from just one soil pit (Table 4.4). At Sangara ρ_b measurements were made at four different times and from three different pits (Table 4.4). Bulk density measurements were repeated on three occasions at Sangara because the results from the first samplings provided unusual retentivity data. There were three replicate soil cores taken from each horizon at Dami and three or five at Sangara (see Table 4.4).

Table 4.4 Dates of soil sampling for ρ_b determinations at Dami and Sangara

Site	Month	Reps/horizon	Pit		
			1	2	3
Dami	December 04	3	X		
Sangara	December 04	3	X		
	April 05	5		X	
	July 05	3	X	X	
	December 05	5	X	X	X

X = sample taken

Soil cores were taken using a wooden mallet to hit the sharpened stainless steel cylinders into the soil. The steel cylinders had an internal diameter of 5 cm and their length was also 5 cm. Except for the December 05 sampling, the soil cylinders were hammered sideways into the different soil layers. For the thicker soil horizons, replicate soil cores were taken diagonally across the pit face to cover the whole horizon depth. In December 2005, soil cores were sampled, horizon by horizon, starting at the surface working down to the lowest horizon. Soil from the cylinders was emptied onto stainless steel plates and dried at 105 °C for 2-3 days to determine oven-dry weight.

4.2.1.1.2 Water retentivity and gravimetric water content

Soil samples were collected, as outlined in the next paragraph, from the above mentioned soil pits down to 1.5 m depth at Dami and 2.0 m at Sangara, assuming that the most active oil palm roots lie within the top 1.5 m of soil. At both sites, the first batch of soil samples was collected from Pit 1 in June 2004. Batches 2 and 3 were collected from Pits 2 and 3 at Sangara in July 2005. Soil samples were collected a second time at Sangara, because the first set of results appeared unusual in that the available water storage capacity was so low in some horizons.

From each pedologically-distinct horizon, about 200 g of 'undisturbed' soil was taken in duplicate. At depth, at both sites, where the texture was sandy and structureless, soil cores could not be obtained so loose soil was collected. The collected soil samples were placed into sealed double plastic bags and taken to Massey University. The samples were packed in boxes with cushioning to avoid them being crushed during transit to try to preserve their natural structure.

At Massey University, gravimetric water contents at pressure potentials of -10 kPa, -100 kPa and -1,500 kPa were determined using suction and pressure plate apparatus. Soil samples were placed on wet ceramic plates and left overnight to fully saturate. The plates were then placed under pressure or suction, creating a pressure difference across the plate. The pressure difference caused water to flow out of the soil until the pressure potential in the soil water equilibrated with the pressure difference across the porous plate. Soil water stopped flowing out when equilibrium was attained at the applied pressure. The soil gravimetric water content was then determined by weighing the soil before and after oven drying at 105 °C overnight.

Gravimetric soil water content data from the *in situ* leaching experiment (8.2.4.4) are also included in this discussion. Water contents were determined for the 5 leaching experiments at 20 cm depth increments (8.2.4.5).

4.2.1.1.3 Infiltrability measurements

Four 3.0 mm thick steel sheets were rolled and welded to form infiltrometer rings with an internal diameter of 45 cm and height of 25 cm. One end of each ring was sharpened from the outside in.

Each ring was driven into the soil to a depth of about 5 cm (Plate 4.1). A bund of soil was then pressed firmly against the outside of the ring to prevent any seepage from the edges. A piece of cloth was then placed inside the ring on the soil surface, to minimize the impact of water directly striking the soil surface, dispersing soil particles and causing clogging of soil macro-pores. A 20 cm strip of tape measure was inserted inside the ring, and the top edge was pegged to the top end of the ring with a wooden clothes peg. Water was then poured into each ring, directly onto the cloth, until it reached a height of 3-4 cm from the top of the ring. When pouring stopped, timing started, using a stop watch. The height of the water column at 2 minute intervals was recorded for the next 8 to 10 minutes. The time interval between readings was then increased to 5 minutes and eventually to 10 and 15 minutes. When water levels reached the lowest height possible without exposing any of the soil surface, the ring was topped up again with water and timing resumed. Recording continued for 30 minutes to 1 hour, depending on water availability and the rate at which the water level dropped. The exception to the above was for measurements done in the frond piles at Dami. The time taken for all the water to infiltrate was less than 1 minute, so the time was recorded when the water level reached the lowest height, and then more water was poured into the ring for the next timing, and measurements continued in this way for 20 to 30 minutes.

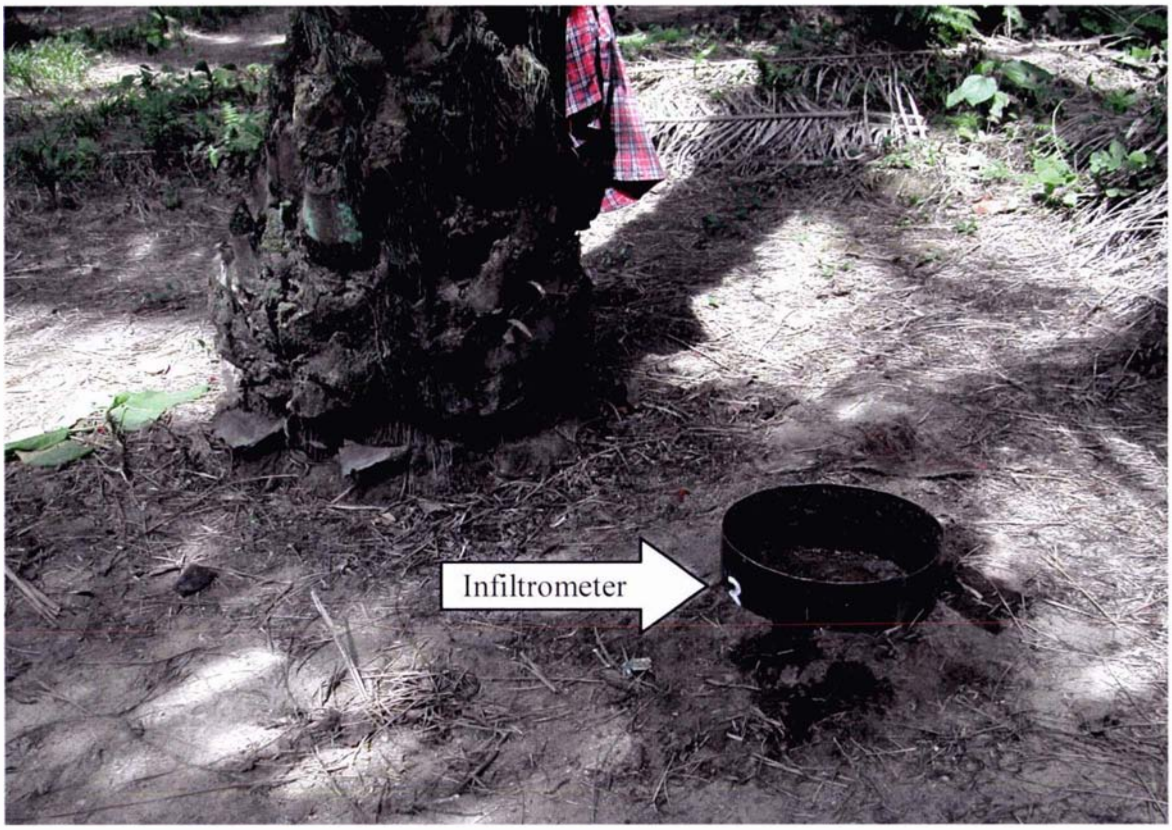


Plate 4.1 Inserted infiltrometer in the weeded circle

At Sangara, ten replicate measurements were made in each of the zones, whereas only five replicate measurements were made at Dami. At both sites, measurements were done in the FP, FT, WC and HP zones. At Sangara, measurements were later done in the BZ area, with nine replicates.

At Sangara, infiltration rates were also measured in the subsoil, below 20 cm depth where the soil texture changes to a fine sandy clay. To make subsoil measurements, the surface layers were removed and the exposed subsoil was chipped off with a small knife so that smearing did not close the macro-pores and affect water entry into the soil. Four replicate measurements were made in each zone.

At Sangara, rainwater stored in a tank at Igora OPIC station was used for the experiment. Because measurements at Dami were done during the low rainfall months, ground water was used. Total dissolved solids for water used at Dami was 42 ppm.

4.2.1.2 Results and discussion

4.2.1.2.1 Bulk density

As already mentioned ρ_b measurements were done three times at Sangara but only once at Dami. The measurements at Sangara showed higher ρ_b at 30 – 60 cm depth and below 160 cm depth (Figure 4.1). The detailed data are given in Appendix A2.1.

The mean ρ_b values are lower at Dami at all depths than at Sangara (Figure 4.1). The variation in ρ_b with depth at both sites reflects the different soil textural and structural properties of the various soil horizons. Elevated ρ_b at some depths at Dami (40-60 cm) is due to the presence of a slightly denser volcanic ash/sand layer. The ρ_b at Dami range from 0.7 to 1.06 g cm^{-3} while at Sangara all values were greater than 1.00 (ranging from 1.14 to 1.43 g cm^{-3}). The high ρ_b at 30 – 60 cm depth at Sangara is associated with increased clay content. Similar results have been reported by Tyrie and Bleeker (1990) for soils at Sangara in the Higaturu/Sangara soil families. They also suggested that the increase in ρ_b at depth is due to an increase in clay content in the B horizon. Clay skins can be observed on the peds in these soils. The ρ_b of the Higaturu/Sangara soils that they surveyed were 1.29 g cm^{-3} at 0-23 cm depth and 1.49 g cm^{-3} in the subsoil, at 49 - 80 cm depth. Such high ρ_b values are not found in other soil types in oil palm areas in Oro Province, where values range from 0.80 - 1.0 g cm^{-3} in the surface layers to more than 1.3 g cm^{-3} in the subsurface (Tyrie and Bleeker, 1990). Volcanic ash soils usually have low ρ_b, and this is reflected in the soils at Dami, but not at Sangara. The high clay content at Sangara suggests poorer soil structure which is probably reflected in the compacted subsoil layer at depth (30 – 60 cm) (Bleeker, 1987). Zijsvelt and Torlarch (1975) did a soil survey in the Ala-Kapiura area which included the Dami site in WNB Province. They found ρ_b to be 0.47 – 0.64 g cm^{-3} for weathered volcanic ash soils and 0.94 g cm^{-3} for non-weathered volcanic ash beds in the area; values that are close to those reported here.

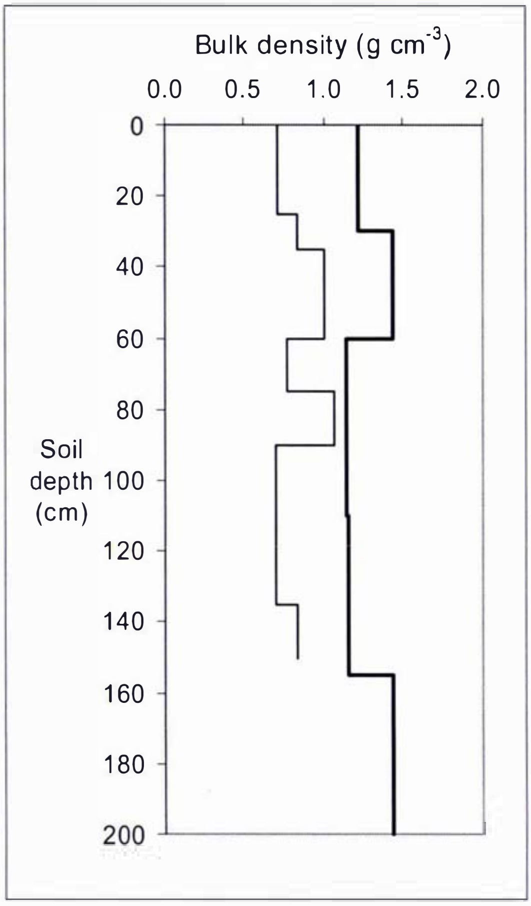
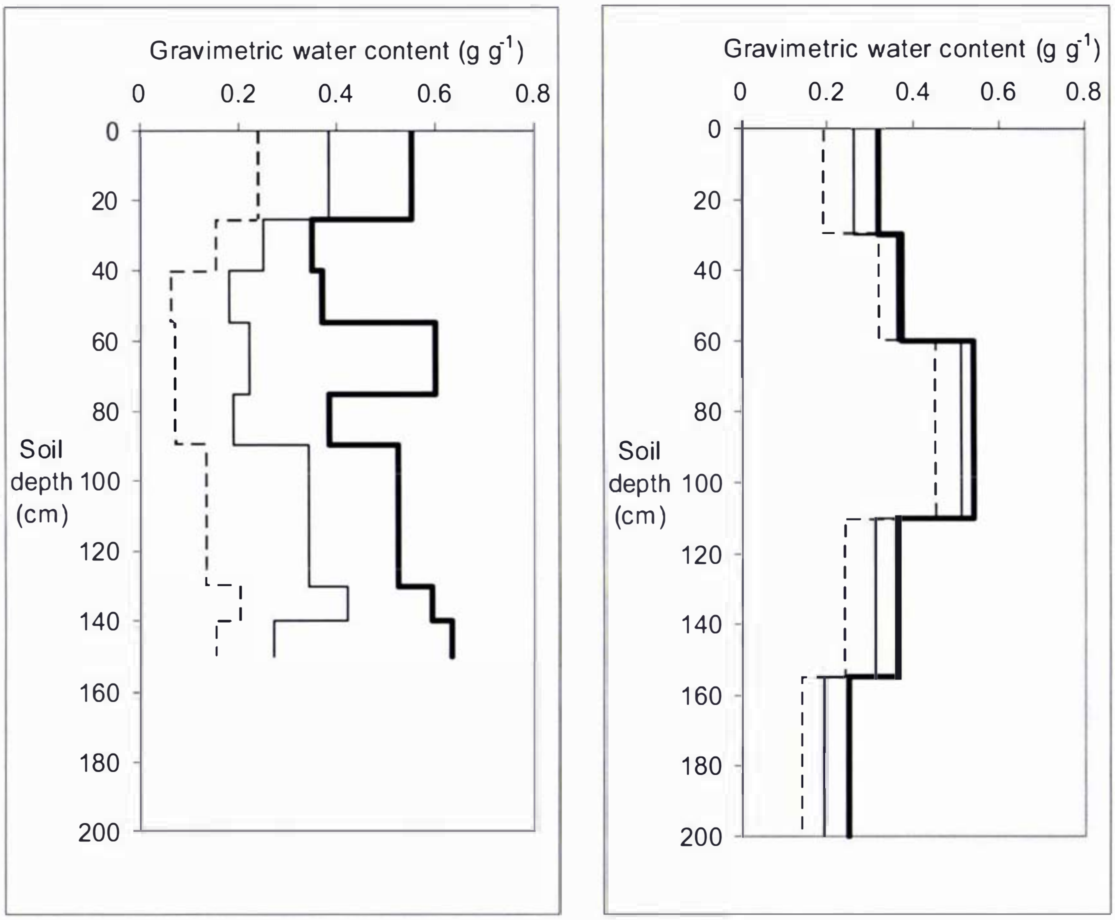


Figure 4.1 Soil bulk density in soil pits (FT) in the experimental sites, the horizon designations are shown in Appendices A1.1 and A1.2
Dami (———) and Sangara (—)

The higher ρ_b in the 30 – 60 cm depth at Sangara implies a lower porosity and probably a lower macro-porosity than at Dami (where ρ_b was < 1.0 g cm^{-3}), and this could slow water movement in the soil leading to a temporary perched water table during heavy rain, and consequently an increase in the amount of surface runoff water.

4.2.1.2.2 Water retentivity

At both Sangara and Dami, the gravimetric soil water contents at all pressure potentials fluctuated with depth, reflecting differences in soil textural and structural properties (Figures 4.2 (a) and (b)). The detailed data are given in Appendix A2.1. Differences in soil texture are discussed in 3.1.1. These differences in gravimetric water content for the three different pressure potentials are larger at Dami than at Sangara. At 30 – 60 cm depth at Sangara, the difference in gravimetric water content between -10 kPa and –100 kPa is negligible. The larger differences found at Dami than at Sangara suggest that the soils at Dami have a larger water holding capacity than do those at Sangara, a feature that is discussed in more detail in the next section.



a) Dami b) Sangara

-10 kPa (**—**), -100 kPa (———) and -1,500 kPa (- - - -)

Figure 4.2 Gravimetric soil water content at Dami and Sangara

4.2.1.2.3 Water availability and porosity

The calculated total and readily available storage capacities in each horizon are shown in Table 4.5. Also shown are ρ_b, and porosity (f) calculated as,

$$f = 1 - \rho_b / \rho_s \qquad [4.10]$$

where ρ_s is the particle density, assumed to be 2.5 g cm^{-3}. The macro-porosity is also given, calculated as the difference between the total porosity (f) and the volumetric water content at -100 kPa, as macropores (defined here as pores larger than 0.03 mm diameter) drain at -100 kPa (McIntyre, 1974).

Table 4.5 Readily (W_R) and total available water (W_T) and porosity of soils at Dami and at Sangara

Sites	Depth (cm)	Bulk density (g cm^{-3})	W_R (mm)	W_T (mm)	Porosity	Macro – porosity
Dami	0-25	0.71	31.5	55.7	0.72	0.44
	25-35	0.84	27.2	35.2	0.66	0.41
	35-43	0.84	16.0	20.0	0.66	0.41
	43-53	1.00	15.5	28.6	0.60	0.21
	53-60	1.00	12.0	22.0	0.60	0.21
	60-77	0.77	7.1	78.3	0.69	0.37
	77-90	1.06	16.3	33.2	0.58	0.19
	90-133	0.70	87.1	133.8	0.72	0.47
	133-144	0.83	10.4	30.4	0.67	0.27
	144-150	0.84	22.5	56.4	0.66	0.26
Total	0 - 150		246	494		
Sangara	0-30	1.22	23.9	47.9	0.51	0.23
	30-60	1.43	7.7	28.5	0.43	0.05
	60-110	1.14	15.2	54.0	0.54	-0.01
	110-155	1.15	24.6	64.4	0.54	0.17
	155-200	1.43	28.5	63.6	0.43	0.26
Total	0 – 200		100	260		

Readily and W_T water at Dami for the whole profile are much higher than at Sangara (Table 4.5). Again the W_R and W_T for the various depths reflect the different soil textural and structural properties (See Appendices 1.1 and 1.2). Considering just the topsoil, a W_R value of 24 mm in the top 30 cm depth at Sangara implies that palms would stress after just 4-6 days of nil rain compared to palms at Dami which would reach the same condition after 11-15 days, (assuming 4 mm day^{-1} evaporation). However, because of the deep rooting nature of perennial tree crops, palms will explore the soil to much greater depths for both water and nutrients. At Sangara, W_R and W_T values down to 200 cm depth represent 100 mm and 260 mm of water respectively and at Dami, equivalent values are 246 mm and 494 mm in the top 1.5 m of soil. These values imply that palms will experience stress after 25 days of nil rain at Sangara, while at Dami it will be after about 54 days, assuming the effective rooting depth is 1.5 – 2.0 m. So water stress is unlikely to be encountered at Dami because mean monthly rainfall is always greater than mean monthly E_r (3.4.7) and the soil stores a large amount of available water. Some water stress could occur at Sangara, in lower rainfall months due to the lower plant-available soil water storage capacity.

Macro-porosity values at Dami are high (Table 4.5), suggesting good aeration properties and rapid drainage after heavy rain events. Minimal surface runoff is expected at Dami. At Sangara, the very low macro-porosity at 30 – 110 cm depth suggests poor aeration and poor drainage at these depths that could lead to a possible perched water table and surface ponding of water during heavy rainfall events. The calculated negative macro-porosity at 60 – 110 cm depth is obviously anomalous. It is caused by different soil samples being used for measurements of bulk density and retentivity.

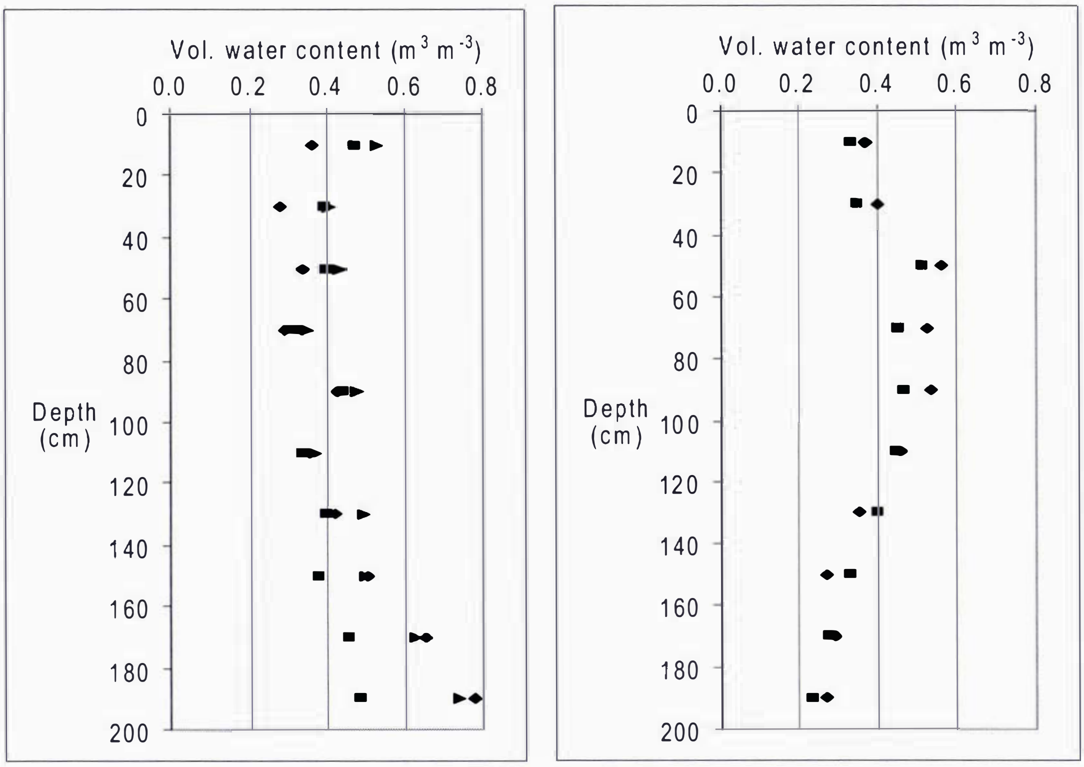
4.2.1.2.4 Field estimates of field capacity

The gravimetric water contents determined from the final sampling of the five *in situ* leaching experiments (to be described in 8.2.4.4 and 8.2.4.5) were multiplied by the bulk density (Table 4.5) to get volumetric water contents down to 2 m depth for the experimental sites at Dami and Sangara. The results are shown in Figure 4.3. The water balance calculations suggest that soil water deficit values at the time of sampling were 2 mm, 9 mm and 0 mm respectively for Experiments 1, 2 and 3 at Dami, and 17 mm and

10 mm respectively for Experiments 1 and 2 at Sangara, so these values can be used as estimates of field capacity.

At Dami, the soil volumetric water content at "field capacity" was fairly constant at around 0.4 $m^3\ m^{-3}$ in the top 1.4 m, but then gradually increased with depth down to 2 m, reaching over 0.7 $m^3\ m^{-3}$ in Experiments 1 and 3 (Figure 4.3 (a)). This increase in volumetric water content with depth is probably due to the presence of a very coarse textured horizon just below 2 m depth, which means that at field capacity less water is sucked out of the soil immediately above as explained by Clothier *et al.* (1977). The increase with depth was a lot less pronounced for Experiment 2 at Dami. This may perhaps have been because the soil profile had not completely rewet following a previous dry period, despite what the water balance suggested. Alternatively, the coarse-textured layer may have been deeper at the particular location where Experiment 2 was conducted.

At Sangara the water content at "field capacity" was highest between 0.4 and 1.0 m depth (Figure 4.3 (b)). This is probably due to a higher clay content in the soil at this depth (3.1.1.2). Similar water content profiles to those shown in Figure 4.3 were reported by Nelson *et al.* (2006) (see Figure 4 in Appendix A2.2). However the actual water contents are slightly different, probably because the data in the Appendix were obtained using the factory calibration of the Sentek Diviner 2000® soil moisture monitoring equipment. While this calibration is likely to be satisfactory for temporal changes in water content, the absolute inferred values inferred are likely to be less accurate.



(a) Dami (b) Sangara

Experiment 1 = ◆ Experiment 2 = ■ Experiment 3 = ▶

Figure 4.3 Volumetric water content of *in situ* leaching experiment at Dami and Sangara

4.2.1.2.5 Infiltrability

The infiltrability data are shown in Figures 4.4 to 4.6. Generally all measured infiltrabilities were very high initially, and then gradually decreased with time until a steady or near-steady rate was reached, as illustrated in Figure 4.4. The very high rates observed in the initial stages are due to both a pressure potential gradient ("sponge effect") and the effect of gravity pulling the water into the soil. However with time, as the surface soil becomes fully saturated, the rate at which water infiltrates depends only on gravity. The near steady infiltration rate is also approximately equal to the saturated hydraulic conductivity of the least permeable layer above the water front. The mean of the last three points, e.g. A, B and C in Figure 4.4, at the end of the curve was taken as the infiltrability for that particular zone in subsequent calculations. A check on the infiltrability data suggested that the values were roughly normally distributed, therefore no transformation was required before statistical analysis.

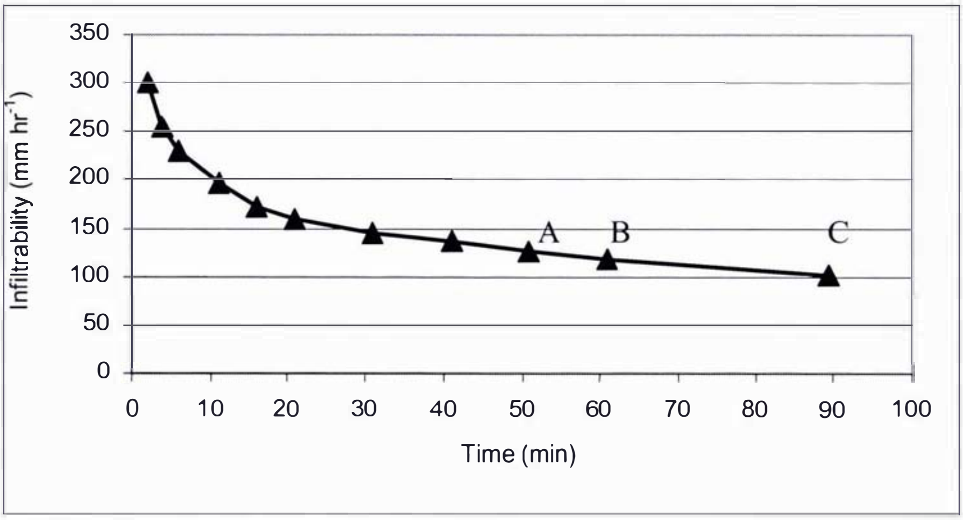


Figure 4.4 Change in infiltrability with time in the HP at Sangara

Statistical tests (ANOVA) on the infiltration rates indicated significant differences ($p<0.001$) between the zones under palms and between the two provinces. Infiltration rates under frond piles at Dami were higher than for other zones, except at Sangara where the rates under the frond piles and frond tips were comparable, but lower, than at Dami (Figure 4.5). Low infiltration rates in the WC and HP are probably due to the surface soil being compacted. The soil surface in the WC is cleared either manually or with herbicide spray or both, and it also receives falling harvested bunches. A single fresh fruit bunch weighs between 15 and 25 kg for mature palms. Workers also walk on the WC during harvesting, pruning and fertiliser spreading. As a result, the soil in the WC is somewhat compacted. Along the HP, fruit bunches are wheel-barrowed out from the field at Sangara. At Dami, tractors are driven along the wider HP to move bunches to the roadsides and to distribute fertiliser, and all these can cause compaction. The HP is also cleared of any vegetation either manually or with herbicides, and therefore the soil probably has less biological activity to reverse the effect of compaction by creating macro-pores. No infiltration measurements were made in the BZ at Dami because at the time of measurement, BZ was not required as a zone.

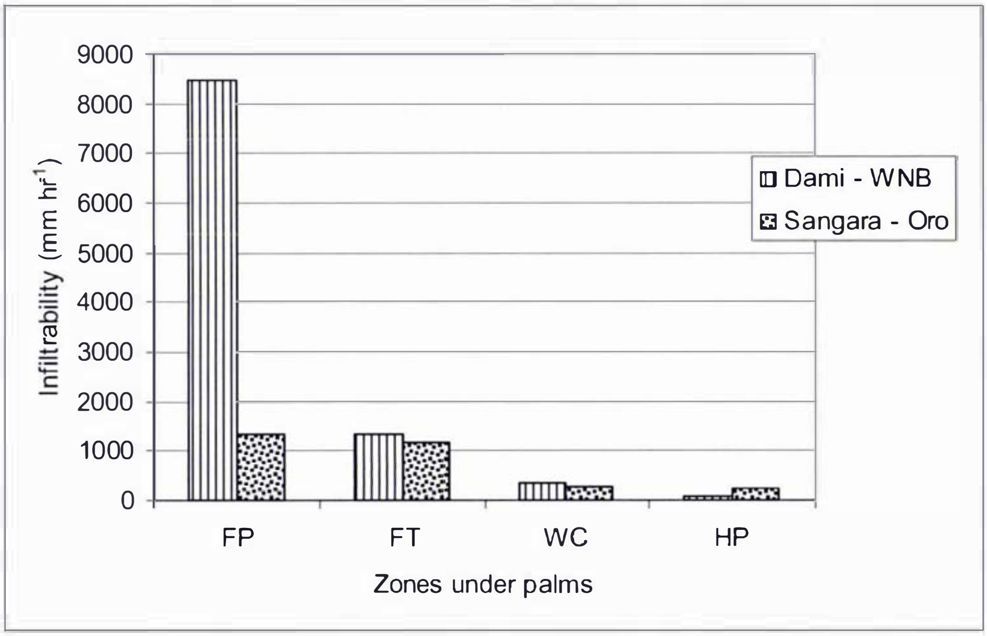


Figure 4.5 Infiltrability under the different zones under the palms at Dami and Sangara

The infiltrability in the FP is higher at Dami than at Sangara. At both sites, similar quantities of pruned fronds are placed in the frond piles every year. However, the FP at Dami has been receiving pruned fronds for two generations of palms while at Sangara due to realigning before the replant, the FP has only been in place during the second generation of palms. Therefore the age of the piles and soil C contents beneath the piles

(3.3.3.2) are higher at Dami than at Sangara resulting in greater biological activity that could be one reason for the high infiltrability at Dami. Another possible reason could be due to the compacted clay layer at 30-60 cm depth at Sangara (4.2.1.2.1) that slows the movement of water into the soil and contributes to the lower infiltrability compared to Dami.

Subsoil infiltrabilities at Sangara are significantly ($p< 0.002$) lower than for the topsoils in the FP and FT zones (Figure 4.6) and appear relatively constant across all zones, suggesting management practices have only affected the topsoils. The data also suggest that infiltrabilities at Sangara are reduced by the nature of the subsurface layers. This phenomenon can result in a temporary perched water table, that could reduce the volume of water moving into the soil, and eventually lead to increased surface runoff when the water table reaches the surface.

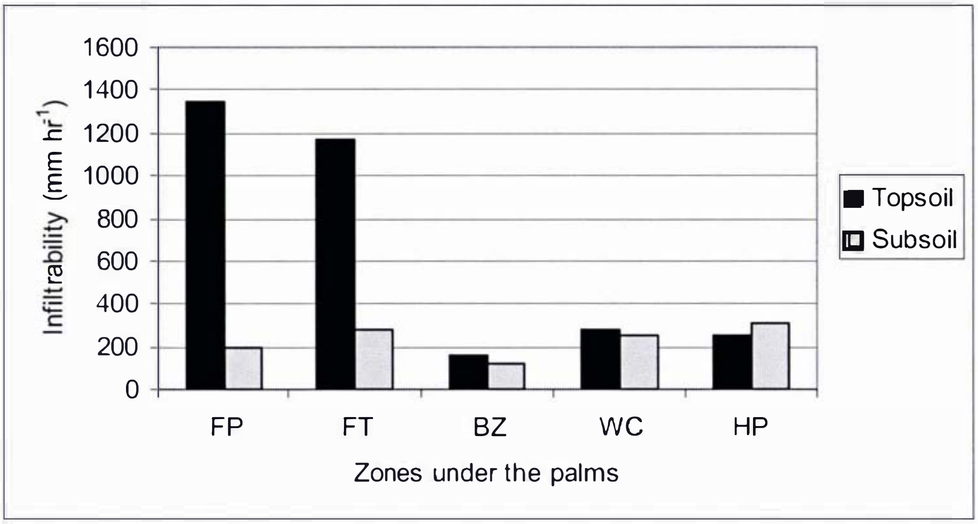


Figure 4.6 Infiltrability on the surface and subsurface soil at Sangara

Various studies have shown that infiltrability is a highly variable soil property, with a CV of 48 – 320 % for saturated hydraulic conductivities and of 23 – 97 % for infiltration rates (Jury and Horton, 2004). The CV in this present study was 113 %. However these results suggest that a lot of the variation seen under oil palm at the two sites may be due to the combination of cultural practices and subsoil texture.

4.2.1.2.6 Summary

- Soil bulk density at Dami ranges from 0.7 to 1.06 g cm^{-3} and is generally lower than at Sangara. Sangara soils have bulk densities of 1.14 to 1.43 g cm^{-3}
- The soil at Dami can store more plant-available water than can the soil at Sangara
- Mean volumetric water contents in the FP and BZ were 0.42 m^3 m^{-3} at both Dami and Sangara
- The Dami soil has a higher macro-porosity than the Sangara soil
- The infiltrability in the FP area at Sangara is comparable to that for FT, but higher than those in the WC and HP
- At Sangara the lower infiltrability of the subsoil compared to the topsoil could cause a temporary perched water table to develop after heavy rain. This might also result in increased surface runoff.

4.2.2 Rainfall redistribution under oil palm

4.2.2.1 Methods and materials

Two separate experiments were set up to determine the redistribution of rainfall and its variability under oil palm canopy. The first experiment at Sangara involved the use of 200 L steel drums (large catch cans) that were either cut in half for catching throughfall or not cut in half for concurrent stemflow measurements. The large catch "cans" were 570 mm in diameter. The second experiment involved the use of small catch cans for throughfall measurements around the *in situ* leaching plots at both Dami and Sangara (8.2.4).

The small cans (fish cans that were 70 mm in diameter by 150 mm deep) were mounted on stakes so that they were 400 - 500 mm above the ground, and just clear of any existing frond piles. Funnel-shaped clear plastic sheeting was placed inside the cans to minimise water splashing out of them. The drums and cans were emptied at about 0730 h each day and the water volume collected was measured.

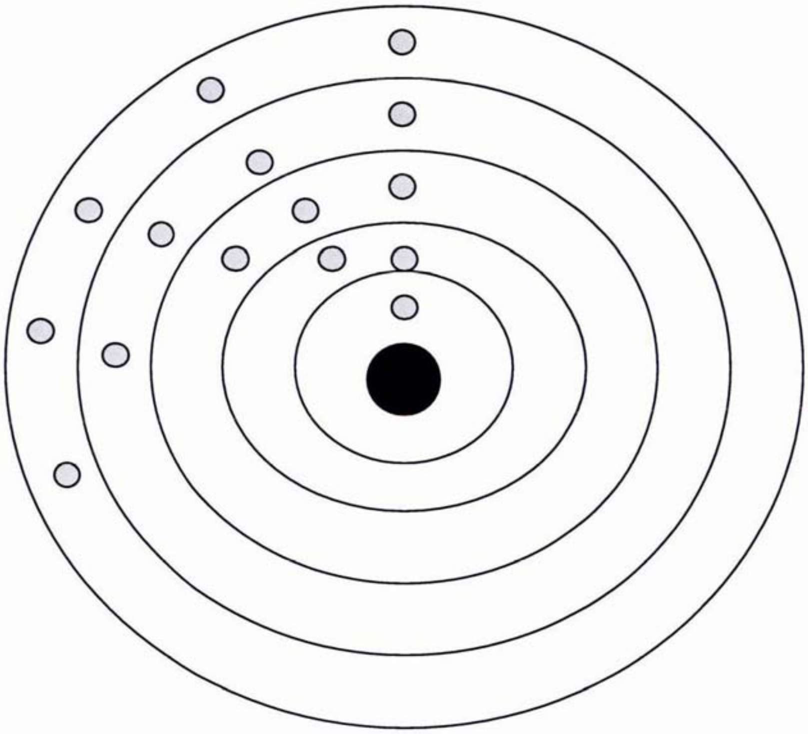
To collect stemflow, the bud ends at a height of about 1.5 m above ground were removed from three palms and clear plastic was pinned around each trunk so that it funnelled stemflow into a length of plastic guttering (square profile, 920 mm by 920 mm) which fed the water into a covered 200 L drum (Plate 4.2). During rainfall events, these drums were tipped over, when full, and the number of times this was done was recorded along with the water volume when the drums were only partly full.

The first experiment at Sangara was done in two phases. The first phase was a preliminary experiment, in January 2003, and the second phase was a more comprehensive experiment in August-September 2003. A 270 mm diameter rain gauge was placed in an open area 40-50 m from the actual experimental site.

For the preliminary January 2003 experiment, stemflow was measured on three palms as described above. Also five of the large drums were placed under the canopy of each of these palms to collect throughfall. One drum was placed so there was a 400 mm gap between the drum and the oil palm trunk (Plate 4.2). The remaining four drums were placed at increasing radial distances from the trunk, with a 300 mm gap between adjacent drums. Assuming that throughfall was a function of radial distance from the trunk, the results for the five drums were taken to represent the throughfall in five notional annular zones around each trunk. The trunk radius was 0.4 m so the area occupied by the stem was 0.5 m^2. The outer radii of the annular zones were taken as 1.45, 2.34, 3.23, 4.12 and 5.08 m, so their respective areas were 6.1, 10.6, 15.6, 20.5 and 20.8 m^2.

Plate 4.2 Throughfall drum numbers 1 – 5 and stem flow field set-up

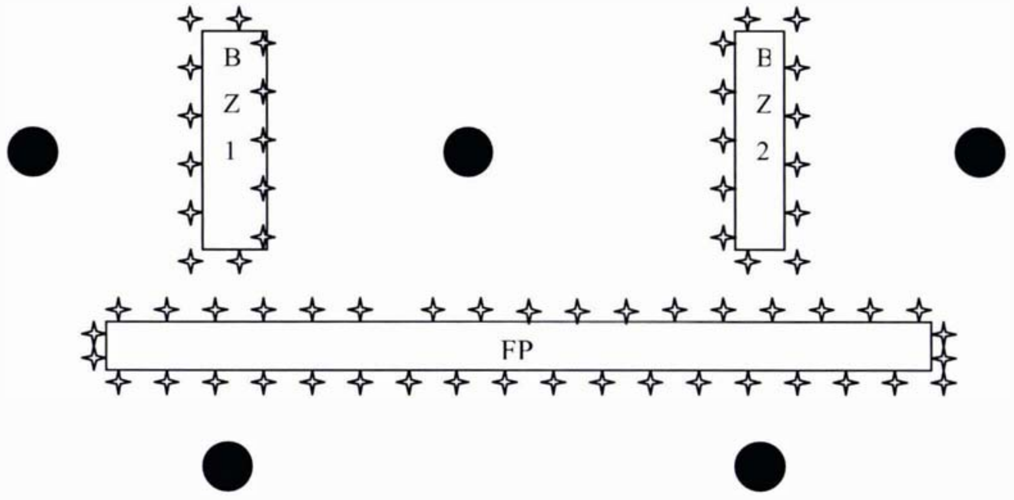
The large variability observed in the throughfall found in the preliminary experiment suggested more replication was needed. So for the main experiment (phase 2) conducted in August-September 2003, fifteen large drums were placed under each of three palms. The number of drums placed in each annular area was 1, 2, 3, 4 and 5, with the largest number in the annular area furthest from the trunk. This meant that there was a drum for each 5.4 m^2 of area and the drums covered between 4 and 5 % of the surface in each notional zone. The layout is shown in Figure 4.7.



Drum (○) and oil palm trunk (●)

Figure 4.7 Layout of half 200 L drums under palm trunks at Sangara

In the second experiment, small catch cans were used to measure throughfall around plots of the five *in situ* leaching experiments (three at Dami and two at Sangara). The cans were positioned 0.5 m apart around the plots (Figure 4.8). For the three leaching experiments at Dami, 26 cans were placed around the two BZ plots and 46 around the FP plot for the first and second experiments and 50 for the third experiment. For the two leaching experiments at Sangara, 32 cans were placed around each of the BZ plots and for the FP plot 54 cans were used for the first experiment and 60 for the second. The number of cans per plot varied depending on whether the stakes were inside or outside the earth bunds built around the plots. The volume of throughfall in the cans was measured after every rain event from the time when fertiliser was applied to when the plots were covered prior to taking soil samples.



Standing palm = ●, plots = ▭ and catch cans = ✧

The layout is not drawn to scale

Figure 4.8 Field layout of small catch cans around the plots for the *in situ* leaching experiments at Dami and Sangara

4.2.2.2 Results and discussion

4.2.2.2.1 Amount of stemflow

To determine the amounts of rainfall appearing as stemflow and throughfall, measured volumes of redistributed rainfall collected as stemflow, and as throughfall at various radial areas from the trunk, were divided by the volume of rainfall that was collected per area occupied by each palm. Rainfall received per area of a palm during a rain event was taken as the product of rainfall recorded from a rain gauge in the open and the area occupied by the palm. The area occupied by each palm was determined from the planting density (at 135 palms ha^{-1}, each palm occupies 10,000 m^2 ha^{-1}/135 palms ha^{-1} = 74 m^2). The sum of throughfall collected from the five annular areas from the trunk was taken as the total throughfall for the palm. The calculated difference between total rainfall per palm, stemflow and total throughfall, was assumed to be the rainfall amount that was intercepted by the palm.

Stemflow results from the preliminary and main experiments were combined and treated as a single data set. Over the January, and then August-September periods, there were 30 wet days and a total of 480 mm of rain, of which 11 % (Table 4.6) appeared as stemflow. This is much larger than the stemflow of 1 –5 % observed for forests (Lee, 1980), presumably due to palm fronds funnelling rainwater to the trunk in a way that most trees do not. As already reported, similar values of 11 – 13 % have been found for oil palm by other workers (Table 4.1). Stemflow in palm 1 (14 %) was significantly ($p<0.01$ and lsd $_{(0.05)}$ 3.2 %) different from palms 2 and 3 which each had 10 %. From visual observation, palm 1 appeared to have fewer bunches and the fronds were at a more acute angle to the stem than palms 2 and 3, which had a lot of bunches and the fronds were less acutely angled. The more acute the fronds, the more intercepted rainfall can be was diverted to the trunk, resulting in higher stemflow.

Table 4.6 Redistributed rainfall (%) at Sangara

Components	**% of total rainfall for each palm**			**Mean**
Palm	**1**	**2**	**3**	
Stemflow (S_f)	14	10	10	11
Throughfall (T)	72	80	104	85
Interception *(I_r)	14	10	-14	4
Total	100	100	100	100

* = Determined by difference from Equation [4.2]

The percentage of rainfall appearing as stemflow showed considerable variation (CV = 58 %), both between replicates and from day to day. On individual days, of the three replicate palms measured, the one producing the most stemflow produced up to twice as much stem flow as the one with the least amount of trunk flow. To show the day-to-day variation, the percentages of the daily rainfall that appeared as trunk flow are plotted as a function of daily rainfall (Figure 4.9). Each data point is the average of three replicate measurements on that day. Stemflow was typically less than 7 % of rainfall for days with less than 5 mm of rain, but ranged from 10 to 22 % on wetter days with minimum and maximum stemflow of 1.3 and 29 %, respectively. The large range of stemflow (7

% to 21 % of rainfall) on days with 29 mm of rainfall, is most probably due to differences in those rainfall intensities on these days.

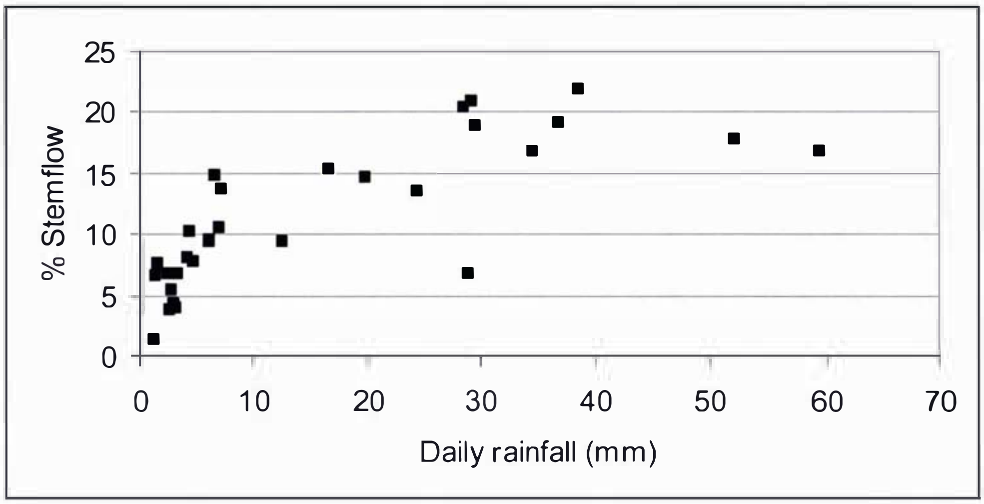


Figure 4.9 Mean daily stemflow expressed as a percentage of daily rainfall, plotted against daily rainfall

4.2.2.2.2 The source and fate of stemflow

Observations were made at the start of, and during, rain events to see where the stemflow water was coming from, and going to, after it reached the soil surface. When it first started raining, intercepted water on the canopy was seen flowing down the frond spines towards the frond bases in the oil palm cabbage. Then from the cabbage this water either flowed down the stems, moving from one spiral to another, or dripped from epiphytes onto the soil surface.

It was apparent that flow down the stem was not uniform but tended to concentrate on one side of the stem. At the base of the trunk, water flowed from one side of the palms onto the soil surface. This was evident under many palms, where the soil just next to the base of the trunk had been eroded away, exposing oil palm roots. In the plantations and smallholder blocks there were palms that grew slanted or were bent at some point on the trunk. On such palms stemflow water moved towards the bent side of the trunk and dripped off onto a small area under the trunk where it also eroded the soil and exposed oil palm roots. For bent palms, stemflow water falling off the trunk lands some distance away from the trunks, either in the WC or in the BZ. A picture of a bent palm is shown in Plate 4.3.

Plate 4.3 Bent stem at Dami experimental site

It may be possible to differentiate parts of the WC or BZ where this additional water is received from the rest of the WC where stemflow water has not reached the soil surface. The WC is the area where the most active water uptake occurs (Appendix A2.2), but parts of this zone may also be particularly prone to leaching because of the extra contribution from stemflow. This has possible implications in terms of fertiliser placement that are explored later (9.3).

Once stemflow water reaches the soil surface, it depends on the micro-topography within the WC as to where the water then flows. Water that does not infiltrate moves downslope either spreading out or remaining in a preferential flow pathway. Where there are hollow areas, water ponds and eventually flows across the WC and enters other zones. The hollowed-out areas in the WC are usually caused by the falling oil palm bunches which weigh 20 – 30 kg, and cause compaction when they fall during harvesting. In the other zones, deep hollow areas of 30 – 50 cm can be formed when oil palm boles are removed during the clearing of previous oil palm stands prior to replanting. Depending on the size of the rainfall event, water flowing into the hollow areas ponds and can eventually overflow onto other areas. With the very porous soils at Dami, most of the water collecting in the hollow areas quickly infiltrates into the soil.

At both Dami and Sangara, the general topography of the soils is slight to gently undulating, and therefore the areas in the WC are often sloping. Stemflow reaching the soil surface flows down the slope, and again this could have implications for fertiliser application and uptake, and will be discussed later.

4.2.2.2.3 Large drum measurements of throughfall

The preliminary experiment done in January 2003 covered 16 rain events with rainfall amounts ranging from 1.2 mm to 38 mm. The percentage of rainfall collected as throughfall in the preliminary experiment with 15 drums was 76 % of the 229 mm total rainfall recorded. While this is similar to the values found by other workers (Table 4.1), due to the small number of drums used for throughfall collection in this experiment, and the large variability between replicates, this value is regarded as very approximate.

However confirmation of this estimate of throughfall came in the main experiment where 45 drums placed around the three palms caught 84 % of the 251 mm of total rainfall (Table 4.6). Rainfall not appearing as stemflow, or throughfall, was assumed to have evaporated after interception. As the stemflow in this experiment was 11 %, interception was estimated at 4 % of the rainfall. As there were 14 wet days over the study period, this amount of interception equates to less than 1 mm day^{-1}, which is much lower than the published values reported in Table 4.1. This low % interception is probably due to the rainfall being higher and more intense at Sangara than at the sites listed in Table 4.1. Estimates of interception are prone to error because it is calculated as the small difference between rainfall and the much larger quantities of stemflow and throughfall, whose combined standard errors of 6 and 16 % can add up to more than the amount of rainfall intercepted.

The percentages of rainfall collected as throughfall in the five annular zones (Figure 4.10) were all significantly different ($p<0.001$, $lsd_{(0.05)} = 6.4$ %), except for zones 4 and 5. Throughfall varied markedly from 28 % in zone 1, 1.1 m from centre of the trunk, to around 100 % in zones 4 and 5, between 3.7 m – 4.6 m from the trunk (mean = 71 %). This three-fold difference in throughfall also has implications for fertiliser management that will be discussed later. However it must be noted that most of the stemflow water probably infiltrates within zone 1, which covers only 8.2 % of the total area of the plantation. Thus parts of zone 1 are probably subject to the most, rather than the least, leaching as already mentioned.

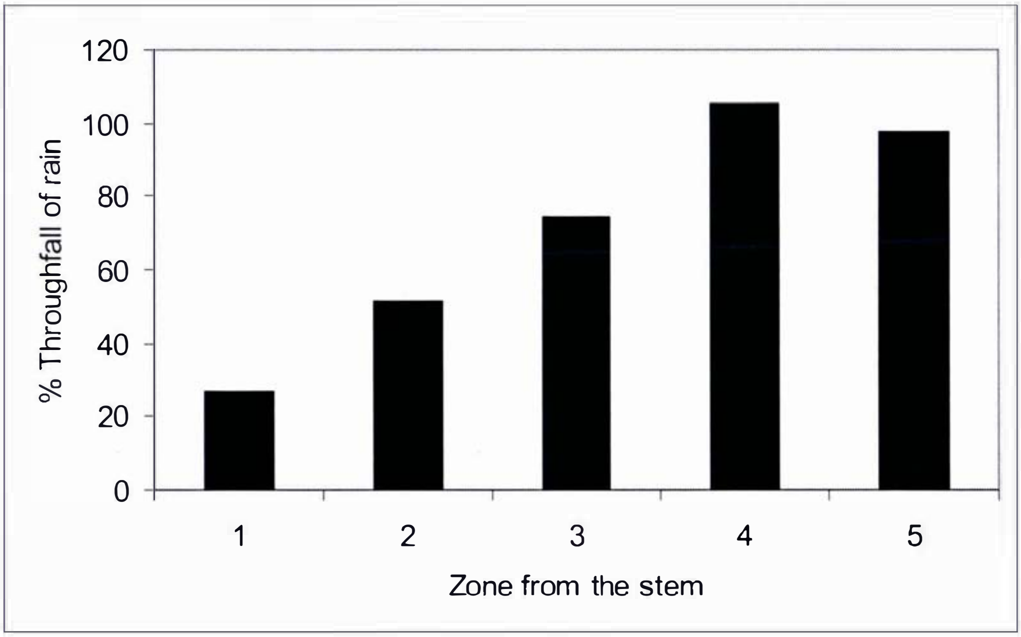


Figure 4.10 The measured throughfall in the large drums as a function of radial distance from the stem at Sangara

While Figure 4.10 shows that throughfall varies with distance from the trunk, it provides no information about throughfall variability within each zone. To examine this variability, the 27 drums in zones 4 and 5 were treated as replicates, since these two zones had similar average throughfalls. A frequency distribution of percentage rainfall collected on three wet days (with 28.8, 52.2 and 59.6 mm of rainfall) for 79 of these 81 total measurements is shown in Figure 4.11. The two outlier values not included, had abnormally high percentage catches of 236 % and 329 %. Thus, even with the large drums, throughfall was again highly variable. Thirty of the 81 drum measurements (37 %) collected either less than 50 % or more than 150 % of the measured rainfall. The distribution in Figure 4.11 seems roughly normal (with mean = 105 %, S.D = 54 % and CV = 51 %).

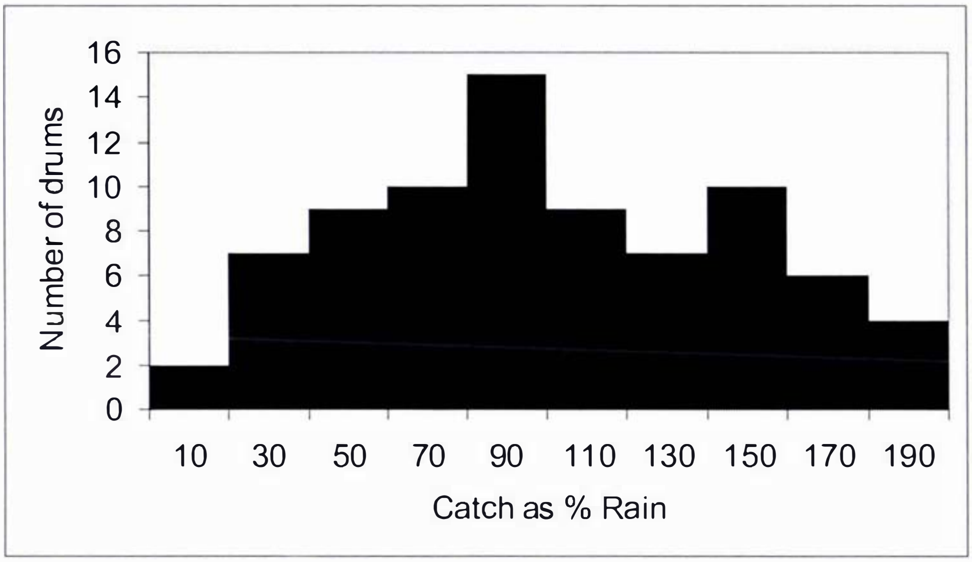


Figure 4.11 Frequency distribution of throughfall as a percent of rainfall in drums in zones 4 and 5 for three days with rainfall of 28.8 mm, 52.2 mm and 59.8 mm

4.2.2.2.4 Small can measurements

As already mentioned, there were two sets of catch can data from Sangara and three sets from Dami associated with the *in situ* leaching experiments. The data sets were incomplete because there was overflow from some cans and others fell off the stakes. The percentage of missing data ranged from less than 0.5 % in the later experiments (Experiments 3 at Dami and 2 at Sangara) to 5 % in Experiment 1 at Sangara (Table 4.7). Data collection improved during the final experiments at both sites. Results from all experiments are presented and discussed.

Mean volumes of throughfall collected in the cans were related to rainfall in the open by dividing the catch (in mm) by the amount of rain recorded in the rain gauge at the on-site weather stations. There was a difference between the two sites in the percentage of rain caught in the catch cans. The percentages of rain as throughfall measured at Sangara in the cans were 53 % and 74 % for the two experiments while at Dami the values were 136, 96 and 92 % for the three experiments (Table 4.7). The difference between the two sites is most likely due to the difference in the canopy structures of the palms. At Dami the palms are Dura type planted for seed production and their fronds are acutely-angled and open (Plate 4.4). At Sangara the commercial palms have a closed canopy. Closed canopies are more typical of these palms in plantations and smallholder blocks. The mean throughfall was 90 % for all five experiments.

There was also large variability in the catch can data from the two sites. The catch can data were about twice as variable at Sangara as at Dami (Table 4.7). At Sangara there was a can that collected 470 % of the rainfall while a number of them collected around 200 % of total rainfall for the period 6/12/05 – 3/01/06. The within-site differences are most probably due to differences in the canopy of individual palms. Expanding oil palm bunches push the fronds and bend the end tips down which can then divert water away from the trunk towards the end of the fronds. This may account for the very high values of throughfall measured in some catch cans. The bending of fronds, making them less acute, is typical in well-fertilised commercial palms. It may also explain the high throughfalls measured in the large catch cans (half 200 L drums) in the outer zones where frond tips overlap with tips from neighbouring palms.

Table 4.7 Summary of catch can data from the *in situ* leaching experiments

	Dami			Sangara	
	Experiment 1	Experiment 2	Experiment 3	Experiment 1	Experiment 2
Date	**16/12/04 – 21/03/05**	**1/05/05 – 9/10/05**	**24/01/06 – 30/01/06**	**9/12/04 – 25/03/05**	**6/12/05 – 3/01/06**
No. of days	**96**	**152**	**6**	**107**	**34**
Total data Set	**4214**	**3038**	**612**	**4130**	**2232**
Missing Data	**69**	**75**	**3**	**212**	**6**
% missing	**1.6**	**2.5**	**0.5**	**5.1**	**0.3**
Total Rainfall (mm)	**1708**	**836**	**310**	**934**	**218**
Average % of throughfall	**136**	**96**	**92**	**53**	**74**
CV%	**49**	**17**	**23**	**72**	**86**

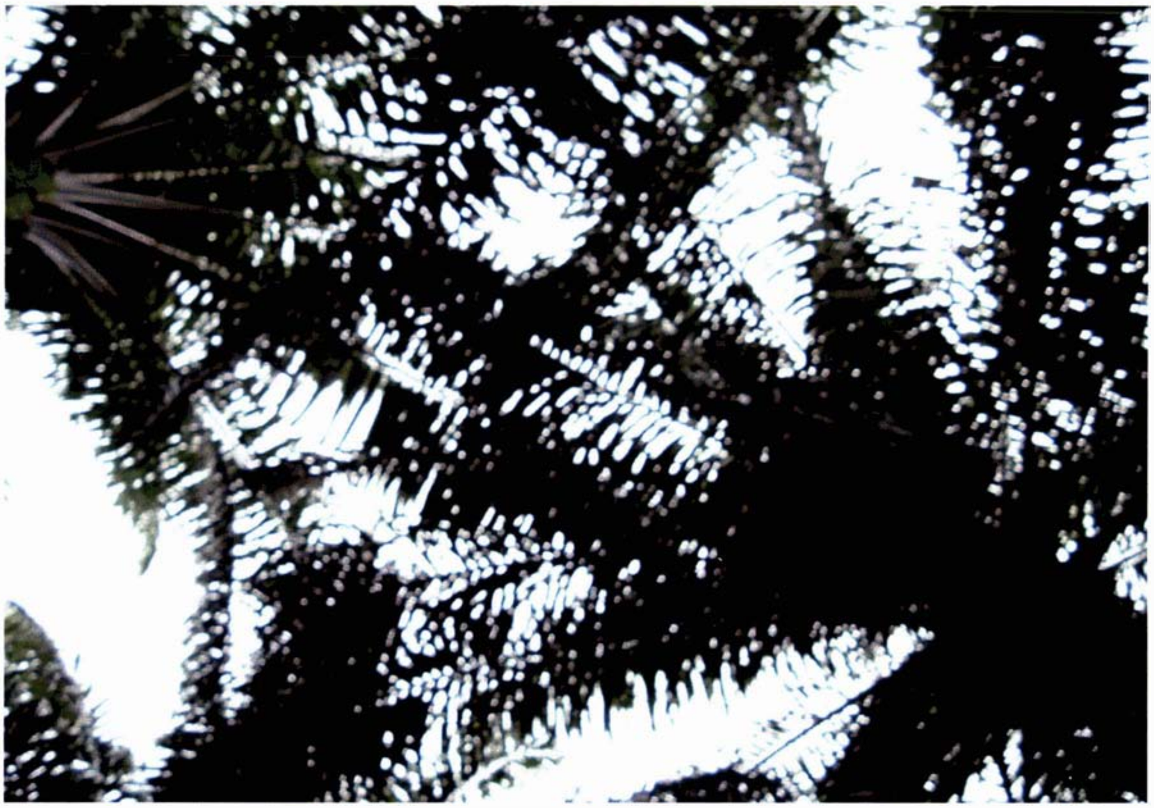
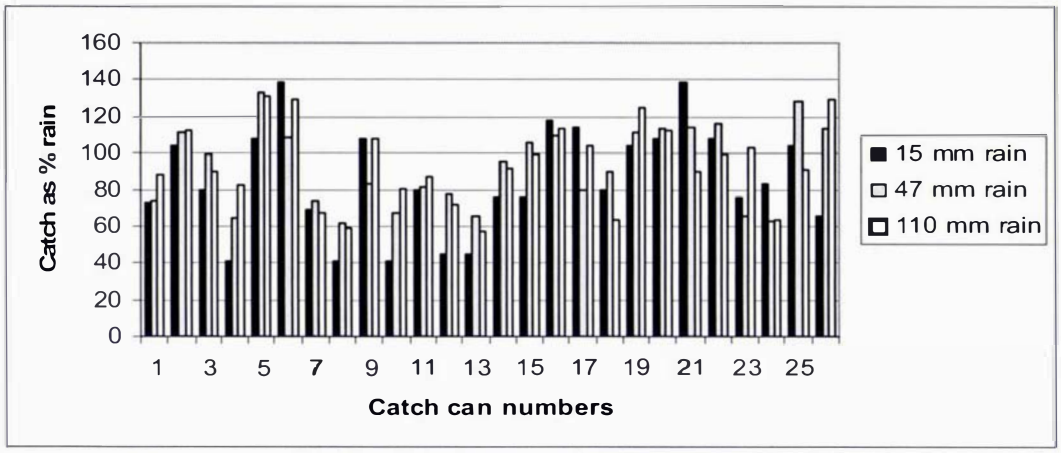


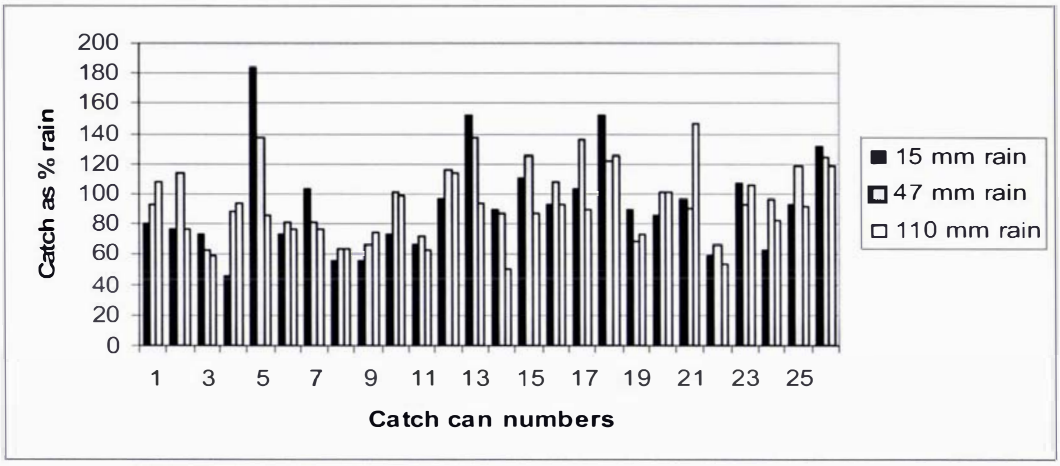
Plate 4.4 Open oil palm canopy at Dami

For each of the plots (BZ-1, BZ-2 and FP) at each of the two sites, Dami and Sangara, throughfall for three different rain events were chosen to illustrate the variability between the two sites and for different rain events within a site. The rainfall amounts chosen for Dami were 15 mm (25/01/06), 47 mm (30/01/06) and 110 mm (28/01/06) and for Sangara were 8.8 mm (22/12/05), 16.2 mm (10/12/05) and 38.6 mm (11/12/05). The throughfall values were not as variable between the cans at Dami (CV = 25, 26 and 33 %) for the three different plots (Figures 4.12 (a), (b) and (c)) as they were at Sangara (CV = 78, 95 and 146 %) (Figures 4.13 (a), (b) and (c)).

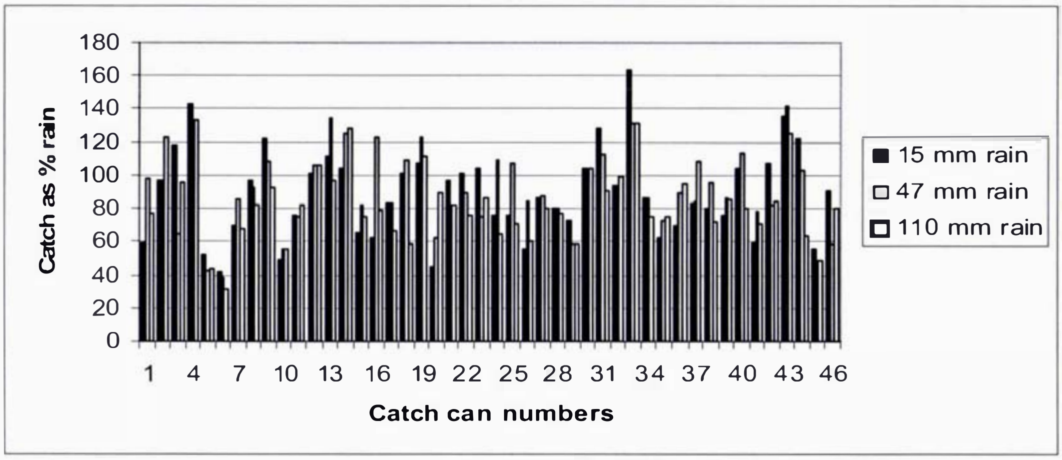
The large variations in throughfall, and the concentration of stemflow in zone one, have important implications in that the flux of water into the soil is very non-uniform across a plantation. This variability is further complicated by differences in soil water infiltrability, leading to localised ponding and runoff into other areas where there is greater infiltration.



(a) Dami BZ-1

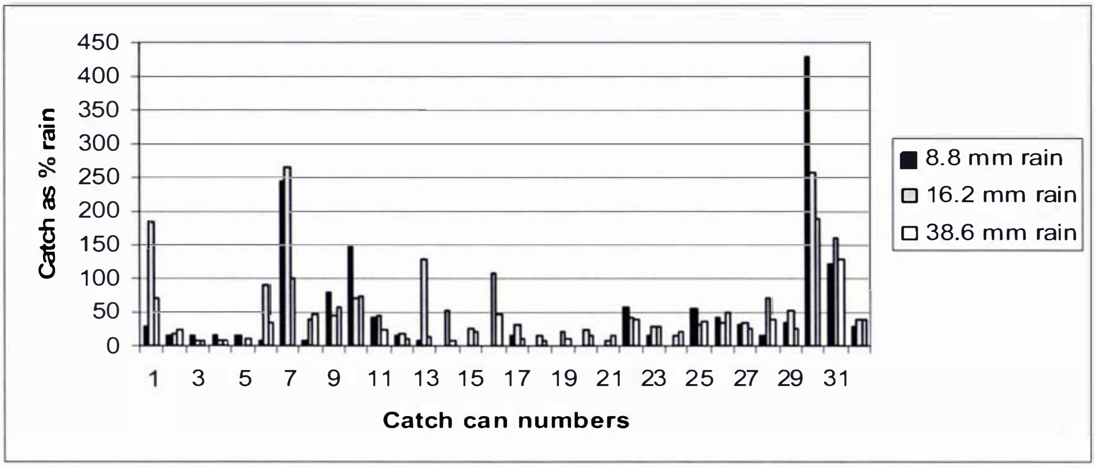


(b) Dami BZ-2

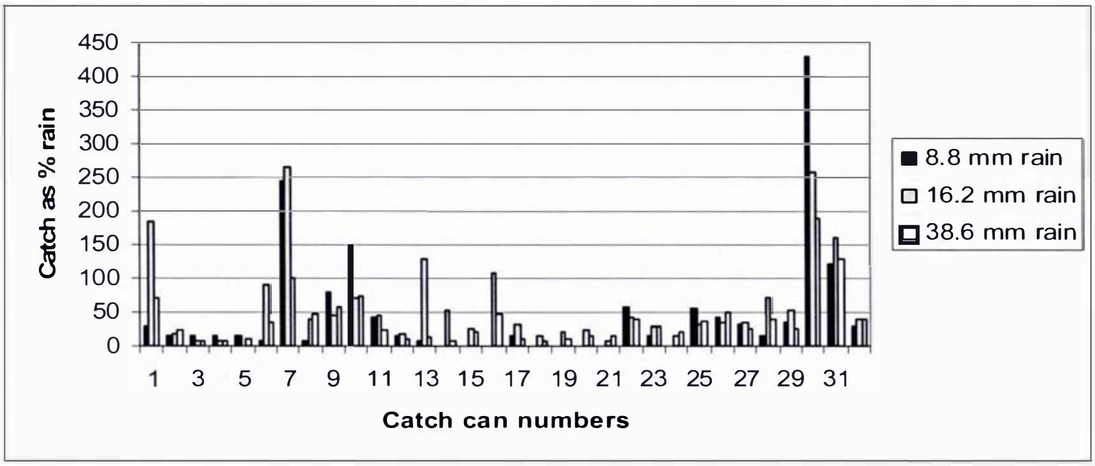


(c) Dami FP

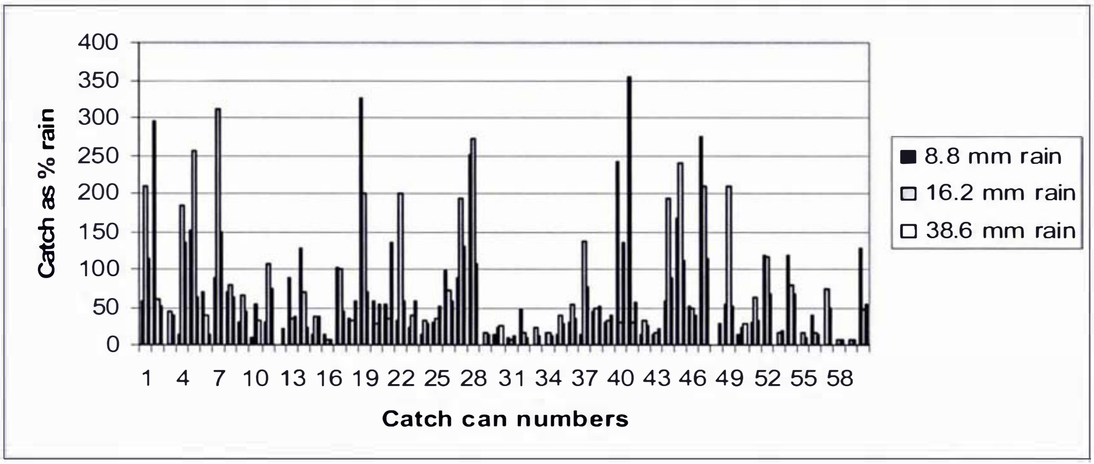
Figure 4.12 Throughfall catch on three wet days for the two BZ and the FP plots at Dami



(a) Sangara BZ-1



(b) Sangara BZ-2



(c) Sangara FP

Figure 4.13 Throughfall catch on three wet days for the two BZ and the FP plots at Sangara

4.2.2.3 Summary

- Of the total rainfall, 11 % appeared as stemflow, and 85 % as throughfall, implying that about 4 % was intercepted
- For individual events, stemflow could be > 20 % of rainfalls greater than 30 mm
- Where stemflow ends up depends on whether the palm trunks are straight or lightly bent, the micro topography of the weeded circle, the presence of depressed areas within and near to the weeded circle zone, and the soil infiltrability within the weeded circle
- Throughfall tended to increase with distance from the stem
- Throughfall amounted to 28 % of rain in zone 1 (1.1 m from centre of trunk) to near 100 % in zones 4 and 5 (3.7 – 4.6 m from the trunk) with an overall mean of 71 % of total rainfall
- This large local variation in throughfall reaching the soil surface seemed to depend to some extent on the canopy structure of the palms.

4.2.3 Surface runoff plot measurements

4.2.3.1 Introduction

Nutrient loss in surface runoff water in PNG is potentially significant because of the high rainfall (2,500 – 4,500 mm yr^{-1}) in the major oil palm areas. Nutrient loss in surface runoff water is a function of the amount of surface runoff that occurs when the rate that rainwater reaching the surface exceeds the maximum infiltration rate (or infiltrability). There have been no detailed studies of the water balance of porous volcanic ash soils in PNG and no studies have been done to determine water and nutrient loss via surface runoff, despite its obvious potential importance to oil palm production and the environment.

This study was carried out to quantify surface runoff and N losses in an oil palm ecosystem. N loss in the runoff is covered in Chapter 7.

4.2.3.2 Methods and materials

4.2.3.2.1 Plot setup

At both Dami and Sangara, three runoff plots were established on nearly flat areas, each of which included four standing palms and covered all the different zones (FP, FT, BZ, WC and HP) under the palms. Each plot was trapezoidal in shape with sides 18 m long. An earth bund 40 cm wide and 30 cm high was built around the plots to retain water inside the plots, and restrict water from outside entering the plots. The bunds were then covered with black polythene plastic to protect them from rain drop damage (Plate 4.5). To further restrict surface water entering the plots from adjacent areas, especially during heavy storms, a 30 cm deep x 40 cm wide trench was dug around each plot. At the lowest end of the plots, a cement outlet was built. A 15 cm internal diameter PVC pipe, carried runoff water to the collection pit. A shelter built with bamboo posts and a sago leaf roof was built over each collection pit to stop rainwater and throughfall from being collected in the drums. It also provided shelter during the rain for the workers who stayed to monitor the plots and empty the full collection drums during rainfall events.

4.2.3.2.2 Surface runoff water measurements.

For each plot, two 200 L plastic drums were placed in the pit to collect surface runoff water (Plate 4.6). The drums were calibrated and when they filled during the rain events, they were tipped over and the number of times this was done was recorded. For the drums that did not overflow, calibrated 12 L buckets were used to measure the volume.

At Dami, because the experimental site was further away from the local weather station, an extra rain gauge was installed in an open area next to the plots.

Three additional plots were later established at Sangara, to make six plots in total. Once some runoff data had been obtained, the six plots were treated as three paired plots and were used for the fertiliser loss studies described later (7.2).

A = Bund covered with plastic, B = cemented collection point and C = PVC pipe leading to outlet.

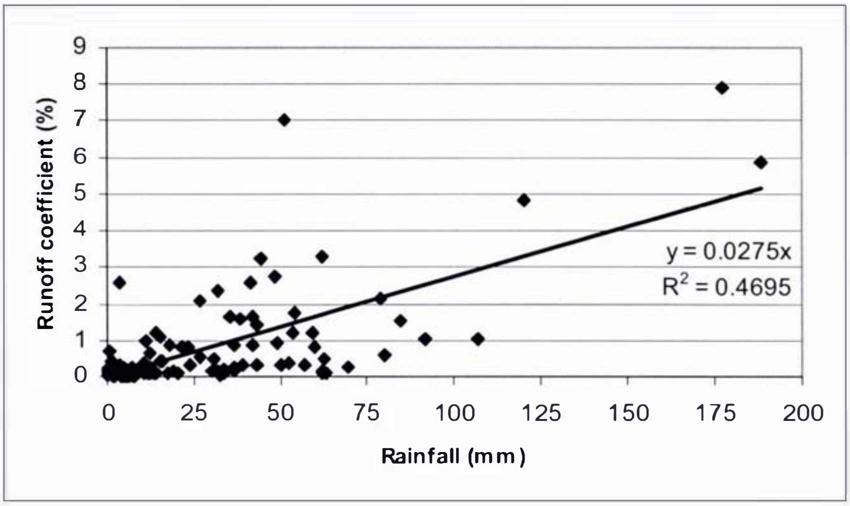
Plate 4.5 A surface runoff plot at Sangara

Plate 4.6 Runoff collection pit. Note shelter not yet built over

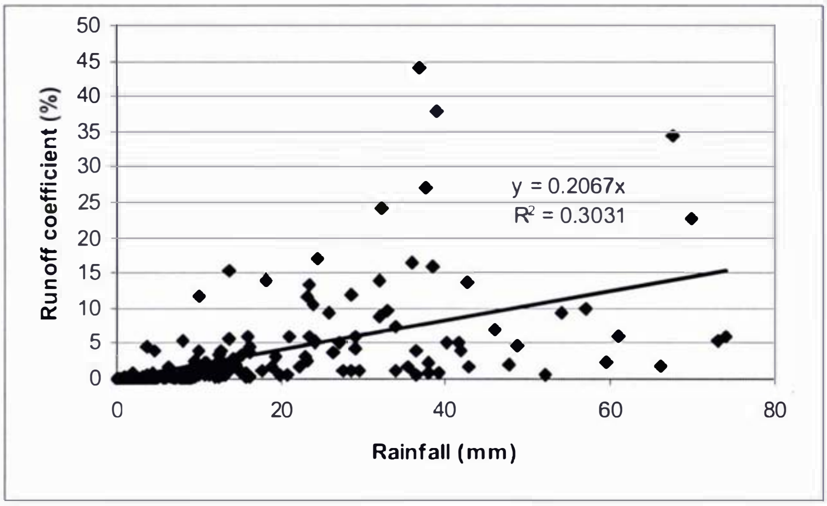
Data collection at both sites was done during both low and high rainfall months. At Dami, surface runoff water from 107 rain events with daily rainfall figures ranging from 3 mm to 188 mm were measured from 15th March 2004 to 20th April 2005 i.e. from one wet season to another. At Sangara, for the first 3 plots, measurements were done from 13th August 2003 to 11th July 2004 for 108 rain events with daily rainfall figures ranging from 2 mm to 74 mm. After the addition of three more plots, runoff water from a further 77 rain events, with daily rainfall figures ranging from 3 mm to 68 mm, was measured from 30th August 2004 to 30th April 2005. Measurements of surface runoff at both sites covered low rainfall ("dry season") and high rainfall ("wet season") months. For statistical analysis of runoff water, data from the first three plots and the three additional plots were treated as replicates.

4.2.3.3 Results and discussion

Runoff coefficients, defined here as the percentage of rainfall appearing as surface runoff, were determined for each site. At Dami, the mean runoff coefficient was 0.8 % with a relatively narrow range of 0 % to 8 % (Figure 4.14 (a)). However, at Sangara the mean surface runoff coefficient was 4 % with a wider range of 0 % to 45 % (Figure 4.14 (b)). The scatter graphs (Figures 4.14 (a) and (b)) suggest that the runoff coefficient increased linearly with rainfall with a stronger correlation at Dami (R^2 = 0.47) than at Sangara (R^2 = 0.30). However at both sites, 50 % or more of the variation in runoff coefficient was unexplained. The large variation in runoff coefficients for similar rainfall amounts at both sites was most likely due to different rainfall intensities and/or soil wetness. The relationship between runoff and soil wetness relative to field capacity is discussed in 4.2.4.3.2. The large difference in runoff coefficients found between the two sites is most likely due to differences in soil texture and structure, which determine the soil's infiltrability (3.2.1). The soils at Dami are sandy loams or are coarser at all depths, and are highly porous with high infiltrability. Thus nearly all the rain soaks into the soil where it lands. At Sangara the soils are generally sandy clay loams at the surface grading to sandy clays at 20 cm depth. As discussed in 4.2.1.1.1, the clay content in the Sangara subsoil is probably sufficient to create a temporary perched water table during heavy rain events, which slows infiltration into the soil, and results in increased surface runoff and therefore a higher runoff coefficient.



(a) Dami



(b) Sangara

Figure 4.14 Relationship between runoff coefficient and daily rainfall for the surface runoff plots at Dami and Sangara

Even though the mean runoff coefficients at Sangara are higher than those at Dami, they are still smaller than values found in Malaysia (Table 4.2), where runoff coefficients in oil palm plantations ranged from 18-49 % (Kee *et al.*, 2000). The highly porous nature of the volcanic soils in PNG compared to the more weathered older soils, with higher clay contents, in Malaysia may explain the differences.

4.2.3.4 Summary

- Surface runoff at Sangara was higher than at Dami, and varying soil physical properties appear to explain the difference
- Mean runoff coefficients were 0.8 % at Dami and 4 % at Sangara
- More than 50 % of the variability in the runoff coefficient cannot be explained from the amount of rainfall alone
- The potential nutrient N loss via surface runoff would be expected to be greater at Sangara than at Dami

4.2.4 Water balance for the oil palm systems at Dami and Sangara.

4.2.4.1 Introduction

Water balance models use rainfall and evaporation data to estimate surplus water (surface runoff and deep drainage) and soil water deficits for a cropping system over a given period of time. Such estimates have a variety of uses, however for this study they were used to model N leaching losses and also to estimate the amount of N lost in surface runoff. The model developed here is used later to predict leaching losses from applied fertilisers.

4.2.4.2 FAO 56 Model and data input

The evaporation model chosen for the water balance study was a modified Penman-Monteith model (Allen *et al.*, 1998). This model is used to determine the reference crop evaporation, E_r, and is referred to as FAO 56 from here on. The model requires the following data for each site:

Height above sea level (Z, m), latitude (φ, radians), and wind run (z, m) including the height above the ground of the wind run anemometer. Note that latitude is negative in the southern hemisphere.

Daily data required:

Rainfall (P, mm), maximum and minimum temperatures (T_{max} and T_{min}, ^{o}C), sunshine hours (n, h), wind run (u_z, km/d) and dew point or vapour pressure.

For Dami, weather data from 1993 to 2005 were compiled. For Sangara, daily weather data from 1983 to 2005 were compiled. Where wind run data were not available the wind speed at 2 m was assumed to be 0.5 m/s. The reference crop evaporation (E_r) was relatively insensitive to variations in this parameter. The dew point values at Sangara were higher than expected, most likely due to the wet bulb not working properly, so at that location the dew point was assumed equal to the minimum temperature. In some cases, there were missing air temperature and sunshine hour data. Where there were 1-10 days of missing data, the mean for the month was used for the missing days. Where a whole month of data were missing, the previous year's mean for that month was used. Where there were highly unusual temperature or sunshine hour data, the mean for the month was used. The checked and corrected data were then fed into the model. Details of FAO 56 are given in Appendix A2.3.

For tropical palms FAO56 suggests a crop coefficient of 1.00 (Allen *et al.*, 1998, Table 12, p.112) implying that the evaporation from oil palm equals E_o. It is also assumed that the available soil water storage capacity always exceeds the soil water deficit, so water stress does not affect evaporation. The deep rooting system of established oil palms, and the high rainfall at the two study sites, make this assumption reasonable. Thus the actual evaporation rate is always estimated as E_r.

If W_n (mm) is the soil water storage in the root zone, relative to field capacity, on day n, then rewriting Equation [4.1] in a slightly different form, and assuming $C = 0$,

$$W_n = W_{n-1} + P - E_r - S \qquad [4.11]$$

where P is rainfall (mm), and D is deep drainage plus surface runoff (mm) on day n. Note that W is always zero or negative when defined this way. D is estimated as the daily excess of water once the soil profile has been rewet to field capacity. Thus

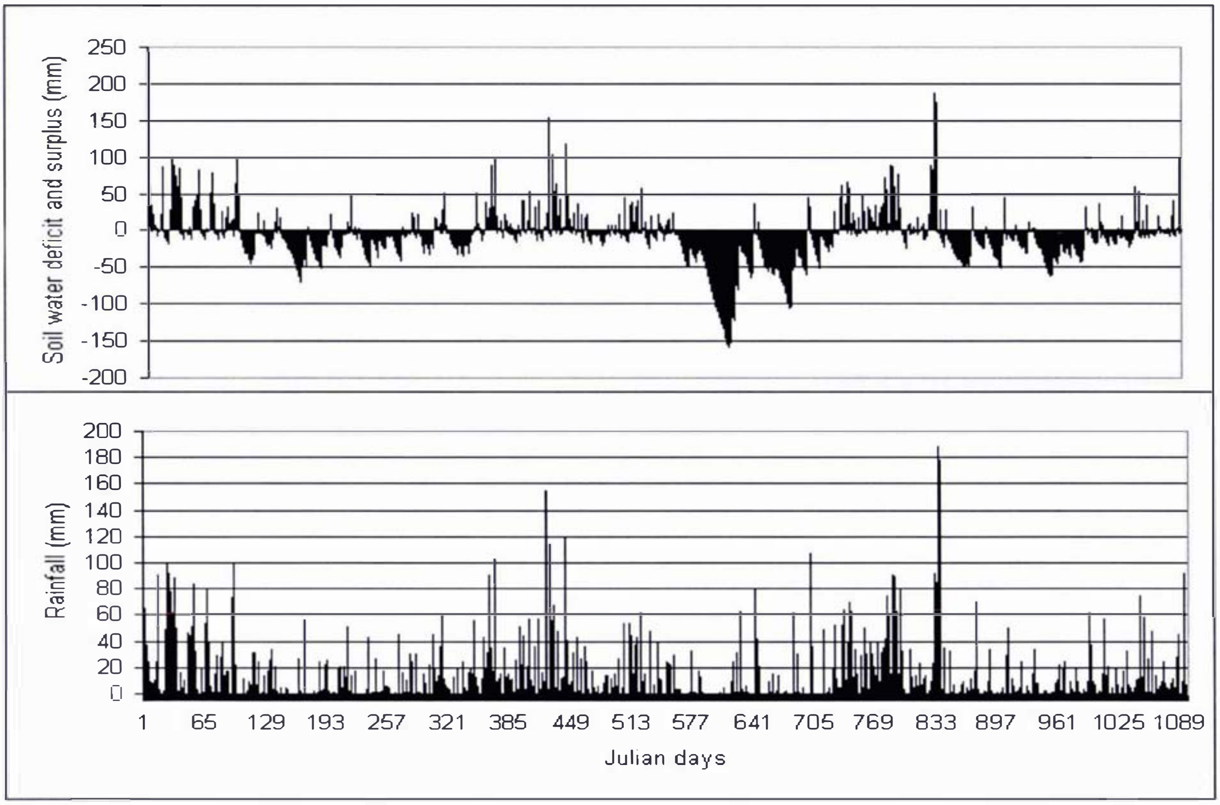
If $(W_{n-1} + P - E_r) < 0$, [4.12]
then $D = 0$
else $D = W_{n-1} + P - E_r$ [4.13]

The surface runoff component of the model was determined from the relationship between the surplus water (D) and actual runoff measured from the surface runoff plots (4.2.3). Deep drainage was found as the difference between D and surface runoff.

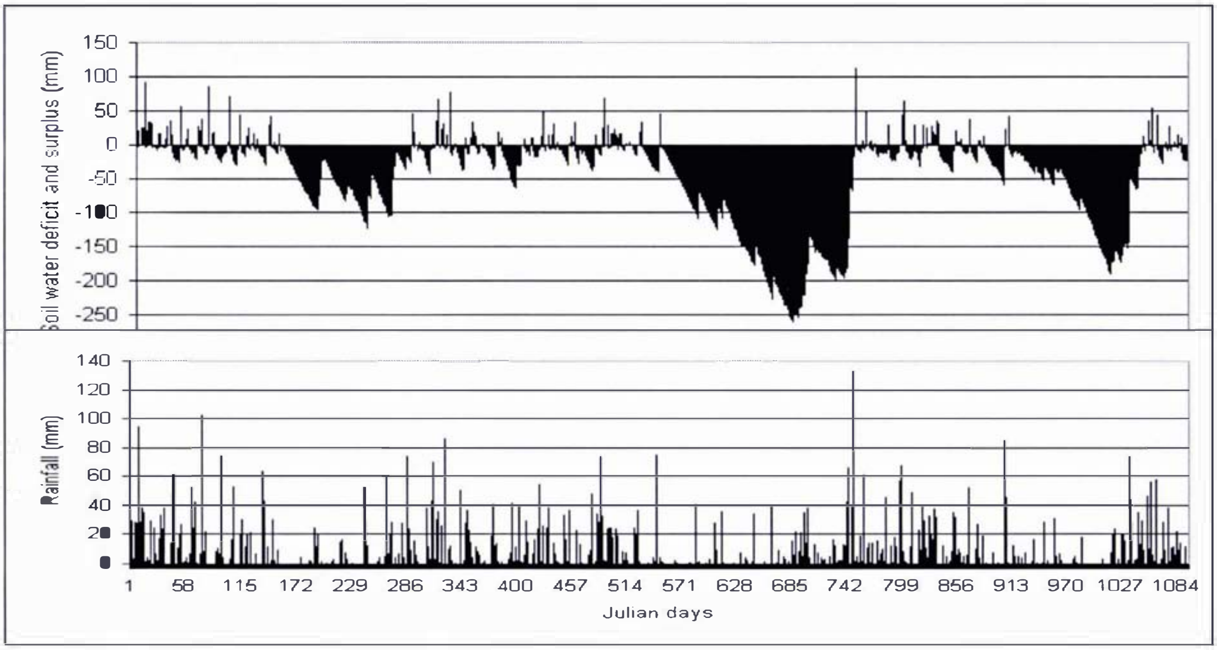
4.2.4.3 Results and discussion

4.2.4.3.1 Deficit and surplus water

Using the model, the water deficits and surpluses at Dami (1993-2005) and Sangara (1983-2005) were estimated. There were distinct water deficit and surplus periods that coincided with low and high rainfall months at both sites. Representative figures for the sites for 2003-2005, the years over which the experimental work was carried out, are shown in Figures 4.15 (a) and (b). For the 2003-2005 period, there was a maximum deficit of 158 mm at Dami and 260 mm at Sangara. The maximum daily surplus was 186 mm at Dami and 112 mm at Sangara. In general the water deficit periods were shorter at Dami than at Sangara. At Dami, the longest deficit period was 46 days (August-September) in 2003, 84 days (July-October) and 52 days (October-December) in 2004, and 26 days (April) and 52 days (August-September) in 2005. At Sangara, the deficit periods were much longer. In 2003 the longest period was 137 days (June-October), in 2004 it was 202 days (July 04 - January 05) and in 2005 it was 139 days (July-November). The length of soil water deficit has implications for the residence time of nutrients in the root zone. Thus at Dami, other things being equal, fertiliser would probably stand a greater chance of being leached because of the short deficit periods as compared with Sangara. However, at times of deficit, uptake may not be as effective because of the soil being dry.



(a) Dami

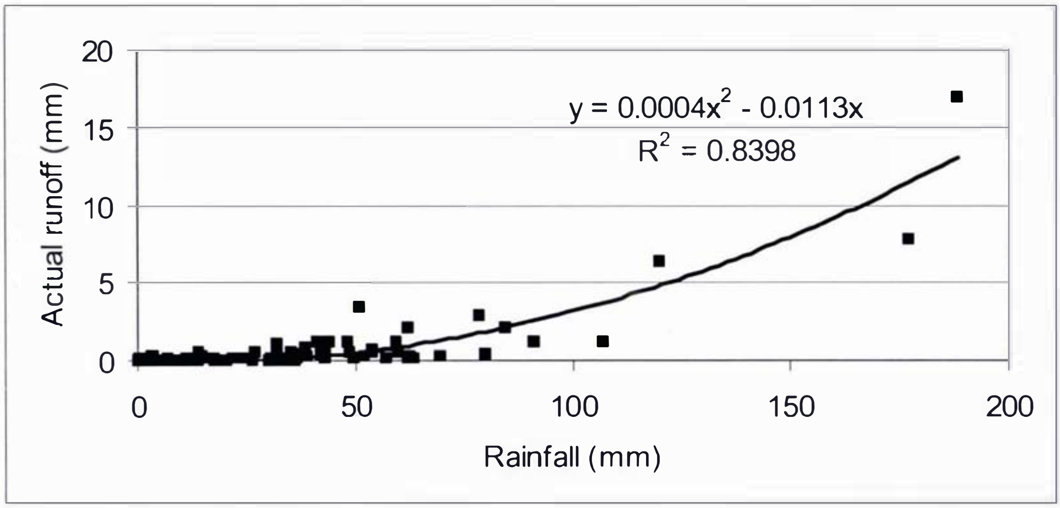


(b) Sangara

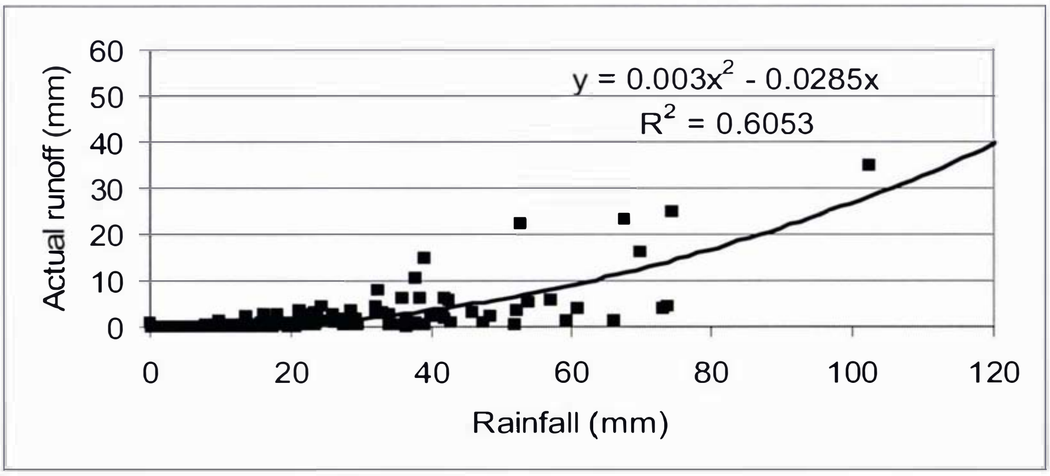
Figure 4.15 Rainfall (mm), water deficit (mm) and surplus (mm) at Dami and Sangara from 1st January, 2003 to 31st December 2005. Negative values indicate water deficit

4.2.4.3.2 Modelling surface runoff and deep drainage

As shown in 4.2.3.3 (Figures 4.14 (a) and (b)) the runoff coefficients showed only weak linear correlations (R^2 = 0.47 for Dami and 0.30 for Sangara) with daily rainfall. As expected, stronger correlations (R^2 of 0.84 for Dami and 0.61 for Sangara) were obtained when quadratic equations were fitted to the relationship between the amount of runoff and the daily rainfall (Figures 4.16 (a) and (b)).



(a) Dami.



(b) Sangara

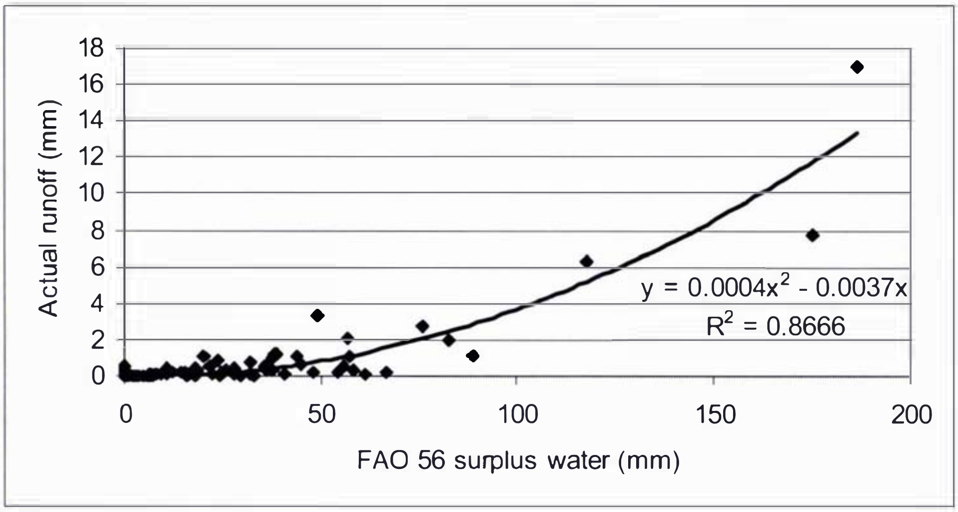
Figure 4.16 Relationship between rainfall and measured surface runoff at Dami and Sangara

However even stronger correlations were found when quadratic equations were fitted to the relationship between daily surface runoff and surplus water calculated using the water balance, as shown in Figures 4.17 (a) and (b). This was particularly true at Sangara where the topsoil dries out more often than it does at Dami. The improved correlations were expected, as the ability of the soil profile to soak up rainfall is usually greater when the soil is drier than when it is at, or near, field capacity.

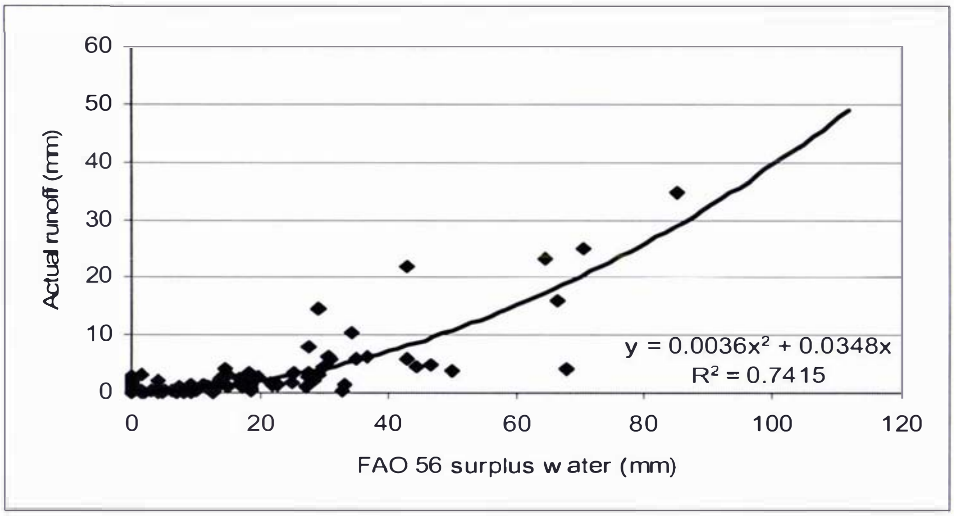
So the regression equations chosen to simulate surface runoff in the water balance model are those shown in Figures 4.17 (a) and (b). Daily values for drainage were found as the difference between the simulated water surplus and surface runoff values.

4.2.4.3.3 Estimated surface runoff and deep drainage

Surplus water was separated into surface runoff and deep drainage using the quadratic relationship, between surplus water and actual measured runoff, shown in Figure 4.17 (a) and (b). Surface runoff and deep drainage followed closely the rainfall distribution pattern at both sites (Figure 4.18 (a) and (b)). During the study period (2003-2005), estimated maximum daily runoff at Dami was 13 mm and deep drainage was 173 mm for a rainfall event of 188 mm, while at Sangara, the maximum daily surface runoff was 46 mm with deep drainage of 67 mm for a rainfall event of 133 mm.

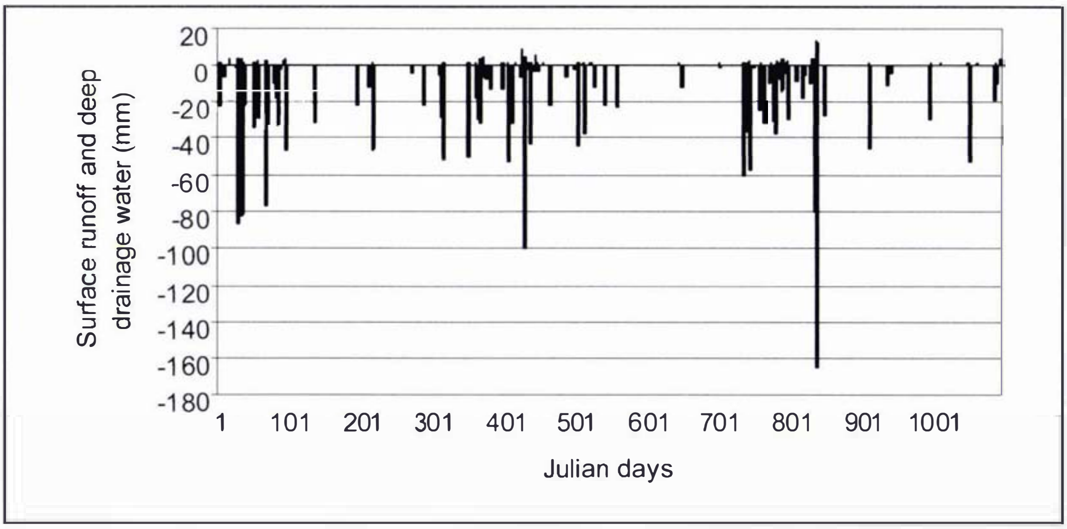


(a) Dami

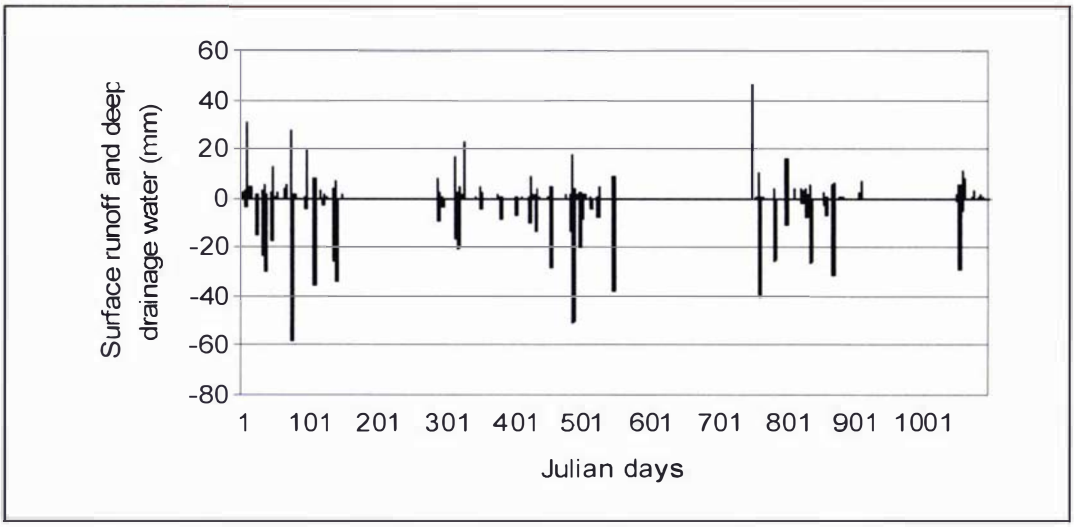


(b) Sangara

Figure 4.17 Relationship between FAO 56 surplus water and measured surface runoff at Dami and Sangara



(a) Dami



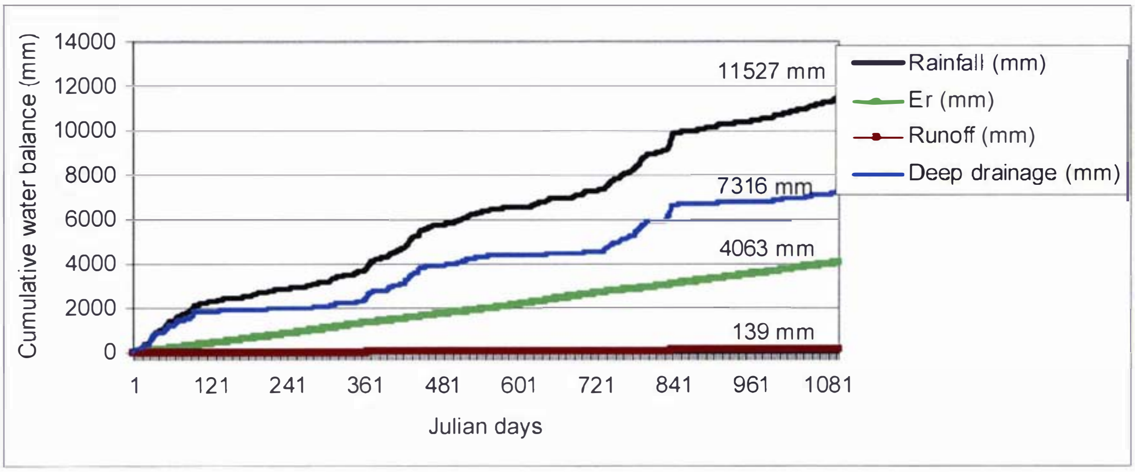
(b) Sangara

Figure 4.18 Estimated surface runoff (mm) and deep drainage (mm) at Dami and Sangara (2003-2005). The negative scale is for deep drainage

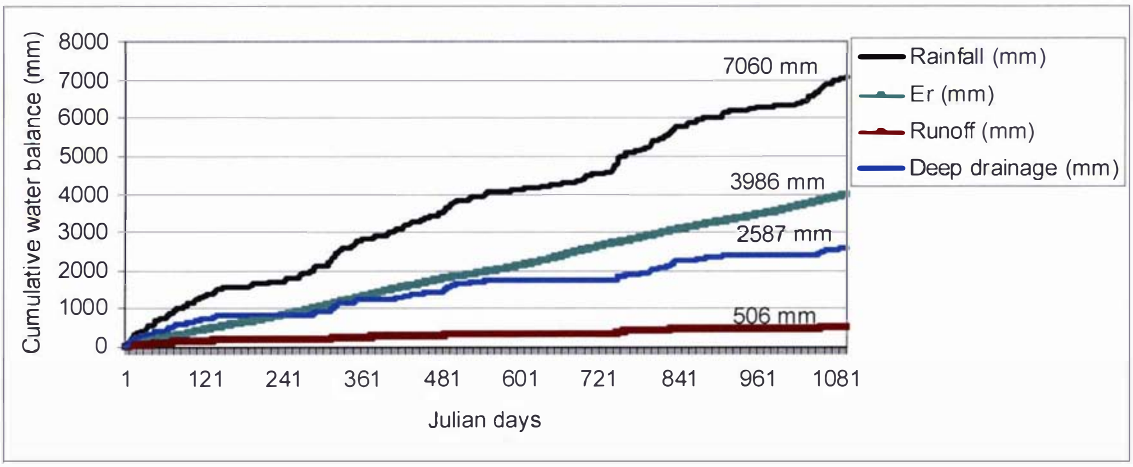
4.2.4.3.4 Cumulative water balance for study period 2003-2005

The cumulative water balance for the three consecutive years (2003-2005) of the field study, was determined using the water balance model developed in 4.2.4.3.3. The model output showed large differences in water components for the two sites (Figure 4.19 (a) and (b)). At Dami, 35 % (4,063 mm) of the cumulative rainfall (11,527 mm) appeared as E_r, 1 % (139 mm) as surface runoff and 68 % (7,316 mm) as deep drainage. At

Sangara, 56 % (3,986 mm) of the cumulative rainfall (7,060 mm) appeared as E_r, 7 % (506 mm) as surface runoff and 37 % (2,587 mm) as deep drainage. This analysis would imply that losses of N by leaching could be expected to be higher at Dami than at Sangara. However, losses via surface runoff would most likely be higher at Sangara than at Dami.



(a) Dami



(b) Sangara

Figure 4.19 Cumulative water balance components at Dami and Sangara (2003-2005)

Compared with studies done in Malaysia, deep drainage values in volcanic soils in PNG are larger, while surface runoff values are lower (Table 4.8).

Table 4.8 Percentage of rainfall as E_r, runoff and deep drainage estimated for Malaysian and PNG conditions

Site	Country	E_r	Runoff	Deep drainage
*Sri Kunak Estate	Malaysia	65	22	13
*Balau Estate	Malaysia	60	30	11
*Lepan Kabu	Malaysia	40	32	28
Dami	PNG	38	1	60
Sangara	PNG	55	8	37

*Source: Kee *et al.* (2000)

4.2.4.3.4 Longer term water balance summary

Estimated water balance components for all available years of data at Dami and Sangara are summarised in Table 4.9. The mean maximum yearly deficits at Dami and Sangara were similar, at about 150 mm. The highest deficit was 512 mm at Dami and 404 mm at Sangara, and both were in 1997 during the *El Nino* year. The mean E_r at both sites was 3.7 mm day^{-1}.

4.2.4.4 Summary

- Mean maximum deficit was approximately the same at Dami (154 mm) and Sangara (150 mm) with a range of 8-10 times from minimum to maximum deficit over all years
- Mean annual E_r, runoff and deep drainage as a % of annual rainfall were 39, 1 and 61 % for Dami and 55, 8 and 37 % for Sangara.

Table 4.9 Summary of soil water balance components for Dami (1993-2005) and Sangara (1983-2005)

Year	Water balance components (mm)											
	Sangara						Dami					
	P	E_r	Max Def	*D*	*R*	*S*	*P*	E_r	Max Def	*D*	*R*	*S*
2005	2482	1322	-196	1007	172	834	4133	1332	-61	2800	61	2739
2004	1767	1340	-261	599	80	519	3462	1392	-158	2072	36	2036
2003	2811	1324	-122	1487	254	1234	3941	1347	-71	2582	41	2541
2002	2326	1362	-212	969	176	792	3586	1483	-153	2178	39	2139
2001	2513	1372	-123	1132	200	932	3621	1368	-92	2348	35	2313
2000	2427	1404	-77	1006	161	846	3402	1355	-79	2178	39	2139
1999	2176	1348	-64	850	163	687	3331	1382	-73	1816	46	1770
1998	2661	1340	-187	1145	230	915	4488	1271	-224	2953	46	2907
1997	1397	1291	-404	289	46	243	2595	1545	-512	1316	18	1298
1996	2261	1412	-104	832	124	709	2770	1320	-69	1643	25	1619
1995	2280	1298	-143	988	135	853	3623	1285	-55	2299	27	2272
1994	2046	1285	-107	767	107	660	3438	1320	-293	2166	42	2124
1993	2442	1298	-227	1025	243	782	3353	1305	-165	2049	41	2009
1992	2090	1394	-217	817	144	673						
1991	2592	1298	-76	1292	243	1049						
1990	3071	1241	-75	1810	405	1405						
1989	2768	1322	-133	1470	258	1211						
1988	2651	1351	-53	1300	195	1105						
1987	2329	1360	-237	970	173	797						
1986	2360	1334	-98	1015	158	857						
1985	2808	1304	-71	1498	245	1253						
1984	2421	1315	-84	1126	187	938						
1983	3130	1341	-173	1789	346	1443						
mean	2426	1333	-150	1095	193	902	3519	1362	-154	2185	38	2147
%*		55		45	8	37		39		62	1	61
SD	390	41	84	358	80	283	502	77	129	445	11	438
CV %	16	3	56	33	42	31	14	6	84	20	28	20
max	3130	1412	-53	1810	405	1443	4488	1545	-55	2953	61	2907
Min	1397	1241	-404	289	46	243	2595	1271	-512	1316	18	1298

* % of mean annual rainfall

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Chapter 5

Nitrification

The interactions between soil and climatic factors determine the availability of N (NO_3^--N and NH_4^+-N) for crop uptake or loss from the system by denitrification (Chapter 6), surface runoff (Chapter 7) or leaching (Chapter 8). This section backgrounds the nitrification process, factors affecting the process in soils, studies done under oil palm systems or other tropical crops, and methods used to measure the rate of nitrification in the field.

5.1 Nitrification process

Nitrification refers to the biological oxidation of NH_4^+-N to NO_3^--N that is carried out by chemoautotrophic soil bacteria (Schmidt, 1982). There are two major steps in the process in soils. The first step is carried out by bacteria of the genus Nitrosomonas (however Nitrosococcus, Nitrosospira, Nitrosolobus and Nitrosovibrio can also be involved) and the second step involves only one genus Nitrobacter, as shown in Schematics 5.1 and 5.2.

$NH_4^+ + 1\tfrac{1}{2} O_2$ ------Nitrosomonas bacteria----- $NO_2^- + H_2O + 2H^+$ + Energy [Schematic 5.1]

$NO_2^- + \tfrac{1}{2} O_2$ -------Nitrobacter bacteria------ NO_3^- + energy [Schematic 5.2]

Nitrification is strictly an aerobic process. Under certain conditions, nitrification can be carried out by heterotrophic microorganisms (pH <4.5), methylotrophic microorganisms (partly or saturated soil conditions) or by chemical reactions (low pH soils) (Haynes, 1980).

5.1.1 Factors affecting nitrification

Since a narrow range of micro-organisms is involved in the nitrification process, any unfavourable change in the environment can completely halt the process. The main factors affecting nitrification include the quantity and availability of the substrate (NH_4^+-N), soil pH, aeration, water content, temperature, soil nutrient deficiencies and other chemicals such as pesticides (Haynes, 1980).

5.1.1.1 Substrate quantity

The concentrations required to give half the maximum nitrification rate range from 1 – 10 mg N L^{-1} for NH_4^+-N at 20 – 30 °C (Haynes, 1980). The population and activities of nitrifiers in the soil are usually limited by the production and availability of NH_4^+-N.

High rates of N fertiliser can inhibit the nitrification process. Yoshida *et al.* (1973) observed that the addition of 200 µg NH_4^+-N ml^{-1} soil affected soil microorganisms and their activities. Darrah *et al.* (1987) found no inhibition of nitrification when the osmotic pressure was less than 200 kPa however 350 kPa produced 90 % inhibition.

Chao and Chao (1997) found that soils that had received organic N inputs had higher nitrification potentials than soils receiving an inorganic N source.

5.1.1.2 Soil water content

Maximum nitrification occurs at field capacity and almost stops in very dry soil at 1500 kPa (Haynes, 1980). Breuer *et al.* (2002) found that gross nitrification was negatively correlated to soil water-filled pore space.

5.1.1.3 Optimum temperature and pH

The optimum soil temperature range for nitrification is 25-30 °C but the process generally stops at temperatures < 5 °C and > 40 °C (Haynes, 1980). Vitousek and Matson (1988) found that nitrification rates in the lowland tropics were higher than in soils from temperate forests due to higher temperatures in the tropics.

The optimum pH range for nitrification is 4.5 – 7.5, however in very acidic soils, inhibition of nitrification may occur due to a deficiency of Ca or Mg and/or Al toxicity (Haynes, 1980). Low pH is unlikely to be a major factor in oil palm soils in PNG since soil pH values are mostly within the optimal range for nitrification.

5.1.1.4 Herbicides and fungicides

The use of herbicides and fungicides can affect nitrifying organisms and their activities. Bunemann *et al.* (2006) reported that copper fungicides were amongst the most toxic and persistent chemicals in this regard. Herbicides in oil palm plantations are selectively used while no fungicides are normally used. In smallholder blocks, very few herbicides are used.

5.1.2 Methods and procedures for studying nitrification in soils.

The nitrification potential of a soil can be measured using four methods; a) aerobic incubation, b) periodic leaching of micro-lysimeters, c) laboratory incubation of soil slurries and d) incubation of soils in perfusion columns. All of these methods provide estimates of nett nitrification rather than gross nitrification (Hart *et al.*, 1994). The most common method used is aerobic incubation in which inorganic N is measured before and after incubation. The standard laboratory procedure for aerobic incubation is described by Keeney and Bremner (1966). Nett nitrification is taken as a measure of the nitrification potential of the soil under standard conditions of temperature and soil water content.

However, this method is normally used to assess the amount of soil 'mineralisable" N as a way of rating the nitrate-forming capability of a soil. In this study, the focus is more on the nitrification of added ammonium fertiliser.

The most probable number count of nitrifying organisms is used to determine nitrification activity in soils and is useful when used along with an estimate of the nitrification potential. A high nitrifying population but low nitrification potential (low nitrate) could lead to immobilisation of N into organic forms.

5.1.3 Nitrification in oil palm soils

Few studies have investigated nitrification in tropical soils. Two relevant studies are: a) a study in Indonesia, though not under oil palm, was done in an oil palm growing region and b) a study done in an oil palm plantation in South America.

Krave *et al.* (2002) did an experiment to look at the nitrification potential, and factors controlling nitrifier activities under tropical pine forests and agricultural soils in Central Java, Indonesia. They concluded that fertilised agricultural soils had high nitrification potentials and high numbers of nitrifying microorganisms most probably due to high substrate addition in the form of ammonium fertilisers.

Schroth *et al.* (2000) measured N mineralisation by burying disturbed soils in sealed nylon plastic bags at three distances from the palm trunk. The results showed that the NH_4^+-N content was higher at 1 m than at 2.5 or 4 m from the palm. Nitrate content, however was lower at 1 m but higher at 2.5 and 4.0 m from the palm. The 1 m distance will be within the WC. They concluded that nitrification was low within 1 m radius of the palm trunk probably due to soil compaction and the cleared surface around the palms. It is presumed that the same would hold for the nitrification of added ammonium fertilisers that would also nitrify at a relatively slow rate in the WC zone.

Schroth *et al.* (2000) did not clarify which zones the 2 outer distances (2.5 and 4.0 m) were in. However, from the other studies the following conclusions can be drawn;

a) nitrification rates are probably higher in tropical than in temperate soils
b) in soils with continuous inputs of inorganic N fertilisers, nitrification rates are high due to the build up of a nitrifying population. However the rates are even higher under cover crops and where there is a continuous input of organic N. This finding has implications with respect to nitrification rates in the different management zones as discussed in 5.3.2.2.
c) nitrification rates decrease with soil depth and are usually higher in the litter layers.

The present study aimed to determine nitrification rates in an oil palm system, under constant but realistic field moisture and temperature conditions. The objective was to provide information on nitrification rates for leaching models that are described in 8.3.4.

5.2 Field nitrification studies

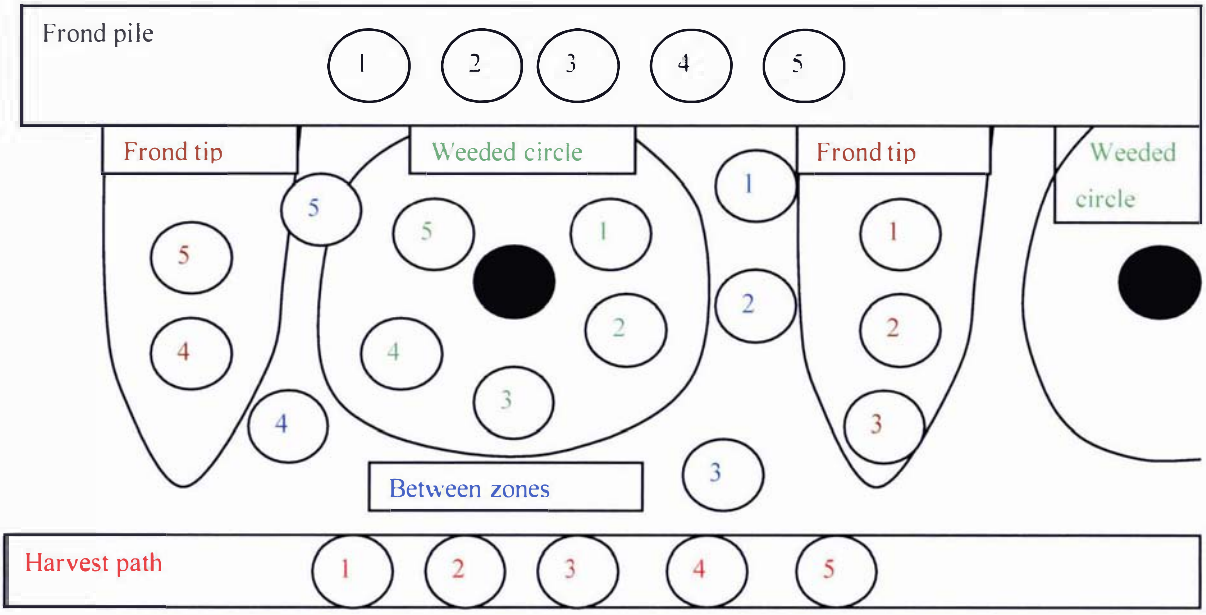
Two field experiments were carried out to determine the rate of nitrification of ammonium-based fertilisers in oil palm soils at Dami and Sangara. The experiments were done in the field in soils from different management zones at both sites. The first experiment used a very high rate of fertiliser while the second used a more realistic rate. The second experiment (5.3) was modified after results from the first experiment gave unexpected results for reasons that can now be explained.

The first experiment aimed to determine the rate of conversion of NH_4^+-N, added as AMC fertiliser, to NO_3^--N in soils under ambient conditions but with disturbed soils. The second experiment used undisturbed soil.

5.2.1 Methods and materials

5.2.1.1 Sampling sites, zones and depths

For each site (Dami and Sangara), samples were taken from five locations which were 3-4 palms apart. The locations covered the five zones; FP, FT, BZ, WC and HP. In each zone within a location, soil samples were collected from five sampling points that were between 1 to 2 m apart except at Dami where the choice of sampling area was more limited due to the fact that fertiliser had been applied to the alternate rows so soil samples were taken one palm apart. A sketch of the sampling protocol is shown in Figure 5.1. This worked out to 25 sampling points (cores) per zone from an area of approximately one hectare. At each point, soil samples were taken from three depths; 0-7.5 cm, 7.5-15 cm and 15 – 30 cm. In the FP, the non-decomposed recognizable frond prunings were removed leaving only the fully-decomposed material on the surface. The fully-decomposed material was very dark and contained some hard, partly-decomposed materials and many live tertiary and quaternary oil palm roots.



● = standing palm and ○ = sampling points (not to scale)

Figure 5.1 Soil sampling outline at a location showing the five sampling points (1-5) under the five different zones

However, for WC and HP zones, samples were taken at only the 0-7.5 cm depth on the basis that less nitrification is likely to occur at lower depths and also that any nitrification at depth would probably be similar to that for the other three zones, as seen from the results of a previous preliminary laboratory incubation experiment (not reported). The other reason was to rationalise the number of samples for analysis. At Dami, because of the obvious trash layer on the soil surface under the FP, the top 5 cm of this litter layer was also sampled.

At each sampling point, a 30 cm deep hole was dug with a spade and 250 - 350 g of fresh soil was taken from each of the three sampling depths. For each zone, this sampling amounted to 7 to 9 kg of soil. Bulked soil samples were then brought to the office, sieved (<2 mm) and mixed thoroughly on a plastic sheet. Plant roots, earthworms and insects were removed by hand during the sieving process. Field-moist, sieved, soils were then mixed by mounding four times. Finally 2 x 250 g sub-samples were placed in plastic bags ready for the incubation trial.

5.2.1.2 Soil preparation and field incubation

One sub-sample had fertiliser added while the other did not. For the nil-fertilised soils, 100 g of field-moist sieved soil was loosely packed into a 5 cm diameter x 7 cm length pvc drain pipe section. Each pipe had a volumetric capacity of 137.4 cm^3 so the resulting soil bulk density was 700 kg m^{-3}. For the Dami FP litter samples, only 50 g was able to be packed into each pvc pipe because of its low bulk density. For the fertilised soils, 0.5 g of AMC (equivalent to 2,083 kg N ha^{-1} assuming bulk density of 1.00 and 40 % water content,) fertiliser was thoroughly mixed with 100 g of field-moist soil and packed as described above for the nil-fertilised samples. For the Dami litter samples, 0.25 g AMC was added per 50 g of litter. Each treatment was replicated five times.

The open end of each pipe was closed with nylon cloth and fly wire held together with a rubber band. Nylon cloth and fly wire were selected to allow water and temperature to equilibrate between the tubes and the outside soil. The packed pipes were then buried horizontally in an open 50 cm deep soil pit, to preclude the movement of water and therefore leaching of soluble N into, or out of, the tube. The fertilised soils were buried in a separate hole from the unfertilised samples to avoid cross-contamination of unfertilised samples during handling of the tubes. The pits were covered with a loose single plastic cover sheet to allow air circulation, and a 10 cm thick layer of soil was then placed over the plastic. The whole incubation site was covered with a sheet of plastic to prevent rainwater from getting into the pit and wetting the incubating soils. Soil temperature was measured by inserting an ordinary thermometer 5 cm deep into the layer of soil covering the incubating pipes.

5.2.1.3 Soil extraction and analysis

After field incubation periods of 1, 3, 7, 14 or 28 days, pipes were removed from the pits and soil was emptied onto a plastic bowl and mixed thoroughly by hand. For the day 0 samples, extractions were done on the same day that the samples were prepared for incubation. A 5 g sub-sample of mixed soil was weighed into a 375 ml screw-capped plastic bottle. Fifty ml of 2.0M KCl was then added and the soil was shaken end-over-end at 60 r.p.m at 25 °C for 1 hour on the modified clothes drier shaker (Plate 5.1).

After shaking, bottles were allowed to stand for 15 – 30 minutes before the soil-KCl extracts were decanted and filtered through a Whatman No 41 filter paper into 60 ml plastic storage bottles. Each extract was split in half; one sample was retained as a backup while the other was sent to NZ for analysis. The samples were stored in a freezer at – 10 °C prior to being shipped to Massey University. A 60 ml blank sample of 2.0M KCl was also taken to check for contamination of each batch of extractant used. The water content of the field moist soil samples was determined for each sample on each extraction day.

The NH_4^+-N and NO_3^--N contents of the extract were determined using a Technicon AutoAnalyzer (Technicon Instruments Corporation). The equipment consisted of a sampler, a manifold, a cartridge, a pump and a flow cell colorimeter for measuring absorbance and data was recorded on a computer. Nitrate was determined by hydrazine reduction while NH_4^+-N was determined after reaction with phenol and hypochlorite in alkaline solution (Hart *et al.*, 1994). The auto-analyzer had a sensitivity of 0.25 μg N ml^{-1}. Where concentrations exceeded 12.0 μg N ml^{-1}, extracted solutions were diluted as required and the dilution factors taken into account during calculation of NH_4^+-N and NO_3^--N contents of soil.

Plate 5.1 Modified clothes drier used as end-over-end shaker for extractions

5.2.2 Results and discussion

Analysis was not done on all samples after it was realized from the first lot of check samples that there was a problem in the total recovery of N at Sangara and very little or no NO_3^--N had been formed at Dami. Results of those samples analysed are discussed below.

5.2.2.1 Recovery of added N

The near total (85-99 %, Table 5.1) recovery of added N fertiliser found in the Dami trial, for both zones and across all sampling times, was as expected. The high and consistent recoveries suggest that the trial design was adequate for measuring the rate of nitrification should it occur within the buried pipes. However, for Sangara, a very different result was found for soil from the FP, FT and BZ zones. Here, by day 14, recoveries of total inorganic N were often less than 50 % and by day 28 they were often less than 30 %. For WC and HP soils, near total recovery was achieved as in the Dami situation.

Table 5.1 N recovery (% of added N) in field nitrification studies at Dami and Sangara

Site	**Zone**	**Depth (cm)**		**Days of incubation**					
				0	1	3	7	14	28
				% recovery					
Dami	FP	Litter		87	86	89	99	88	91
		0-7.5		89	90	90	89	82	92
	WC	0-7.5		85	94	91	87	90	93
Sangara	FP	0 - 7.5		95	88	87	41	27	8
		7.5 – 15		82	NA	NA	NA	38	32
		15 – 30		92	NA	NA	NA	58	34
	FT	0 - 7.5		84	NA	NA	NA	59	29
		7.5 – 15		78	NA	NA	NA	34	23
		15 – 30		97	NA	NA	NA	54	36
	BZ	0 - 7.5		79	NA	NA	NA	60	37
		7.5 – 15		86	NA	NA	NA	63	55
		15 – 30		85	NA	NA	NA	96	75
	WC	0 - 7.5		91	102	89	95	96	90
	HP	0 - 7.5		85	NA	NA	NA	94	105

NA = not analysed

The finding of lower-than-expected recoveries of added N at Sangara suggests that some other process(es), most probably leading to loss of N as gaseous denitrification products, had occurred in these soils. Although the Sangara soils are relatively well-drained, the presence of the fine clay horizon just below the incubation pit, together with the high rainfall (45 mm) received on day 7 of the trial, could have resulted in a temporary flooding of the pits. Whilst no direct rainfall fell on the plots, because of the presence of the plastic cover, lateral water or water from beneath the pits may have invaded the soils. Further evidence for water intrusion is seen in the data in Table 5.2 where soil water contents for Sangara soils tended to increase from day 7 onwards. This increase in wetness with time is most apparent for the FP soil but most soils, except those from WC and HP zones, showed a slight increase when comparing soil water contents on day 28 with those on day 0. Interestingly for WC and HP soils at Sangara where the good recoveries of added N were found, soil water contents during the whole incubation remained relatively constant.

Table 5.2 Gravimetric soil water contents (g g^{-1}) on different extraction days at Sangara

	Extraction Day	**Day 0**	**Day 1**	**Day 3**	**Day 7**	**Day 14**	**Day 28**
	Date	16/02/2005	17/02/2005	19/02/2005	23/02/2005	2/03/2005	26/03/2005
	*Rainfall (mm)	2.6	6.4	9.8	45	1	0
Zone	**Depth (cm)**	**Mean water content (g g^{-1})**					
FP	0-7.5	0.42	0.40	0.44	**0.49**	**0.49**	**0.47**
	7.5-15	0.29	0.28	0.32	0.36	0.37	0.31
	15-30	0.28	0.28	0.30	0.28	0.29	0.28
FT	0-7.5	0.36	0.38	0.42	0.37	0.39	0.38
	7.5-15	0.28	0.28	0.28	0.37	0.35	0.33
	15-30	0.27	0.25	0.28	0.30	0.30	0.28
BZ	0-7.5	0.30	0.34	0.39	0.35	0.35	0.35
	7.5 –15	0.27	0.27	0.32	0.31	0.29	0.29
	15 – 30	0.29	0.26	0.26	0.26	0.26	0.29
WC	0-7.5	0.31	0.26	0.27	0.28	0.30	0.27
HP	0-7.5	0.28	0.28	0.26	0.24	0.28	0.25

*The rainfall was on the actual extraction dates

5.2.2.2 Nitrate formation during incubation

The other notable feature of this trial is the amount of nett NO_3^--N formed during incubation (Table 5.3). This data shows that only in soil from the FP zone at Sangara was any appreciable nett NO_3^--N formed and this only occurred at the 14 and 28 day samplings. However at Sangara, more NH_4^+-N was lost than could be accounted for as nett NO_3^--N formed.

Table 5.3 Nett NO_3^--N formed (mg kg^{-1} dried soil) with time in the FP and WC soils (0 – 7.5 cm depth) at Dami and Sangara during 28 days incubation

Site	Zone	N form	Days					
			0	1	3	7	14	28
Dami	FP	NH_4^+-N	1748	1761	1770	1761	1637	1815
		NO_3^--N	1	0	0	0	0	0
	WC	NH_4^+-N	1556	1731	1673	1597	1667	1726
		NO_3^--N	5	2	1	0	0	0
Sangara	FP	NH_4^+-N	1720	1583	1576	740	337	31
		NO_3^--N	9	0	0	0	152	116
	WC	NH_4^+-N	1459	1638	1433	1520	1524	1450
		NO_3^--N	3	0	0	0	0	0

The poor recoveries of added N at Sangara (Table 5.1) plus the nil production of NO_3^--N at Dami (Table 5.3) would appear to be the result of a combination of internal and external factors that may have impacted on this trial. The most likely "internal" factor is probably related to the osmotic pressure induced in the incubating soils by the dissolution of the soluble AMC fertiliser (5.2.2.3). The most obvious "external" factor would appear to be the high rainfall on day 7 that could have increased the soil water content of the buried soils at Sangara as already discussed in 5.2.2.2.

5.2.2.3 Nitrification inhibition by fertiliser addition

Soil solution osmotic pressure was calculated to see if it might be a factor inhibiting nitrate formation in the fertilised and incubated soils. This calculation was done using Equation [5.1] as given by Hillel (1998) (page 33);

$$\Pi = MRT \qquad [5.1]$$

Where π = osmotic pressure (atmosphere)

M = molar concentration of ions (mol L^{-3})

R = gas constant (0.08205 L atm/deg mol)
T = temperature in °K

Equation [5.1] gives the osmotic pressure in atmospheres but can be expressed in kPa where 1 atm = 100 Pa = 0.1 kPa. The formula is only approximate because it assumes activity is equal to concentration, i.e. the salt has completely dissociated and the soil has no effect on the osmotic potential.

Note, the fertiliser rate applied in this experiment was very high (0.5 g AMC 100 g^{-1} wet soil) and this apparently resulted in very high osmotic pressure, e.g. the mean osmotic pressure for Dami was 1,378 kPa and 1,963 kPa for Sangara soils (Table 5.4). Darrah *et al.* (1987) reported that whereas no inhibition of nitrification was observed at osmotic pressures less than 200 kPa, an osmotic pressure of 350 kPa gave 90 % inhibition of nitrification. The osmotic pressures calculated for the rate of fertiliser used here were 4 (Dami) and 6 (Sangara) times that required to inhibit nitrification. Hence it is likely that high osmotic pressure in the soils was the single most likely factor inhibiting the nitrification process.

However some NO_3^--N was formed (Table 5.3) between days 7 and 14 for the FP soil at Sangara although the amount of NO_3^--N formed did not equate with the amount of NH_4^+-N lost. Perhaps the water that entered the incubation containers either leached out some of the AMC fertiliser or may have lowered the osmotic pressure and allowed the nitrification process to commence forming NO_3^--N. Some NH_4^+-N did disappear between days 3 and 7 of incubation, but again this loss of NH_4^+-N was not recovered as NO_3^--N.

Table 5.4 Calculated osmotic pressures (kPa) in the incubated fertilised soils at Dami and Sangara

Zone	Depth (cm)	Osmotic pressure (kPa)	
		Dami	Sangara
FP	Litter layer	1382	
	0-7.5	1220	1518
	7.5-15	1323	2009
	15-30	1360	2069
FT	0-7.5	1275	1688
	7.5-15	1352	2067
	15-30	1529	2120
BZ	0-7.5	1301	1945
	7.5 -15	1409	2108
	15 – 30	1507	2023
WC	0-7.5	1460	1909
HP	0-7.5	1420	2133
Mean		**1378**	**1963**

5.2.2.4 General Discussion

A possible explanation to link the two factors of high internal osmotic effect and high external rainfall is as follows. The dissolution of the AMC produced a high salt content that stopped nitrification altogether. Hence low NO_3^--N was formed in the FP soils, especially at the free-draining Dami site. This effect persisted throughout the 28-day duration of the trial. The same factor would also impact on nitrification at the Sangara site, except that water intrusion into, and possibly movement through the incubating pipes, reduced the level of soluble salts and nitrification could then proceed. Hence NO_3^--N started to appear after day 7 in the FP soil at Sangara. However the wetter soil either lost NH_4^+-N and/or NO_3^--N by leaching or underwent some degree of anaerobiosis and the resulting loss of gaseous denitrification products lead to the lower recovery of added N found on day 7 and beyond. This series of events was not evident in soil from the WC and HP zones because they probably had a much lower population of nitrifying microorganisms (since they do not usually receive N fertiliser in the field) and so neither soil produced much NO_3^--N. Also these were the two soils that did not show any increase in soil water content during incubation. Consequently, near total recovery of added N was obtained.

Whilst difficult to prove, the facts are that a high osmotic potential resulting from the dissolution of added AMC fertiliser in the enclosed pipes together with the coincidental high rainfall event at Sangara just around the time of the large drop in recovery of added N strongly supports such an hypothesis. Visual observations at the time of the extractions, confirmed that the samples were really wet and sticky, although no water table was actually observed in the incubation pits at the Sangara site.

The combination of factors that impacted on this trial effectively negated its usefulness for the purpose intended, viz to provide a measure of the rate of nitrification of added ammonium fertiliser. This lead to the design of another *in situ* experiment, but this time using a reduced rate of AMC addition, undisturbed soil, and destructive soil sampling at pre-determined times after fertiliser addition. This trial is discussed in 5.3.

5.3 *In situ* nitrification experiments

This *in situ* nitrification experiment was done after the previous in-field nitrification experiment (Section 5.2) produced anomalous results presumably due to either high osmotic pressure, water logging of the incubation pit, or some combination of the two.

5.3.1 Methods and materials

This experiment was done to assess the rate of nitrification in fertiliser-amended soil using undisturbed (*in situ*) field plots. Two plots were used with three replicates of each, and four sampling times at Dami and five at Sangara.

5.3.1.1 Choice of zones and experimental plot setup

Two zones were selected for this experiment; FP and WC. These contrasting zones have different soil chemical properties (3.4). Frond pile zones normally receive fertiliser at the mature phase (along with BZ and FT) but WC zones do not. However the WC zone has the highest leaching potential due to the contribution from stemflow (4.2.2.2.1) and also has the highest uptake of water and nutrients presumably due to high root density and/or activity (Appendix A2.2). Therefore it was reasoned that results from these two zones could represent extremes of the nitrification process within the oil palm plantation.

Six plots each of 2.88 m^2 (1.2 m x 2.4 m) were marked out in both zones (FP and WC). Fertiliser (AMC) was applied to three of the plots (+ fert) while the other three did not receive any fertiliser (nil-fertilised). Each plot replicate was separated by 2-3 palms. In all, there were a total of 12 plots at each of the Dami and Sangara sites.

In the WC zone, after each plot was pegged out, a vertical slot 30 mm wide and 50 mm deep was cut into the soil surface. A frame (1.2 m x 2.4 m) made from 20 mm x 300 mm plywood was placed over the marked area and fitted into the slot (Plate 5.2) to stop surface runoff water entering the plots after application of fertiliser. A black polyethylene sheet was placed over each frame to stop throughfall water getting into the plots, as shown in Plate 5.3. For plots in the FP zone, pruned fronds and partially-decomposed plant litter were first removed before the plots were similarly set up.

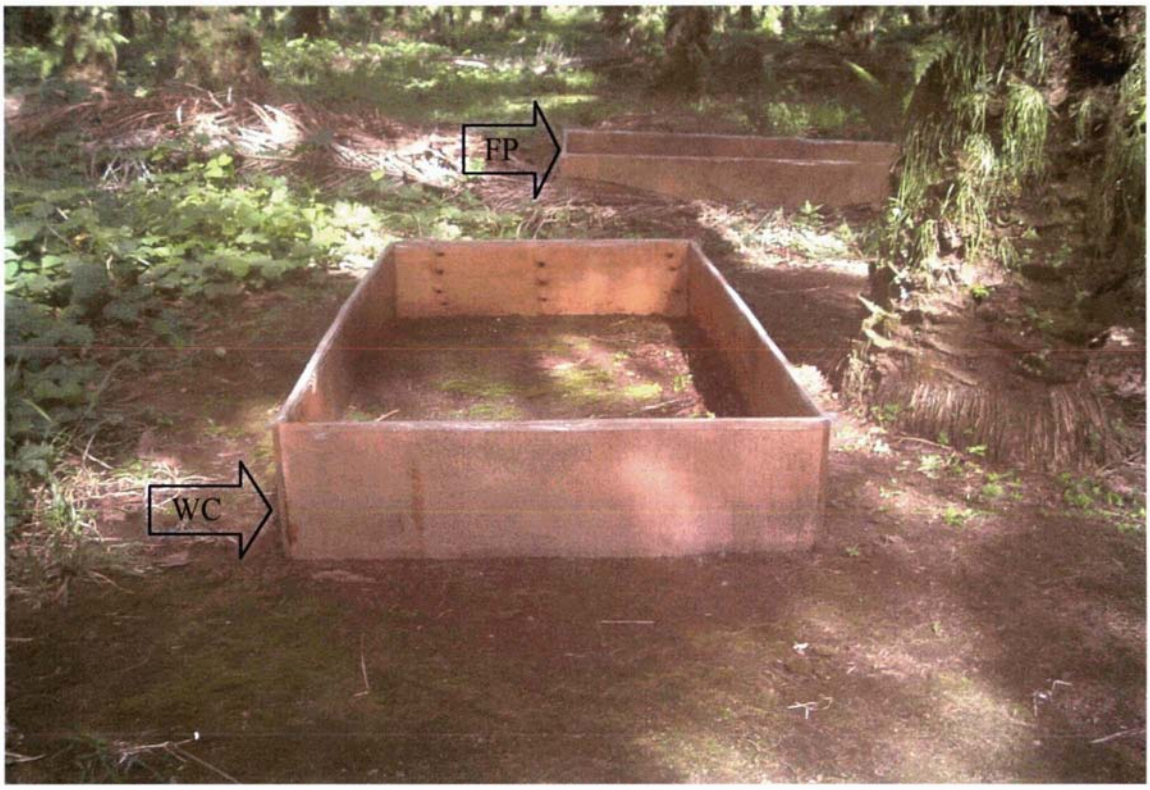


Plate 5.2 Plot setup in the WC and FP zones at Dami

Plate 5.3 Plastic cover to prevent throughfall from reaching the plots

5.3.1.2 Fertiliser application

To equalize soil water content, at the start of the experiment, all plots were watered to above field capacity with 12.5 mm (36 L) of rainwater that had been collected in tanks. The plots were watered with a 10 L watering can along and across the plots to ensure that the whole plot was equally watered (Plate 5.4). Each plot was then covered with plastic sheet and left for two days to allow the soil to return to field capacity. On the third day, the plastic covers were removed and fertiliser was applied. The rate of AMC fertiliser used was determined on the basis of a realistic field application rate of 205 kg N/ha/application, which scales down to an equivalent plot rate of 82 g AMC m^{-2}. This amount of AMC was estimated to produce an osmotic potential of 184 kPa when fully-dissolved (see calculation in Appendix A3.1). Commercial grade AMC was spread evenly by hand over the surface of each +fert plot. Approximately 7 – 8 hours later, 6.25 mm (18 L) of rainwater was added to each plot to wash the fertiliser in. Assuming a field capacity of 0.4 m^3 m^{-3} volumetric soil water content, this amount of water would be sufficient to move the fertiliser to a maximum soil depth of 1.56 cm. The nil-fertilised plots were given the same watering. The plastic covers were then replaced over all plots.

Plate 5.4 Wetting up soils pre-fertiliser addition

5.3.1.3 Soil sampling

Soil samples were taken from all plots 3, 7, 14, 28 and 56 days after fertiliser application, except for day 56 at Dami where the experimental set up was vandalized by villagers. All soil samples collected were extracted on the same day with 2M KCl using the method described in section 5.2.1.3.

Soil samples (0-20 cm) were taken from the field plots using a 5.5 cm-diameter steel corer. Twelve samples were collected from each plot on each sampling day. Soil samples were collected in a random zigzag pattern across each plot at least 15 – 20 cm away from each other and from previous sampling points. Samples from each plot were bulked together, sieved through a 2 mm sieve, and then mixed thoroughly before taking a sub-sample for KCl-extraction. Sampling was done on all nil-fertilised plots first and then on the fertilised plots to avoid cross-contamination between fertilised and nil-fertilised soil. During sieving, mixing and extraction, nil-fertilised soils were handled first followed by fertilised samples, again to avoid cross-contamination.

5.3.1.4 Extraction and analysis

10 g of field moist soil was extracted with 100 ml of 2.0M KCl as before (5.2.1.3). In addition to extraction with 2M KCl, on day 14, a second sample of soil from each plot was extracted with 100 ml distilled water. These aqueous extracts were required for Cl^- analysis which was used to determine the recovery of applied fertiliser. All extractions were done in duplicate; one remained in PNG while the other was sent to Massey University for analysis. Later, due to a lower-than-expected recovery of Cl^- and N in soils from FP at Sangara, fertilised soil samples from Sangara on days 3, 7 and 14, were sent to Massey University where they were extracted with water and re-analysed for Cl^-.

Soil extracts were analysed for NH_4^+-N, NO_3^--N and Cl^- as described earlier (5.2.1.3). A subsample of moist soil was weighed and oven-dried at 105 °C for two days to determine soil water content.

5.3.2 Results and discussion

5.3.2.1 Recovery of total inorganic N and Cl^-

The % recoveries of total inorganic N and Cl^- assessed as the amounts extracted from fertilised plots less the amounts from nil-fertilised plots divided by the amount in the added AMC fertiliser and expressed as a % for all sampling dates are shown in Table 5.5.

At Dami, recovery of inorganic N was high (96 – 132 %) at all sampling times for both the FP and WC soils suggesting that no substantial amounts of N had been incorporated into soil organic matter or lost as gaseous products during the trial. However NH_4^+-N levels were high and therefore would have swamped any loss from immobilisation. At Sangara, recovery of inorganic N in the WC soil was also high (76 – 109 %) at all sampling times as found at Dami. However, low % N recovery was found for FP soil on day 3 (41 %) and day 7 (39 %).

Chloride recovery was assessed on the day 14 sampling for all soils and also on days 3 and 7 for the Sangara FP soil. This was done to assess whether the pattern of Cl^- recovery paralleled that of inorganic N.

Chloride recoveries on day 14 for Dami (FP and WC) and Sangara (WC) were generally high (Table 5.5) which confirmed that most of the applied AMC fertiliser in the plots was still resident within the top 20 cm of soil. The low Cl^- recovery for FP soil at Sangara however was virtually the same as that found for the recovery of inorganic N.

Table 5.5 Mean inorganic N and Cl$^-$ recoveries (%) in the top 20 cm of fertilised soil for the *in situ* incubation experiment at Dami and Sangara

Site	Zone	Days after fertiliser addition							
		% inorganic N recovered					% Cl$^-$ recovered		
		3	7	14	28	56	3	7	14
Dami	FP	108	97	99	132	NS	NA	NA	87
	WC	96	97	110	119	NS	NA	NA	99
Sangara	FP	41	39	66	74	67	54	48	65
	WC	96	76	109	98	84	NA	NA	109

NA = not analysed and NS = not sampled due to vandalism of trial

It is unlikely that this low inorganic N and Cl$^-$ recovery in the FP soil at Sangara could be due to leaching because the plots were covered with plastic during the trial. It is also highly unlikely that the low recoveries were due to uptake by the crop within such a short time. The cause of the recovery was also unlikely to be related to soil chemical interactions since high recoveries were found for soil from WC plots. The fact that low % recoveries were seen on all sampling dates and for both N and Cl$^-$ suggests some type of systematic sampling error had occurred.

Kanchanasut and Scotter (1982) reported on a similar low (mean = 54 %, range = 33-85 %) recovery of Br$^-$ in a field experiment in NZ. Their study was done to determine the distribution of surface applied Br$^-$ in soil profiles under long term pasture and an oat crop after leaching with 50 mm of ponded water. During the process of sampling, using a 18 mm diameter corer, they proved that during sampling they unconsciously tended to avoid sampling pasture plants and instead collected soil samples from between plants. This led to a biased sampling. A similar sampling bias could have occurred at Sangara. What probably happened was that during sampling, some partially broken down litter and surface soil could have been moved aside with the augur. “Unrecovered” inorganic N and Cl$^-$ would still remain in the soil and litter that was pushed away by the corer. The higher inorganic N recovery found on days 28 and 56 may have been due to remaining fertiliser diffusing out and mixing with the rest of the soil. This was also the experience of Kanchanasut and Scotter (1982) who found that recoveries of Br^- improved with time after addition to the soil.

5.3.2.2 Rates of nitrification

A classical pattern of nitrification was shown by the data for FP soil at Dami where the decrease in NH_4^+-N over time was accompanied by an increase in NO_3^--N. Almost complete nitrification occurred by day 28 in this soil (Table 5.6). A similar trend was found at Sangara, but comparisons between the two sites were complicated because of the low recoveries found at Sangara.

At both sites, however, the nitrification rate was much lower in the WC soil than in the FP soil, and even after 28 days of incubation (at Dami) and 56 days (at Sangara), the amount of NO_3^--N produced was less than that found on Day 7 (at Dami) or Day 14 (at Sangara). Presumably these slower initial rates of nitrification found in the WC soils at both sites (as compared with FP soils) relate to the need for a build-up in the nitrifying microorganism populations in the largely unfertilised WC soils at both sites.

Table 5.6 Ammonium, nitrate and total inorganic N contents (mg kg^{-1} dried soil) of soils in the FP and WC zones at Dami and Sangara

Zone	Days *	N contents (mg N kg^{-1} dried soil) in top 20 cm of soil					
		Dami			Sangara		
		NH_4^+-N	NO_3^--N	Total N_i**	NH_4^+-N	NO_3^--N	Total N_i**
FP	3	166	31	197	19	11	30
	7	109	70	179	17	13	30
	14	72	101	173	20	32	52
	28	13	212	225	16	37	53
	56	NS	NS		5	45	50
WC	3	141	3	144	78	0	78
	7	139	7	146	59	3	62
	14	151	18	169	82	9	91
	28	137	41	178	60	20	80
	56	NS	NS		38	28	66

NS = not sampled

* days after fertiliser addition.

** Total N_i = inorganic N (NH_4^+-N + NO_3^--N)

Theoretical total inorganic N from fertiliser addition shown as different for the two sites due to differences in bulk densities; Dami FP = 193 and WC = 144 mg N kg^{-1} dried soil while at Sangara for both FP and WC = 79 mg N kg^{-1} dried soil.

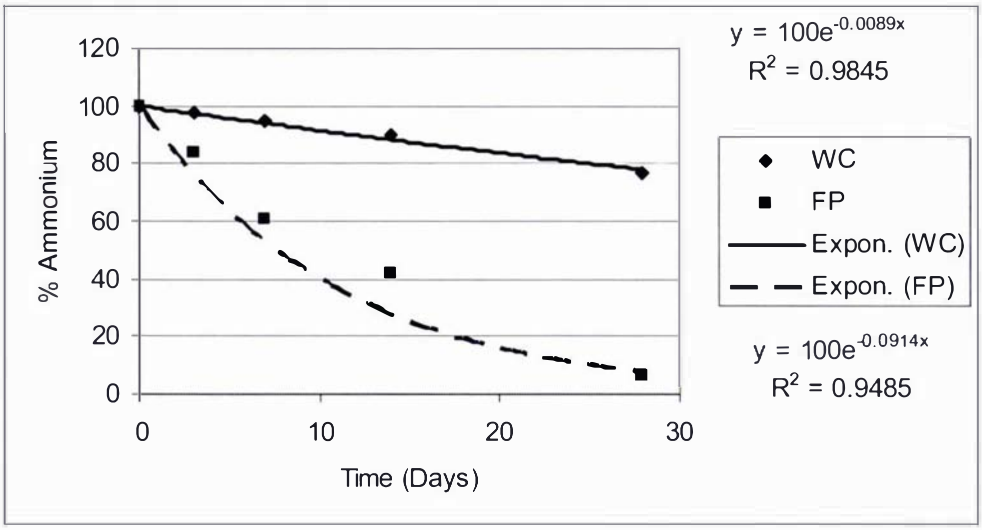
5.3.2.3 Nitrification model

One of the major objectives of this research was to use the experimental data to help develop and parameterise a model describing the main loss pathways of fertiliser N (often applied as AMC) from an oil palm system. It will become clear in a later section that leaching is a, and probably the, main loss pathway. But ammonium cations are subject to cation exchange and nitrate anions are not, so the two ions therefore move at different speeds through a soil. Thus a description of the rate of transformation of NH_4^+-N to NO_3^--N is needed as part of any N leaching model.

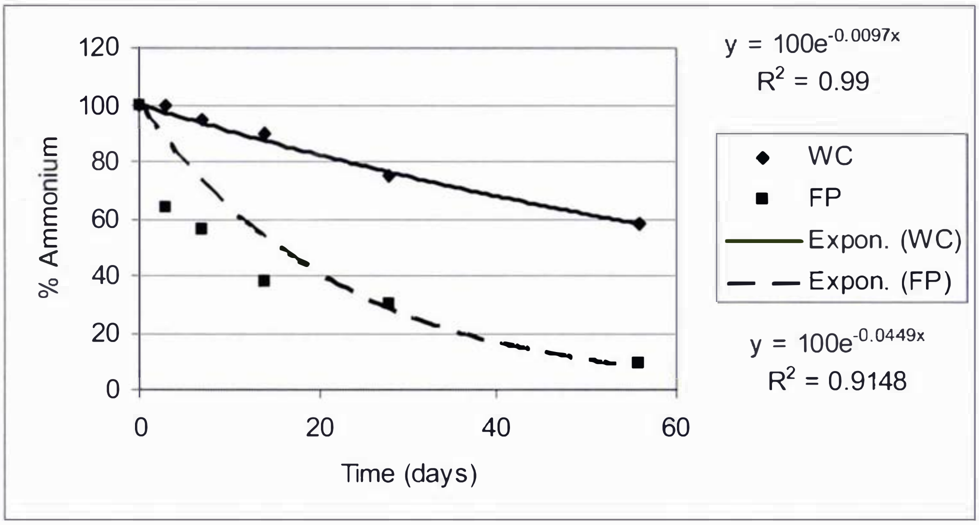
To make for more amenable analysis, data from the *in situ* nitrification experiment was reprocessed as follows: firstly the NH_4^+-N and NO_3^--N concentrations for the nil-fertilised control plots were subtracted from the corresponding values for the fertilised plots. Secondly, each of the resulting NH_4^+-N concentrations was divided by the sum of the NH_4^+-N plus associated NO_3^--N concentrations. This was done to reduce the influence of sampling error and spatial non-uniformity in the application of AMC to the plots. The resulting normalised data, shown in Figures 5.2 (a) and (b), suggests a roughly exponential drop in NH_4^+-N concentration with time. So the data were fitted to Equation [5.2] using the least squares best fit

$$C / C_o = \exp(-a\, t) \qquad [5.2]$$

where C is the normalised NH_4^+-N concentration, t is time (day), and a is a rate constant (d^{-1}). $C_o = 1$, is the value of C when $t = 0$ and all the applied N is present as NH_4^+-N. The fitted curves are shown in Figures 5.2 (a) and (b). The very high R^2 values suggest that the disappearance of original NH_4^+-N content with time fits well to the decay curve.



(a) Dami



(b) Sangara

Figure 5.2 Ammonium "decay curves" in the FP and WC soils at Dami and Sangara

Equation [5.2], which is the same as the one used to describe radioactive decay, applies when the rate of nitrification is proportional to the NH_4^+-N concentration. Once values for a have been found, $t_{1/2}$, (i.e. the time for half the NH_4^+-N to be nitrified), can be found as

$$0.5 = \exp(-a t_{1/2}) . \qquad [5.3]$$

Taking the logarithm of both sides and rearranging terms gives the following;

$$t_{1/2} = -\ln(0.5)/a = 0.693 / a \, . \qquad [5.4]$$

Using the normalised NH_4^+-N concentration and applying Equation [5.4], the $t_{1/2}$ values found at Sangara were 71 days for the WC and 15 days for the FP soil. For Dami, the corresponding values were 78 days for WC and 8 days for FP soil.

The data suggest that the nitrification rate is faster in the FP than in the WC soil at both sites. The FP zonc receives fertilisers as well as pruned fronds so there is a continuous supply of N which is the energy source for most chemoautotrophic nitrifiers and this appears to support a large population of actively nitrifying microorganisms. Shorter $t_{1/2}$ values (1-2 weeks) for NH_4^+-N conversion to NO_3^--N at both locations, could be interpreted as evidence for the presence of such an active nitrifying microbial population. In the WC zone, where hardly any fertiliser is ever applied much longer half-lives (> 2 months) were found; again at both locations.

The $t_{1/2}$ of the NH_4^+-N in the FP and WC zones will be compared to those derived from other studies and used in the leaching models in 8.3.4.

5.3.2.4 Summary

- Percentage recovery of extractable inorganic N and Cl^- in the FP at Sangara was low due most likely to a sampling error bias
- The $t_{1/2}$ of NH_4^+-N at Dami were 8 and 78 days and at Sangara 15 and 71 days for FP and WC respectively
- Nitrification rates are higher in the FP at Dami than at Sangara, however the rates are similar for the WC at both sites
- Nitrification rates are probably linked to traditional fertiliser and cultural practices whereby N fertilisers are broadcast over FP zones, but rarely within the WC, and fresh fronds are added to FP zones after pruning and harvesting events.

5.4 References

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Chapter 6

Emission of N_2O

As well as being lost from farming systems in soluble and particulate forms, N is also lost in gaseous forms via the process of denitrification. It is recognised that gaseous N loss can also occur via ammonia volatilisation but this study is more concerned with denitrification from acidic soils. Denitrification is an integral part of the natural biological cycling of N between soil and the atmosphere. The gaseous loss of N from fertilisers is of economic (maintaining the supply of plant available-N) and environmental concern (build-up of N_2O in the atmosphere and its effect on the ozone layer (Intergovernmental Panel on Climate Change, 1996). Some relevant literature on denitrification losses, factors affecting losses, methods of measuring N_2O emissions, and gaseous losses from tropical soils is briefly summarised below.

6.1.1 Denitrification and N losses from soil

Denitrification is the biological respiratory reduction of NO_3^--N and NO_2^--N to gaseous N forms, N_2O, NO and N_2. The process commences when NO_3^--N replaces O_2 as an electron acceptor in soils (Hutchinson and Davidson, 1993).

Denitrification is carried out by a wide range of different bacterial groups growing under conditions of limited soil oxygen supply in a step-by-step process in which NO_3^--N is reduced first to NO_2^--N then to gaseous N_2O and N_2 as illustrated in Schematic 6.1.

$NO_3^-\text{-N} \longrightarrow$	$NO_2^-\text{-N} \longrightarrow$	$NO \longrightarrow$	$N_2O \longrightarrow$	N_2	Schematic 6.1
Nitrate	nitrite	nitric oxide (gas)	nitrous oxide (gas)	N gas (gas)	

(Granli and Bockman, 1994)

Many soil microorganisms are facultative anaerobes that can use O_2 and NO_3^--N for respiration. They are capable of respiring under reduced O_2 conditions with oxidisable substrate and NO_3^--N (Burford and Bremner, 1975). Under well-aerated soil conditions, heterotrophic microorganisms oxidize organic C to provide energy and respiratory electrons that are usually transferred to O_2. However in wet soils because of the lack of O_2 as the terminal electron acceptor, electrons are instead transferred to NO_3^--N, and this results in NO_3^--N being reduced to N_2O (an intermediate) and N_2 gases both of which can escape from the soil (Groffman, 1995).

In soils, a number of inorganic compounds can accept electrons generated from the oxidation of C by soil microorganisms. They include oxygen, NO_3^--N, manganese (Mn^{4+}), iron (Fe^{3+}), and sulphur (SO_4^{2-}) depending on the redox value (Eh) of the soil environment (Killman, 1994). A well-aerated oxidising soil environment will have an Eh value of around +500mV. When the soil Eh value falls to below +400 mV, NO_3^--N becomes the electron sink. Because of the variability of Eh values, between and within soil aggregates, denitrification and therefore the emission of gaseous N from soils can be highly variable, both in space and time.

Letey *et al.* (1981) suggested from experimental data that N_2O emission from soils will be greater under conditions of fluctuating redox potentials (extremes of wetting and drying) than where soils have a continuously high (well-aerated) or low (poorly-aerated) redox potential.

6.1.2 Factors affecting denitrification losses from soil

Many soil factors affect the denitrification process and the resultant production of N gases. These include:

6.1.2.1 Soil water content and oxygen supply

Excess soil water affects the denitrification process by reducing oxygen transport to plant roots or to sites of microbial activity. Oxygen diffusion in water is 10,000 times slower than in air (Aulakh *et al.* 1992). However even though soils may be drained to field capacity, micro-sites inside soil aggregates can become anaerobic and denitrification can take place at these sites (Smith and Tiedje, 1979).

The rate of N_2O gas production in soil increases rapidly, as soil water content increases to 55-65 % water filled pore space (WFPS) (Dalal *et al.*, 2003). Above 60-70 %, O_2 is further reduced leading to losses as N_2O and N_2. Factors affecting WFPS, such as compaction, can affect denitrification rates due to increased bulk density and reduced O_2 diffusion within the soil (Bhandral *et al.*, 2005). Soil compaction increased N_2O emissions seven-fold (from 2.6 to 18.4 kg N ha^{-1}). Greatest N_2O emission occurred in NO_3^--N fertilised areas (57 kg N ha^{-1}), that was 10 times higher than in nil-fertilised areas (5.3 kg N ha^{-1}) (Bhandral *et al.*, 2005).

6.1.2.2 C and NO_3^--N availability

A supply of soluble organic C is essential for microorganisms that are involved in denitrification. Soil organic matter, root exudates and crop residues are important C substrates. McCarty and Bremner (1992) evaluated the effect of C on denitrification in Iowa subsoils, in the laboratory. They found a slow rate of denitrification that was due to a shortage of organic carbon in the soils rather than to the lack of denitrifying microorganisms. They concluded from this experiment that water soluble C from plant residues decomposed rapidly at the soil surface and that very little of it moved to depth.

When all other soil conditions are at an optimum, the availability of NO_3^--N itself can be a limiting factor for denitrification. However, Aulakh *et al.* (1992) have argued that in the field, NO_3^--N does not generally seem to be a limiting factor.

6.1.3 Methods for measuring denitrification losses

Methods for measuring denitrification losses in soils have been summarised by Aulakh *et al.* (1991), Aulakh *et al.* (1992), Dalal *et al.* (2003), Granli and Bockman (1994), Groffman (1995) and Payne (1991).

It is difficult to measure denitrification losses of N_2 from fertiliser or soil in the field because of the high background N_2 content of the atmosphere (79 % v/v). It is however possible to measure even low concentration of N_2O because it only occurs naturally in trace amounts (288-310 ppb) in the atmosphere.

There are three methods that can be used to measure denitrification losses *in situ* (Aulakh *et al.*, 1992) and they include, a) measuring N_2O concentration gradients in soil profiles, b) using micrometeorological procedures (Dalal *et al.*, 2003) and c) using chamber methods. Of these 3, the chamber method is the cheapest and most convenient for use in the field.

The chamber can be either an open or closed system. An open system involves continuous movement of gas through the chamber and emitted N gases are continuously removed. In the closed system, gas samples are collected before and after a pre-determined time interval. Use of chambers to collect N_2O is useful in small scale studies. However, extrapolating results to larger scale landscapes can be difficult due to high spatial and temporal variabilities. Closed chamber collection is more appropriate for field studies since the amounts of N_2O produced can be very low and otherwise undetectable, especially in well-aerated soils.

The discovery in the early 1970's that acetylene inhibited the biological reduction of N_2O to N_2 by Federova *et al.* (1973) as quoted by Mosier and Klemedtsson (1994), made it possible to quantify gaseous losses of N from soil and fertiliser based solely on N_2O emission. By using acetylene, N_2O becomes the end product which can be more easily quantified because of low atmospheric background content and a sensitive detection method using gas chromatography (Aulakh *et al.*, 1992). Unfortunately, acetylene also inhibits the nitrification process and consequently the rate of denitrification with the result that N losses from a soil can be seriously underestimated. The $||$ in Schematic 6.2 shows where inhibition by acetylene occurs in the nitrification and denitrification processes.

$NH_4^+\text{-N} \xrightarrow{||} NO_2^- \rightarrow NO_3^-\text{-N} \longrightarrow NO_2 \longrightarrow NO \rightarrow N_2O \xrightarrow{||} N_2$ Schematic 6.2

Others have used N isotopes to trace the movement of N through various N pools in soil systems and the unaccounted N is the N assumed to have gone through the denitrification process and been converted into gaseous form. This method is subject to cumulative errors from the various measurements required to determine N in the other pools (Groffman, 1995).

6.1.4 N_2O emissions from tropical soils

Although tropical soils may potentially be a source of significant levels of N oxide gases on a global scale, very few studies have actually been done on such system (Nobre *et al.,* 2001). Veldkamp and Keller (1997) studied the effect of N fertiliser on soil emissions of N_2O and NO from banana plantations in the humid tropics of Costa Rica, on Andisol and Inceptisol soils where 360 kg N ha^{-1} had been applied. They estimated that between 1.3 and 3.0 % of the applied fertiliser was emitted as N_2O and between 5.1 and 5.7 % as NO.

Ishizuka *et al.* (2005) measured fluxes of three greenhouse gases (N_2O, CO_2 and CH_4) from soils of six different land-use types at 27 field sites in Jambi Province, Sumatra, Indonesia. The mean daily N_2O flux for all land uses was 2.26 g N ha^{-1} (range 0.03 – 13.39 g N ha^{-1}), for an average equivalent annual N loss of about 0.8 kg N ha^{-1}. Emissions from an oil palm plantation amounted to 2.76 g N ha^{-1} day^{-1} (1 kg N ha^{-1} yr^{-1}). An obvious feature was the high CV for each of the different land uses ranging from 46 % in oil palm to 90 % for grassland.

In a study in Costa Rica, Keller *at al.* (1986) reported that annual N_2O emissions from tropical forest soils averaged about 3 kg N ha^{-1}. The mean of 2.76 kg N ha^{-1} yr^{-1} reported earlier in Indonesia for oil palm, suggests that emissions in oil palm system are similar to those measured for forest systems.

6.1.5 Conclusions from studies done to date relative to oil palm systems

Very little research has been done on gaseous N emissions from oil palm systems. Though the review suggests that gaseous N losses via denitrification are agronomically insignificant, the contributions to atmospheric N_2O build-up may be significant.

The proportion of N_2 to N_2O resulting from denitrification is highly variable and cannot be used to reliably determine total N loss from field studies where only N_2O is measured. Advanced methods of studying denitrification involving N^{15} and acetylene inhibition in the field are expensive and not appropriate for many field studies. Gaseous losses of fertiliser-N in tropical soils and especially under oil palm systems have not been widely studied. However, losses from banana plantations suggest such losses probably amount to < 5 % of applied fertiliser.

This pilot study was done to see if emissions of N_2O PNG oil palm soils were measurable and to compare such emissions with these reported for other tropical landuses.

6.2. Methods and materials

6.2.1 Soil gas collection chambers

The modified chamber method of Saggar *et al.* (2004) was used for collecting gas samples. PVC pipes (15 cm internal diameter x 30 cm length), with welded galvanized sheets as lids at one end were used as gas collection chambers. A 1 cm diameter hole, was made in the centre of the lid and a rubber septum glued over the hole. A syringe needle (size 10 gauge) was used to penetrate the rubber septum to collect gas samples from inside each chamber. The lids of each collection chamber were sealed with vaseline before closing. Grey duct tape was then wrapped around the pipe and the lid to further seal the chambers (Plate 6.1).


(a) (b) (c)

Plate 6.1 Gas collection chamber; (a) PVC pipe and metal lid with a septum in the middle, (b) the lid fitted onto the pvc pipe and (c) a syringe piercing the septum for gas sampling

6.2.2 Installation of chambers

One end of the pvc pipes was sharpened from the outside in so that insertion into the soil would not cause any major compaction at the edges. The cut fronds in each FP being sampled were moved aside leaving only largely-decomposed material on the soil surface. Before each chamber was pressed into the soil, a circular groove (4-5 cm deep) approximately the same diameter as the pipe, was cut in the soil with a sharp knife. The sharp end of the pipe was placed into this groove and then pushed into the soil to a depth of 5 cm. Soil was then pressed against the chamber at soil level to anchor each chamber firmly in the soil. This was done to minimise the escape of gas generated inside the chamber during each sampling period.

6.2.3 Collection sites

Collection of soil gas samples for N_2O determination was carried out at both Dami (31/05/05 – 28/06/05) and Sangara (15/03/05 – 11/04/05) sites. At each site, four collection chambers were used; two had KNO_3 fertiliser spread over the soil surface at 20 g KNO_3 per chamber (1,132 g KNO_3 m^{-2} = 1,629 kg N ha^{-1}) while the other two "control" plots had no KNO_3 added. Note here that although no KNO_3 was added, the soil had been receiving N fertilisers previously as part of the plantation. KNO_3 was added to ensure NO_3^--N was not a limiting factor for the denitrification process. Soil gas sampling was done only in the FP to see if any N_2O could be detected that would warrant more in-depth experiments other zones as well. Rainfall was recorded at the weather stations at each experimental site.

6.2.4 Gas sampling

The chambers were left open overnight to equilibrate the system inside and out prior to collection of gas samples the following day. On Day 0 of sampling, NO_3^--N (as KNO_3) was added in solid powder form to the soil surface of two of the four chambers.

Prior to extraction of each gas sample from the closed chambers, gas inside the head space was first mixed by withdrawing about 40 cm^3 of gas from the chambers and expelling it back and forth into the chamber three times before finally withdrawing 25 cm^3 of gas for analysis. Samples of gas were collected using 50 cm^3 polypropylene syringes, and injected into 12 cm^3 septum-sealed, pre-vacuumed, screw-capped glass vials. At the Sangara site, two 25 cm^3 samples of ambient air were collected from above ground at the start of the experiment. The collection chambers were closed in the morning (0700 hours) and 25 cm^3 samples were taken six hours later. After sampling, the chamber lids were removed. The gas sampling procedure was repeated using the same collection sites on days 1, 3, 7, 14 and 28 of the experiment. Above-ground gas sampling was only done on day 0. Soil temperature at 5 cm soil depth was a near constant 26 – 26.5 °C throughout the experiment.

Three changes were made to the procedure used at Dami. Firstly, background samples were collected from the chambers straight after the lids were closed. Secondly, gas collection chambers were sampled after one hour, (not 6 hours) after closure. Thirdly, no samples were collected on days 1 or 3. The changes were made because the correct sampling procedure of Saggar *et al* (2004) was not fully understood, at the time of the Sangara experiments.

6.2.5 Analysis

All gas samples were sent to Manaaki Whenua Landcare Research, Palmerston North (New Zealand) for analysis within 7 days of the last day of sampling at each site. Freight from PNG to NZ took no more than 6 days. The gas samples can be stored up to 3 months without appreciable loss of gas (Hedley *et al.*, 2006). At Landcare Research, the samples were analysed for N_2O using a Shimadzu GC-17 gas chromatography as described by Saggar *et al.* (2004). Because this could also determine CO_2 and CH_4 content of samples, these two gases were also analysed and results are presented in the Appendix A4.1. N_2O fluxes were calculated using the method of Mosier and Mack (1980).

6.3 Results and discussion

6.3.1 Emissions before and after closure of chambers

Results from both Dami and Sangara are presented and discussed despite;

a) gas collection sampling at Sangara having not followed the established method of Saggar *et al.* (2004) and
b) the fact that fertiliser (KNO_3) was added at a very high rate (1,629 kg N ha^{-1}) that may have affected plot biology and denitrification due to a high osmotic pressure (Dami = 2,564 kPa and Sangara = 1,057 kPa) effect

The amounts of N_2O collected at times 0 and +1 hour at Dami, and calculated for 1 hour emissions at Sangara are presented in Table 6.1. Gas sampling at Sangara was done after 6 hours of chamber closure however according to Saggar (pers. Comm., 2006)..."We have collected samples after 30 min, 1 h, 2h and 3h in the past and have found a linear increase in concentration above the background levels. The extended time is used in conditions where the emission levels are very low. The time is not a major factor as long as long as the increase in emissions is linear. You should be able to work out daily fluxes." Therefore results were calculated for 1 hour.

At Dami, N_2O emitted from soils in the unfertilised chambers at Time 0 for all days had a mean of 294 ppb (+/- 6 ppb) while in the fertilised plots, the mean for Time 0 was 315 ppb (+/- 42 ppb). This data suggests that the ambient N_2O content was relatively constant for the four samples measured at the start of of the experiment, just after the chambers were closed (nil fertilised = 294 ppb and fertilised = 315 ppb) compared to the measured and reported atmospheric content which is 310 ppb. For Time 1, the greatest N_2O emissions were seen in the fertilised chambers (mean = 529 ppb). This suggests the modifications made to the chamber experiment procedure and the subsequent sending of gas samples to NZ prior to analysis did not jeopardise the experiment.

Results at Sangara, for time 0, were not reliable since there were no background levels determined for all sampling days other than day 0. However for time 1, a similar trend to Dami is evident with, the greatest emission being from the fertilised chambers (mean = 1,531 ppb).

Table 6.1 N_2O concentrations measured before and after closure of chambers at Dami and Sangara

			N_2O concentrations (ppb)			
Site	**Days**	**Rainfall (mm)**	**Nil fertilised**		**Fertilised Chambers**	
			Time 0	**Time 1**	**Time 0**	**Time 1**
Dami	0	1.8	289	326	288	325
	7	34	288	339	357	1048
	14	0	289	311	293	349
	28	49	310	347	320	392
Mean			**294 +/-6**	**330 +/-16**	**315 +/- 42**	**529**
Sangara	0	1.6	389	514	389	674
	1	0	NS	178	NS	372
	3	0	NS	122	NS	366
	7	48	NS	221	NS	4869
	14	23	NS	501	NS	2529
	28	2.6	NS	136	NS	377
Mean				**278 +/- 236**		**1531**

NS = not sampled

6.3.2 N_2O fluxes from fertilised and unfertilised soils

Table 6.2 shows rainfall data for the night before the gas samples were collected, the change in the N_2O concentrations of chambers after 1 hour of closure and the flux calculated in equivalent g N ha^{-1} day^{-1}. To determine the changes and flux values for Sangara, it was assumed that the ambient N_2O concentration measured at time 0 (389 ppb) was constant over all the sampling days.

At Dami, throughout the duration of the experiment, the change in N_2O content ranged from 22 to 51 ppb and 37 to 691 ppb for the unfertilised and fertilised chambers, respectively. The changes were greater in fertilised (mean = 214 ppb) than in unfertilised chambers (mean = 37 ppb). The largest hourly change in both unfertilised (51 ppb) and fertilised (691 ppb) chambers was recorded on day 7 after 34 mm of rainfall. A similar trend is seen at Sangara where changes were greater in fertilised than in unfertilised chambers and the greatest changes in both cases were just after 48 mm rainfall on day 7. An increase in soil water content after rain appears to have induced an increase in N_2O emission. This increase was magnified in the presence of N fertiliser. Though there may have been sufficient N in the NO_3^--N form in unfertilised chambers, such soluble N may have leached to depths where there was insufficient C for denitrification to occur. In fertilised chambers, however there was ample NO_3^--N for denitrification to proceed due to the high rate of fertiliser added.

Table 6.2 Increase and flux of N_2O gas from fertilised and unfertilised chambers at Dami and Sangara

Site	Day*	Rainfall (mm)	Increase of N_2O over ambient levels (ppb)		N_2O flux (g N ha^{-1} day^{-1})	
			Unfertilised	Fertilised	Unfertilised	Fertilised
Dami	0	1.8	37	37	4	4
	7	34	51	691	5	103
	14	0	22	56	2	6
	28	49	37	72	4	8
	Mean		**37**	**214**	**3.72**	**31**
	SD				2	48
	CV %				48	158
Sangara	0	1.6	125	285	41	56
	1	0	0	0	10	28
	3	0	0	0	5	28
	7	48	0	4480	14	443
	14	23	112	2140	40	227
	28	2.6	0	0	7	29
	Mean		**40**	**1151**	**20**	**135**
	SD				24	168
	CV %				119	124

* = Day after fertiliser addition

The mean daily flux of N_2O from Dami FP sites in the unfertilised chambers was 3.72 g N ha^{-1} with a range from 2 to 5 g N ha^{-1} (in kg equivalent, mean = 1.36 kg N ha^{-1} yr^{-1}

and range, 0.73 to 1.83 kg N ha^{-1} yr^{-1}). At Sangara, the mean daily flux in the unfertilised chamber (20 g N ha^{-1}; range = 5 – 41 g N ha^{-1}, in kg equivalent, mean = 7.3 kg N ha^{-1} yr^{-1} and range = 1.8 – 15 kg N ha^{-1} yr^{-1}) was higher than at Dami. This might suggest that the soils at Dami are better drained than those at Sangara. The range of estimated daily fluxes in the unfertilised Dami chambers were similar or within the range reported for forests and oil palm in Indonesia (0.03 – 13.39 g N ha^{-1}) (Ishizuka *et al.*, 2005) but the values at Sangara are higher. Saggar *et al.* (2004) measured daily N_2O fluxes in ungrazed pasture of 2.7g N ha^{-1} in a fine sandy loam soils and 3.2 g N ha^{-1} in silty loam soils. For fertilised and grazed pastures, they reported daily fluxes of 16 g N ha^{-1} in the fine sandy loam and 20.1 g N ha^{-1} in the silty loam soil. The N_2O emissions in the oil palm soils reported here are lower (especially at Dami) than those in NZ pasture soils but not very different to other land uses in the tropics.

6.3.3 Estimated total gaseous N loss

Because the ratio of N_2 and N_2O produced during denitrification is highly variable and unpredictable (Weier *et al.*, 1993), the N_2 component cannot be reliably estimated and therefore total N loss cannot be assessed. Likewise losses from added fertilisers are presented with some reservation since the osmotic pressures were high and could have seriously affected soil microbial activities. Even if tolerable, the fertiliser rates were well above normal field application rates. In addition, gas samples were collected from only one of five zones and this was only during the wet season.

Losses of N_2O denitrification from oil palm systems are assessed for 2 scenarios;

a) "unfertilised" chambers were located on areas that had been receiving the normal plantation fertiliser rates in previous years. Assuming fertiliser had been previously to plantations at 100 kg N ha^{-1} yr^{-1}, at Dami, a mean daily flux of 3.72 g N ha^{-1} for a year would amount to a loss of 1.35 kg N ha^{-1} yr^{-1} which represents only 1 % of the fertiliser applied. At Sangara the mean loss of 20 g N ha^{-1} day^{-1}, would amount to 7.3 kg N ha^{-1} yr^{-1} which would represent 7 % of the applied fertiliser.

b) assuming that N emissions from fertilised chambers returned to baseline levels after 28 days, then at Dami, a mean daily flux of 31 g N ha^{-1} for 28 days would amount to 868 g of N ha^{-1} which represents <1 % of added fertiliser. At Sangara, a mean daily flux of 135 g ha^{-1} for 28 days amounts to 3,780 g N ha^{-1} which also represents <1 % of the added fertiliser.

From these two calculations, it is obvious that N_2O losses from added fertiliser in the month following fertiliser application are small, ranging from <1 % at Dami to around 7 % at Sangara. The very good (and high) recovery of N in leaching experiment (8.3.3.1) also suggests that unaccounted for gaseous N losses are low and agronomically insignificant.

6.3.4 Summary

- Determination of N_2O emissions from fertilised N treated oil palm soils suggests that denitrification does occur at least in FP zones
- Increased losses of N_2O were found after rainfalls for up to 4 weeks after fertiliser addition
- N_2O losses probably account for <1 % of the applied fertiliser as determined in this short term trial
- Calculated losses of N_2O are probably agronomically insignificant
- Gaseous losses of N_2O are lower than emissions from NZ pasture soils but comparable to other land uses in the tropics
- Total gaseous loss (N_2O + N_2) is uncertain but obviously would be higher than losses from N_2O above.

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Chapter 7

N losses in surface runoff water

Surface runoff occurs when rainfall intensity is greater than the infiltration rate. N losses in surface runoff water can be in the particulate, dissolved inorganic N or organic forms (Smith *et al.*, 1993). The inorganic N lost in the process originates from mineralisation and nitrification of soil organic matter or from fertilisers. Factors that affect infiltration rate, discussed earlier (4.2.1.2.5), will impact on N losses via surface runoff.

Very few studies have been made of N losses in surface runoff from oil palm systems. Maena *et al.* (1979) reported that, in Malaysia, 11 % of applied N fertiliser could be lost as surface runoff each year (details of their experimental setup were discussed in 4.1.4). Kee and Chew (1996) did an experiment in which AMC fertiliser was applied and runoff water samples collected from five subsequent rain events. The calculated N loss as surface runoff was between 5 % and 9 % of that applied. The gross annual N loss was estimated to be 15-22 kg N ha^{-1} with 4 – 7 kg ha^{-1} being from applied fertiliser. Losses in sediments were very low (viz 0.7 – 1.8 kg N ha^{-1} yr^{-1}). These Malaysian studies were on clayey soils that have a large amount of surface runoff compared to the situation in PNG where oil palm grows, typically, on porous volcanic soils with high permeability.

This study aimed to provide an estimate of background annual losses of N via runoff, and to determine the contribution of applied fertilisers to such runoff under PNG conditions.

7.1 Methods and materials

7.1.1 General

Water samples from the surface runoff plots (4.2.3.2.1) were analysed for inorganic N content. Two sampling periods were analysed. The first involved collecting water samples from plots that had received no fertiliser within the previous three months. Water samples were taken from each of the plots during six rain events at Dami (February – May 2004) and 32 rain events at Sangara (September 2003 – April 2004). The second sampling period involved an intensive sampling of one to six rain events just before, and then after, fertiliser was added to determine the contribution of fertilisers to surface runoff losses. At each sampling the volume of runoff water generated was also measured as described earlier (4.2.3.2.2). The two sampling periods are discussed below.

7.1.2 Sampling prior to fertiliser application

The contents of the 200 L plastic drums that were filled with runoff water were first stirred with a 1.5 m length wooden paddle. Then a calibrated 3 L plastic container, attached to a wooden stick, was lowered into the centre of the drum so that a sample was obtained from near the middle of the drum. A full scoop of water was obtained from every full 200 L plastic drum that filled with runoff water from the plots. If the drums were half full, only half a scoop of water was taken. In large rain events when there was more than 1 full drum of runoff water, all water samples collected from a plot during the event were combined into a single 12 L bucket. The buckets of water were then taken to the office, stirred with a shorter wooden paddle, and left to stand over night for the suspended sediments to settle. The next day, duplicate sub-samples from each bucket were collected in small 60 ml plastic bottles and three drops of 1M HCl acid was added to each sample to preserve against microbial action. Samples were then stored in a freezer at -10 °C before being sent to Massey University for analysis.

7.1.3 Sampling fertilised plots

For the second sampling period, at Sangara, three additional plots were established; making six large plots in total (4.2.3.2.1). Once some runoff data had been obtained, the six plots were paired on the basis of approximately equal amounts of runoff water produced. To one of each of the paired plots, fertiliser was applied to the FP and BZ areas, while the other plot was left as an unfertilised control. Fertiliser was applied as AMC at the rate of 1 kg per palm (4 kg/plot = 1 kg N/plot) on 6/12/2004. However no water samples were collected after fertiliser application, because though there was 70 mm of rain during the remainder of December (maximum = 16.4 mm day^{-1}), no surface runoff eventuated. This was because the soil was very dry, with a calculated soil water deficit of between 143 and 197 mm. A second dose of fertiliser was applied three months later on the 5/03/2005. Two days later, on 8/03/2005 during a rain event of 57 mm, water samples were taken from every full 200 L drum collected.

At Dami, because of the unavailability of suitable areas to set up additional plots, sampling was only done on the existing three plots, but sampling prior to fertiliser addition did provide some baseline data. Water samples were collected and runoff volumes measured for two rain events (24/12/05 and 29/12/05) before fertiliser was applied to the plots on the 10/01/06. The first lot of water samples were collected on the same day after a 23 mm rainfall event and for four subsequent events. Samples had to be taken from the subsequent rain events as well, as runoff from the 23 mm (the first after fertiliser addition) event was very small. After the fifth sampling (of a rain event of 104 mm on 27/01/06), it was decided not to continue sampling because it was reasoned that most of the applied fertilisers would have either been washed off or moved into the soil along with the infiltrating water.

During the second sampling period at each site, two 60 ml samples were taken of the runoff collected in each full 200 L container. One sample had three drops of 1M HCl added to stop microbial growth, while the second did not have acid added. The acidified samples were destined to be analysed for NH_4^+-N and NO_3^--N, while the second set of samples were to be analysed for Cl^- and so obviously could not be preserved with HCl.

The plan was to use Cl^- as an inert tracer for N loss via surface runoff. All water samples were sent to Massey University for analysis of dissolved inorganic N and Cl^- contents.

7.2 Results and discussion

7.2.1 Inorganic N loss from areas not recently-fertilised

The mean, maximum and minimum concentrations of NH_4^+-N and NO_3^--N found in runoff during the baseline measurements are shown in Table 7.1. Although baseline data was only obtained over four months at Dami and eight months at Sangara, very rough estimates were made of the annual "background" losses of inorganic N in surface runoff by multiplying the average NH_4^+-N and NO_3^--N concentrations by the estimated average annual amounts of surface runoff (4.2.4.3.3). These estimates are also given in Table 7.1.

Mean totals of 0.25 kg and 2.2 kg N ha^{-1} yr^{-1} were estimated to be lost in surface runoff water at Dami and Sangara, respectively (Table 7.1). The higher loss at Sangara than at Dami was due to the much higher amount of surface runoff water generated. At Dami, the amount of NH_4^+-N lost was higher than NO_3^--N but the opposite was found at Sangara. The high infiltrability of Dami soils (4.2.1.2.5) probably means that soluble nutrients are more likely to be washed into the soils with infiltrating water than be lost in surface runoff water. However the amounts of N lost at both sites are low in comparison with the amounts (15 – 22 kg N ha^{-1} yr^{-1}) lost in Malaysia (Kee and Chew, 1996). The results of this present study suggests that background N loss via surface runoff is unlikely to be large or of major agricultural significance for PNG volcanic soils.

Table 7.1 NH_4^+-N and NO_3^--N concentrations and estimated total annual inorganic N lost via surface runoff water at Dami and Sangara

		Dami (n=6)			Sangara (n=35)		
		NH_4^+-N	NO_3^--N	Total	NH_4^+-N	NO_3^-N	Total
N conc (µg ml^{-1})							
	Mean	0.47	0.2	0.67	0.35	0.78	1.13
	Min	0.16	0.11	0.34	0.04	0.11	0.17
	Max	0.92	0.39	1.09	1.38	5.20	6.18
Av.Runoff	(mm yr^{-1})	38	38	38	193	193	193
	L ha^{-1} yr^{-1}	380000	380000	380000	1930000	1930000	1930000
Est Loss	(kg ha^{-1} yr^{-1})	0.18	0.08	**0.25**	0.68	1.51	**2.18**

n = number of rain events sampled.

7.2.2 Inorganic N losses from fertilised plots

7.2.2.1 Dami

In all events at Dami, surface runoff coefficients were very low (0.1 – 3.2 %) (Table 7.2). The runoff coefficients for the five rain events after fertiliser was applied were all less than 1 %, indicating that more than 99 % of the rainfall infiltrated into the soil.

After the fertiliser was added on the 10/01/2006, there was a 23 mm rain event that occurred on the same day, of which very little was collected as runoff (0.1 % runoff coefficient). Between 10th and 24th January, there were two rainfall events, of 21 and 40 mm, however runoff coefficients were again very low, viz 0.1 and 0.6 %, respectively. The rain events produced very little runoff and much of the fertiliser probably leached into the soil. On the 24/01/2006 there was a 71 mm rain event followed by a larger one (104 mm) on the 28/01/2006. All samples collected on 23rd January, which was the 2nd major event after fertiliser was added, were preserved with HCl by mistake and therefore Cl^- could not be analysed.

The amounts of both inorganic N and Cl^- in runoff were low, and similar, before and after fertiliser application, suggesting negligible loss of fertiliser in runoff (Table 7.2). The high NH_4^+-N loss on the day fertiliser was applied (10/01/2006) was probably not from the AMC, as it was not accompanied by increased Cl^- loss. As paired plots were not set up at Dami, corrections for background levels were not possible. However as the total runoff losses were so low, it can be concluded that runoff losses N are of little importance.

Table 7.2 Mean Cl^- and inorganic N losses from surface runoff plots (area = 324 m^2) at Dami just before and after AMC fertiliser was applied

Date	**Rainfall (mm)**	**Runoff Co-efficient (%)**	**Solute in runoff (g)**		
			NH_4^+-N	**NO_3^--N**	**Cl^-**
24/12/2005	51	1.1	0.00	0.04	0.09
29/12/2005	128	3.2	0.00	0.01	0.28
10/01/2006	Fertiliser	applied			
10/01/2006	23	0.6	1.14	0.00	0.05
23/01/2006	42	0.6	0.03	0.05	NA
24/01/2006	71	0.8	0.00	0.00	0.57
25/01/2006	22	0.1	0.00	0.00	0.15
27/01/2006	104	1.5	0.09	0.09	0.24
Amount after 10/01/2006			1.26	0.12	0.82
Fertiliser applied (g)			1000		2654
Inorganic N lost (%)			**0.14**		**0.03**

NA = not analysed

7.2.2.2 Sangara

At Sangara two days after fertiliser was applied, (5/03/05), there was a major rainfall event (57 mm, runoff coefficient = 11 %), and water samples were collected throughout. The amounts of inorganic N and Cl^- lost from the applied fertiliser was determined as the difference between the fertilised and unfertilised plots for each full drum of runoff water. The total loss was the sum of losses from the individual drums for the event (Table 7.3).

The amount of Cl^- and NH_4^+-N lost in the surface runoff was high in the first 600 L (1.7 mm rainfall equivalent) of runoff, but dropped very quickly after 800 litres of runoff (Table 7.3). The total amount of Cl^- lost in the event was 40 g, which was only 1.5 % of that applied. For N, the total inorganic N lost in the surface runoff water was 12 g, which was equivalent to 1.2 % of applied fertiliser and the losses were mostly in the NH_4^+-N form. The amount of fertiliser N lost via surface runoff in these volcanic ash soils that have very high infiltration rates was surprisingly low and not of major agronomic significance.

Table 7.3 Mean NH_4^+-N, NO_3^--N and Cl^- losses from surface runoff plots (area = 324 m^2) immediately after a 57 mm rainfall event at Sangara

Cumulative	**Losses (g) in runoff**							**Nett loss from fertiliser (g)**		
Runoff (L)	**Unfertilised plots**				**Fertilised plots**					
	NH_4^+-N	**NO_3^--N**	**Cl^-**		**NH_4^+-N**	**NO_3^--N**	**Cl^-**	**NH_4^+-N**	**NO_3^--N**	**Cl^-**
78 *	0.00	0.07	0.2		0.00	0.02	0.2	0.00	0.00	0.00
206	0.05	0.15	0.6		2.33	0.14	9.3	2.28	0.00	8.77
412	0.00	0.16	0.5		2.03	0.13	7.6	2.03	0.00	7.05
618	0.00	0.09	0.4		2.08	0.15	8.0	2.08	0.06	7.61
824	0.00	0.05	0.4		1.35	0.10	4.3	1.35	0.05	3.85
1030	0.02	0.00	0.3		0.75	0.06	2.1	0.73	0.06	1.74
1236	0.00	0.00	0.3		0.91	0.08	3.0	0.91	0.08	2.72
1442	0.00	0.00	0.4		0.58	0.08	1.9	0.58	0.08	1.50
1648	0.00	0.02	0.5		0.39	0.07	1.1	0.39	0.06	0.70
1854	0.00	0.02	0.5		0.17	0.02	0.7	0.17	0.00	0.28
2060	0.00	0.00	0.4		0.16	0.00	1.4	0.16	0.00	1.01
2266	0.00	0.00	0.2		0.19	0.00	1.6	0.19	0.00	1.40
2472					0.20	0.00	1.8	0.20	0.00	1.77
2678					0.14	0.00	1.1	0.14	0.00	1.09
2884					0.05	0.00	0.4	0.05	0.00	0.40
Sum	0.06	0.55	4.62		11.35	0.85	44.46	11.28	0.39	39.86
Total loss (g)								N**		Cl
								11.67		39.86
Equiv fert (g)								1000		2654
% recovery								**1.2**		**1.5**

* = runoff event on the 3/03/05, before fertiliser was applied.
** = sum of NH_4^+-N and NO_3^--N contents

No measurements were made of the time required for surface runoff to commence after rain started. However, the presence of cut fronds, cover crops and uneven topography at the experimental sites would most likely add to the time required for runoff water to reach the water collection system. Such a delay would provide an opportunity to dissolve and move fertilisers into the soil along with the infiltrating water. Also water flowing onto areas zones with high infiltration rates, such as the FP and FT zones, would create minimal runoff. In mature palms, fertilisers are normally applied to the FP, FT and BZ zones which already have high infiltration rates, so obviously as more water moves into the soil, less is likely to occur as runoff.

7.2.3 Summary

- Annual background N losses via surface runoff in these PNG volcanic soils are higher at Sangara (2 kg ha^{-1}) than at Dami (0.2 kg ha^{-1}) where they are negligible. Even at Sangara the losses are low in comparison to those reported for oil palm soils in Malaysia of up to 22 kg N ha^{-1} yr^{-1}
- Although fertiliser was applied during the wet season at both sites, the high soil infiltration rates resulted in only small N losses via surface runoff
- Total annual inorganic N losses in runoff from applied AMC fertiliser in PNG amounted to 0.1 % and 1.2 % of that applied at Dami and Sangara respectively, and were much lower than reported losses in Malaysia of up to 11 %
- Surface runoff losses of N are therefore not considered to be a major cause of N loss in on volcanic oil palm soils in PNG
- Losses of Cl^- confirmed the findings of low loss of N via surface runoff.

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Chapter 8

Leaching of inorganic N from soils

The transport of solutes out of the root zone into the subsoil below, or beyond is called leaching. Wild and Cameron (1980) report that annually between 2 and 100 kg N ha^{-1} is commonly lost through the process of leaching through soils. Because of the high rainfall and permeable soils in the oil palm growing areas of PNG, leaching of inorganic N has the potential to be an important pathway by which N is lost from the system. Although more than 90 % of soil N occurs in insoluble organic forms, mineralised N is water soluble and susceptible to loss (particularly via leaching) if not taken up by the palms.

For leaching of soluble N to occur there are two basic requirements; a soil water flux moving downwards and a significant concentration of N in the soil solution (Keeney, 1986). The redistribution of rainwater and factors affecting the soil water balance are discussed in 4.1.3. This present chapter outlines the basics of the leaching process; the main models used to describe it; the different experimental methods available for measuring leaching N from soils and studies of N leaching from oil palm growing systems.

8.1 The leaching process

Water in soil is not chemically pure. Rainwater adds some solutes to the soil, for example sodium and potassium chloride, the concentrations of which vary with wind direction and distance from the sea (Wiklander, 1974). Rainwater also contains small amounts of ammonium formed in the atmosphere by electric discharge (Stevenson, 1982). Further, as rainfall infiltrates and starts percolating through the soil, it dissolves other solutes derived from the weathering of soil minerals and the decomposition of organic matter, together with fertiliser and pesticide residues (Hillel, 1998). Internal drainage then transports these solutes down through the soil profile. However not all the dissolved solutes move with the water. Some solutes are taken up by plants, some are adsorbed onto soil surfaces through chemi-sorption, or are precipitated out under certain conditions. The major sources of leached N are N fertilisers and soil organic matter.

8.1.1 Convection, diffusion and hydrodynamic dispersion

For solutes in soils, it is useful to define two distinct concentrations; the concentration in the soil solution (C_s) with common units of g or mol of solute per m^3 of soil solution, and the total concentration (C_{tot}) with units of g or mol of solute per m^3 of soil. This second concentration includes adsorbed solute. It follows from these definitions that where there is no adsorption,

$$C_{tot} = \theta C_s . \qquad [8.1]$$

The movement of solutes in soil involves two processes, convection, and molecular diffusion. The interaction of these processes leads to what is called hydrodynamic dispersion, which involves the solutes being carried along with the soil water, but also being spread out or dispersed throughout the soil with time (McLaren and Cameron, 1995).

Convection refers to the movement of solutes with flowing water. Where the concentration of a solute in the soil solution is locally uniform, and the solute is passively carried along by the moving soil water, the flux density of that solute, q_s (the mass of solute carried across unit cross-sectional area per unit time), may be found as

$$q_s = q_w C_s \qquad [8.2]$$

where q_w is the Darcy flux density (the volume of water flowing across unit cross-sectional area per unit time). Further, for non-adsorbed solutes, the average speed of movement down through the profile (V) can be found as

$$V = q_w / \theta \qquad [8.3]$$

If reversible adsorption, such as cation exchange, occurs the speed with which a pulse of solute moves down through the soil will be slower than this however.

Equation [8.2] is widely used to estimate the amount of solute leached. But it is, at best, approximate as at a pore scale level soil solution concentration is rarely uniform, and soil water velocity is also highly non-uniform. Water, and the solutes it carries, move fastest through the centre of each pore and are stationary at the pore wall. Also water moves much faster through larger pores than smaller ones; the average velocity being proportional to the square of the pore radius. The length of various pore pathways between any two depths also varies. So at the pore scale, convection is a highly non-uniform process, and will result in a wide range of solute travel times between any two depths. The effect of this appears on the larger scale as a lot of mixing between an invading solution and the soil solution initially present.

However, solutes are not only carried along with the moving soil water. Ions or molecules in solution also move around randomly, which tends to smooth out local concentration gradients. This process is called molecular diffusion (Hillel, 1998). It is only effective over distances of the order of a few millimetres, but causes the solute concentration within pores, and in adjacent interconnected pores, to equilibrate and become more uniform within a day or so. This reduces the effect of the local variation in velocity described in the previous paragraph, and means that solutes can move into or out of effectively stationary water in tiny pores, allowing such water to participate in the leaching process.

8.1.1.1 Two models describing hydrodynamic dispersion

The most common model used to describe hydrodynamic dispersion is the convection-dispersion model or equation (CDE). In simple terms it implies that a pulse of solute (for example an application of soluble fertiliser) applied to the soil surface moves down through the soil at some average velocity V, but also tends to gradually spread out in a roughly bell-shaped or normal distribution as it moves down through the soil. To quote

Jury *et al.* (1991, p. 221), the CDE model only applies when "the time required for solutes in stream tubes of different velocity to mix (by diffusion or transverse dispersion) along a direction normal to the direction of mean convection is short compared to the time for solutes to move through the volume by mean convection." Stream tubes are pore pathways with different local water velocities. This model is used later in this present study to describe the flow of ammonium ions through lysimeters, and the equation for the appropriate boundary and initial conditions is given there (8.3.2.3).

Sometimes preferential flow occurs in soil, where most of the flow is through a few widely-spaced macropores such as cracks, old root channels or worm holes. Then there is little convective mixing or molecular diffusion between the flowing water in the isolated macropores and the bulk of the soil water in smaller pores which moves much more slowly. Preferential flow can lead to the rapid movement of some surface-applied fertiliser deep down into the soil profile, but also implies the relative immunity to leaching of solutes resident in the smaller pores (Jury *et al,* 1991). The presence of macropores does not necessarily mean that preferential flow will occur. The soil has to be very close to saturation for those pores to fill and become conductive, and this will not usually occur in permeable soils that are conductive enough to allow rainfall to infiltrate while still unsaturated.

Where preferential flow does occur, or other conditions such as variable throughfall under oil palm (4.2.2.2.4) cause highly non-uniform infiltration, the convection-dispersion model will not apply, and a quite different model, called the convective lognormal transfer function model (CLT) is often more appropriate (Jury *et al,* 1991). In complete contrast to the CDE model, the CLT model assumes that there is no mixing between different flow pathways as solutes move down through the soil profile, and that the travel time distribution for solute in the various flow pathways can be described by a lognormal distribution. Because of the highly variable throughfall induced by the oil palm canopy, the CLT model was found to be more suitable than the CDE model for the *in situ* leaching experiments described later (8.3.4). The relevant equations for the appropriate boundary and initial conditions are also given later.

8.1.1.2 Resident and flux concentrations

It is sometimes useful to distinguish between two soil solution concentrations, the flux and resident concentrations. From the above discussion it will be apparent that when preferential flow occurs through isolated macropores and the CLT model applies, the flux-averaged solution flowing through the soil will usually be quite different to the volume-averaged solution in all the soil pores. In contrast, when conditions are such that the CDE model is applicable, the difference between the flux and resident concentrations is usually small enough to be ignored. Note that it is the flux-averaged soil solution concentration that is needed for Equation [8.2] to be valid.

8.1.2 Measurement of N leaching

Determining the amount of N or any other nutrient being leached from a soil usually involves measurement of the flux concentration in the soil solution, and measurement or estimation of the flux of water moving through the soil. The following methods have been used to assess N leaching (Cameron and Haynes, 1980; Keeney, 1986; Snyder, 1996; Wild and Cameron, 1980);

8.1.2.1 Lysimeters

A lysimeter is an isolated volume of soil from which the leachate can be collected and measured. Here inputs and outputs of water and nutrients are clearly defined, allowing mass balances to be calculated for water and the individual nutrients of interest. An advantage of lysimeters is that they reduce the effects of field variability. There are three main types of lysimeters used: 1) undisturbed soil columns, either walled or fitted into containers, 2) mini-lysimeters and 3) field tension lysimeters based on fitting suction plates at some depth in the soil (Haynes and Williams, 1993). Types 1 and 2 have walls but type 3 does not. Lysimeter types 1 and 2 are usually free-draining, with free water exiting from the base, while for type 3, suction is created at the bottom to better simulate the field situation. Type 2 lysimeter studies are mostly done in the laboratory. With type 1 and 2 lysimeters, there can be problems caused by edge effects if there are gaps between the container and the soil, leading to preferential flow. Also because of the lack of suction at the base, the soil near the bottom remains effectively saturated even when drainage has stopped. This means the soil in the lysimeter usually has a higher water content than the same soil in the field, which could lead to enhanced N loss via denitrification. In some type 1 lysimeters, suction is applied at the bottom via porous tubing or by using wicks and hanging columns. The problem with type 3 lysimeters is that the volume of soil sampled is not clearly defined. Also they can be difficult to install and operate in loose sandy or pumice soils, such as those at Dami. Lysimeters provide a measure of the flux concentration.

Instead of collecting and analysing drainage water, another approach is the use of resin beds at the base of lysimeters as discussed by Schnabel (1983) and Lehmann *et al.* (2001). The exchange sites in the resin beds capture anions and cations from the effluent solution. Ions adsorbed by the resins are later extracted with either KCl or $CaCl_2$ solution depending on which nutrients are of interest. This method provides an estimate of the total amount of leaching occurring over time without the need to measure or estimate the water flux. However it does not allow monitoring of changes in nutrient output with time, and it is necessary to ensure that the ion retention capacity of the resin is not exceeded.

8.1.2.2 Suction cups

Suction cups are sealed porous ceramic thimbles installed in the soil, at several depths or at a specific depth of interest, with a connecting access tube to the surface. When suction is applied, a sample of the soil solution collects in the porous cup. This sample can then be sucked out and analysed for the nutrient, or pollutant, of interest. The concentration found can then be used in Equation [8.2] with an estimate of the Darcy flux density to get an estimate of leaching. The Darcy flux density is usually estimated from the soil water balance. The advantage of suction cups is that they can be continuously monitored when drainage is occurring. Also their installation involves little soil disturbance (Grossmann and Udluft, 1991). The soil solution samples are drawn mainly from the larger pores and therefore they may not fully represent the "true" soil solution. In other words they tend to provide a flux rather than a resident sample of the soil solution, as required for Equation [8.2]. However suction cups cannot sample bypassing water when preferential flow occurs (Keeney, 1986). Also, due to the small soil volume sampled and the large spatial variability usually occurring in the field, a lot of replicate cups are needed to get a good estimate of the average soil solution concentration. Further, clay particles, bio-films or phosphate precipitates can clog the porous ceramic cups.

8.1.2.3 Soil core sampling

Soil core sampling is one of the more direct methods of determining nutrient movement in soils. It involves destructively taking soil samples down to a pre-determined depth and extracting the nutrient of interest (Keeney, 1986). This method allows a profile of extractable nutrient with soil depth to be determined, providing the mass of the sample, the gravimetric water content and bulk density profiles are also measured. The method has its limitations; it is labour-intensive, and processes such as mineralisation can occur during the period between sampling and extraction. Further, as it is destructive, it can only be done once at any location. It measures the resident concentration plus any adsorbed solute removed by the extractant, not the flux concentration, and this needs to be remembered if the values found are to be used in Equation [8.2]

8.1.2.4 Catchment sampling

Catchment sampling involves taking water samples for analysis from a creek or river, and also measuring or estimating the volume of water flowing from the catchment. The product of the two gives an estimate of the rate of nutrient loss from the catchment. As the loss from a large area is measured, it reduces sampling problems, and the need for replication (Wild and Cameron, 1980). A requirement for catchments to be used for this sort of study is that they have an impermeable substratum so that most of the excess water leaves as surface water rather than as groundwater. Thus the method cannot be used for studies in most oil palm areas, where the soils are usually deep and free-draining. Also in oil palm plantations, the catchments are large and often involve different land uses, including roads and workers' residential houses and gardens as well as the actual oil palms. So it is difficult to relate results to specific management practices. It is also difficult to separate those nutrients reaching streams directly via surface runoff from those leaching to groundwater and then to the stream.

8.1.2.5 Aquifer and borehole sampling

This involves taking water samples from bores, or from deep cores taken from unsaturated zones just above the aquifers to provide data on nutrients entering the groundwater (Cameron and Haynes, 1980). Difficulties in determining the rate at which nutrients have moved to the sampling depth, and in relating the data to management practices, are the major drawbacks of these methods. It is almost impossible to determine precisely where nutrients found in aquifers have come from, and the rate at which they arrived.

8.1.2.6 Drain studies

This method is limited because it can only be used in areas with shallow ground water table (Cameron and Haynes, 1980). The method involves taking water samples from either open or buried drains. The disadvantage of this method is that not all water percolating through the profile is intercepted and therefore samples are not usually fully representative of the total drainage flow. This procedure is not suitable for many oil palm plantations, because the soils are usually deep and naturally well-drained.

8.1.3 Leaching of N from oil palm systems

A survey of the literature reveals that few studies have been made of the leaching losses of N from oil palm systems. This is rather surprising, as fertiliser N is often the single most important nutrient input to oil palms, and there is usually high rainfall in oil palm growing areas. Chang and Zakaria (1986) published a review of earlier studies of leaching from perennial crops in Malaysia and concluded that: "Field results indicate that such [leaching] losses are not as serious as was expected but are too few for reliable quantification."

A few years later Foong (1991) reported on an experiment in Malaysia using a single large lysimeter (8.8 m internal diameter and 1.5 m deep), into which an oil palm seedling was planted. The experiment ran for 15 years; the first 6 years with an immature palm and the remaining 9 years with a mature palm. In the mature phase (from years 7 to 15) N fertilisers were applied at rates between 120 and 172 kg N ha^{-1} yr^{-1} (mean 152 kg N ha^{-1} yr^{-1}), and on average 628 mm per year of drainage water was collected. Although N loss as a percentage of added fertiliser averaged 8 % (range = 0.8 – 26.5 %) for the first 6 years, it was significantly lower in the mature phase, averaging only 2.4 % (range = 0.7 – 6 %). The average actual loss over the mature phase was 3.6 kg N ha^{-1} yr^{-1} (range = 1 – 9 kg N ha^{-1} yr^{-1}). They attributed the higher initial leaching losses to the smaller palms taking up only a small fraction of the applied N. They did not research the fate of the added N that did not appear in the drainage water.

In Nigeria, Omoti *et al.* (1983) conducted a leaching experiment using small tension lysimeters in an attempt to measure nutrient losses under oil palm in deep sandy soils with an annual rainfall of 1,923 mm. However the small number of working lysimeters and large variability of the data from replicate lysimeters precluded their drawing any firm conclusions from the study.

Chang and Chow (1985) used a very simple water balance model to estimate fertiliser residence times for two sites growing oil palm in Malaysia. They concluded that "leaching losses of nutrients are likely to be small in view of the long time the nutrients would be in the soil before being leached". While the residence time approach has merit, and in fact a more sophisticated form of it is used later in this study, it cannot be assumed that the conclusions reached for Malaysian conditions apply in PNG. It is interesting that in their summary they speculate on the effects of "an uneven distribution of rainfall under the crop canopy", a theme that is central to this present study.

8.1.4 Conclusions

The few published studies of the leaching in oil palm systems in Malaysia suggest that in mature plantations leaching losses of fertiliser N are low (averaging less than 3 % per annum over 9 years). However the wetter climate and different soils in PNG mean that data from Malaysia may not be in terms of relevant to N losses from PNG oil palm soils.

The rest of this chapter describes a series of leaching studies carried out under field conditions at both Dami and Sangara. Also leaching models are developed from, and parameterised with, the results of these studies. The studies and the models were aimed at providing information which might suggest how N fertilisers can best be managed under PNG conditions.

8.2. Methods and materials

8.2.1 General

Three quite different experimental approaches were used to determine the form and quantity of N leached from the different zones within oil palm plantations at Dami and Sangara. The approaches taken involved the use of suction cups, lysimeters, and a destructive soil sampling procedure referred to as the *in situ* leaching trial. The leaching experiments were conducted with the following general aims:

(i) Suction cups – to study the seasonal and spatial variability of inorganic N at 150 cm depth, where N was assumed to have passed beyond the active oil palm root system

(ii) Lysimeters – to measure the effect of added fertilisers on N leaching losses from soils taken from different zones under the palms but subjected to the same leaching conditions in an above-ground controlled leaching system

(iii) *In situ* leaching – to determine the rate and extent of leaching of N following fertiliser addition to selected zones, with undisturbed soil and natural rainfall.

8.2.2 Suction cups

8.2.2.1 Apparatus

Suction cups and associated apparatus were purchased from Soil Moisture Equipment Corp. The kit consisted of a 50 ml syringe, a vacuum hand pump, and plastic tubes (154 cm length) with porous ceramic cups (8 cm length and 2.3 cm wide) at one end. Suction created using the hand pump sucks soil solution into the ceramic cup due to the pressure difference.

8.2.2.2 Installation plan

Ten suction cups were installed in the FP zone and another ten in the BZ zone at both Dami and Sangara. These two zones were chosen because they are the most commonly-fertilised areas in oil palm plantations. Each of the cups was installed 3 – 4 palms distant from each other within the experimental area. In the BZ, cups were installed 2.5 m from the palm trunk.

8.2.2.3 Installation procedure

To install each suction cup, holes (5.5 cm diameter) were augured to a depth of 1.5 m. Soil was placed into a bucket and made into a slurry by adding water. This slurry was then poured into the hole to about one third of the overall depth. The slurry was used to provide good contact between the suction cup and the surrounding soil. At Sangara, clayey subsurface soil was used to make the slurry while at Dami, clayey soils from Kumbango and Walindi, both NBPOL Plantations in WNB, were imported for use in preparing the slurry. The subsoil at Dami was not suitable for making a good slurry because of its sandy texture. After adding the slurry, a suction cup was inserted into each hole with the ceramic cup embedded into the slurry at the bottom of the hole. The rest of the hole was then back-filled with soil from the augured hole and tamped to limit water flowing down the sides of the tube. The end above the soil surface was covered with a pvc pipe and capped with an empty can (Plate 8.1).

Plate 8.1 A suction cup installed in a frond pile at Sangara, showing an empty can capping the pvc pipe

8.2.2.4 Sample collection and preservation

Samples of soil solution were collected the day after significant rain events mostly during the wet season. To collect them, a suction of 60 – 70 centibar was created in the cups using the hand pump. After 5 – 6 hours, water samples were removed from the cups using a 2,000 mm length of 1 mm diameter tube attached to a syringe. Three or four drops of 1.0M HCl acid were then added to each sample to prevent microbial growth during storage.

At Dami there were a total of 23 sampling days between 2/02/2004 and 15/02/2005, providing a total of 403 (460 expected) samples, and at Sangara there were 22 sampling days between 12/01/2004 and 29/03/2005, providing 392 (440 expected) samples (Table 8.1). The number of samples collected was less than expected because solution samples could not be collected from all cups at each sampling. During low rainfall months, samples were not available because there was no drainage, and the suction created was not sufficient to extract water from the soil. However, sample collection also depended on the availability of staff involved with other higher priority experiments that were running concurrently. For two months, June at Dami and May at Sangara, there was some drainage but samples could not be collected.

Table 8.1 Number of sampling events and water samples collected from suction cups at Dami and Sangara, 2004-2005

Month	Number of sampling events and samples collected			
	Dami		Sangara	
	Events	Samples	Events	Samples
Jan-04			2	34
Feb-04	4	58	5	91
Mar-04	3	78	6	115
Apr-04	3	52	2	31
May-04	2	30	NS	NS
Jun-04	NS	NS	2	37
Jul-04	1	14	ND	ND
Aug-04	ND	ND	ND	ND
Sep-04	ND	ND	ND	ND
Oct-04	1	16	ND	ND
Nov-04	2	31	ND	ND
Dec-04	2	30	ND	ND
Jan-05	3	57	2	35
Feb-05	2	37	1	17
Mar-05			2	32
Total	**23**	**403**	**22**	**392**

Note NS = no samples collected though there was drainage and ND = no sampling because there was no drainage.

8.2.3 Lysimeters

The aim of the lysimeter experiment was to determine the amount of N leached from the different zones after a single fertiliser application. The experiment was conducted under shelter away from the oil palms. The reason for this was because of the highly variable amount of throughfall (4.2.2.2) received by the five zones at varying distances from the palm stem. If left *in situ* the number of lysimeters that would have been required would have been large to cater for the large variation in throughfall, and it would have been impossible to fund and manage the experiment.

Setting up the lysimeters away from their normal position in the plantation did not provide the same rainfall intensities that would occur in the field, however it meant that all the zones could be treated similarly.

8.2.3.1 Construction of lysimeters

The lysimeter tubes were rolled from 2.0 mm (at Dami) and 1 mm (at Sangara) thick steel sheets. The internal diameter of the tubes was 20 cm and the length was 70 cm at Sangara and 50 cm at Dami. The length was 20 cm shorter at Dami because the deeper sandy pumice horizons made it harder to obtain long intact soil cores at the site. At the top end, two 15 cm metal rods were welded on opposite sides of the tubes for handling purposes. The bottom end of the tubes was sharpened on the outside, in an attempt to minimize soil compaction as they were being pressed into the soil. However as became obvious later on, avoiding compaction was not always successful, particularly at Sangara. Fifteen large cores were taken at each site.

8.2.3.2 Obtaining the large cores

Large soil cores were collected from each of the five zones (FP, FT, BZ, WC and HP) at each site by pressing the steel tubes into the soil using an excavator at Sangara, and a front end timber loader at Dami. Cores were taken from each zone by pressing on wooden planks to drive the tubes into the soil. The operators were told when to stop and adjust the blades as the tubes were being pushed into the ground. The tubes were then carefully dug out from the ground by hand. Some soil was left protruding from the bottom end of the tubes.

8.2.3.3 Post-insertion preparation of lysimeters

The tubes were turned upside down and soil removed from the bottom 1.5 cm of the cylinder using small kitchen knives, to minimize any smearing effects that might clog the larger soil pores. A coarse sand/gravel mixture (washed with dilute HCl), collected from Arehe Creek at Sangara, was placed inside the space left by the soil that was removed from the core. The bottom end of each tube was then covered with a 20 cm diameter galvanized lid, that was glued onto the tubes. Nylon cloth and fly wire were glued inside the lids to stop the sand and gravel falling out when the tubes stood upright. The lids had a 20 mm diameter hole in the middle, with a 20 mm external diameter pvc pipe that lead to a collection container. The tubes were then placed on a wooden bench (Plate 8.2).

At the top end of the tubes, welded galvanized tubing extensions were attached. These extensions, 20 cm long for the BZ, WC and HP and 50 cm for the FP and FT lysimeters, were added so that simulated rainwater could be applied to the lysimeters. Decaying fronds and litter were placed in the extensions of the FP and FT lysimeters.

At both sites, the lysimeters were covered with plastic to stop natural rainwater from entering.

A = plastic cover to stop rainwater from entering the lysimeters, B = lysimeter, C = covered plastic containers for collecting leachates and preventing external contamination, D = extensions on lysimeters, E = welded handles and F = cut drum for standing on to work with and inspect lysimeters.

Plate 8.2 Lysimeter setup at Sangara

8.2.3.4 Soil sampling for determination of bulk density

Small soil cores were taken close to (within 20 cm of) where the large lysimeter soil cores were obtained, to determine bulk density. There were three replicate soil cores taken per depth around each lysimeter. Soil sampling depths were chosen on the basis of differences in field textural and structural properties as shown in Table 8.2. At Sangara there were two main soil horizons in the top 70 cm depth, while at Dami there were three main horizons in the top 50 cm depth. At Sangara, soil samples were taken from 0 -30 cm depth (friable sandy clay loam) and 30 – 70 cm depth (friable to firm clay loam). In the WC and HP zones, the top layer was sandy clay loam but was firm to hard because of compaction. At Dami, soil samples were taken at 0 – 10 cm (very friable, moderately-developed sandy loam), 10 – 20 cm (weakly-developed sandy loam) and 20 – 50 cm (loose to very friable structureless loamy sand) depths. Soil samples were collected by pressing in 50 mm internal diameter and 50 mm long aluminium soil corers. Soils were then oven-dried at 105 ^{o}C and weighed for the determination of soil water contents. Bulk density was determined as in 4.2.1.1.1.

Table 8.2 Soil properties of lysimeter cores at Dami and Sangara.

Zones	Soil layers	Dami		Sangara	
		Consistence Texture	BD (g cm^{-3})	Texture	BD (g cm^{-3})
FP	1	vfr, md, sl	0.55	fr, scl	1.1
	2	wd, sl	0.74	fr, fm, cl	1.0
	3	lvfr, stless, s	0.83		
FT	1	vfr, md, sl	0.72	fr, scl	1.2
	2	wd, sl	0.74	fr, fm, cl	1.1
	3	lvfr, stless, s	0.80		
BZ	1	vfr, md, sl	0.77	fr, scl	1.2
	2	wd, sl	0.80	fr, fm, cl	1.0
	3	lvfr, stless, s	0.94		
WC	1	vfr, md, sl	0.79	fr, fm, scl	1.3
	2	wd, sl	0.80	fr, fm, cl	1.1
	3	lvfr, stless, s	0.93		
HP	1	vfr, md, sl	0.84	fr, fm, scl	1.3
	2	wd, sl	0.80	fr, fm, cl	1.0
	3	lvfr, stless, s	0.86		

vfr = very friable, fr = friable, lvfr = loose to very friable, fm = firm, md = moderately developed, wd = weakly developed, stless = structure less, s = sandy, sl = sandy loam, scl = sandy clay loam and cl = clay loam. BD = bulk density

8.2.3.5 Leaching studies

8.2.3.5.1 Pre-wetting

To wet up the soil, water was added in batches of 750 ml every hour for four hours on two successive days, i.e. 6 L was added over two days as shown in Table 8.3. The water used was stored rainwater. Water was added using an empty can that had holes at the bottom. Drainage water was not sampled because this phase was to wet up the soils. However the volume of leachate was measured to determine the frequency of sampling later in the experiment.

On the 7th and 8th day (6/07/04 and 7/07/04 at Dami, and 15/06/04 and 16/06/04 at Sangara), a second water addition was made. This time the leachate was collected and the volume of drainage was measured.

8.2.3.5.2 Fertiliser addition and sampling

Before the 3rd batch of water was added on the 14th and 15th day (13/07/04 and 14/07/04 at Dami, and 22/06/04 and 23/06/04 at Sangara), a mixture of 10 g AMN and 6 g AMC (a total equivalent application of 1,611 kg N ha^{-1}) was added. Thus 65 % of the added N was ammonium.

Table 8.3 Sequence of water and fertiliser additions, and leachate sampling of lysimeters at Dami and Sangara in 2004

Batches	Activity	Dates	
		Dami	Sangara
1	Pre-wetting added 6 L water	30/06 – 1/07	9/06 - 10/06
2	Pre-fertiliser 6 L water added	6/07 – 7/07	15/06 – 16/06
3	Added fertiliser and 6 L water and sampled	13/07 – 14/07	22/06 – 23/06
4	Added 6 L water and sampled	20/07 – 21/07	29/06 – 30/06
5	Added 6 L water and sampled	27/07 – 28/07	6/07 – 7/07
6	Added 6 L water and sampled	4/08 – 5/08	13/07 – 14/07
7	Added 6 L water and sampled	10/08 – 11/08	21/07 – 22/07
8	Added 6 L water and sampled	17/08 – 18/08	27/07 – 28/07
9	Added 6 L water and sampled	___	3/08 – 4/08
10	Added 6 L water and sampled	___	10/08 – 11/08
11	Added 6 L water and sampled	___	17/08 – 18/08

8.2.4 *In situ* leaching experiment

The *in situ* leaching experiments were set up to reflect what might be happening in the field in terms of N loss via leaching whilst encompassing all the normal soil and hydrological variabilities, without any added effect of soil disturbance.

8.2.4.1 Design

These experiments were conducted at both Dami and Sangara. The initial experiment was done at Sangara, and the next at Dami, to coincide with the earlier peak rainfall period at Sangara (normally around December) as compared with Dami (normally around February/March). The experiments were carried out at the same sites as all other N loss experiments. A total of five experiments were carried out; three at Dami and two at Sangara. Details of the experiments are summarized in Table 8.4. The experiments covered a range of rainfall events, fertiliser rates and durations.

At Dami, Experiment 1 involved a high fertiliser application rate (500 g AMC m^{-2}) with very high rainfall during the experimental period (1,708 mm). This experiment was done during the wet season. Experiment 2 also had a high fertiliser application rate, but was done from the end of one wet season through to the beginning of the next wet season. Experiment 2 was a repeat of Experiment 1, after realising from water balance calculations that, due to the very high rainfall received, the peak Cl^- content in Experiment 1 probably would have gone past the 200 cm maximum sampling depth. Experiment 2 went for a longer duration (five months) than Experiment 1 with a moderate accumulated rainfall (836 mm). Experiment 3 was done, again during the wet season, with a lower but more typical application rate of 82 g AMC m^{-2}, over a short duration (six days).

At Sangara, Experiment 1 was done going into the wet season with a high fertiliser rate (333 g AMC m^{-2}) over a long period (about three months) with a moderate accumulated rainfall (934 mm). Experiment 2 was done during the wet season as well, but using a lower and more typical fertiliser application rate (82 g AMC m^{-2}), and was of short duration (one month). Experiment 3 at Dami and Experiment 2 at Sangara were done to determine N leaching losses over the wet season.

Table 8.4 Details of *in situ* leaching experiments at Dami and Sangara (2004-2006)

	Dami			Sangara	
	Experiment 1	Experiment 2	Experiment 3	Experiment 1	Experiment 2
Dates	16/12/04 – 21/03/05	1/05/05 – 9/10/05	24/01/06 – 30/01/06	9/12/04 – 25/03/05	6/12/05 – 3/01/06
Duration (days)	96	152	6	107	34
Fertiliser applied	500 g AMC m^{-2} (1300 kg N ha^{-1})	500 g AMC m^{-2} (1300 kg N ha^{-1})	82 g AMC m^{-2} (213 kg N ha^{-1})	333 g AMC m^{-2} (866 kg N ha^{-1})	82 g AMC m^{-2} (213 kg N ha^{-1})
Rainfall (mm)	1708	836	310	934	218
Extractants	0.5M K_2SO_4	2.0M KCl and water	2.0M KCl and water	0.5M K_2SO_4	2.0M KCl and water.

Note: sampling was done in the BZ only in the 1st experiment at both Dami and Sangara

8.2.4.2 Layout

The experiments were conducted under the palms in the FP and BZ zones because these are the two main areas that normally receive fertilisers. For the FP, a 10 m x 1.5 m area was pegged out. The experimental area in the BZ was split into two 5 m x 1.5 m areas on either side of a palm. The layout of the experiment is shown in Figure 4.8 and in Plates 8.3 and 8.4. Each plot was surrounded by an earth bund covered with plastic to stop surface water moving into, or out of, the plot from surrounding areas.

8.2.4.3 Fertiliser rates and application

For the FP plots, the large undecomposed fronds were temporarily moved to one side of the marked out areas, leaving only the partially and fully-decomposed litter layer intact. Fertiliser was then spread evenly over the areas in each zone. The fronds were then returned to the plots. At Sangara, fertiliser was applied directly to the BZ area because there were no pruned fronds. However, at Dami there are front tips in the BZ, so they were temporarily moved aside and later replaced after spreading the fertiliser. Any undergrowth was slashed and removed from the trial plots at both locations.

AMC was applied at various rates for the different experiments as shown in Table 8.4. The reason for adopting high rates (500 g AMC m^{-2}) in the early experiments was to swamp background levels of Cl^- and N. The lower rates used in later experiments represent the more normal rates applied within the plantations. The fertiliser was weighed into small plastic bags for each of the areas and then spread as evenly as possible by hand over the plots.

Plate 8.3 An *in situ* leaching plot in the BZ

8.2.4.4 Soil sampling

As already described, the experiments ran for different periods (six days to five months) with different total amounts of accumulated rainfall (218 mm to 1,708 mm) (see Table 8.4). The date of sampling was determined when there was an excess of about 300 mm of rainfall over evaporation but this was misunderstood for Experiment 1 at Dami, and sampling was done much later than planned. For the other experiments, after the prescribed amount of rainfall had been reached, the plots were covered with plastic (Plate 8.4) to stop further rain reaching the soil until sampling could be carried out.

The blue catch cans on the stakes were used for estimating throughfall

Plate 8.4 An *in situ* leaching plot in the FP covered with plastic to stop rain water entering the plot just before sampling

In Experiment 1 at Sangara, a 3.0 m deep trench was dug with an excavator next to the sampling site and soil samples were then collected using bulk density corers, at 10 cm depth intervals along a transect every 15 cm along the length of the plot. The samples were later bulked for each 20 cm depth interval. At Dami, (all experiments) and at Sangara (Experiment 2), soil samples were taken using an augur (5.5 cm diameter) at 20 cm depth intervals and 20 cm apart to a depth of 2 m. In the FP, there were 50 sampling points and in the BZ, there were 25 sampling points along the centre of each of the plots. In all cases, soil samples from each 20 cm depth interval were bulked and then thoroughly mixed. Unfertilised "control" soil samples were also collected to 2 m depth from adjacent areas at five sampling locations within the FP and BZ to provide background levels of NH_4^+-N, NO_3^--N and Cl^-. These unfertilised areas were within 5 m of the experimental plots. Soil water content was determined using a subsample of each of the bulked soils.

8.2.4.5 Soil extraction

Subsamples of each soil were extracted with either 0.5M K_2SO_4, 2.0 M KCl or water (see Table 8.4). For the 0.5M K_2SO_4, 17 g moist soil was extracted with 50 ml of solution, while for 2M KCl and water, 10 g moist soil was extracted with 100 ml of extractant. In the first experiments, 0.5 M K_2SO_4 was used so that Cl^- content could also be determined. However during analysis precipitates formed in the tube linings of the auto analyzer, therefore in subsequent experiments water was used to extract Cl^-, and 2M KCl as used to extract inorganic N. All samples were extracted in 350 ml plastic bottles. The samples were shaken end-over-end in a modified clothes drier for 1 hour (Plate 5.1 in 5.2.1.3). The bottles were then allowed to stand for 30 minutes to settle suspended solids, before carefully decanting the supernatant into small 50 ml plastic screw-capped bottles. All extracts were stored in a freezer prior to being shipped to NZ for analysis of Cl^- and inorganic N contents. Blank samples of each extractant were also sent for analysis.

8.3 Results and discussion

8.3.1 Suction cups

The mean monthly suction cup concentrations of inorganic N are presented in Tables 8.5 and 8.6 for Dami and Sangara, respectively. The statistical mean, minimum, maximum, standard deviation and coefficient of variation were determined for the whole data set, not for the monthly means shown in these tables.

For two of the missing months, June 2004 at Dami (Table 8.5) and May 2004 at Sangara (Table 8.6), the amount of drainage was predicted however samples were not collected. The inorganic N concentrations for the missing months were estimated by taking the average of the four months prior to, and the month just after, the missing month; so for Dami average N concentration for June 2004 was determined using data from February 2004 to May 2004 and July 2004 and for Sangara May 2004 was determined using data from January 2004 to April 2004 and June 2004. The average for the missing months was determined this way since the missing rain events were considered as part of the preceding season. At Dami in November 2004, although samples were collected, there was no drainage predicted so the loss for that month was not calculated. The gaps at Dami (Table 8.5, August and September 2004) and at Sangara (Table 8.6, July – December 2004) were months with no drainage and the applied suction was insufficient to draw soil solution into the cups.

8.3.1.1 Variations in NH_4^+-N and NO_3^--N concentrations

The CV values for both NH_4^+-N and NO_3^--N for the different zones at both Dami and Sangara were very high, ranging from 142 % to 233 % (Tables 8.5 and 8.6). There were large variations between sampling dates for the individual cups, and on each sampling date between the individual cups within a zone at each of the two sites (Figures 8.1 (a) – (h)). At Dami, NO_3^--N concentrations ranged from 0 (both zones) to 87 µg ml^{-1} in the BZ, while (NH_4^+-N concentrations ranged from 0 (both zones) to 11 µg ml^{-1} in the FP.

At Sangara, NO_3^--N concentrations ranged from 0 to near 39 μg ml^{-1} (both zones), while NH_4^+-N concentrations ranged from 0 (both zones) to 2.3 μg ml^{-1} in FP. The gaps in the figures were for samples that were taken but the N concentrations were below detection level, or where a sample was not obtained.

There are many possible reasons for the large CV values in Tables 8.5 and 8.6. The most obvious one is that fertiliser would not have been evenly applied across the areas. Also the huge variation in throughfall could cause large spatial variation in the rate of leaching, leading to different suction cup concentrations. Different background levels of N could result from different frond pile loadings, leading to a different release of inorganic N from decomposing fronds.

Table 8.5 Mean monthly inorganic N concentrations (μg ml^{-1}) in suction cups and estimated N leaching losses from February 2004 – February 2005 at Dami

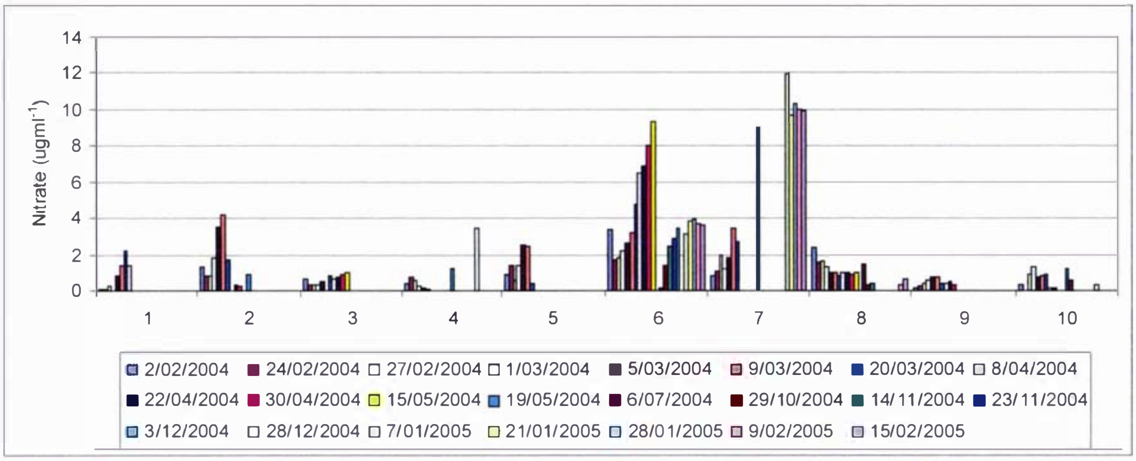
Months	Inorganic N concentrations (μg ml^{-1})					Drainage (mm)	Loss (kg N ha^{-1})
	FP		BZ		Total *		
	NH_4^+-N	NO_3^--N	NH_4^+-N	NO_3^--N			
Feb-04	0.23	0.95	0.23	6.89	4.14	458.7	19.0
Mar-04	0.17	1.47	0.17	2.09	1.95	589.0	11.5
Apr-04	0.15	1.19	0.15	0.60	1.04	62.2	0.6
May-04	0.07	1.58	0.07	0.36	1.04	209.6	2.2
Jun-04					2.12	180.5	3.8
Jul-04	0.20	0.33	0.20	4.08	2.41	59.9	1.4
Aug-04						0.0	
Sep-04						0.0	
Oct-04	0.57	0.24	0.70	19.27	10.39	67.6	7.0
Nov-04	0.40	0.44	0.28	17.84	9.48	0.0	
Dec-04	0.66	0.53	0.32	20.44	10.98	109.9	12.1
Jan-05	0.68	1.50	0.72	11.45	7.18	509.2	36.5
Feb-05	1.30	1.49	0.57	4.32	3.84	596.3	22.9
Mean	0.44	1.20	0.34	7.00			
Min	0.00	0.00	0.00	0.00			
Max	11.30	12.00	2.90	87.00			
Std dev	0.90	2.10	0.50	15.40			
CV %	218	175	142	221			

* Averaged total inorganic N concentration

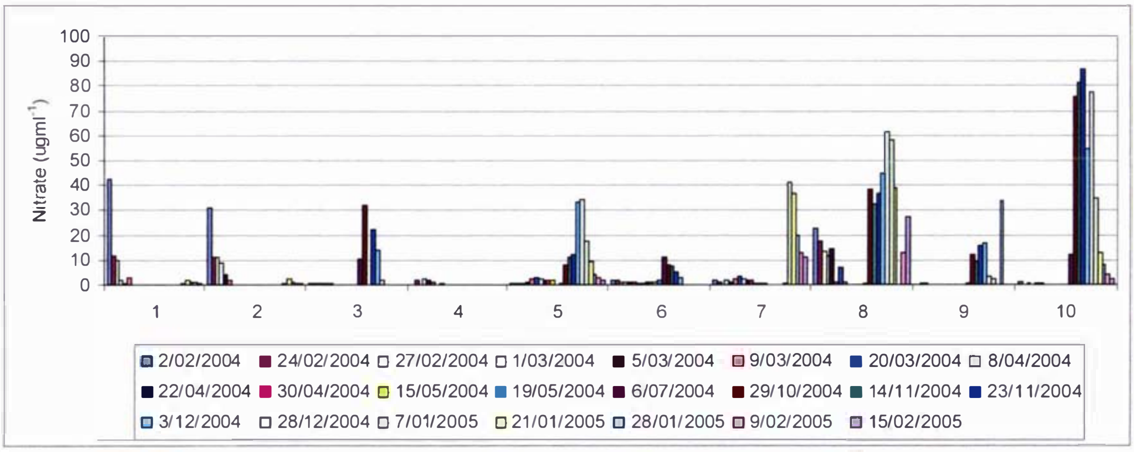
Table 8.6 Mean monthly inorganic N concentrations (μg ml^{-1}) in suction cups and estimated N leaching losses from February 2004 – February 2005 at Sangara

Months	Inorganic N concentrations (μg ml^{-1})					Drainage (mm)	Loss (kg N ha^{-1})
	FP		BZ		Total *		
	NH_4^+-N	NO_3^--N	NH_4^+-N	NO_3^--N			
Jan-04	0.06	4.16	0.08	5.56	4.9	27.9	1.4
Feb-04	0.09	2.46	0.10	3.42	3.0	74.3	2.3
Mar-04	0.17	0.94	0.20	1.12	1.2	99.6	1.2
Apr-04	0.26	0.11	0.05	0.05	0.2	48.4	0.1
May-04					3.0	179.4	5.4
Jun-04	0.13	3.70	0.18	6.76	5.4	89.6	4.8
Jul-04						0.0	0.0
Aug-04						0.0	0.0
Sep-04						0.0	0.0
Oct-04						0.0	0.0
Nov-04						0.0	0.0
Dec-04						0.0	0.0
Jan-05	0.02	2.89	0.05	5.07	4.0	146.7	5.9
Feb-05	0.00	3.04	0.06	5.72	4.4	36.2	1.6
Mar-05	0.02	3.76	0.02	5.22	4.5	157.8	7.1
Mean	0.09	2.77	0.09	5.00			
Min	0.0	0.0	0.0	0.0			
Max	2.3	38.0	1.0	38.9			
Std dev	0.3	3.9	0.2	7.2			
CV %	233	142	155	145			

* Averaged total inorganic N concentration

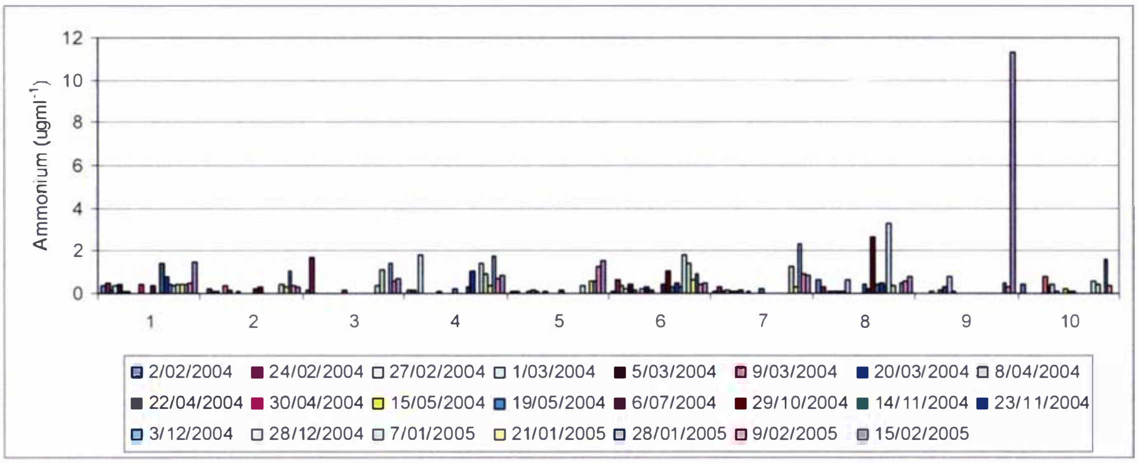


(a) Dami FP NO_3^--N

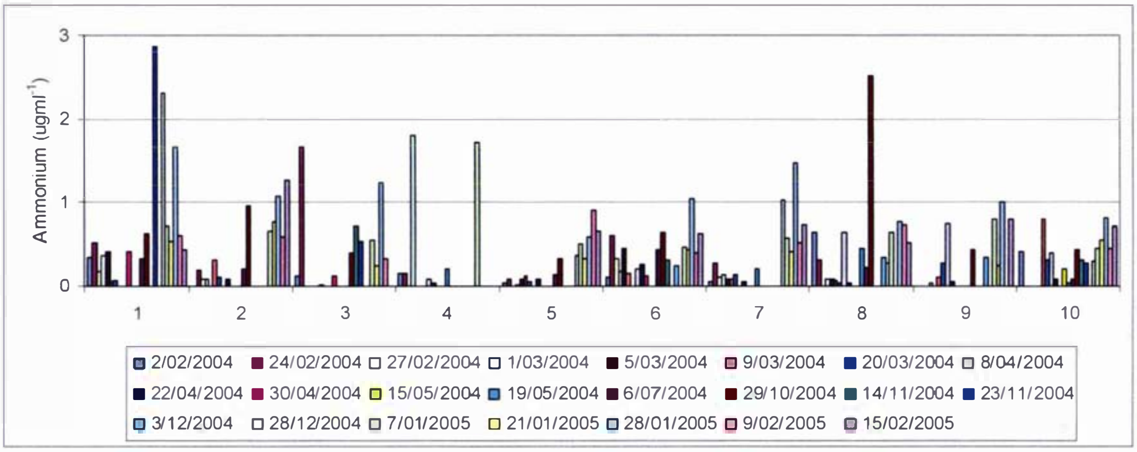


(b) Dami BZ NO_3^--N

Figure 8.1 NH_4^+-N and NO_3^--N concentrations for individual suction cups at Dami and Sangara (2004 – 2005) FP and BZ. Numbers 1-10 are replicate cups and within each replicate are the individual sampling dates

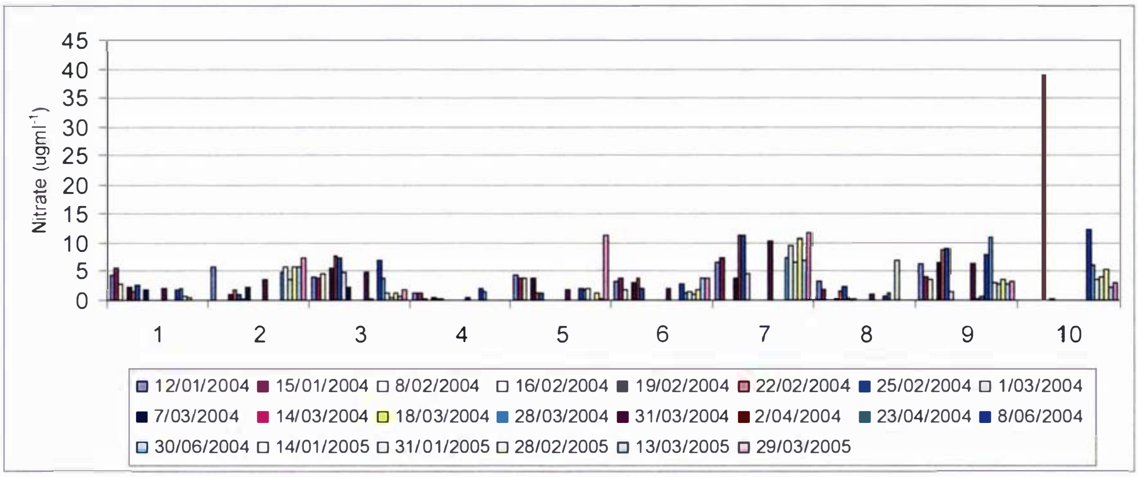


(c) Dami FP NH_4^+-N

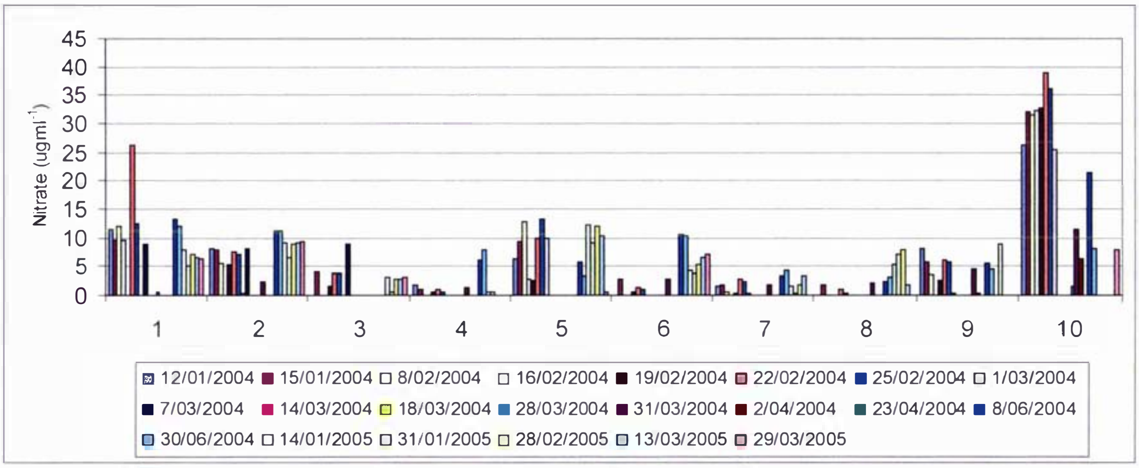


d) Dami BZ NH_4^+-N

Figure 8.1 (continued)

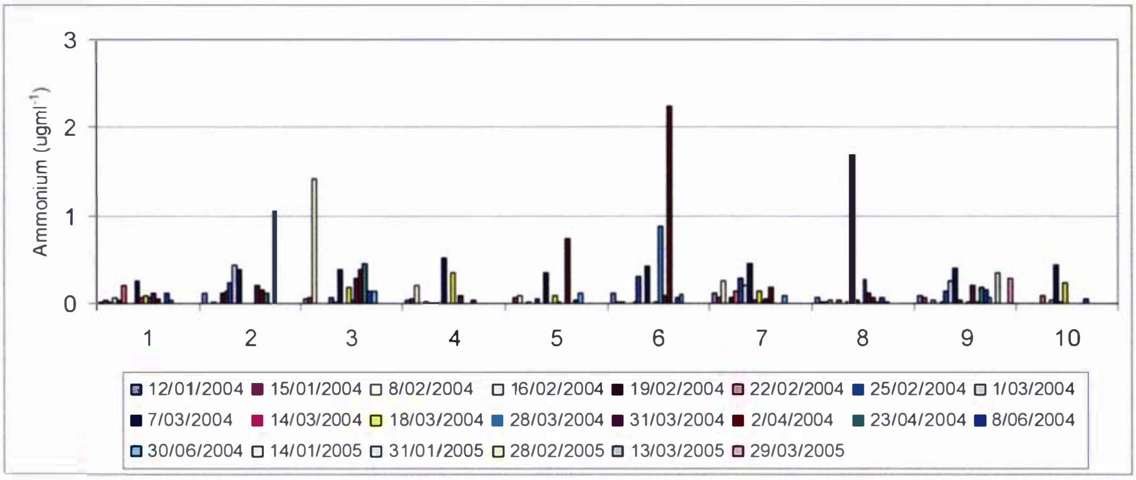


(e) Sangara FP NO_3^--N

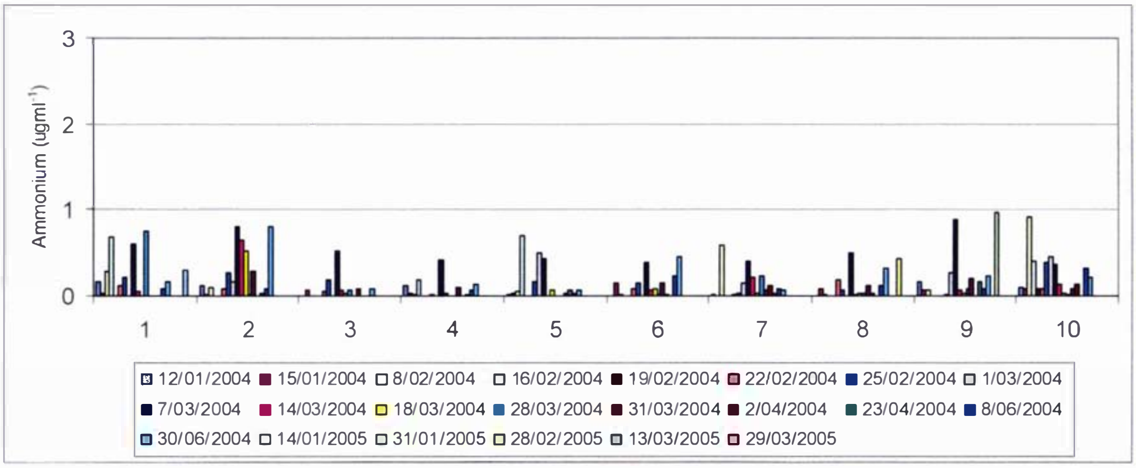


f) Sangara BZ NO_3^--N

Figure 8.1 (continued)



g) Sangara FP NH_4^+-N



h) Sangara BZ NH_4^+-N

Figure 8.1 (continued)

8.3.1.2 NH_4^+-N and NO_3^--N concentrations

At both sites mean NO_3^--N was much higher than mean NH_4^+-N in both the FP and BZ samples (Tables 8.5 and 8.6). However at Dami in the FP for the period October 2004 to February 2005, for four out of the five months, NH_4^+-N was either higher or approximately equal to NO_3^--N. For the same period in the BZ, NO_3^--N was always much higher than NH_4^+-N. At Sangara, in both the FP and BZ, NO_3^--N was consistently higher than NH_4^+-N, for all months, except for samples collected in April 2004 in the FP where NO_3^--N was less than NH_4^+-N but similar in the BZ.

At Sangara where concentrations of inorganic N were low, no N fertiliser was applied to the palms over the duration of the year-long experiment. At Dami, fertilisers were applied in May, June and September of the sampling period and this is probably one cause of the elevated inorganic N concentrations found from October to December, 2004.

8.3.1.3 Estimated annual leaching losses of N

Inorganic N present at 150 cm depth is considered "leached", assuming that the active oil palm rooting zone is within the top 1.5 m. Using the water balance model (4.2.4), estimated drainage water for each sampling month was multiplied by the average inorganic N (NH_4^+-N + NO_3^--N) concentrations for both the FP and BZ zones to get an estimate of inorganic N leached each month. Estimated monthly losses were then added together to give an estimated total annual loss. For the months that appear twice in the tables, the mean of the two values was used, so the calculated total was for a 12-month period. Mean inorganic N concentration was determined by averaging the inorganic N values for each of the FP and BZ zones.

Total estimated inorganic N loss was 96 kg N ha^{-1} yr^{-1} at Dami and 20 kg N ha^{-1} yr^{-1} at Sangara (Table 8.7). The amount of inorganic N lost at Dami was almost 5 times higher than at Sangara as a result of both the higher average soil solution N concentration and the greater amount of drainage water estimated at Dami. The amount of leached N is far higher than the estimated amounts for surface runoff (7.2.1) and denitrification (6.3.3), respectively. However in this experiment it was not possible to isolate losses from applied fertiliser from background losses from the soil. The estimated annual leaching losses are higher than those reported from oil palm systems (about 12 kg N ha^{-1} yr^{-1}) in other tropical countries (Chang and Zakaria, 1986). However, due to the large coefficients of variation in the N concentrations between the suction cups and between sampling dates, actual losses could be higher or lower than the estimated means shown.

The high coefficients of variation also suggest that more than 10 replicate suction cups would be required to get a reasonable estimate of leaching losses under field conditions.

Table 8.7 Estimated monthly and annual N leaching losses from suction cup and water balance data at Dami and Sangara

Months	Dami			Sangara		
	N* (µg ml^{-1})	Drainage (mm)	N Loss (kg ha^{-1})	N* (µg ml^{-1})	Drainage (mm)	N Loss (kg ha^{-1})
Jan	7.18	509.2	36.5	4.9	27.9	**3.6
Feb	4.14	458.7	**21.0	3.0	74.3	**4.2
Mar	1.95	589.0	11.5	1.2	99.6	**2.1
Apr	1.04	62.2	0.6	0.2	48.4	0.1
May	1.04	209.6	2.2	3.0	179.4	5.4
Jun	2.12	180.5	3.8	5.4	89.6	4.8
Jul	2.41	59.9	1.4		0.0	0.0
Aug		0.0	0.0		0.0	0.0
Sep		0.0	0.0		0.0	0.0
Oct	10.39	67.6	7.0		0.0	0.0
Nov	9.48	0.0	0.0		0.0	0.0
Dec	10.98	109.9	12.1		0.0	0.0
Total			**96**			**20**

* Average inorganic N concentration
** mean of 2004 and 2005 data.

8.3.1.4 Summary

- Variability of inorganic N concentration between the sampling dates and between the replicate suction cups was high
- There was evidence that some NH_4^+-N was leached in the Dami soils, while at Sangara it was nearly all NO_3^--N that leached to 150 cm depth
- Inorganic N concentrations from samples collected just after low rainfall months were higher than those sampled just before the low rainfall months
- Estimated N losses were 96 kg N ha^{-1} yr^{-1} at Dami and 20 kg N ha^{-1} yr^{-1} at Sangara, but there is a large uncertainty in these values.

8.3.2 Lysimeters

8.3.2.1 Faulty lysimeters

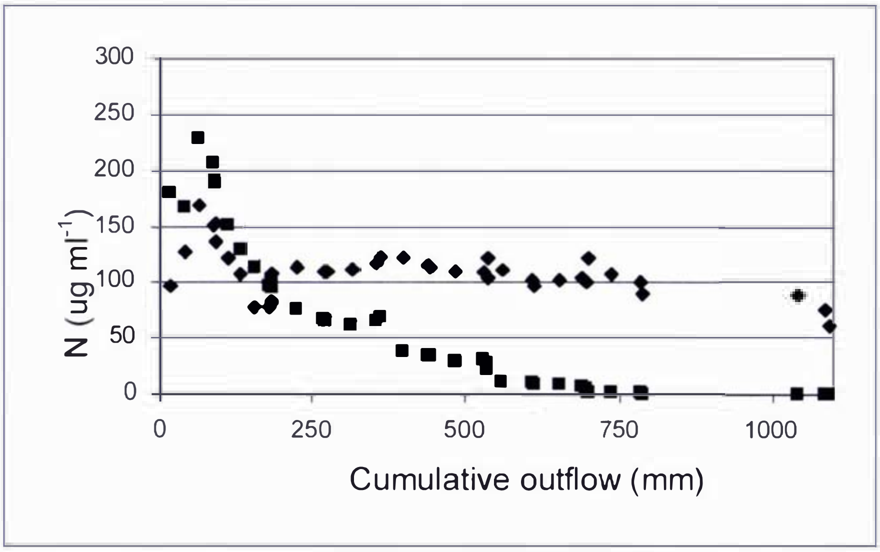
As already described, at each of the two sites, Dami and Sangara, initially there were 15 lysimeters, three from each of the five zones under the palms. However, not all lysimeters functioned well. Most of the problems were with the lysimeters at Sangara. The problems included;

a) Ponding – 11 of the 15 lysimeters at Sangara ponded when rainwater was added. This was probably the result of compaction. The clayey texture of the soil at depth (> 20 cm) apparently caused compaction as the tubes were being pressed into the soil. This compaction slowed water movement through the soil, resulting in prolonged ponding at the surface.

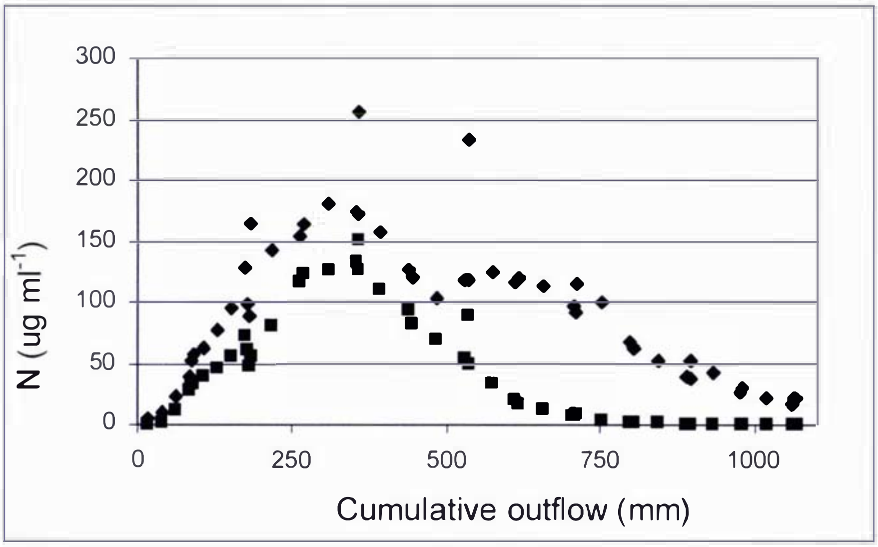
b) Preferential flow – all four of the lysimeters that did not pond at Sangara exhibited preferential flow. When pressed into the soil with force, the lysimeter casing bent, and this created gaps between the soil and the wall of the lysimeter. When water was poured onto the surface, some fertiliser went down this gap, instead of moving more uniformly through the soil. This resulted in high initial NH_4^+-N and NO_3^--N concentrations in the outflow, as shown in Figure 8.2 (a). Classical behaviour of a lysimeter is exhibited in Figure 8.2 (b). At Dami, only three of the fifteen lysimeters exhibited preferential flow and none had prolonged ponding.

Unfortunately the fertilisers applied were a mixture of AMC and AMN, so it was not possible to differentiate NO_3^--N originating from the AMN fertiliser that formed from the nitrification of AMC. Also because 1.0M HCl acid was inadvertently added to the drainage water samples, Cl^- from AMC could not be used as a tracer.

Results showing the amount of inorganic N leached from the lysimeters at Dami that did NOT exhibit preferential flow, are shown in Figure 8.2 (b) and discussed in 8.3.2.2.



(a) Faulty lysimeter



(b) Working lysimeter

Figure 8.2 Examples of NH_4^+-N (■) and NO_3^--N (♦) concentrations in outflow from a faulty and a working lysimeter at Dami

Note the bell shaped curve in (b) in contrast to the high initial concentrations in (a) that decrease with further outflow

8.3.2.2 Recovery of applied N fertiliser

Recovery of fertiliser N was determined by summing the amounts of inorganic N from all outflows after fertiliser was applied, and comparing it to the amount of N applied in the fertiliser. Pre-leaching had removed any readily-leached non-fertiliser N. Recoveries of between 80 % and 105 % of added inorganic N from the Dami lysimeters (Figure 8.3) suggest there was relatively little nett immobilisation/mineralization or denitrification of N occurring in the lysimeters over the six-week duration of the experiment. Although the soil water content at the bottom of the lysimeters may well have been higher than the water content at field capacity, little denitrification occurred there probably because of a lack of C at that depth. The height of the lysimeters was 50 – 70 cm and assuming a volumetric water content at field capacity of the soil during the experiment to be 0.5 $m^3\ m^{-3}$, then the liquid-filled pore volume was 25-35 cm or 250-350 mm. So during the experiment about four pore volumes of leaching occurred, enough to leach both NH_4^+-N and NO_3^--N through the soil, assuming NH_4^+-N moves at half the speed of non-adsorbed ions like NO_3^--N and Cl^-. This assumption is justified in 8.3.2.3.

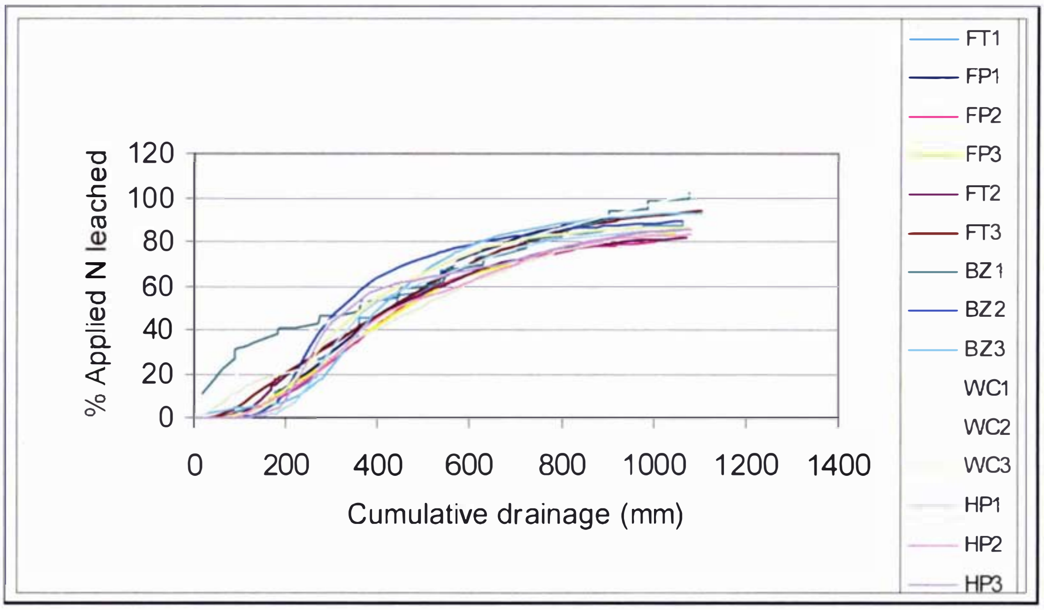


Figure 8.3 Cumulative drainage and % applied inorganic N recovered in the lysimeter outflows at Dami from the individual lysimeters

In the Dami lysimeters that did not show obvious preferential flow, (e.g. Figure 8.2 (b)), significant amounts of NH_4^+-N moved through the soil, perhaps in part due to the heavy AMC fertiliser application rate. While some preferential flow may also have occurred, the shape of the BTCs suggests it was not a major factor in this experiment. The finding NH_4^+-N movement through the lysimeters tied in well with the suction cup data for Dami (8.3.1) which showed NH_4^+-N movement to 150 cm depth.

Nitrification must have occurred relatively slowly because an appreciable amount of NH_4^+-N was still measurable in the leachate three weeks after it was applied to the surface. Sixty-five percent of the total N applied was NH_4^+-N. A comparison of the ratios of NH_4^+-N to total inorganic N recovered in the outflow from the lysimeters (Figure 8.4), shows that the ratio for FP lysimeters (of 0.16) was significantly ($p<0.001$, $lsd_{(0.05)} = 0.140$) lower than the ratio found for all other zones, which were all similar and ranged from 0.34 to 0.46. The ratio was also slightly lower in the FT lysimeters, although it was not significantly different to those of the BZ, WC and HP lysimeters. The significantly lower ratio of NH_4^+-N in the FP implies that NH_4^+-N was nitrified at a much faster rate in this soil compared with the other zones, probably due to a higher overall biological activity in the FP soil.

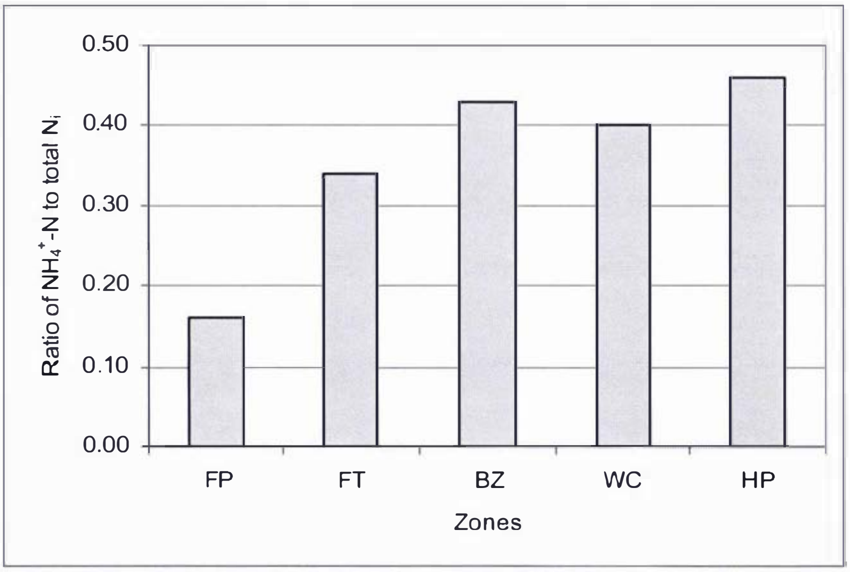


Figure 8.4 Mean ratio of NH_4^+-N to total inorganic N in the Dami lysimeter leachate for soils from different zones ($p<0.001$, $lsd_{(0.05)} = 0.140$)

The sandy textured volcanic soils at Dami, with their very high infiltration rates appear to be suitable soils for leaching studies using lysimeters. However at Sangara, the higher clay content in the B horizon appears to have frustrated attempts to extract intact cores for this study. However the lysimeter study did produce some interesting results in terms of the BTC's, the movement of NH_4^+-N and the relatively insignificant denitrification that occurred during the experiment.

8.3.2.3 Modelling NH_4^+-N transport through the lysimeters

The reason for attempting to model the NH_4^+-N data from the Dami lysimeters was to obtain an index of retardation and nitrification rates that could be used later for modelling the *in situ* leaching experiment. As already indicated, Cl^- data were not available for the lysimeters. Also, at Sangara, applied water ponded on many of the lysimeters, and where outflow did occur, the flow was highly preferential. Thus the only data from the lysimeter experiments suitable for use with the convection-dispersion equation (CDE) model were the NH_4^+-N breakthrough data for soil at Dami. As variable throughfall was not a factor in the lysimeter experiments, solute flow through lysimeters ought to be describable using the CDE.

Although water was applied at weekly intervals, rather than continuously, it is assumed in the model that water was applied continuously to the lysimeters at the time-averaged rate, J_w, in order to be able to use a simple analytical solution of the CDE.

However both the retardation of NH_4^+-N due to cation exchange adsorption, and its transformation due to nitrification throughout the experiment, need to be taken into account in the version of the CDE used. The following simple assumptions were made about these processes:

(a) adsorption is instantaneous and reversible, and can be described by a linear isotherm going through the origin. This leads to the definition of a dimensionless retardation factor, R (Jury and Roth, 1990) such that if for example R = 2, for NH_4^+-N, then NH_4^+-N moves at half the speed of the water (and Cl^- and NO_3^--N).

(b) the "decay" rate of NH_4^+-N to NO_3^--N is proportional to the concentration of NH_4^+-N present in the soil. This leads to the definition of a decay constant a with dimensions of [T^{-1}], as described earlier for the *in situ* nitrification experiment (5.3.2.3).

The initial and boundary conditions assumed were that there was no NH_4^+-N initially present in the soil and that at time t = 0, M of solute was applied to the soil as a pulse, that is dissolved in a very small volume of water. The dimensions of M are [M L^{-2}], so it is the application rate of the solute.

The required solution for the breakthrough concentration as a function of time, found by combining equations (2.17), (2.59) and (4.68) in Jury and Roth (1990), is then

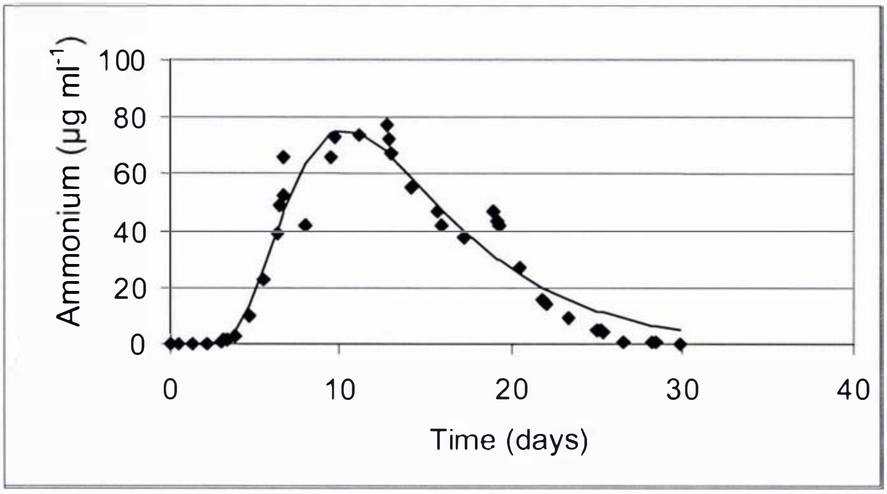
$$C = \frac{M}{R J_w} \exp(-at) \frac{z}{2\sqrt{\pi D (t/R)^3}} \exp\left[\frac{-(z - Vt/R)^2}{4Dt}\right] \qquad [8.4]$$

Here J_w is the flux density of water flowing through the lysimeter [L T^{-1}], z is the depth of soil in the lysimeter [L], D is the dispersion coefficient [L^2 T^{-1}] and V is the mean water velocity found as J_w/θ where θ is the volumetric water content in the lysimeter, assumed to be 0.5 rather than the field value of 0.4 (4.2.1.2.4), due to lack of suction at the outlet of the lysimeters, making them wetter than the soil at true "field capacity".

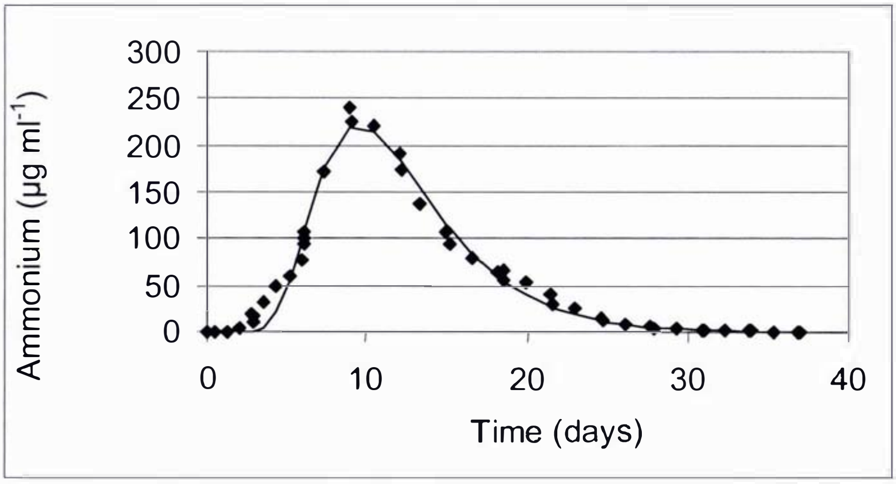
Solver in Excel was used to find a least-squares best fit of Equation [8.4] to the lysimeter breakthrough data for each lysimeter, and therefore optimized values for a, R and D. The dispersivity [L] was then found as D/V and the half-life for the nitrification of NH_4^+-N ($t_{1/2}$) found as before;

$$t_{1/2} = 0.693 / a \quad . \qquad [8.5]$$

Two examples of the fitted curves are shown in Figures 8.5 (a) and (b) where it can be seen that the CDE model fitted the measured data well for those lysimeters that did not show preferential flow.



(a) FP-1



(b) WC-3

Figure 8.5 Observed (♦) and simulated (—) NH_4^+-N (μg ml^{-1}) in the outflows for two lysimeters (FP-1 and WC-3) at Dami

The retardation factors (*R*) and the half-lives of NH_4^+-N found are given in Table 8.8. The mean *R* value was 1.7 (range, 1.2 – 2.5), which meant NH_4^+-N moved at about half the speed of water in the lysimeters. Movement of NH_4^+-N within the soil is affected by the soil cation exchange capacity and this slows its leaching.

The mean $t_{1/2}$ of NH_4^+-N found was 8 days for the FP, and for the other four zones it was between 16 and 26 days (mean = 21 days). See later (page 263) for comparison with $t_{1/2}$ values found earlier (page 163).

The median of the fitted dispersivity values was 48 mm.

Table 8.8 *R* and $t_{1/2}$ values found for lysimeters at Dami

Zone	*R*	Mean *R*	$t_{1/2}$ (days)	Mean $t_{1/2}$ (days)
FP-1	2.1	1.9	9	8
FP-2	1.6		5	
FP-3	1.9		10	
FT-1	1.8	2.0	14	19
FT-2	1.6		21	
FT-3	2.5		21	
BZ-1	NA	1.5	NA	26
BZ-2	1.2		20	
BZ-3	1.7		32	
HP-1	1.4	1.5	13	16
HP-2	1.9		20	
HP-3	1.3		14	
WC-1	NA	1.5	NA	23
WC-2	NA		NA	
WC-3	1.5		23	
Overall mean		**1.7**		

NA = not analysed because showed preferential flow occured

8.3.2.4 Summary of main findings for lysimeters

- At least 80 % of the applied N was recovered in the drainage from working lysimeters, with no consistent difference in the recovery between the different zones
- Between 16 % and 46 % of the N in the drainage was present as NH_4^+-N, compared to 65 % in the applied fertiliser
- Nitrification was relatively slow because even after 3 weeks, some NH_4^+-N was still coming out in the leachate. This was probably due to the high application rate. Nitrification was significantly ($P < 0.001$) faster in the FP lysimeters than for the other zones which were more or less similar
- The overall mean R value found was 1.7
- The $t_{1/2}$ for nitrification of NH_4^+-N was 8 days for the FP lysimeters and 21 days for the other lysimeters
- No useful data were obtained from the Sangara lysimeters due to compaction, ponding and preferential flow.

8.3.3 *In situ* leaching experiments

There were five *in situ* leaching experiments done, three at Dami and two at Sangara. For Experiment 1 at each of the sites, soil samples were extracted from only the BZ zones, but for Experiments 2 and 3 at Dami and Experiment 2 at Sangara, extractions were done on soils from both FP and BZ zones. To express the inorganic N and Cl^- contents on a per unit soil volume basis, the bulk densities, shown in Table 8.9, were used for all experiments at each site.

Table 8.9 Bulk densities (g cm^{-3}) at Dami and Sangara used for calculations

Depth (cm)	Bulk densities (g cm^{-3})	
	Dami	Sangara
0-20	0.77	1.29
20-40	0.84	1.35
40-60	1.00	1.42
60-80	0.77	1.11
80-100	1.06	1.11
100-120	0.70	1.20
120-140	0.83	1.34
140-160	0.84	1.34
160-180	0.84	1.47
180-200	0.84	1.47

8.3.3.1 Recovery of N and Cl^- from added fertiliser

Calculated recoveries of fertiliser N and Cl^- for each of the experiments are presented in Table 8.10. Recoveries were calculated as the amount of total inorganic N extracted from the top 200 cm of soil as a percentage of the amount of N or Cl^- applied, after subtracting the amount extracted from the untreated control samples. At Dami, in Experiment 1, only 10 % and 16 % of the Cl^- and 27 % and 20 % of the inorganic N were recovered from the BZ-1 and BZ-2 leaching plots, respectively. These low recoveries were probably mainly due to the inorganic N and Cl^- being leached beyond 200 cm depth by the time sampling was done, although no doubt some plant uptake also occurred. The higher recovery of inorganic N (27 and 20 %) over Cl^- (10 and 16 %) in Experiment 1 at Dami suggests that Cl^- moved somewhat faster than inorganic N, with some of the N retained in the soil as exchangeable NH_4^+-N.

Recoveries in all other experiments at both sites were mostly close to 100 %, indicating the bulk of the inorganic N and Cl^- was still within the top 200 cm of soil at the time of sampling. However, the large variations suggest a lot of spatial variability, that even the relatively large number of samples taken could not completely override.

Table 8.10 Recovery rates for Cl^- and N for the *in situ* leaching experiments at Dami and Sangara

Zones	Nutrient	% recovery				
		Dami			Sangara	
		Exp 1	Exp 2	Exp 3	Exp 1	Exp 2
	Rainfall (mm)	1708	836	310	934	218
FP	Cl^-	NS	108	130	NS	130
BZ-1	Cl^-	10	43	83	62	116
BZ-2	Cl^-	16	77	83	77	104
FP	N	NS	102	139	NS	90
BZ-1	N	27	52	123	76	136
BZ-2	N	20	62	77	89	149

NS = not sampled

8.3.3.2 Leaching of N and Cl^- at Dami

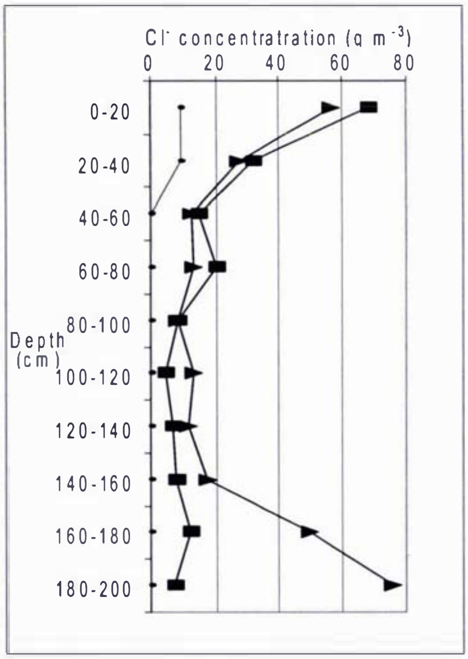
The movement and dispersion of the ions of interest (Cl^-, NH_4^+-N and NO_3^--N) at Dami are discussed in this section.

In Experiment 1, in BZ at Dami, the peak concentrations of Cl^- and NO_3^--N must have been below the maximum sampling depth of 200 cm as shown in Figures 8.6 (a) for Cl^- and (b) and (c) for inorganic N. During this experiment, there was a total of 1,708 mm of rainfall over 96 days which would have flushed most of the ions below 200 cm. This accounts for the low % recovery figures calculated for Cl^- and N (Table 8.10, Dami Experiment 1 BZ). However the tail ends of the NO_3^--N and Cl^- profiles were still evident within the top 200 cm. It can be seen also that although NH_4^+-N was leaching, unlike Cl^- and NO_3^--N, the peak NH_4^+-N concentration found was still within the sampling window (between 40 cm and 80 cm) (Figures 8.6 (b) and (c)). Some NH_4^+-N was still present after 96 days, so it did not fully nitrify over that time. This failure to fully nitrify could have been due to a) rapid movement into the subsoil where there was probably a lack of nitrifying microorganisms to carry out the nitrification process and/or b) the high rate of fertiliser application may have induced a high osmotic pressure that initially inhibited microbial activity. The Cl^- remaining at 0-20 cm depth and to a lesser extent at 20 – 40 cm depth in the BZ (Figure 8.6 (a)) is a small fraction of the amount applied and therefore does not negate the conclusion that most of the applied Cl^- had moved below the 2.0 m sampling depth.

In Experiment 2, in the BZ at Dami, the maximum Cl^- (Figure 8.6 (d)) and NO_3^--N (Figure 8.6 (e) and (f)) peaks occurred at around 60 – 100 cm depth, with the Cl^- peak slightly ahead of the NO_3^--N peak. Again the NH_4^+-N peak was retarded, but only slightly. For Cl^- it seems that there was some movement to below the 2 m maximum sampling depth (Figure 8.6 (d) BZ-2). In the same experiment but in the FP, the peak Cl^- (Figure 8.6 (g)) and inorganic N (Figure 8.6 (h)) concentrations were found at 40 – 60 cm depth, which suggests somewhat slower movement than in the BZ. This slower movement in the FP was most likely due to the placement of cut fronds on the FP, that provided an "umbrella-type" effect. Such an effect would have further redistributed the throughfall. As a result of this "umbrella" effect, some areas under the fronds receive more, and some less, rainfall which would affect the pattern of leaching.

In Experiment 3 at Dami in the BZ, the Cl^- peak (Figure 8.6 (i)) moved to between 60 and 100 cm depth and the leading edge spread down as far as 2 m. In the BZ (Figure 8.6

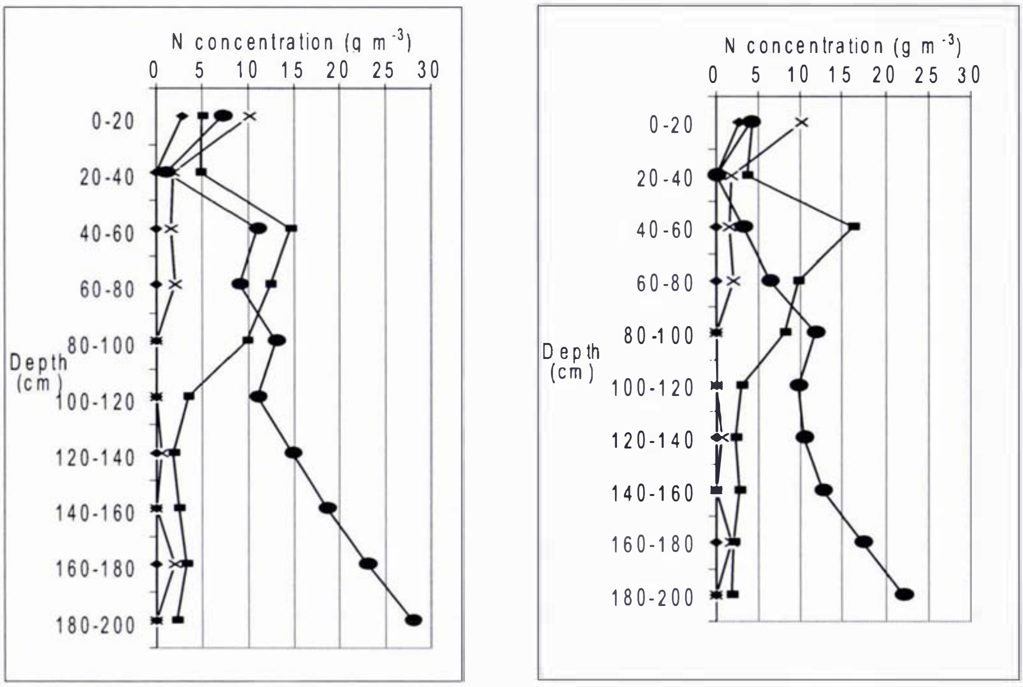
(j) and (k)), the NH_4^+-N peak was at 40-60 cm depth with the leading edge at 80-100 cm, while most of the NO_3^--N remained within the top 20 cm with the leading edge at 80-100 cm depth. It appears that, due to the short six-day experiment with high rainfall (310 mm), NH_4^+-N moved rapidly to lower depths where there was probably no nitrification taking place and therefore less NO_3^--N appeared in the subsoil. In the FP, the Cl^- profile (Figure 8.6 (l)) was more dispersed than in the BZ. For inorganic N (Figure 8.6 (m)), most of the NH_4^+-N nitrified to NO_3^--N despite the experiment lasting only six days. This again illustrates the faster rate of nitrification in the FP as compared to the other zones as found in the Dami lysimeter study. The results imply that fertiliser applied during the wet season can be lost rapidly via leaching as both NH_4^+-N as well as NO_3^--N.



(a) Dami Experiment 1 BZ Cl^-

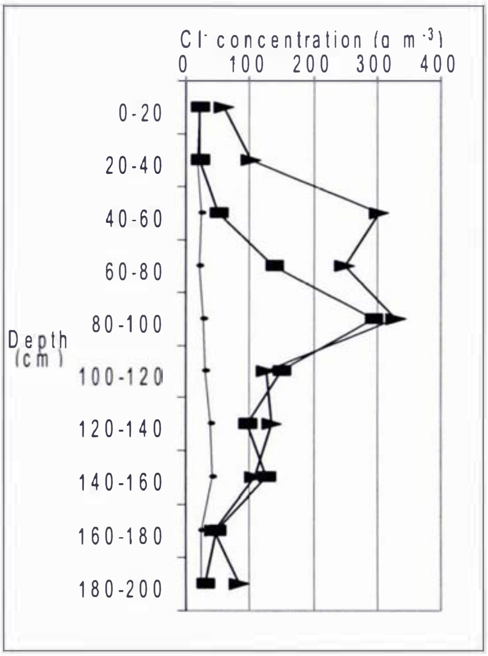
(■) Cl^- in fertilised BZ-1, (▶) Cl^- in fertilised BZ-2 and (•) Cl^- unfertilised plots

Figure 8.6 Cl^- and inorganic N concentrations at various depths to 200 cm in the *in situ* leaching experiments 1 – 3 at Dami



(b) Dami Experiment 1 BZ-1 inorganic N (c) Dami Experiment 1 BZ-2 inorganic N

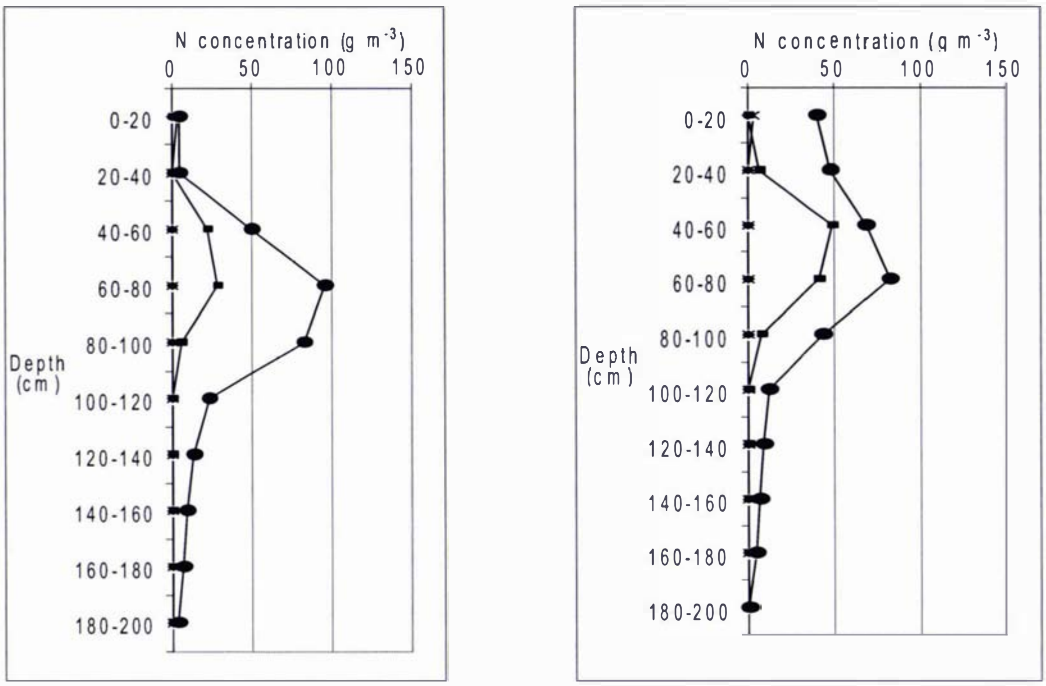
(●) NO_3^--N in fertilised, (♦) NO_3^--N in unfertilised, (■) NH_4^+-N in fertilised and (x) NH_4^+-N in unfertilised plots



(d) Dami Experiment 2 BZ Cl^-

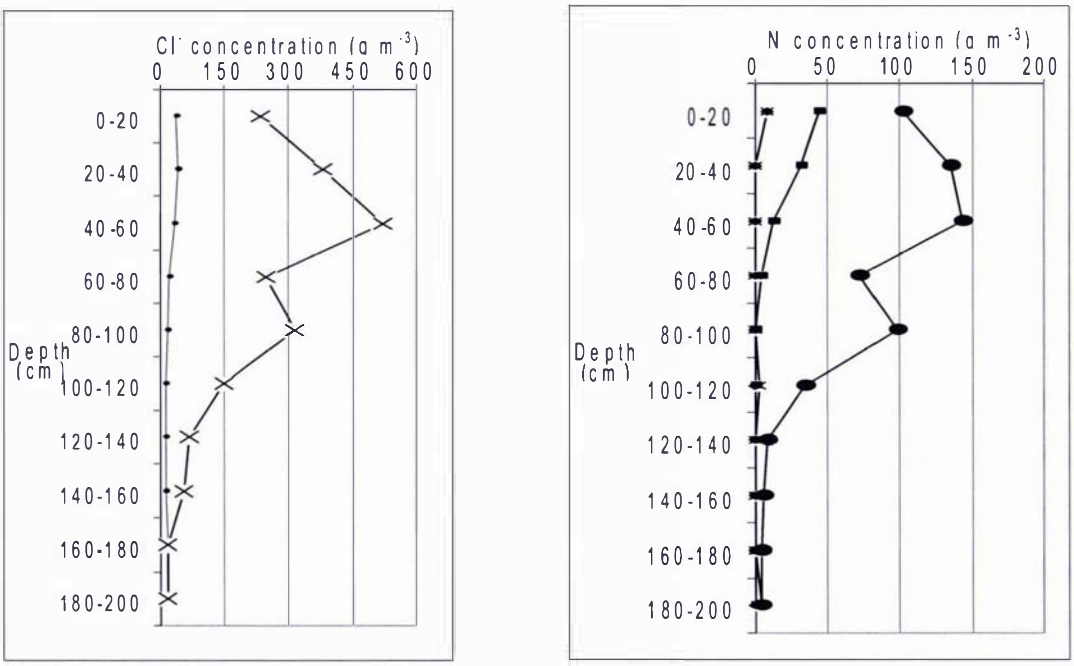
(■) Cl^- in fertilised BZ-1, (▶) Cl^- in fertilised BZ-2, (•) Cl^- unfertilised

Figure 8.6 continued



(e) Dami Experiment 2 BZ-1 inorganic N (f) Dami Experiment 2 BZ-2 inorganic N

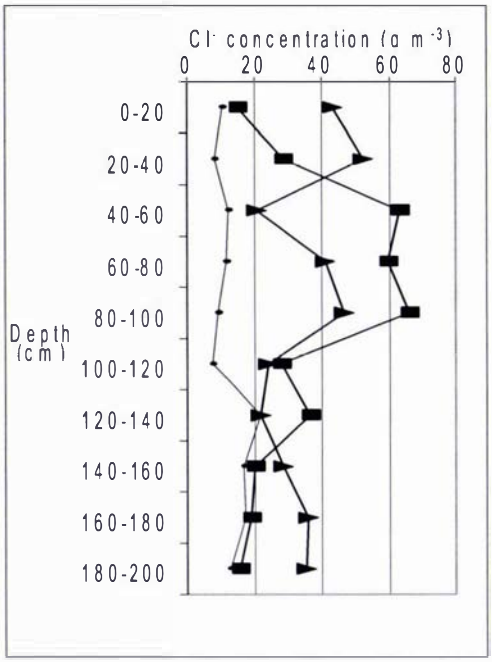
(●) NO_3^--N in fertilised, (♦) NO_3^--N in unfertilised, (■) $NH4^+$-N in fertilised and (x) NH_4^+-N in unfertilised plots



(g) Dami Experiment 2 FP Cl^- (h) Dami Experiment 2 FP inorganic N

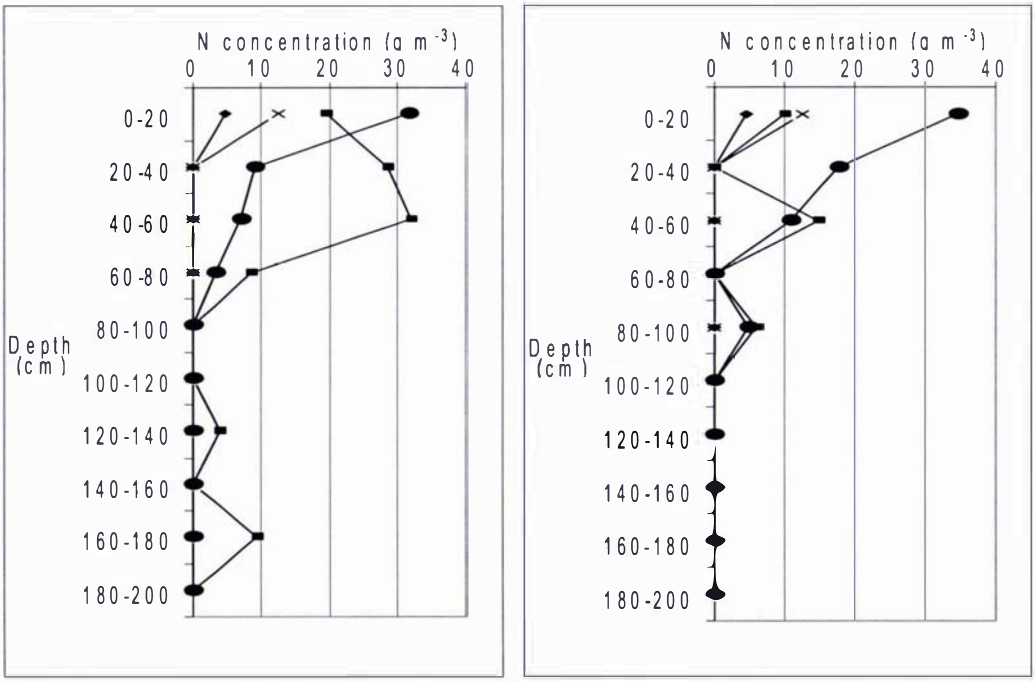
(X) Cl- in fertilised FP (•) Cl^- unfertilised plots, (●) NO_3^--N in fertilised, (♦) NO_3^--N in unfertilised, (■) $NH4^+$-N in fertilised and (x) NH_4^+-N in unfertilised plots

Figure 8.6 continued



(i) Dami Experiment 3 BZ Cl$^-$

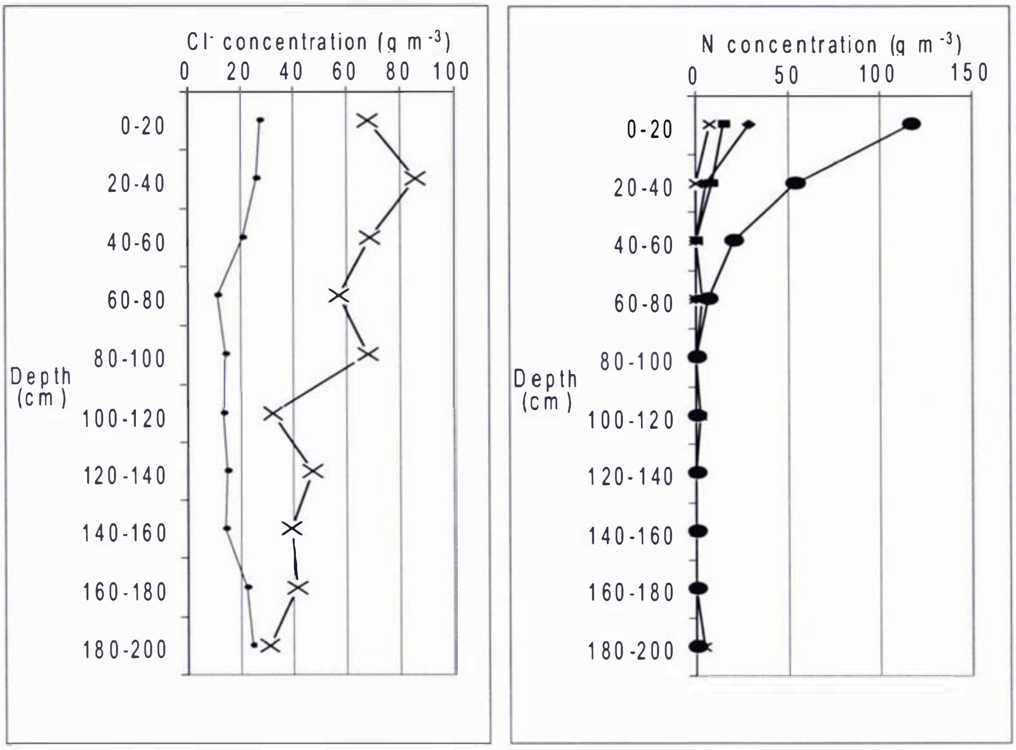
(■) Cl$^-$ in fertilised BZ-1, (▶) Cl$^-$ in fertilised BZ-2 and (•) Cl$^-$ unfertilised plots



(j)Dami Experiment 3 BZ-1 inorganic N (k) Dami Experiment 3 BZ-2 inorganic N

(●) NO_3^--N in fertilised, (♦) NO_3^--N in unfertilised, (■) $NH4^+$-N in fertilised and (x) NH_4^+-N in unfertilised plots

Figure 8.6 continued



(l) Dami Experiment 3 FP Cl^- (m) Dami Experiment 3 FP inorganic N

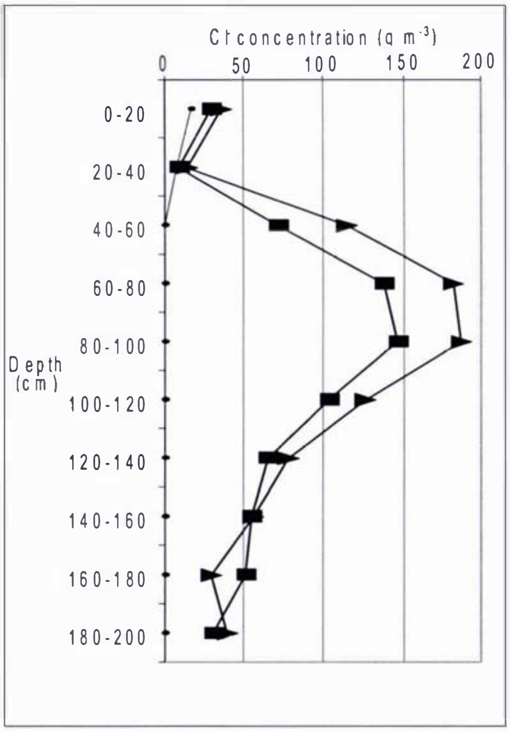
(X) Cl- in fertilised FP (•) Cl^- unfertilised plots, (●) NO_3^--N in fertilised, (♦) NO_3^--N in unfertilised, (■) $NH4^+$-N in fertilised and (x) NH_4^+-N in unfertilised plots

Figure 8.6 continued

8.3.3.3 Leaching of N and Cl^- at Sangara.

At Sangara, for Experiment 1 in the BZ, the Cl^- peak was between 80-100 cm depth (Figure 8.7 (a)) and was ahead of the NO_3^--N peaks (Figure 8.7 (b) and (c)) which were at around 40 – 60 cm depth. The leading edge of the Cl^- and NO_3^--N profiles went past the 2 m depth. There was no indication that NH_4^+-N had moved to depth, as was seen in the Dami experiments. The difference in the location of the Cl^- and NO_3^--N peaks was probably due to the different times required for NH_4^+-N to be converted to NO_3^--N; a contributing factor could have been high salinity from the high rate of AMC (333 g AMC m^{-2}) used in the trial, that may have slowed, microbial activity and delayed nitrification. However after major rain events, salinity would fall and microbial activity would return to normal. Such a delay in recovery of microbial activity may have resulted in NO_3^--N being formed much later (and therefore N moved more slowly to depth than was the case for Cl$^-$) with the NH_4^+-N being retained at cation exchange sites. There were no FP soil samples taken in this experiment.

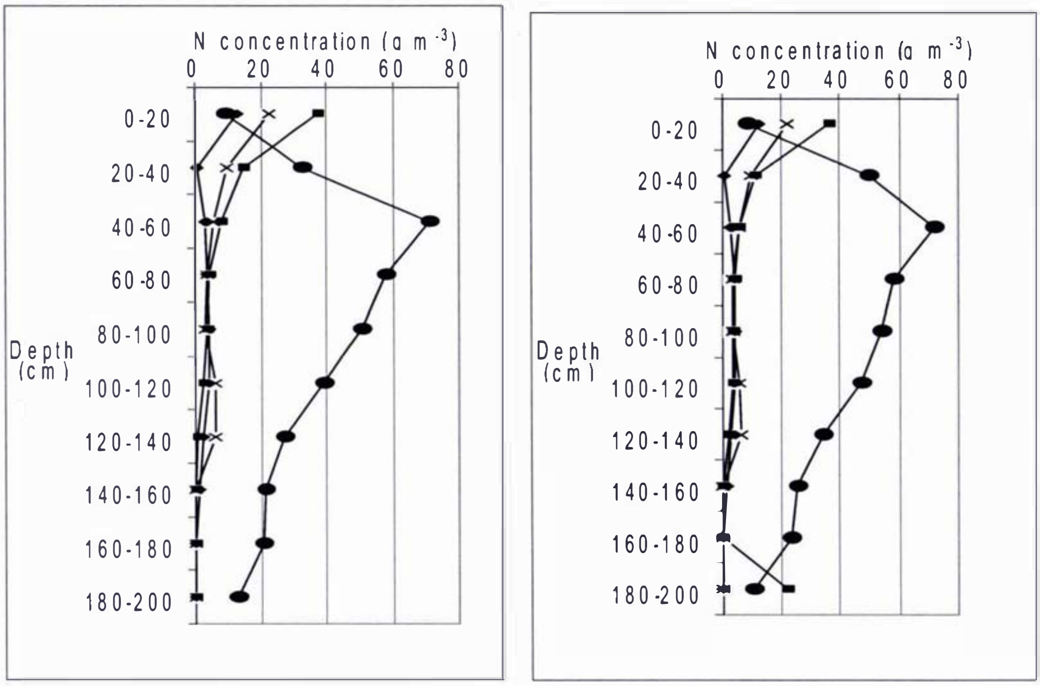
For Sangara Experiment 2 in both BZ (Figure 8.7 (d), (e) and (f)) and FP (Figure 8.7 (g) and (h)) soil, most of the ions remained in the top 40. However the Cl$^-$ and NO_3^--N leading edges appeared to have gone down to at least 80 cm depth in all cases. The Cl$^-$ peak in the BZ (Figures 8.7 (d)) appeared to be at 20-40 cm, but it was still within the top 20 cm in the FP (Figure 8.7 (g)). The cut fronds in the FP appear to have slowed the movement of the bulk of the Cl$^-$ by providing the same "umbrella-type" effect that was invoked before in 8.3.3.2. The NH_4^+-N in both BZ plots and the FP plot had effectively all nitrified to NO_3^--N during the 34-day duration of the experiment.



(a) Sangara Experiment 1 BZ Cl$^-$

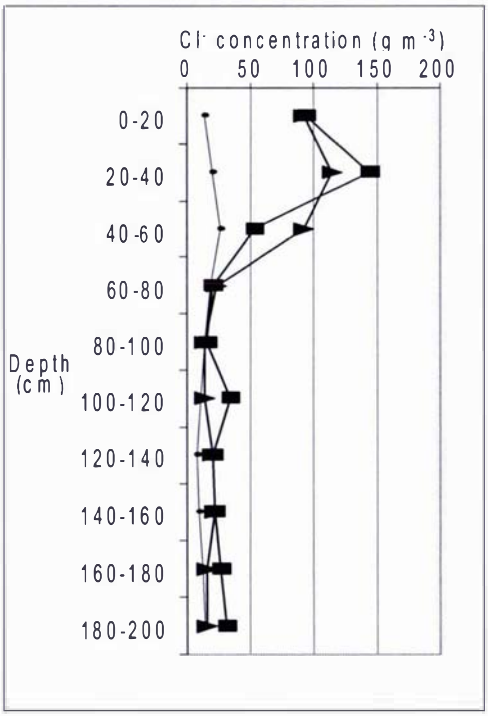
(■) Cl$^-$ in fertilised BZ-1, (▶) Cl$^-$ in fertilised BZ-2 and (•) Cl$^-$ in unfertilised BZ plots

Figure 8.7 Cl$^-$ and inorganic N concentrations at various depths to 200 cm in the *in situ* leaching Experiments 1 and 2 at Sangara



(b) Sangara Experiment 1 BZ-1 inorganic N (c) Sangara Experiment 1 BZ-2 inorganic N

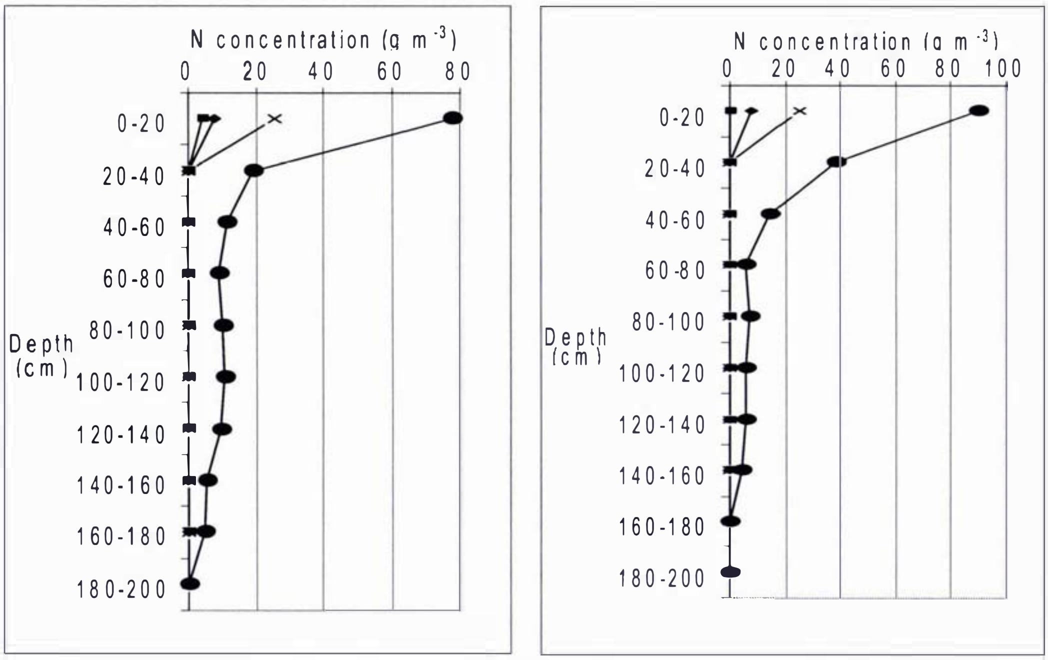
(●) NO_3^--N in fertilised, (♦) NO_3^--N in unfertilised, (■) NH4$^+$-N in fertilised and (x) NH_4^+-N in unfertilised plots



(d) Sangara Experiment 2 BZ Cl$^-$

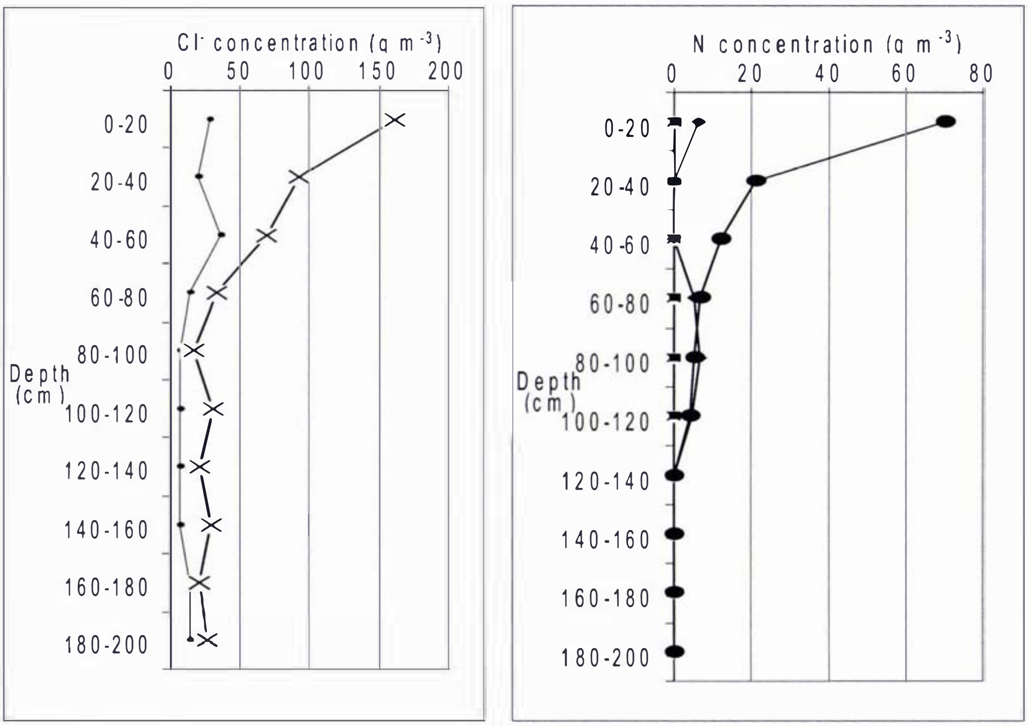
(■) Cl$^-$ in fertilised BZ-1, (▶) Cl$^-$ in fertilised BZ-2 and (•) Cl$^-$ unfertilised BZ plots,

Figure 8.7 continued



(e) Sangara Experiment 2 BZ-1 inorganic N (f) Sangara Experiment 2 BZ-2 inorganic N

(●) NO_3^--N in fertilised, (♦) NO_3^--N in unfertilised, (■) $NH4^+$-N in fertilised and (x) NH_4^+-N in unfertilised plots



(g) Sangara Experiment 2 FP Cl^- (h) Sangara Experiment 2 FP inorganic N

(X) Cl- in fertilised FP (•) Cl^- unfertilised plots, (●) NO_3^--N in fertilised, (♦) NO_3^--N in unfertilised, (■) $NH4^+$-N in fertilised and (x) NH_4^+-N in unfertilised plots

Figure 8.7 continued

8.3.3.4 Ratios of NH_4^+-N to total inorganic N present in the soils at the time of sampling at Dami and Sangara

Table 8.11 gives the fraction of NH_4^+-N in relation to the total amount of inorganic N found in the soil taken from each of the fertilised plots, after correction for the amounts of NH_4^+-N and inorganic N found in the unfertilised control soils. The values for Experiment 1 at Dami are misleading, as most of the NO_3^--N had moved past the 2 m sampling depth at the time of sampling. However, the other values indicate that:

- nitrification was faster in the FP than BZ plots at Dami (lower fraction of NH_4^+-N to total inorganic N in the FP zone compared to the BZ zones in all the 3 experiments)
- nitrification was faster at Sangara than at Dami (in both Sangara experiments, more of the NH_4^+-N had disappeared at the time of sampling than at Dami)
- there was considerable variation in the NH_4^+-N/inorganic N ratio in the two BZ plots.

Table 8.11 Fraction of nett inorganic N present as NH_4^+-N at the time of final sampling of the *in situ* leaching experiments following the application of AMC

Site and Experiment	Duration (days)	N applied (kg N ha^{-1})	Ratio of NH_4^+-N/inorganic N		
			BZ-1	BZ-2	FP
Dami 1	96	1300	0.23	0.27	NS
Dami 2	152	1300	0.15	0.24	0.12
Dami 3	6	213	0.66	0.25	0.02
Sangara 1	107	866	0.05	0.08	NS
Sangara 2	34	213	0	0	0

NS = not sampled

8.3.4 Modelling *in situ* leaching

8.3.4.1 The models

This section describes four models. The first model looks at simulating leaching of Cl^- to determine the distribution parameters that are used in the two subsequent models. The second model simulates leaching of NH_4^+-N to obtain values for *R* (the retardation factor) and *a* (the decay constant for nitrification). The third model looks at the leaching of total inorganic N applied as NH_4^+-N. The fourth model combines most of the parameters used in the other models to estimate the residence time of inorganic N applied as AMC within the oil palm root zone using historical water balance data.

8.3.4.2 The approach

The five *in situ* leaching experiments conducted at Dami and Sangara in effect each provided a 'snapshot' of the Cl^-, NH_4^+-N and NO_3^--N profiles on a certain day, some time after the surface application of AMC fertiliser. The aim of the modelling exercise was to provide a 'movie' that could be used to extrapolate the experimental data to answer some "What if?" questions. Examples of such questions might be: what would have happened if the experiment had been conducted at a different time of the year, or if the taking of soil samples had been carried out some time earlier or later than it was?

The application of N fertiliser as AMC provided an opportunity to use the relatively inert chloride ion as a tracer. Chloride ions are not completely inert. They are taken up by plants, and in soils with anion exchange capacity they can be weakly-adsorbed by soil solids. But they are usually inert enough to be used as a tracer. A disadvantage of Cl^-, compared to say Br^-, which is also commonly used as a tracer, is that Cl^- is naturally present in soils, being added via rainfall and dry deposition, particularly at coastal sites. So enough Cl^- needs to be added as AMC to produce soil solution concentrations significantly greater than the background levels already present.

As discussed in Chapter 4.0, the hydrology of oil palm plantations is complex and spatially very variable. As the focus of this research is more experimental than theoretical, it was decided to develop a fairly simple model, rather than adopt a more complex and mechanistic approach, using for example software like Hydrus-2d (Rassam *et al.*, 2003). It was also decided to work at a daily time scale, and not try to simulate the hydrology in detail. The very high rainfall at both sites during the wet season means that excess water moving down through the soil profile is a major component of the soil water balance, so even a simple model should be able to estimate the associated leaching with some success.

8.3.4.3 The amount of leaching water

The forcing function for leaching is the movement of water down through the soil, the first input required for any simple leaching model is the equivalent depth of such water (I). Good current and historic daily rainfall data are available for both Dami and Sangara. However, as previously discussed, in 4.2.2, throughfall of this rainfall is highly variable some of it is stemflow, and some of it runs off rather than soaks in. To take account of this, it was assumed that 90 % of the daily rainfall (P) reached the soil surface; a typical value for the amount of throughfall. Surface runoff (R) was simulated as already described in 4.2.4.3.2.

The next issue to be addressed was how evaporation affects leaching. As a first step towards estimating this, the median leaching depth (z_m) was calculated for the Cl^- tracer as the depth above which half the total mass of Cl^- was found. This could only be determined for four of the five leaching experiments, as most of the applied Cl^- had been leached beyond the 2 m sampling depth in the Dami Experiment 1. The median depth could only be found approximately due to the 200 mm depth intervals used when sampling. The values found are shown in Table 8.12. If the average volumetric water content of the top 1 m of soil at field capacity of 0.4 (4.2.1.2.4) is used, the equivalent depth of leaching water (I_m) for the Cl^- would be 0.4 z_m.

Standard meteorological data allowed estimates of the reference crop evaporation (E_r) to be computed, as already described (4.2.4). However, even assuming that the total evaporation is approximately the reference crop evaporation, not all that evaporation affects leaching. Transpiration, involving root uptake of water from the soil above the depth where the solute of interest is located, reduces subsequent leaching. This is because infiltrating water stays in the topsoil and does not reach the solute depth. In contrast, transpiration involving root uptake from below the solute depth does not affect subsequent leaching because it does not affect the water content of soil above the fertiliser. As I is the difference between effective rainfall and effective evaporation (E_{eff}), it follows that

$$E_{\mathrm{eff}} = 0.9P - R - I_{\mathrm{m}} \qquad [8.6]$$

Values of P, R, E_{r} and the ratio $E_{\mathrm{eff}} / E_{\mathrm{r}}$ are shown in Table 8.12. It was decided to ignore the $E_{\mathrm{eff}} / E_{\mathrm{r}}$ value found for the Dami Experiment 3, as the anomalous negative value is probably due to evaporation being such a small fraction of rainfall during this experiment. The other three values average 0.77. Thus the simple model used to predict I from R and E_{r} was

$$I = 0.9P - R - 0.77E_{\mathrm{r}} \qquad [8.7]$$

and z_{m} was then estimated as $I / 0.4$. Also shown in Table 8.12 are the simulated values of z_{m}.

The simulated z_{m} values were close to the observed z_{m} values with differences of less than 200 mm, which is acceptable for this study since the differences were less than the sampling depth intervals used. There was no observed z_{m} in Dami Experiment 1 because the peak had already moved below 2 m after 107 days of leaching. The simulated depth was 3.1 m (3,187 mm).

Use of Equation [8.7] simulated the Cl^- peak concentrations well and therefore will be used later in the residence time model 8.4.3.6.

Table 8.12 Hydrological inputs for *in situ* leaching experiments and model parameters

Site	Exp.	Duration (days)	*P* (mm)	Est *R* (mm)	E_r (mm)	Obs z_m (mm)	Eeff/Er	I_m (mm)	Sim z_m (mm)
Dami	1	96	1708	20	315	------		1275	3187
	2	151	817	2	557	800	0.74	304	761
	3	8	353	7	22	850	-1.33	294	734
Sangara	1	107	951	95	404	950	0.94	450	1125
	2	35	206	6	155	200	0.64	60	150

8.3.4.4 The spreading out, or dispersion, during leaching

Having simulated the median depth to which a non-reactive solute is leached, the next step was to describe how a pulse of that solute spreads out, or is dispersed, as it moves down the soil profile. As discussed in 8.1.1, by far the most common equation used to describe this process is the convection-dispersion equation. However as shown earlier (4.2.2.2) throughfall under oil palm is hugely variable. This variability is likely to be the major cause of dispersion of a solute pulse, as it occurs at a much larger scale than the local variations in pore size that are the usual cause of hydrodynamic dispersion in soil. This much larger scale is likely to have a characteristic length similar to the dimensions of a palm frond, which means that molecular diffusion will have little influence in moving solute between locations in the soil with different leaching velocities. Therefore the model that Jury *et al.* (1991) call the stochastic-convective lognormal transfer function model (CLT) is likely to be more suitable than the convection-dispersion equation. The CLT model is also better able to simulate the highly skewed distributions of solute observed under the frond piles than is the convection-dispersion equation.

The particular boundary and initial conditions used to describe the system were:

1. No solute initially present in the soil
2. When $I = 0$ a narrow pulse of solute becomes resident in the soil at the surface (i.e. where $z = 0$).

The solution of the CLT for these boundary and initial conditions for a non-reactive conservative solute is (Jury and Scotter, 1994):

$$C = \frac{MI}{(2\pi)^{1/2}\sigma z^2 I_c} \exp\left[\frac{-[\ln(zI_c/I)-\mu]^2}{2\sigma^2}\right]\exp(\mu-\sigma^2/2)\ . \qquad [8.8]$$

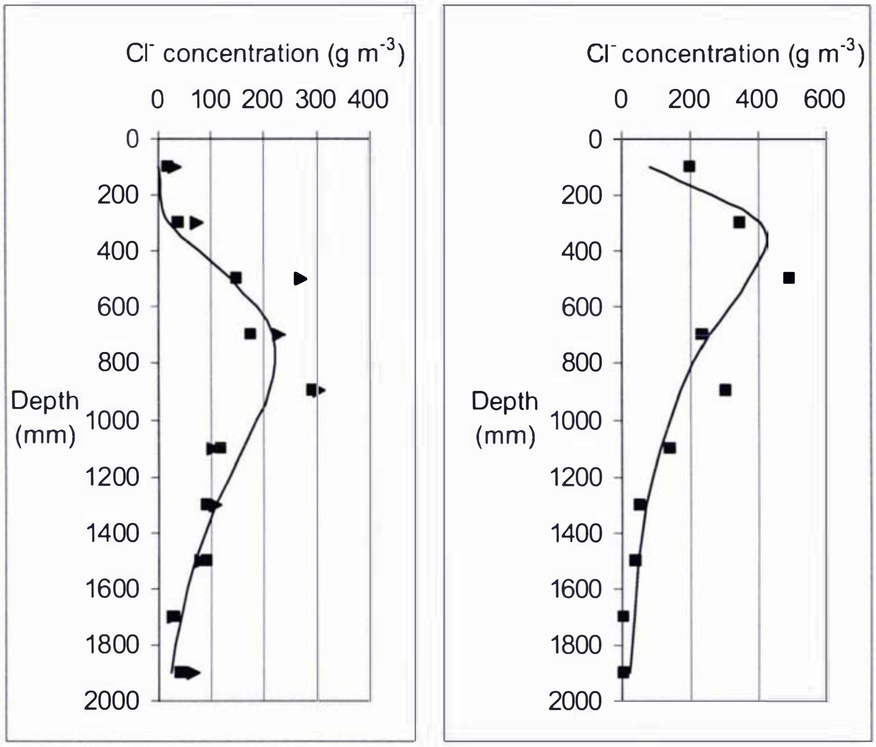
Here C is the average concentration of the solute of interest per unit soil volume with dimensions [M L^{-3}], M is the application rate at which that solute was applied to the surface [M L^{-2}], μ is the mean and σ is the standard deviation of the log normal distribution, and I_c is the calibration value of I, that is the equivalent depth of leaching water applied to obtain the data used to calculate the values for μ and σ. A difference between Equation [8.8] and the equivalent equation in Jury and Scotter (1994) is that the variable I is used instead of time t. To quote Jury and Roth (1990, p. 107):

> "To avoid having to model transient water flow in the field, Jury (1982) proposed substituting net applied water I or cumulative drainage for time in the travel time pdf [probability density function]. It was hoped this pdf would be approximately independent of the water flow rate, i.e. that solutes would move from the inlet end of the transport volume in a unique manner as a function of the amount of water passing through the system."

Equation [8.8] predicts only the average concentration as a function of z and I, not the local concentration. The CLT model implies a highly variable local concentration at any depth. In the field this is due to the large variability in throughfall.

The Cl^- leaching patterns found in the *in situ* leaching experiments seemed to fall into two groups, depending on whether they were for BZ or FP soils. Given this distinction, the patterns (Figure 8.8) for Sangara and Dami looked similar. It is not surprising that the frond piles changed the leaching pattern, as they would have made the already-variable throughfall even more heterogeneous as it entered the soil.

It was decided somewhat arbitrarily to use the data from one experiment, Experiment 2 at Dami, to calibrate the model, i.e. to obtain values for μ and σ. This was done using Solver in Excel to obtain a least-squares fit to Equation [8.8] with $I = I_c$. The resulting values found were $\mu = 7.01$ and $\sigma = 0.43$ for the BZ soil and $\mu = 6.85$ and $\sigma = 0.70$ for the FP soil. The measured and simulated profiles are shown in Figure 8.8, and from Table 8.12, the value of I_c is 304 mm.

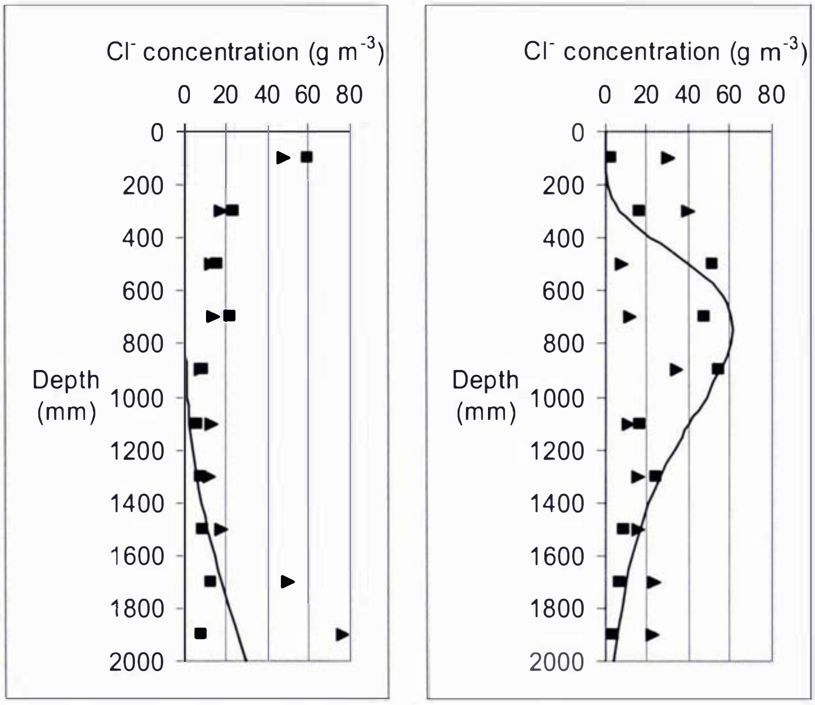


(a) BZ (b) FP

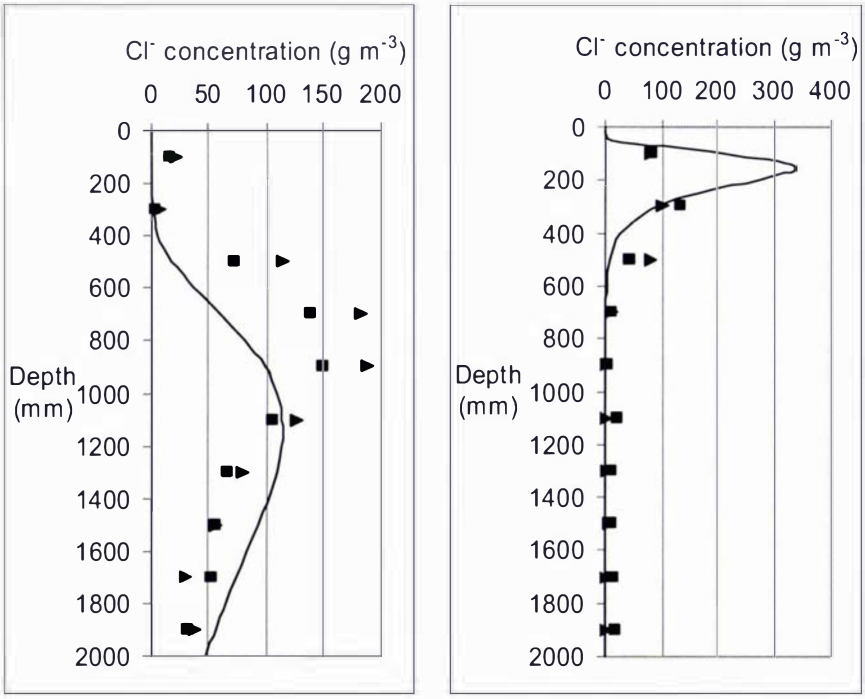
Simulated (—) and observed (■) (▶) Cl⁻ profiles

Figure 8.8 Simulated and observed Cl⁻ profiles (g Cl⁻ m⁻³ soil volume) in Dami Experiment 2 BZ and FP soils used for model calibration

Cl⁻ data for the other four leaching experiments were then used to validate the model. The results are shown for the BZ soils in Figure 8.9, and for the FP soils in Figure 8.10. The general agreement between the measured and simulated profiles suggests that the model is accurate enough to be useful.



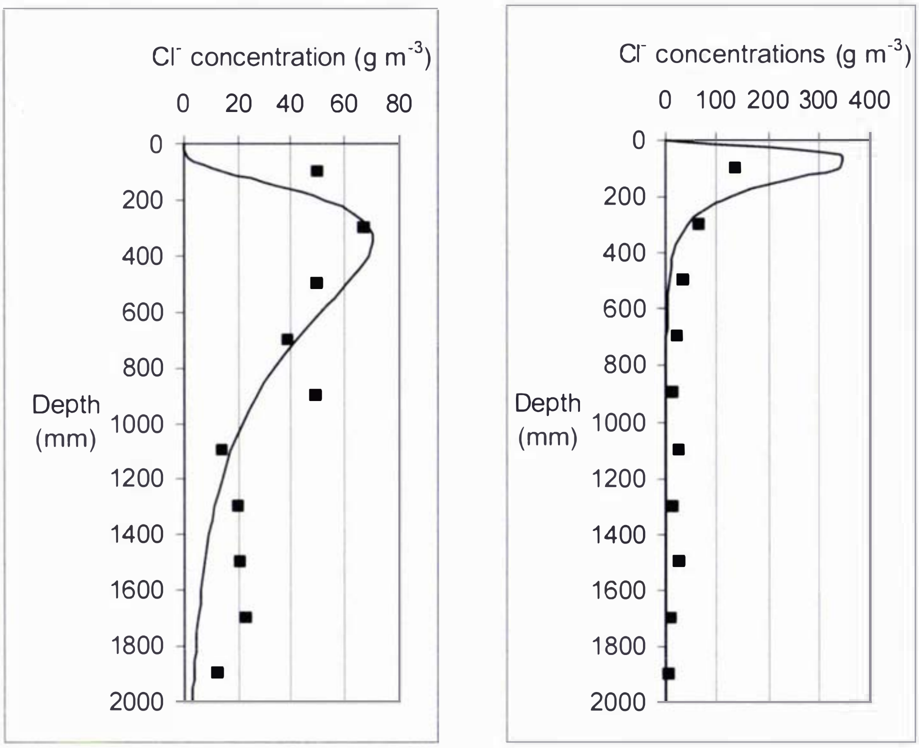
(a) Dami Experiment 1 BZ (b) Dami Experiment 3 BZ



(c) Sangara Experiment 1 BZ (d) Sangara Experiment 2 BZ

Simulated (—) and observed in BZ-1(■) and BZ-2 (▶)

Figure 8.9 Simulated and observed Cl^- profiles (g Cl^- m^{-3} soil volume) for BZ soils of *in situ* leaching experiments at Dami and Sangara



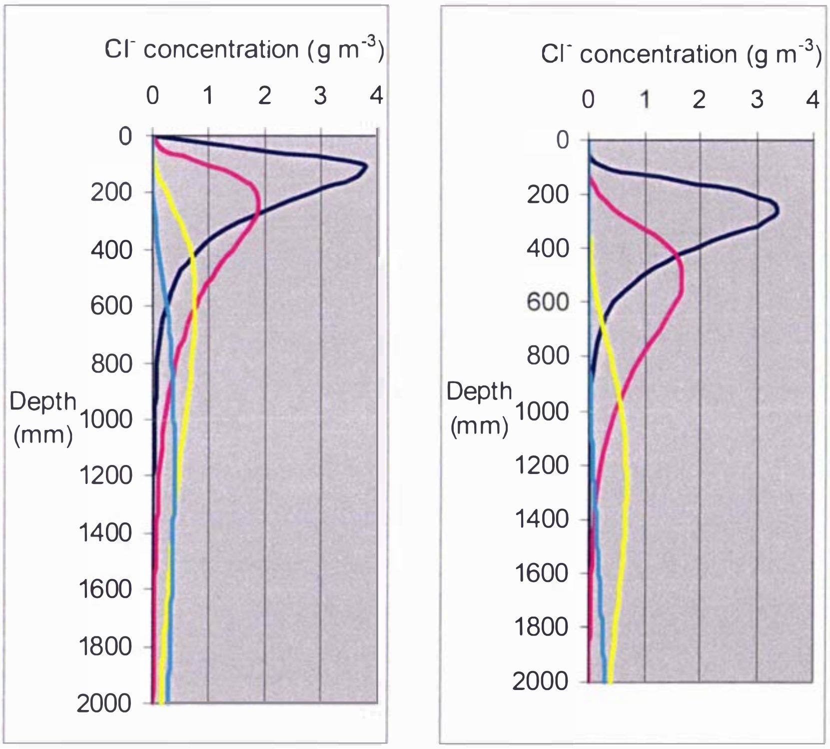
(a) Dami Experiment 3 FP (b) Sangara Experiment 2 FP

Simulated (—) and observed (■) Cl^-

Figure 8.10 Simulated and observed Cl^- (g m^{-3} soil volume) leaching profiles for FP soils of *in situ* leaching experiments at Dami and Sangara

The next step was to use the model to simulate the Cl^- profiles in the BZ and FP soils for a range of *I* values, viz. 100, 200, 500 and 1,000 mm. The results are shown in Figure 8.11. For both FP (Figure 8.11 (a)) and BZ (Figure 8.11 (b)), when *I* increased from 100 to 1,000 mm, the peak concentrations were reduced and the spread of the profile widened. However the peak reduced more, and the spread was wider, in the BZ than in the FP soil for any given increase in *I*. The peak also appeared to have moved faster down the soil in the BZ than in the FP soil with increasing *I*. For example, at *I* = 200 mm, the peak for FP was at around 250 mm depth (Figure 8.11 (a)) but for BZ, the peak was at 500 mm depth (Figure 8.11 (b)). The simulated Cl^- profiles for the different *I* values demonstrated clearly the differences in Cl^- (or NO_3^--N) movement for the two different zones for any given amount of *I*. The "umbrella" effect of pruned fronds, as discussed earlier in section 8.3.3.2 appears to explain the differences in the speed of the peak, the peak concentrations reached and the dispersion in these two soils. If this umbrella effect is the reason for the difference, the movement of anions in other zones might be expected to resemble the BZ curves rather than the FP curves because no pruned fronds are placed on the soil surface of the other zones in the plantation.

The profile for movement of Cl^- at different *I* values is also applicable to NO_3^--N because they are both mobile anions. However results would be different for NH_4^+-N ions which are retarded, as previously discussed (8.3.2.3).



(a) FP (b) BZ

I values of 100 (—), 200 (—), 500 (—) and 1000 mm (—).

Figure 8.11 Simulated leaching profiles following the surface application of 100 kg ha^{-1} of Cl^- to the FP and the BZ soils for various *I* values

8.3.4.5 Leaching of fertiliser N

The theory described above applies to the leaching of non-reactive solutes, such as Cl^- and NO_3^--N. However when considering the leaching of N following NH_4^+-N fertiliser application, the relative mobility of NH_4^+-N and NO_3^--N ions becomes important, along with the rate of transformation of NH_4^+-N to NO_3^--N in the soil, via the process of nitrification described in 5.1.

NH_4^+-N, being subject to cation exchange, usually leaches more slowly through soil than does NO_3^--N. Given the 'broad-brush' modelling approach being adopted here as already mentioned with regards to the CDE, it was decided to model cation exchange as an instantaneous reversible process using a linear adsorption isotherm. This assumption implies that the amount of absorbed NH_4^+-N per unit soil volume is proportional to the amount in solution. Jury and Roth (1990) defined a dimensionless retardation factor, *R* such that for example when $R = 2$, NH_4^+-N moves at half the speed of water (and Cl^- and NO_3^--N).

The approach taken here is in many ways similar to that adopted for the Dami lysimeters, in that values for *R* and *a* are obtained to describe the retardation factor and the rate of nitrification of NH_4^+-N. However, as variable throughfall occurs, the log-normal stochastic convection transfer function model was used instead of the CDE. Also, as the soil profile was only sampled at one time, *I* rather than *t* was used in the model except for the *t* in the exponential decay expression, where $I = J_w t$. The solution found by combining equations (2.17), (2.60) and (2.68) in Jury and Roth (1990) is then

$$C = \exp(-at)\frac{MI}{(2\pi)^{1/2}\sigma z^2 I_c R}\exp\left[\frac{-[\ln(zRI_c/I)-\mu]^2}{2\sigma^2}\right]\exp(\mu-\sigma^2/2)\ . \quad [8.9]$$

All the variables and parameters in this equation have been defined previously.

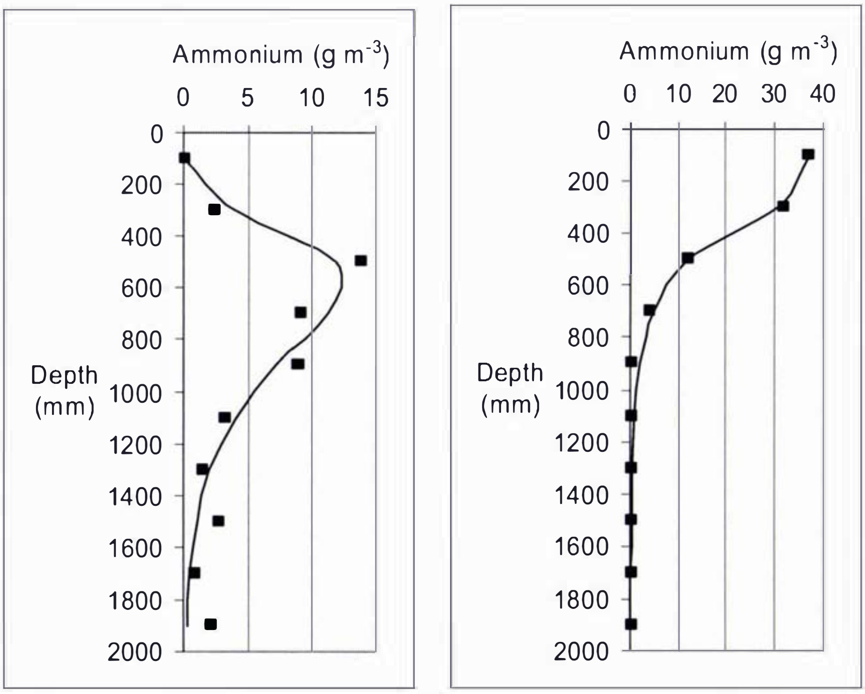
The initial and boundary conditions assumed are that there was no NH_4^+-N initially present in the soil and at $t = 0$ (so also $I = 0$), *M* of solute was applied to the soil surface.

Again the dimensions of M are [M L^{-2}], so it is the application rate of the NH_4^+-N in mass per unit area.

Solver in Excel was used to find a least-squares fit for equation (8.9) to the resident NH_4^+-N profiles for the experiments, and so to optimise values for a and R. Values used for μ and σ were those found earlier for the Cl^- data. The half-life for the nitrification of NH_4^+-N ($t_{1/2}$) was then found as;

$$t_{1/2} = 0.693 / a \qquad [8.10]$$

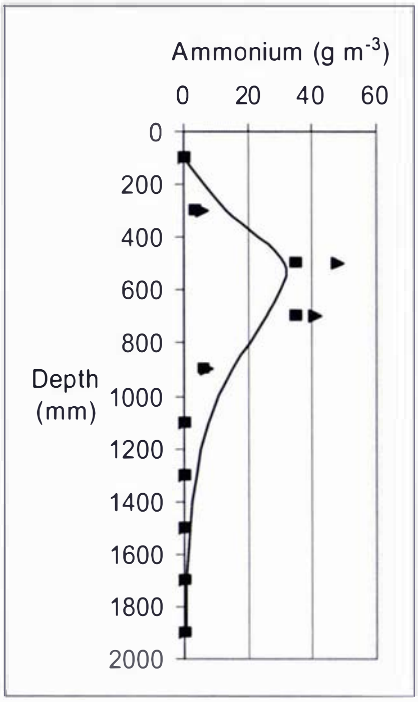
The simulated NH_4^+-N data using Equation [8.9] gave a good fit to the observed data (Figure 8.12). Average values for the two BZ soils are shown, corrected for the NH_4^+-N found in the control soil. Since no NH_4^+-N was found at Sangara for FP (Experiment 1) and BZ and FP (Experiment 2), the model could not be applied to these situations.



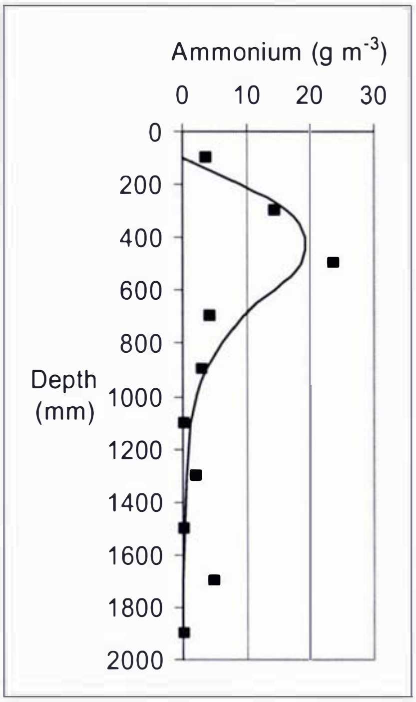
(a) Dami Experiment 1 BZ (b) Dami Experiment 2 FP

Simulated (—) and observed (■)

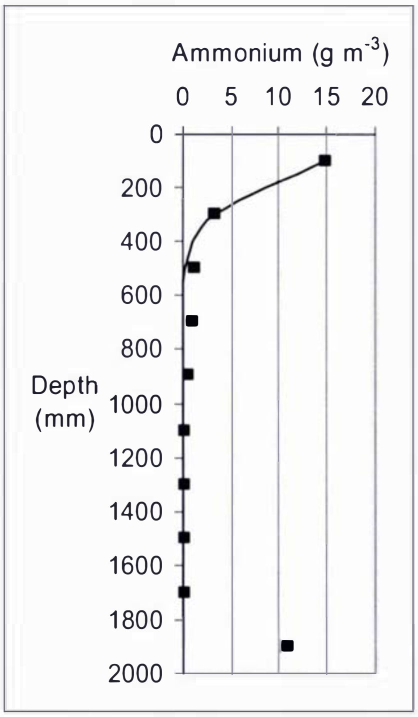
Figure 8.12 Simulated and observed NH_4^+-N profiles (g m^{-3} soil volume) at Dami and Sangara



(c) Dami Experiment 2 BZ



(d) Dami Experiment 3 BZ



(e) Sangara Experiment 1 BZ

Simulated (—) and observed (■) or (▶)

Figure 8.12 (continued)

The R and $t_{1/2}$ values found for NH_4^+-N from the *in situ* leaching experiments are shown in Table 8.13. Also shown in this table are R and $t_{1/2}$ values from the Dami lysimeters (8.3.2.3) and the $t_{1/2}$ values from the *in situ* nitrification experiments (5.3.2.3).

Table 8.13 Summary of half-life ($t_{1/2}$) (days) and retardation factor (R) values for NH_4^+-N from various experiments

Site	Experiment	***In situ* leaching**			
		FP		**BZ**	
		$t_{1/2}$ (days)	**R**	**$t_{1/2}$ (days)**	**R**
Dami	1	NS	NS	29	5.6
	2	50	2.2	74	1.4
	3	NA	NA	5	1.8
Sangara	1	NS	NS	53	8.5
	2	NA	NA	NA	NA
	Mean*			**42**	
				Lysimeter leaching	
Dami	Mean	8	1.9	26	1.5
				***In situ* nitrification**	
				WC	
Dami	Mean	8		78	
Sangara	Mean	15		71	

NA = No NH_4^+-N found
NS = not sampled
Mean* = $t_{1/2}$ for FP and BZ at Dami and Sangara

The average $t_{1/2}$ from the *in situ* leaching experiments at both Dami and Sangara was 42 days, however values ranged from 5 days for the BZ soil (Dami Experiment 3) to 74 days in the longer term experiment (151 days) again at Dami (BZ, Experiment 2). The $t_{1/2}$'s for FP at Dami (Experiment 3) and Sangara (Experiment 2), were not determined since no NH_4^+-N was detected, suggesting that the NH_4^+-N ions had already been nitrified. This suggests that in the FP soil, nitrification rates were rapid with a $t_{1/2}$ of NH_4^+-N of ≤ 6 days at Dami (Experiment 3), which went for only 6 days duration and had no NH_4^+-N remaining.

In the lysimeter experiment, the mean $t_{½}$ of NH_4^+-N in the FP soil was 8 to 26 for BZ. This again suggests nitrification was faster in the FP than BZ soil.

The $t_{½}$ from the *in situ* nitrification experiment were 8 and 15 days in the FP soil and 78 and 71 days in the WC soil at Dami and Sangara, respectively. Again the $t_{½}$ values suggest nitrification occurs faster in the FP than in the WC soil.

Overall the $t_{½}$ values for NH_4^+-N (Table 8.13) exhibited a wide range from 5 to 78 days. It is likely that the higher values occurred when high osmotic pressures inhibited nitrification. Such inhibition is taken into account in the models described next. In those models a $t_{½}$ value of 7 days is assumed after rainfall has diluted the osmotic effects.

The *R* values, from the *in situ* leaching experiments at Dami, fell between 1.4 and 2.2, which are similar to the average value of 1.9 found from the lysimeter data (8.3.2.3). The one exception was the 5.6 found for Experiment 1 at Dami, where it is likely that most of the NH_4^+-N movement occurred at relatively low concentrations. Although the definition of a constant *R* over all concentrations assumes a linear adsorption isotherm, the cation exchange process follows a non-linear isotherm with a greater slope, and higher *R*, at low concentrations. As it is the relatively high NH_4^+-N concentrations following AMC addition that are of interest here, an *R* value of 2 for NH_4^+-N at Dami was assumed subsequently. The only *R* value found for Sangara was 8.5, and it is likely that this value only applies to the dilute NH_4^+-N situation, and so is not relevant to the high concentration situation induced by fertiliser. Thus the Dami value of $R = 2$ was also used for Sangara. The sensitivity of the residence time for assumed values of *R* and *a* is discussed later (8.3.4.6.1).

Although nitrification happens over a number of days, treating it as a time-dependent process would have considerably complicated the derivation of the AMC leaching model. So it was assumed that all the applied N changed from NH_4^+-N to NO_3^--N, a given number of days after fertiliser application. The 'half-life' was used as the delay time needed for NH_4^+-N to change to NO_3^--N, assuming that nitrifying bacteria are active.

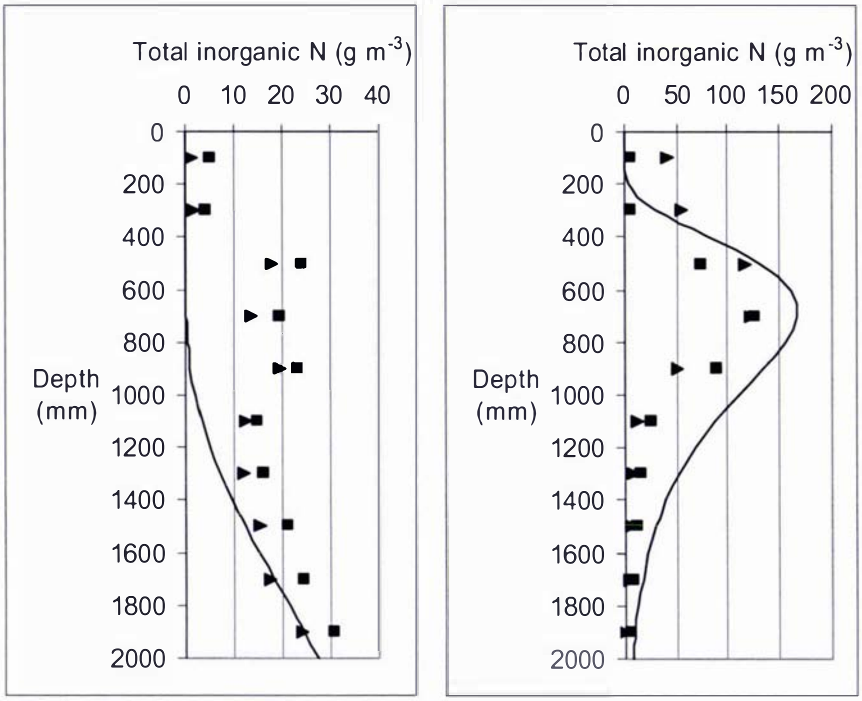
The results from the *in situ* nitrification experiment (5.3), and from Darrah *et al.* (1987), suggest that nitrification is inhibited at high solute concentrations. A typical AMC application rate of 82 g m^{-2}, dissolved in 20 mm of water (i.e. 20 L m^{-2}) would produce a concentration of 82/20 or 4.1 g L^{-1}. As the molecular weight of AMC is 53.5 g mol^{-1}, this solution will be 0.08 M. From Weast (1965), dilute AMC and sodium chloride have almost identical osmotic potentials, so from Lang (1967) the osmotic potential of this solution at 25 °C will be -376 kPa. Darrah *et al.* (1987) found that when sufficient AMC was added to soil to produce an osmotic potential of -350 kPa, there was 90 % inhibition of nitrification. Therefore the model will assume an extra "dilution" delay until $I > 20$ mm is reached after which nitrification commences.

So it is assumed that the N applied stays in the NH_4^+-N form for the sum of the dilution delay and nitrification delay periods. The value of I at this time, found using Equation [8.7], is designated I_d. So for $I < I_d$, applied N moves $1/R$ as fast as the soil water. It follows that for the N in AMC the effective value of I for use in Equation [8.8] (I_{eff}) is

$$I_{eff} = I/R \qquad \text{if } I < I_d \qquad [8.11]$$

$$I_{eff} = I_d/R + I_m - I_d \qquad \text{if } I \geq I_d\,. \qquad [8.12]$$

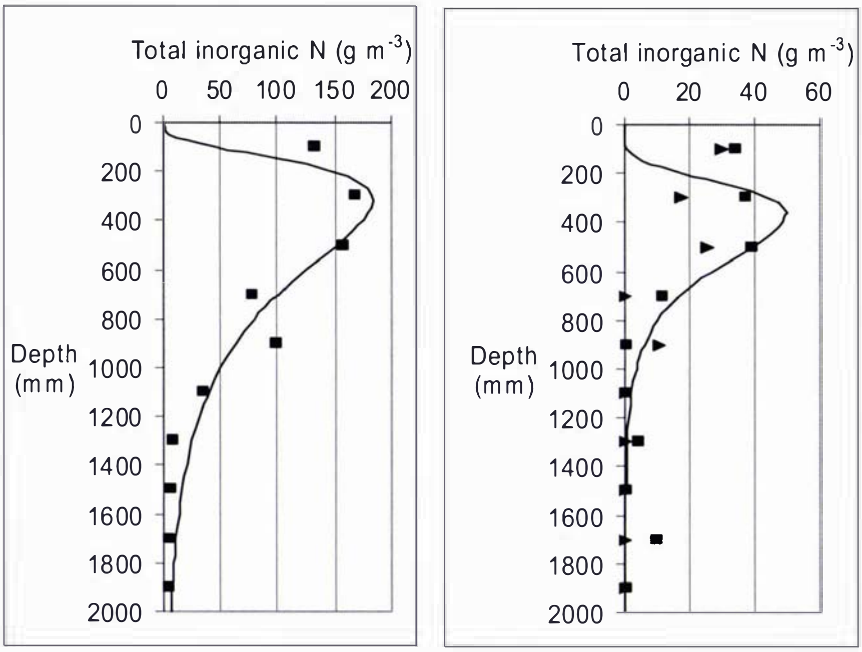
The observed and simulated total inorganic N data are presented in Figures 8.13 and 8.14 for Dami and Sangara, respectively. For Dami Experiment 1 (Figure 8.13 (a)) the simulated N between 0 and 1 m depth was not in agreement with the observed data. Most of the N found at this depth was NH_4^+-N while at depths lower than 1 m, there was more NO_3^--N. However the concentrations were low (<30 g N m^{-3}) and therefore when compared to other experiments with high concentrations of N and where the simulated data fitted well with the observed data, the lack of fit is considered not too important. Below 1 m depth, observed and simulated data agreed well. In contrast, if the CDE model had been used, it would have predicted no N remaining in the top 2 m. In the other experiments and zones, the simulated data fitted well with the observed data (Figures 8.13 (a) – (e) and 8.14 (a) – (c)). This suggests that the assumptions in the model are accurate enough to be used to extrapolate the results obtained to other situations and conditions.



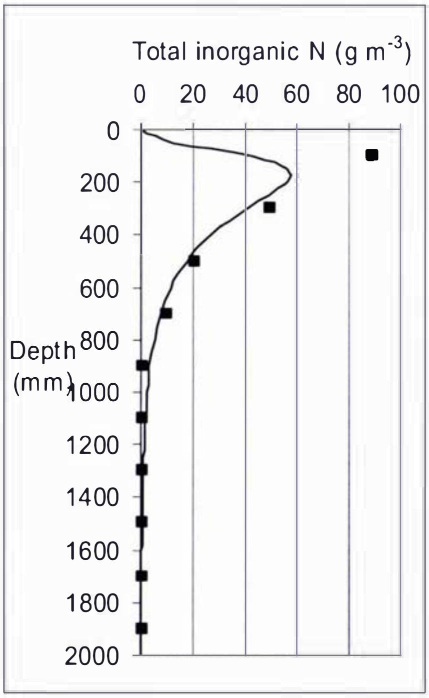
(a) Experiment 1 BZ (b) Experiment 2 BZ

Simulated (—) and observed (■) or (▶)

Figure 8.13 Simulated and observed total inorganic N concentrations with depth at Dami



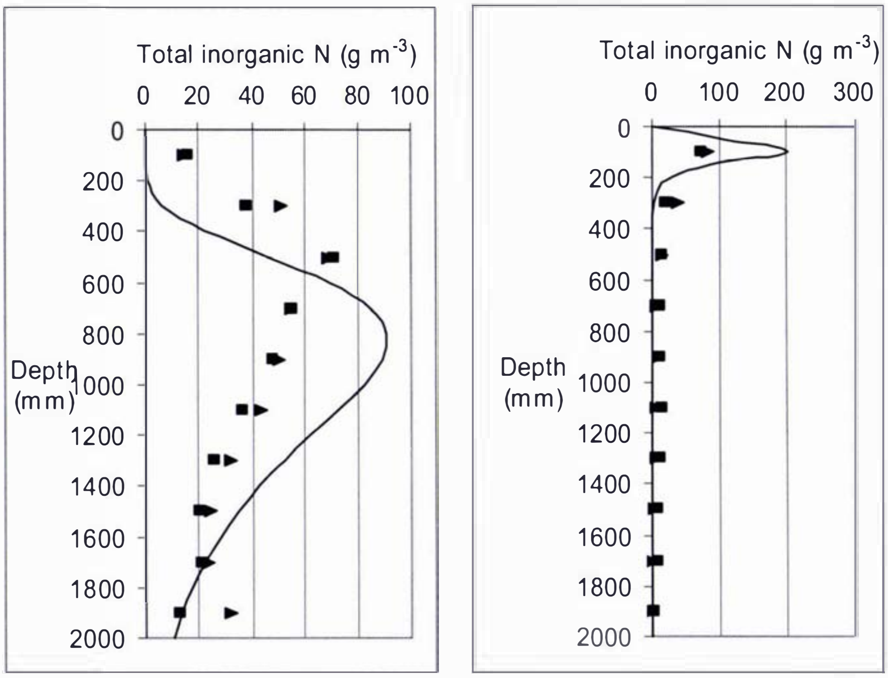
(c) Experiment 2 FP (d) Experiment 3 BZ



(e) Experiment 3 FP

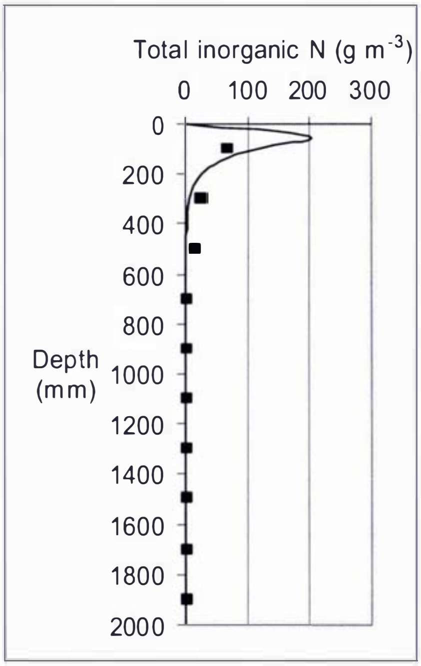
Simulated (—) and observed (■) and (▶)

Figure 8.13 continued



(a) Experiment 1 BZ

(b) Experiment 2 BZ



(c) Experiment 2 FP

Simulated (—) and observed (■) or (▶)

Figure 8.14 Simulated and observed total inorganic N concentrations at depths at Sangara

8.3.4.6 A residence time model for fertiliser N

This section describes how the residence times in the root zone were estimated for fertiliser N applied as AMC on each day for which historical 10 or 12 year weather data was available at Sangara and Dami. The active root zone was assumed to be within the top 500 mm of soil. The assumptions about leaching in the model used to simulate the *in situ* leaching experiments were carried over into the residence time model, except for the log-normal distribution of soil water velocities and travel times. For each day a single soil water velocity was assumed, calculated as the effective Darcy flux density divided by the volumetric water content. Note that this velocity can be negative if effective evaporation is greater than rainfall. A volumetric water content at field capacity of 0.4 m^3 m^{-3} as determined in 4.2.1.2.4 was used. Thus 200 mm of downward water movement was needed to move non-adsorbed solute (with R = 1) from the surface to a depth of 500 mm. The effective Darcy flux density was calculated as described earlier (8.3.4.3), i.e. assuming throughfall was 90 % of rainfall, and the effective evaporation was 77 % of the FAO56 E_r estimates. $t_{½}$ for nitrification of NH_4^+-N to NO_3^--N was taken as 7 days (8.3.4.5). It was assumed that 20 mm of excess rainfall was needed to dilute the dissolved AMC enough for nitrification to commence. Applied N was assumed to change instantaneously, from NH_4^+-N to NO_3^--N, 7 days after the 20 mm of excess rainfall had occurred following AMC application. The retardation constant, R, was taken as 2 for NH_4^+-N and 1 for NO_3^--N. Losses of N via plant uptake, volatilisation, denitrification, immobilisation, and surface runoff have all been ignored.The computations were done in Excel spreadsheets using a Visual Basic macro. The values for each month were collected together and the monthly mean, median, and standard deviations were computed. Computed residence times can be thought of as estimates of the number of days required to leach about half of the applied N to below a depth of 500 mm.

The results are presented as the mean number of residence days for each month since annual plantation work is normally divided into monthly programmes so monthly values are easy to relate to actual plantation and smallholder practices.

Table 8.14 gives the computed mean and median residence times for fertiliser N applied as AMC in different months over the years of available weather data computed for each day of all months for the 10 year period. Mostly the standard deviations are much smaller than the means, and the means and median values are quite similar. The exception is for January, February and March at Sangara, where the means and standard deviations are similar in magnitude and the medians are considerably lower than the means, implying a large year-to-year variation in the values. This needs to be remembered when considering the means. The mean values are repeated in Table 8.15, where the annual mean values are also given.

Table 8.14 Mean and median residence times in days for N applied as AMC

	Dami 1994 - 2005											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Mean	24	21	45	87	114	111	120	103	84	74	49	32
SD	9	10	52	72	68	58	52	35	28	20	11	11
median	22	18	30	67	111	110	116	97	80	73	49	32
	Sangara 1991 - 1999											
mean	91	98	118	173	190	172	147	115	87	67	50	60
SD	93	95	93	81	51	41	37	37	32	19	17	23
median	63	68	71	184	190	171	145	115	83	62	52	56

SD = standard deviation

The average residence time is 42 days longer at Sangara (mean = 114 days) than at Dami (mean = 72 days) (Table 8.15). There are also some large differences between months in the residence times at each site. For example, at Dami the average residence time is nearly six times longer for N applied in July than in February; while at Sangara the average residence time is nearly four times longer for N applied in May than in November. These findings have obvious implications for the timing of fertiliser applications.

8.3.4.6.1 Scenarios and sensitivity analysis

The residence time model provides a mechanism for exploring some alternative scenarios. Some of these are shown in Table 8.15. These scenarios also provide some insights into the sensitivity of the model to some of the input parameters.

Table 8.15 Fertiliser N mean residence times in days for various scenarios.

	R	$t_{1/2}$	Month												Annual
		(days)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
Dami															
Standard Model	2	7	24	21	45	87	114	111	120	103	84	74	49	32	72
Scenario 1	1	-	19	15	35	72	91	90	112	94	76	68	46	28	62
Scenario 2	2	∞	32	32	82	130	155	152	150	138	112	89	66	44	99
Scenario 3	2	14	27	25	50	91	115	115	123	104	86	76	51	35	75
Sangara															
Standard Model	2	7	91	98	118	173	190	172	147	115	87	67	50	60	114
Scenario 1	1	-	76	89	98	156	180	168	146	112	82	62	43	52	105
Scenario 2	2	∞	147	178	234	239	230	211	185	151	120	105	111	141	171
Scenario 3	2	14	95	101	120	183	191	172	147	115	89	68	54	64	117
Scenario 4	8	7	101	105	135	190	194	174	150	117	91	71	55	66	121

At each site, the first row for each set of data in Table 8.15 is the standard model with *R* = 2 and $t_{1/2}$ = 7 days. The first scenario assumes *R* = 1 at all times. This scenario models what would happen if N was applied as NO_3^--N rather than as NH_4^+-N. The result suggests that the mean residence time would be 10 days shorter at Dami and 9 days shorter at Sangara.

The second scenario simulates what would happen if a way could be found to inhibit nitrification indefinitely ($t_{1/2}$ = ∞). The residence times are then substantially increased, doubling in some cases (Sangara, Nov–Dec). But more interestingly is that the residence time is still small in wetter months (Jan-Feb) at Dami. This relates to NH_4^+-N leaching.

The third scenario assumes a change in the nitrification rates; NH_4^+-N $t_{½}$ from 7 to 14 days. This results in an increased residence time of only three days on average. Thus the residence times calculated are not very sensitive to changes in $t_{½}$ when $R = 2$.

The fourth and last scenario considered was to assume that R at Sangara was 8 (Table 8.13) rather than 2, as no reliable data for R at Sangara were obtained. An R of 8 (indicative of highly retentive soil) was the highest value found in this study (8.3.4.5). This increases the average residence time by 7 days. Thus the residence time at Sangara is not highly sensitive to the R value chosen when the NH_4^+-N $t_{½}$ is 7 days or less.

The implications of these scenarios for fertiliser application are discussed in 9.3.

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Chapter 9

Main findings and fertiliser management implications

This chapter summarises the main findings from the preceding chapters, highlights the information used to develop the leaching and residence time models, and discusses some fertiliser management strategies, using the models, for reducing N leaching losses.

9.1 Main findings

Oil palm is a very important industrial crop to the PNG economy in terms of providing employment and for rural development. It is grown on over 80,000 ha of land in five Provinces.

The soils at Dami and Sangara, the two experimental sites, are of recent volcanic origin and have very good physical (deep and well-drained) and chemical (pH 5.5 – 6.5) properties for tree crop production. The Dami soils are sandy and coarser with lower bulk densities (<1.06 g cm^{-3}) while those at Sangara are fine sandy clay with bulk densities of 1.15-1.43 g cm^{-3} with increased clay content in the B horizon.

Under oil palm, the soils become non-uniform as a result of various cultural practices. There are five recognisable distinct zones; FP (8 % of total area), FT (6 %), BZ (73 %), WC (10 %) and HP (3 %). The soil pH, total C and total N values in these zones are different as a result of current and historical management. The differences in chemical characteristics are more obvious at Dami than at Sangara due to the fact that zones at Dami have been in existence for two generations of palms. The relatively high total C (6.1 %) and N (0.55 %) contents in the topsoil (0-20 cm) of the FP compared to other zones (where total C is <4 % and N <0.4 %) indicate that this zone is more biologically-active than other zones, and acts as a significant nutrient source and sink. Soil pH in the FP (0-20 cm) at Dami is >6 while in the other zones, pH ranges from 4.6 to 5.5. The relatively high pH in the FP may be due to the alkalinising effect of decomposing fronds. Differences in soil properties between the zones affect the N transformation processes occurring in the soil, the supply of N for nitrifiers, C and N for denitrification and soil infiltrability which in turn affects the availability of N for crop uptake or loss.

At Dami, infiltrability in the FP is 8,500 mm hr^{-1} while in the other zones it ranges from 80 (in HP) to 1,300 mm hr^{-1} (in FT). At Sangara, the rates are high in FP and FT (1,000 – 1,300 mm hr^{-1}) however they are low in BZ, WC and HP (150 – 300 mm hr^{-1}). At both sites FP and FT soils are more permeable than those in WC and HP, presumably due to differences in organic matter content and/or compaction. The lower infiltrability in the HP and WC means that these areas are potential zones of runoff generation. At Sangara, a sandy clay subsoil horizon at 30 – 60 cm appears to slow the movement of water, and probably leads to a temporary perched water table occurring at times and greater surface runoff at this site.

Of all the nutrients, N (apart from K) is required by oil palm in the largest quantity (170 - 200 kg ha^{-1} yr^{-1}) and is also the major limiting nutrient in PNG oil palm soils. Of the fertilisers used in the oil palm industry, between 50 and 100 % contain N and the costs range from 50 to 70 % of field input costs. Oil palm plantations typically apply 80 -100 kg N ha^{-1} annually. The palms are estimated to take up 160 – 200 kg N ha^{-1} from the soil every year. Of that, on average, 60 kg N ha^{-1} yr^{-1} is removed in the harvest and a further 50 – 60 kg N ha^{-1} yr^{-1} is estimated to be lost via surface runoff, denitrification or leaching (unaccounted N). The unaccounted N is of significant economic importance because it amounts to >15 million kina loss to the industry and has significant environment implications by affecting the quality of drinking water, eutrophication of waterways and N_2O build-up in the atmosphere.

To maintain high yields (22-26 tonnes FFB ha^{-1} yr^{-1}), N fertilisers are applied at 520 – 850 g N palm^{-1} yr^{-1} however the actual application practices (rates, timing and placement) vary across the industry. Most fertiliser management trials done in both PNG and other oil palm producing countries have looked mostly at uptake and crop responses with no real emphasis on losses.

Though the soils used in oil palm production are of high quality at the two sites, their porous nature coupled with high rainfalls (3,500-4,000 mm at Dami and 2,500–3,000 mm at Sangara annually), implies that nutrients such as N are highly susceptible to loss via leaching or surface runoff. Mean annual E_r, runoff and deep drainage measured as a % of annual rainfall were 39, 1 and 61 % for Dami and 55, 8 and 37 % for Sangara respectively. The significant proportion of rainfall lost as deep drainage at these two sites implies that leaching is probably the main process by which N is lost from the oil palm system. However the entry of water into the soil and downward flow in the soil profiles does not occur uniformly across the field as a result of three factors;

a) rainfall redistribution by the oil palm canopy is non-uniform. Average throughfall under palms increases with distance from the trunk, from about 30 % in the WC to 100 % of the rainfall in the areas which are further from the trunk. Within the different zones, throughfall is also highly variable (e.g. for FP and BZ, CVs range from 25 to 146 % with a mean of 90 %). Also approximately 11 % of total rainfall reaches the ground unevenly via stemflow. This all means that leaching is greater in some areas than others

b) placement of fronds on the FP further redistributes the rainfall. This was not measured directly in this study however the large spread in the distribution of inorganic N and Cl^- ions in the *in situ* leaching experiments suggests that this occurred

c) soil surface characteristics can cause local ponding in some areas as evidenced by the large variation in infiltrability measurements found for different zones.

The probability of N losses is likely to be greatest where root activity is low. Root activity studies showed that water uptake was highest in the WC at both Dami and Sangara compared to other zones. Root distribution studies at Sangara also confirmed that the greatest density of roots was in the WC. However along with the high root density in the WC, a high influx of stemflow is also received by this zone so nutrients are probably more susceptible to leaching in the WC than in other zones further from the trunk.

Oil palm fertilisers are applied mostly in the NH_4^+-N form which is then biologically converted to NO_3^--N. Nitrification studies showed that the rate at which half of the amount of fertiliser NH_4^+-N was changed to NO_3^--N depended on the rate at which it was applied (cause of osmotic effects), the amount of rainfall (to reduce the salinity and allow nitrification to proceed) and where the fertilisers were placed under the palms (nitrification capacity of the zone). Nitrification rates were faster in the FP ($t_{1/2}$ = 8-15 days) at Dami and Sangara than in the WC ($t_{1/2}$ = 70 – 80 days). However from the *in situ* leaching experiments, $t_{1/2}$ for NH_4^+-N in the FP was less than 3 days due to heavy rainfall diluting the fertiliser and allowing nitrification to proceed soon after fertiliser application. The Dami lysimeter study also showed that the nitrification rate was higher in the FP than in other zones. The high nitrification rates found in the FP suggest that no natural nitrification inhibitors exist in these soils. The FP appears to be an active nitrifying area as well as a N source in terms of pruned frond additions.

Denitrification calculated from the emissions of N_2O was minor in agronomic terms (< 1 % of fertiliser added annually) however it may be of concern for the ozone layer and could become an issue in the future given the rapid growth of the oil palm industry in PNG, the amounts of N fertiliser being used and the sensitivity of the atmosphere to receiving increased contributions of N_2O. However the full extent of denitrification was not determined in these experiments since only N_2O emissions were measured. The ratio between N_2O and N_2 is not constant and N could not be determined in this study because of the large background levels in the ambient atmosphere.

Surface runoff losses of N were also very low in these soils although they were higher at Sangara (2 kg ha^{-1} yr^{-1}) than at Dami (0.2 kg ha^{-1} yr^{-1}). Losses of N from applied fertiliser were equivalent to <1.5 % of the added fertiliser, suggesting that most of the fertiliser remained within the plots and was either taken up by the crop, immobilised by soil microorganisms or leached from the oil palm system. Losses by runoff appear to be small and agronomically insignificant but it should be noted here that the experiments were done on volcanic soils with high infiltrability and the situation may change with other oil palm soils of lower infiltrability.

The high infiltrability combined with high annual rainfall (2,500 – 4,000 mm vs E_r of 1,350 mm) suggests that N loss via leaching is probably the major loss process in these volcanic soils. Combining the suction cup data with deep drainage estimates from the water balance produced annual N losses via leaching of 96 kg/ha at Dami and 20 kg/ha at Sangara. However the relatively small number of replicate suction cups installed, and the large variability in the data obtained from them mean that there is large uncertainty with these estimates. Also there was no attempt to partition this loss between soil and fertiliser sources.

The use of lysimeters created its own problems, however for those that worked at Dami, the retardation factor was determined for use later in the models. Results from the lysimeters showed that for Dami soils, N was leached in both NH_4^+-N and NO_3^--N forms, however NH_4^+-N moved through the soil at half the speed of NO_3^--N.

The *in situ* leaching studies showed that most of the N applied as AMC leached as NO_3^--N, but some NH_4^+-N also leached at Dami. Leaching was highly variable, spatially, due mainly to the variability in throughfall but also to a contribution from the "umbrella" effect caused by fronds being placed on top of the fertiliser on the FP.

The data obtained, and used to develop the leaching and residence time models, are discussed in 9.2.

9.2 Inputs to residence time and CLT models

Information was drawn from various chapters to develop the models as follows.

From Chapter 4 Hydrology

- field capacity of *in situ* leaching soils – 0.4 m^3 m^{-3}
- rainfall redistribution data provided the 90 % throughfall estimate and suggested that the CLT model would be more appropriate than the CDE model
- runoff data lead to runoff sub-model
- soil water balance section provided rainfall data and FAO56 evaporation estimates

From Chapter 5 *In situ* nitrification

- indication of osmotic inhibition, leading to the assumption of 20 mm of rainfall to cause dilution before nitrification
- the similar recoveries for Cl- and inorganic N in AMC suggested that N losses via volatilisation and denitrification were small enough to ignore in the model
- estimates of $t_{1/2}$ values for nitrification of NH_4^+-N.

From Chapter 6 Denitrification losses

- further evidence that denitrification was small enough to ignore in the model

From Chapter 7 Runoff losses

- evidence that N losses in runoff following AMC application were small enough to ignore in the model

From Chapter 8 Dami lysimeters

- $t_{1/2}$ estimates for NH_4^+-N nitrification
- estimates of retardation factor (R) for NH_4^+-N
- high recoveries of applied N in leachate provided evidence that volatilisation and denitrification were small enough to ignore in the model

From Chapter 8 NH_4^+-N data for *in situ* leaching experiments

- more half life estimates for NH_4^+-N nitrification
- more estimates of retardation factor (R) for NH_4^+-N

From Chapter 8 Cl^- data for *in situ* leaching experiments

- dispersion parameters for CLT model
- value for effective evaporation of 77 % E_r

From Chapter 8 NO_3^--N plus NH_4^+-N ammonium data for *in situ* leaching experiments

- verification of detailed CLT model for fertiliser N

From Appendix A2.2 Root activity paper

- 500 mm estimate of active rooting depth

9.3 Implications and recommendations

This discussion of fertiliser management and recommendations is based on Tables 8.14 and 8.15 from the previous chapter. The tables are repeated below as Tables 9.1 and 9.2 for convenience. The two tables are based on many of the findings from the various experiments in the preceding chapters. However caution is required in any interpretation of this data because of the large standard deviations of residence times as shown in Table 9.1 for several months at both sites. Further, the averages of the 10 year historic climatic data may not hold true in future if any major changes in climate occur.

Table 9.1 Mean and median residence times in days for N applied as AMC

	Dami 1994 – 2005											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Mean	24	21	45	87	114	111	120	103	84	74	49	32
SD	9	10	52	72	68	58	52	35	28	20	11	11
CV (%)	38	48	116	83	60	52	43	34	33	27	22	34
median	22	18	30	67	111	110	116	97	80	73	49	32
	Sangara 1991 – 1999											
mean	91	98	118	173	190	172	147	115	87	67	50	60
SD	93	95	93	81	51	41	37	37	32	19	17	23
CV (%)	102	97	79	47	27	24	25	32	37	28	34	38
median	63	68	71	184	190	171	145	115	83	62	52	56

SD = standard deviation

Table 9.2 Fertiliser N mean residence times in days for various scenarios.

	R	$t_{1/2}$	**Month**												
		(days)	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual Mean**
Dami															
Standard Model	**2**	**7**	**24**	**21**	**45**	**87**	**114**	**111**	**120**	**103**	**84**	**74**	**49**	**32**	**72**
Scenario 1	1	-	19	15	35	72	91	90	112	94	76	68	46	28	62
Scenario 2	2	∞	32	32	82	130	155	152	150	138	112	89	66	44	99
Scenario 3	2	14	27	25	50	91	115	115	123	104	86	76	51	35	75
Sangara															
Standard Model	**2**	**7**	**91**	**98**	**118**	**173**	**190**	**172**	**147**	**115**	**87**	**67**	**50**	**60**	**114**
Scenario 1	1	-	76	89	98	156	180	168	146	112	82	62	43	52	105
Scenario 2	2	∞	147	178	234	239	230	211	185	151	120	105	111	141	171
Scenario 3	2	14	95	101	120	183	191	172	147	115	89	68	54	64	117
Scenario 4	8	7	101	105	135	190	194	174	150	117	91	71	55	66	121

(a) When is the most suitable time for N fertiliser application and how often should fertiliser be applied in a year?

At Dami from Table 9.1, the model suggests that if N fertiliser is applied from May to August, on average half of it will stay within the top 50 cm depth of soil for more than 100 days. For the other months the residence time is less than 100 days. If necessary, N fertiliser could be applied in September (residence time = 84 days, CV = 33 %) or October (residence time = 74 days, CV = 27 %). But application in April is more risky even though it has the same average residence time of 87 days, because of the high (CV = 83 %). The average residence times for the period November to March are low (<50 days), so fertilisers applied during these five months are more at risk from leaching loss.

At Sangara, modelled average residence times are mostly longer than at Dami and there is a six month period (from March to August) where average residence times are >100 days. The best months to apply fertiliser would appear to be April, May and June, since all of these have residence times > 170 days. March is a more risky month with a CV of 79 %.

Currently applications of fertiliser have usually been avoided during high rainfall months in an attempt to minimise losses. But the model suggests that fertilisers are just as susceptible to losses via leaching if applied a couple of months prior to the main rainfall season. For example at Dami from the monthly rainfall distribution data (Figure 3.4), it might be considered reasonable to apply fertiliser in November or even December, when rainfall is lower than in January-March but expected to increase. However the residence time model shows average residence times of <50 days for November and December applications. Fertiliser applied at the end of the wet season in May would be a better option for plantations, when the residence time is >100 days.

As mentioned above, there is a wider window of opportunity for the safe application of N fertilisers at Sangara than at Dami. This has implications for the ordering of fertilisers, and for deciding whether or not to split applications. For the plantations, it is probably better to have only one or two applications per year at a site like Dami, and two or three applications at sites similar to Sangara. The first application at Dami could be in May and the second in August, while at Sangara, the first could be in March-April, a second in June, and a third in August-September. This scheduling would allow two months between applications, and avoid the months with low residence times thereby minimising leaching losses.

For smallholder blocks, where N fertiliser is normally only applied once a year, application in June-July would appear to be optimal for growers at Dami (>111 days average residence time) and May-June at Sangara (>172 days average residence time and relatively low CV).

(b) Where best to apply fertiliser?

Results (Appendix A2.2) show that though there were roots in the HP, water uptake was least from this zone, while the greatest water uptake occurred from WC followed by FP. In many oil palm systems, it is recommended that fertilisers be applied to WC as this is where the roots are densest. Also from the rainfall redistribution study (4.2.2.2.3), average throughfall was about 30 % of the rainfall within WC. This would equate to about 1,050 and 730 mm of throughfall annually at Dami and Sangara respectively, which at both sites is less than the average E_r of 1,330 mm. Thus ignoring stemflow, little or no leaching would be expected from the WC. However, a significant proportion (11 %) of rainfall is also received by the WC as stemflow, which mostly infiltrates into the soil and will cause significant leaching in some parts of this zone. In addition to the large potential for leaching from the influx of stemflow soil pH was lowest in the top 20 cm in WC at both Dami and Sangara. Thus applying fertiliser in this zone would further reduce pH and so may not be good for the long-term sustainability of the soils. Hence spreading fertilisers in zones other than WC is likely to be the preferred option.

The FP zone had the next highest water uptake, and also appeared to be buffered against changes in soil pH from continuous previous fertiliser additions. The results from the leaching experiments also showed that fertilisers applied to this zone were somewhat protected from being leached by a type of "umbrella" effect of frond replacement on top of the applied fertilisers, so this would appear to be a preferred zone in which to apply fertiliser. However the umbrella effect due to fronds being placed over the fertiliser, would not apply in situations where the fertiliser is sprinkled directly over the piles as is normal practice. In such cases the umbrella effect could even enhance leaching. This suggests that the FP may not always be the ideal zone in which to apply fertiliser. It depends on the timing of frond additions in relation to the next heavy rainfall.

All things considered, a semi-circular band about 1 m wide just outside the WC, covering a mix of BZ, FT and FP zones may be the preferred option for fertiliser placement for the following reasons;

- This area receives about 50 % throughfall compared to >80% further out from the palm trunk. Application of fertilisers further from the palms in the FT and some parts of the FP would probably result in more leached N because of higher average throughfall
- This area would be unlikely to be affected by stemflow, most of which probably infiltrates within the WC, except during very heavy rain events

- This area has the second highest water uptake after WC reflecting root activity as shown from the water uptake studies
- This area is convenient for plantation workers and smallholders to enter and spread fertilisers.

(c) Form of N fertiliser

The most commonly-used fertilisers in the oil palm industry are AMC, SOA, AMN and urea. Field trials suggest that there may be no differences in yield response to any of these different N types. The *in situ* leaching trials indicated that within a month, and sometimes in less than a week, most of the NH_4^+-N was nitrified. This implies that it does not matter greatly which form of N is used, because within a relatively short time, all N will be converted to NO_3^--N. The residence time model (Table 9.2, Scenario 1) suggests that at both Dami and Sangara, the average residence time was 9 – 10 days shorter if N was applied as NO_3^--N rather than as NH_4^+-N. This difference is not large therefore while NH_4^+-N may be the preferred form, the residence times for NO_3^--N are not all that different. In the end cost and fertiliser availability will often be of practical significance as will the requirement for accessory nutrients.

If an effective economical nitrification inhibitor, suitable for use on tropical tree crops did become available sometime in the future, Scenario 2 in Table 9.2 suggests that the mean residence time would only be increased by 22 and 57 days at Dami and Sangara, respectively. In some of the months, the residence time would be doubled e.g. for the months of November and December at Sangara. If such an inhibitor were found, NH_4^+-N or urea-N would then need to be the forms used.

(d) Implications for field experiment techniques

Many of the conventional experimental approaches used to study the fate of N from agriculture systems appear inappropriate for the type of study done here because of scale, due to the palms being large with differently managed areas under them, the unavailability of modern analytical facilities on-site for analysis, and the time taken to transfer samples and return data. Appropriate methods and approaches were designed to implement the project and they worked well. The normal 1 m x 1 m plot sizes for surface runoff studies was inappropriate and therefore 4 large palm plots were used that covered all the managed zones. The use of AMC fertiliser with Cl as an inert tracer proved useful. Use of lysimeters had its own problems so a soil coring approach was used, with extraction on-site. The soil extracts were sent off-shore for analysis.

Appendices

Appendix 1

A1.1 Dami soil profile description

Location	Dami OPRS
Trial	OPRS Trial 239
Parent Materials	Alluvial and volcanic ash/pumice
Landform	Composite alluvial volcanic ash outwash plain
Slope	1 – 5 degrees
Previous Land Use	Oil Palm Plantation (seed garden)
Vegetation	Oil palm plantation
Surface features	Nil
Ground cover	60% mixture of ferns, cover crop and grasses
Soil Drainage	Well drained
Comments	There are buried soils. There is a hard sand/gravel/pumice layer at 43 – 55 cm depth and there is a mixture of alluvial and volcanic ash materials forming different horizons. In most layers there is a high percentage of pumice and fine sand mixed within the B horizons.
Authors	Murom Banabas and Hanson Injik (06/04/04)

Horizon	Depth (cm)	Description
A	0 – 07	Moist very dark gray (10YR 3/1) sandy loam; very friable; moderately to strongly developed; fine – medium subangular blocky structure; slightly sticky; slightly plastic; rapid porosity; many fine and medium pores; many fine and medium roots (oil palm secondary and tertiary roots); positive pH (NaF) reaction; diffuse and smooth boundary to
AB	07 – 19	Moist brown (10YR 4/3) loamy sand; very friable; weakly - moderately developed, fine crumb structure; slightly sticky, slightly plastic; rapid porosity; many fine and medium pores; few fine (tertiary), many medium (secondary) and few coarse primary oil palm roots, distinct wavy boundary to
BC1	19 – 43	Moist yellowish brown (10YR 5/6) loamy sand - sand; loose - very friable; structure less - weakly developed medium crumb structure; non sticky non plastic; very rapid porosity; many fine pores; few fine, medium and coarse roots; distinct smooth boundary to
C1	43 – 55	Moist light olive brown (2.5Y 5/6) loamy sand – sand structure less fine loose sand; (compacted ash/sandy layer) very friable to loose, non sticky and non plastic; very rapid porosity; many fine pores; few fine, medium and coarse roots; diffuse boundary to

C2	55 – 73	Moist yellowish brown (10YR 5/6) coarse loamy sand, structure less to weakly developed fine crumby structure; very friable to loose, non sticky, non plastic; very rapid porosity; many fine pores; few fine, medium and coarse roots; diffuse boundary to
Bw1	60 – 72	Moist dark yellowish brown (10YR 4/6) sandy loam; weakly developed, fine crumb structure; friable, non sticky and non plastic; very rapid porosity, many fine pores; few fine, medium and coarse roots; distinct smooth boundary to
C3	73 – 130	Moist light gray (2.5Y 7/1) sandy/pumice/gravel; structure less medium – large pumice/gravel; loose, non sticky, non plastic, very rapid porosity, few medium and coarse roots; distinct smooth boundary to
ABC2	130 – 137	Moist yellowish brown (10YR 5/6) sandy loam; weakly developed, fine crumby structure; very friable slightly sticky, slightly plastic, very rapid porosity, many fine and medium pores; few medium roots, distinct straight boundary to
bA?	137 – 150	Moist gray (2.5Y 6/1) loamy sand; weakly developed, fine crumby structure; very friable, slightly sticky, non plastic; very rapid porosity, many fine pores; distinct straight boundary to
C5	150 – 156 (Ash)	Moist yellowish brown (10YR 5/8) sandy clay loam; weakly developed, fine crumby structure, very friable sticky, plastic; many fine and medium pores; very rapid porosity, distinct straight boundary to
BC2	156 – 176	Moist dark yellowish brown (10YR 4/6) sandy clay loam with gravel (pumice) inclusions (weathered pumice layer), weakly developed medium subangular blocky structure; friable, slightly sticky, slightly plastic, many fine and medium pores; very rapid porosity; diffuse straight boundary to
C6	176 – 200	Moist yellowish brown (10YR 5/8) gravel/pumice (80%), weakly developed, medium to large gravel pumice, loose, non sticky, non plastic; many fine and medium pores, very rapid porosity
	200 - 224	Moist dark brown (10 YR 3/3), loamy sand (with pumice inclusions 40%) moderately developed fine – medium sub angular blocky structure friable non sticky slightly plastic many fine and medium pores, very rapid porosity, few fine, medium and coarse roots (buried soil layer)

A1.2 Sangara soil profile description

Location	Sangara (OPRA Popondetta)
Trial	OPRA Base Site 10 m from rubbish dump
Parent Materials	Mt. Lamington volcanic ash materials
Landform	Volcanic ash plain
Slope	1 – 5 degrees
Previous Land Use	Oil palm plantation (2nd planting and 6 year old)
Vegetation	Oil palm plantation
Surface features	Surface was hard and dry in the weeded circle.
Ground cover	Mixture of pueraria and mimodica (~80 %) over frond piles and between palms but none on weeded circle and harvest paths
Soil Drainage	Well drained
Comments	Inclusions of ~2% gravel from 80 to 175 cm depth. Most fine roots were dead and were from first planting palms
Authors	Murom Banabas and Mason Japara (13/10/03)

Horizon	Depth (cm)	Description
A1	0 – 30	Black to very dark brown (10YR 2/1 – 2/2) sandy clay loam; very friable to friable; moderately developed; fine – medium subangular blocky structure; slightly sticky; plastic; rapid porosity; many fine and medium pores; few fine and medium roots (oil palm secondary and tertiary roots); diffuse boundary to
AB	30 - 40	Very dark grayish brown (10YR 3/2) sandy clay; friable; moderately developed, fine – medium subangular blocky structure; sticky, plastic; rapid porosity; many fine pores; few fine (tertiary) and medium (secondary) oil palm roots, diffuse boundary to
B1	40 – 80	Dark brown (10YR 4/3) clay loam; friable to firm; moderately developed, fine - medium subangular blocky and crumb structure; very sticky, plastic; moderately rapid porosity; many fine pores; few fine (tertiary) oil palm roots, diffuse boundary to
B2	80 – 120	Dark brown (10YR 5/3) sandy clay loam; friable; weakly developed, fine - medium crumb structure; sticky, plastic; rapid porosity; many fine and medium pores; few fine (tertiary and secondary) oil palm roots, diffuse boundary to
C1	120 – 140	Light olive brown (2.5Y 5/4) loamy sand; loose to very friable; structure less, fine single grain and crumb structure; non-sticky, non-plastic; very rapid porosity; many fine pores; few fine (tertiary and secondary) oil palm roots, diffuse boundary to
C2	140 - 200	Light yellowish brown (2.5Y 6/2) sand; loose; structure less, fine single grain; non-sticky, non-plastic; extremely rapid porosity; many fine pores; few fine (tertiary and secondary) oil palm roots.

A1.3 Monthly rainfall (mm) data for various oil palm plantations in PNG

a) Recording sites in NBPOL Plantations (WNB)

Site	Year:	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Dami	1980	532	900	681	319	167	200	253	209	93	58	308	298
	1981	501	808	372	379	138	318	298	97	152	241	259	414
	1982	758	665	378	356	139	57	51	60	64	31	30	364
	1983	751	797	808	388	285	287	248	226	164	111	400	304
	1984	197	241	565	373	126	219	185	104	180	197	233	572
	1985	530	409	889	139	267	246	205	126	247	181	454	386
	1986	596	566	229	629	285	140	43	25	175	176	155	197
	1987	430	725	537	159	92	8	157	53	181	96	122	803
	1988	855	1006	255	414	314	134	354	421	182	443	274	833
	1989	85	131	219	384	167	277	163	111	199	224	152	506
	1990	696	524	835	268	186	224	181	190	91	334	287	928
	1991	515	677	910	249	108	94	244	214	3	100	144	248
	1992	401	558	684	433	179	43	84	229	95	71	106	317
	1993	501	775	324	163	82	389	217	157	69	109	259	307
	1994	737	611	187	220	217	73	428	390	134	53	46	343
	1995	426	469	563	529	205	133	147	219	68	425	130	309
	1996	302	437	520	165	244	170	82	83	292	118	123	222
	1997	406	600	439	86	152	113	214	0	152	0	169	256
	1998	638	850	569	468	345	352	175	145	95	288	288	245
	1999	380	1088	234	477	78	122	209	244	101	326	147	197
	2000	529	157	442	293	565	138	156	249	217	207	179	270
	2001	234	701	347	254	305	390	236	111	200	86	182	575
	2002	672	845	617	304	81	292	181	4	64	215	161	149
	2003	756	649	505	391	162	109	203	151	130	186	277	421
	2004	408	579	707	168	319	276	150	36	195	206	120	297
	2005	613	692	379	881	144	181	131	95	204	213	292	309
Kumbango	1997	417	431	594	102	173	88	151	0	118	0	10	402
	1998	479	422	595	367	230	155	188	112	164	311	261	408
	1999	175	806	343	272	172	170	220	220	220	467	467	282
	2000	338	141	323	190	276	91	115	264	134	165	170	434
	2001	269	683	348	265	176	324	150	130	159	124	229	376
	2002	556	799	627	236	147	141	148	4	53	168	225	225
	2003	643	390	728	308	291	46	231	135	112	189	348	438
	2004	473	285	636	208	244	213	160	63	155	195	160	137
	2005	777	558	432	877	180	58	98	110	109	141	264	355
Kapiura	1997	533	569	657	154	258	50	261	0	73	5	144	403
	1998	462	478	611	409	522	223	213	212	240	346	355	463
	1999	418	911	338	356	158	249	266	194	149	312	190	323
	2000	514	343	460	260	417	500	129	346	57	212	304	297
	2001	192	668	342	375	222	380	327	251	209	66	228	396
	2002	605	576	467	295	137	248	262	7	82	212	321	278
	2003	422	314	686	334	334	72	286	293	180	162	141	255

Site	Year:	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Garu	1997	488	950	432	158	196	62	132	0	53	45	104	132
	1998	748	418	939	335	412	229	216	174	269	401	286	663
	1999	457	990	411	398	199	219	189	323	139	254	260	384
	2000	834	229	446	280	481	121	157	318	102	247	290	444
	2001	213	901	362	384	337	328	118	182	257	54	276	774
	2002	537	1272	744	360	95	137	221	0	37	121	262	225
	2003	826	873	588	432	259	127	244	219	178	153	213	675
	2004	730	523	618	184	419	164	28	14	139	103	313	165
	2005	1225	875	843	862	131	85	128	201	138	235	247	302
Numundo	1979	874	468	429	338	336	119	187	135	635	479	542	263
	1980	1289	346	310	208	156	65	26	197	100	2	242	270
	1981	316	790	443	211	0	106	85	106	162	206	625	870
	1982	1305	1471	1013	375	113	45	29	115	72	0	16	71
	1983	599	543	559	411	852	797	104	69	215	306	316	313
	1984	417	266	582	387	194	92	154	73	136	170	132	725
	1985	583	558	865	247	125	210	83	107	89	166	427	443
	1986	1101	437	205	769	202	99	117	66	149	81	166	121
	1987	126	539	738	530	73	3	132	20	92	175	84	827
	1988	779	643	319	427	214	199	219	197	82	295	419	740
	1989	345	507	229	471	161	126	120	123	238	334	280	520
	1990	711	702	484	315	218	334	117	47	152	165	125	1113
	1991	719	776	577	172	188	61	101	222	120	96	141	543
	1992	1052	594	779	352	152	38	97	134	25	138	90	236
	1993	301	807	724	14	104	313	230	102	119	83	307	456
	1994	853	640	392	151	336	52	332	182	67	5	0	363
	1995	711	533	620	418	222	180	172	139	74	336	189	223
	1996	345	382	701	109	202	0	173	62	212	273	170	221
	1997	386	794	533	186	191	62	43	0	63	9	63	163
	1998	658	579	793	351	415	171	172	218	167	162	253	378
	1999	332	920	762	332	261	426	297	219	285	175	836	655
	2000	764	213	380	91	420	149	70	225	36	120	193	408
	2001	210	774	380	212	281	149	95	80	112	57	250	624
	2002	585	1207	609	200	80	103	163	8	29	174	281	197
	2003	789	487	601	565	256	57	153	118	103	133	229	617
	2004	745	818	619	168	162	253	99	28	144	141	94	72
	2005	853	622	624	775	201	31	91	117	126	173	149	292
Navarai	1996	296	419	714	245	316	59	100	72	151	139	230	322
	1997	444	675	524	178	155	13	42	0	37	19	116	301
	1998	900	659	839	315	298	232	181	265	208	373	346	520
	1999	367	1060	365	238	107	235	148	89	32	82	180	79
	2000	777	200	318	151	415	120	144	136	61	202	211	508
	2001	99	580	373	475	203	146	83	82	138	31	167	533
	2002	617	964	655	248	76	93	96	27	21	103	286	423
	2003	715	920	886	332	238	45	59	67	48	147	206	489
	2004	618	454	589	153	169	126	9	17	48	127	74	257
	2005	1079	1036	594	735	307	9	62	128	47	46	230	452

Site	Year:	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Healla	1990	711	702	484	315	218	334	117	47	152	165	125	1113
	1991	719	776	577	172	188	61	101	222	120	96	141	543
	1992	1052	594	779	352	152	38	97	134	25	138	90	236
	1993	301	807	724	14	104	313	230	102	119	83	307	456
	1994	853	640	392	151	336	52	332	182	67	5	0	363
	1995	711	533	620	418	222	180	172	139	74	336	189	223
	1996	345	382	701	109	202	0	173	62	212	273	170	221
	1997	386	794	533	186	191	62	43	0	63	9	63	163
	1998	658	579	793	351	415	171	172	218	167	162	253	378
	1999	332	809	318	372	172	313	265	203	101	190	361	357
	2000	486	199	452	185	357	82	150	309	72	171	308	333
	2001	286	1029	346	216	256	172	102	124	183	70	272	687
	2002	648	1208	735	249	164	143	146	9	40	159	262	162
	2003	864	538	618	473	316	68	178	118	162	147	271	642
	2004	816	1183	1497	354	693	489	328	73	501	205	102	201
	2005	773	834	508	617	171	40	101	224	125	134	143	294
Daliavu													
	2001	248	925	308	279	286	325	160	161	334	92	215	616
	2002	649	1332	686	216	109	250	146	7	34	123	239	191
	2003	1048	494	800	560	336	50	244	218	156	144	282	797
	2004	548	502	596	251	358	229	158	38	225	230	187	131
	2005	832	670	606	783	174	133	62	135	165	257	296	409
Sapuri	2001	248	925	308	279	286	325	160	161	334	92	215	616
	2002	649	1332	686	216	109	250	146	7	34	123	239	191
	2003	1048	494	800	560	336	50	244	218	156	144	282	797
	2004	544	440	573	233	337	191	177	68	167	271	263	65
	2005	807	738	669	837	135	142	87	193	284	228	290	364

b) Monthly rainfall (mm) recording sites in Oro Province

Site	Year:	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Sangara	1976	174	123	250	218	185	97	28	66		112	106	
(OPRA)	1977	236	163	303	123	246	46	47	40	77	282	411	252
	1978	290	232	294	177	149	56	131	85	134	90	188	244
	1979	135	175	207	292	151	71	35	28	83	214	234	278
	1980	288	277	398	307	186	29	77	27	104	165	290	392
	1981	203	88	246	321	220	163	159	97	229	244	321	322
	1982	222	357	503	169	178	133	22	116	32	64	87	349
	1983	457	526	504	178	193	211	27	90	106	262	253	358
	1984	55	176	289	204	229	180	88	164	144	362	239	291
	1985	196	223	272	178	232	192	65	141	203	365	366	371
	1986	203	315	148	435	134	225	64	180	44	123	306	184
	1987	327	157	586	307	114	61	34	23	276	96	103	277
	1988	387	183	232	249	140	138	306	113	232	311	217	192
	1989	438	250	268	361	111	38	53	106	165	307	292	426
	1990	461	280	170	358	255	135	228	32	315	381	202	254
	1991	365	252	167	289	68	157	102	110	74	350	290	355
	1992	355	325	346	305	137	84	59	59	56	139	111	170
	1993	438	118	337	360	189	39	82	50	78	81	243	426
	1994	208	195	146	239	190	50	123	255	30	156	121	373
	1995	289	301	191	174	201	54	62	100	101	246	160	353
	1996	167	261	377	144	282	129	64	82	93	257	181	256
	1997	236	279	57	82	131	1	87	24	33	67	83	315
	1998	226	369	461	115	165	72	176	53	139	178	263	415
	1999	153	180	132	238	72	233	117	114	142	213	193	393
	2000	242	108	317	174	215	236	188	115	171	214	181	241
	2001	300	261	308	201	108	137	87	62	157	275	155	461
	2002	194	157	406	230	150	105	55	73	38	286	393	239
	2003	443	298	305	281	236	20	101	44	229	192	451	216
	2004	116	256	215	169	289	192	10	90	54	85	141	132
	2005	493	132	327	251	221	158	58	79	29	125	431	178
Ambogo	1986	184	227	200	273	119	190	37	165	30	141	312	162
	1987	323	162	503	258	91	62	16	11	200	109	170	242
	1988	313	186	243	214	209	97	231	147	164	317	259	217
	1989	392	153	263	407	229	53	65	159	132	221	186	307
	1990	259	283	237	300	236	115	202	58	287	287	189	405
	1991	291	286	182	224	47	70	55	244	106	253	135	283
	1992	432	246	310	250	139	34	42	65	12	63	109	200
	1993	275	69	266	198	357	62	69	20	88	61	112	360
	1994	765	598	208	226	155	18	120	144	0	132	71	417
	1995	287	258	230	156	181	73	52	56	101	304	275	374
	1996	82	167	350	129	93	129	86	77	59	211	200	433
	1997	195	198	75	0	105	0	106	0	13	0	125	321
	1998	185	448	581	97	266	35	215	43	246	183	253	434
	1999	118	93	135	183	122	253	116	131	95	219	140	NR
	2000	180	114	383	277	220	125	241	104	84	113	250	229
	2001	374	346	177	95	104	124	113	104	48	63	137	224

Site	Year:	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
(continue)	2002	180	180	162	221	155	59	18	108	71	236	23	262
	2003	390	365	370	214	172	20	110	22	243	179	126	198
	2004	188	107	170	160	345	145	8	63	4	138	112	
	2005	368	188	136	158	169	129			28	146		155
Embi	1989										92	264	406
	1990	206	222	150	307	226	155	173	51	218	149	89	347
	1991	432	257	74	257	74	100	181	59	50	443	207	330
	1992	301	445	416	249	85	68	77	57	41	146	200	395
	1993	625	37	257	491	111	45	25	27	78	149	175	29
	1994	187	116	112	235	149	33	124	137	0	0	0	407
	1995	0	357	301	357	0	0	0	80	84	276	193	528
	1996	84	94	399	131	234	202	88	45	160	378	255	243
	1997	257	351	123	0	231	0	72	19	20	293	255	234
	1998	410	0	463	107	266	79	243	122	281	331	373	495
	1999	261	170	84	223	224	280	271	207	104	487	177	265
	2000	406	88	471	190	357	123	135		182	195		384
	2001	555	483	456	386	145	121	46	49	131	107	206	211
	2002	196	142	203	162	41	83	3	14	130	215	578	225
	2003	973	236	225	180	141	19	45	48	90	307	679	286
	2004	193	299	351	158	324	127	40					
	2005	241	186	271	164	145	121	107	28	38	89	89	463
Sumbiripa	2000										143		382
	2001	168	209		462	46	111	173	187	195		174	113
	2002	43	243	181	335	136	52	53	51	106	72	366	364
	2003	380	321	239	221	240	21	135	19	219	283	225	375
	2004	66	224	258	197	318	219	6	140	74	155		
	2005	477	187	305	151	241	208	78	95	48	155	472	96
Mamba	1990	248	207	176	452	331	297	326	286	750	561	342	333
	1991	388	256	116	374	116	188	747	446	90	585	409	658
	1992	455		260	224	536	324	182	85	126	192	361	530
	1993	530	446	172	276	252	112	184	42	135	119	342	529
	1994	336	299	307	313	317	124	232	356	209	146	142	194
	1995	381	347	352	243	280	159	160	153	197	305	159	391
	1996	224	294	165	293	173	232	263	211	327	267	405	
	1997	589	756	25	123	97	4	205	30	62	22	204	694
	1998	329	603	493	556	247	235	272	357		322	494	588
	1999	366	241	384	319	251	414	230	503	525	363	403	542
	2000	372	474	699	326	490	236	335	246	440	478	719	854
	2001	344	325	508	441	474	353	288	100	262	183	302	219
	2002	333	225	588	298	276	238	164	127	277	265	470	854
	2003	604	608	454	215	351	13	194	134	393	356	683	442
	2004	362	482	272	302	267	267	136	195	323	444	360	260
	2005	822	278	581	189	386	109	148	375	325	239	551	555

c) Monthly rainfall (mm) recording sites at Ramu Sugar (Morobe Province)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1979					135	16	27	23	1	145	331	149
1980	242	128	98	118	37	17	22	42	85	100	178	483
1981	213	244	91	237	182	220	11	81	160	199	266	182
1982	298	263	493	249	237	169	5	49	44	145	111	215
1983	248	527	297	202	304	141	18	23	12	232	191	285
1984	116	141	189	106	233	79	12	27	109	146	205	261
1985	257	302	246	180	46	118	54	26	134	162	330	169
1986	301	138	105	403	125	202	202	146	161	89	140	140
1987	247	212	501	191	90	0	8	0	65	58	121	243
1988	147	239	401	97	105	130	79	20	45	288	95	165
1989	102	255	260	152	348	30	47	172	71	240	181	260
1990	339	96	158	308	112	76	35	74	187	183	91	270
1991	109	264	300	323	89	0	64	13	17	189	218	318
1992	156	234	402	366	113	87	13	14	58	237	55	285
1993	342	134	310	247	41	29	20	29	0	98	252	477
1994	318	99	283	255	158	77	163	18	83	18	131	115
1995	437	382	352	341	63	26	45	20	120	231	155	351
1996	212	375	175	177	170	74	88	28	83	200	234	120
1997	172	320	126	174	64	9	15	12	4	46	93	424
1998	218	150	297	135	230	59	12	13	67	203	269	241
1999	95	196	392	193	143	157	39	221	60	197	217	165
2000	208	133	164	92	208	53	96	92	184	157	158	167
2001	132	142	205	169	128	82	139	1	34	151	164	140
2002	244	160	466	279	396	74	21	11	21	169	156	159
2003	276	279	292	118	73	88	30	66	189	264	206	310
2004	195	205	427	94	204	14	20	37	52	179	384	125
2005	188	151	199	261	177	54	53	81	189	141	340	255

d) Monthly rainfall (mm) recording sites at Bialla in WNB Province

Site	Year:	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Navo	1989	260	276	370	307	208	144	112	188	202	270	449	402
	1990	1431	367	1980	479	237	194	194	180	245	151	167	809
	1991	379	1060	1163	204	159	336	260	295	36	337	135	281
	1992	1044	753	1045	455	257	202	478	245	117	179	152	562
	1993	694	654	839	348	118	417	248	237	144	66	126	658
	1994	872	739	440	330	442	283	420	448	192	128	60	205
	1995	728	186	578	302	176	98	180	226	137	202	347	244
	1996	34	469	428	179	106	212	238	98	352	186	210	377
	1997	412	697	931	244	334	36	142	25	100	18	138	329
	1998	469	481	829	474	312	223	150	118	223	381	183	490
	1999	137	1068	227	378	167	319	361	247	170	211	287	171
	2000	456	103	253	292	448	237	169	278	264	233	237	339
	2001	240	1143	457	273	291	232	246	265	98	131	228	768
	2002	650	1325	467	386	391	155	189	35	84	300	202	147
	2003	588	510	892	418	236	31	160	451	275	107	219	666
	2004	693	589	708	277	371	369	180	287	415	423	74	103
	2005	725	488	656	983	203	126	334	290	366	384	317	360
Hargy	1989	329	276	331	509	47	41	28	157	83	216	347	589
	1990	1077	595	2429	539	159	74	299	285	92	270	226	1150
	1991	556	1158	1439	378	238	207	294	333	9	268	260	358
	1992	1287	878	1071	538	319	206	468	231	76	196	195	665
	1993	937	768	715	192	271	502	437	288	203	135	76	660
	1994	1490	993	386	420	430	280	517	715	158	93	33	358
	1995	914	576	547	672	294	216	168	264	168	164	207	146
	1996	172	276	597	140	348	123	251	147	194	100	228	368
	1997	442	448	976	162	203	35	121	13	48	7	325	366
	1998	594	555	614	194	114	348	246	110	132	322	157	940
	1999	208	946	285	265	107	209	185	197	119	170	247	314
	2000	414	951	270	164	482	225	126	239	119	236	193	642
	2001	98	860	277	211	226	180	291	304	107	82	219	612
	2002	480	964	712	212	216	194	63	46	51	174	184	143
	2003	762	579	1015	256	177	58	252	753	156	126	85	642
	2004	604	505	400	256	232	185	332	246	401	464	224	199
	2005	725	449	743	1332	153	61	272	233	308	173	268	224

e) Monthly rainfall (mm) recording sites in Milne Bay Province

Sites	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Giligili	1987							139	26	119	21	157	384
	1988	238	131	333	63	206	152	457	534	567	121	61	144
	1989	103	233	168	393	118	341	526	429	271	237	298	71
	1990	344	19	239	217	337	410	485	39	279	240	163	232
	1991	167	193	66	345	437	160	105	455	3	160	79	49
	1992	141	255	164	161	360	124	187	58	10	43	66	294
	1993	151	219	214	344	490	120	118	29	54	100	84	261
	1994	234	106	131	122	647	99	100	295	60	397	56	0
	1995	157	126	344	257	264	253	102	535	186	223	417	158
	1996	186	119	213	110	150	95	328	261	312	707	66	76
	1997	159	171	150	150	68	74	184	49	52	27	86	19
	1998	111	78	344	65	223	130	193	393	494	208	274	283
	1999	71	107	130	23	167	388	435	154	109	102	211	219
	2000	204	112	223	236	219	364	90	184	202	240	183	36
	2001	72	206	204	280	125	400	98	118	419	287		97
	2002	118	217	230	204	237	337	139	32	91	93	301	110
	2003	123	62	218	368	212	215	213	103	133	143	273	172
	2004	67	148	262	104	244	233	35	15	123	150	185	115
	2005	159	114	375	132	255	26		113			171	119
Padipadi	2000							66	260	232	176	131	96
	2001	30	137	361	329	145	233	55	141	266	108		208
	2002	327	201		132	290	124	144	58	29	202	185	47
	2003	207	152	197	336	214	190	175	23	194	88	514	427
	2004	300	237	410	363	95	475	55	75	35	136	159	52
	2005	380	220	161	284	160	131		96			102	102
Bomata	1986	330	295	173	238	131	290	246	78	68	83	109	270
	1987	158	456	160	301	148	35	187	46	139	51	70	330
	1988	497	308	239	135	159	190	310	491	430	188	87	169
	1989	141	247	328	217	75	383	217	286	262	162	121	111
	1990	348	46	256	179	297	293	468	87	289	273	102	226
	1991	180	244	59	255	650	140	132	283	9	298	177	127
	1992	102	361	226	212	255	142	227	88	57	64	23	208
	1993	233	224	319	455	395	122	65	60	42	63	65	162
	1994	374	18	367	182	351	72	123	473	38	185	20	18
	1995	149	139	359	231	354	121	83	331	88	170	75	245
	1996	279	295	243	68	209	94	159	296	333	493	204	133
	1997	330	304	414	165	90	167	116	34	38	30	24	64
	1998	196	102	377	8	165	36	155	183	126	108	158	278
	1999	211	253	43	168	175	321	242	150	106	61	200	184
	2000	312	223	251	123	161	348	57	229	351	180	67	235
	2001	119	133	231	220	174	357	73	98	202	84		135
	2002	39	294	212	409	520	142	294	56	48	186	164	0
	2003	151	177	284	208	231	236	202	45	50	74	555	185
	2004	173	221	247	333	244	399	294	27	11	173	207	34
	2005	268	141	132	294	207	117		136			206	103

Sites	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Waigani	1987	167	244	163	303	160	18	165	35	101	32	90	353
	1988	229	203	242	189	200	143	407	467	504	241	46	142
	1989	148	283	328	328	152	283	359	284	303	154	114	72
	1990	337	24	227	164	274	359	500	65	315	232	117	275
	1991	181	221	39	314	432	178	164	316	4	205	154	123
	1992	104	259	256	220	328	124	197	64	2	68	24	291
	1993	148	287	145	362	597	153	82	40	44	123	51	183
	1994	358	127	160	113	488	105	87	321	43	412	36	31
	1995	208	87	502	283	313	200	88	570	147	150	180	353
	1996	187	166	237	77	140	182	293	253	340	583	156	109
	1997	210	154	209	162	89	92	232	72	76	31	30	33
	1998	159	116	291	80	245	110	259	302	238	202	292	204
	1999	93	156	92	55	111	257	195	182	211	115	211	309
	2000	212	106	604	206	520	676	25	70	628	140	139	114
	2001	97	182	214	229	92	221	99	97	186	110	161	93
	2002	208	128	194	152	172	212	164	58	58	144	201	84
	2003	99	110	144	249	121	184	217	93	38	79	47	157
	2004		117	215	216	188	241	88	55	66	146	157	128
	2005	230	152	245	210	176	105		110			134	242
Hagita	1986	223	202	314	268	103	180	107	89	56	87	87	184
	1987	126	237	174	222	165	28	168	45	115	25	97	335
	1988	247	211	222	171	207	145	413	397	544	168	44	178
	1989	128	252	209	401	157	290	431	317	281	225	128	83
	1990	391	11	253	204	329	367	526	91	267	210	140	260
	1991	134	182	23	292	349	165	141	316	6	174	117	81
	1992	59	269	160	143	340	91	196	63	0	47	17	227
	1993	160	317	339	326	414	129	78	31	39	89	80	207
	1994	319	117	143	122	443	105	92	279	39	374	52	5
	1995	240	60	379	531	242	273	103	435	124	149	280	217
	1996	156	100	256	73	117	167	272	202	311	615	122	54
	1997	150	127	186	173	67	104	184	45	96	29	40	41
	1998	211	128	426	50	235	116	357	337	382	181	287	174
	1999	81	134	140	59	114	249	346	178	62	118	289	202
	2000	263	141	314	224	271	526	118	188	282	234	13	157
	2001	70	164	264	290	92	330	82	84	323	149		115
	2002	158	175	248	256	200	271	122	53	38	155	240	96
	2003	84	109	136	249	164	175	182	90	107	109	340	139
	2004	109	60	283	327	209	716	1042	38	58	87	233	61
	2005		408	241	196	222	73		160			174	146
Bomata	1988		132	213	225	188	134	96		154	214	243	463
	1989	273	286	121		175	182		112	151	215		247
	1990	206	280	172		181	160	107	155	47	165	228	
	1991	206	168	197	190	104	128						239
	1992			125		142						248	157
	1993	140	179	212	122	105	87	116	164	148	199		152
	1994		142	155	113	52	83				114	232	148
	1995	157	146	84	97	99	77	64	55	89	191	206	191
	1996	169	128	144	192	84	137	83	141	110	94	183	214
	1997	243	265	273	286			145	202	187	256	232	229
	1998	180	194	148	245	116	163	166	138	192	258	193	141
	1999	204	147	234	197	184	69	88	73	153	237	163	115
	2000	181	176	119	177	134	24	69	195			163	115

Sites	Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
	2001	140	99	163	94	113	12	69	114	100	168		100
	2002	149	69	120									
	2003										228	127	181
	2004	212	212		85	115		124	179	89		80	188
	2005		80			66	110					95	0
Nawae	2000	209	230	0	0	0	0	91	204	197	219	19	166
Nursery	2001	44	168	288	272	102	293	94	69	368	117		87
	2002	92	177	211	233	168	305	163	47	115	91	185	139
	2003	94	91	175	345	212	215	176	93	0	180		121
	2004	72		249		96	343	116	15	51	136	237	
	2005	141	114	11	169	86	79		100			128	143

f) Monthly rainfall (mm) recording sites in New Ireland Bay Province

Sites	Year:	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Lakurumau	1990	217	335	309	451	182	205	361	286	177	144	263	483
	1991	325	604	295	82	281	118	305	208	173	196	197	262
	1992	344	317	354	151	215	150	107	201	126	338	178	391
	1993	312	272	230	309	253	609	200		100	111	50	294
	1994	268	400	297	380	259	118	250	151	105	144	104	467
	1995	410	279	392	661	321	102	119	131	125	225	276	380
	1996	113	240	434	161	304	38	108	108	251	265	152	167
	1997	193	370	42	242	379	2	44	1	52	22	50	368
	1998	255	525	243	344	295	227	166	204	216	185	274	192
	1999	146	243	236	49	12	155	210	164	50	98	274	218
	2000	252	26	177	156	386	150	134	312	78	318	134	214
	2001	127	499	247	444	472	264	314	209	95	247	231	679
	2002	377	474	447	198	275	403	62	11	9	102	368	124
	2003	860	539	449	345	368	399	220	384	251	233	278	467
	2004	334	455	406	434	326	256	146	83	162	239	187	120
	2005	572	416	285.6	532.3	266.8	65.0	357	171.1	499.9	375.9	298.9	
Maramakas	2002								16	27	113	293	106
	2003	793	475	280	380	227	257	181	257	255	195	260	388
	2004	0	245	331	253	265	269	174	95	88	235	255	139
	2005	520	430	293	397	328	50		170	309	285	239	

Appendix 2

A2.1 Soil bulk density (g cm^{-3}) and gravimetric water content at various pressure potential measurements at Dami and Sangara

(a) Soil bulk densities (g cm^{-3})

Dami					Sangara										
								12/2004	04/2005	07/2005		12/2005		
Depth	Reps		BD		Depth (cm)	Reps		Pit 1	Pit 2	Pit 2	Pit 3	Pit 1	Pit 2	Pit 3
0-25	1		0.61		0-30	1		1.35	1.16	1.22	1.29	1.12	1.28	1.22
0-25	2		0.73		0-30	2		1.40	1.43	1.15	1.25	1.28	1.27	1.04
0-25	3		0.80		0-30	3		1.32	1.29	1.51	1.33	1.34	1.21	1.18
25-35	1		0.88		0-30	4			1.33			1.20	1.16	1.19
25-35	2		0.82		0-30	5			1.25			1.20	1.33	1.31
25-35	3		0.82		30-60	1		1.33	1.28	1.19	1.02	1.59	1.54	1.35
35-53	1		1.01		30-60	2		1.31	1.45	1.25	0.94	1.39	1.51	1.40
35-53	2		1.04		30-60	3		1.58	1.50	1.22	1.25	1.44	1.53	1.35
35-53	3		0.94		30-60	4			1.38			1.46	1.44	1.22
60-77	1		0.72		30-60	5			1.46			1.44	1.43	1.43
60-77	2		0.82		60-110	1		1.21	1.13	0.97	1.31	1.10	1.36	1.11
60-77	3		0.76		60-110	2		1.12	1.05	0.98	1.11	1.13	1.16	1.13
77-90	1		1.13		60-110	3		1.10	1.15	0.95	1.20	1.15	1.09	1.05
77-90	2		1.02		60-110	4			1.08			1.17	1.30	1.03
77-90	3		1.03		60-110	5			1.16			1.00	1.27	1.09
90-133	1		0.78		110-155	1		1.36	1.39	1.18	1.13	1.22	0.96	1.13
90-133	2		0.60		110-155	2		1.15	1.36	1.33	0.99	1.13	1.11	1.05
90-133	3		0.71		110-155	3		1.26	1.33	1.24	1.00	1.12	1.17	1.07
133-144	1		0.78		110-155	4			1.33			1.36	1.58	1.28
133-144	2		0.84		110-155	5			1.27			1.14	1.22	0.68
133-144	3		0.86		155-200	1		1.53	1.50	1.32	1.53	1.52	1.40	1.69
144-150	1		0.88		155-200	2		1.45	1.48	1.27	1.06	1.44	1.39	1.69
144-150	2		0.86		155-200	3		1.43	1.47	1.33	1.36	1.46	1.52	1.40
144-150	3		0.79		155-200	4			1.40			1.39	1.38	1.36
					155-200	5			1.49			1.60	1.40	0.75
Mean			0.84											1.27
SD			0.134											0.18
CV %			16											14

(b) Gravimetric water content at various pressure potentials

(i) Dami

Depth (cm)	Pressure potential (-kPa)		
	-10	**-100**	**-1500**
0-25	0.55	0.38	0.24
25-35	0.35	0.25	0.15
35-43	0.35	0.25	0.15
43-53	0.37	0.18	0.06
53-60	0.37	0.18	0.06
60-77	0.60	0.22	0.07
77-90	0.38	0.19	0.07
90-133	0.52	0.34	0.13
133-144	0.59	0.42	0.20
144-150	0.63	0.27	0.15

(ii) Sangara

Depth (cm)	Pressure potential (-kPa)				
	1st	**2nd**	**1st**	**2nd**	
	-10	**-10**	**-100**	**-100**	**-1500**
0-30	0.32	0.32	0.28	0.31	0.19
0-30	0.25	0.29	0.25	0.20	0.16
30-60	0.41	0.37	0.39	0.34	0.35
30-60	0.35	0.34	0.36	0.34	0.29
60-110	0.56	0.56	0.55	0.50	0.45
60-110	0.56	0.56	0.56	0.50	0.45
110-155	0.29	0.30	0.26	0.23	0.17
110-155	0.29	0.30	0.29	0.24	0.19
155-200	0.26	0.24	0.22	0.17	0.11
155-200	0.26	0.25	0.23	0.18	0.13

A2.2 Appended paper

Using soil water depletion to measure spatial distribution of root activity in oil palm (Elaeis guineensis Jacq.) plantations

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ORIGINAL PAPER

Using soil water depletion to measure spatial distribution of root activity in oil palm (*Elaeis guineensis* Jacq.) plantations

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Abstract Knowledge of where roots are active is crucial for efficient management of nutrients in tree crops but measurement of root activity is problematic. Measurement using soil water depletion is an approach that has not been tested in a humid climate. We hypothesised that the three dimensional distribution of root activity of a tree crop in the humid tropics (a) can be determined by measuring soil water depletion during rain-free periods, and (b) is influenced by environment (soil type and climate) and surface management. A field study was carried out in which soil water content was measured and water uptake calculated (by difference between soil water content at beginning and end of rain-free periods) for different surface management zones and depth (0.1 m intervals to 1.6 m depth) under oil palm (*Elaeis guineensis* Jacq.) at a loam–clay site and a sandy site. Significant differences were measured between sites and between surface management zones at each site. At both sites water uptake was highest under the weeded zone close to the palm stem, slightly lower under the zone where pruned fronds are placed, and lowest under the path used for removing harvested fruit. Vertical distribution of root activity differed between the sites, with higher activity near the surface at the finer textured site. Total water uptake values were lower than estimates of evapotranspiration made using climate data. The difference was probably largely due to water uptake from deeper than 1.6 m. This study showed that the spatial distribution of tree root activity in a humid climate could be quantified using a relatively simple method.

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Keywords Evapotranspiration · Humid tropics · Root biomass · Root distribution · Tree crops · Water uptake

Introduction

In order to understand, manage and model uptake of water and nutrients by plants we need to know where roots are active. There have been few studies of root systems of perennial crops in the humid tropics, where the potential loss of nutrients by leaching is high. Root activity is often inferred from root density parameters such as mass, length or surface area, determined by excavation and sampling. However, excavation methods are laborious and destructive and it is difficult to quantitatively measure fine roots due to their fragility. In addition, there are differences between root density and activity, because root density measurements cannot distinguish effective roots from ineffective ones (Radersma and Ong 2004; Zuo et al. 2004). In tree crops and forests, the disparity between root abundance and activity can be larger than in field crops (Lehman 2003; Radersma and Ong 2004). Where we are interested in uptake of water and nutrients, it is therefore preferable to measure activity directly.

The spatial distribution of tree root activity has been estimated using uptake of labelled solutes applied at different points in the soil (e.g. IAEA, 1975). Studies with labelled solutes can provide accurate spatial distribution of uptake of the solute used. However, a new plot is required for each depth, and sufficient distance must be maintained between them to prevent cross-contamination as lateral root activity can be considerable. According to the data of Zaharah et al. (1989), plots would have to be spaced at more than 72 m apart for oil palm. Also, as plants have a variety of mechanisms for active uptake of particular solutes, which they activate depending on supply and demand (Tinker and Nye 2000), the patterns of root activity derived from one solute may not apply to water or to other solutes. In some situations the vertical distribution of water uptake can be determined from the natural isotopic composition of water taken up (e.g. Bonal et al. 2000), but the technique does not allow lateral distribution to be determined. Measuring the spatial distribution of water uptake by measuring changes in soil water content has become feasible due to developments in devices such as neutron moisture meters, time domain reflectometry and capacitance probes, which allow measurements of soil water content to be made quickly and non-destructively at many points. The approach provides a means of estimating the root system's ability to take up solutes by convection, as well as providing direct measurements of water uptake for hydrological modelling.

Estimation of tree root activity using water uptake has generally been carried out in irrigated crops, where the whole profile can be wetted up in a controlled manner, and soil drying can therefore be attributed to uptake (e.g. Green et al. 2003; Koumanov et al. 2004; Vrugt et al. 2001). In rain-fed plantations, orchards and forests the approach is not as straight-forward, due to variable inputs of water. However, it is possible to use the same approach, following wetting of the soil by rainfall, if the rainfall is followed by a sufficiently long dry period, which is what was done in the work described here. The approach has been used successfully in rain-fed forests (Katul et al. 1997; Meinzer et al. 2004; Musters and Bouten 1999).

The objective of this work was to test the hypotheses (a) that the vertical and horizontal distribution of root activity of a tree crop in a humid climate (oil palm) can be determined by measuring water uptake, and (b) that the spatial distribution of root activity is influenced by environment (soil type and climate) and surface management. The approach is simpler and requires considerably less space than the isotopic tracer approach and is less laborious and easier to replicate than the excavation approach. This is the first time the approach has been tested in a rain-fed tree crop in a humid climate.

Materials and methods

Study site locations and characteristics

The study was carried out in Papua New Guinea at two sites with different soil properties and climate. The Dami site (150°5′ E, 5°6′ S, altitude 19 m) has an average annual rainfall (1980–2002) of 3614 mm, with a pronounced wet season. Oil palm (*Elaeis guineensis* Jacq.) was planted in 1989 in an equilateral triangular pattern, at a spacing of 9.81 m between palm centres (density of 120 palms ha^{-1}). The soil is a Typic Udivitrand (Soil Survey Staff 1999) consisting of distinct layers of recent volcanic ash falls with little pedological development except for the presence of an A horizon with high organic matter content. The horizons have loamy sand to sandy loam texture and dry bulk densities of 0.71–1.06 Mg m^{-3} down to the lowest observed depth of 1.5 m, except for a gravelly pumice horizon (0.70 Mg m^{-3}) at 0.90–1.33 m depth. The Sangara site (148°12′ E, 8°44′ S, altitude 130 m) has an average annual rainfall (1978–2002) of 2415 mm, with a less pronounced wet season than the Dami site. The palms were planted in 1996 in an equilateral triangular pattern, at a spacing of 9.25 m between palm centres (density of 135 palms ha^{-1}). The soil is a Typic Hapludand consisting of horizons with sandy clay loam to sandy clay texture (bulk density 1.14–1.43 Mg m^{-3}) from the surface to 1.10 m depth and sand to loamy sand texture from 1.10 to 2.00 m depth (bulk density 1.15–1.43 Mg m^{-3}). At both sites the watertable is >5 m deep and therefore unlikely to influence root distribution. Nitrogen fertiliser is applied at both sites at rates of approximately 100 kg N ha^{-1} year^{-1}. In the past, fertiliser was spread over the 'weeded circle', but for approximately the last 10 years it has been spread over the 'frond pile' and 'between other zones' areas (Fig. 1). Palms at both sites were considered mature, as net growth in canopy biomass and leaf area ceases by about 5 years of age and net growth in root biomass ceases by about 9 years of age (Ng et al. 1968).

Soil water content was measured and root activity estimated in different management zones, which are shown in Fig. 1. Pruned fronds are placed on the 'frond pile' (FP) and 'frond tip' (FT) zones. The 'weeded circle' (WC) is kept weed-free with herbicide to facilitate harvesting. The main difference in surface management between the two sites is the 'harvest path' (HP); at Dami it is wide because harvested fruit is removed by tractor and trailer whereas at Sangara it is narrow because fruit is removed using wheelbarrows. The 'between other zones' (BZ) area is vegetated with herbaceous legumes and other shrubs. Due to the oil palm foliage, rainfall reaches the ground in a non-uniform manner. Rainfall is generally funneled towards the centre and dispersed toward the outer edges of the canopy of each palm. Measurements not reported here found that 1 m from the trunk only 27% of the rainfall depth appeared as through-fall, while on average 15% of the rainfall volume appeared as stem flow down the trunks.

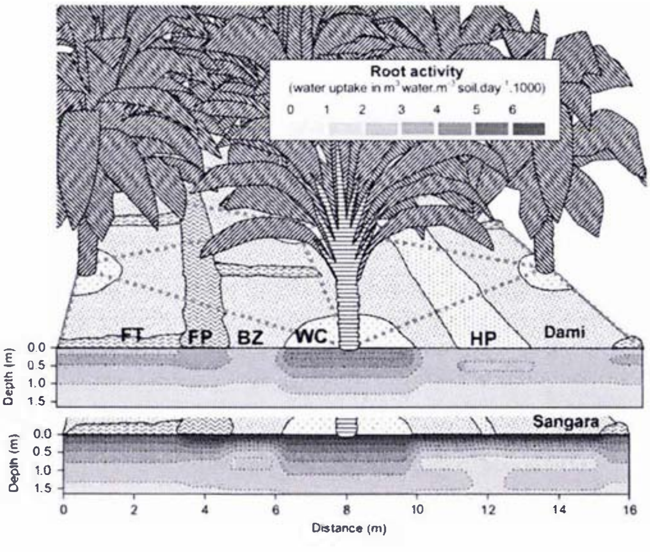

Fig. 1 Surface management zones in two inter-rows (pattern is repeated throughout plantation) and calculated root activity profile at the two sites. Surface management zones are 'frond tips' (FT), 'frond pile' (FP), 'weeded circle' (WC), 'harvest path' (HP) and 'between other zones' (BZ). The proportions of the plantations under each of the surface management zones are, for Dami and Sangara respectively: Trunk 0.3 and 0.4%, FT 4.2 and 4.7%, FP 7.1 and 7.5%, WC 13.3 and 14.9%, HP 13.5 and 5.6%, and BZ 61.6 and 66.9%. Dashed lines show equilateral triangular spacing of palms

Soil water content measurements

The overall period of study was 26/10/2003 to 25/10/2004 at Sangara (except for BZ, where measurements commenced on 12/01/2004), and 2/02/2004 to 29/11/2004 at Dami. Volumetric water content of soil was measured at 0.1 m depth increments to 1.6 m depth using a mobile capacitance probe (Sentek Diviner 2000®). These probes have been found effective for measuring water content in the field in several studies (e.g. Chanzy et al. 1998; Starr and Paltineau 1998). The factory calibration was used, as Groves and Rose (2004) showed that soil texture has little influence on readings, with actual water contents differing from the factory calibration value by < 0.05 m^3 m^{-3} over the 0–0.40 m^3 m^{-3} range for mineral soils with sand to clay texture. In particular, they found that the slopes of the calibration curves for the soils they tested were very similar over a wide range of water contents, making the instrument suitable for measuring changes in water content over time without in situ calibration. At each site, 3 access tubes were installed in each zone, plus 3 access tubes at the point equidistant between 3 palms (B3P). The mean distance from the access tubes to the nearest palm centre for each management zone was, for Dami and Sangara respectively: weeded circle 0.6 and 0.8 m, harvest path 3.7 and 3.6 m, frond pile 3.5 and 3.1 m, frond tip 4.2 and 4.5 m, between other zones 2.5 and 2.1 m and the point equidistant between 3 palms 4.9 and 4.7 m. Measurements were taken daily at approximately 10 am.

Root activity calculations

Root activity was defined as water uptake. This definition encompasses root density as well as activity per unit of root length, mass or surface area, and the study could not discriminate between these components. Water uptake was determined by measuring the decrease in soil water content during periods of 7 days or longer during which little or no rain fell. The first 3 days was taken as the 'drainage period' to allow water to be re-distributed following the cessation of rainfall, and the subsequent 4 or more days were used as the 'measurement period'. The 3 day 'drainage period' is consistent with the classical definition of 'field capacity' and a negligible drainage rate being reached after 2 or 3 days of redistribution following infiltration in free draining coarse-textured soils (Jury et al. 1991). There were very few periods with zero rain during 7 or more days so the criteria allowed up to 0.6 mm during the 'drainage period' and up to 1.8 mm in the 'measurement period'. These small amounts of rain could be ignored as they would have been largely intercepted by the foliage and evaporated directly from there. Measurements not reported here showed that on average 1 mm day^{-1} was intercepted by the oil palm foliage when it rained. At Sangara there were 8 periods that met the criteria, with the 'measurement periods' ranging from 4 to 17 days in length (Fig. 2), except for the BZ zone, for which there were 6 periods due to measurements starting later. At Dami there were 4 periods that met the criteria, with the 'measurement periods' ranging from 4 to 16 days in length (Fig. 2).

For each 0.1 m depth increment of the soil profile, the water content (m^3 m^{-3}) on the last day of the 'measurement period' was subtracted from the water content on the first day of the 'measurement period', and divided by the number of days to obtain a daily rate of water uptake (A, with units m^3 water · m^{-3} soil · day^{-1}) from that layer. Water uptake from each depth was multiplied by the 100 mm thickness it represented, and these 16 values were added to obtain the cumulative water uptake (mm day^{-1}) from the profile to 1.6 m depth. Total water uptake in the plantation (from the 0–1.6 m depth layer) was calculated by multiplying uptake in each zone by the fraction of area in that zone and adding the results.

It was assumed that during the 'measurement periods' water flux through the profile was negligible relative to the extraction rate. Evaporative demand from the soil surface would have been low due to the dense oil palm canopy shading it, and sheltering it from wind. A small component of water uptake would be due to the understory vegetation, although we expect transpiration from the understory to be insignificant compared to oil palm canopy transpiration for the same reasons.

The effect of surface management (zone) on water uptake at each depth and from the whole

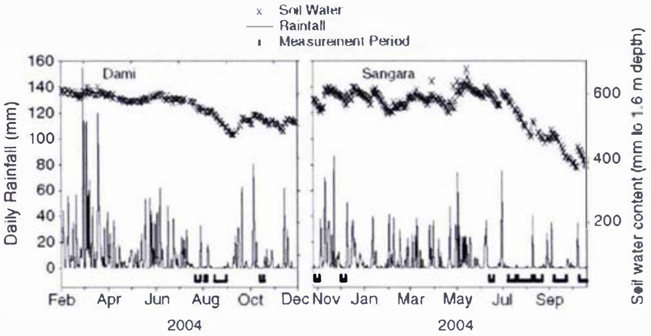

Fig. 2 Daily rainfall, soil water content (Frond pile, Profile 1) and time of water uptake calculation periods at the two sites during the whole study period

profile was examined using one-way analysis of variance. Tukeys Honestly Significant Difference ($\alpha = 0.05$) was used to group the zones into homogeneous subsets for each depth.

Evapotranspiration estimates

The accuracy of the water uptake estimates was assessed by comparing them with estimates of evapotranspiration during the measurement periods made using the FAO56 method, which has been found to be consistent with actual crop water use data world-wide (Allen et al. 1998). This involved the reference crop evaporation being estimated using the Penman–Monteith equation, assuming a surface resistance of 70 s m^{-1}, and then a crop coefficient being applied. The meteorological data needed for the Penman–Monteith equation were daily maximum and minimum temperature, dew point, solar radiation and wind run. Solar radiation was estimated from sunshine hour data. Wind run was measured at 4 m height, and then the average speed at 2 m height estimated assuming a logarithmic profile. A minimum value of 0.5 m s^{-1} was assumed, to take into account the effects of profile instability and buoyancy at low wind speeds. Reliable dew point data were not available for Sangara, so for that location the dew point was assumed equal to the minimum temperature. A crop coefficient of 1.0 was assumed for the mature palms, as recommended by Allen et al. (1998). For Sangara, four measurement periods were not included in the comparison, because two had no water uptake data for the BZ zone, and the other two had no sunshine data for the FAO56 calculations. The small amounts of rain that fell during the measurement periods were subtracted from the FAO56 estimates of evapotranspiration as they would have reduced transpiration.

Model of vertical distribution of root activity

In order to compare the vertical distribution of root activity with previous work, and in order to estimate uptake below the measured depth, we fitted our data to the power function relationship between the cumulative root activity (C) and depth (z) of Gale and Grigal (1987) as modified by Lehman (2003). That relationship is

$$C = C_{\max}(1 - k^{z}) \qquad (1)$$

where $C_{\max}$ is the maximum cumulative activity (i.e. total activity), and k is a fitted constant. As C is the integral of the root activity (A) with respect to z, we can find A from the above equation as

$$A = dC/dz = -C_{\max}\ln(k)k^{z}. \qquad (2)$$

The measured uptake (A) values were fitted to Eq. 2 by the least squares method using Solver in Excel. Solving Eq. 1 for z allows the depth above which a certain fraction of the total root activity ($C/C_{\max}$) occurs to be found as

$$z = \frac{\ln(1 - C/C_{\max})}{\ln(k)}. \qquad (3)\leftarrow$$

As the measure of root activity studied here is water uptake, C has dimensions [L T^{-1}], and A [T^{-1}]. From Eq. 3, ln(k) has dimensions [L^{-1}].

Root mass distribution

At Sangara the distribution of root mass was measured by drying and weighing roots separated by hand and a 2 mm sieve from auger samples. The auger samples were taken from three replicate locations. At each location three lines were drawn from a central palm to three of the six surrounding palms (lines 120° apart). The lines intersected all management zones. Samples were taken at 0.2 m intervals along each of the lines, at 0.2 m depth increments to 1.6 m.

Results

The outstanding feature of the results, shown in Table 1 and Fig. 1, is the contrasting uptake patterns at the two sites. At Dami uptake was relatively uniform in the top 0.3 m, and then decreased gradually with increasing depth. All values were less than 0.004 m^3 water · m^{-3} soil · day^{-1}. In contrast, at Sangara the uptake was greater than 0.005 m^3 water · m^{-3} soil · day^{-1} near the surface and decreased markedly with increasing depth down to about 1.0 m depth. Below that it was fairly constant to 1.6 m depth.

Root activity changed with time, but changes with time were not well correlated with changes in soil water content at either site. At Sangara the decrease in soil water content with time in the latter part of the study period was accompanied by an increase in uptake (Fig. 3), which may reflect varying meteorological conditions. At both sites the profile of soil water content and water uptake with depth was similar at all times, irrespective of how wet the soil was (Fig. 4).

At both sites total uptake from the profile was highest in the weeded circle (Table 1). The high water uptake from the weeded circle at both sites must be due to high root activity rather than extra water being available there, because at both sites the water content of the weeded circle was lower than all other zones during the calculation periods (Fig. 3). There was also a zone of high activity near the soil surface under the frond piles at both sites (Table 1). Uptake was lowest in the harvest path, particularly at Sangara, where it was significantly lower than in most other zones. Lower water contents were also observed in this zone (Fig. 3).

At Dami the biggest differences between zones occurred in the top 0.8 m, with uptake being highest in the weeded circle (and frond pile at 0.1 m), and lowest in the harvest path and BZ zones. At Sangara there were significant effects of zone throughout the profile, with uptake being highest in the weeded circle and frond pile in the top 0.8 m and highest in the weeded circle below that. Uptake was lowest in the BZ and B3P zones in the top 0.3 m and lowest in the harvest path below that. Of the total amount of water taken up from the 0–1.6 m depth (2.2 mm day^{-1} at Dami and 3.3 mm day^{-1} at Sangara), about 22% came from the weeded circle (21.8% at Dami and 22.6% at Sangara), despite that zone only covering about 14% of the area. The proportions coming from the other zones were, for Dami and Sangara respectively: frond pile 7.8 and 8.5%, frond tips 4.0 and 5.1%, harvest path 12.4 and 3.9% and between other zones 54.1 and 59.9%.

Before fitting Eq. 2 to the uptake data, some grouping of the results seemed sensible. The statistical differences in Table 1 suggested the Dami data could be grouped into just two sets, the weeded circle (WC) data and the rest (All-WC). For Sangara the WC and HP data seemed different to the rest, so the data were grouped into three sets, the weeded circle (WC), the harvest path (HP) and the rest (All-WC&HP). The resulting curves for uptake with depth only approximately fitted with the measured values (Fig. 5). The largest discrepancies were between the surface and 0.5 m at Dami (where uptake tended to peak at 0.3 m depth), and between 1.0 and 1.6 m depth at Sangara (where uptake changed little with increasing depth). The values found for C_{max} and k are given in Table 2. The weighted average C_{max} values were 3.2 mm day^{-1} at Dami and 4.1 mm day^{-1} at Sangara. These values were found by multiplying the fractional surface areas of each surface management zone with the C_{max} values in Table 2, and adding together the resulting numbers.

Table 1 Mean water uptake at each depth (m^3 water · m^{-3} soil · day^{-1} · 1000) and from the whole profile (mm day^{-1}) and the effect of zone at each depth (*P* value)

Depth (m)	FP	FT	WC	HP	BZ	B3P	*P* value
Dami							
0.1	3.11 bc	1.70 ab	**3.73 c**	1.33 a	1.70 ab	1.89 ab	*< 0.001*
0.2	2.38 ab	1.83 a	**3.83 b**	1.51 a	1.81 a	2.05 a	*< 0.001*
0.3	2.39 ab	2.49 ab	**3.91 b**	2.37 a	1.69 a	2.24 a	*0.003*
0.4	2.58 ab	2.13 ab	**3.53 b**	1.98 ab	1.69 a	2.63 ab	*0.019*
0.5	2.23 a	1.63 a	2.79 a	1.48 a	2.50 a	2.50 a	*0.102*
0.6	1.78 a	1.50 a	2.45 a	1.59 a	2.33 a	1.60 a	*0.166*
0.7	1.73 ab	1.73 ab	**2.71 b**	1.17 a	1.55 ab	1.59 ab	*0.009*
0.8	1.68 ab	1.74 ab	**2.21 b**	1.26 a	1.52 ab	1.43 ab	*0.048*
0.9	1.46 a	1.36 a	1.91 a	1.33 a	1.24 a	1.61 a	*0.204*
1.0	0.86 a	1.48 a	1.48 a	1.14 a	1.05 a	1.71 a	*0.051*
1.1	0.82 a	0.87 a	0.93 a	0.85 a	0.93 a	1.27 a	*0.717*
1.2	0.62 a	0.68 a	0.99 a	0.80 a	0.49 a	0.96 a	*0.550*
1.3	0.63 a	0.52 a	0.83 a	0.68 a	0.27 a	0.85 a	*0.332*
1.4	0.52 a	0.48 a	0.73 a	0.47 a	0.38 a	0.66 a	*0.642*
1.5	0.47 a	0.42 a	0.58 a	0.65 a	0.30 a	0.56 a	*0.564*
1.6	0.34 a	0.22 a	**1.00 b**	0.37 ab	0.33 a	0.27 a	*< 0.008*
0–1.6	2.36 ab	2.07 a	**3.36 b**	1.90 a	1.98 a	2.38 ab	*0.001*
Sangara							
0.1	**7.43 b**	5.64 ab	6.35 ab	5.78 ab	6.72 ab	5.14 a	*0.005*
0.2	**5.00 b**	4.42 ab	**4.95 b**	3.71 ab	3.99 ab	3.24 a	*0.010*
0.3	3.85 bc	3.38 abc	**4.00 c**	2.47 ab	2.34 a	2.43 ab	*0.001*
0.4	**3.46 b**	2.95 ab	**3.43 b**	1.85 a	2.13 ab	2.71 ab	*0.003*
0.5	**2.93 b**	2.44 ab	**2.95 b**	1.38 a	1.77 ab	2.43 ab	*0.001*
0.6	**2.58 b**	2.09 ab	2.38 ab	1.30 a	1.43 a	2.01 ab	*0.007*
0.7	**2.02 b**	1.88 ab	**2.37 b**	0.86 a	1.37 ab	**2.03 b**	*0.001*
0.8	**1.93 b**	1.53 ab	**2.03 b**	0.77 a	1.31 ab	1.51 ab	*0.008*
0.9	1.38 ab	**1.63 b**	**1.99 b**	0.63 a	1.24 ab	1.19 ab	*0.001*
1.0	1.40 ab	1.43 ab	**1.84 b**	0.72 a	1.21 ab	1.14 ab	*0.002*
1.1	1.03 ab	**1.43 b**	**1.57 b**	0.42 a	1.13 ab	**1.27 b**	*< 0.001*
1.2	1.09 ab	**1.53 b**	**1.59 b**	0.66 a	1.07 ab	1.22 ab	*0.001*
1.3	0.88 ab	1.49 bc	**1.63 c**	0.73 a	0.87 ab	1.20 abc	*< 0.001*
1.4	0.85 ab	1.40 bc	**1.44 c**	0.65 a	1.01 abc	**1.42 c**	*< 0.001*
1.5	0.91 ab	**1.32 b**	**1.30 b**	0.69 a	1.09 ab	**1.32 b**	*< 0.001*
1.6	0.98 ab	1.40 bc	**1.53 c**	0.68 a	1.04 abc	1.08 abc	*< 0.001*
0–1.6	3.78 bc	3.60 bc	**4.15 c**	2.33 a	2.98 ab	3.14 abc	*< 0.001*

Letters indicate homogeneous subsets for each depth using Tukey's honestly significant difference ($\alpha = 0.05$). For each zone, $n = 12$ for Dami (3 profiles × 4 calculation periods) and 24 for Sangara (3 profiles × 8 calculation periods). At each depth the highest uptake is shown in bold and the lowest is underlined

The water uptake values were generally lower than estimates of evapotranspiration made using the FAO56 method, especially for Dami (Fig. 6).

Root mass at Sangara differed significantly between zones in the top 0.6 m, being higher in the weeded circle than all other zones (Table 3). The decrease in root mass with depth was more marked than the decrease in root activity with depth. When Eq. 2 was fitted to the root mass data, by substituting root mass (kg m^{-3} soil) for A and total root mass (kg m^{-2}) for C_{max}, k values were 3.0×10^{-2}, 1.3×10^{-5} and 1.0×10^{-4} for WC, HP and All-WC&HP, respectively. The depth for 75% of root mass was 0.39, 0.12 and 0.15 m for WC, HP and All-WC&HP, respectively. Total measured root mass, calculated by multiplying the average mass in each zone by the fractional area of each zone, was 20.0 t ha^{-1}.

Discussion

Differences between sites

Palm age differed between the two sites, but palms at both sites could be considered mature,

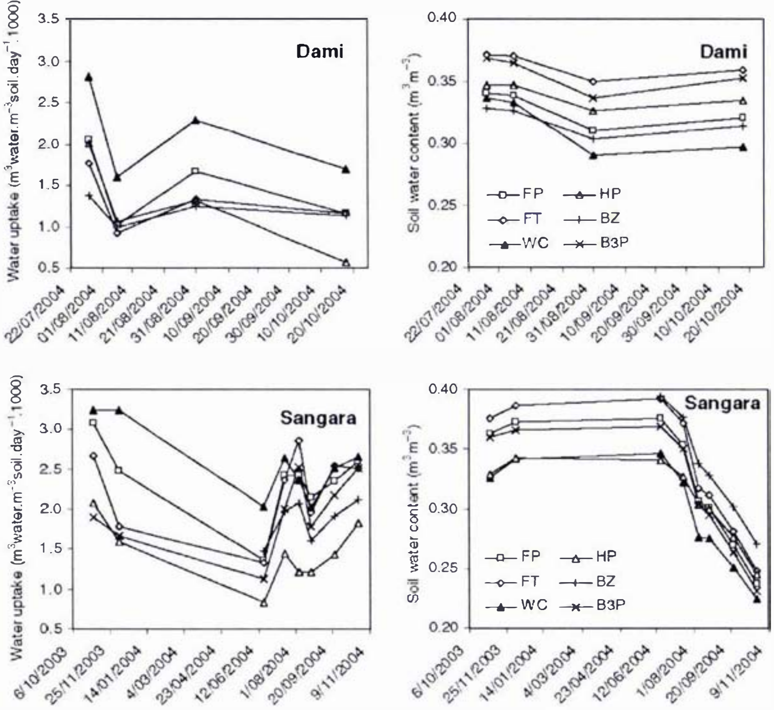

Fig. 3 Changes in water uptake and soil water content (mean over profile) with time at each site

with no net annual increase in canopy or root biomass (Ng et al. 1968). We therefore interpret the differences in the spatial distribution of root activity between the sites as being due to differences in soil characteristics and possibly climate.

Lateral distribution of root activity

High root activity in the weeded circle and to a lesser extent in the frond pile and frond tip zones was consistent with root abundance studies that have shown proliferation of quaternary roots in those zones in other plantations (Bachy 1964; Fairhurst 1996; Purvis 1956; Ruer 1967; Tailliez 1971). Although we discuss the results in terms of management zones, water uptake was highest in the weeded circle probably because it was the zone closest to the stem. Decreases in water uptake with distance from the stem may be partially due to the increasing flow resistance with distance that exists in branching root systems (Radersma and Ong 2004). Low uptake from the harvest path was probably due to compaction and reduced infiltration, particularly for the narrow path at Sangara. Measurements not reported here confirmed that infiltration rates were lower in the harvest path zone than in the other zones at Sangara.

When simulating water and nutrient uptake in models of water and nutrient movement, it seems that uptake from under the weeded circle within a metre of the trunk needs to be treated differently to uptake from the rest of the root zone. Thus a simple one dimensional model of the effective root distribution would probably be inadequate. On the other hand, given the problems and uncertainties involved in modelling the large spatial variation in through-fall, and unknown

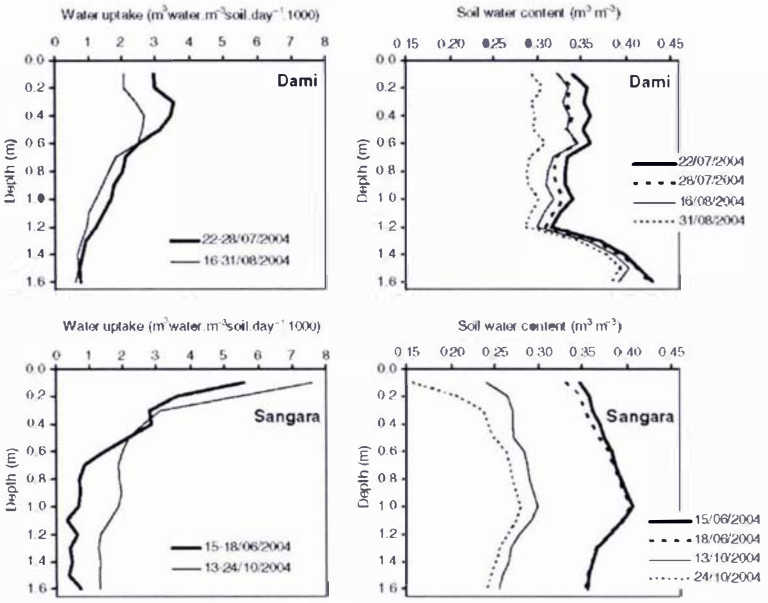

Fig. 4 Mean depth profile of water uptake and soil water content for the driest and wettest calculation periods at each site

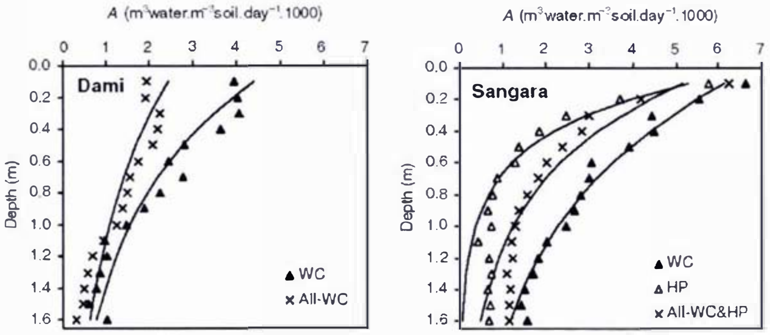

Fig. 5 Profiles of water uptake with depth (points) with Eq. 2 fitted (lines). See Table 2 for Eq. 2 parameters

fate of the 15% of rain appearing as stem flow, development of a more sophisticated description of uptake may not be justified.

Water uptake from any given zone cannot be attributed to any particular palm due to the overlapping of palm root systems. However, that is not important for the purpose of modelling water and solute flow in the plantation and for determining management recommendations. As a matter of interest though, 32P tracer experiments have shown different extents of overlap for 7-year old palms in Ivory Coast and 11-year old palms in Malaysia. In the Ivory Coast, when labelled solute was introduced at one point, 86% of the label taken up by the surrounding 12 palms was taken up by the closest three (IAEA 1975). In Malaysia

Table 2 Parameters for modelled distribution of water uptake with depth, from Eq. 2

Zone	C_{max} (mm day^{-1})	k	Depth for 75% of uptake (m)	Depth for 99% of uptake (m)	Uptake within 1.6 m as % of C_{max}
Dami					
WC	4.3	0.319	1.2	4.0	84
All-WC	3.0	0.409	1.6	5.2	76
Sangara					
WC	6.2	0.331	1.3	4.2	83
HP	2.4	0.051	0.5	1.6	99
All-WC & HP	3.8	0.206	0.9	2.9	92

the corresponding figure was only 31% (calculated from data of Zaharah et al. 1989).

Vertical distribution of root activity

In all zones at both sites there was significant root activity at 1.6 m depth, and we do not know to what depth it extended. We expect no greater physical or chemical constraints to deep penetration of roots at these two sites than at other places where oil palm roots have been measured to 3–5 m depth (Dufrêne et al. 1993; Jourdan and Rey 1997; Lambourne 1935; Schroth et al. 2000). We therefore speculate that roots probably extend to at least similar depths at these sites. In the very free-draining Dami soil profile 30% of the measured uptake occurred from the top 0.3 m. At Sangara, with the less hospitable sandy clay subsoil horizon, 42% of the measured uptake occurred from the top 0.3 m. This difference is presumably due to the contrasting soil profiles.

The proportion of root activity at depth was much greater in our study than that measured previously for oil palm in the wet season in Malaysia using 32P tracer (IAEA 1975). In our study the estimated depth for 75% of root activity was >0.8 m in all zones except the Sangara harvest path (Table 2), compared to values of 0.22 m for 75% of root activity in the Malaysian study (Lehman 2003, using data from IAEA 1975). The Malaysian study site was a similar deep freely drained sandy clay loam with no restrictions to deeper root activity reported, and an annual average rainfall of 2620 mm. A likely explanation for this difference is that plant-available P is usually concentrated in the topsoil. Another probable contributing factor is that, in contrast to inorganic N, P in soil is highly buffered and uptake occurs predominantly due to molecular diffusion from close to root and mycorrhizal surfaces, with little P uptake occurring due to convection with water uptake from further away. It is thus much more dependent on root surface area per unit soil volume than is water (and N) uptake (Tinker and Nye 2000). Note that the value of the parameter k depends on the depth units chosen. As depth is expressed in m here but in cm in Lehman (2003), to obtain k values comparable to those quoted by Lehman the values in Table 2 must be raised to the power of 0.01. Thus for example 0.299 becomes 0.988. As they involve data extrapolation, it is hard to access the accuracy of the total uptake (C_{max}) values, and of the estimated depths for 99% of root activity in Table 2 of about 4 m at Dami and 3 m at Sangara. While the exponential model of root activity with depth provides a useful means of comparing the relative depth of activity between species and sites, the model did not fit actual activity particularly well for either of our sites.

Comparison of water uptake and root mass profiles at Sangara suggested that water uptake per mass unit of root increased with depth. However it is also possible that root mass was underestimated at depth due to difficulty in separating fine roots from the clayey soil.

Comparison of water uptake with estimates of evapotranspiration

The water uptake estimates were generally lower than estimates of evapotranspiration using the

FAO56 method. At Dami, for 3 of the 4 measurement periods the mean FAO56 estimate was 1.75 mm day^{-1} higher than the water uptake estimates. That difference could be accounted for if water uptake was constant from 1.6 to 5.6 m depth at the value measured at 1.6 m (4.4×10^{-4} m^3 water · m^{-3} soil · day^{-1}, weighted for zone areas). Root activity to 5.6 m depth is feasible for this site based on the results of Dufrêne et al. (1993). For the period at Dami when the two estimates disagree most (13–18/10/2004), the FAO56 value may have been an overestimate due to high vapour pressure deficit (VPD) and wind, as this period was unusually windy. The FAO56 estimate assumes constant and low stomatal resistance, whereas stomatal conductance and transpiration of oil palm decreases as VPD increases (Dufrêne and Saugier 1993; Henson 1995). Henson (1995) showed that canopy photosynthesis was approximately halved when the largest daily VPD was 2 kPa, compared with a VPD of 0.8 or smaller. During the period under question, the average VPD was 1.1 kPa at the meteorological site, but it would have gone up to about 1.8 kPa during the day. Also, the wind would have increased the aerodynamic conductance, strengthening the effect of VPD on the stomata.

At Sangara, the FAO56 estimates corresponded reasonably well with water uptake for three of the four measurement periods, the mean FAO56 estimates for those three periods being within 0.6 mm day^{-1} of the water uptake estimates (Fig. 6). For the period at Sangara when the two estimates diverged most (13–24/10/2004), the soil was unusually dry, with a water deficit of about 226 mm at the end of the period. It is therefore likely that most of the uptake of water was from deeper than 1.6 m during this period, and/or transpiration was reduced due to water stress.

Green et al. (2003) found for a mature apple tree that on a daily basis, water uptake corresponded well with transpiration losses determined by sapflow and evapotranspiration estimates. However, the total water balance showed that 'water uptake' from the soil was greater than transpiration due to losses of water from the soil by deep drainage and evaporation from the soil surface. The significance of similar losses will be less in our study because of the 3-day 'drainage period' allowed after rainfall ceased, and the dense canopy.

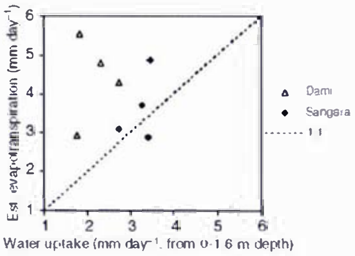

Fig. 6 Comparison of water uptake from the profile (0–1.6 m depth) during the selected measurement periods with evapotranspiration, estimated using the FAO56 calculations, during the same periods

Advantages and disadvantages of the approach used

In this humid tropical climate, calculations of water uptake for all rain-free periods of 4 or more days duration over the course of a year were adequate to measure significant differences between sites and between management zones at each site. Although the method used was sufficiently precise to show differences between zones, there were considerable differences in water uptake between profiles in the same zone, so a sensitivity analysis of the type carried out by Musters and Bouten (2000) in a forest would be warranted for further work in orchards or plantations. The number of access tubes does not greatly influence the amount of effort involved, assuming they are not too far apart, so the number of calculation periods used is likely to be the most influential element of the method. A disadvantage of the method was that in the climate concerned it took 1 year of monitoring to obtain a sufficient number of calculation periods. However, it is the first direct measurement of water uptake by a tree crop in this humid environment. The method provides a starting point for modelling water and solute fluxes to enable predictions of the most efficient means of applying fertiliser,

Table 3 At Sangara, mean dry root mass at each depth (kg m^{-3} soil) and in the whole profile (kg m^{-2}) and the effect of zone at each depth (*P* value)

Depth (m)	FP	FT	WC	HP	BZ	*P* value
0.0–0.2	4.78a	6.61ab	**10.79b**	4.28a	5.32ab	< *0.001*
0.2–0.4	0.75a	0.79a	**5.35b**	0.44a	1.01a	< *0.001*
0.4–0.6	0.22a	0.28a	**2.71b**	0.09a	0.47a	< *0.001*
0.6–0.8	0.28a	0.19a	0.91a	0.09a	0.47a	*0.068*
0.8–1.0	0.31ab	0.22ab	**0.75b**	0.00a	0.25ab	< *0.001*
1.0–1.2	0.03a	0.03a	0.57a	0.35a	0.22a	*0.020*
1.2–1.4	0.16a	0.19a	0.57a	0.00a	0.19a	*0.003*
1.4–1.6	0.09a	0.06a	0.25a	0.00a	0.25a	*0.517*
0.0–1.6	1.33a	1.67a	**4.38b**	1.05a	1.64a	< *0.001*

Letters indicate homogeneous subsets for each depth using Tukey's honestly significant difference ($\alpha = 0.05$). *N* = 27 for FP, 21 for FT, 176 for WC, 21 for HP and 124 for BZ. At each depth the highest mass is shown in bold and the lowest is underlined

particularly in relation to the location and frequency of applications.

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A2.3 The FAO 56 E_r estimation procedure:

Allen et al. (1998) (subsequently referred to as FAO56) suggest the use of a version of the Penman-Monteith equation to estimate the reference crop evaporation (E_r, mm/day). Assuming that the daily soil heat flux density is negligible (as suggested for daily values, p.54, FAO56), the equation is (FAO56 equation 6)

$$E_r = \frac{0.408\Delta R_n + \gamma \dfrac{900u_2(e_s - e_a)}{T_{av} + 273}}{\Delta + \gamma(1 + 0.34u_2)} \qquad [A2\text{-}1]$$

where R_n is the net radiation (MJ m^{-2} d^{-1}), e_s is the saturated vapour pressure (kPa), e_a is the actual vapour pressure (kPa), Δ is the slope of the saturated vapour pressure – temperature curve (kPa $^oC^{-1}$), γ is the psychrometric constant (kPa $^oC^{-1}$), u_2 is the average wind speed at 2 m height (m s^{-1}), and T_{av} is the average air temperature (^{o}C), found as

$$T_{av} = \frac{T_{max} + T_{min}}{2}. \qquad [A2\text{-}2]$$

As reliable vapour pressure data are not available, the dew point (T_d, ^{o}C) is estimated as being equal to the minimum temperature, as suggested for non-arid regions in FAO56 (p.58). The vapour pressure is then found from the dew point using equation (14) of FAO56 as

$$e_a = 0.6108 \exp\left(\frac{17.27T_d}{T_d + 237.3}\right). \qquad [A2\text{-}3]$$

The saturated vapour pressure for each day is found as the average of the saturated vapour pressures at T_{max} and T_{min}, using equations (11) and (12) from FAO56. So

$$e_s = 0.3054\left[\exp\left(\frac{17.27T_{max}}{T_{max} + 237.3}\right) + \exp\left(\frac{17.27T_{min}}{T_{min} + 237.3}\right)\right]. \qquad [A2\text{-}4]$$

The slope of the saturated vapour pressure – temperature curve is found using equation (13) from FAO56 as

$$\varDelta = \frac{4098\left[0.6108\exp\left(\dfrac{17.27T_{\mathrm{av}}}{T_{\mathrm{av}}+237.3}\right)\right]}{(T_{\mathrm{av}}+237.3)^2}. \qquad \text{[A2-5]}$$

The psychrometric constant is given by equation (8) in FAO56 as

$$\gamma = 0.665\mathrm{x}10^{-3}\,p \qquad \text{[A2-6]}$$

where p is the atmospheric pressure (kPa), estimated using equation (7) in FAO56 as

$$p = 101.3\left(\frac{293-0.0065\,Z}{293}\right)^{5.26}. \qquad \text{[A2-7]}$$

To find the incoming net radiation the following calculations are necessary.
Firstly find the extraterrestrial radiation (R_{a}, MJ/m^2/day) using equation (21) of FAO56.

$$R_{\mathrm{a}} = \frac{1440}{\pi}G_{\mathrm{sc}}d_{\mathrm{r}}\left[\omega_{\mathrm{s}}\sin(\varphi)\sin(\delta)+\cos(\varphi)\cos(\delta)\sin(\omega_{\mathrm{s}})\right]. \qquad \text{[A2-8]}$$

In this equation:
δ is the solar declination (radians) given as a function of the Julian day (J) by equation (24) in FAO56 as

$$\delta = 0.409\sin\left(\frac{2\pi}{365}J-1.39\right) \qquad \text{[A2-9]}$$

ω_{s} is the sunset hour angle (radians) given by equation (25) in FAO56 as

$$\omega_{\mathrm{s}} = \arccos\left[-\tan(\varphi)\tan(\delta)\right] \qquad \text{[A2-10]}$$

G_{sc} is the solar constant (0.0820 MJ m^{-2} min^{-1}) and

d_r is the inverse relative Earth-Sun distance, given as a function of the Julian day by equation (23) in FAO56 as

$$d_r = 1 + 0.033\cos\left(\frac{2\pi J}{365}\right). \qquad [A2\text{-}11]$$

Then estimate the solar radiation (R_s, MJ/m^2/day) from sunshine hour data using equation (35) from FAO56 with the default constants as

$$R_s = \left(0.25 + 0.50\frac{n}{N}\right)R_a. \qquad [A2\text{-}12]$$

Here n is the number of sunshine hours, and N is the maximum possible duration of sunshine on that date at that latitude, found using equation (34) in FAO56 as

$$N = \frac{24}{\pi}\omega_s. \qquad [A2\text{-}13]$$

Assuming an albedo (short-wave reflectivity) of 0.23, find the incoming net short-wave radiation (R_{ns}) using equation (38) in FAO56 as

$$R_{ns} = (1 - 0.23)R_s \qquad [A2\text{-}14]$$

Next estimate the clear-sky solar radiation (R_{so}, MJ/m^2/day), using equation (37) in FAO56 (for law altitudes) as

$$R_{so} = 0.75R_a, \qquad [A2\text{-}15]$$

then find the outgoing net long-wave radiation (R_{nl}) using equation (39) in FAO56 as

$$R_{\mathrm{nl}} = 4.903\mathrm{x}10^{-9}\left[\frac{(T_{\max}+273.16)^4+(T_{\min}+273.16)^4}{2}\right](0.34-0.14\sqrt{e_{\mathrm{a}}})\left(\frac{1.35R_{\mathrm{s}}}{R_{\mathrm{so}}}-0.35\right)$$

.

[A2-16]

Lastly, calculate the net radiation (R_{n}, MJ m^{-2} day^{-1}) as the difference between the incoming net short-wave radiation and the outgoing net long-wave radiation,

$$R_{\mathrm{n}} = R_{\mathrm{so}} - R_{\mathrm{nl}}. \quad [\text{A2-17}]$$

To estimate the wind speed at 2 m height (u_2) from that at the measured height, use equation (47) of FAO56, modified slightly to change the units from km/d to SI units of m/s, as

$$u_2 = \left(\frac{1000}{86400}\right)\left[\frac{4.87u_z}{\ln(67.8z-5.42)}\right]. \quad [\text{A2-18}]$$

However, if the above equation gives a value less than 0.5 m s^{-1}, u_2 is taken as 0.5 m s^{-1} (FAO56, p.63), as at low wind speeds vertical mixing is due to more to surface warming and buoyancy effects rather than the forced convention assumed in the FAO56 form of the Penman-Monteith equation.

Appendix 3

A3.1 Example calculation of fertiliser application rate for *in situ* nitrification experiment

Though the realistic effective rate per single dose of fertiliser is very high, the rate here will be low to determine the nitrification rate for modeling purpose and is also sufficient to cover any background levels.

N to be applied at a rate of 205 kg N ha^{-1}.

205 kg N ha^{-1} = 205 000 g N per 10 000 m^2
= 20.5 g N m^{-2}

For calculations of concentration in the soil, it is assumed the ρ_b = 1 g cm^{-3}, soil gravimetric water content is 0.4 and the soil is wet down to 10 cm depth.

Weight of soil = 10 cm (depth) x 100 cm x 100 cm x 1.0 (ρ_b)
= 100 000 cm^3
= 100 kg soil

N concentration = 20.5 g N/ 100 kg soil
= 20500 mg N/ 100 kg soil
= 205 mg N /kg soil

Amount of AMC to be applied/m^2 = 20.5g N/0.25 (25 % N in AMC)
= 82 g AMC

AMC per kg dry soil = 82 g/100 kg
= 0.82 g AMC/kg
= 820 μg AMC/g

AMC per g soil solution = 820 μg (AMC/g dry soil) /0.4 (θ)
= 2050 μg AMC/g soil solution

Molarity = AMC in soil solution/molecular wt of AMC/1000000 x 1000
= 3000/53.5/1000000x1000
= 0.0383 M

Osmotic pressure = 0.056 x 4800 = 183.84 kPa

Appendix 4

A4.1 N_2O, methane and carbon dioxide emission data

Table A4.1 N_2O, methane and carbon dioxide emissions at Dami and Sangara in 2005

			Dami					
Day	**Rainfall (mm)**		**Nitrous oxide (g ha^{-1} day^{-1})**		**Methane production (g ha^{-1} day^{-1})**		**Carbon dioxide (g ha^{-1} day^{-1})**	
	Daily	**Cum.**	**Nil fert**	**Fert**	**Nil fert**	**Fert**	**Nil fert**	**fert**
0	1.8	1.8	4	4	-12	-13	174956	177852
1								
3								
7	34	47.4	5	103	-15	-11	215312	196947
14	0	52.1	2	6	-18	-15	196996	157566
28	49	180.0	4	8	-14	-12	220349	181637
Mean			**4**	**31**	**-15**	**-12**	**201903**	**178500**
Std dev			2	48	4	2	43694	49072
CV %			48	158	25	19	22	27
					Sangara			
0	1.6	1.6	41	56	-16	-17	137593	172808
1	0	1.6	10	28	0	9	106213	117535
3	0	1.6	5	28	-13	-14	101270	109345
7	48	63.0	14	443	-15	-15	91159	135271
14	23	64.0	40	227	-14	-14	64163	80342
28	2.6	271.0	7	29	0	3	96372	126333
Mean			**20**	**135**	**-10**	**-8**	**99462**	**123606**
Std dev			24	168	9	12	22812	30727
CV %			119	124	91	148	23	25

Appendix 5

A5.1 Volumetric water content of soils from *in situ* leaching experiments

Site	Exp.	Depth	BD (g cm^{-3})	Volumetric water content (cm^3 cm^{-3})					
Dami	1			**BZ-1**	**BZ-2**	**BZ-nilfert**	**FP**	**FP-nilfert**	**Mean**
		0-20	0.77	0.39	0.34	0.36			0.36
		20-40	0.84	0.29	0.27	0.27			0.28
		40-60	1.00	0.33	0.34	0.34			0.34
		60-80	0.77	0.30	0.28	0.29			0.29
		80-100	1.06	0.43	0.41	0.43			0.42
		100-120	0.70	0.35	0.34	0.36			0.35
		120-140	0.83	0.46	0.39	0.40			0.42
		140-160	0.84	0.43	0.53	0.54			0.50
		160-180	0.84	0.62	0.66	0.67			0.65
		180-200	0.84	0.75	0.79	0.80			0.78
		mean		**0.44**	**0.44**	**0.45**			**0.44**
		W=							**878**
	2			**Volumetric water content (cm^3 cm^{-3})**					
				BZ-1	**BZ-2**	**BZ-nilfert**	**FP**	**FP-nilfert**	**Mean**
		0-20	0.77	0.42	0.40	0.37	0.67	0.47	0.46
		20-40	0.84	0.41	0.29	0.31	0.50	0.44	0.39
		40-60	1.00	0.40	0.35	0.34	0.41	0.47	0.39
		60-80	0.77	0.35	0.30	0.29	0.33	0.28	0.31
		80-100	1.06	0.50	0.38	0.38	0.46	0.43	0.43
		100-120	0.70	0.44	0.34	0.29	0.31	0.27	0.33
		120-140	0.83	0.49	0.40	0.37	0.41	0.30	0.39
		140-160	0.84	0.44	0.37	0.35	0.35	0.35	0.37
		160-180	0.84	0.55	0.51	0.48	0.35	0.35	0.45
		180-200	0.84	0.57	0.50	0.46	0.45	0.41	0.48
		mean		**0.46**	**0.38**	**0.36**	**0.42**	**0.38**	**0.40**
		W=							**802**
	3			**Volumetric water content (cm^3 cm^{-3})**					
				BZ-1	**BZ-2**	**BZ-nilfert**	**FP**	**FP-nilfert**	**Mean**
		0-20	0.77	0.45	0.54	0.42	0.64	0.57	0.53
		20-40	0.84	0.34	0.39	0.37	0.44	0.47	0.40
		40-60	1.00	0.41	0.46	0.42	0.40	0.46	0.43
		60-80	0.77	0.35	0.36	0.34	0.35	0.32	0.34
		80-100	1.06	0.47	0.53	0.49	0.45	0.45	0.48
		100-120	0.70	0.36	0.39	0.40	0.35	0.32	0.36
		120-140	0.83	0.46	0.51	0.51	0.52	0.44	0.49
		140-160	0.84	0.49	0.57	0.49	0.46	0.48	0.50
		160-180	0.84	0.70	0.70	0.64	0.61	0.48	0.63
		180-200	0.84	0.83	0.82	0.70	0.75	0.58	0.74
		mean		**0.49**	**0.53**	**0.48**	**0.50**	**0.46**	**0.49**
		W=							**978**

Site	**Exp.**	**Depth**	**BD (g cm^{-3})**	**Volumetric water content (cm^3 cm^{-3})**					
				BZ-1	**BZ-2**	**BZ-nilfert**	**FP**	**FP-nilfert**	**Mean**
Sangara	1	0-20	1.29	0.40	0.40	0.32			0.37
		20-40	1.35	0.39	0.42	0.38			0.40
		40-60	1.42	0.56	0.63	0.50			0.56
		60-80	1.11	0.52	0.59	0.48			0.53
		80-100	1.11	0.49	0.61	0.51			0.53
		100-120	1.20	0.39	0.54	0.45			0.46
		120-140	1.34	0.30	0.41	0.34			0.35
		140-160	1.34	0.25	0.33	0.23			0.27
		160-180	1.47	0.29	0.33	0.26			0.29
		180-200	1.47	0.27	0.28	0.27			0.27
		mean		**0.38**	**0.45**	**0.38**			**0.40**
		W=							**808**
	2			**Volumetric water content (cm^3 cm^{-3})**					
				BZ-1	**BZ-2**	**BZ-nilfert**	**FP**	**FP-nilfert**	**Mean**
		0-20	1.29	0.29	0.30	0.34	0.38	0.32	0.33
		20-40	1.35	0.38	0.31	0.34	0.36	0.33	0.34
		40-60	1.42	0.53	0.46	0.47	0.58	0.50	0.51
		60-80	1.11	0.45	0.43	0.42	0.50	0.43	0.44
		80-100	1.11	0.45	0.51	0.42	0.51	0.43	0.46
		100-120	1.20	0.42	0.47	0.42	0.46	0.43	0.44
		120-140	1.34	0.46	0.44	0.36	0.35	0.36	0.39
		140-160	1.34	0.38	0.36	0.29	0.26	0.34	0.33
		160-180	1.47	0.32	0.32	0.23	0.19	0.28	0.27
		180-200	1.47	0.24	0.24	0.21	0.20	0.26	0.23
		mean		**0.39**	**0.38**	**0.35**	**0.38**	**0.37**	**0.37**
		W=							**748**