

Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.

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

**A thesis presented in partial fulfilment of the
requirements for the degree of**

Doctor of Philosophy

in

Soil Science

at Massey University, Palmerston North, New Zealand.



Massey University

Murom Banabas

2007

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.

Acknowledgements

Thanks to my three supervisors at Massey University, Dr Max Turner (Chief Supervisor) for the overall direction and for ensuring that work was on track, Dr David Scotter (Co-supervisor) for his guidance and his help and especially for providing the theoretical basis and Excel spreadsheet for the models in 8.3.4 that so elegantly linked the various elements of this research, and to Dr Neil MacGregor (Co-supervisor) for help with the nitrification and the denitrification trials. Thanks also to my two supervisors on site in PNG, Dr Paul Nelson (2003) and later Dr Mike Webb (2004 – 2006) for guidance and providing useful ideas during the course of this study. All your contributions into this broad range study is much appreciated.

In the Soils and Earth Sciences Group, INR, at Massey University, thanks to Professor Mike Hedley for useful discussions and providing literature materials on aspects of change in soil pH. In the laboratory, thanks to Mr Lance Currie (Laboratory Manager) for facilitating analysis of samples and making available bench space for my laboratory work. Many thanks to Mr Ian Furkert for analysing water samples and to Ms Anne West for help with statistical analysis of data. Thanks also to Mr Bob Toes, Mr Ross Wallace and Ms Glenus Wallace for providing general assistance in the laboratory. Thanks to Mr Mike Bretherton for help with sorting out computer-related issues and Ms Moira Hubbard for assistance with the formatting of this thesis.

Thanks to Dr Surindar Saggar and Mrs Carolyn Hedley at Landcare Research (NZ) for providing assistance with procedure for gas sampling and useful comments on the analysed data.

Many thanks to Mr. Ian Orrell (Director of Research – PNGOPRA) for facilitating funding and allowing me time away from work to conduct this study. Thanks also to Mrs Pole Crompton (Administrator - PNGOPRA) for providing the logistical support. Thanks to EU for providing the funds for the project and also to ACIAR for funding support equipment used in the study.

The work in the field with all the associated difficulties of theft, vandalism, and communication hiccups cannot have been done without dedicated contributions from the two N Loss Teams. At PNGOPRA Higaturu Station, my thanks to Mason Japara and David Joe and those who helped, Rex Suma and Andy Ullian, Ambex Raynold and William Sirabis (Trainee Unitech Student), and at Dami Station, to Hanson Hinjik, Jeffrey Tamunda, Mark Erick, Maori Nara, Peter Mapa, Levi Atam, Daniel Kuri and Norma Konimor (Supervisor). Thanks for all your keenness and work even late into the night and early hours of mornings to monitor trials during the wet season. Your contributions are much appreciated.

Thanks to Rose Toby and Janet Suru for timely collation of weather data and doing data entries for me when required. Thanks also to Serah Naemon from Ramu Sugar for providing useful weather data from the valley. Thanks to Steven Nake, Rachael Pipai and James Kraip, four field supervisors; Paul Simin, Graham Bonga, Pauline Hore and Graham Dikop for making available their time and workers as, and when, required. Thanks to Fredius Julius, Agatha Owens, Elizabeth Kibikibi and Joe Rusu for providing the required logistical support.

To OPIC officers, at Popondetta thanks for allowing us to collect tank water at Igora OPIC Station. At Nahavio, thanks for the use of dumpy level at Dami.

Higaturu Oil palms, thanks to the Building Department for use of the dumpy level and the Mill and Vehicle workshops for assisting with welding of metal pipes and cutting of drums and thanks to the field department for providing the excavator at short notices. Thanks to HOP (Building and Mill and VWS workshops) for assisting with welding of metal pipes and cutting drums for various experiments. Thanks for allowing me to conduct the experiment on your plantation.

Thanks to the Management of Dami OPRS for allowing me to conduct experiments in the plantation fields. Thanks to Ruth Pipai and Judith Makai for providing the Dami weather data. Assistance from Mr and Mrs Betitis (Agronomy Section), Mr Patrick Mungore (Station Manager), Mr Harry Brook (former Station Manager) and Dr. Simon Lord (Head of OPRS) and the Librarian, Maria Luanga, is much appreciated.

At Massey University, TVL Building, thanks to the other postgraduate students for useful discussions and help while writing; Jagratti, Monica, Tham, Bambang and Tin.

A special thanks to my wife (Nambua) and our four children (Enzeng, Serah, Yandi and Elizah) and my little friend Bana for putting up with my regular away trips from home. Thanks to all our family friends at Popondetta for supporting my family while I was away studying; Pastor Ken Tinzanga, Yasaking Bobby, Awa Erap, Feberth Nasine, Veronica Owedo, Rex Suma, and Yaso and Jacob families, Ross and Cath Safitua and Dambi and many others not mentioned. My parents at home for their moral support and a special tribute to my younger brother (Nanaim), who passed away during my study in NZ and was not able to attend his funeral.

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

Table of Contents

Abstract	i
Acknowledgements.....	ii
Table of Contents.....	v
List of Tables.....	x
List of Figures.....	xiii
List of Plates.....	xvi
List of abbreviations and symbols	xvii
Chapter 1.....	1
General information	1
1.1 Background.....	1
1.2 Objectives	3
1.3 Thesis outline	3
1.4 References.....	5
Chapter 2.....	7
N requirements, balance and fertiliser use	7
2.1 Functions of N.....	7
2.2 N requirement of oil palm.....	9
2.3 N balance	10
2.3.1 N recycling within the system.....	10
2.3.2 N input into oil palm.....	11
2.3.3 N output from oil palm system.....	12
2.4 N fertiliser trials in PNG.....	15
2.5 N fertiliser trials in other oil palm producing countries	18
2.6 N fertiliser use on oil palm in PNG	18
2.6.1 General.....	18
2.6.2 Forms of N	21
2.6.3 Fertiliser recommendations.....	22
2.6.4 Timing of fertiliser applications	24
2.6.5 Fertiliser placement	25
2.7 Summary.....	27

2.8 References.....	28
Chapter 3.....	33
General background information.....	33
3.1 Soils and site descriptions.....	34
3.1.1 Experimental sites.....	34
3.2 Characterisation of zones.....	40
3.2.1 Spacing and age of palms.....	40
3.2.2 Zone characterisation and % of area covered.....	40
3.3 Soil chemical characteristics of the different zones.....	43
3.3.1 Introduction.....	43
3.3.2 Methods and materials.....	43
3.3.3 Results and discussion.....	44
3.3.4 Summary.....	45
3.4 General climate of oil palm growing areas in PNG.....	47
3.4.1 Introduction.....	47
3.4.2 Climate data.....	47
3.4.3 Rainfall.....	49
3.4.4 Air temperature.....	52
3.4.5 Sunshine hours.....	53
3.4.6 Wind run.....	54
3.4.7 Evapotranspiration (Er).....	55
3.4.8 Summary.....	58
3.5 References.....	59
Chapter 4.....	61
Hydrology.....	61
4.1.1 The overall soil water balance.....	61
4.1.2 Rainfall redistribution under oil palm canopy.....	64
4.1.3 Soil surface water runoff.....	70
4.1.4 Soil water.....	72
4.1.5 Evapotranspiration.....	76
4.1.6 The water balance summary.....	77
4.1.7 Findings from the review.....	77

4.2 Field research	78
4.2.1 Bulk density, water retention and infiltrability.	78
4.2.1.1 Methods and materials	79
4.2.2 Rainfall redistribution under oil palm.....	95
4.2.3 Surface runoff plot measurements.....	111
4.2.4 Water balance for the oil palm systems at Dami and Sangara.....	118
4.3 References.....	129

Chapter 5

Nitrification	135
5.1 Nitrification process	135
5.1.1 Factors affecting nitrification.....	136
5.1.2 Methods and procedures for studying nitrification in soils.....	137
5.1.3 Nitrification in oil palm soils	138
5.2 Field nitrification studies	140
5.2.1 Methods and materials	141
5.2.2 Results and discussion	145
5.3 <i>In situ</i> nitrification experiments	152
5.3.1 Methods and materials	152
5.3.2 Results and discussion	157
5.4 References.....	164

Chapter 6

Emission of N ₂ O	167
6.1.1 Denitrification and N losses from soil.....	167
6.1.2 Factors affecting denitrification losses from soil	168
6.1.3 Methods for measuring denitrification losses	169
6.1.4 N ₂ O emissions from tropical soils.....	171
6.1.5 Conclusions from studies done to date relative to oil palm systems	172
6.2. Methods and materials.....	173
6.2.1 Soil gas collection chambers.....	173
6.2.2 Installation of chambers.....	173
6.2.3 Collection sites	174
6.2.4 Gas sampling	174

6.2.5 Analysis.....	175
6.3 Results and discussion	176
6.3.1 Emissions before and after closure of chambers	176
6.3.2 N ₂ O fluxes from fertilised and unfertilised soils.....	177
6.3.3 Estimated total gaseous N loss	179
6.3.4 Summary	180
6.4 References.....	181

Chapter 7

N losses in surface runoff water.....	185
7.1 Methods and materials	186
7.1.1 General.....	186
7.1.2 Sampling prior to fertiliser application.....	186
7.1.3 Sampling fertilised plots	187
7.2 Results and discussion	189
7.2.1 Inorganic N loss from areas not recently-fertilised	189
7.2.2 Inorganic N losses from fertilised plots.....	190
7.2.3 Summary	194
7.3 References.....	195

Chapter 8

Leaching of inorganic N from soils	197
8.1 The leaching process.....	197
8.1.1 Convection, diffusion and hydrodynamic dispersion	198
8.1.2 Measurement of N leaching	201
8.1.3 Leaching of N from oil palm systems.....	204
8.1.4 Conclusions	206
8.2. Methods and materials.....	207
8.2.1 General.....	207
8.2.2 Suction cups	208
8.2.3 Lysimeters	211
8.2.4 <i>In situ</i> leaching experiment	216
8.3 Results and discussion	221
8.3.1 Suction cups	221

8.3.2 Lysimeters	230
8.3.3 <i>In situ</i> leaching experiments.....	240
8.3.4 Modelling <i>in situ</i> leaching.....	251
8.4 References.....	274
Chapter 9	
Main findings and fertiliser management implications.....	277
9.1 Main findings	277
9.2 Inputs to residence time and CLT models	282
9.3 Implications and recommendations.....	284
Appendices	
Appendix 1	291
A1.1 Dami soil profile description.....	291
A1.2 Sangara soil profile description.....	293
A1.3 Monthly rainfall (mm) data for various oil palm plantations in PNG	294
Appendix 2	304
A2.1 Soil bulk density (g cm^{-3}) and gravimetric water content at various pressure potential measurements at Dami and Sangara	304
A2.2 Appended paper.....	306
A2.3 The FAO 56 E_r estimation procedure:	320
Appendix 3	324
A3.1 Example calculation of fertiliser application rate for <i>in situ</i> nitrification experiment	324
Appendix 4	325
A4.1 N_2O , methane and carbon dioxide emission data.....	325
Appendix 5	326
A5.1 Volumetric water content of soils from <i>in situ</i> leaching experiments	326

List of Tables

Table 2.1 Nutrient removal by plantation crop products	9
Table 2.2 N distribution ($\text{kg palm}^{-1} \text{ yr}^{-1}$) in oil palm trees in Nigeria and Malaysia	10
Table 2.3 Effects of N losses from soil on the environment	14
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	17
Table 2.5 Tonnage of N fertilisers used by major plantations and smallholders in relation to other fertilisers used (1997 to 2005)	20
Table 2.6 Common N fertilisers and cost (kina/kg N) in 2006	21
Table 3.1 Soil pH (H_2O), total C (%) and total N (%) contents at different depths and zones at Dami and Sangara	45
Table 3.2 Summary of years of data available for rainfall, rain days and sunshine hours for various sites in PNG	48
Table 3.3 Mean annual rainfall, E_r (mm) and surplus water (mm) for Dami, Sangara and Ramu Sugar	56
Table 4.1 Rainfall partitioning under oil palm canopy in Malaysia	66
Table 4.2 Surface runoff (% of rainfall) under oil palm in various plantations in Malaysia	71
Table 4.3 Percentage of rainfall as evaporation (mean 5 years 1992 – 1996)	77
Table 4.4 Dates of soil sampling for ρ_b determinations at Dami and Sangara	80
Table 4.5 Readily (W_R) and total available water (W_T) and porosity of soils at Dami and at Sangara	87
Table 4.6 Redistributed rainfall (%) at Sangara	99
Table 4.7 Summary of catch can data from the <i>in situ</i> leaching experiments	106
Table 4.8 Percentage of rainfall as E_r , runoff and deep drainage estimated for Malaysian and PNG conditions	127
Table 4.9 Summary of soil water balance components for Dami (1993-2005) and Sangara (1983-2005)	128
Table 5.1 N recovery (% of added N) in field nitrification studies at Dami and Sangara	146
Table 5.2 Gravimetric soil water contents (g g^{-1}) on different extraction days at Sangara	147

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.....	148
Table 5.4 Calculated osmotic pressures (kPa) in the incubated fertilised soils at Dami and Sangara.....	150
Table 5.5 Mean inorganic N and Cl^- recoveries (%) in the top 20 cm of fertilised soil for the <i>in situ</i> incubation experiment at Dami and Sangara	158
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.....	160
Table 6.1 N_2O concentrations measured before and after closure of chambers at Dami and Sangara.....	177
Table 6.2 Increase and flux of N_2O gas from fertilised and unfertilised chambers at Dami and Sangara	178
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.....	190
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.....	191
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.....	193
Table 8.1 Number of sampling events and water samples collected from suction cups at Dami and Sangara, 2004-2005	210
Table 8.2 Soil properties of lysimeter cores at Dami and Sangara.....	214
Table 8.3 Sequence of water and fertiliser additions, and leachate sampling of lysimeters at Dami and Sangara in 2004.....	215
Table 8.4 Details of <i>in situ</i> leaching experiments at Dami and Sangara (2004-2006).....	217
Table 8.5 Mean monthly inorganic N concentrations ($\mu\text{g ml}^{-1}$) in suction cups and estimated N leaching losses from February 2004 – February 2005 at Dami.....	222
Table 8.6 Mean monthly inorganic N concentrations ($\mu\text{g ml}^{-1}$) in suction cups and estimated N leaching losses from February 2004 – February 2005 at Sangara.....	223

Table 8.7 Estimated monthly and annual N leaching losses from suction cup and water balance data at Dami and Sangara.....	229
Table 8.8 R and $t_{1/2}$ values found for lysimeters at Dami.....	237
Table 8.9 Bulk densities (g cm^{-3}) at Dami and Sangara used for calculations.....	240
Table 8.10 Recovery rates for Cl^- and N for the <i>in situ</i> leaching experiments at Dami and Sangara.....	241
Table 8.11 Fraction of nett inorganic N present as NH_4^+ -N at the time of final sampling of the <i>in situ</i> leaching experiments following the application of AMC	251
Table 8.12 Hydrological inputs for <i>in situ</i> leaching experiments and model parameters	255
Table 8.13 Summary of half-life ($t_{1/2}$) (days) and retardation factor (R) values for NH_4^+ -N from various experiments	264
Table 8.14 Mean and median residence times in days for N applied as AMC	271
Table 8.15 Fertiliser N mean residence times in days for various scenarios.	272
Table 9.1 Mean and median residence times in days for N applied as AMC	284
Table 9.2 Fertiliser N mean residence times in days for various scenarios.	285

List of Figures

Figure 2.1 N balance in an oil palm system in PNG in $\text{kg ha}^{-1} \text{ yr}^{-1}$ (data from Tinker (1976), Agamuthu and Broughton (1985) and Kee and Chew (1997).....	12
Figure 3.1 Map of Papua New Guinea oil palm growing areas showing the two experimental sites	34
Figure 3.2 Schematic showing palm planting arrangement and different management zones.....	41
Figure 3.3 Mean annual rainfalls (mm) in oil palm growing provinces in PNG.....	49
Figure 3.4 Mean monthly rainfall distribution at Dami and Sangara	50
Figure 3.5 Mean number of rain days per month at Dami and Sangara	51
Figure 3.6 Mean daily minimum and maximum temperatures ($^{\circ}\text{C}$) for each month at Dami and Sangara	53
Figure 3.7 Mean daily sunshine hours distribution for each month at Dami and Sangara.....	54
Figure 3.8 Mean daily wind run (km) for each month for 2003-2005 at Dami and Ramu Sugar	54
Figure 3.9 Monthly mean E_r (mm) and rainfall (mm) at Dami, Sangara and Ramu Sugar	57
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.....	85
Figure 4.2 Gravimetric soil water content at Dami and Sangara	86
Figure 4.3 Volumetric water content of <i>in situ</i> leaching experiment at Dami and Sangara.....	90
Figure 4.4 Change in infiltrability with time in the HP at Sangara	91
Figure 4.5 Infiltrability under the different zones under the palms at Dami and Sangara.....	92
Figure 4.6 Infiltrability on the surface and subsurface soil at Sangara.....	93
Figure 4.7 Layout of half 200 L drums under palm trunks at Sangara.....	97
Figure 4.8 Field layout of small catch cans around the plots for the <i>in situ</i> leaching experiments at Dami and Sangara	98

Figure 4.9 Mean daily stemflow expressed as a percentage of daily rainfall, plotted against daily rainfall.....	100
Figure 4.10 The measured throughfall in the large drums as a function of radial distance from the stem at Sangara	103
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.....	104
Figure 4.12 Throughfall catch on three wet days for the two BZ and the FP plots at Dami.....	108
Figure 4.13 Throughfall catch on three wet days for the two BZ and the FP plots at Sangara	109
Figure 4.14 Relationship between runoff coefficient and daily rainfall for the surface runoff plots at Dami and Sangara	116
Figure 4.15 Rainfall (mm), water deficit (mm) and surplus (mm) at Dami and Sangara from 1 st January, 2003 to 31 st December 2005. Negative values indicate water deficit	121
Figure 4.16 Relationship between rainfall and measured surface runoff at Dami and Sangara	122
Figure 4.17 Relationship between FAO 56 surplus water and measured surface runoff at Dami and Sangara.....	124
Figure 4.18 Estimated surface runoff (mm) and deep drainage (mm) at Dami and Sangara (2003-2005). The negative scale is for deep drainage.....	125
Figure 4.19 Cumulative water balance components at Dami and Sangara (2003-2005)	126
Figure 5.1 Soil sampling outline at a location showing the five sampling points (1-5) under the five different zones.....	141
Figure 5.2 Ammonium “decay curves” in the FP and WC soils at Dami and Sangara.....	162
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.....	224
Figure 8.2 Examples of NH_4^+ -N (■) and NO_3^- -N (◆) concentrations in outflow from a faulty and a working lysimeter at Dami.....	231

Figure 8.3 Cumulative drainage and % applied inorganic N recovered in the lysimeter outflows at Dami from the individual lysimeters.....	232
Figure 8.4 Mean ratio of NH_4^+ -N to total inorganic N in the Dami lysimeter leachate for soils from different zones ($p < 0.001$, $\text{lsd}_{(0.05)} = 0.140$).....	233
Figure 8.5 Observed (\blacklozenge) and simulated (—) NH_4^+ -N ($\mu\text{g ml}^{-1}$) in the outflows for two lysimeters (FP-1 and WC-3) at Dami	236
Figure 8.6 Cl^- and inorganic N concentrations at various depths to 200 cm in the <i>in situ</i> leaching experiments 1 – 3 at Dami.....	243
Figure 8.7 Cl^- and inorganic N concentrations at various depths to 200 cm in the <i>in situ</i> leaching Experiments 1 and 2 at Sangara.....	248
Figure 8.8 Simulated and observed Cl^- profiles ($\text{g Cl}^- \text{ m}^{-3}$ soil volume) in Dami Experiment 2 BZ and FP soils used for model calibration	257
Figure 8.9 Simulated and observed Cl^- profiles ($\text{g Cl}^- \text{ m}^{-3}$ soil volume) for BZ soils of <i>in situ</i> leaching experiments at Dami and Sangara.....	258
Figure 8.10 Simulated and observed Cl^- (g m^{-3} soil volume) leaching profiles for FP soils of <i>in situ</i> leaching experiments at Dami and Sangara	259
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	260
Figure 8.12 Simulated and observed NH_4^+ -N profiles (g m^{-3} soil volume) at Dami and Sangara	262
Figure 8.13 Simulated and observed total inorganic N concentrations with depth at Dami.....	267
Figure 8.14 Simulated and observed total inorganic N concentrations at depths at Sangara.....	269

List of Plates

Plate 2.1 Palms in a smallholder block in the Popondetta Plains showing N-deficient (yellow) palms and well fertilised (green) palms.....	8
Plate 2.2 A smallholding block showing uneven fertiliser applications Palms furthest from the road and the village are yellow showing N deficiency symptoms	26
Plate 3.1 A 200 cm soil profile at Dami showing the major horizons – more details in Appendix A1.1.....	36
Plate 3.2 An exposed side of a gully showing the soil horizons at Sangara.....	38
Plate 3.3 Rows of oil palm at Dami showing WC, HP and FP	41
Plate 4.1 Inserted infiltrometer in the weeded circle	83
Plate 4.2 Throughfall drum numbers 1 – 5 and stemflow field set-up.....	96
Plate 4.3 Bent stem at Dami experimental site.....	101
Plate 4.4 Open oil palm canopy at Dami.....	106
Plate 4.5 A surface runoff plot at Sangara.....	113
Plate 4.6 Runoff collection pit. Note shelter not yet built over.....	113
Plate 5.1 Modified clothes drier used as end-over-end shaker for extractions.....	144
Plate 5.2 Plot setup in the WC and FP zones at Dami	153
Plate 5.3 Plastic cover to prevent throughfall from reaching the plots.....	154
Plate 5.4 Wetting up soils pre-fertiliser addition.....	155
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.....	173
Plate 8.1 A suction cup installed in a frond pile at Sangara, showing an empty can capping the pvc pipe	209
Plate 8.2 Lysimeter setup at Sangara	213
Plate 8.3 An <i>in situ</i> leaching plot in the BZ	218
Plate 8.4 An <i>in situ</i> leaching plot in the FP covered with plastic to stop rain water entering the plot just before sampling.....	219

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	Fronde pile
FT	Fronde 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_0	Normalised concentration of ammonium N when $t = 0$	-
C_s	Solute concentration in soil solution	ML^{-3}
C_{tot}	Total solute concentration	ML^{-3}
C	Average solute concentration	ML^{-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	LT^{-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	ML^{-2}
M_s	Mass of soil solid	M
M_w	Mass of water	M
n	Sunshine hours	T
ρ_b	Soil bulk density	ML^{-3}
ρ_s	Soil particle density	ML^{-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