

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.

# **Developing Sustainable Soil Fertility in Southern Shan State of Myanmar**

*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.*



**Tin Maung Aye**  
**August 2001**



13 August 2001

**TO WHOM IT MAY CONCERN**

This is to state the research carried out for the PhD thesis entitled "Developing Sustainable Soil Fertility in Southern Shan State of Myanmar" was done by Tin Maung Aye in the Institute of Natural Resources, Massey University, Turitea Campus, New Zealand. The thesis material has not been used for any other degree.

**Supervisor:** M. J. Hedley  
(Associate Professor M. J. Hedley)

**Date:** 14/8/01



13 August 2001

**TO WHOM IT MAY CONCERN**

This is to state the research carried out for my PhD thesis entitled "Developing Sustainable Soil Fertility in Southern Shan State of Myanmar" in the Institute of Natural Resources, Massey University, Turitea Campus, New Zealand is all my own work.

This is also to certify that the thesis material has not been used for any other degree.



**Candidate:** \_\_\_\_\_

(Tin Maung Aye)

**Date:** \_\_\_\_\_

14/8/01

## ABSTRACT

Literature review and a farm survey results indicated that the productive capacity of the Red Earths and Yellow Earths (Acrisols in FAO/UNESCO system) in Southern Shan State, Myanmar, continues to decline as poor, near-subsistence, farmers usually fallow-crop these soils and are unable, for economic reasons, to provide the necessary fertilisers and crop management strategies that could improve and maintain soil fertility.

This thesis reports on investigations undertaken to determine ways in which the fertility of these soils can be improved in an economical and sustainable manner.

A preliminary soil survey confirmed that soils of the Southern Shan State study area had low soil P status, low pH, low SOM (low reserves of N, P and S) and low base saturation, which are likely constraints to crop production on these marginal soils.

A farmers' survey indicated farmers were aware of the P availability and soil acidity problems, however, they use low levels of N, P, K fertilisers, green manure and liming material because their economic margins were insufficient to buy expensive P fertilisers and liming materials.

Preliminary glasshouse trials were conducted to establish the key soil fertility constraints. These trials included testing the P responsiveness of crops (pigeon pea (*Cajanus cajan*), rice bean (*Vigna umbellata*) and upland rice (*Oryza sativa* L)), the influence of liming materials on legume growth (black gram (*Vigna mungo*), cowpea (*Vigna unguiculata*), kidney bean (*Phaseolus vulgaris*), lentil bean (*Culinaris lentil*), pigeon pea, soybean (*Glycine max*), stylosanthes (*Stylosanthes quyanensis*)), and the effectiveness of green manures for building SOM and P reserves in the Red Earths and Yellow Earths.

The glasshouse trials confirmed that low P status is the factor most limiting to crops particularly legumes grown in the Yellow Earths. Upland rice, however, did not respond to added P suggesting that upland rice may not be a suitable test plant for evaluating the relative P effectiveness of fertilisers in the Red Earths and Yellow Earths. This pot experiment with the upland rice trial also demonstrated that indigenous Myanmar

phosphate rock (MPR) and Farmyard manure (FYM) were ineffective P sources for raising soil plant-available P in the short-term. Local dolomite, however, was an effective liming material and when added with P enhanced the nodule formation of pigeon pea.

Laboratory incubation studies showed that incorporating organic amendments (FYM, pigeon pea and upland rice residues) into the Red Earths and Yellow Earths significantly increased soil organic C, improved soil pH buffering, increased the total P content and increased labile-P fractions that could be used for plant growth. The Walkley and Black organic C determination can be used as a suitable 'low tech', portable method for the determination of organic C to monitor soil organic matter levels.

Based on the results from the preliminary glasshouse trials, field trials were designed to establish relationships between P fertiliser form, application rate and soil P test levels for maize (*Zea mays*) and legumes (rice bean and black gram) grown in a Yellow Earth. In soils with initial Olsen-P values of approximately 8 kg P kg<sup>-1</sup> soil, two maize field trials consistently indicated that near maximum yield (90%) of maize can be obtained by application of water-soluble P fertiliser (Triple superphosphate, TSP) at 40 to 50 kg P ha<sup>-1</sup> in year one and reapplication of TSP at 25 kg P ha<sup>-1</sup> in year two. Phosphate supplied as FYM, *Tithonia diversifolia*, Chinese partially acidulated phosphate rock (CPAPR) and Sechura reactive phosphate rock (SPR) were agronomically less effective as short-term P sources for maize than TSP, with TSP substitution ratio of 0.1, 0.17, 0.61 and 0.07 respectively at an application of 40 kg P ha<sup>-1</sup> rate. A legume-wheat rotation field trial showed that rice bean (the legume) yield was significantly increased by the application of TSP at 40 kg P ha<sup>-1</sup> plus local dolomite. Subsequently, rice bean plots fertilised with 40 kg P ha<sup>-1</sup> as TSP produced the largest wheat grain yields in the Yellow Earth.

In all trials the Olsen-P test was a suitable soil P test for providing an index of plant-available P. Olsen-P values at which optimum crop growth occurred (90% maximum yield) ranged between 30 to 40 mg P kg<sup>-1</sup> in the Red Earths and Yellow Earths, depending on the season, plant age when harvested and crop grown.

Use of the sulphuric acid acidulated CPAPR and elemental S (S<sup>0</sup>) with SPR confirmed that plant growth in the Yellow Earths was very responsive to sulphur application. Chinese PAPR can be used as a cost-effective P and S fertiliser to increase the crop yield in these Red Earths and Yellow Earths, particularly where S is also deficient. Use of local dolomite (2.5 t ha<sup>-1</sup>) in the field trials caused significant increases in soil pH in the first season and in the legume-wheat trials resulted in increases in legume yield.

The research findings on soil P testing, alternative P sources and liming materials presented in this thesis are discussed in terms of the role they might have in the establishment of sustainable agriculture practice in Southern Shan State, Myanmar. Future research directions that should be taken to realise the productivity of these soils and farming systems are also discussed.

## ACKNOWLEDGEMENTS

I would like to express my appreciation to the following people and organizations because without their help and encouragement this thesis would not have been possible.

My supervisors; Assoc. Prof. Mike J. Hedley and Assoc. Prof. Nanthi S. Bolan (Massey University, New Zealand), and Dr. Rod D. B. Lefroy (International Board for Soil Research and Management (IBSRAM), Thailand), for their guidance, encouragement and valuable suggestions, I am extremely grateful.

My former supervisor Dr. Robert J. K. Myers (International Crops Research Institute for Semi-Arid Tropics (ICRISAT), India), who help me to initiate studies in Soil Science at Massey University, thank you for your encouragement.

Dr Nyi Nyi (MAS-Land Use Department, Myanmar) for his encouragement and support, and my colleagues at Shan State for their help while I was in Myanmar.

Lance Currie (Fertilizer and Lime Research Centre, Massey University, New Zealand), for the MAF import permit for soil and plant samples from Myanmar.

Carolyn Hedley (Landcare Research, Palmerston North, New Zealand) for her help with analysing Leco Carbon.

All the staff and postgraduate students of the Soil and Earth Sciences Group, Massey University, for their assistance and friendship throughout the course of my study, including: Mrs Denise Brunskill and Mrs Hera Kennedy for their assistance; Ann West, Glenys Wallace, Bob Toes, Ian Furkert and Ross Wallace for their helpful advice and assistance with laboratory work; Mike Bretherton for helping with computer; Stephen Trolove (proof-reading), Asoka Senerath, Afiquir Khan and Qianhe Liu for their comments and morale support.

Ann and Warren Woodgyer, Jolanda and James Hanly, Sri Wlai and Brian Payne, for their tremendous support and encouragement.

The Ministry of Foreign Affairs and Trade of New Zealand, for the scholarship grant, the ASIALAND management of Acid soils network of IBSRAM, and Fertilizer and Lime Research Centre of Massey University, for financial and technical support during my studies. The Open Society Institute, USA, for the Supplementary Grant awarded in 2000 and 2001.

Finally, but most importantly, my late mother Baby Khin Nyein, my father Shwe Mra, my wife Yuzana for being an excellent support, and my children Phway Su Aye and Pyone Su Aye, for being patience and loving during my time of study in New Zealand.

## TABLE OF CONTENTS

ABSTRACT .....	II
ACKNOWLEDGEMENTS.....	V
TABLE OF CONTENTS.....	VII
LIST OF FIGURES .....	XIX
LIST OF TABLES.....	XXVII
LIST OF PLATES .....	XXXII
LIST OF MAPS .....	XXXIII

### CHAPTER 1 Developing Sustainable Soil fertility in Southern Shan State of Myanmar: General Information ..... 1

1.1	Introduction .....	1
1.2	Objectives.....	2
1.3	Location, Climate and Natural Vegetation.....	2
1.4	Population and Land area for Cultivation .....	3
1.5	Soil Resources .....	6
1.6	A survey of current farming systems.....	7
1.6.1	Farmers' attitudes and their options.....	10
1.6.2	Common cropping pattern.....	11
1.6.3	Farmers' Agronomic Practices .....	12
1.7	Discussion of constraints to crop production .....	13
1.8	Possible solutions to soil fertility constraints.....	15
1.8.1	Increasing soil P status.....	15
	<i>Water-soluble P fertilisers</i> .....	16
	<i>Phosphate rocks</i> .....	16
	<i>Partially water-soluble P fertilisers</i> .....	17
	<i>Advantages and disadvantages of using PR or high analysis soluble P         fertiliser</i> .....	18
	<i>Integrated nutrient management</i> .....	19
1.8.2	Reducing soil acidity.....	19
	<i>Liming materials available in Southern Shan State</i> .....	21
1.8.3	Crop rotations with legumes.....	22

1.8.4	Potential organic inputs as green manure.....	24
1.8.5	Integrating livestock.....	25
1.9	Conclusions .....	26

## **CHAPTER 2 Characterisation of Soil Resources ..... 29**

2.1	Introduction .....	29
2.2	Objectives.....	31
2.3	Materials and Methods.....	31
2.3.1	Description and classification of soil profiles .....	31
2.3.2	Soil samples.....	31
2.3.3	Soil chemical analysis .....	32
2.4	Results and Discussion.....	33
2.4.1	Soil classification.....	35
	<i>Profile 1: Aungban Soil</i> .....	35
	Site description and information on the site .....	35
	General information on the soil .....	35
	Profile Description.....	36
	<i>Profile 2: Thayetkon Soil</i> .....	36
	Site description and information on the site .....	36
	General information on the soil: .....	37
	Profile Description .....	37
2.4.2	Major soil grouping of Red Earths and Yellow Earths.....	38
	<i>The soil units of the Red Earths and the Yellow Earths</i> .....	39
2.4.3	Soil pH .....	40
2.4.4	Olsen-P .....	41
2.4.5	P retention .....	41
2.4.6	Conductivity and soils soluble salts.....	42
2.4.7	Soil C and SOM.....	42
2.4.8	Exchangeable cations.....	43
2.4.9	Effective cation exchange capacity, Al <sup>3+</sup> saturation and %BS.....	44
2.4.10	Total N .....	45
2.4.11	Mineralisable N .....	46
2.4.12	Total P .....	47
2.4.13	Limitations and potential use of Red Earths and Yellow Earths.....	49
2.5	Conclusions .....	52

<b>CHAPTER 3</b>	<b>Lime and Phosphorus Responsiveness of the Red Earths and Yellow Earths: A Glasshouse Study .....</b>	<b>54</b>
3.1	Introduction .....	54
3.2	Objectives.....	55
3.3	Materials and methods .....	56
3.3.1	Characterisation of fertilisers, manures and the liming agent.....	56
	<i>Phosphorus fertilisers</i> .....	56
	Triple superphosphate (TSP).....	56
	Myanmar phosphate rock (MPR).....	56
	<i>Relative reactivity of MPR</i> .....	57
	Assessment of the chemical reactivity of PR for direct application .....	58
	<i>Local dolomite</i> .....	59
	Liming agent.....	59
	Neutralising Value or Calcium Carbonate Equivalent .....	60
3.3.2	Experiment (1): Agronomic effectiveness of MPR and dolomite on pigeon pea growth in a Yellow Earth.....	61
	<i>Test crop used and seed germination</i> .....	61
	<i>Soils</i> .....	61
	<i>Phosphorus fertilisers</i> .....	62
	Local dolomite.....	62
	<i>Lime and fertiliser requirements</i> .....	62
	<i>Preparation of soil, fertiliser application and layout of pots</i> .....	62
	<i>Design of Experiment (1)</i> .....	63
	<i>Treatments</i> .....	63
	Basal fertilisers .....	64
	<i>Planting and harvesting</i> .....	64
	<i>Herbage and soil analysis</i> .....	65
3.3.3	Experiment (2): Agronomic effectiveness of local FYM and MPR on upland rice growth in a Yellow Earth .....	66
	<i>Test crop and seed germination</i> .....	66
	<i>Soils</i> .....	66
	<i>Phosphorus and N fertilisers used</i> .....	66
	<i>Preparation of soil, fertiliser application and layout of pots</i> .....	66
	<i>Treatments</i> .....	67

	<i>Planting and harvesting</i> .....	68
3.3.4	Experiment (3): Effect of initial soil Olsen-P levels on the growth of tropical legumes in Red Earths and Yellow Earths.....	69
3.3.5	Test crop.....	69
	<i>Soils</i> .....	69
	<i>Phosphorus fertiliser used</i> .....	70
	<i>Preparation of soil, fertiliser application, and layout of pots</i> .....	70
	<i>Treatments</i> .....	70
	<i>Planting and harvesting</i> .....	71
3.3.6	Statistical analysis.....	72
3.4	Results .....	72
3.4.1	Experiment (1): Agronomic effectiveness of MPR, TSP and dolomite on pigeon pea growth in a Yellow Earth.....	72
	<i>Dry matter yield of pigeon pea</i> .....	72
	<i>Soil pH and Olsen-P</i> .....	73
	<i>Relationship between soil Olsen-P and DM yield of pigeon pea</i> .....	75
	<i>Root nodulation of pigeon pea</i> .....	77
3.4.2	Experiment (2): Agronomic effectiveness of local FYM and MPR on upland rice growth in a Yellow Earth .....	78
	<i>Dry matter yield of upland rice</i> .....	78
	<i>Soil pH and Olsen-P</i> .....	79
3.4.3	Experiment (3): Effect of initial soil Olsen-P values on the growth of tropical legumes in Red Earths and Yellow Earths.....	80
	<i>Dry matter yields of pigeon pea grown in Red Earths and Yellow Earths</i> .....	80
	<i>Root nodulation of pigeon pea</i> .....	82
	<i>Dry matter yields of rice bean grown in pots of Red Earth</i> .....	82
	<i>Root nodulation of rice bean</i> .....	83
3.5	Discussion .....	84
	<i>Estimation of optimum P status and P responsiveness of Yellow Earth</i> .....	84
	<i>Nitrogen and P requirements for upland rice</i> .....	86
	<i>Optimum Olsen-P values for pigeon pea and rice bean</i> .....	86
	<i>The suitability of the Yellow Earth for direct PR use</i> .....	87
	<i>Local dolomite as an effective liming agent</i> .....	89
	<i>Effect of N inputs on upland rice yield</i> .....	89

3.6	Conclusions .....	90
-----	-------------------	----

## **CHAPTER 4 Evaluating Organic Amendments for Building Soil Organic Matter and Phosphorus Reserves in Red Earths and Yellow Earths ..... 92**

4.1	Introduction .....	92
4.1.1	Factors leading to change in SOM content .....	93
4.1.2	Beneficial effects of SOM.....	94
	<i>Soil physical properties</i> .....	94
	<i>Nutrient source (N, P, S)</i> .....	96
	<i>Cation exchange capacity (CEC)</i> .....	99
	<i>pH buffering and detoxification of Al in low pH soils</i> .....	99
	<i>Other positive effects</i> .....	100
4.1.3	Focus on soils of the study area.....	101
4.2	Experimental design.....	102
4.3	Experimental Objectives .....	103
4.4	Materials and methods .....	103
4.4.1	Soil samples.....	103
4.4.2	Organic amendments .....	103
	<i>Ash-alkalinity of organic amendments</i> .....	104
4.4.3	Incubation of soils.....	104
4.4.4	Part 1. Evaluation of C in soils, organic materials and soils mixed with organic materials .....	105
	<i>Brief review of methods</i> .....	105
	<i>Methods adopted for evaluation</i> .....	106
4.4.5	Part 2. Effect of the organic matter amendments on soil C content .	107
4.4.6	Part 3. Effect of the organic matter amendments on soil N and soil pH. ....	107
4.4.7	Part 4. Effect of the organic matter amendments on soil P .....	107
	<i>Sequential extraction of soil P fractions</i> .....	108
	Ion exchange membranes .....	109
4.4.8	Statistical analysis.....	111
4.5	Part 1. Evaluation of the Walkley-Black procedure for a wide range of soils and organic amendments .....	111

4.5.1	Results .....	111
	<i>Soils without amendments</i> .....	111
	<i>Dry soil mixed with organic materials</i> .....	114
	<i>Soils after incubation with organic materials</i> .....	115
	<i>Organic materials alone</i> .....	116
4.5.2	Discussion .....	118
	<i>Common relationships for soils and soils incubated with organic materials</i> .....	120
4.6	Part 2. Use of the Walkley-Black method to measure changes in soil C after amendment of soil with organic materials.....	121
4.6.1	Results .....	121
	<i>Initial soils</i> .....	121
	<i>Effect of organic amendment</i> .....	121
	<i>Effect of soil type on changes in soil C</i> .....	124
4.6.2	Discussion .....	124
4.7	Part 3. Effect of organic amendments on changes in N and pH in soils. .....	125
4.7.1	Results .....	125
	<i>Changes in soil N</i> .....	125
	<i>Changes of soil pH</i> .....	127
4.7.2	Discussion .....	129
4.8	Part 4. Effect of organic amendments on soil P fractions.....	130
4.8.1	Results .....	130
	<i>Effect of amendments</i> .....	130
	Resin-Pi.....	131
	0.1 M NaOH-Pi.....	131
	0.1 M NaOH-Po.....	132
	1 M NaOH-Pi .....	133
	1 M NaOH-Po.....	133
	0.5 M H <sub>2</sub> SO <sub>4</sub> -Pi .....	134
	Residual-P .....	134
	Total P.....	135
	Labile-Pi.....	136
	Labile-Po.....	137
	<i>Effect of soils</i> .....	138
	Labile-Pi.....	138

Labile-Po .....	138
4.8.2 Discussion .....	139
4.9 Conclusions .....	140
<i>Part 1</i> .....	140
<i>Part 2</i> .....	141
<i>Part 3</i> .....	141
<i>Part 4</i> .....	141

## **CHAPTER 5 Plant-induced Changes to Rhizosphere Soil by Seven Sub-tropical Legume Species Grown in Low pH Red Earth..... 143**

5.1 Introduction .....	143
5.1.1 Legumes grown in Myanmar .....	144
5.2 Objectives.....	145
5.3 Materials and methods .....	145
5.3.1 Soils.....	145
5.3.2 Legume growth in rhizosphere study containers (RSC).....	146
<i>Soil and Fertiliser</i> .....	147
<i>Relative reactivity of SPR</i> .....	147
<i>Seed preparation, pre-germination and sowing</i> .....	148
<i>Plant care</i> .....	148
5.3.3 Harvesting of legume crops and soil sectioning of RSC .....	150
5.3.4 Nodule and root length measurements.....	151
5.3.5 Plant analysis.....	152
<i>Ash-alkalinity of legume shoots</i> .....	152
<i>Cation uptake excess</i> .....	152
5.3.6 Soil analysis.....	152
<i>Preliminary standardisation of P fractionation</i> .....	152
<i>Rhizosphere pH and sequential P fractionation</i> .....	153
5.3.7 Statistical analysis.....	153
5.4 Results and discussion .....	153
5.4.1 Dry matter yield, root length and nodule formation .....	153
<i>Nitrogen uptake</i> .....	155
5.4.2 Plant nutrients and cation excess in legumes .....	156

	<i>Cation uptake excess</i> .....	156
	<i>The relationship between dry matter and cation excess</i> .....	158
	<i>The relationship between cation excess and N concentration</i> .....	159
5.4.3	Ash-alkalinity .....	161
	<i>Ash-alkalinity compared to cation excess</i> .....	161
5.4.4	Soil pH .....	163
	<i>Observed acid or H<sup>+</sup> production</i> .....	168
	<i>Acid (H<sup>+</sup>) consumption by SPR dissolution</i> .....	169
	<i>Total acid (H<sup>+</sup>) production</i> .....	170
5.4.5	Interrelationship among N forms, cation excess and H <sup>+</sup> production into rhizosphere.....	170
5.5	Soil P fractionations of Red Earth and Ramiha hill soils.....	174
5.5.1	P fraction in native soils (without SPR added).....	174
	Resin-P.....	175
	Alkali-P.....	175
	H <sub>2</sub> SO <sub>4</sub> -P.....	175
	Residual-P .....	176
5.5.2	P fractions in the Red Earth and Ramiha hill soils mixed with SPR	176
5.6	Effect of legumes on soil P fractions in Red Earth.....	177
5.6.1	Effect of plant species on rhizosphere pH.....	177
5.6.2	Depletion of P fractions .....	178
	<i>Effect of legume species on P utilisation efficiency</i> .....	183
5.7	Conclusions .....	184

## **CHAPTER 6 Effect of Different Sources of Phosphorus Fertilisers on Maize Growth and their Residual Value ..... 186**

6.1	Introduction .....	186
6.2	Objective of this experiment .....	188
6.3	Materials and Methods.....	188
6.3.1	Experimental site description .....	188
	<i>Location</i> .....	188
	<i>Topography and climate</i> .....	189
	<i>Soil characteristics</i> .....	190
6.3.2	Establishment of maize experiment.....	190

	<i>Experimental design and treatment</i> .....	190
6.3.3	Review of P fertiliser sources.....	192
	<i>Agronomic effectiveness of PAPR</i> .....	192
	<i>Wild sunflower (Tithonia diversifolia) as a potential green manure</i> .....	193
	<i>Nature of common FYM in Southern Shan State</i> .....	195
	<i>P fertiliser sources used in field trials (1998 and 1999)</i> .....	195
	<i>Nitrogen and K fertilisers (1998 and 1999)</i> .....	196
	<i>Other fertilisers, rate and application (1999)</i> .....	196
	Application method of fertilisers (1998 and 1999) .....	197
	<i>Soil samples</i> .....	197
	<i>Herbage samples</i> .....	197
	<i>Substitution ratio (SR) of P fertiliser</i> .....	197
	<i>Statistical analysis</i> .....	198
	<i>Biosecurity</i> .....	198
6.4	Results and Discussion.....	198
6.4.1	Maize field trial results in 1998.....	198
6.4.2	Effect of P fertilisers on soil P test values.....	198
	<i>Effect of P fertilisers on soil pH</i> .....	200
	<i>Effect of P fertilisers on DM yield of maize</i> .....	201
	<i>Relationship between soil Olsen-P status and DM yield of maize in 1998..</i>	204
6.4.3	Maize field trial results in 1999.....	206
	<i>Effect of P fertilisers on soil P test values (1999)</i> .....	206
	<i>Relationship between Olsen-P values and maize yield in 1999</i> .....	206
	<i>Effect of P fertilisers on DM yield of maize (1999)</i> .....	209
	Grain yield of maize at harvest 1999.....	211
6.4.4	General discussion .....	212
	<i>Residual effect of TSP fertilisers</i> .....	213
	Olsen-P values and yields.....	213
	Residual fertiliser P effects on maize yields .....	214
	<i>Residual effect of organic fertilisers</i> .....	219
	Organic fertiliser effects on maize yield.....	219
	Organic fertiliser effects on Olsen-P.....	219
	<i>Effect of local dolomite</i> .....	220
6.5	Conclusion.....	220

## **CHAPTER 7 The Effect of Phosphate Fertiliser Form and Application Rate on the Yield Response of Maize Grown in a Yellow Earth ..... 223**

7.1	Introduction .....	223
	<i>The important role of elemental S (S<sup>0</sup>) used in agriculture</i> .....	224
7.2	Objectives.....	225
7.3	Materials and Methods.....	226
7.3.1	Experimental site description .....	226
	<i>Location</i> .....	226
	<i>Topography and climate</i> .....	226
	<i>Soil type and characteristics</i> .....	226
	<i>P fertiliser sources</i> .....	226
	<i>Elemental S</i> .....	227
	<i>Nitrogen, K and other fertilisers</i> .....	227
7.3.2	Experimental design and treatments .....	227
7.3.3	Cultivation and crop establishment.....	228
	<i>Application of fertilisers</i> .....	228
	<i>Soil samples</i> .....	228
	<i>Chemical analysis of soil and herbage</i> .....	229
	<i>Relative agronomic effectiveness of CPAPR, SPR and FYM</i> .....	229
	<i>Statistical analysis</i> .....	230
7.4	Results and discussion .....	230
7.4.1	Effect of P fertilisers on Olsen-P test values .....	231
7.4.2	Effect of P fertilisers on maize yield .....	234
	<i>Relationships between Olsen-P values and maize yield</i> .....	240
	<i>General discussion</i> .....	242
	<i>Relative agronomic effectiveness of CPAPR, SPR and FYM</i> .....	243
	<i>Effect of elemental S</i> .....	245
7.5	Conclusion.....	246

## **CHAPTER 8 Managing of Phosphorus Fertilisers and Legume Crop Management on a Yellow Earth..... 248**

8.1	Introduction .....	248
-----	--------------------	-----

8.1.1	Legume green manure.....	249
	<i>Green manure N and P contribution to subsequent crop</i> .....	249
8.1.2	Nitrogen and phosphorus requirements of wheat.....	250
8.2	Experimental Objectives.....	250
	<i>Site of field experiment</i> .....	251
	<i>Treatments</i> .....	251
	<i>Fertiliser treatments</i> .....	252
	Part (1): Green manure crop production.....	252
	Part (2): Wheat crop production.....	253
	Sowing and harvesting of wheat.....	253
	<i>Soil sampling</i> .....	253
	<i>Plant and grain sampling</i> .....	254
	<i>Soil analysis</i> .....	254
	<i>Plant analysis</i> .....	254
	<i>Climatic data</i> .....	254
8.3	Results.....	255
8.3.1	Part (1): Green manure crops production.....	255
	<i>Establishment of legume green manures</i> .....	255
	<i>Yield of legume green manures</i> .....	256
	<i>Legume grain yield</i> .....	257
	<i>Green manure N and P status and C:N ratio</i> .....	258
	<i>Relationship between soil Olsen-P test and DM yield of green manures</i> .....	259
	<i>Effect of P fertiliser and dolomite on soil pH at different times of green manure growth</i> .....	261
8.3.2	Part (2): Wheat crop production.....	263
	<i>Effect of incorporating green manures on wheat yield at 21 DAE, at heading and at harvest</i> .....	263
	<i>Relationship between green manure N and P accumulation and wheat straw and grain yields at harvest</i> .....	264
	<i>Effect of P fertiliser and the incorporation of green manures on available P status in soil</i> .....	267
	<i>Effect of incorporating green manures on soil pH during the wheat growth</i> .....	270
	<i>Relationship between total N and P uptake of wheat and available Olsen-P status at 21 DAE of wheat</i> .....	270
	<i>Effect of green manure N and C:N ratio on wheat N uptake at harvest</i> .....	272

	<i>Economic consideration of alternative use of legume green manure .....</i>	275
8.4	Conclusion.....	277
<b>CHAPTER 9 Summary, Conclusions and Suggestions for Future Work .....</b>		<b>278</b>
9.1	Current farming practice .....	278
9.2	Soil resources.....	278
9.3	Preliminary soil fertility research .....	279
9.4	Maize trials (1998 and 1999).....	280
	<i>Optimum Olsen-P test values.....</i>	<i>281</i>
	<i>Agronomic value of alternative P sources.....</i>	<i>281</i>
9.5	Legume trials .....	282
9.6	Summary of amounts of P required to raise Olsen-P test to optimum levels for crop growth .....	282
9.7	Dolomite responsive of crops.....	284
9.8	Sulphur responsive of crops .....	284
9.9	Alternative use of legume green manure .....	285
9.10	Future work .....	285
<b>REFERENCES</b>		<b>287</b>
<b>APPENDIX</b>		<b>312</b>

## LIST OF FIGURES

Figure 1.1 Monthly rainfall (mm) and temperature ( $^{\circ}\text{C}$ ) in Southern Shan State, average of five years (1994-1998). .....	3
Figure 1.2 Schematic presentation of the thesis structure.....	28
Figure 2.1 Relationship between SOM (%) and ECEC ( $\text{cmol (+) kg}^{-1}$ soil) for the Red Earths and Yellow Earths in this study. ....	45
Figure 2.2 The relationship between total N (%) and mineralizable N ( $\text{mg kg}^{-1}$ soil) in Red Earths and Yellow Earths. ....	47
Figure 2.3 The relationship between total P ( $\text{mg P kg}^{-1}$ soil) and Olsen-P ( $\text{mg P kg}^{-1}$ soil) for Red Earths and Yellow Earths.....	48
Figure 3.1 Effects of different rates of P applied as MPR and TSP on DM yield of pigeon pea growing in pots of Yellow Earth (LSD=0.41). Columns are means of 3 data points.....	73
Figure 3.2 Effects of MPR and TSP application at different rates on Olsen-P values of a Yellow Earth (9 weeks after application).....	75
Figure 3.3 Effects of Olsen-P on DM yield of pigeon pea growing in pots of Yellow Earth. ....	76
Figure 3.4 Relationships between the actual yield of pigeon pea and the yield predicted using Olsen values and Olsen response curve of TSP fertilised pots (Figure 3.3) for MPR alone and MPR plus K addition treatments. ....	77
Figure 3.5 Effect of P addition to Red Earths and Yellow Earths on DM yield of pigeon pea (columns are soil treatment means across all initial Olsen-P values). The error bar is the LSD of mean ( $P < 0.05$ ). ....	81
Figure 3.6 Relationships between the DM yield response ( $\Delta$ yield 80 P – 0 P) of pigeon pea and initial Olsen-P values of Red Earths and Yellow Earths. ....	81
Figure 3.7 Relationships between the DM yield response ( $\Delta$ yield 80 P – 0 P) of rice bean yield and initial Olsen-P values of Red Earths. ....	83
Figure 4.1 A simple model of soil organic matter dynamics (Massey University, 2000). .....	93
Figure 4.2 The relationship between C determined by the Leco and Walkley-Black methods for 20 samples of Red Earths and Yellow Earths (intercept is non-significant). ....	112

Figure 4.3 The relationship between weight loss on ignition and Leco OM for Red (◇) and Yellow (◆) Earths.....	112
Figure 4.4 The relationship between weight loss on ignition (LOI) and Walkley-Black OM for Red (◇) and Yellow (◆) Earths. ....	114
Figure 4.5 The relationship between C determined by the Leco and Walkley-Black methods from 6 samples (see Table 4.5 for treatment codes) of dry soils mixed with different organic materials (intercept is non-significant). ....	115
Figure 4.6 The relationship between C determined by the Leco and Walkley-Black methods for 16 samples of incubated soils with different organic materials (intercept is non-significant).....	116
Figure 4.7 The relationship between C determined by the Leco C and Walkley-Black methods for seven samples of organic materials (see Table 4.5 for material code). ....	117
Figure 4.8 The relationship between weight loss on ignition (LOI) and Leco OM for a range of organic materials (see Table 4.5 for material code). ....	117
Figure 4.9 The relationship between weight loss on ignition (LOI) and Walkley-Black OM for a range of organic materials (see Table 4.5 for material code).....	118
Figure 4.10 The relationship between determined C by Leco C and Walkley-Black C from 36 samples including incubated and initial soils. ....	121
Figure 4.11 Effect of incubating (6 months) organic amendments with Red Earths and Yellow Earths on Walkley-Black C content (Main effect of adding organic amendment across all soils). The bar is the LSD of mean. ....	122
Figure 4.12 The relationship between soil organic C (● Walkley-Black) and soil N (Kjeldahl) in Red Earths and Yellow Earths (○ Walkley-Black values × 1.29 correction factor).....	126
Figure 4.13 The effect of organic amendments on the pH (1:2.5 in water) of Red Earths and Yellow Earths at the end of the incubation period (The error bar is the LSD for main effect on soil means, $\alpha=0.05$ ). ....	129
Figure 4.14 The amount of resin-Pi in Red Earths and Yellow Earths incubated alone (CON) or with organic amendment (See Table 4.5). The error bar is the LSD ( $\alpha=0.05$ ) between the soil means. ....	131
Figure 4.15 (a) The amount of 0.1 M NaOH-Pi and (b) the amount of 0.1 M NaOH-Po, in Red Earths and Yellow Earths incubated alone (CON) or with an organic	

amendment (See Table 4.5). The error bar is the LSD ( $\alpha=0.05$ ) between the soil means.....	132
Figure 4.16 (a) The amount of 1 M NaOH-Pi, (b) the amount of 1 M NaOH-Po, in Red Earths and Yellow Earths incubated alone (CON) or with an organic amendment (See Table 4.5). The error bar is the LSD ( $\alpha=0.05$ ) between the soil means. ....	133
Figure 4.17 The amount of 0.5 M H <sub>2</sub> SO <sub>4</sub> -Pi in Red Earths and Yellow Earths incubated alone (CON) or with organic amendment (See Table 4.5). The error bar is the LSD ( $\alpha=0.05$ ) between the soil means. ....	134
Figure 4.18 The amount of residual-P in Red Earths and Yellow Earths incubated alone (CON) or with organic amendment (See Table 4.5). The error bar is the LSD ( $\alpha=0.05$ ) between the soil means. ....	135
Figure 4.19 The amount of total-P in Red Earths and Yellow Earths incubated alone (CON) or with organic amendment (See Table 4.5). The error bar is the LSD ( $\alpha=0.05$ ) between the soil means. ....	136
Figure 4.20 (a) The amount of labile-Pi (resin-Pi + 0.1 M NaOH-Pi) (b) The amount of labile-Po in Red Earths and Yellow Earths incubated with and without (CON) organic amendment (means of all soils). The error bar is the LSD ( $\alpha=0.05$ ) between the soil means. See Table 4.5 for treatment code.....	137
Figure 4.21 (a) The amount of labile-Pi (resin-Pi + 0.1 M NaOH-Pi) (b) The amount of labile-Po in Red Earths and Yellow Earths incubated alone (CON) or with organic amendment (See Table 4.5). The error bar is the LSD ( $\alpha=0.05$ ) between the soil means.....	138
Figure 4.22 The amount of change in P fraction as % P added in Red Earths and Yellow Earths incubated with and without (CON) organic amendment (means of all soils). See Table 4.5 for treatment code. ....	140
Figure 5.1 Schematic representation of the rhizosphere study container (RSC) technique.....	149
Figure 5.2 The relationship between DM yields RSC <sup>-1</sup> (g) and cation excess (mmol <sub>c</sub> RSC <sup>-1</sup> ) of legume shoots (All three replications are included for each legume species). ....	159
Figure 5.3 The relationship between N concentration (cmol kg <sup>-1</sup> ) and cation excess (cmol(+) kg <sup>-1</sup> ) of legume shoots. ....	160
Figure 5.4 The relationship between N uptake (mmol RSC <sup>-1</sup> ) and cation excess (mmol (+) RSC <sup>-1</sup> ) of legume shoots. ....	160

Figure 5.5 The relationship between ash-alkalinity ( $\text{cmol (+) kg}^{-1}$ ) and cation excess ( $\text{cmol (+) kg}^{-1}$ ) of legume shoots. ....	162
Figure 5.6 The relationship between DM of legume shoots and their rhizosphere pH. ....	167
Figure 5.7 The relationship between ash-alkalinity ( $\text{mmol RSC}^{-1}$ ) of legume shoots and their rhizosphere pH. ....	167
Figure 5.8 The relationship between cation excess ( $\text{mmol RSC}^{-1}$ ) of legume shoots and their rhizosphere pH. ....	168
Figure 5.9 pH buffering curve of the composite Red Earth used in this study. ....	168
Figure 5.10 P fractions in SPR fertilised and unfertilised air-dried Red Earth and Ramiha soils immediately after the addition of RPR at the rate of $125 \mu\text{g P g}^{-1}$ soil. ....	174
Figure 5.11 Effect of legume species on rhizosphere pH at harvest. ....	178
Figure 5.12 The effect of plant species on various P fractions in the rhizosphere (a) Resin-P, (b) $0.1 \text{ M NaOH-Pi}$ , (c) $0.1 \text{ M NaOH-Po}$ , (d) $1 \text{ M NaOH-Pi}$ . ....	179
Figure 5.13 The effect of plant species on various P fractions in the rhizosphere: (e) $1 \text{ M NaOH-Po}$ , (f) $0.5 \text{ M H}_2\text{SO}_4\text{-Pi}$ (g) Residual-P, (h) Total-P. ....	180
Figure 5.14 Weak Alkali-Pi (Resin-P+ $\text{NaOH-Pi}$ ) fraction of the rhizosphere soil and soil dry mixed with SPR (initial alkali-Pi). ....	181
Figure 5.15 Weak Alkali-Pi (Resin-P+ $\text{NaOH-Pi}$ ) fraction of the bulk soil and soil dry mixed with SPR (initial alkali-Pi). ....	181
Figure 5.16 Weak Alkali-Po ( $\text{NaOH-Po}$ ) fraction of the rhizosphere soil and soil dry mixed with SPR (initial alkali-Po). ....	182
Figure 5.17 Weak Alkali-Po ( $\text{NaOH-Po}$ ) fraction of the bulk soil and soil dry mixed with SPR (initial alkali-Po). ....	182
Figure 5.18 $\text{H}_2\text{SO}_4\text{-Pi}$ fraction of the rhizosphere soil and soil dry mixed with SPR (initial $\text{H}_2\text{SO}_4\text{-Pi}$ ). ....	183
Figure 5.19 $\text{H}_2\text{SO}_4\text{-Pi}$ fraction of the bulk soil and soil dry mixed with SPR (initial $\text{H}_2\text{SO}_4\text{-Pi}$ ). ....	183
Figure 6.1 Temperature (maximum and minimum $^{\circ}\text{C}$ ) and rainfall distribution (mm) for Aungban Reserch Station during January 1998 to December 1999. ....	189
Figure 6.2 Planting spacing on an experimental plot (20 planting hills by 8 rows) and the key symbols of plants sampled at 21DAE (3), silking (S) and final harvest (H). ....	191

Figure 6.3 The effects of different P fertilisers of 20 and 40 kg P ha <sup>-1</sup> rate on Olsen-P test values at 21 DAE of maize (1998).....	199
Figure 6.4 The effects of P rates on dry matter yield of maize at silking in June planting 1998.....	203
Figure 6.5 The effects of P rates on maize grain yield at harvest in June planting 1998. ....	204
Figure 6.6 The relationship between soil Olsen-P value at 21 DAE and maize DM yield at silking in June planting 1998 (● = TSP response curve). ....	205
Figure 6.7 The relationship between soil Olsen-P value at 21 DAE and maize grain yield at harvest in June planting 1998 (● = TSP response curve). ....	205
Figure 6.8 Long-term effect of organic manures and TSP applied at 20 kg P ha <sup>-1</sup> on Olsen-P soil test values.....	207
Figure 6.9 The relationship between soil Olsen-P value at 21 DAE and maize DM yield at silking in 1999 (●= TSP response curve). ....	208
Figure 6.10 The relationship between soil Olsen-P value at 21 DAE and maize grain yield at harvest from June 1999 planting (● = TSP response curve). ....	208
Figure 6.11 The effects of P rates on maize dry matter yield at silking from the June 1999 planting (● = TSP response curve). ....	210
Figure 6.12 The effects of P rates on grain yield at harvest from June 1999 planting (● = TSP response curve).....	211
Figure 6.13 The effects of P added as TSP rates on Olsen-P values at initial and 21 DAE of maize planting in 1998 and 1999.....	213
Figure 6.14 The percentage relative yield response of maize to P applied as TSP in 1998 and 1999. ....	215
Figure 6.15 The maize grain yield produced by different rates of TSP in 1998 and 1999. ....	216
Figure 6.16 The relationship between the rate of TSP applied (kg ha <sup>-1</sup> ) and percent residual value of TSP. ....	217
Figure 6.17 The relationship between the application rate of P (kg ha <sup>-1</sup> ) and percentage efficiency of P fertiliser use (TSP).....	218
Figure 7.1 Temperature (maximum and minimum °C) and Rainfall (mm) for the Maize Field Trial 2 growing periods at Aungban Research Farm (1999).....	230
Figure 7.2 The effects of P fertiliser forms and rates on soil Olsen-P at 21 DAE of maize in June planting 1999 (Field Trial 2).....	233

Figure 7.3 The increase in $\Delta$ Olsen-P values at 21 DAE caused by the addition of P as (a) water-soluble applied P ( $\text{kg P ha}^{-1}$ ) and (b) citric-soluble applied P ( $\text{kg P ha}^{-1}$ ) (Field Trial 2).....	235
Figure 7.4 The effects of P rates on dry matter yield of maize at silking in Field Trial 2 June 1999 planting. ....	236
Figure 7.5 The effects of P rates on maize stover yield at harvest in June planting 1999 (Field Trial 2).....	237
Figure 7.6 The effects of P rates on maize grain yield at harvest in June planting 1999 (Field Trial 2). Lines in this figure are estimated for SR values of P fertilisers...	238
Figure 7.7 The effects of P added as water-soluble P ( $\text{kg P ha}^{-1}$ ) on maize grain yield ( $\text{kg ha}^{-1}$ ) in Field Trial 2. ....	239
Figure 7.8 The effects of P added as citric-soluble P ( $\text{kg P ha}^{-1}$ ) on maize grain yield ( $\text{kg ha}^{-1}$ ) in Maize Field Trial 2.....	239
Figure 7.9 The relationships between Olsen-P values at 21 DAE and maize DM yield at silking stage in June planting 1999 (Field Trial 2) ( $\bullet$ = TSP data point for every plot). ....	241
Figure 7.10 The relationships between Olsen-P values at 21 DAE and maize grain yield at harvest in June planting 1999 (Field Trial 2).....	242
Figure 7.11 The effect of S with SPR on stover and grain yield of maize. (The error bar is the LSD ( $\alpha=0.05$ ) between three replicates).....	246
Figure 8.1 Rice bean and black gram DM yields influenced by rate of TSP and dolomite application to a Yellow Earth in Southern Shan State, Myanmar. The error bar is the standard error between the replicates. ....	256
Figure 8.2 The effect of dolomite and P application on black gram bean yields on a Yellow Earth in Southern Shan State, Myanmar. The error bar is the standard error between the replicates. ....	258
Figure 8.3 The relationships between Olsen-P values at 45 DAE and DM yield of rice bean grown in the field trial.....	260
Figure 8.4 The relationships between Olsen-P values at 45 DAE and DM yield of black gram in the field trial. ....	260
Figure 8.5 The effect of P fertiliser and dolomite on soil pH during green manure (at initial, at 45 DAE and at harvest) and wheat growth (at 21 DAE and at heading). ....	262

Figure 8.6 The wheat straw yield ( $\text{kg ha}^{-1}$ ) at harvest plotted against the amount of P applied ( $\text{kg P ha}^{-1}$ ) in green manure. ....	264
Figure 8.7 The wheat straw yield ( $\text{kg ha}^{-1}$ ) at harvest plotted against the amount of N applied ( $\text{kg N ha}^{-1}$ ) in green manure. ....	265
Figure 8.8 The wheat grain yield ( $\text{kg ha}^{-1}$ ) at harvest plotted against the amount of P applied ( $\text{kg P ha}^{-1}$ ) in green manure. ....	265
Figure 8.9 The wheat grain yield ( $\text{kg ha}^{-1}$ ) at harvest plotted against the amount of N applied ( $\text{kg N ha}^{-1}$ ) in green manure. ....	266
Figure 8.10 Effect of P applied (with or without dolomite) and the seedbed incorporation of rice bean on soil Olsen-P status at the different times.....	268
Figure 8.11 Effect of P applied (with or without dolomite) and the seedbed incorporation of black gram on soil Olsen-P status at the different times. ....	268
Figure 8.12 Effect of fallow and P applied after weed incorporation on soil Olsen-P status at the different times. ....	269
Figure 8.13 The relationship between P added ( $\text{kg P ha}^{-1}$ ) in green manure and elevation of Olsen-P ( $\text{mg P kg}^{-1}$ ) during the period between the green manure harvest and 21 DAE of wheat. ....	270
Figure 8.14 The relationship between total N uptake ( $\text{kg N ha}^{-1}$ ) of wheat and Olsen-P status ( $\text{mg P kg}^{-1}$ soil) at 21 DAE of wheat, grown in a Yellow Earth. ....	271
Figure 8.15 The relationship between total P uptake ( $\text{kg P ha}^{-1}$ ) of wheat and Olsen-P status ( $\text{mg P kg}^{-1}$ soil) at 21 DAE of wheat, grown in a Yellow Earth. ....	271
Figure 8.16 Relationship between green manure (rice bean, black gram and weeds) N uptake ( $\text{kg N ha}^{-1}$ ) and wheat N uptake ( $\text{kg N ha}^{-1}$ ). ....	272
Figure 8.17 Relationship between C:N ratio of green manure and wheat N uptake ( $\text{kg N ha}^{-1}$ ). ....	273
Figure 8.18 Relationship between predicted wheat N uptake ( $\text{kg N ha}^{-1}$ ) and the total potential amount of N mineralised ( $C_g (N_g/C_g - 0.05)$ ) derived from equation 8.1. ....	274
Figure 8.19 Relationship between actual wheat N uptake ( $\text{kg N ha}^{-1}$ ) and predicted wheat N uptake ( $\text{kg N ha}^{-1}$ ). ....	275
Figure 9.1 The effect of amount of P added as TSP ( $\text{kg ha}^{-1}$ ) to cultivated soils for periods of 25 (maize trials) to 35 (legume-wheat rotation trial) days before measurement of Olsen-P values ( $\text{mg kg}^{-1}$ ) in the field trials (1998 and 1999) on Yellow Earths. ....	283

Figure 9.2 The change in Olsen-P values (3-5 weeks) after FYM and green manure application to field trials.....	284
---	-----

## LIST OF TABLES

Table 1.1 Current land use in Southern Shan State in 1998.....	6
Table 1.2 Major soil groupings in Myanmar.....	7
Table 1.3 Summary of responses from 42 surveyed farmers in Southern Shan State (June - October 1998).....	8
Table 1.4 Two-year cropping pattern on marginal upland soils in Southern Shan State. .....	11
Table 1.5 Preliminary survey of farmers' agronomic practices. ....	12
Table 1.6 Nutrient balances for the common crop rotations (2 years) in Southern Shan State.....	13
Table 2.1 Area of acid soils worldwide and in the Southeast Asia and Pacific regions ( $\times 1000$ ha) by main soil groups (FAO/UNESCO).....	30
Table 2.2 Code, site and history of soil samples from Southern Shan State.....	32
Table 2.3 Selected chemical properties of Red Earths and Yellow Earths.....	34
Table 2.4 Selected chemical properties of Red Earths and Yellow Earths (Continued). 34	
Table 2.5 Selected chemical properties of Red Earths and Yellow Earths (Continued). 34	
Table 2.6 The soil units of the Red Earths and Yellow Earths in Southern Shan State. 39	
Table 2.7 Mineralisable N in Red Earths and Yellow Earths and tropical crop N requirements ( $\text{kg N ha}^{-1}$ ).....	47
Table 3.1 Selected physical characteristics of P fertilisers. ....	57
Table 3.2 The percentage of total P content and the percentage of total P extracted by water, 2% citric acid and 2% formic acid from TSP and MPR obtained from Myanmar and SPR from Peru.....	57
Table 3.3 The chemical analysis of fertiliser materials and dolomite (% w/w, air-dry basis).....	57
Table 3.4 Relative neutralising value (NV) of pure forms of some liming materials. ...	60
Table 3.5 Treatments and codes of upland rice grown in pots of the composite Yellow Earth fertilised with different N and P fertiliser sources and rates. ....	68
Table 3.6 Soil number, code and Olsen-P content of Red Earths and Yellow Earths used in Experiment (3). ....	69
Table 3.7 Soil $\text{pH}_{\text{water}}$ (1:2.5) after harvest of pigeon pea from pots of Yellow Earth with different fertiliser treatments.....	74
Table 3.8 Effect of fertiliser treatments on average number of nodules on pigeon pea. 77	

Table 3.9 The dry matter yield of upland rice grown in pots of the composite Yellow Earth (initial Olsen-P 8 mg P kg <sup>-1</sup> ) fertilised with different N and P fertiliser sources and rates. ....	78
Table 3.10 Soil pH (H <sub>2</sub> O) after harvest of upland rice grown in pots of the composite Yellow Earth fertilised with different N and P fertiliser sources and rates.....	79
Table 3.11 Olsen-P in soil after harvest of upland rice grown in pots of the composite Yellow Earth fertilised with different N and P fertiliser sources and rates.....	80
Table 3.12 Effect of P added (kg P ha <sup>-1</sup> ) on nodule formation in pigeon pea grown in Red Earth. ....	82
Table 3.13 Effect of added P (kg P ha <sup>-1</sup> ) on nodule formation in pigeon pea grown in Yellow Earth. ....	82
Table 3.14 Effect of added P (kg P ha <sup>-1</sup> ) on DM yield of rice bean in Red Earths. ....	83
Table 3.15 Effect of added P (kg P ha <sup>-1</sup> ) on nodule formation of rice bean in Red Earths. ....	84
Table 4.1 Total N and P contents and C:N ratios of selected organic materials. ....	97
Table 4.2 The pH, organic C (OC %), total N, available P (Olsen-P) and P retention in the soils of the study area and similar soils from other regions.....	101
Table 4.3 Selected chemical characteristics of samples (0-15 cm depth) from cultivated (CU) and uncultivated (UN) Yellow (YE) and Red (RE) Earths. ....	103
Table 4.4 Selected chemical composition of organic amendments.....	104
Table 4.5 The mean loss of weight (g kg <sup>-1</sup> ) on ignition from seven soils and seven manures. The Standard error of the mean is in brackets. ....	113
Table 4.6 The effect of incubation (6 months) with or without organic amendments on the Walkley-Black C (g kg <sup>-1</sup> ) content of Red Earths and Yellow Earths.....	122
Table 4.7 Recovery (%) of C added as organic amendments, and estimation of respired C (g kg <sup>-1</sup> ) at the end of the incubation period in mineral soils with different organic amendments. ....	123
Table 4.8 Change in soil Walkley-Black C (i.e. final C in soil - initial C in soil) after 6 months incubation with organic materials. (The standard error of the mean is in brackets). ....	124
Table 4.9 Total N (Kjeldahl-N), organic N and mineral N content of air-dried Red Earth and Yellow Earth samples. (The standard error of the mean is in brackets).....	125
Table 4.10 Change in total soil N (i.e. final soil N - initial soil N) after 6 months incubation with organic materials, and the C:N ratio in the incubated soil. ....	127

Table 4.11 The effect of organic amendments on soil pH of Red Earths and Yellow Earths under different management systems, after 6 months incubation.....	128
Table 4.12 The main effect of incubation with and without of organic amendments on P fractions ( $\mu\text{g P g}^{-1}$ soil) in Red Earths and Yellow Earths after a short-term (6 months) incubation.....	130
Table 5.1 Important legume species grown in Myanmar.....	145
Table 5.2 Name, type and some chemical properties of the soils used. ....	146
Table 5.3 Percentage of seed germination and growing period of legume species grown in Red Earth. ....	146
Table 5.4 The root length in upper 3 mm soil slice, number of nodules, shoot DM, Shoot N (%), Root DM, Root N (%), Seed weight, Seed N (%), Shoot + Root-Seed N, and estimate of symbiologically fixed-N in a range sub-tropical legumes grown in RSCs filled with Red Earth. ....	154
Table 5.5 Cation and anion composition, N concentration, cation excess (CE), ash-alkalinity (AA) and cation excess (CE) to N ratio in legumes shoots. ....	157
Table 5.6 Probable calculated available-N depletion ( $\mu\text{g N RSC}^{-1}$ ) by different legumes in the planted and unplanted soil (from resin extraction solution at harvest).....	163
Table 5.7 Estimation of $\text{H}^+$ consumption based on SPR dissolution and total $\text{H}^+$ production in the rhizosphere of legumes in fertilised with SPR.....	165
Table 5.8 Effect of different assumed $\text{NH}_4^+:\text{NO}_3^-$ uptake ratio on the excess of cations over anions, which correspond to the release of $\text{H}^+$ from roots of different legume varieties into the rhizosphere soil ( $\mu\text{eq RSC}^{-1}$ ).....	173
Table 5.9 P fractions in SPR-mixed dry Red Earth and Ramiha hill soil, and percent recovery of added SPR in the various P fractions.....	177
Table 5.10 The effect of legume species on external and internal P use efficiencies. .	184
Table 6.1 Selected chemical characteristics of the Yellow Earth at the field trial site at Aungban, Southern Shan State (the average of 30 soil samples). ....	190
Table 6.2 Dry matter production of <i>Tithonia diversifolia</i> at Kalaw-Pindaya area in Southern Shan State. ....	194
Table 6.3 Percent nutrient concentration in dry matter of <i>Tithonia diversifolia</i> from different sources (adapted from Cong, 2000). ....	195
Table 6.4. Physical and chemical properties of the P fertilisers and the prices of P. ...	196

Table 6.5 Soil Olsen-P values at prior to fertiliser application (initial), 21 DAE and silking of maize grown on Yellow Earth fertilised with different P fertilisers and rates at the Aungban (1998).....	199
Table 6.6 Soil pH values at prior to fertiliser application (initial), 21 DAE and silking stage of maize grown on Yellow Earth fertilised with different P fertiliser sources and rates at Aungban field trial in 1998. ....	200
Table 6.7 Dry matter maize yield at 21 DAE and silking stage, and stover and grain yields at harvest of maize grown on Yellow Earth fertilised with different P fertiliser sources and rates in June planting 1998. ....	201
Table 6.8 Soil Olsen-P values at initial, 21days after emergence and silking stage of maize grown on Yellow Earth fertilised with different P fertiliser sources and rates in the 1999 field trial. ....	207
Table 6.9 Maize dry matter yield at 21 DAE and silking, and maize stover and grain yields at harvest when grown on a Yellow Earth and fertilised with different P fertiliser sources and rates in the 1999 field trial. ....	209
Table 6.10 Substitution ratio values (SR)* of P fertilisers with respect to TSP in the Yellow Earth.....	210
Table 6.11 The rate of TSP applied and relative maize grain yields (%) in year 1 (1998) and application rate of TSP to give the same relative yield in year 2 (1999) and percent relative residual value of year 1 (1998).....	217
Table 7.1 Fertiliser treatments for the Maize Field Trial 2 on a Yellow Earth at Aungban Research Farm. ....	227
Table 7.2 The soil Olsen-P status at cultivation (initial), 21days after emergence and silking stage of maize grown in a Yellow Earth fertilised with different P sources (Field Trial 2).....	232
Table 7.3 The effects of different P fertilisers on the maize DM yield (g plant <sup>-1</sup> ) at 21 DAE and silking stage, and maize grain and stover yield (kg ha <sup>-1</sup> ) at harvest. ....	234
Table 7.4 The RAE % and substitution value (kg P ha <sup>-1</sup> ) of CPAPR, SPR and FYM at different rates with respect to TSP.....	244
Table 8.1 Amount of total crop N and N derived from N <sub>2</sub> fixation for some tropical and sub-tropical legumes. ....	249
Table 8.2 Nitrogen and P concentration and requirement of wheat (grain yield 4 t ha <sup>-1</sup> ) (adapted from Glendinning, 1999).....	250

Table 8.3 The code and description of the different treatments used on legumes, fallow and the wheat crop. ....	252
Table 8.4 The activity of green manure and wheat crop management practices. ....	253
Table 8.5 The fresh biomass, dry matter and bean yield of legumes at harvest prior to incorporation of green manures. ....	257
Table 8.6 The effect of treatments on the concentration and uptake of N, P and C in the green manures grown on a Yellow Earth in Southern Shan State, Myanmar. ....	259
Table 8.7 Soil Olsen-P values at initial, 45 days after emergence and harvest of green manure crops, and at 21 days after emergence and heading of wheat. ....	261
Table 8.8 Soil pH values at cultivation (initial), 45 days after emergence and harvest of green manure crops, and at 21 days of emergence and heading stage of wheat...	262
Table 8.9 Dry matter yield of wheat at 21 days after emergence, heading stage and wheat straw and grain yields at harvest.....	263
Table 8.10 Percentage of total P and N content in wheat straw and grain.....	267
Table 8.11 Production of DM yield of green manures, N and P fertiliser value of green manures and forage values of green manures in one season. ....	276
Table 9.1 A summary of critical Olsen-P test values ( $\text{mg P kg}^{-1}$ ) estimated to produce 90% maximum maize yields at silking and grain harvest. ....	281

## LIST OF PLATES

Plate 3.1 Pigeon pea grown on the Yellow Earth at glasshouse Massey University.....	63
Plate 3.2 Effect of liming on nodulation of pigeon pea in the Yellow Earth. ....	65
Plate 3.3 Upland rice grown in the Yellow Earth at the Massey University glasshouse.	67
Plate 3.4 Pigeon pea grown on the Red Earths and Yellow Earths at glasshouse in Massey University.....	71
Plate 3.5 Rice bean grown in the Red Earths at the Massey University glasshouse. ....	72
Plate 5.1 Legumes growing in the rhizosphere study container (RSC). ....	147
Plate 5.2 Organisation of RSC's growing legumes species in the glasshouse experiment. .....	149
Plate 5.3 The piston microtome used for slicing soils from the lower RSC. ....	150
Plate 5.4 legume root mats formed on the 22 $\mu\text{m}$ polyester mesh above the SPR fertilised Red Earth. ....	151
Plate 6.1 Maize field experiment at Aungban Research Farm in Southern Shan State of Myanmar (Author pictured consoling P deficient plants!).....	191
Plate 6.2 <i>Tithonia diversifolia</i> plants in Southern Shan State. ....	194
Plate 6.3 The effects of P rates (0 to 120 kg P ha <sup>-1</sup> as TSP) on DM yield of maize at silking in June Planting 1998.....	202
Plate 7.1 The effect of TSP rates (0 to 120 kg P ha <sup>-1</sup> ) on maize DM yield at silking stage. .....	236
Plate 7.2 The effect of S with SPR on maize growth at silking. ....	243
Plate 8.1 Plant growth and vigour of rice bean and black gram in the field trial at DAE.....	255

## LIST OF MAPS

Map 1.1 Country Map of Union of Myanmar. ....	4
Map 1.2 Shan State Map of Myanmar. ....	5
Map 1.3 A farmers' option survey area in the Kalaw and Pindaya area. ....	9

# **CHAPTER 1    Developing Sustainable Soil fertility in Southern Shan State of Myanmar: General Information**

## **1.1    Introduction**

Myanmar (Map 1.1) is one of the least developed countries in the Southeast Asia region, being eighth out of the ten nations in ASEAN in terms of the UNDP Human Development Index (2001). Both food and arable land area for food production are scarce in this relatively densely populated area of Southeast Asia. The area of productive arable land is commonly limited by soil salinity (Ponnamperuma and Bandyopadhyaya, 1980; Tha Tun Oo, 1990) and soil acidity (Kamprath, 1980; von Uexküll and Mutert, 1995a). Most land available for agricultural production in the sub-tropical highlands of Southern Shan State of Myanmar is rainfed and can be classified as infertile acid upland soils (Red Earths and Yellow Earths, MAS-LUD, 1994). The main soil constraints to crop production on these strongly weathered tropical soils are the low pH, low phosphorus (P) availability, and low soil organic matter (SOM). The low SOM commonly results in low cation exchange capacity and provides low reserves of nitrogen (N) and sulphur (S) (Sanchez, 1976). Currently, the productive capacity of these soils continues to decline as poor, near-subsistence, farmers usually fallow-crop these soils and are unable, for economic reasons, to provide the necessary fertilisers and crop management strategies that could improve and maintain soil fertility. Despite this, increasing food demand from the expanding population in the tropics and sub-tropics will force farmers to increase the use of these marginal hill soils for food production (FAO, 1987; Stangel and von Uexküll, 1990; von Uexküll and Mutert, 1995a).

In most highland regions in Asia, the communities (or farmers) are poorer than those of the more fertile lowland areas, they are more isolated from the mainstream of urbanisation, and many do not have secured land tenure (Craswell *et al.*, 1998). The hill communities in Southern Shan State can no longer maintain an adequate living from agriculture because of the uneven distribution of productive arable land and declining productivity (IRRI, 1996). Nevertheless, these acid upland soils are the last and largest reserve of potential arable land in Southern Shan State. This thesis reports on

investigations undertaken to determine management (or agronomic) practices by which the fertility of these soils can be improved in an economical and sustainable manner.

Research into fertility management of infertile acid upland soils of Myanmar has been very limited. In this chapter an overview of the major constraints in current farming systems and possible solutions to the problem of infertile acid upland soils in Southern Shan State are presented.

## **1.2 Objectives**

The specific objectives of the work reported in this chapter are:

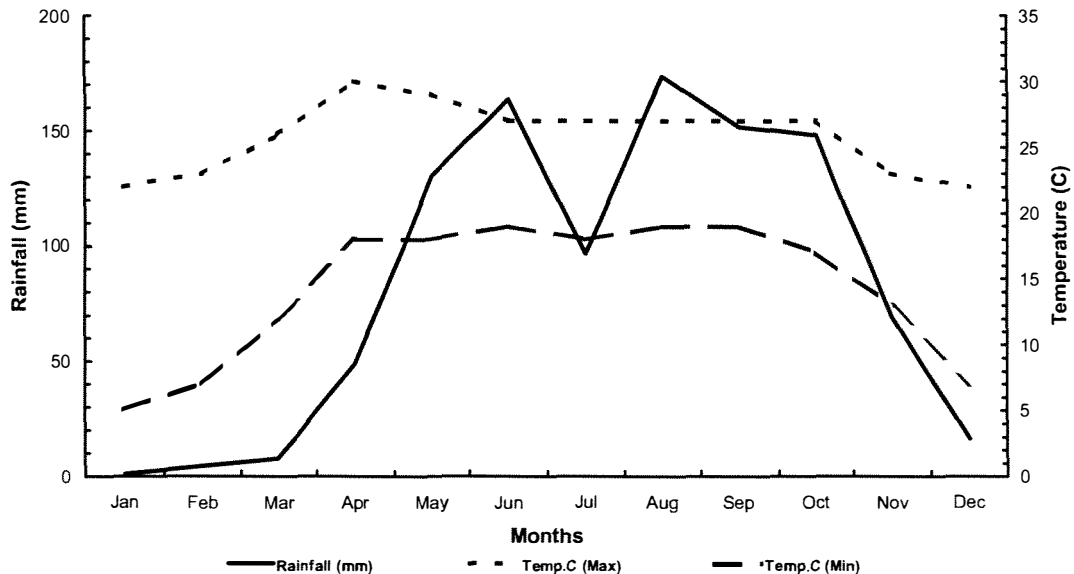
1. To review current farming systems and identify constraints to crop production on Red Earths and Yellow Earths in Southern Shan State.
2. To ascertain whether current agronomic practices address the soil fertility constraints on these soils, and to survey the productivity and farmers' socio-economic conditions in Southern Shan State.
3. To plan a research programme outline, which aims to investigate management practices to improve soil fertility in Southern Shan State.

## **1.3 Location, Climate and Natural Vegetation**

The whole country of Myanmar lies between 92° 10' and 101° 11' East longitude and 9° 58' and 28° 31' North latitude. Myanmar has diverse topography, climate and natural vegetation (see Map 1.1).

This study concentrates on the adjacent administration townships of Kalaw and Pindaya (see Map 1.2), which are located in the Southern Shan State of Myanmar between 96° and 97° East longitude and 20° and 21° North latitude. The topography of Shan State is undulating with hills and slopes, and elevation is between 900 m to 1500 m above sea level. Average annual rainfall of about 1000 mm is concentrated within a growing period of six months (May to October) during the rainy season (Figure 1.1). The climate is described as sub-tropical, with maximum temperatures of 35°C in summer, however,

the minimum temperature can fall to freezing point on hill tops in the winter season. The natural vegetation of the area is the rainforest and evergreen woodland, comprising trees of varying species, size and density, with ground cover of perennial grasses and associated herbs and bushes.



Maximum temperature (°C), Minimum temperature (°C) on legend and (°C) on the second axis

Figure 1.1 Monthly rainfall (mm) and temperature (°C) in Southern Shan State, average of five years (1994-1998).

#### 1.4 Population and Land area for Cultivation

Myanmar, with a total area of 67.7 million hectares, is the second largest country in Southeast Asia and shares borders with Bangladesh, India, China, Laos and Thailand. In regional terms, it has the fifth largest population (approximately 47 million in 2000), comprising about 9% of the regional total, a growth rate of 1.9% in 1999, and the sixth highest average population density (69 people per km<sup>2</sup>).



Map 1.1 Country Map of Union of Myanmar.



Map 1.2 Shan State Map of Myanmar.

Southern Shan State occupies 5.59 million hectares (Table 1.1). The administrative area of Kalaw and Pindaya townships is representative of the landforms and population pressure in Southern Shan State. At present, the population of Kalaw and Pindaya area is about 170,000 people living on an area of 210,900 hectare, of which approximately one third is considered arable land. Farmers permanently cultivate some of the more suitable land in densely populated areas, these soils are representative of the Alluvial and Meadow soils and generally have high clay content and are fertile. These farmers generally receive higher income from urban sales of produce, and use more fertiliser inputs. The potential for expansion of cultivated land is limited, due to the fact that land suitable for agriculture is almost completely utilised. With low potential for expansion in the area under cultivation, unused, or under used arable areas and abandoned lands (1.3 million ha, Table 1.1) need to be redeveloped to meet the future land requirements for agricultural production.

Table 1.1 Current land use in Southern Shan State in 1998.

Type of land	Area (×1000 ha)	Share percentage (%)
Total land area	5,589	100.0
Net sown area of crop land	272	4.9
Fallow land	144	2.6
Waste land	846	15.1
Reserved forest	496	8.9
Other forest	2,840	50.8
Unclassified land not suitable for crops	991	17.7

Source: *The department of settlement and land records (1998).*

On the more marginal Red Earth and Yellow Earth hill soils, an average household is 5 to 10 family members and landholding size varies from about 0.5 to larger than 5 hectare per farm family (see Table 1.3). On average, farmers cultivate approximately 50% of the arable land during a growing season, and the remainder is left fallow. The increasing population density forces the farmer to cultivate the marginal land resulting in reduced fallow periods. Any reduction in fallow period without nutrients and organic matter inputs results in decreasing soil fertility and low productivity per unit area.

## 1.5 Soil Resources

The major soil groupings of the six geographical regions of Myanmar are based on topography, landforms and climate (Table 1.2). The soils of Southern Shan State are

classified as Red Earths and Yellow Earths, lateritic soils, degraded soils and peat soils. Large parts of the Southern Shan State are covered by the Red Earths and Yellow Earths in Myanmar classification system (Tha Tun Oo, 1990). Red Earths and Yellow Earths, classified as Acrisols in the FAO system (MAS-LUD, 1994), are the most common soils in Kalaw and Pindaya administration area.

Table 1.2 Major soil groupings in Myanmar.

Region	Myanmar classification	FAO/UNESCO
Mountainous	Mountainous Red Brown Mountainous Yellow Brown	Cambisols Cambisols
Shan Plateau	Red Earth* Yellow Earth*	Ferralsols or Acrisols* Ferralsols or Acrisols*
Arid and Semi-arid	Dark Compact Brown Compact Red Brown Savanah	Pellic Vertisols Chromic Vertisols Chromic/Ferric Luvisols
Ayeyarwady Delta	Meadow Gley Meadow Alluvial	Gleyic Cambisols Eutric Cambisols Fluvisols
Coastal Strips	Meadow Gley Meadow Laterite	Gleyic Cambisols Eutric Cambisols Plinthic Acrisols

Source: Tha Tun Oo, 1990; \* Myanmar land use Division (MAS-LUD), 1994

The Red Earths and Yellow Earths are the oldest soils of Myanmar, formed on surfaces over a period of at least two million years. They are formed on different parent materials but more than 90% of the area occupied by these soils is associated with different limestone outcrops. Red Earths and Yellow Earths have developed chiefly on the limestone and dolomite of the so-called “Limestone Plateau” formation. Over this long period of soil formation and continuous leaching in these high rainfall areas the top soils have lost all trace of the initial limestone (Rozanov and Rozanova, 1963) and have become acidic upland soils with a thick mantle of weathered clay.

## 1.6 A survey of current farming systems

Successful sustainable management of acid soils depends on integration of soil/crop science and socio-economic consideration on the development of suitable strategies (Myers and De Pauw, 1995). Recently, the accelerated economic development in Southern Shan State has widened the gap between rich and poor as well as the gap between urban and rural communities. Absolute land ownership is vested in the state in

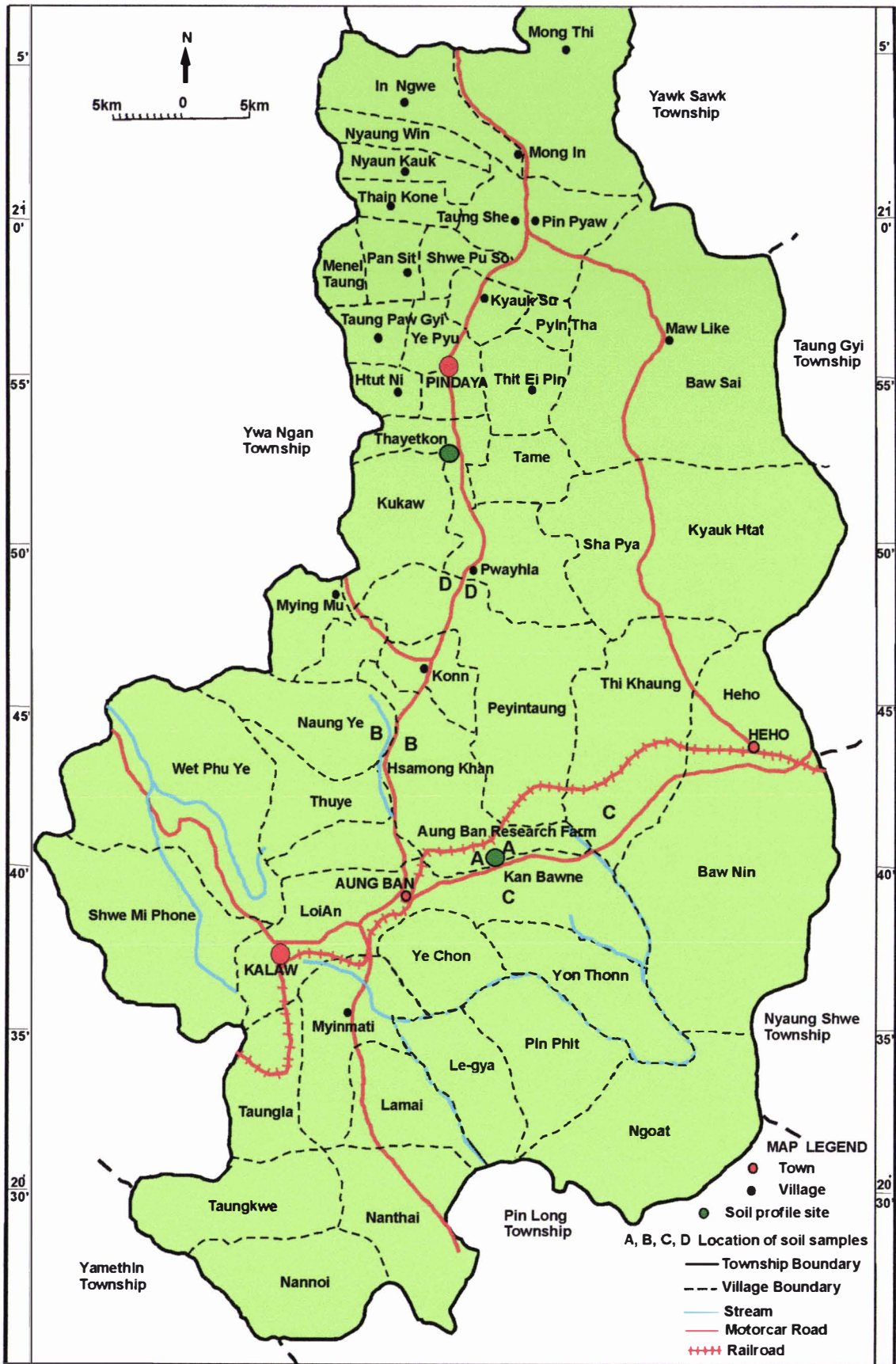
Myanmar. Farmers are granted the right to cultivate the land, but that right can be transferred to the next generation. Where uncertain ownership or tenure exists, soil conservation practices and careful fertility managements are less likely to occur (Pingali *et al.*, 1997).

A farmers' option survey was carried out by author during June to October in 1998, to get socio-economic data on the major farming systems in the Kalaw and Pindaya area (Map 1.3). A reconnaissance questionnaire survey was undertaken from July to September in 1999, to establish current soil fertility management practices on Red Earths and Yellow Earths.

Table 1.3 Summary of responses from 42 surveyed farmers in Southern Shan State (June - October 1998).

Character	Groups	Response	Character	Groups	Response
Age of farmer	20-35	10	Root and tuber crops	Potatoes	24
	>35-50	18		Ginger	12
	>50.	14		Taro	3
Educational Level	Primary	15	Edible oil crops	Groundnut	15
	Secondary	2		Soybean	8
	Monastic*	25		Niger	28
Household size	Small (1-4)	5	Vegetables	Cabbage	6
	Medium (5-8)	23		Cauliflower	2
	Large (>9)	14		Tomatoes	3
Land holding Size (ha)	Small (0-2)	7	Soil	Red Earth	15
	Medium (>2-5)	26		Yellow Earth	27
	Large (>5)	9	No. of cattle	Small (0-5)	31
Cropping Systems	Intensive	3		Medium (5-20)	11
	Semi-intensive	7		Large (>20)	Nil
	Extensive	32	Fertility management	Own FYM	36
Land Cultivation	Cattle	37		Crop residues used	35
	Power tiller	1		N fertilizer	34
	Tractor	4		P fertilizer	31
Transportation	Cattle	31		K fertilizer	4
	Power tiller	11		Lime	3
	Tractor	Nil		Dolomite	Nil
Cereal crops	Rice	35	Crop management	Weedicide	Nil
	Maize	16		Fungicide	15
	Wheat	8		Insecticide	26
Legume crops	Rice bean	4	Greatest needs	Buy fertilizers	35
	Lentil bean	2		Buy pesticide	7

Monastic\* Basic education taught by Monk.



Map 1.3 A farmers' option survey area in the Kalaw and Pindaya area.

### ***1.6.1 Farmers' attitudes and their options***

A survey was undertaken by conducting face-to-face interviews with 42 farmers covering the entire area. The survey provided data on farmers' attitudes and objectives, availability of resources, crop and fertility management practices. The summary of characteristics and grouping of respondents is shown in Table 1.3. The proportion of young age farmers (below 35 years) was very low. A high proportion, about 76%, of farmers were over 35 years of age and about 43% farmers were between the age of 35-50 years. About 60% of farmers had been taught basic education by monks at Buddhist monasteries. Approximately 35% of farmers held a formal primary level of education and only 5% went to secondary school. One third of farmers cultivated Red Earths and about 64% Yellow Earths. All families depended on the farm income, but nearly 14% had family members who worked off-farm for additional income.

The majority of the crops in Shan State are produced by traditional methods of slash and burn shifting cultivation, with ever-shortening fallow periods. Some farmers practice permanent upland rice-based cropping systems. The most common crop categories and crops include: grains - upland rice (*Oryza sativa*), maize (*Zea mays*), and wheat (*Triticum aestivum*); edible oil crops - groundnut (*Arachis hypogea*), soybean (*Glycine max*), and niger seed (*Guizotia abyssinica*); roots and tuber crops - Irish potato (*Solanum tuberosum*), ginger (*Zingiber officinale*); horticultural crops - tomato (*Lycopersicon esculentum*), cabbage (*Brassica oleracea* var. *capitata*), cauliflower (*Brassica oleracea* var. *botrytis*). The majority of farmers (85%) indicated that the lack or limited use of fertiliser is the most important factor limiting crop production in these soils.

Small areas of lowland rice occupy seasonally flooded lowlands, which are unsuitable for other crops in the rainy season. In upland areas, Irish Potato is by far the most important tuber crop and is used either for home consumption or for sale as a cash crop. The farmers still grow upland rice for home consumption. Rice production is a major concern for the government, because local rice production on the Shan plateau does not meet the local demand and rice has to be imported regularly from other regions. While the potential yields of rice in this climate are very high, actual yields vary greatly,

depending on seasonal rain and on soil fertility and fertiliser inputs. Rainfed agriculture is predominant, however, given the unpredictability of the rainfall, the yields are very low. In heavily populated areas, some farmers irrigate vegetables by carrying water in buckets from nearby wells and streams during the dry season. Cereal-based cropping systems are important in the Southern Shan State. However cereal-legume rotations are practiced by only a small number of farmers, although only a few farmers grow legumes for forage or green manure purposes.

### 1.6.2 Common cropping pattern

In the cropping rotation, the long fallow land has to be cleared from herbs and bushes, and burnt before soil tillage operations. The predominant form of tillage is by bullocks, although a small proportion are cultivated by tractors.

Table 1.4 Two-year cropping pattern on marginal upland soils in Southern Shan State.

Two-year rotation	J	F	M	A	M	J	J	A	S	O	N	D
Rainfall (mm)	1	4.6	7.9	49	130	164	97	174	152	148	69	17
Cultivation time			■	■				□	□			
Time of planting				■	■			□	□			
Crop growth period				Potato			Upland rice or maize					
Harvest time	□						Upland rice or maize			Niger		□
Time of fertiliser application			1 ■	2 ■	5 □							
				3 ■	6 □							
				4 ■								

1 FYM 1,300 kg ha<sup>-1</sup>

2 Urea 160 kg ha<sup>-1</sup>

3 TSP 50 kg ha<sup>-1</sup>

4 KCL 50 kg ha<sup>-1</sup>

5 Urea 25 kg ha<sup>-1</sup>

6 TSP 25 kg ha<sup>-1</sup>

The most common cropping patterns on marginal upland soils follow a two-year rotation (Table 1.4). In the first year, Irish potato is usually planted in April and harvested in July. Due to its high nutrient demand, it is planted as a first crop after the fallow period. Usually, soil preparation is started at the beginning of the rainy season. If possible, soil preparation for potato is started at the end of the previous rainy season. Organic materials like farmyard manure, plus small amounts of N, P, and K mineral

fertilisers, are applied at sowing time. After potato the upland rice or maize is sown without fertiliser addition during July and harvested in November. If possible niger (*Guizotia abyssinica* (L.f) Cass) is grown and harvested in January-February. The land is fallowed during the dry period before the next growing season. In the second year, organic materials and N, P, and K mineral fertilisers are applied followed by soil tillage. During May-June to October, upland rice or maize is grown. Niger crop is sown after the grain crop, and then the land is left fallow again for a number of years. Fallow land is grazed by cattle.

### 1.6.3 Farmers' Agronomic Practices

A preliminary survey of 30 farmers within Southern Shan State was undertaken to ascertain whether current agronomic practices addressed the soil fertility constraints of these soils and to assess the level of production that result from these practices (Table 1.5). The farmers' survey indicated that all farmers use farmyard manure (FYM) and crop residue frequently, but they use only low levels of phosphatic (e.g. triple superphosphate-TSP,  $<10 \text{ kg P ha}^{-1}$ ) and nitrogenous (e.g. urea,  $<50 \text{ kg N ha}^{-1}$ ) fertilisers. Very few farmers (17%) use potassium (K) fertiliser or grow green manure crops in their existing cropping systems. Although the pH values of the soils were found to be low ( $\text{pH}<5.5$ ) only 20% of farmers use any liming materials. FYM is produced locally, but most of the chemical fertilisers are imported with some urea manufactured in the country. Local liming materials, such as dolomite and ground limestone are available.

Table 1.5 Preliminary survey of farmers' agronomic practices.

Farmers (n= 30)	Management practice	Quantity	Frequency (No. of years between applications)
6	Liming	$<0.5 \text{ t ha}^{-1}$ (Low)	$>4$ (Low)
23	Crop residues	$<2 \text{ t ha}^{-1}$ (Low)	2-3 (Medium)
1	Green manure	$<2 \text{ t ha}^{-1}$ (Low)	$>4$ (Low)
30	FYM	$1-5 \text{ t ha}^{-1}$ (Medium)	2-3 (Medium)
30	N fertiliser	$<50 \text{ kg N ha}^{-1}$ (Low)	1-2 (High)
30	P fertiliser	$<10 \text{ kg P ha}^{-1}$ (Low)	2-3 (Medium)
5	K fertiliser	$<25 \text{ kg K ha}^{-1}$ (Low)	$>4$ (Low)

Many farmers keep a few cattle and bullocks for land preparation and transporting their farm products. These animals are allowed to graze on poor common rangeland and to feed on rice straw, and other crop residues from the farms. A few farmers grow small areas of fodder maize or sorghum for their own cattle. These practices produce the local FYM. Fuel wood, which can return a wood ash fertiliser, is collected in the form of small trees and branches from the forest. But due to deforestation and the scarcity of fuel wood (Current, 1988), farmers are forced to decrease the use of wood ash fertiliser. A nutrient balance (Analysis of fertilisers is presented in Chapter 2) for the various crops grown in the area was calculated (Table 1.6). In the first year, all fertiliser inputs (FYM 1,300 kg ha<sup>-1</sup>, urea 160 kg ha<sup>-1</sup>, TSP 50 kg ha<sup>-1</sup>, and KCl 50 kg ha<sup>-1</sup>) were applied at the time of planting of potatoes in April. In the second year, only urea (25 kg ha<sup>-1</sup>) and TSP (25 kg ha<sup>-1</sup>) were applied at the time of rice or maize planting in May-June. The quantities of nutrients removed relative to the quantities of fertiliser and manure used show that insufficient quantities of nutrients, except P are added to balance nutrient loss in crops.

Table 1.6 Nutrient balances for the common crop rotations (2 years) in Southern Shan State.

Crop	Yield (t ha <sup>-1</sup> )	Fertiliser Nutrient Inputs				Product Nutrient Outputs				Balance			
		N	P	K	S	N	P	K	S	N	P	K	S
Potato	10.1	96.1	24.9	36.2	2.5	59.0	5.3	61.9	5.1	37.1	19.6	-25.7	-2.6
Rice	1.8	0	0	0	0	25.4	5.7	23.3	1.5	-25.4	-5.7	-23.3	-1.5
Rice	2.1	11.3	5.0	0	0	29.1	6.6	26.7	1.7	-17.8	-1.6	-26.7	-1.7
Niger	0.3	0	0	0	0	1.5	0.8	1.2	1.8	-1.5	-0.8	-1.2	-1.8
Closing balance (- Use of nutrient from soil)										-7.6	11.5	-76.9	-7.6

## 1.7 Discussion of constraints to crop production

Large areas of Red Earths and Yellow Earths are used for shifting cultivation or subsistence agriculture in Southern Shan State, as in Indonesia (Sudjadi, 1984) and Vietnam (Cong, 2000). The farmers' survey indicates that plant nutrients removed by crops are not replaced with fertiliser applications, resulting in the likelihood of soil depletion and unsustainable crop yields (Table 1.6).

The major soil fertility constraints to crop growth in these Red Earth and Yellow Earth upland soils are low P availability, moderate soil acidity and low organic matter

contents, leading to poor water retention and low N, S and micronutrients reserves (Dent, 1980; Current, 1988). Soil fertility characteristics of Red Earths and Yellow Earths are discussed in more detail in Chapter 2.

Long-term soil erosion has contributed to a decrease in soil depth and thereby to a loss of arable land surface. Therefore, the yield of crops in the upper slopes has declined more than those on the lower slopes, due to the movement of topsoil from the upper slopes to the lower slopes and the accelerated loss of P from soils.

Others have noted that sustained crop production on related soil, Acrisols, requires heavy fertiliser inputs and careful management because they have low inherent fertility and a severe acidity problem (Dent, 1980). Myanmar is one of the lowest chemical fertiliser users in Asia (von Uexküll, 1989).

No agricultural extension service system of technology transfer is available to give fertiliser recommendations relevant to upland agriculture in Southern Shan State. Costa and Rehman (1999) reported that Southern Shan farmers have less knowledge on the proper management of infertile acid soils compared to farmers' on similar soils in Brazil. In most areas, the soil has reached a low level of productivity for most crops in terms of production per unit area (e.g. Paddy yield 350 kg ha<sup>-1</sup> without fertiliser). Under the existing agricultural practices, it is difficult to calculate a general nutrient budget for crops because nutrient contents of FYM are very variable and harvest indices for nutrient removal calculations vary. If nutrients in harvestable crop parts equal the nutrients applied to the soil, then nutrients in the rest of the plant are available for recycling to the soil. The removal of greater portions of plant residue during harvesting, possibly for livestock feeding, will result in larger negative nutrient balances than shown in Table 1.6.

Weeds compete vigorously with cultivated plants and weed control is a serious problem for farmers. 'That Grass' (*Imperata cylindrica*) usually covers the abandoned areas of the more acidic Red Earths and Yellow Earths. These soils became less productive for crop production.

## **1.8 Possible solutions to soil fertility constraints**

The gap in fertiliser price between the local market and government agencies is narrowing due to the government fixed retail price of fertilisers with non-subsidy programme to farmers since 1989. The current government has a monopoly on procurement and distribution of fertiliser through their agencies or joint ventures with private business (FADINAP, 1994) in Myanmar.

In order to develop the objectives for the experimental chapters in this thesis, this section considers possible solutions to overcome the main soil fertility constraints of the Red Earths and Yellow Earths in Southern Shan State, and highlights gaps in information.

### **1.8.1 Increasing soil P status**

The main soil fertility limitation in Red Earths and Yellow Earths is low soil P status (see chemical properties of Red Earths and Yellow Earths in Chapter 2), which results in P deficiency for many crop plants. The solution is to raise the plant-available P concentration in soils through application of P fertilisers (Sanchez and Uehara, 1980). Whereas there is no data published on the relationships between recommended rates of P fertiliser addition and the change in plant-available P status of the Red Earths and Yellow Earths in Myanmar, work on similar soils (Acrisols) has been conducted in Fiji (Naidu, 1985), Indonesia (Tambunan, 1992; Budianta, 1999) and Vietnam (Cong, 2000). Commonly, these soils have high but variable phosphate fixation capacity, which transforms much added fertiliser P into occluded phosphates of low availability (Naidu, 1985). This creates two problems. Firstly, relatively large additions of P fertiliser may be required to raise the size of the plant-available P pool (Hedley *et al.*, 1995) thus making the cost for effective P fertilisation very high. Secondly, the amount of P required to raise the plant-available P status to an adequate level may vary from site to site. For example, Tambunan (1992) and Cong (2000) showed that, within a climatic zone, crop yield response to P fertilisers differed between soils. In addition, the choice of P fertilisers form may also affect the rate of application required to raise the plant-

available P to an adequate level (Tambunan, 1992; Budianta, 1999 and Cong, 2000). This aspect is discussed in the following section.

### ***Water-soluble P fertilisers***

Conventional water-soluble P fertilisers, particularly TSP, have been applied to correct the P deficiency in the Red Earths and Yellow Earths in Myanmar, however, locally researched recommendations for TSP use are not available. Triple superphosphate is costly and needs to be used in the most cost-effective manner. Research indicates that improved agronomic effectiveness of soluble P fertiliser can be achieved by banding in acid soils. In a recent example, Trolove (2000), working on a Philippine Ultisol, showed improved P uptake from banding P with upland rice in an acid soil. Crop yield response curves to P are required for the Shan State Red Earths and Yellow Earths and research into P placement methods are also required.

### ***Phosphate rocks***

Directly applied phosphate rocks (PR) can be expected to become a more cost-effective form of P fertiliser in situations where the PR dissolves rapidly to provide plant-available P, such as on South American Oxisols (Hammond *et al.*, 1986). Acid soils of the humid tropics, such as Red Earths and Yellow Earths of Shan State, are potentially suitable for direct application of PR, as an alternative to combined soluble P fertiliser and liming material (Yeats and Allen, 1987; Tambunan, 1992). Reactive phosphate rocks (RPRs) have been shown to increase soil P availability on acidic soils and increase crop yield and income from tropical crops (von Uexküll and Mutert, 1995b). It has also been suggested that an additional benefit from the use of the slow release RPR fertilisers is the liming effect. Unlike soluble P fertiliser, regular use of PRs may help to overcome soil acidity and thereby reduce the amount of fertiliser P fixed by the soil and improve the P use efficiency by crops (Bolan *et al.*, 1997; Zoysa *et al.*, 1997). There is little direct evidence supporting the hypothesis with respect to RPR application, however, benefits are likely to arise from the undissolved RPR residues remaining in the soil.

Reactive phosphate rock (RPR) is recommended for rehabilitation of low fertility acid soils. The initial application of one tonne of RPR per hectare, or an equivalent value of RPR in monetary terms of TSP and lime applications, plus the establishment of cover crops, such as *Mucuna cochinchinensis*, has resulted in an increase in production, with higher income, over 5 cropping seasons, on acid uplands in Indonesia (von Uexküll and Mutert, 1995b).

Care must be taken in selecting the type of PR to be used because the agronomic effectiveness of PRs depends on the chemical reactivity and the particle size. The soil and climate also play a large role in the agronomic effectiveness. For example, direct application of RPRs has been recommended for areas in New Zealand with low pH soil (less than pH 6) and an annual rainfall of >800 mm (Hedley and Bolan, 1997).

An indigenous deposits of PR called Myanmar phosphate rock (MPR) is available in Myanmar. However, MPR has not been extensively evaluated for direct application (see Chapter 3 for MPR characterisation and preliminary agronomic value assessment).

### ***Partially water-soluble P fertilisers***

Hammond *et al.* (1986) recommended partial acidulation of PR as an efficient alternative P source for food production in the tropics. Partially acidulated phosphate rocks (PAPRs) can be viewed as a method of making less reactive PRs suitable for use as P fertilisers. Partially acidulated phosphate rocks represent an improvement in the agronomic value of cheap sources of unreactive PR, particularly if these rocks are unsuited for conventional fertilisers production (Hammond *et al.*, 1986; Bolan *et al.*, 1990a). Partially acidulated phosphate rock (50% acidulation with sulphuric acid) was found to be as effective as TSP for maize production on silt loam (pH4.5) in Colombia (Menon and Chien, 1990) and on permanent pasture in a P-leaching sandy soil in Australia (Lewis *et al.*, 1997). Sulphuric acid PAPR may have the additional advantage of supplying plant-available sulphate. As mentioned earlier, imported expensive TSP is the major phosphatic fertiliser used to correct P deficiency in Myanmar. These soils are commonly S deficient, however, little or no S fertiliser is used to correct S deficiency. The mixing of elemental S and P fertilisers increased maize yield on a highly weathered

Red Earth in Indonesia (Santoso *et al.*, 1995). In general PAPRs acidulation with sulphuric acid offer better flexibility to match P and S nutrient requirements for P and S deficient soils in food production. A partially acidulated phosphate rock from China (CPAPR) is also available in Myanmar, although its agronomic effectiveness has not been extensively evaluated on the Red Earths and Yellow Earths in Myanmar (see Chapter 6 for the agronomic effectiveness of CPAPR).

### ***Advantages and disadvantages of using PR or high analysis soluble P fertiliser***

Transportation represents a significant component of P fertiliser cost. The price of P in imported PRs has increased much more rapidly than the price of P in high analysis soluble P fertilisers. When PRs are locally available, they may be cheaper to use. For example, PR is sometimes used in Indonesia where transportation costs are not excessive (Sudjadi, 1984).

The price of importing soluble, manufactured P fertilisers is a major constraint to their use by subsistence farmers in Myanmar. If MPRs deposits are used to supplement other imported fertilisers, it would allow a saving of much needed foreign exchange in Myanmar (Chien and Menon, 1995).

Applied to strongly acidic soils (<5.5) PRs would have liming effects and consume soil acidity (Loganathan *et al.*, 1995), and to some extent the cost of supplying PR could be discounted for the liming value, by assuming it has 50% the liming value of pure calcium carbonate (CaCO<sub>3</sub>). This liming effect increases with increasing rate of RPRs on pastoral soils at pH less than 5.5 (Sinclair *et al.*, 1993). The relative agronomic effectiveness of lime plus soluble P (TSP) versus RPR should be investigated in Red Earths and Yellow Earths.

Therefore, sources of P cheaper than TSP fertilisers, such as MPR or CPAPR have potential to be used as alternative P sources on acid upland soils in Myanmar. There is, however, limited information available on recommended P fertiliser rates for use on these soils. Providing information to fill this gap provides the objectives of Chapters 3, 6 and 7.

### ***Integrated nutrient management***

Another inefficiency in current fertiliser use in Southern Shan State is due to the adoption of unbalanced fertiliser applications (e.g. 50 kg N ha<sup>-1</sup> with 10 kg P ha<sup>-1</sup>, but no K and S additions) combined with the absence of comprehensive soil and plant testing for nutrient deficiency diagnosis. The government recommended fertiliser rates are 25 kg N ha<sup>-1</sup>, 22 kg P ha<sup>-1</sup>, and 12 kg K ha<sup>-1</sup> for farmers in the region. Such recommendations on marginal soils are inadequate and are largely wasted because they often result in poor crop establishment and do not lead to improvement in soil fertility. Soils supplied with balanced fertilisers may produce higher crop yields, generate greater income and encourage farmers to undertake strategies to conserve and increase SOM.

#### ***1.8.2 Reducing soil acidity***

Soil acidity of these Red Earths and Yellow Earths can be corrected by liming. The pH of Red Earths and Yellow Earths in Southern Shan State ranges from pH 6.2 to less than pH 5. Where pH is less than 5, liming can be used to raise soil pH (to between 5.5 to 6.5) and the following benefits can be expected:

##### **1. Reduction in solubility of toxic ions, particularly Al and Mn toxicities**

Reduction of the concentration of toxic elements (Al, Mn) for crops can be achieved by liming acid soils (Naidu, 1985; Haynes and Naidu, 1991). Liming has been shown to significantly decrease exchangeable Al and increase peanut yields in Ultisols (Blamey, 1983). Friesen *et al.* (1980) showed that liming an Ultisol improved root growth of maize by increasing the Ca:Al ratio in the soil solution.

##### **2. Increasing P availability**

Appropriate liming of acid soils can be expected to increase the availability of P for uptake by plants (Naidu, 1985; Rajj and Quaggio, 1990), by stimulating organic P mineralisation (increased microbial activity) in acid soils (Haynes, 1982), decreasing phosphate sorption strength, and improving plant root growth (see later discussion).

Cregan *et al.* (1989) also reported that improved legume plant performances with lime were due to a release of plant-available P in acid soils.

### 3. Increasing S and Mo availability

Increases in S and Mo availability for crops can be achieved by raising the soil pH in acid soils through liming (Haynes, 1983; Cregan *et al.*, 1989), which can have significant impact where these elements are deficient.

### 4. Improving N-fixation by legumes

Coventry *et al.* (1985) reported that liming acid soils increased rhizobial population and increased nodulation on legume roots (Munns, 1965) and thus, enhanced their N-fixing capacity.

### 5. Increasing CEC in soils of variable charge

The cation exchange capacity of low activity clay minerals in tropical acid soils is pH-dependent. By liming, soil CEC is increased as the acid soil become less acidic. Budianta and Vanderdeelen (2000) found that the application of dolomite ( $4.14 \text{ t ha}^{-1}$ ) to an Ultisol in Indonesia increased CEC significantly, from 9.69 to  $11.25 \text{ cmol (+) kg}^{-1}$ . Nutrient retention improved as CEC is raised.

### 6. Improving the soil physical conditions

The adsorption of Ca may encourage aggregation of soil particles, and thus encourages a more desirable soil structure (Brady, 1974).

The benefits of liming are interrelated in acid soils. For example, liming raises pH and increases exchangeable Ca. Increased Ca availability improves root development of plants and increases P availability. Also, liming increases S availability by decreasing the number of positively charged non-specific adsorption sites for  $\text{SO}_4^{2-}$ . Raising soil pH also stimulates the activity of micro-organisms (Coventry *et al.*, 1985) and thus, promotes SOM mineralisation and improved physical properties of soils. The overuse of liming materials can cause detrimental effects in tropical soils. Detrimental effects can be soil structural deterioration, reduced P availability, and decreased availability of K, Mg, Zn, Cu and B. Liming highly weathered acid soils to near neutrality is not advised

as this can depress the yield of many plant species (Sumner, 1979). Liming needs to be done judiciously to overcome the Al and Mn toxicity but not to induce nutrient deficiencies on the infertile Red Earths and Yellow Earths (Bouton *et al.*, 1981). However, von Uexküll and Bosshart (1989) reported that when similar soils were limed to near neutrality (pH 6.5) crop yields were often variable and lime required to raise the pH to neutrality was not economically feasible because many of soils had high buffer capacities.

Organic matter addition is an alternative approach to liming acid soils to reduce toxic metal concentrations. Incorporation of crop residues, green manure, animal manure and other organic wastes into soils can help to overcome problems associated with soil acidity (Wang, 1996; Budianta, 1999; Cong, 2000; Haynes and Mokolobate, 2001). Particularly legume green manures with high ash alkalinity (Tambunan, 1992), which can be used to supply N in soils, neutralise the acidity of soil, and bind toxic Al with the added organic matter. Legumes, however, will tend to acidify soils due to excess cation uptake during biologically N fixation, particularly where there is large removal of product or leaching of nitrate. Consequently, the only effective long-term remedy for soil acidity is to lime soils.

### ***Liming materials available in Southern Shan State***

Limestone ( $\text{CaCO}_3$ ) and dolomite ( $\text{CaMgCO}_3$ ) are commonly used, and burnt lime ( $\text{CaO}$ ) and slaked lime ( $\text{Ca(OH)}_2$ ), have also been used as liming materials in America, Australia, Britain and New Zealand (MAFF/ADAS, 1981; Cregan, *et al.*, 1989, Black, 1993; Hedley and Loganathan, 1999). These liming materials are available in Southern Shan State. The liming materials differ in their neutralising ability to counteract the effects of soil acidity.

As presented in Section 1.6.3, very few farmers lime acid soils in Myanmar. Currently, government recommended rates of liming is 0.5 t pure burnt lime powder ( $\text{CaO}$ )  $\text{ha}^{-1}$  per year in Southern Shan State. The burnt lime is white powder, also known as unslaked lime or quicklime. Complete mixing of burnt lime with soils is difficult for farmers, because immediately after application, absorbed water causes the materials to form

flakes or granules of  $\text{Ca}(\text{OH})_2$  and then calcium carbonate ( $\text{CaCO}_3$ ) slowly forms. There is a very limited trial information for liming with burnt lime powder on the Red Earths and Yellow Earths. The disadvantage of burnt lime is that its production consumes a lot of fuel wood and results in deforestation. Consequently its price is relatively expensive compared to the price of dolomite in Shan State. Hydrated lime, also called slaked lime or builders' lime, is a white powder but difficult to handle as well. The aspects of selecting liming materials are discussed in Section 3.1.4.

The dolomite that is available locally in Southern Shan State, which is relatively cheap, is underutilised currently. Most of the dolomite mines in Southern Shan State (Maung, 1966) have been mined by open-pit methods, and used only for steel factories and the building industries. The quality of crystalline dolomite limestone depends on the degree of impurities, such as clay. If the Ca and Mg supplied in dolomite eliminates the deficiency of one or both of these elements as plant nutrients, the dolomite can be used also as a true fertiliser on acid soils deficient in these nutrients.

As mentioned in Section 1.8.2, increasing SOM in acid soils, by incorporating organic materials, may reduce the soil acidity due to complexing of exchangeable Al with OM in Red Earths and Yellow Earths (Budianta, 1999; Cong, 2000). Plant and animal residues with high ash alkalinity will be effective liming materials. Locally available organic residues require evaluation as liming materials, and this is discussed in Chapter 5.

### ***1.8.3 Crop rotations with legumes***

One of the aims of the research reported in this thesis is to identify economically sustainable crop rotations that allow more sustainable permanent cultivation of acid soils. Crops can be varied in rotation, according to the farmers' needs, and the chemical and physical conditions of the land. Legumes play a very important role in the provision of biologically fixed N, which limits the rate of improvement of soil nutrient status in natural vegetation or long fallows. Legumes in rotations are the natural partners of the cereal crops, because soil incorporation and decomposition of legume N supports the rapid growth of cereals. Further, the root system of the two groups tend to be different,

extracting nutrients from different depths of the profile, and the common pests and pathogens of one group tend not to attack the others (Smartt, 1976). Additional value of the legume rotation is that certain weeds (e.g. *Imperata cylindrica*) can sometimes be controlled and destroyed by rotations with legume crops (eg. *Mucuna cochinchinensis*) as cover crops (von Uexküll *et al.*, 1992). However, the slow initial growth of some legumes, such as stylosanthes, may not compete with fast growing weeds such as Shan-pyay (*Richardia brasiliensis*), Hmo-chin (*Oxalis latifolia*), Yasoe (*Conyza canadensis*) and That Grass (*Imperata cylindrica*) in Southern Shan State. Protein rich legume grain crops are found to be effective as a major supplement to carbohydrate staple crops, such as rice, wheat, maize, cassava, yam, taro, sweet potatoes and potatoes, in tropical regions. Legume crops can be self-sufficient for N but also are efficient scavengers of other nutrients (Smartt, 1990), particularly sparingly soluble forms of phosphate (Haynes, 1992; Trolove *et al.*, 1996b). In tropical and sub-tropical agriculture, the additional fixed N may contribute to soil reserves for the benefit of other crops or forage crops (Peoples and Craswell, 1992).

The value of each major crop as a preceding crop for continued growth of the same crop or of other crops needs to be determined. For example, in the study area, legume crops can be raised as either pure green manure (e.g. Rice bean) or green manure with forage value (eg. Stylosanthes) or green manure and cash crop (e.g. Pigeon pea). The consumption of grain legumes in the diets of different people ranges from very low level (e.g. 3-7 grams per head per day in New Zealand and Australia) to relatively high level (e.g. 68-71 grams per head per day in Brazil and India). Potentially, grain legumes can meet the protein needs of humans where animal protein is less readily available (Smartt, 1990). Legumes are under-utilised, with negligible use of either green manure or forages in this area of Myanmar.

There is evidence for positive economic benefit for farmers through better management of grain legume-cereal production systems in Nepal and Pakistan.

#### 1.8.4 Potential organic inputs as green manure

Organic inputs, such as FYM and crop residues, have played an important role in traditional farming systems for a very long time. Essentially, nutrients released from the decomposition of organic inputs need to be in synchrony with crop demands, thus residues need to be chosen that are economically viable and environmentally acceptable (Lefroy and Craswell, 1997). For example, during the monsoon season, Cowpea (*Vigna unguiculata*) and Velvet bean (*Mucuna sp.*) are grown as green manure crops for sugarcane in the tropical regions (FAO, 1988). The careful use of other plant residues (for instance wild sunflower, *Tithonia diversifolia*) have potential to provide an N and P source for optimum crop growth, because inorganic P fertilisers become increasingly expensive, not widely available and the opportunity cost for labour is very low in developing regions. *Tithonia diversifolia*, which grows wild in Southern Shan State, can produce large amounts of fresh biomass (about 50-60 t ha<sup>-1</sup> in Kalaw and Pindaya areas). As compared to leguminous plants, the *Tithonia diversifolia* biomass has relatively high P and K concentration (2 to 5.6 g P kg<sup>-1</sup> DM and 23 to 55 g K kg<sup>-1</sup> DM, respectively) (Cong, 2000). *Tithonia diversifolia* has been used as a green manure for rice field in Sri Lanka as well as for upland soils in Vietnam (Cong, 2000).

The use of legumes as green manure crop in rotations, can be aimed at building SOM, adding available N to soil, providing animal feed and protecting soil during periods of high erosion hazard (FAO, 1988). Although legume crop residues can be expected to raise both nitrogen and carbon content of the soil, increasing soil acidity may be a consequence (Jarvis and Robson, 1983a,b). Nutrient balances indicated net positive N and P balances of up to 457 and 60 kg ha<sup>-1</sup>, respectively after five seasons of legume leaf residue application in rice cropping systems in Northeast Thailand (Whitbread *et al.*, 1999). In Southern Shan State, increases in upland rice yield have been achieved when rice bean was sown during the fallow period. Other forage legumes that produce high biomass include *Stylosanthes*, *Calopogonium*, and *Centrosema* (IRRI, 1996).

With the inclusion of legumes, the fertility of farmers' land may be maintained through increased inputs of P fertilisers and organic matter.

### ***1.8.5 Integrating livestock***

Inclusion of legume-based forage and grass in a crop rotation is the most efficient method of increasing SOM and improving soil structure. For farmers to adopt such a rotation the pasture phase must be profitable.

There are opportunities for production of meat and milk products in Southern Shan State. Meat, fresh milk and dairy products such as skim milk powder, sweetened condensed milk, butter, cheese and yogurt are in demand in the urban cities of Myanmar and neighbouring Thailand (Samithisawad, 1992). The retail price of ultra high temperature-treated (UHT) milk, dairy products are more expensive in Myanmar than Thailand. Therefore continued growth in demand for dairy products can be expected. There is also a growing export market for meat as live cattle and goats traded to Bangladesh, Malaysia and Thailand. Thailand has been a 'black market' destination for live cattle or smuggled meat from Myanmar for a long time.

On the one hand, meat, milk and dairy products are in strong demand, but farmers are faced with very limited production capacity, particularly due to a lack of dedicated forage pastures. To increase the areas of forage crops cultivated, it needs to be demonstrated to farmers that the potential income from a forage crop is similar to or greater than a cash crop. For example, the return from one ha of maize producing 1,800 kg grain per ha is expected to be K 36,000 (at K 20 per kg of grain). In one season equivalent to maize production, it should be possible to grow 8 t of DM forage per ha. Assuming 80% utilisation by a dairy cow, this can be expected to yield (for a lactation of 0.68 of a year) 6 litres of milk per 16 kg DM per day, which equals to 1,632 litres per ha. The return from milk production is expected to be K 81,600 per ha (at K 50 per litre of milk). The equivalent amount of DM forage utilised by beef cattle, based on an expected yield of 0.4 kg of meat from 1kg of live weight per 10 kg DM, would be 256 kg meat per ha. The return from meat production is expected to be K 153,600 per ha (at K 600 per kg of meat). Comparing these values with the gross return for maize highlights that raising livestock, particularly beef and dairy cattle, would generate more income than arable crop production for farmers. Once the country regains economic and

political stability, meat and milk production may become an important source of income for farmers in Myanmar.

By diversifying the food producing activities of the farming families, they can increase their level of subsistence security. Farming families have ample labour to operate small-scale livestock farming in Shan State. Therefore, productivity in this region depends not only on food crops, but also on livestock production with pasture development. Integrating livestock production with crops and green manures for forage would hopefully allow a general improvement in soil fertility, leading to higher crop yields of greater marketable value.

## **1.9 Conclusions**

It appears possible to manage these infertile acid uplands effectively by application of cost effective P fertilisers, by improvement in organic amendments and by introduction of improved crop rotations. Research is needed urgently, therefore, to provide recommendations for P fertiliser use in a sustainable crop production system on these infertile acid soils. Research concerned with developing sustainable soil fertility management in Southern Shan State must involve a multi-disciplinary approach that considers the likely adoption of information by the local farmers. The research requires detailed studies on various aspects concerning appropriate organic amendments, proper practices for fallow land and selection of potential legume crops. In addition, this research project should investigate methods of improving P fertiliser efficiency in these high P-fixation soils by evaluating combinations of P fertilisers, organic manures, green manure crops and lime and developing practices suited to, and accepted by, local farmers that will improve crops yields and the soil fertility of these soils.

Above all, the essential requirement for development of the hill lands of Shan State is research followed by education in integrated nutrient management of crops and manures, if higher and more stable soil productivity is to be achieved. New agricultural systems, which are economically viable, technologically sustainable, and socially acceptable, are essential for agricultural development. The farmers who are shifting to

alternative farming systems may earn better income, increase productivity, and sustainability, and enhance the land and water resources in Southern Shan State.

The objective of this thesis is to evaluate locally available P sources, liming material and green manure crops that can be used to improve the fertility of Red Earths and Yellow Earths in Southern Shan State.

This thesis comprises 9 chapters and the structure of this thesis is schematically presented in Figure 1.2. Following this general introduction (**Chapter 1**), **Chapter 2** describes characterisation of soil resources, soil chemical characteristics constraint to crop optimum yields. In **Chapter 3**, properties of locally available fertilisers and liming materials are analysed for potential use for the improvement of fertility of the research project area of Southern Shan State in Myanmar. In **Chapter 4**, the value of organic materials for building SOM and P reserves in the Red Earths and Yellow Earths are evaluated. Plant-induced changes to rhizosphere by seven sub-tropical legume species in the Red Earth are discussed under glasshouse in **Chapter 5**. Field trials were conducted for evaluation of different P sources and their residual value in **Chapter 6** and the effect of P fertiliser form and application rates on the yield response of maize grown in a Yellow Earth are discussed in Chapter 7. Legume crop management with P fertilisers and its effect on a subsequent crop under field conditions are studied in **Chapter 8**. In **Chapter 9**, summary, conclusions and suggestions for future work are presented.

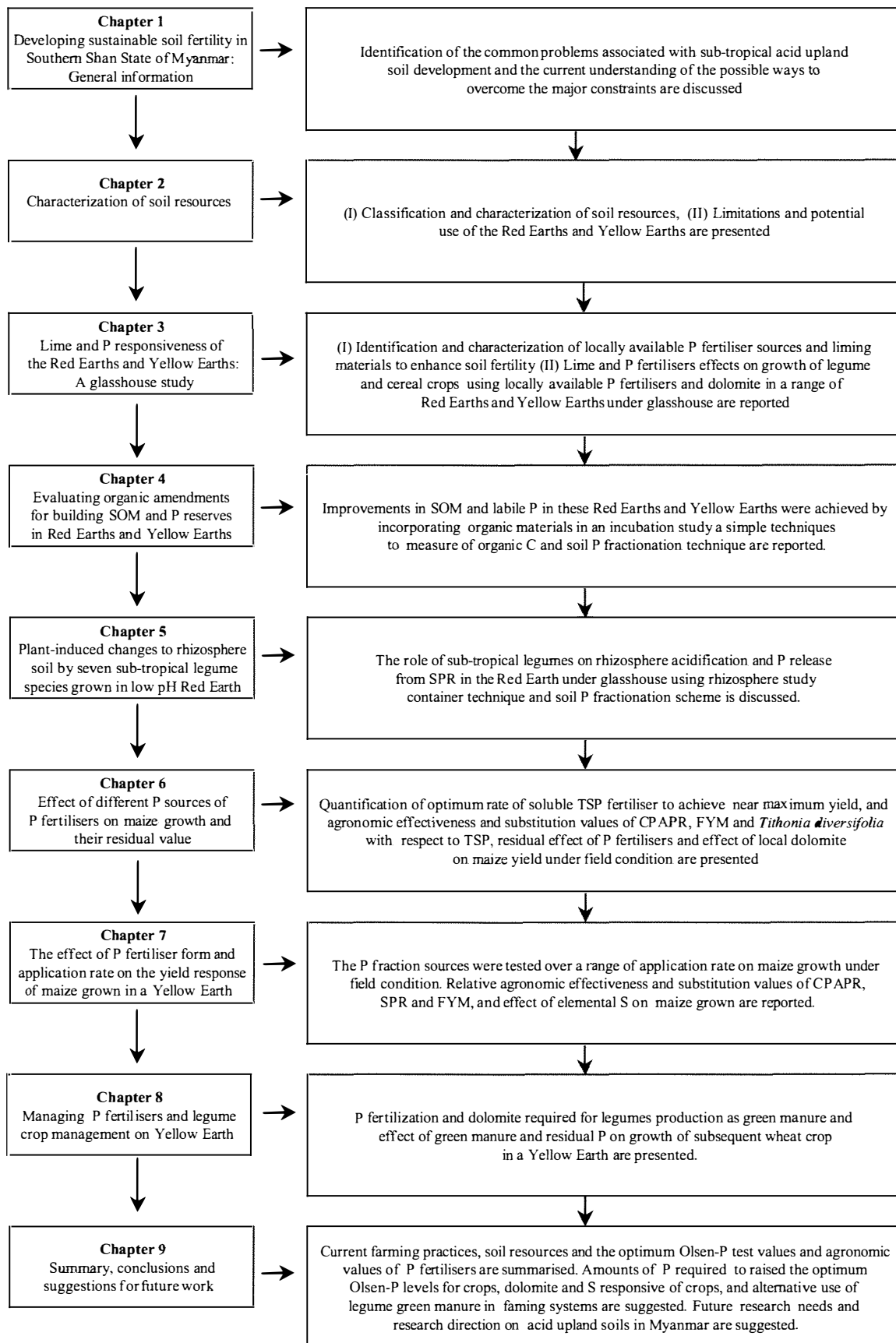


Figure 1.2 Schematic presentation of the thesis structure.

## **CHAPTER 2 Characterisation of Soil Resources**

### **2.1 Introduction**

The common soil constraints to crop growth in Southern Shan State of Myanmar were discussed in Chapter 1. The purpose of this Chapter is to select study areas representative of those constraints. The relationships between increasing population density in Southern Shan State and land degradation were also discussed in Chapter 1.

The extent of land degradation is a function of the natural environment of the soil (climate, topography, parent material, age of surface) and the nature of land development system (soil cultivation intensity and frequency, soil conservation practices).

Sustained food production is essentially dependent on maintaining adequate soil fertility. Soil fertility is dependent upon the chemical, physical and biological characteristics of a soil. The chemical properties of soils are a function of the soil parent materials, climate, topography, type of vegetation, soil age and current soil management practices. The Red Earths and Yellow Earths of Southern Shan State have formed on a limestone plateau. More detail about the natural environment under which they formed is given in Section 2.4.2.

For more than five hundred years they have been subjected to shifting cultivation as explained in Chapter 1. Over this time these upland soils have become more acid and more infertile due to insufficient use of fertilisers and lime.

According to von Uexküll and Mutert (1995a), 3950 million ha (approximately 30%) of the global land is composed of acid soils under udic and ustic moisture regions. Of the two main geographical regions; tropical and temperate, about 1,700 million ha are located in humid tropics mainly, as Oxisols and Ultisols; of these, only 179 million ha (approximately 4.5% of total acid soils area) is used for arable crop cultivation. Southeast Asia and the Pacific (excluding Australia and New Zealand) shares the

highest regional acid soils, which is 63% (315 million ha) of the Southeast Asia and Pacific regional land area, with Ultisols alone accounting for 57.6% (181 million ha) of the region's acid soils. The global and Southeast Asia and Pacific region land areas of acid soils grouped on the basis of FAO/UNESCO classification and approximate analogues of USDA soil taxonomy is presented in Table 2.1.

Table 2.1 Area of acid soils worldwide and in the Southeast Asia and Pacific regions ( $\times 1000$  ha) by main soil groups (FAO/UNESCO).

FAO soil group	Global area	Southeast Asia and Pacific <sup>a</sup>	Approx. analogues in soil taxonomy
Fluvisols	49,741	18,614	Fluvents
Gleysols	401,747	18,975	Aquents, Aquepts
Regosols	293,166	1,441	Psamments
Arenosols	280,291	5,436	Psamments
Rankers	60,878	3,890	Haplumbrepts
Andosols	33,975	2,592	Andisols
Cambisols	299,539	45,202	Orchrepts, Tropepts
Podzoluvisols	254,881	53	Boralfs, Aqualfs
Podzols	415,186	4,358	Spodosols
Planosols	15,262	612	Aquults
Acrisols	731,032	164,241	Ultisols
Nitisols	117,907	16,370	Ultisols
Ferralsols	726,592	15,599	Oxisols
Histosols	270,224	17,272	Histosols
Total	3,950,421	314,655	

<sup>a</sup>Excluding Australia and New Zealand

Source: von Uexküll and Mutert (1995a)

Red Earths and Yellow Earths are classified as Acrisols and Ferralsols by FAO/UNESCO soil taxonomy. The major characteristics of these soils are a low CEC and low percent base saturation (%BS) (Table 2.3). Reports on problem soils in the tropics refer mostly to infertile red soils (Ferralsols and Acrisols), but Acrisols are more extensive than Ferralsols in Southeast Asia (Dudal, 1980). The strongly weathered soils of the humid tropics are low in SOM, C, N, P and S reserves (Sanchez, 1976), and minimal rates of N mineralisation (Munns and Fox, 1977). Moreover they are relatively low in available P for optimum plant growth and total phosphorus (P) as a legacy of pedogenesis (Hedley *et al.*, 1995). The Red Earths and Yellow Earths are susceptible to crusting, especially erosion and compaction. These soils have severe limitation to permanent cropping unless used for subsistence farming as shifting cultivation (Dent, 1980; Driessen and Dudal, 1989).

Accurate information on soil resources in the Southern Shan State is required to obtain objective knowledge on how to improve the management of infertile acid upland soils. However, little research has been conducted on these acid upland soils of Myanmar. Research is required to provide information on the sustainable use of these soils. This chapter characterises and classifies the soils in the study area.

## **2.2 Objectives**

The main objective of the thesis is to provide information on how to improve soil fertility of the main soil groups in the Southern Shan State of Myanmar. In line with this main goal, the following specific objectives were established for the initial study described in this chapter.

1. To describe the representative soil groups in the Kalaw-Pindaya area of Southern Shan State.
2. To select an area representative of low fertility soil for field experimentation.
3. To confirm that the soil chemical constraints to crop growth at the research sites are those common to the soils of the region.

## **2.3 Materials and Methods**

### ***2.3.1 Description and classification of soil profiles***

Representative soil profiles of major soils of Southern Shan State are described. A soil profile at Aungban research farm in Kalaw Township and another soil profile at Thayetkon village in Pindaya Township were studied and classified according to the FAO/UNESCO systems (see later Section in 2.4.1).

### ***2.3.2 Soil samples***

Bulk soil samples (0-15 cm depth) of approximately 5 kg for each sample were taken from four different locations (A, B, C and D, see Table 2.2 and Map 3) in Kalaw-Pindaya area to reflect the major soil groups of Red Earths and Yellow Earths. Each bulk sample was dried at room temperature (25°C) over a period of 3 days. These

samples were lightly crushed and sieved through a 2 mm sieve. Sub samples (2 kg) were taken for chemical analysis at Massey University, New Zealand. Adjacent to each location, samples were also taken from two different management regimes: uncultivated soils; and cultivated soils under farmer management (Table 2.2).

Table 2.2 Code, site and history of soil samples from Southern Shan State.

Location	Site	Soil Type	Code	History
A	Aungban research farm	Yellow Earth	YE Exp.	1 year fallow, previous crop: niger
A	Farmer's land, adjacent to Aungban research farm	Yellow Earth	YEUN I	4 years fallow previous crops: upland rice
B	Farmer's land, about 10 km north of Aungban town	Yellow Earth	YECU II	Under potato cultivation, previous fallow
B	Farmer's land, about 10 km north of Aungban town	Yellow Earth	YEUN II	2 years fallow, previous crop: upland rice
C	Farmer's land, about 5 km north east of Aungban town	Red Earth	RECU I	Under upland rice cultivation, previous crop: potato
C	Farmer's land, 1 km opposite of Aungban research farm	Red Earth	REUN I	1 year fallow, previous crop: upland rice
D	Farmer's land, about 18 km north of Aungban town	Red Earth	RECU II	Under upland rice cultivation, previous crop: potato
D	Farmer's land, about 18 km north of Aungban town	Red Earth	REUN II	1 year fallow, previous crop: upland rice

### 2.3.3 Soil chemical analysis

Soil pH, Olsen-P, P retention, soil conductivity, SOM, exchangeable cations ( $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{K}^+$ ,  $\text{Na}^+$ ), effective cation exchange capacity (ECEC), Aluminum saturation, base saturation, total C, N, P and K, soil acidity and lime requirement were measured in Red Earths and Yellow Earths.

Soil pH was measured using a glass electrode pH meter (Farr, 1972) with a soil:water ratio of 1:2.5. An index of plant-available P (Olsen-P) in soils was determined by extraction with 0.5 M sodium bicarbonate pH 8.4 (Olsen *et al.*, 1954) and P retention was measured by the method of Saunders (1965). Soil conductivity was determined using a conductivity meter (soil:water ratio of 1:5) and then total soluble salts (% salts) were calculated using an equation: % salts = Soil conductivity at 25°C ( $\text{mmho cm}^{-1}$ )  $\times$  0.35 (Blakemore *et al.*, 1987). Soil C was determined by both the chemical oxidation method of Walkley and Black (1934) and by the Leco dry combustion method (Searle, 1967; Bremner and Tabatabai, 1971). The dry combustion method gives both inorganic

and organic C. Since the inorganic C is low in these soils, the value of Leco C was used as organic C. Soil OM was estimated using the equation: % SOM = % organic C  $\times$  1.72 (Helling *et al.*, 1964).

Exchangeable cations were extracted in 1 M ammonium acetate (NH<sub>4</sub>AOC) at pH 7. The Ca<sup>2+</sup> and Mg<sup>2+</sup> concentration in the extracts were determined by atomic absorption spectroscopy, and the K<sup>+</sup> and Na<sup>+</sup> concentrations were determined by flame emission spectroscopy (Anderson and Ingram, 1993). Exchangeable acidity (Al<sup>3+</sup> plus H<sup>+</sup>) was determined by extraction in 1 M KCl and titrating Al<sup>3+</sup> and H<sup>+</sup> in soil extract using standard NaOH (Coleman *et al.*, 1959). Al<sup>3+</sup> in the extract was determined by atomic absorption spectroscopy. H<sup>+</sup> in the extract was determined by subtracting exchangeable Al<sup>3+</sup> from exchangeable acidity. The ECEC was calculated by summing exchangeable acidity and exchangeable cations (IBSRAM, 1994). Aluminum saturation (%) was calculated from the ECEC and exchangeable Al<sup>3+</sup> values using the following equation (IBSRAM, 1994): Al<sup>3+</sup> saturation % = Exchangeable Al<sup>3+</sup> / ECEC  $\times$  100. Base saturation (%) is calculated from the ECEC and total exchangeable base (Sum of Ca<sup>2+</sup>, Mg<sup>2+</sup>, K<sup>+</sup> and Na<sup>+</sup>) values using the following equation: %BS = Total exchangeable base / ECEC  $\times$  100.

Total N and P were determined by Kjeldahl wet digestion (Parkinson and Allen, 1975) followed by auto analysis. Mineralisable N (N<sub>m</sub>) was determined by the anaerobic incubation method (Keeney and Bremner, 1966). Total S in soils was measured by wet oxidation (Tabatabai and Bremner, 1970). Total Fe and Al in soils were determined by dithionite-citrate-extractable method (Holmgren, G.G.C. 1967). Lime requirements were determined by the buffer method of Adams and Evans (1962).

## 2.4 Results and Discussion

Chemical characterisation of soils is required to describe the major soil groups and to identify the different soil units (FAO, 1974).

Selected chemical properties of Red Earths and Yellow Earths under different management are shown in Tables 2.3, 2.4 and 2.5. All values in the tables are the means of two replicates.

Table 2.3 Selected chemical properties of Red Earths and Yellow Earths.

Soil	pH <sub>H2O</sub> (1:2.5)	Olsen-P (mg kg <sup>-1</sup> )	P retention	Conductivity (mmho cm <sup>-1</sup> )	%Salts	Soil C <sup>1</sup> (%)	Soil C <sup>2</sup> (%)	SOM (%)
YE Exp.	5.00	8	53	0.09	0.03	1.1	1.3	2.3
YEUN I	5.46	8	46	0.05	0.02	1.1	1.4	2.4
YECU II	6.10	3	39	0.06	0.02	0.6	0.9	1.5
YEUN II	5.72	4	41	0.04	0.02	0.8	0.9	1.6
RECU I	6.17	2	53	0.05	0.02	0.7	1.1	1.9
REUN I	6.16	3	44	0.05	0.02	0.8	1.1	1.8
RECU II	6.01	8	61	0.07	0.02	1.2	1.3	2.2
REUN II	6.16	7	71	0.08	0.03	1.5	1.9	3.3

<sup>1</sup> by using Walkley and Black method; <sup>2</sup> by using Leco combustion method

SOM determined from soil C<sup>2</sup> × 1.72

Table 2.4 Selected chemical properties of Red Earths and Yellow Earths (Continued).

Soil	Exchangeable cations						ECEC <sup>1</sup>	Al <sup>3+</sup>	BS
	Mg <sup>2+</sup>	Ca <sup>2+</sup>	K <sup>+</sup>	Na <sup>+</sup>	Al <sup>3+</sup>	H <sup>+</sup>			
	(cmol (+) kg <sup>-1</sup> soil)						% saturation		
YE Exp.	1.04	1.90	0.09	0.09	0.03	0.92	4.06	0.7	77
YEUN I	0.95	2.07	0.07	0.05	0.02	0.76	3.92	0.5	80
YECU II	2.43	4.40	0.06	0.04	0.02	0.29	7.24	0.3	95
YEUN II	1.76	3.46	0.04	0.07	0.02	0.39	5.74	0.3	92
RECU I	1.06	4.06	0.36	0.07	0.01	0.26	5.83	0.2	95
REUN I	1.91	0.36	0.09	0.02	0.02	0.22	2.62	0.8	90
RECU II	2.55	0.47	0.85	0.01	0.02	0.22	4.12	0.5	94
REUN II	3.65	0.46	0.78	0.09	0.01	0.07	5.06	0.2	98

<sup>1</sup>ECEC =  $\sum (Mg^{2+}, Ca^{2+}, K^+, Na^+, Al^{3+}, H^+)$

Table 2.5 Selected chemical properties of Red Earths and Yellow Earths (Continued).

Soils	Total N (%)	C/N ratio	N <sub>m</sub> <sup>a</sup> (mg kg <sup>-1</sup> )	Total P (mg kg <sup>-1</sup> )	Total S (mg kg <sup>-1</sup> )
YE Exp.	0.15	9.3	58	327	90
YEUN I	0.14	10.4	32	309	97
YECU II	0.08	10.3	39	216	60
YEUN II	0.09	10.8	39	195	74
RECU I	0.11	7.9	34	409	79
REUN I	0.10	10.5	43	239	75
RECU II	0.15	10.5	38	583	117
REUN II	0.17	11.5	44	713	179

<sup>a</sup> mineralizable N

### **2.4.1 Soil classification**

Description of two individual soil profiles of Kalaw-Pindaya areas in Southern Shan State using FAO (1977) guidelines for soil profile description is presented below. Colour notation is according to the Munsell soil colour charts (MUNSELL<sup>®</sup>, 1994).

#### ***Profile 1: Aungban Soil***

##### *Site description and information on the site*

- (a) Profile No. AB.1
- (b) Soil Name: Yellow Earth
- (c) Higher category classification:
  - FAO/UNESCO; Orthic Acrisol
  - USDA; Haplustult
- (d) Location: About 300 m west of car road to Aungban Agriculture Research Farm, Kalaw township, Southern Shan State
- (e) Elevation: Approximately 1,082 m above sea level
- (f) Land form:
  - (i) Physio-graphic position: On gently sloping land near the summit of the slope
  - (ii) Surrounding landform: rolling
  - (iii) Micro-topography: Slight depression at the foot of the slope
- (g) Slope on which profile is sited: Approximately 11%
- (h) Land use: Wheat and upland rice
- (i) Climate: Hot sub-tropical (Myanmar), sub-humid tropic (FAO/UNESCO) annual rainfall 850 mm (8-year average)

##### *General information on the soil*

- (a) Parent material: Limestone
- (b) Moisture condition in the profile: Moist in the upper horizons and wet (soggy) in the lowest horizon.
- (c) Drainage: Class 4, well drained

- (d) Depth of ground water table: Not detected
- (e) Presence of surface stone, rock outcrop: Nil
- (f) Evidence of erosion: Slight sheet erosion
- (g) Presence of salt or alkali: Nil
- (h) Human influence: Intensive to plough layer
- (i) Soil temperature at 50 cm from the surface: 25°C

### *Profile Description*

A 0-13 cm: Dark brown (7.5YR4/4); fresh; silty clay; weak fine granular; soft; non-plastic; non-sticky; many fine roots; boundary clear by colour.

AB 13-40 cm: Yellowish red (5YR5/6); fresh; silty clay; sub angular blocky; soft; slightly plastic; slightly sticky; few fine roots; diffuse boundary.

B<sub>1</sub> 40-64 cm: Yellowish red (5YR 4/8); moist; clay loam; sub angular blocky; slightly hard; slightly plastic; slightly sticky; few fine roots; transition clear by texture.

B<sub>2</sub> 64-77 cm: Yellowish red (5YR 5/8); moist; clay loam; slightly hard; sub angular blocky; plastic; sticky; few roots; some iron concretion; transition clear by moisture and colour.

B<sub>3</sub> >77 cm: Red (2.5 YR 5/8) Soggy; clay; sub angular blocky; plastic; sticky.

### ***Profile 2: Thayetkon Soil***

#### *Site description and information on the site*

- (a) Profile No. TYK-1
- (b) Soil name: Red Earth, silt loam
- (c) Higher category classification:  
FAO-UNESCO; Ferric Acrisol,  
USDA; Paleustult
- (d) Location: Approximately 5 km south from Pindaya about 100 m west of car road to Pindaya near Thayetkon village, Southern Shan State

- (e) Elevation: about 1,336 m above sea level
- (f) Land form:
  - (i) Physio-graphic position: rid of gently straight slope
  - (ii) Surrounding landform: Rolling
  - (iii) Micro-topography: Nil
- (g) Slope on which profile is sited – About 16°
- (h) Land use: Sunflower at present. Probably upland rice next season
- (i) Climate: Hot sub-tropical (Myanmar), sub-humid tropic (FAO/UNESCO), annual rainfall 977 mm (10-year average)

*General information on the soil:*

- (a) Parent material: Limestone
- (b) Moisture condition in the profile: Moist
- (c) Drainage: Class 4, well drained
- (d) Depth of ground water table: not detected
- (e) Presence of surface stone, rock out crop: Nil
- (f) Evidence of erosion: Moderate sheet erosion (Evidence: deposition of soils deposited on the contour band constructed 8 years ago)
- (g) Presence of salt or alkali: Nil
- (h) Human influence: Intensive to plough layer
- (i) Soil temperature at 50 cm from the surface: 25°C

*Profile Description*

Ap 0-14 cm: Dark reddish brown (2.5YR3/4); fresh; silt loam, fine granular; non-plastic; non-sticky; friable, few fine roots; soft: transition clear by colour.

B<sub>1</sub> 14-46 cm: Dark red (2.5YR3/6); moist; silty clay loam; moderate medium granular; slightly plastic; slightly sticky; slightly hard; no roots; transition diffuse.

B<sub>2</sub> 46-89 cm: Dark red (2.5YR 3/6); moist; silty clay; slightly hard; very fine sub angular blocky; sticky; plastic; no roots; transition diffuse.

B<sub>3</sub> 89 cm+: Dark red (2.5 YR 3/6); moist; clay; fine sub angular blocky; slightly hard; sticky; plastic; no roots.

#### ***2.4.2 Major soil grouping of Red Earths and Yellow Earths***

It is not clear as to which of the major soil groupings the Red Earths and Yellow Earths (the most common soils in the Kalaw-Pindaya area) should be classified in. Rozanov and Rozanova (1963) classified the Red Earths and Yellow Earths of Shan State in Myanmar as the red-coloured eluvium of limestone. Tha Tun Oo (1990) classified these Red Earths and Yellow Earths of Shan State in Myanmar as Ferralsols in FAO/UNESCO system. In contrast these Red Earths and Yellow Earths in Southern Shan State have been classified as Red Earths and Yellow Earths in Myanmar system and Acrisols in the FAO/UNESCO system (MAS-LUD, 1994).

Ferralsols (from the Latin words ferrum and aluminum; connotative of a high content of sesquioxides) are defined as soils that have a ferralic horizon at some depth between 30 and 200 cm from soil surface. A ferralic horizon is a fine textured horizon which has been formed by strong weathering and leaching over a long period of time resulting in the accumulation of stable sesquioxides of iron and aluminium (FAO, 2001).

Acrisols (from the Latin word acris, very acid; connotative of low base saturation) are characterized by a clay accumulation horizon, the argillic horizon, in combination with the occurrence of low activity clays (cation exchange capacity of  $<24 \text{ cmol (+) kg}^{-1}$ ) and a low base saturation (i.e.  $<50\%$ ) (FAO, 2001).

Both Acrisols and Ferralsols are tropical and subtropical soils of old landscapes under high rainfall conditions. The formation and parent materials of the Red Earths and Yellow Earths are described in Chapter 1. The profiles of the Aungban and Thayetkon sites are usually deep, yellowish red to dark red coloured, extremely weathered and leached, and the slope class is rolling to hilly (see Section 2.4.1).

The two profiles were lacking an oxic B horizon and plinthite within 125 cm of the surface. However both profiles have a clay accumulation horizon, an argillic B horizon

in combination with the occurrence of low activity clays (2.6 to 7.2 cmol (+) kg<sup>-1</sup> of ECEC (see Table 2.4). The Red Earths and Yellow Earths have little weatherable material left and the clay minerals present in these soils may be mainly crystallised kaolinite and some gibbsite, being Acrisols (Driessen and Dudal, 1989). Pedogenic processes of Acrisols are stimulated mainly by climate (predominating soil forming factor) (Kabata-Pendias and Pendias, 1984). Therefore the Red Earths and Yellow Earths are broadly categorized as Acrisols, rather than Ferralsols in the major soil groupings of the FAO/UNESCO system (FAO, 1974).

### ***The soil units of the Red Earths and the Yellow Earths***

The Yellow Earths from the Aungban site (Kalaw township) and the Red Earths from the Thayetkon site (Pindaya township) are significantly different in some morphology, and physical and chemical characteristics. According to their morphological, physical and chemical characteristics these soils must be related to a single type of Acrisol. The two soil profiles can be classified to the 'great group' level within Acrisols.

In the profiles of Aungban site (Yellow Earth), the uppermost layer was dark brown, and distributed to yellowish in the lower layer down to 77 cm from top, the lower layer was yellowish red in colour. The texture class is fine because the upper 30 cm of the surface soil was a silty clay with more than 35% clay. The profile of the Aungban is lacking in hydromorphic properties within 50 cm of the surface. The Yellow Earths have a low SOM content. The SOM content in the surface soils (0-15 cm) is between 1% and 3% (Table 2.3). This soil profile has an Ochic A horizon, but no Plinthite within 125 cm of the surface. The Yellow Earths have a low pH and no ferric properties or red mottles. Analytical data of the soil samples show that Yellow Earths have low levels of nutrients (i.e. N, P, K, S and Mg) and contain low levels of exchangeable Al<sup>3+</sup> and H<sup>+</sup> (see Table 2.4). Therefore the Yellow Earth profiles of Aungban site can be classed as Orthic Acrisols (Ao) in FAO/UNESCO system (FAO, 1974).

Table 2.6 The soil units of the Red Earths and Yellow Earths in Southern Shan State.

<b>Myanmar system</b>	<b>USDA soil taxonomy</b>	<b>FAO/UNESCO system</b>
Red Earths	Paleustults	Ferric Acrisols (Af)
Yellow Earths	Haplustults	Orthic Acrisols (Ao)

The Red Earth was dark reddish brown in the top layer (0-14 cm) and dark red colour in the lower horizons. Compared to the Yellow Earth profiles, the Red Earth profiles are more uniform and monotonic in soil colour. The texture class is medium textured because the upper 30 cm of the surface soil was silt loam with less than 35% clay and less than 65% sand. The profile of the Thayetkon site is also lacking in hydromorphic properties within 50 cm of the surface. The Red Earths also have a low SOM content and have similar chemical properties to the Yellow Earths (Table 2.3, 2.4 and 2.5). These soil profiles also have an Ochic A horizon, but no Plinthite within 125 cm of the surface. But the Red Earth has the ferric properties because colour hue was redder than 7.5YR. Therefore the Red Earth profile of Thayetkon site can be classed as a Ferric Acrisols (Af) in the FAO/UNESCO system (FAO, 1974).

These FAO/UNESCO soil units do not correspond to equivalent categories in USDA classification system, but they are generally comparable to the great group level (FAO, 1974). Therefore the Yellow Earth can be classified as Orthic Acrisols (Ao) in FAO/UNESCO soil unit and Haplustults in USDA soil classification systems (USDA, 1975). The Red Earths can be classified as Ferric Acrisols (Af) in FAO/UNESCO soil unit and Paleustults in USDA soil classification systems (USDA, 1975) (see Table 2.6).

The additional laboratory data along with the classification of the soil units level is necessary to develop the soil fertility management for sustained food production and future land use in Southern Shan State of Myanmar.

### **2.4.3 Soil pH**

Soil pH measurement is used to indicate soil acidity or alkalinity (Vries and Breeuwsma, 1987). The pH of the Yellow Earths ranged from 5.0 to 6.1 (Table 2.3). Acid intolerant crops, such as soybean and maize, grown in many of these soils (pH <5.5) are likely to be lime responsive. The pH of the Red Earths ranged from 6.0 to 6.2. The pH range indicates a mildly acidic soil reaction. The probability of a lime response in these soils is unlikely except for very acid intolerant crops such as sugarcane and cotton (Edmeades *et al.*, 1985; Myers and De Pauw, 1995). According

to Blakemore *et al.* (1987), these Red Earths and Yellow Earths were rated as low to medium acidity. It is confirmed that these Red Earths and Yellow Earths in Southern Shan State are acid soils.

#### **2.4.4 Olsen-P**

The Olsen-P test is used to indicate the plant-available phosphorus status of the soil (Kamprath and Watson, 1980; Hedley *et al.*, 1995). Since its development (Olsen *et al.*, 1954) this test has been calibrated against plant yield response in many countries (e.g. Brazil (van Raij *et al.*, 1994) and New Zealand (Sinclair *et al.*, 1997). In general, the Olsen-P test value shows a high correlation with plant yields for acid soils as well as alkaline soils in tropics (Dabin, 1980). Olsen extractable P values for Yellow Earths ranged from 3 to 8 mg kg<sup>-1</sup> and for Red Earths it ranged from 2 to 8 mg kg<sup>-1</sup> (see Table 2.3). Thus only a small portion of the total P (less than 0.46 to 2.1% of the total P, Table 2.5) in these soils appears to be in an easily extractable form. According to Blakemore *et al.* (1987), Olsen-P values <10 mg kg<sup>-1</sup> are rated as having very low levels of plant-available P for pasture species in New Zealand soils.

Previous work on Indonesian Ultisols (Tambunan, 1992) indicated that maize grown in soil with Olsen-P values of 1 to 2 mg P kg<sup>-1</sup> can be expected to give a yield response to fertiliser P. There was a lower probability of yield response to applied fertiliser P if the Olsen-P test value was around 8 mg P kg<sup>-1</sup>. Olsen-P values ranging from 2 to 8 mg P kg<sup>-1</sup> indicate that crop yield in these Red Earths and Yellow Earths are likely to be P limited.

#### **2.4.5 P retention**

The P retention is an empirical measure of the ability of the soil to remove fertiliser phosphorus rapidly from solution by adsorption reactions (Blakemore *et al.*, 1987). On a scale of 0 to 100%, Red Earths and Yellow Earths give P retention values of 39 to 71 (see Table 2.3), indicating moderate P retention (Saunders, 1965; Blakemore *et al.*, 1987). Hedley *et al.* (1995) suggested that P sorption capacity of a soil is commonly correlated to soil clay or soil silt content and amount of hydrous Fe and Al oxide

surface exposed which can be indicated by reductant-soluble Fe and associated Al. In general, highly weathered tropical soils show strong P-sorption due to the high content of Fe and Al oxides in the clay (Cong, 2000; Driessen and Dudal, 1989; Hedley *et al.*, 1995). The total Al and Fe were 0.56% and 2.86% in the Yellow Earths and 0.97% and 6.86% in the Red Earths, respectively. These levels are consistent with the observation that the range of P retention values was greater in Red Earths (44 to 71%) compared with Yellow Earths (39 to 53%).

#### **2.4.6 Conductivity and soils soluble salts**

Yellow Earth samples indicated slightly wider range of (0.04 to 0.09 mmho cm<sup>-1</sup>) conductivity values in water extract than Red Earth samples (0.05 to 0.08 mmho cm<sup>-1</sup>) (Table 2.3). According to Blakemore *et al.* (1987), the rating for conductivity of these Red Earths and Yellow Earths are very low (<0.15 mmho cm<sup>-1</sup>). It can be inferred that these soils have no detrimental salinity effects for plants because both soils did not exceed conductivity measures of 0.1 mmho cm<sup>-1</sup> indicative of values likely to cause osmotic stress (Mengel and Kirkby, 1979).

The calculated salt % of these soils was very low indicating these soils were highly weathered and strongly leached and had not been heavily fertilised or manured.

#### **2.4.7 Soil C and SOM**

Soil C contents were determined by two methods, chemical oxidation (Walkley-Black) and by combustion (Leco dry combustion). Both methods show soil C in these Red Earths and Yellow Earths to be <2% (Table 2.3). These soil C amounts are common for most Acrisols, however soil C values are low for Ferralsols in Indonesia and Vietnam (Budianta, 1999; Cong, 2000).

The SOM content was calculated by assuming an organic C content of 58% in SOM. For each pair of cultivated and uncultivated (fallow) soils, SOM was higher in the uncultivated phase, indicating that cultivation caused a decrease in SOM content. The decline in SOM levels under cropping is due partly to the much reduced input of

organic residues to the soil and partly to increased oxidation in the soil due to cultivation (Shang and Tiessen, 1997). With a longer fallow in this area, the SOM may have been increased in the topsoil layers. Greenland and Nye (1959) show that the C and N contents of tropical soils can increase under natural fallow in Ghana.

It is generally accepted that tropical soils such as Yellow Earths and Red Earths have low SOM contents because of the faster rate of plant residue and SOM decomposition in the warm moist climate regime of the tropics (see Chapter 4 for discussion of SOM).

Greenland *et al.* (1992) reviewed the major benefits of increased SOM content, which include: increased available nutrient supply and CEC, improved water holding capacity, soil aggregation and structure, reduced soil surface temperature, erosion and water run off. Thus lower SOM may create problems for the farmer. Retaining and building SOM can be achieved by selecting appropriate crop management techniques. To monitor changes in SOM it may be more appropriate to measure a labile fraction of the soil C. Lefroy *et al.* (1995) suggested that total C is not an appropriate measure because it is not sensitive to short-term changes in the quality of soil. The relation between total C and easily oxidisable C in soils are more discussed in Chapter 4.

A decline in SOM is associated with reduced fertility and low crops yield. For food crops production, using crop residues and/or green manure crops in rotation or as intercrops must be one of the key components of crop management systems for acid upland soils (von Uexküll and Bosshart, 1989).

#### **2.4.8 Exchangeable cations**

The amounts of exchangeable base cations ( $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$  and  $\text{K}^{+}$ ) in Red Earths and Yellow Earths varied according to soil group, where the samples were taken from, and the management of that particular soils (see Table 2.4). These soils were rated as having very low to low levels of exchangeable base cations. But the cultivated Red Earth (RECU II) was high in exchangeable  $\text{K}^{+}$  (0.8 - 1.2 cmol (+)  $\text{kg}^{-1}$ ) (Blakemore *et al.*, 1987). The reason would be that farmers in these areas used wood ash fertilisers.

These soils might have received a considerable quantity of  $K^+$  from wood ash fertilisers and/or potassium fertilisers (i.e. murate of potash, KCl).

The amounts of acidic cations were higher in Yellow Earth samples (from 0.29 to 0.92  $\text{cmol (+) H}^+ \text{ kg}^{-1}$  and from 0.02 to 0.03  $\text{cmol (+) Al}^{3+} \text{ kg}^{-1}$ ) compared to Red Earths (from 0.07 to 0.26  $\text{cmol (+) H}^+ \text{ kg}^{-1}$  and from 0.01 to 0.02  $\text{cmol (+) Al}^{3+} \text{ kg}^{-1}$ ). As Yellow Earths were more acidic than Red Earths, the  $H^+$  and  $Al^{3+}$  ions comprised greater proportion of exchange sites of Yellow Earths. But the  $Al^{3+}$  content in these soils (see Table 2.5) was very low (Blakemore *et al.*, 1987).

#### **2.4.9 Effective cation exchange capacity, $Al^{3+}$ saturation and %BS**

The Yellow Earths and Red Earths in this study had a similar range of ECEC values, 3.92 to 7.24 and 2.62 to 5.83  $\text{cmol (+) kg}^{-1}$  of soil, respectively. In general, these soils are considered low ECEC soils ( $\text{ECEC} < 10 \text{ cmol (+) kg}^{-1}$ ), mainly due to the mineralogy of soil. Usually montmorillonite (2:1) clay minerals have a higher exchange capacity than kaolinite (1:1) clay minerals (Sanchez, 1976). Sanchez (1976) cited that the CEC of montmorillonite and kaolinite in Kenya were found to be 118 and 4  $\text{cmol (+) kg}^{-1}$  soil, respectively.

The CEC not only depends on the nature of clay minerals, but also on the amount and form of SOM present. Soil OM contributes the bulk of the exchange sites in many highly weathered tropical Oxisols, Ultisols, and Alfisols. Due to small amounts of variable charge ECEC in these soils, liming to pH levels of 5.5 or 6.0 can increase the CEC (Sanchez, 1976). However, there is a no relationship between SOM and ECEC in these Red Earths and Yellow Earths (Figure 2.1).

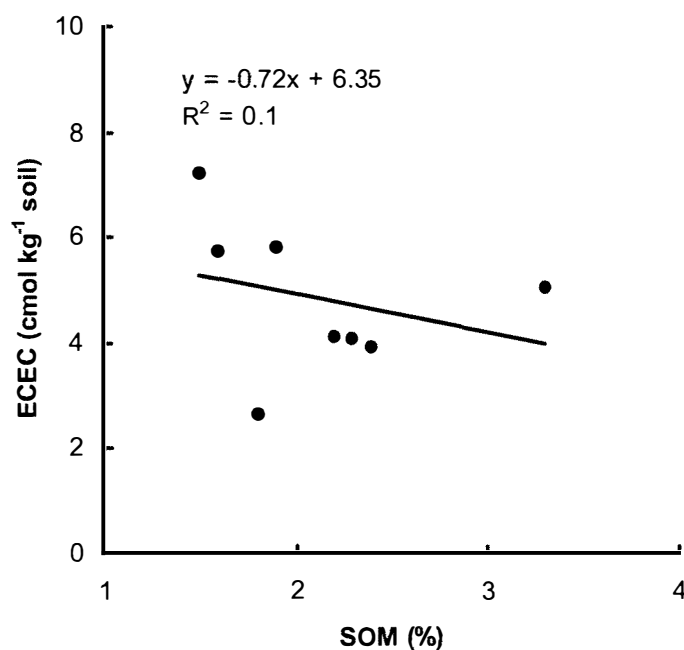


Figure 2.1 Relationship between SOM (%) and ECEC (cmol (+) kg<sup>-1</sup> soil) for the Red Earths and Yellow Earths in this study.

All the Red Earths and Yellow Earths had a low Al<sup>3+</sup> saturation (Table 2.4). Thus the Red Earths and Yellow Earths in Southern Shan State are generally show no Al<sup>3+</sup> toxicity (Kamprath, 1984).

The Red Earths and Yellow Earths had a high base saturation (>77%, Table 2.4) compatible with soil pH of 5.0-6.2 (Table 2.3). However, when %BS is calculated from the sum of exchangeable bases expressed as a percentage of the CEC calculated as exchangeable cations plus exchangeable acidity estimated from the pH drop in 1M NH<sub>4</sub>AOc (Hesse, 1971) and total exchangeable bases low (21%) to medium (60%) base saturation values are computed. This reinforces the fact that ECEC should be used for soil fertility diagnostics.

#### 2.4.10 Total N

Only 2 to 5% of soil N is normally present as mineral N (extractable nitrate (NO<sub>3</sub><sup>-</sup>) or ammonium (NH<sub>4</sub><sup>+</sup>)). Soil N is mostly a component of SOM therefore soil N content depends very much on management of the soils and biological processes. The value of

this organic N for plant growth is dependent on the process of mineralisation of organic N, which is influenced by soil moisture and temperature (Mengel and Kirkby, 1979).

The results of total N of Yellow Earths varied from 0.08% to 0.15%, and the total N contents of Red Earths varied from 0.10% to 0.17% (see Table 2.5). These Red Earths and Yellow Earths are rated as very low to low for total N (Blakemore *et al.*, 1987).

#### **2.4.11 Mineralisable N**

Less than 5% of the total N in Red Earths and Yellow Earths is available to plants as mineralisable N (see Table 2.5). Keeney and Bremner (1966) found that the estimation of the ammonium N produced under an anaerobic incubation method provides a good index of soil N availability. The anaerobic N mineralisation assay measures N released mainly from the microbial biomass. It results in greater amount of net N mineralisation and/or less gross N immobilisation (Myrold, 1987). Keeney and Bremner (1966) found that the relationship between N uptake by ryegrass and  $N_m$  was closer than the relationship between N uptake and total soil N. If N uptake is not replaced by N fertilisation or mineralisation in these Red Earths and Yellow Earths, the amount of plant-available N becomes even lower.

There is no relationship between total N and mineralizable N for Red Earths and Yellow Earths (Figure 2.2). Yellow Earths released similar amounts of mineralisable N (32 to 58 mg kg<sup>-1</sup>) as the Red Earths (34 to 44 mg kg<sup>-1</sup>).

The amount of mineralisable N represented 2.3 to 4.9% of the total soil N and would provide adequate N for the single crops listed in Table 2.7. In agricultural soils, mineralisation of N is the major cause for soil acidification if biomass is removed each year (Vries and Breeuwsma, 1987). In addition, if the N demand by the vegetation (crop) is lower than the N supply, acidification by nitrification can be important.

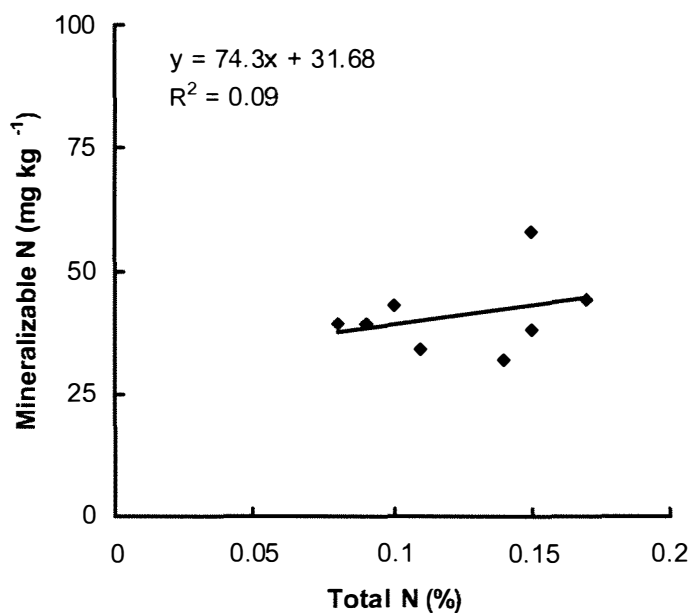


Figure 2.2 The relationship between total N (%) and mineralizable N (mg kg<sup>-1</sup> soil) in Red Earths and Yellow Earths.

Table 2.7 Mineralisable N in Red Earths and Yellow Earths and tropical crop N requirements (kg N ha<sup>-1</sup>).

Soil	Mineralisable N	Rice <sup>1</sup>		Potato <sup>2</sup>		Maize <sup>3</sup>	
		grain	straw	tuber	Top	grain	stover
YE Exp.	87	29	18	59	8	38	24
YEUN I	49						
YECU II	59						
YEUN II	58						
RECU I	52						
REUN I	64						
RECU II	57						
REUN II	66						

<sup>1</sup> rice grain yield 1.8 t ha<sup>-1</sup> + straw yield 3.6 t ha<sup>-1</sup>

<sup>2</sup> potato tuber yield 10 t ha<sup>-1</sup> + top yield 1 t ha<sup>-1</sup>

<sup>3</sup> maize grain yield 1.8 t ha<sup>-1</sup> + stover yield 4 t ha<sup>-1</sup>

Data for N concentrations in crops was taken from Agriculture Research Institute, Yezin, Myanmar.

#### 2.4.12 Total P

Soil chemical analyses revealed a wide range in total P content across locations in Southern Shan State. The total P content of Yellow Earths varied from 195 to 327 mg P kg<sup>-1</sup> and Red Earths varied from 239 to 713 mg P kg<sup>-1</sup> (see Table 2.5). There was also very weak positive relationship between total P and Olsen-P in Red Earths and Yellow Earths (Figure 2.3). The total P content of mineral soils ranges from 50 to over 1,000

mg P kg<sup>-1</sup> soil (Foth and Ellis, 1997). Total P in tropical soils is from lowest in sandy savannah soils of arid regions (about 10 mg P kg<sup>-1</sup> soil) and highest in soils formed on volcanic rocks of humid regions (about 450 mg P kg<sup>-1</sup> soils) (Dabin, 1980). Total P in less weathered soils also varies largely, from 400 to 1,500 mg P kg<sup>-1</sup> soil, but the content of total P in New Zealand soils relates to their fertiliser history and management (Moir *et al.*, 1995). However, the total P in soil is not directly proportional to available P for plants (Havlin *et al.*, 1999).

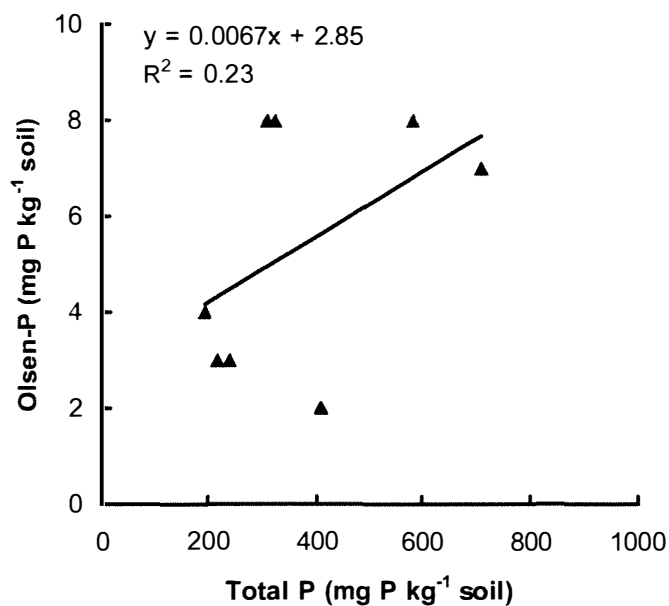


Figure 2.3 The relationship between total P (mg P kg<sup>-1</sup> soil) and Olsen-P (mg P kg<sup>-1</sup> soil) for Red Earths and Yellow Earths.

The quantity of P in the native Red Earths and Yellow Earths is low, although Yellow Earths were relatively lower in total P than Red Earths in Southern Shan State. The Red Earth, REUN II had the largest total P and the Yellow Earth, YEUN II had the lowest total P under uncultivated condition. Total P in cultivated soils are generally lower than uncultivated soils, because of the removal of P by crops from soils at harvest, or it may be due to previous P fertiliser history. However, total soil P is not normally considered to be a good indicator for current reserve P fertility and previous P fertility history and management on the particular soil.

### ***2.4.13 Limitations and potential use of Red Earths and Yellow Earths***

The Red Earths and Yellow Earths of Kalaw-Pindaya area are typically well drained with fine to medium texture in the surface soils. There are no surface stones, good soil depth and easy slope-characteristics that are favourable for crop production. The good texture in these soils is important for tillage and water retention. Soil depth is one of the most important factors in agricultural productivity because it affects root penetration (Dudal, 1980). Association of the cropping system with deep-rooted trees or other crop species for recycling of basic cations can assist in controlling the increase in soil acidity (Moormann and Greenland, 1980).

Bulk density values of surface soils of Red Earths and Yellow Earths are variable due to the variation in soil texture and organic matter content in the soils. The Yellow Earths are less friable and the average bulk density is about 1.3 to 1.5 g cm<sup>-3</sup>, which is greater than the bulk density of the Red Earths. However these Red Earths and Yellow Earths become sticky after heavy rains due to their unstable soil structure. The Red Earths are well aerated, but the Yellow Earths are sometime poorly drained and it may lead to temporary excess wetting and waterlogging (Rozanov and Rozanova, 1963). The author has noted that short-term waterlogging often occurs on flat lands during the heavy rains of the monsoon season in Southern Shan State. Except for the short-term waterlogging, these soils have few limiting physical properties for permanent cropping.

Most soil-related problems for crop growth on the Red Earths and Yellow Earths relate to low water holding capacity and compaction, which are associated with temporary waterlogging in September-October, and usually drought in July (so-called July drought) (see Figure 1.1 in Chapter 1). Upland crops are susceptible to either drought or water logging. Occurrence of drought at a critical growth stage (e.g. upland rice at panicle initiation and maize at silking) is one of the main reasons for low crop yields. Crop yields also decline under reduced conditions because the prolonged waterlogging results in the build-up of toxic amounts of elements such as Fe and Mn and poor aeration for root and microbial respiration. Severe soil physical constraints are formed rapidly in Southern Shan State because the soils have been eroded without cover,

depleted of SOM and compacted by land cultivation (especially using tractors and machinery for tillage). These problems can be solved by introducing new farming systems, changing to tolerant varieties, appropriate irrigation and drainage systems, and using crop residues for mulching.

Chemical analysis of the soils has confirmed that the Red Earths and Yellow Earths are highly weathered and moderately to strongly acidic. The Red Earths and Yellow Earths in Kalaw-Pindaya area are very poor in nutrients for optimum growth of plants, particularly plant-available P and K. Phosphorus deficiency symptoms (deep purple leaves) were observed in the farmers' maize fields. The main constraint appears to be low available P since the soils did not exhibit high P retention. Deficiency symptoms of Mg (interveinal chlorosis) and Zn ("little leaf" rosette with stunted growth) were also observed on maize and legume plants in the farmers' fields.

Soil acidity is another major limitation to growing crops on Acrisols (von Uexküll and Mutert, 1995b; Budianta, 1999; Cong, 2000). Soil acidity can be partitioned into exchangeable and pH dependent acidity (Coleman and Thomas, 1967; Curtin *et al.*, 1984; Tambunan, 1988; Black, 1993). Exchangeable acidity is mostly due to monomeric aluminium ions, and can be displaced by a neutral salt solution such as 1 M KCl. pH dependent acidity, also known as non-exchangeable or titratable acidity (Curtin *et al.*, 1984), is measured as the amount of acidity neutralised in raising the soil pH to a target pH value (Coleman and Thomas, 1967).

The pH of soil solution is ultimately measured from the distribution of  $H^+$  activity between soil surfaces and the soil solution in acid soils (Ritchie, 1989). If the pH of the Red Earths and Yellow Earths in water is less than 5.5, Al and Mn become more soluble and can be toxic to plant growth. This causes major limitations for acid-intolerant crop production on highly weathered soil (Slattery *et al.*, 1999). The toxic amount of Al in a soil depends on the soil properties such as pH and P content. Excess Al accumulating in plant roots reduces their capacity to translocate P (Hesse, 1971). The symptoms of Al toxicity in plants are swollen, stunted and crooked roots. The tolerance to  $Al^{+3}$  can vary widely among varieties of the same species of crops (Kamprath, 1984). Manganese is a plant micronutrient and its optimum range is between 1 to 4  $\mu g\ ml^{-1}$  in soils solution

(von Uexküll, 1986) or between 20-500 mg kg<sup>-1</sup> in mature leaves (Jones and Benton, 1972). Manganese deficiency often appears as interveinal chlorosis and its toxicity is identified as brown spot on older leaves and an uneven distribution of chlorophyll. High concentrations of Mn in the soil solution can be toxic to many plants. Manganese availability to plants increases at low pH (<5.5) (Blamey and Edwards, 1989), and it may appear together with Al toxicity at pH <4.8. The strategies of reducing or eliminating Al and Mn toxicities are discussed later (Sections 4.1.2).

The extent of monomeric hydrolysis of Al can be reduced by the increase of other inorganic (e.g. NO<sub>3</sub><sup>-</sup>, Cl<sup>-</sup>, SO<sub>4</sub><sup>2-</sup>) and organic anions (Ritchie, 1989). The main sources of pH dependent acidity in soils arise from soil organic matter (mainly some weak acid groups in the organic matter) and deprotonation of hydroxy-Al polymer species that block exchange position in the layer silicate clays and also the deprotonation of Al-OH, Si-OH, Fe-OH species in layer silicate and sesquioxides (Curtin et al, 1984; Black, 1993).

The pH value of the soil adjacent to the plant root (rhizosphere pH) differs substantially from the pH value measured in bulk soil (Nye, 1981). pH effects due to the presence of plants may differ between species and cultivars because of the differences in the form of nutrient supplied (e.g. NH<sub>4</sub><sup>+</sup> or NO<sub>3</sub><sup>-</sup> as different N forms), and the ash alkalinity of plants (Jarvis and Robson 1983a,b).

The soluble acids (nitric, sulfuric, phosphoric, and carbonic) are created in soils by microbial decomposition of organic matter, which contributes to soil acidification (Black, 1993). As a biological constraint, soil acidity is harmful to the growth and the population of rhizobia that form nodules on legume roots, and affects microbial activity responsible for the turnover and decomposition of plant and animal residues in soils (Haynes and Williams, 1993). As soil acidity increases, nodules may be formed by less effective rhizobial strains, and/or the efficiency of nitrogen fixation may be reduced. If soils have high concentrations of Al (>50 µM) and Mn (>200 µM), and low concentrations of P (<10 µM) and Ca (<10 µM) in soil solution, nodulation of legume roots may be reduced by limiting the rhizobia population (Coventry and Evans, 1989). A low concentration of Ca ions, and high concentrations of Al, Fe and Mn ions in soil

solution are the predominant chemical factors limiting plant growth in acid soils (Runge and Rode, 1991).

The Red Earths and Yellow Earths analysed in this chapter exhibit negligible  $\text{Al}^{3+}$  toxicity. The soil solution  $\text{Al}^{3+}$  concentration of these Red Earths and Yellow Earths were at non-toxic levels ( $\text{Al}^{3+}$  saturation <10) (Kamprath, 1984). Improved soil structure, increase reserves of N, P and S, increased CEC, reduced acidity and  $\text{Al}^{3+}$  activity, can be achieved in these Red Earths and Yellow Earths by building SOM through appropriate use of crop residues and green manures. For example, Dissanayake *et al.* (1999) showed that the addition of crop residues from shade trees such as *Gliricidia* combined with an application of rock phosphate as P fertiliser for correction of P deficiency was found to be effective in improving the soil fertility and yields of tea in the low pH soils of the Sri Lankan highlands.

Liming acid soils reduces Al and other metal toxicities, improves the physical soil condition, increases the CEC of variable charge soils, increase the P availability and supplies both Ca and Mg (if dolomite is used for liming). For example, the use of lime and P fertiliser produced high sugarcane yields on Oxisols in Hawaii (Uehara and Gillman, 1981). Finally, the least productive of these Red Earths and Yellow Earths may be brought into optimum production by applying heavy fertiliser inputs, particularly P fertilisers and lime, to counter low inherent fertility and acidity (Dent, 1980; Driessen and Dudal, 1989; Hedley *et al.*, 1995).

## 2.5 Conclusions

The Red Earths and Yellow Earths of Southern Shan State are broadly classified as Acrisols in the FAO/UNESCO system. Current study has confirmed that the soil units of Red Earths are Ferric Acrisols and Yellow Earths are Orthic Acrisols in FAO/UNESCO system.

The Red Earths and Yellow Earths have serious problem with erosion by water and wind, which has long been recognised in Shan State of highlands of Myanmar.

The chemical characteristics of the Red Earths and Yellow Earths are low pH and very low available P, moderate P retention with no  $Al^{3+}$  toxicity. These soils have low SOM that commonly results in low ECEC and low reserves of N, P and S. Therefore the main constraints to crop production on rainfed infertile acid upland soils in Southern Shan State are moderate soil acidity, low nutrient availability and low SOM. In particular, the Red Earths and Yellow Earths usually possess limited P reserves and very low available P (Olsen-P) with moderate P retention.

However, the Acrisols in Southern Shan State can be managed for sustainable productivity by optimum fertiliser application, particularly P fertiliser and a liming program, with careful management of farming systems. For economic consideration of poor farmers, one of the strategies to improve P availability and acidity in these Red Earths and Yellow Earths can be the use of cheaper P fertiliser sources (organic and/or inorganic sources), and careful use of local dolomite as a liming agent.

These conclusions highlight the need to develop soluble P fertiliser response curves, and to determine the effects of different P sources and local dolomite under glasshouse and field conditions for further P fertiliser recommendations and fertility management on the Red Earths and Yellow Earths in Southern Shan State (see Chapters 3, 6, 7 and 8). Furthermore, the measurement of organic C in soils is critical for the estimation of SOM in the Red Earths and Yellow Earths, hence a suitable method for measuring soil organic C should be evaluated (see Chapter 4). In addition a soil P fractionation study would provide a means of quantifying the efficiency of RPR fertiliser use, residual P effects and a better understanding of management of these infertile Red Earths and Yellow Earths in Southern Shan State, Myanmar (see Chapters 5 and 6).

## **CHAPTER 3    Lime and Phosphorus Responsiveness of the Red Earths and Yellow Earths: A Glasshouse Study**

### **3.1    Introduction**

As discussed in Chapter 1, large parts of the uplands in Southern Shan State are covered by Red Earths and Yellow Earths (Tha Tun Oo, 1990; MAS-LUD, 1994). In general these are infertile acid upland soils. They have a low SOM content, and the availability of plant nutrients, particularly P, is low for crop production. More details about the properties of Red Earths and Yellow Earths and soil factors limiting to crop production are presented in Chapter 2.

As the population of Myanmar grows, population pressure and land scarcity are the driving forces responsible for bringing these marginal lands under cultivation, as explained in Chapter 1. Many small farmers are increasing the use of these marginal soils to supply their food demand. This occurs partly because there is rapid urbanisation on the more productive agricultural soils due to changed government economic policy in Myanmar since 1989. Crop management practices with low fertiliser inputs used by farmers are unlikely to sustain crop yields (see Chapter 1) and soil fertility because nutrient depletion occurs at much greater rate than restoration.

Such nutrient depletive agriculture is a widespread problem in the highly populated tropics and subtropics. To move towards more sustainable agriculture, Lal and Stewart (1992) stated that the adoption of land use or farming systems must be 'soil-restorative' rather than 'soil-depletive'. From a practical standpoint, it is necessary to determine the economic feasibility of restoring soil fertility conditions to a state that is adequate for a given farming system. Excessive soil improvement may not be economically feasible. Ultimately, some judgement should be made as to the required extent of fertility management, given the high capital, monetary and social costs of soil fertility management (Logan, 1992).

Water-soluble P fertilisers, such as single superphosphate (SSP) and triple superphosphate (TSP), have often been used to overcome low P availability in acid upland soils, as P is one of the most limiting factors for crop production in these high P fixing tropical soils. Most farmers cultivating Red Earths and Yellow Earths in Southern Shan State, however, have been using traditional organic fertiliser, such as FYM, as a N source rather than a P source. Apart from FYM, farmers are currently solely dependent on imported triple superphosphate (e.g. TSP from Tunisia) for a P source, since TSP is the P fertiliser most available in the local market in Myanmar. Indigenous deposits of phosphate rock, MPR, can be produced locally but useful information about the agronomic effectiveness of MPR for the purpose of direct application is not available. However, if agronomically effective, MPR would be a cheaper P resource for small farmers and could be used to supplement other imported fertilisers in Myanmar.

In addition to low P status, acidity is a common problem in Red Earths and Yellow Earths. Generally, soil acidity is corrected by liming. Liming can also enhance P availability (Haynes, 1982) and/or reduces  $Al^{3+}$  toxicity of acid soils (Naidu, 1985; Tambunan, 1988).

In this chapter, preliminary glasshouse experiments are conducted to investigate the P responsiveness of crop plants grown on P deficient and low pH Red Earths and Yellow Earths. In particular, the agronomic effectiveness of local fertilisers such as MPR and FYM and the local dolomite, as a liming agent, are evaluated.

### **3.2 Objectives**

The specific objectives of this chapter are:

1. To obtain preliminary information on the P status of the Yellow Earth at the potential field trial sites on Aungban Research Farm.
2. To investigate the relationship between soil P test values and the growth of pigeon pea and upland rice on the Yellow Earth from Aungban field trial site.

3. To evaluate the agronomic effectiveness of locally available FYM (an organic P source) and MPR (a slow-release P source) relative to water-soluble TSP on low pH soils.
4. To assess the agronomic effectiveness of FYM as an N source for upland rice growth on a Yellow Earth.
5. To evaluate the locally produced dolomite as an effective liming material.

### **3.3 Materials and methods**

#### ***3.3.1 Characterisation of fertilisers, manures and the liming agent***

##### ***Phosphorus fertilisers***

Prior to use in glasshouse trials, samples of TSP and MPR obtained from a fertiliser market in Shan Sate, Myanmar were physically and chemically characterised.

##### ***Triple superphosphate (TSP)***

As mentioned in Section 3.1, TSP is the most widely used water-soluble P fertiliser in Myanmar. Imported TSP from Tunisia is readily available at the local fertiliser market and its agronomic performance is acceptable amongst farmers in Myanmar. The physical characteristics and the selected chemical properties of a sample of TSP are presented in Tables 3.1, 3.2, and 3.3.

##### ***Myanmar phosphate rock (MPR)***

Myanmar phosphate rock is a fluorapatite which is readily available in Myanmar. The particle size distribution of (as received) MPR was measured by sieve analysis and total P by tri-acid digestion and soluble P by water, 2% citric and 2% formic acid extraction, respectively (Syers *et al.*, 1986). The physical and chemical properties of MPR were compared with Sechura phosphate rock (SPR) from Peru, and these results are presented in Tables 3.1, 3.2 and 3.3.

Table 3.1 Selected physical characteristics of P fertilisers.

Fertiliser	Percentage size distribution			
	4 – 6.7 mm	2 – 4 mm	1 – 2 mm	<1 mm
TSP	14	83	3	0
Powder	<0.5 mm	0.25 – 0.5 mm	0.15 – 0.25 mm	<0.15 mm
MPR	7	54	34	5
SPR	5	45	40	10

SPR = *Sechura phosphate rock*

Table 3.2 The percentage of total P content and the percentage of total P extracted by water, 2% citric acid and 2% formic acid from TSP and MPR obtained from Myanmar and SPR from Peru.

Fertiliser	Total P (% W/W)	Percentage total P extracted by		
		Water	2% citric acid	2% formic acid
TSP	20.6	93.5	94.1	97.6
MPR	12.7	0.5	5.5	7.7
SPR	13.1	0.3	42	67

Table 3.3 The chemical analysis of fertiliser materials and dolomite (% w/w, air-dry basis).

Fertiliser	Total N (%)	Total P (%)	Total K (%)	Total S (%)	Total Ca (%)	Total Mg (%)	Total Na (%)
MPR	N.A	12.7	0.8	0.03	39.5	0.5	0.2
SPR	N.A	13.1	N.A	1.4	30.7	0.3	N.A
TSP	N.A	20.6	0.6	1.4	22.7	0.2	0.3
FYM	1.9	2.9	0.7	0.1	0.7	0.1	0.2
Urea	45.8	N.A	N.A	N.A	N.A	N.A	N.A
Dolomite <sup>1</sup>	N.A	N.A	0.7	0.01	29.5	16.6	0.3

<sup>1</sup>CaCO<sub>3</sub> equivalent = 100 %

N.A = not applicable

### **Relative reactivity of MPR**

Phosphate rock (PR) is a generic term that covers a wide variety of rock types that have widely different textures and mineral composition (McClellan and Gremillion, 1980). Phosphate rocks are categorized into 3 types, based on their mineralogical assemblages (McClellan and Gremillion, 1980; Le Mare, 1991). In the order of increasing economic importance they are grouped as: (i) Fe- and Al-phosphates (e.g. wavellite: Al<sub>3</sub>(PO<sub>4</sub>)<sub>4</sub>(OH)<sub>3</sub>.5H<sub>2</sub>O, and strengite: FePO<sub>4</sub>.2H<sub>2</sub>O); (ii) Ca-Fe-Al-phosphates (e.g. crandallite: Ca<sub>2</sub>Al<sub>6</sub>(PO<sub>4</sub>)<sub>4</sub>(OH)<sub>10</sub>.2H<sub>2</sub>O, and millisite: (Na-K)CaAl<sub>6</sub>(PO<sub>4</sub>)<sub>4</sub>(OH)<sub>3</sub>.H<sub>2</sub>O); and (iii) apatites (Ca-phosphates) (e.g. fluorapatite: Ca<sub>10</sub>(PO<sub>4</sub>)<sub>6</sub>F<sub>2</sub>).

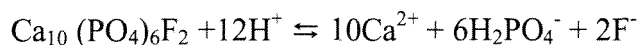
*Assessment of the chemical reactivity of PR for direct application*

There is a wide range of solubility and reactivity among the apatites. More than 25 elements have been reported to occur in the apatite structure of fluorapatite (McClellan and Gremillion, 1980) with varying amounts of substitution. For example, sodium (Na) and Mg may substitute for Ca, carbonate for phosphate, and hydroxyl for fluoride in the crystal structure (Le Mare, 1991). Isomorphic substitution influences the crystal structure, the physical and chemical stability of its apatite. In general, more reactive PRs have more isomorphic substitution of carbonate for phosphate than less reactive PRs (Khasawneh and Doll, 1978; Anderson *et al.*, 1985). The empirical formula of francolite or carbonate apatite can be expressed as follows (McCellan and Lehr, 1969; Tambunan, 1992):



Where  $a = 0$  to  $0.35$ ;  $b = 0$  to  $0.35$ ;  $\beta = 0$  to  $1.26$

The empirical equation for the fluorapatite reaction in soil solution can be expressed as follows (Khasawneh and Doll, 1978; Bolan *et al.*, 1990b):



The chemical extractants 2% citric and 2% formic acid are commonly used for the assessment of PR reactivity (Chien *et al.*, 1978; and MacKay *et al.*, 1984a). Chemical assessments are quick, cheap and can easily be carried out in any laboratory (Tambunan, 1992). A PR that is ground to 95% <63  $\mu\text{m}$  and has 55% or more of its P soluble in 2% formic acid solution is identified as 'soft' or reactive phosphate rock (RPR) by EEC regulation No. 77/535 (Official Journal of the European Communities, 1977) and is recommended for direct application to agricultural soils. According to White *et al.* (1989), a PR (no particle size criteria) that has  $\geq 30\%$  of its P soluble in 2% citric acid solution is ranked as a RPR. Based on the solubility of PR in 2% citric acid and 2% formic acid, Syers *et al.* (1986) ranked the various PRs from different countries from most reactive to less reactive for direct application in agricultural soils. For New Zealand purposes, Quin *et al.* (1987) classified three types of PR based on their

solubility in 2% formic acid: reactive (>55% of total P), medium reactive (30-50% of total P) and unreactive (<30% of total P).

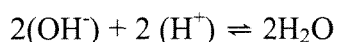
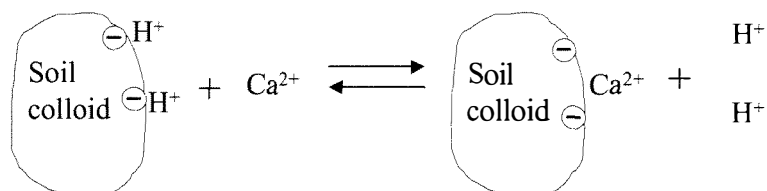
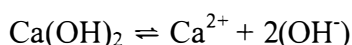
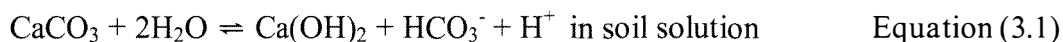
Commercial PRs vary in P content from about 12 to 17% P. Myanmar phosphate rock falls in this range, but contains less total P than SPR (see Table 3.3). The potential of a PR as a direct-application fertiliser depends on its chemical reactivity. Myanmar rock phosphate has only low percentages of its total P soluble in 2% citric and 2% formic acids (Table 3.2). Thus on the basis of the criteria reported by Quin *et al.* (1987), MPR would be ranked as an unreactive rock unsuited to direct application. These chemical reactivity tests are only of empirical in nature and it is important to test the value of PR for direct application in the Red Earths and Yellow Earths.

### *Local dolomite*

The local dolomite was physically and chemically characterised to assess its neutralising value.

### *Liming agent*

As discussed in Chapter 1, liming Red Earths and Yellow Earths is necessary to reduce soil acidity. But the process and reactions by which liming materials reduce soil acidity are very complex. Liming reactions begin with the neutralisation of  $H^+$  in the soil solution by either  $OH^-$  or  $HCO_3^-$  originating from the liming materials. The simple reaction is as follows:



The accompanying anion must lower  $H^+$  and  $Al^{3+}$  activity in the soil solution. During liming of arable crops it is important to allow enough time (i.e. 3 to 6 months ahead of planting the crop, Glendinning, 1999) for the liming materials to react with the soil. Frequency of application of liming materials is influenced by many factors such as soil texture, rate of N fertilisation, rate of crop removal, amount of liming material applied, buffering capacity of soil and the target pH range desired.

The value of a liming material depends on the quantity of acid that a unit weight of lime will neutralise, which is related to its composition and purity. Important considerations in the selection of a liming materials are: chemical composition (especially Ca and Mg content), neutralizing value, particle size (degree of fineness) and cost of the material (Glendinning, 1999).

#### *Neutralising Value or Calcium Carbonate Equivalent*

The neutralising value (NV) or calcium carbonate equivalent (CCE) is defined as the acid-neutralizing capacity of the liming material expressed as a weight percentage of pure  $CaCO_3$ . Pure  $CaCO_3$  is the standard against which other liming materials are measured, and its NV is considered to be 100%.

Table 3.4 Relative neutralising value (NV) of pure forms of some liming materials.

Liming material	Molecular weight (g mole <sup>-1</sup> )	Equivalent weight (g eq. <sup>-1</sup> )	NV (%)
Burnt lime, CaO	56	28	179
Hydrated lime, Ca(OH) <sub>2</sub>	72	36	136
Dolomite, Ca Mg(CO <sub>3</sub> ) <sub>2</sub>	184	46	109
Limestone, CaCO <sub>3</sub>	100	50	100
Myanmar Dolomite	-	-	100 ± 5

The NV of liming materials can be analysed following acid titration (Hesse, 1971) or calculated from the molecular weight. As described in Equation of 3.1, 1 mole of  $CO_3^{2-}$  will neutralise 2 moles of protons ( $H^+$ ). The molecular weight of  $CaCO_3$  is 100, whereas that of  $MgCO_3$  is only 84 and its NV is 119 ( $100/84 \times 100$ ). Therefore,  $MgCO_3$  will neutralise 1.19 times as much acid as the same weight of  $CaCO_3$ , hence the NV of

dolomite is 109%. The same procedure is used to calculate the NV of other liming materials and the relative NV of pure forms of some liming materials are also shown in Table 3.4.

The dolomite used in this study was commercial grade that was crushed into a powdered form (<250  $\mu\text{m}$  particle size). The  $\text{CaCO}_3$  equivalent of the dolomite was measured by the rapid titration method (Wang, 1996). The NV of local dolomite was slightly lower than the pure form of dolomite. The  $\text{CaCO}_3$  equivalent of the local dolomite is 100%. (Table 3.4) This local dolomite contains about 30% by weight of total Ca and 17% Mg. The elemental analysis of the dolomite is presented in Table. 3.3.

### ***3.3.2 Experiment (1): Agronomic effectiveness of MPR and dolomite on pigeon pea growth in a Yellow Earth***

#### ***Test crop used and seed germination***

The major considerations in selecting plant species for the evaluation of P fertiliser and lime responsiveness are (1) native species, (2) proposed farming system, and (3) socio-economical constraints. Thus, pigeon pea (local variety named *Nga San Pae*) was collected from a local market in Myanmar. Pigeon pea is used as a grain legume in many countries in South East Asia including Myanmar. A seed germination test was conducted using moistened filter paper in petridish held at 27°C in an incubator before sowing. The germination rate of pigeon pea was 87%.

#### ***Soils***

A 30 kg sample of Yellow Earth was gathered for this study from Aungban Research Farm, Southern Shan State (96° 39.43' East Longitude and 20° 40.75' North Latitude), where field trials were to be set up. The Yellow Earth was classified as an Orthic Acrisols (see Chapter 2). This composite soil sample was initially acidic (pH 5.0), low in soil C (Walkley-Black C 1.1%), low available P (Olsen-P 8 mg P  $\text{kg}^{-1}$ ), low ECEC (4.06 cmol (+)  $\text{kg}^{-1}$ ), high percent base saturation (77%) and medium P retention (53%) (see Section 2.3.3 for method).

### ***Phosphorus fertilisers***

As mentioned earlier, P fertiliser materials included MPR, an imported TSP from Tunisia, and a locally produced FYM, which are readily available in Myanmar. The physical and chemical characteristics of MPR, TSP and FYM are presented in Tables 3.1, 3.2 and 3.3.

### ***Local dolomite***

As explained in Section 3.3.1 the dolomite used in this study was commercial grade and was hand crushed into a powder form (<250  $\mu\text{m}$  particle size). The chemical properties of dolomite are presented in Table. 3.3.

### ***Lime and fertiliser requirements***

The lime requirement (LR) was based on the relationship between soil pH in water and in an Adams-Evans buffer solution at pH 8 (Adams and Evans, 1962). The dolomite rate of application was calculated to attain the target soil pH value of 6.5. The fertiliser requirement (FR) can be expressed as the amount of fertiliser required per pot and was calculated from the following formula:

The material needed ( $\text{kg pot}^{-1}$ )  $A = N \times P/F$

Where: N = Amount of nutrient ( $\text{kg ha}^{-1}$ )

P = Pot surface area (ha)

F = Fractional weight of element in the fertiliser material

### ***Preparation of soil, fertiliser application and layout of pots***

Soil (270 g air-dried) was placed into polyethylene pots, which had a 64 ( $8 \times 8$ )  $\text{cm}^2$  surface area and were 11 cm high. Each pot was lined with a plastic bag to prevent leaching losses from the soil.

All fertilisers used in this study were ground and sieved to  $<250\ \mu\text{m}$  particle size before application. Myanmar PR, dolomite and muriate of potash (KCl) were thoroughly mixed with the entire soil sample in each plastic bag, to get maximum contact between the soil and fertilisers. Triple superphosphate was mixed with one third of the soil (90 g) and to simulate the field placement of fertiliser, it was placed in the centre core (45 mm diameter) of each pot. These pots were laid out randomly with three replicates of each treatment.

### *Design of Experiment (1)*

The test crop used was a tropical legume species called pigeon pea (*Cajanus cajan*). This experiment was an 8-week glasshouse trial (from 23 December 1997 to 17 February 1998) conducted at Massey University's Plant Growth Unit (Plate 3.1).



Plate 3.1 Pigeon pea grown on the Yellow Earth at glasshouse Massey University.

### *Treatments*

The control treatments did not receive P or K fertiliser application. The other treatments consisted of three rates of P, namely 15, 30 and 60 kg P ha<sup>-1</sup> with different sources of P:

MPR, TSP alone and TSP plus dolomite, and either a zero K application or 50 kg K ha<sup>-1</sup> application.

### *Basal fertilisers*

All treatments, including the control treatment, received 25 kg N ha<sup>-1</sup> as ammonium sulphate [(NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>] as an initial basal application. The (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub> used was a commercial grade and was in a fine crystalline form.

### *Planting and harvesting*

Pigeon pea seeds were sown at a rate of eight seeds per pot and the soil was watered to 80% of pot capacity and allowed to stand for 48 hours. The weight of wet soil at 48 hours after watering became the goal weight for subsequent watering. The soil was not inoculated with pigeon pea rhizobium culture. After two weeks of seedling growth the number of plants were thinned to 3 plants per pot. Pots were watered every day to constant weight. Nutrient solution (Middleton and Toxopeus, 1973) at half strength without N, P and K was applied (20 ml) to each pot three times a week for the first 3 weeks to prevent any possible deficiencies of other nutrients. Agronomic characteristics of the crop, such as plant height and number of leaves, were measured weekly. Plants were harvested 8 weeks after sowing, by cutting off shoot growth at soil level. Roots were carefully washed with distilled water and all root nodules (>2 mm in diameter) were counted by hand (Plate 3.2).

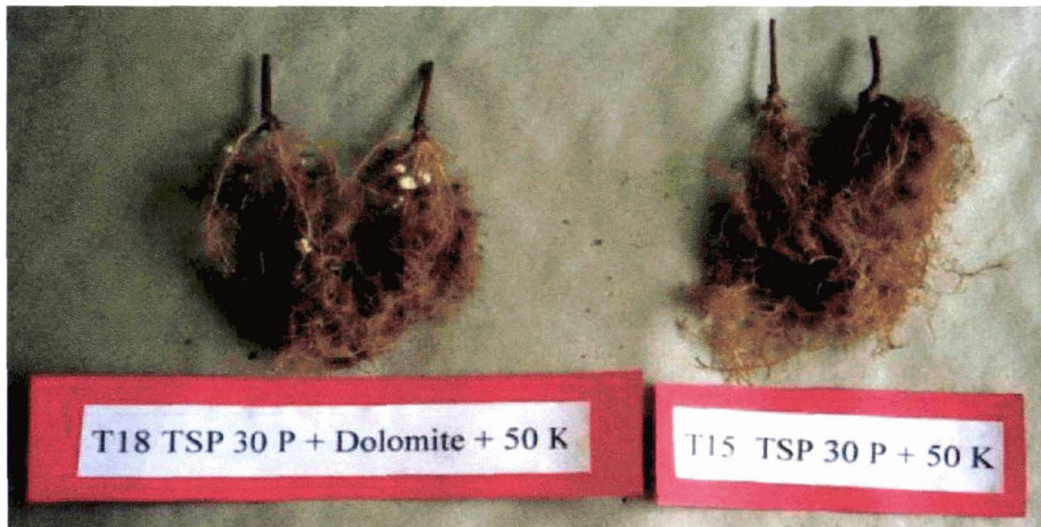


Plate 3.2 Effect of liming on nodulation of pigeon pea in the Yellow Earth.

### *Herbage and soil analysis*

Three fully expanded new leaves from each pot were separately collected for chemical analysis. Roots were carefully separated from bulk soil and washed with distilled water. All root and shoot materials were dried at 70°C to constant weight (approximate 72 hours). Total N and P content of leaves were determined using a Technicon auto-analyser (McKenzie and Wallace, 1954; Blakemore et al, 1987) following Kjeldahl digestion. Total K was analysed by atomic adsorption spectrophotometry following nitric acid digestion. The soil sample from each pot was air-dried and crushed to pass through a 2-mm sieve for soil analysis. Soil samples were analysed using the following methods: soil pH (1:2.5 soil:water ratio) and available P using the Olsen-P method (Olsen *et al.*, 1954). Plant growth response to fertiliser P application was modelled using the following Mitscherlich type equation:

$$Y = A + B (1 - e^{-cx}).$$

Where Y = Yield (e.g. g DM pot<sup>-1</sup>)

x = Parameter value (e.g. soil Olsen-P test value)

B = Yield response (Maximum yield – yield at 0)

A = Yield for a parameter value of 0

c = Curvature coefficient

### ***3.3.3 Experiment (2): Agronomic effectiveness of local FYM and MPR on upland rice growth in a Yellow Earth***

#### ***Test crop and seed germination***

A local variety of upland rice (*Oryza sativa* L), named *Mye Sein*, was collected from Myanmar for use as the test crop. The germination rate of upland rice was 95% (see Section 3.3.2, Experiment (1) for method).

#### ***Soils***

The same composite Yellow Earth used in Experiment (1) was also used in this experiment. Some chemical characteristics of the soil are given in Section 3.3.1.

#### ***Phosphorus and N fertilisers used***

Myanmar PR and TSP (Tunisia) were selected as P sources and urea was selected as the N source. However, the locally available FYM was considered as both an N and P source. Some chemical properties of N and P sources used in this experiment are given in Tables 3.1, 3.2 and 3.3.

#### ***Preparation of soil, fertiliser application and layout of pots***

Soil (270 g air-dried) was placed into a polyethylene pot with the same dimensions as Experiment (1). Each pot was lined with a plastic bag to prevent leaching losses from the soil.

The FYM was air-dried and crushed. All fertilisers used in this study were passed through a sieve (<250 µm particle size) before application. Farmyard manure and MPR were thoroughly mixed with the whole soil in each pot, to get maximum contact between soil and fertilisers. Urea and TSP were mixed with only one third of the soil (90 g) and were placed in a centre core of the each pot. All pots were laid out randomly with three replications of each treatment. Within the replication, pots were rotated weekly.

### *Treatments*

This experiment was conducted over 8 weeks (from 23 December 1997 to 17 February 1998) in a glasshouse at Massey University (Plate 3.3).

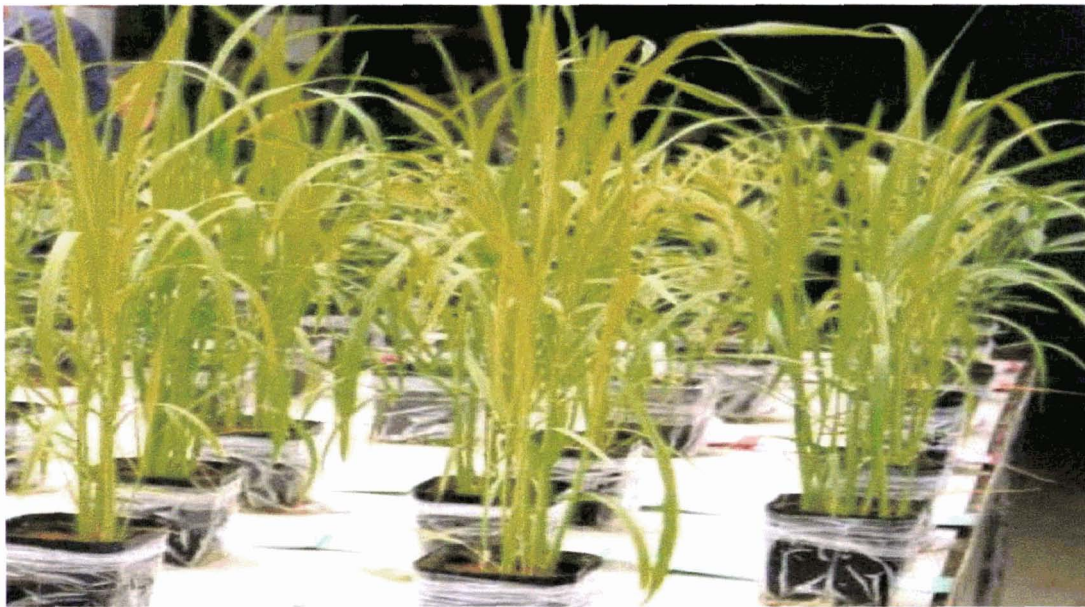


Plate 3.3 Upland rice grown in the Yellow Earth at the Massey University glasshouse.

The control treatments received neither P nor N fertiliser. Other treatments consisted of different P sources (MPR, TSP) at 30 kg P ha<sup>-1</sup> with no N fertilisers, and two P rates (15 and 30 kg P ha<sup>-1</sup>) from different P sources (i.e. MPR, TSP) plus a rate of N (50 kg N ha<sup>-1</sup>) from FYM or urea application. Farmyard manure was also applied at rates supplying 15, 30 and 76 kg P ha<sup>-1</sup>. The total number of treatments was 14. The treatments and codes used in the glasshouse experiment are presented in Table 3.5.

Table 3.5 Treatments and codes of upland rice grown in pots of the composite Yellow Earth fertilised with different N and P fertiliser sources and rates.

Treatment	Code
0 kg N ha <sup>-1</sup> + 0 kg P ha <sup>-1</sup>	Control (0 N + 0 P)
TSP 30 kg P ha <sup>-1</sup>	TSP 30 P
MPR 30 kg P ha <sup>-1</sup>	MPR 30 P
Urea 50 kg N ha <sup>-1</sup> + 0 kg P ha <sup>-1</sup>	Urea 50 N + 0 P
FYM supplying 15 kg P ha <sup>-1</sup> and 10 kg N ha <sup>-1</sup>	FYM (10 N + 15 P)
FYM supplying 30 kg P ha <sup>-1</sup> and 20 kg N ha <sup>-1</sup>	FYM (20 N + 30 P)
FYM supplying 50 kg N ha <sup>-1</sup> and 76 kg P ha <sup>-1</sup> + TSP 15 kg P ha <sup>-1</sup>	FYM (50 N + 76 P) + TSP 15 P
FYM supplying 50 kg P ha <sup>-1</sup> and 76 kg P ha <sup>-1</sup> + TSP 30 kg P ha <sup>-1</sup>	FYM (50 N + 76 P) + TSP 30 P
FYM supplying 50 kg N ha <sup>-1</sup> and 76 kg P ha <sup>-1</sup> + MPR 15 kg P ha <sup>-1</sup>	FYM (50 N + 76 P) + MPR 15 P
FYM supplying 50 kg P ha <sup>-1</sup> and 76 kg P ha <sup>-1</sup> + MPR 30 kg P ha <sup>-1</sup>	FYM (50 N + 76 P) + MPR 30 P
Urea 50 kg N ha <sup>-1</sup> + TSP 15 kg P ha <sup>-1</sup>	Urea 50 N + TSP 15 P
Urea 50 kg N ha <sup>-1</sup> + TSP 30 kg P ha <sup>-1</sup>	Urea 50 N + TSP 30 P
Urea 50 kg N ha <sup>-1</sup> + MPR 15 kg P ha <sup>-1</sup>	Urea 50 N + MPR 15 P
Urea 50 kg N ha <sup>-1</sup> + MPR 30 kg P ha <sup>-1</sup>	Urea 50 N + MPR 30 P

### *Planting and harvesting*

Upland rice seeds were sown at a rate of 12 seeds per pot and the soil was watered to field capacity. After 2 weeks of seedling growth the number of plants were thinned to 4 plants per pot. Pots were watered every day to 80% field capacity as determined by weight. A half-strength N- and P-free nutrient solution (the solution contained half the concentration of the all major and minor nutrients formulated by Middleton and Toxopeus, 1973) was applied (20 ml) three times a week for the first three weeks to each pot to prevent any possible deficiencies of other nutrients.

Agronomic characteristics such as plant height, number of tillers and number of leaves were measured weekly. The plants were harvested 8 weeks after sowing. At harvest the upland rice shoots were cut at the soil surface and the roots were separated from the soil. The shoots and roots were dried at 70°C for 48 hours and were weighed to measure herbage dry matter. Dried herbage was ground and prepared for chemical analysis. The bulk soil from each pot was air-dried and crushed to pass through a 2 mm sieve for soil analysis.

### 3.3.4 Experiment (3): Effect of initial soil Olsen-P levels on the growth of tropical legumes in Red Earths and Yellow Earths

#### 3.3.5 Test crop

The major consideration for selecting a legume species for evaluation of P fertiliser was that legumes are most commonly used as green manures because of their ability to fix atmospheric N. The release of inorganic N from the decomposing residues of legumes helps to meet the N demand of the subsequent crop. Two local Myanmar varieties of subtropical legumes (i.e. pigeon pea and rice bean) were used in this set of glasshouse trials.

#### Soils

Table 3.6 Soil number, code and Olsen-P content of Red Earths and Yellow Earths used in Experiment (3).

Red Earths used for growing pigeon pea					
Soil No.	Code	Olsen-P (mg kg <sup>-1</sup> )	Soil No.	Code	Olsen-P (mg kg <sup>-1</sup> )
SS54	RECU II	1.5	SS50	REUN I	3.8
SS43	RECU I	1.9	SS57	REUN II	6.7
SS44	RECU I	2.0	SS58	REUN II	7.4
SS47	REUN I	2.9	SS53	RECU II	9.7
SS49	REUN I	3.6	SS52	RECU II	11.3
Yellow Earths used for growing pigeon pea					
Soil No.	Code	Olsen-P (mg kg <sup>-1</sup> )	Soil No.	Code	Olsen-P (mg kg <sup>-1</sup> )
SS37	YECU II	2.1	SS36	YECU II	5.0
SS38	YECU II	2.2	SS40	YEUN II	5.4
SS39	YEUN II	2.7	SS34	YEUN I	7.5
SS41	YEUN II	3.8	SS32	YEUN I	8.1
SS35	YECU II	3.9	SS33	YEUN I	8.3
SS42	YEUN II	4.6	SS31	YEUN I	8.4
Red Earths used for growing rice bean					
Soil No.	Code	Olsen-P (mg kg <sup>-1</sup> )	Soil No.	Code	Olsen-P (mg kg <sup>-1</sup> )
SS46	RECU I	1.7	SS56	REUN II	6.7
SS45	RECU I	2.1	SS55	REUN II	7.6
SS48	RECU I	3.6	SS51	RECU II	10.6

The Red Earths and Yellow Earths used in this experiment were from the project areas of Kalaw and Pindaya in Southern Shan State, Myanmar. The chemical characteristics of these soils are presented in Chapter 2 (see Tables 2.3, 2.4 and 2.5). The Olsen-P values for the soils used in this experiment are presented in Table 3.6.

### ***Phosphorus fertiliser used***

The water-soluble P fertiliser used in this experiment was TSP (water-soluble P = 94% of total P). The physical characteristics and selected chemical properties of TSP are shown in Tables 3.1, 3.2 and 3.3.

### ***Preparation of soil, fertiliser application, and layout of pots***

In Experiment (3), a sample of 270 g of air-dried soil was placed into a polyethylene pot which had a 64 (8 × 8) cm<sup>2</sup> surface area and was 11 cm high. The each pot was lined with a plastic bag to prevent leaching losses from the soil.

All fertilisers used were ground and sieved to <250 µm particle size before application. KCl was thoroughly mixed through the whole soil to get maximum contact between soil and fertiliser. Only TSP was mixed with one third of the soil (90 g) and placed in centre core (45 mm diameter) of each pot to simulate the field placement of fertiliser. The experiment was established as a completely randomised block design. Pots were laid out randomly with three replications of each treatment. Within the replication, pots were rotated weekly.

### ***Treatments***

Tropical legume species, pigeon pea and rice bean (*Vigna umbellata*) were used as test crops. This experiment was conducted as an 8-week glasshouse trial (from 14 March to 12 May 1998) at Massey University (Plates 3.4 and 3.5).

This experiment had two fertiliser treatments: a control treatment, which did not receive P, and a P-adequate TSP treatment (80 kg P ha<sup>-1</sup>). Both treatments received 50 kg K ha<sup>-1</sup> as KCl and 25 kg N ha<sup>-1</sup> as (NH<sub>4</sub>)<sub>2</sub>SO<sub>4</sub>. Each treatment was applied to 10 different Red Earths and 12 different Yellow Earths (for pigeon pea) and 6 different Red Earths (for rice bean) with a wide range of Olsen-P values. Two replications were used for all treatments.

### *Planting and harvesting*

Germinated pigeon pea seeds and rice bean seeds were sown at a rate of 8 seeds per pot. After two weeks of seedling growth, the number of plants was thinned to 3 plants per pot (see Plates 3.4 and 3.5). Pots were watered every day to a constant weight (80% of pot capacity). Half strength N- and P-free nutrient solution (Middleton and Toxopeus, 1973) was applied 3 times a week for the first three weeks to each pot to prevent any possible deficiencies of other nutrients. Legume crops were harvested 8 weeks after sowing by cutting off shoot growth at soil level. Roots were carefully washed with distilled water and all root nodules (>2 mm diameter) were hand counted. All herbage was dried at 70°C for 72 hours and weighed for dry matter yield.



Plate 3.4 Pigeon pea grown on the Red Earths and Yellow Earths at glasshouse in Massey University.



Plate 3.5 Rice bean grown in the Red Earths at the Massey University glasshouse.

### **3.3.6 Statistical analysis**

Statistical analysis was performed by the general linear models (GLM) procedure (SAS, 1989). Analysis of variance (ANOVA) was conducted and the differences among the means were deemed significant at the 95% confidence level. Fisher's least significant difference (LSD) was used for multiple comparison procedures of these treatments.

## **3.4 Results**

### **3.4.1 Experiment (1): Agronomic effectiveness of MPR, TSP and dolomite on pigeon pea growth in a Yellow Earth**

#### ***Dry matter yield of pigeon pea***

Pigeon pea grew favourably without any observable deficiency symptoms in all treatments until the 8 weeks at harvest. There was a large variation in dry matter yield within each treatment (c.f. TSP data points, Figure 3.1). Despite this, the DM yield of pigeon pea shoots showed a significant response to water soluble-P fertiliser application (c.f. TSP response curve, Figure 3.1). Ninety-five percentage of maximum yield of

pigeon pea was estimated to occur when  $59 \text{ kg P ha}^{-1}$  of water soluble-P was added as TSP. None of the MPR application rates significantly increased DM yield of pigeon pea compared to the control ( $P < 0.05$ ). Although MPR + K produced yields significantly greater than the control, the yields were greater than those produced by MPR alone suggesting that these soils were responsive to K at low level of P.

Dolomite addition with TSP produced significantly higher DM yields than TSP alone, at two out of three TSP rates ( $15 \text{ kg P ha}^{-1}$  and  $60 \text{ kg P ha}^{-1}$  level,  $P < 0.05$ ). Whereas the addition of K along with TSP (TSP + K) did not result in significantly higher DM yields than TSP alone.

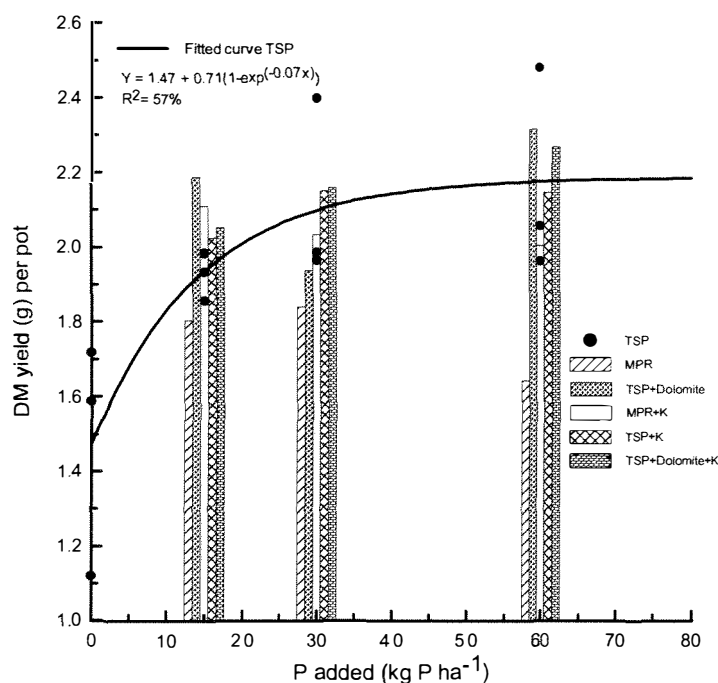


Figure 3.1 Effects of different rates of P applied as MPR and TSP on DM yield of pigeon pea growing in pots of Yellow Earth (LSD=0.41). Columns are means of 3 data points.

### ***Soil pH and Olsen-P***

At the application rates used, both TSP and MPR (with and without K) did not change soil pH significantly, compared to the control treatment. However, the addition of dolomite to soil markedly raised soil pH from pH 4.7 to pH 6.3 at  $P < 0.01$  (Table 3.7). Increasing rates of TSP significantly raised soil Olsen-P (Figure 3.2.). The highest Olsen-P ( $37 \text{ mg kg}^{-1}$ ) occurred at the highest TSP rate. In contrast, the application of

dolomite reduced the Olsen-P values at all TSP rates of application. Compared to the control treatment, increasing rates of MPR were ineffective at increasing Olsen-P values. Figure 3.2 indicates that the addition of between 27 to 48 kg ha<sup>-1</sup> of soluble P (TSP) can provide the optimum range of Olsen-P between 20 to 30 mg kg<sup>-1</sup> for plant growth, on this soil type.

Over the range of Olsen-P values studied the results show that approximately 2.25 kg ha<sup>-1</sup> of TSP are required to raise Olsen-P by one unit on this Yellow Earth.

Table 3.7 Soil pH<sub>water</sub> (1:2.5) after harvest of pigeon pea from pots of Yellow Earth with different fertiliser treatments.

Treatment (kg ha <sup>-1</sup> )	pH <sub>water</sub>	SD	Treatment (kg ha <sup>-1</sup> )	pH <sub>water</sub>	SD
0 P + 0 K	4.67 <sup>d</sup>	0.09	0 P + 50 K	4.71 <sup>cd</sup>	0.03
MPR 15 P + 0 K	4.77 <sup>bcd</sup>	0.01	MPR 15 P + 50 K	4.77 <sup>bcd</sup>	0.06
MPR 30 P + 0 K	4.77 <sup>bcd</sup>	0.02	MPR 30 P + 50 K	4.79 <sup>bc</sup>	0.11
MPR 60 P + 0 K	4.77 <sup>bcd</sup>	0.03	MPR 60 P + 50 K	4.75 <sup>cd</sup>	0.09
TSP 15 P + 0 K	4.81 <sup>bc</sup>	0.12	TSP 15 P + 50 K	4.72 <sup>cd</sup>	0.03
TSP 30 P + 0 K	4.80 <sup>bc</sup>	0.13	TSP 30 P + 50 K	4.74 <sup>cd</sup>	0.08
TSP 60 P + 0 K	4.78 <sup>bcd</sup>	0.09	TSP 60 P + 50 K	4.87 <sup>b</sup>	0.18
TSP 15 P + Dolomite + 0 K	6.17 <sup>a</sup>	0.06	TSP 15 P + Dolomite + 50 K	6.20 <sup>a</sup>	0.10
TSP 30 P + Dolomite + 0 K	6.21 <sup>a</sup>	0.02	TSP 30 P + Dolomite + 50 K	6.25 <sup>a</sup>	0.04
TSP 60 P + Dolomite + 0 K	6.20 <sup>a</sup>	0.06	TSP 60 P + Dolomite + 50 K	6.24 <sup>a</sup>	0.08

SD = standard deviation.

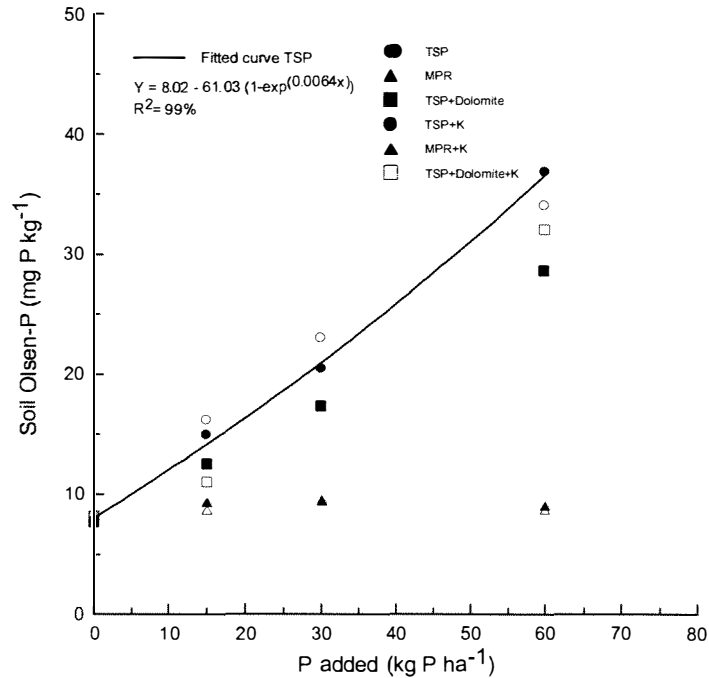


Figure 3.2 Effects of MPR and TSP application at different rates on Olsen-P values of a Yellow Earth (9 weeks after application).

### ***Relationship between soil Olsen-P and DM yield of pigeon pea***

Irrespective of the rates applied, TSP significantly increased soil Olsen-P values and the DM of pigeon pea (Figures 3.1 and 3.2). But MPR did not increase either DM yield of pigeon pea or Olsen-P in the soil.

There was a curvilinear relationship, of the diminishing returns type, between the Olsen-P values of the Yellow Earths at harvest and harvested DM yield of pigeon pea (Figure 3.3). The trend line suggests that 95% of maximum yield occurs at an Olsen-P of 21 mg P kg<sup>-1</sup>.

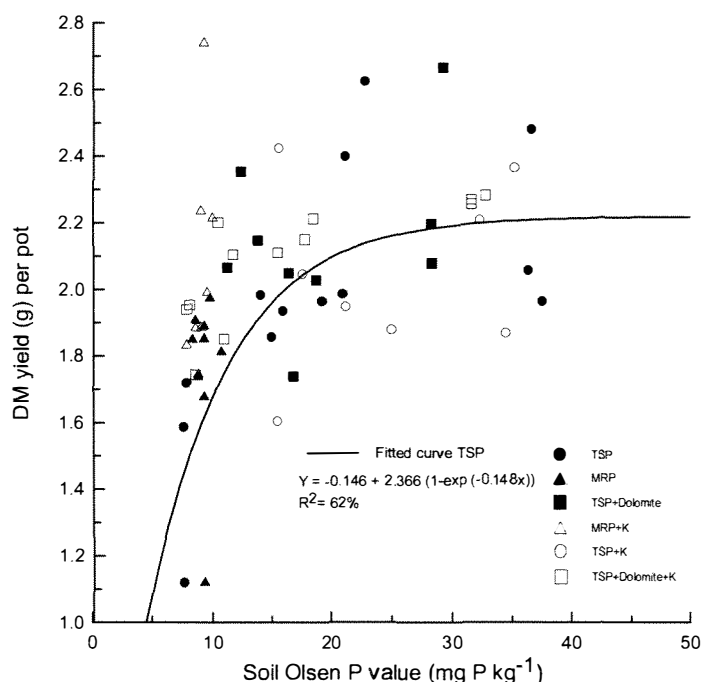


Figure 3.3 Effects of Olsen-P on DM yield of pigeon pea growing in pots of Yellow Earth.

Dry matter yields of pigeon pea grown on pots of Yellow Earth fertilised with MPR all appear above and to the left of the TSP derived trend line (Figure 3.3). This reflects the ability of MPR (15 to 60 kg P ha<sup>-1</sup> rates) increase pigeon pea DM yield without raising Olsen-P values above control levels. This indicates that although Olsen-P values are lower per unit of total P added on MPR fertilised soil, pigeon pea yield is higher per unit Olsen-P in soils fertilised with MPR than in TSP fertilised soils. This is represented more clearly by using the Olsen response curve for TSP from Figure 3.3 to predict pigeon pea yield in MPR fertilised pots from their Olsen-P values (Figure 3.4). At low Olsen values, dolomite addition also appeared to increase yield per unit Olsen-P (cf. TSP and TSP + K vs TSP + Dolomite and TSP + Dolomite + K) (see later Discussion). Care should be taken in drawing the above conclusion because the Olsen-P for the lowest level of TSP 10 kg P ha<sup>-1</sup> (Figure 3.3) is more than the Olsen-P obtained from the highest MPR level, as a consequence Olsen-P levels for the TSP application are not within the range of the Olsen-P levels obtained for the MPR. In hindsight, high rates of MPR may have been helpful in establishing the RAE of MPR.

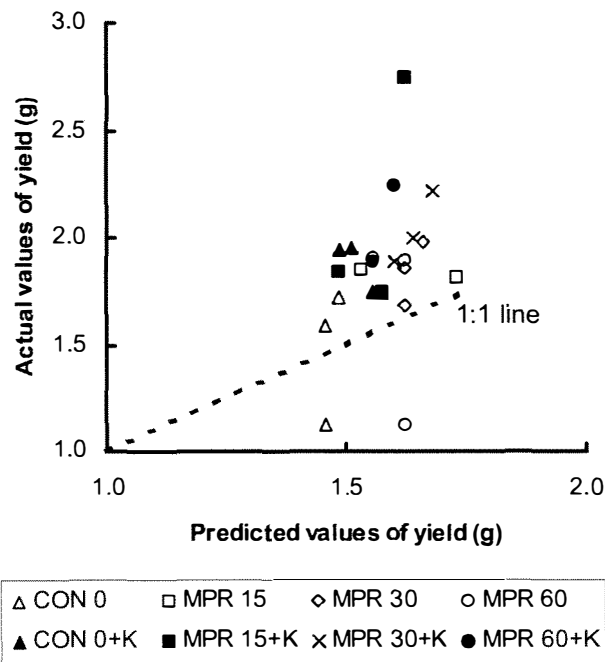


Figure 3.4 Relationships between the actual yield of pigeon pea and the yield predicted using Olsen values and Olsen response curve of TSP fertilised pots (Figure 3.3) for MPR alone and MPR plus K addition treatments.

### *Root nodulation of pigeon pea*

Pigeon pea root nodules were counted to assess the effect of fertiliser and dolomite treatments on indigenous rhizobium activity (Table 3.8).

Table 3.8 Effect of fertiliser treatments on average number of nodules on pigeon pea.

Treatment (kg ha <sup>-1</sup> )	No. of nodules	SD	Treatment (kg ha <sup>-1</sup> )	No. of nodules	SD
0P + 0K	0 <sup>f</sup>	0	0P + 50K	0 <sup>f</sup>	0
MPR 15 P + 0K	0 <sup>f</sup>	0	MPR 15 P + 50K	0 <sup>f</sup>	0
MPR 30 P + 0K	0 <sup>f</sup>	0	MPR 30 P + 50K	0.7 <sup>f</sup>	0
MPR 60P + 0K	1 <sup>f</sup>	1.7	MPR 60P + 50K	2.0 <sup>f</sup>	1.2
TSP 15 P + 0K	0 <sup>f</sup>	0	TSP 15 P + 50K	1.3 <sup>f</sup>	2.0
TSP 30 P + 0K	0.7 <sup>f</sup>	1.2	TSP 30 P + 50K	4.7 <sup>de</sup>	1.2
TSP 60P + 0K	2.3 <sup>ef</sup>	2.5	TSP 60P + 50K	5.7 <sup>cd</sup>	2.3
TSP 15 P + Dolomite + 0K	4.7 <sup>de</sup>	1.5	TSP 15 P + Dolomite + 50K	5.7 <sup>cd</sup>	0.6
TSP 30 P + Dolomite + 0K	6.7 <sup>bcd</sup>	1.5	TSP 30 P + Dolomite + 50K	8.7 <sup>b</sup>	1.53
TSP 60P + Dolomite + 0K	8.0 <sup>bc</sup>	1.0	TSP 60P + Dolomite + 50K	11.3 <sup>a</sup>	3.1

Means with the same letter are not significantly different.

SD = standard deviation.

Pigeon pea root nodulation in MPR fertilised pots was not significantly different from that of the control treatment. Irrespective of the rates applied, TSP alone did not significantly increase nodules in pigeon pea. However, the highest number of nodules was achieved when dolomite was used with TSP. Triple superphosphate plus dolomite treatments produced significantly more nodules than TSP alone at all rates of P (Plate 3.2).

### 3.4.2 Experiment (2): Agronomic effectiveness of local FYM and MPR on upland rice growth in a Yellow Earth

#### *Dry matter yield of upland rice*

Upland rice grew favourably without any observable deficiency symptoms in all treatments until the 8 weeks at harvest. Dry matter yields of upland rice grown per pot are presented in Table 3.9.

Table 3.9 The dry matter yield of upland rice grown in pots of the composite Yellow Earth (initial Olsen-P 8 mg P kg<sup>-1</sup>) fertilised with different N and P fertiliser sources and rates.

Treatment <sup>1</sup>	DM yield (g) per pot <sup>2</sup>
Control (0 N + 0 P)	2.61 <sup>e</sup>
TSP 30 P	3.02 <sup>d</sup>
MPR 30 P	3.09 <sup>cd</sup>
Urea 50 N + 0 P	3.60 <sup>ab</sup>
FYM (10 N + 15 P)	3.12 <sup>cd</sup>
FYM (20 N + 30 P)	3.20 <sup>cd</sup>
FYM (50 N + 76 P) + TSP 15 P	3.21 <sup>cd</sup>
FYM (50 N + 76 P) + TSP 30 P	3.43 <sup>bc</sup>
FYM (50 N + 76 P) + MPR 15 P	3.11 <sup>cd</sup>
FYM (50 N + 76 P) + MPR 30 P	3.37 <sup>bcd</sup>
Urea 50 N + TSP 15 P	3.60 <sup>ab</sup>
Urea 50 N + TSP 30 P	3.80 <sup>a</sup>
Urea 50 N + MPR 15 P	3.38 <sup>bcd</sup>
Urea 50 N + MPR 30 P	3.59 <sup>ab</sup>

<sup>1</sup>Treatment codes were defined in Table 3.5

<sup>2</sup>Treatment means followed by the same letter in a column are not significantly different at  $P < 0.05$

Addition of P and/or N in any form resulted in a significant increase in the DM yields ( $P < 0.05$ ). The largest increases in yield resulted from the addition of 50 kg N ha<sup>-1</sup> as urea, irrespective of the P rate or source (TSP or MPR). Although not significantly different from other treatments, the highest yield was produced by urea and TSP applied

at 50 kg N and 30 kg P ha<sup>-1</sup>. These results indicate that N rather than P is the factor most limiting upland rice DM yield when grown in the Yellow Earth of initial Olsen-P value of 8 mg P kg<sup>-1</sup>, under glasshouse conditions. Farmyard manure, when applied at the same rate of P as TSP or MPR, produced lower yields even the combined rate of the P application (FYM + TSP or MPR) did not exceeded that of the urea treatment.

### ***Soil pH and Olsen-P***

There was only a small effect of fertiliser treatment on soil pH (Table 3.10). Application of urea at 50 kg N ha<sup>-1</sup> tended to cause small reductions in soil pH which were consistent with the low rates of N applied. Similarly the low rates of FYM, TSP and MPR applied caused little change in soil pH.

Table 3.10 Soil pH (H<sub>2</sub>O) after harvest of upland rice grown in pots of the composite Yellow Earth fertilised with different N and P fertiliser sources and rates.

<b>Treatment<sup>1</sup></b>	<b>Soil pH (soil:water, 1:2.5)<sup>2</sup></b>
Control (0 N+ 0P)	5.08 <sup>bc</sup>
TSP 30 P	5.06 <sup>bcd</sup>
MPR 30 P	5.06 <sup>bcd</sup>
Urea 50 N + 0 P	5.03 <sup>d</sup>
FYM (10 N + 15 P)	5.06 <sup>bcd</sup>
FYM (20 N + 30 P)	5.09 <sup>ab</sup>
FYM (50 N + 76 P) + TSP 15 P	5.09 <sup>ab</sup>
FYM (50 N + 76 P) + TSP 30 P	5.13 <sup>a</sup>
FYM (50 N + 76 P) + MPR 15 P	5.13 <sup>a</sup>
FYM (50 N + 76 P) + MPR 30 P	5.08 <sup>bc</sup>
Urea 50 N + TSP15 P	5.04 <sup>cd</sup>
Urea 50 N + TSP 30 P	5.03 <sup>d</sup>
Urea 50 N + MPR 15 P	5.05 <sup>bcd</sup>
Urea 50 N + MPR 30 P	5.03 <sup>d</sup>

<sup>1</sup>Treatment codes were defined in Table 3.5.

<sup>2</sup>Treatment means followed by the same letter in a column are not significantly different at  $P < 0.05$ .

The effect of fertiliser treatments on soil Olsen-P is shown in Table 3.11. The major finding is that FYM and MPR caused little increase in Olsen-P values. This finding is consistent with data presented in Figure 3.2 for Experiment (1). Application of TSP consistently increased Olsen-P values, irrespective of the accompanying form of N fertiliser (FYM or urea). It is worth noting that similar increase in Olsen-P from 30 kg P ha<sup>-1</sup> applied as TSP was also achieved when TSP was applied in combination with FYM.

Table 3.11 Olsen-P in soil after harvest of upland rice grown in pots of the composite Yellow Earth fertilised with different N and P fertiliser sources and rates.

Treatment <sup>1</sup>	Olsen-P (mg P kg <sup>-1</sup> soil) <sup>2</sup>
Control (0 N + 0 P)	7.1 <sup>f</sup>
TSP 30 P	22.1 <sup>ab</sup>
MPR 30 P	9.7 <sup>c</sup>
Urea 50 N + 0P	8.4 <sup>ef</sup>
FYM (10 N + 15 P)	8.7 <sup>ef</sup>
FYM (20 N + 30 P)	9.7 <sup>c</sup>
FYM (50 N + 76 P) + TSP 15 P	17.6 <sup>c</sup>
FYM (50 N + 76 P) + TSP 30 P	24.2 <sup>a</sup>
FYM (50 N + 76 P) + MPR 15 P	10.3 <sup>c</sup>
FYM (50 N + 76 P) + MPR 30 P	10.2 <sup>c</sup>
Urea 50 N + TSP 15 P	15.3 <sup>d</sup>
Urea 50 N + TSP 30 P	20.6 <sup>b</sup>
Urea 50 N + MPR 15 P	9.6 <sup>c</sup>
Urea 50 N + MPR 30 P	9.2 <sup>ef</sup>

<sup>1</sup>Treatment codes were defined in Table 3.5.

<sup>2</sup>Treatment means followed by the same letter in a column are not significantly different at  $P < 0.05$ .

### ***3.4.3 Experiment (3): Effect of initial soil Olsen-P values on the growth of tropical legumes in Red Earths and Yellow Earths***

#### ***Dry matter yields of pigeon pea grown in Red Earths and Yellow Earths***

An 'adequate' phosphorus addition of TSP (80 kg P ha<sup>-1</sup>) to Red Earths and Yellow Earths produced marked increases in mean pigeon pea DM yields (Figure 3.5). However, the initial Olsen-P status of these Red Earths (range from 2 to 11 mg P kg<sup>-1</sup> soil, Table 3.6) and Yellow Earths (range from 2 to 8 mg P kg<sup>-1</sup> soil, Table 3.6) did not show any influence on pigeon pea DM yield ( $P < 0.05$ ). There was no relationship between the DM yield response of pigeon pea to P application (0 versus 80 kg P ha<sup>-1</sup>) and initial Olsen-P values of Red Earths and Yellow Earths (Figure 3.6).

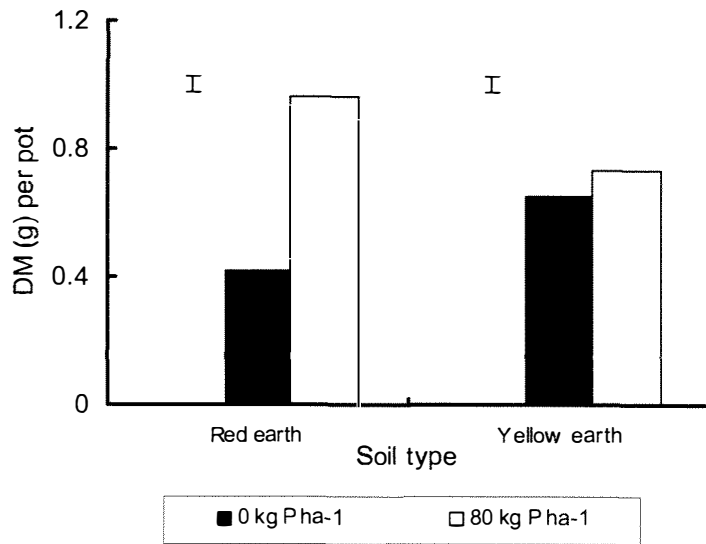


Figure 3.5 Effect of P addition to Red Earths and Yellow Earths on DM yield of pigeon pea (columns are soil treatment means across all initial Olsen-P values). The error bar is the LSD of mean ( $P < 0.05$ ).

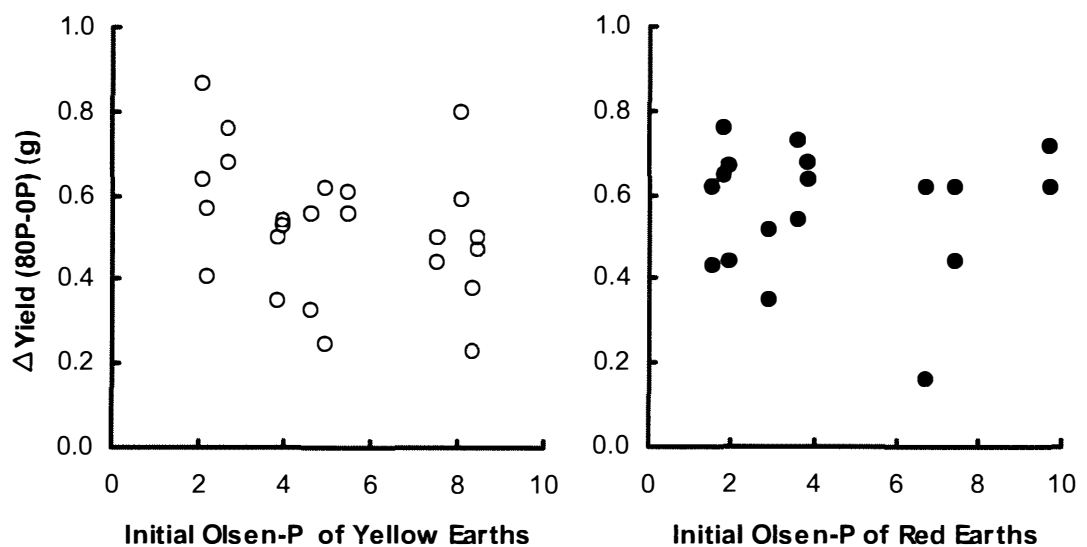


Figure 3.6 Relationships between the DM yield response ( $\Delta$  yield 80 P - 0 P) of pigeon pea and initial Olsen-P values of Red Earths and Yellow Earths.

### ***Root nodulation of pigeon pea***

There was a large effect of P fertiliser treatment on the nodule formation of pigeon pea roots in both Red Earths and Yellow Earths (Table 3.12 and 3.13). The application of TSP at 80 kg P ha<sup>-1</sup> to both Red Earths and Yellow Earths significantly ( $P < 0.05$ ) increased the number of nodules on pigeon pea roots compared to that of the control treatment. However the range of initial Olsen-P status measured in those Red Earths (range from 2 to 11 mg P kg<sup>-1</sup>, Table 3.6) and Yellow Earths (range from 2 to 8 mg kg<sup>-1</sup>, Table 3.6) did not significantly influence pigeon pea nodule formation ( $P < 0.05$ ), which was low for all soils.

Table 3.12 Effect of P added (kg P ha<sup>-1</sup>) on nodule formation in pigeon pea grown in Red Earth.

Red Earth	Number of nodules per pot		Red Earth	Number of nodules per pot	
	0 P added	80 P added		0 P added	80 P added
SS54	0 <sup>a</sup>	53 <sup>b</sup>	SS50	0 <sup>a</sup>	89 <sup>b</sup>
SS43	0 <sup>a</sup>	47 <sup>b</sup>	SS57	4 <sup>a</sup>	67 <sup>b</sup>
SS44	4 <sup>a</sup>	64 <sup>b</sup>	SS58	1 <sup>a</sup>	77 <sup>b</sup>
SS47	7 <sup>a</sup>	71 <sup>b</sup>	SS53	6 <sup>a</sup>	78 <sup>b</sup>
SS49	0 <sup>a</sup>	67 <sup>b</sup>	SS52	2 <sup>a</sup>	58 <sup>b</sup>

Treatment means followed by the same letter in a row are not significantly different at  $P < 0.05$ .

Table 3.13 Effect of added P (kg P ha<sup>-1</sup>) on nodule formation in pigeon pea grown in Yellow Earth.

Yellow Earth	Number of nodules per pot		Yellow Earth	Number of nodules per pot	
	0 P added	80 P added		0 P added	80 P added
SS37	0 <sup>a</sup>	53 <sup>b</sup>	SS36	2 <sup>a</sup>	54 <sup>b</sup>
SS38	0 <sup>a</sup>	63 <sup>b</sup>	SS40	0 <sup>a</sup>	42 <sup>b</sup>
SS39	0 <sup>a</sup>	64 <sup>b</sup>	SS34	8 <sup>a</sup>	54 <sup>b</sup>
SS41	6 <sup>a</sup>	69 <sup>b</sup>	SS32	6 <sup>a</sup>	49 <sup>b</sup>
SS35	0 <sup>a</sup>	62 <sup>b</sup>	SS33	3 <sup>a</sup>	39 <sup>b</sup>
SS42	11 <sup>a</sup>	64 <sup>b</sup>	SS31	3 <sup>a</sup>	28 <sup>b</sup>

Treatment means followed by the same letter in a row are not significantly different at  $P < 0.05$ .

### ***Dry matter yields of rice bean grown in pots of Red Earth***

Dry matter yields of rice bean per pot are shown in Table 3.14. The addition of TSP at 80 kg P ha<sup>-1</sup> to Red Earths significantly ( $P < 0.05$ ) increased the rice bean DM yield compared to control treatment.

The initial Olsen-P status of Red Earths (range 2 to 11 mg kg<sup>-1</sup> soil, Table 3.14) did not significantly affect the rice bean DM yield. There was no relationship between the DM yield response ( $\Delta$  yield 80 - 0 kg P ha<sup>-1</sup>) of rice bean and initial Olsen-P values of Red Earths and Yellow Earths (Figure 3.7).

Table 3.14 Effect of added P (kg P ha<sup>-1</sup>) on DM yield of rice bean in Red Earths.

Red Earth (initial Olsen-P, mg P kg <sup>-1</sup> )	DM yield (g) per pot		Red Earth (initial Olsen-P, mg P kg <sup>-1</sup> )	DM yield (g) per pot	
	0 P added	80 P added		0 P added	80 P added
SS46 (1.7)	0.44 <sup>a</sup>	2.24 <sup>b</sup>	SS56 (6.7)	0.42 <sup>a</sup>	1.60 <sup>b</sup>
SS45 (2.1)	0.33 <sup>a</sup>	1.84 <sup>b</sup>	SS55 (7.6)	0.46 <sup>a</sup>	1.26 <sup>b</sup>
SS48 (3.6)	0.38 <sup>a</sup>	1.92 <sup>b</sup>	SS51 (10.6)	0.49 <sup>a</sup>	2.13 <sup>b</sup>

Treatment means followed by the same letter in a row are not significantly different at  $P < 0.05$ .

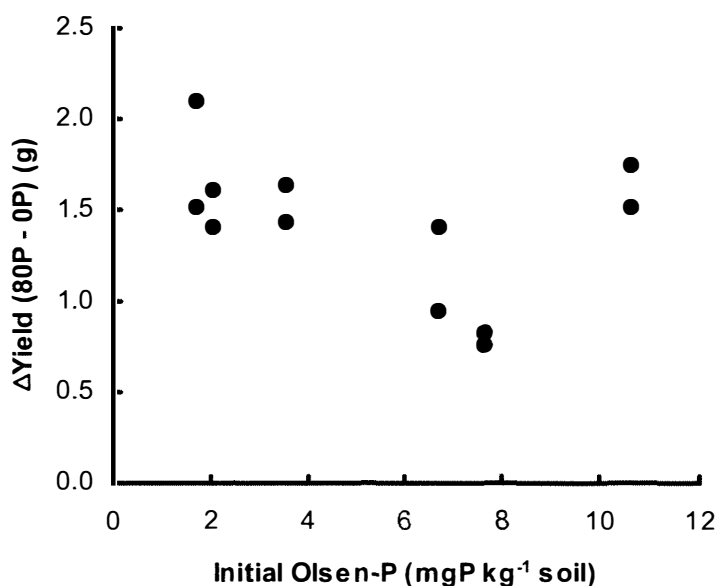


Figure 3.7 Relationships between the DM yield response ( $\Delta$  yield 80 P - 0 P) of rice bean yield and initial Olsen-P values of Red Earths.

### ***Root nodulation of rice bean***

The application of P fertiliser (TSP 80 kg P ha<sup>-1</sup>) to Red Earths significantly ( $P < 0.05$ ) increased nodulation of rice bean roots compared to the control treatment (Table 3.15). However, the range in initial Olsen-P status (from 2 to 11 mg P kg<sup>-1</sup> soil, Table 3.6) of the Red Earths had no significant effect on the number of nodules formed.

Table 3.15 Effect of added P (kg P ha<sup>-1</sup>) on nodule formation of rice bean in Red Earths.

Red Earth (initial Olsen-P, mg P kg <sup>-1</sup> )	Number of nodules per pot		Red Earth (initial Olsen-P, mg P kg <sup>-1</sup> )	Number of nodules per pot	
	0 P added	80 P added		0 P added	80 P added
SS46 (1.7)	0 <sup>a</sup>	81 <sup>b</sup>	SS56 (6.7)	5 <sup>a</sup>	85 <sup>b</sup>
SS45 (2.1)	0 <sup>a</sup>	63 <sup>b</sup>	SS55 (7.6)	3 <sup>a</sup>	52 <sup>b</sup>
SS48 (3.6)	2 <sup>a</sup>	62 <sup>b</sup>	SS51 (10.6)	6 <sup>a</sup>	64 <sup>b</sup>

Treatment means followed by the same letter in a row are not significantly different at  $P < 0.05$ .

### 3.5 Discussion

#### *Estimation of optimum P status and P responsiveness of Yellow Earth*

Experiment (1) was conducted to derive preliminary information on the P status of the Yellow Earth at Aungban research farm that could potentially be used for field trials. The initial Olsen-P values on Yellow Earths did not exceed 11 mg P kg<sup>-1</sup> soil (Table 3.6). In New Zealand (Cornforth, 1998) and Australia (Peverill, 1993) this would indicate low P status for pastures and crops. Whether these low Olsen-P values are indicative of low plant-available P status in Yellow Earths was tested in Experiment (1) by measuring the growth of pigeon pea as influenced by different application rates of soluble P fertiliser to pots of Yellow Earth.

The result from Experiment (1) showed that as the TSP fertiliser application rates increased from 0 to 60 kg P ha<sup>-1</sup>, yield of pigeon pea increased. There was little additional growth response to K fertiliser. This result supports the hypothesis that soil P was yield limiting for tropical legume growth. This result also supports the general concept of P being the major nutrient limitation in Yellow Earth (Acrisols) of the tropics (FAO, 1988).

The application of TSP fertiliser significantly increased soil Olsen-P values. There existed a strong curvilinear relationship between Olsen-P values and pigeon pea yield and the optimum yield of pigeon pea occurred at an Olsen value of 21 mg P kg<sup>-1</sup>. The results in Experiment (1) showed that the relationship between plant yield and Olsen-P values is influenced by P fertiliser form and liming agents (see review by Saggar *et al.* (1992a,b), and Hedley *et al.* (1995)). For example, soil Olsen-P values, but not yields, were relatively lower when dolomite was applied with the TSP treatments (see Figure

3.2). The reason may be partly due to the co-precipitation of Ca-P in the Olsen extract (Sorn-Srivichai *et al.*, 1988). A similar result was found in acids soils from Fiji (Naidu, 1985).

Myanmar PR, was not a reactive phosphate rock: it presumably dissolved little in the Yellow Earth and did not raise the Olsen-P to the same extent per unit P added as TSP (Figure 3.2). Such results are common for non-reactive rocks (Saggar *et al.*, 1993). In Experiment (1) the growth of pigeon pea per unit Olsen-P was greater in rock phosphate fertilised (MPR) soils than in TSP fertilised soils.

This was demonstrated by the fact that the Olsen-P response curve for TSP underestimated the pigeon pea yield for MPR fertilised pots (Figure 3.4). This underestimation of yield probably occurs because Olsen-P does not measure MPR-P that dissolves during pigeon pea plant growth. Also, sparingly soluble Ca phosphates around the dissolving rock particles may be precipitated in the Olsen-P extract. Saggar *et al.* (1993 and 1999) found that Olsen-P values underestimated pasture yield responses to sparingly soluble P fertiliser and that the Olsen-P method gave a poor prediction of yield response in RPR fertilised soils. If RPR becomes used extensively in agriculture then more suitable soil P tests would be needed for assessing the plant-available P status of soil fertilised with sparingly soluble P fertiliser. For soil fertilised with both the water-soluble and sparingly soluble P fertilisers, a resin P test may be a more suitable test than a bicarbonate-based test (Perrott and Kerr, 1994; Saggar *et al.*, 1999).

The Yellow Earth has medium P sorption ability (53% P retention) (Moody and Bolland, 1999). Figure 3.2 shows that between 27 to 48 kg P ha<sup>-1</sup> (as TSP) was needed to raise soil Olsen-P values to between 20 to 30 mg kg<sup>-1</sup>, the range considered optimum in this Yellow Earth. Sinclair *et al.* (1997) reported that a near maximum relative pasture yield was achieved when Olsen-P values exceed 20 mg P kg<sup>-1</sup>. However, Figure 3.3 shows that slightly higher estimated optimum Olsen-P of 21 to 24 mg P kg<sup>-1</sup> is required to achieve >90% maximum pigeon pea yield on the Yellow Earth. This range of Olsen-P values in the Yellow Earth is achieved through approximately 30 to 36 kg P ha<sup>-1</sup> as TSP application (see Figure 3.2). The weight of fertiliser P required to increase Olsen values to the desired value will also depend on the initial Olsen P value of the

soil. Subsequent experiments examined the P responsiveness of potential field trial test crops to single soluble P applications at above the optimum rate.

### ***Nitrogen and P requirements for upland rice***

In Experiment (2), the DM yield of upland rice responded to the addition of P and/or N in the Yellow Earth. However, the DM yield of upland rice was further increased when N (urea 50 kg N ha<sup>-1</sup>) was also applied with P (TSP 30 kg P ha<sup>-1</sup>), which suggests that for cereal crops grown on similar soils to the Yellow Earth, N should be supplied in combination with P in order to improve the efficiency of P use by the crop.

As mentioned earlier in Section 3.4.2, the local FYM and MPR caused little increase in Olsen-P values, indicating these materials would not be effective P sources for upland rice crops on the Yellow Earth in the short-term.

### ***Optimum Olsen-P values for pigeon pea and rice bean***

Experiment (3) showed that the addition of a non-P limiting rate of soluble P fertiliser (80 kg P ha<sup>-1</sup>) caused a marked increase in the DM yield of pigeon pea and rice bean grown in the Red Earths and Yellow Earths. Within a short growing period, the local rice bean produced a higher DM yield than pigeon pea on the Red Earths and Yellow Earths, thus rice bean can be expected as a suitable green manure crop for the field trials to be conducted in Southern Shan State.

Although initial soil Olsen-P values ranged from as low as 2 mg P kg<sup>-1</sup> to 8 mg P kg<sup>-1</sup> on Yellow Earths and <2 mg P kg<sup>-1</sup> to 11 mg P kg<sup>-1</sup> on Red Earths, the P response of pigeon pea and rice bean growth was not significantly related to the initial Olsen-P status of the soils. The high P response of rice bean was achieved on low initial P status soils with a high P rate, but the results were not clear for pigeon pea grown on the Red Earths and Yellow Earths.

### ***The suitability of the Yellow Earth for direct PR use***

Many workers reported that soils which have characteristics of P deficiency, low pH, low base saturation, low Ca and medium CEC are suited to PR dissolution (Khasawneh and Doll, 1978; Tambunan, 1992; Chien and Menon, 1995; Rajan *et al.*, 1996; Hedley and Bolan, 1997). The Yellow Earth used in this experiment had some of these characteristics (i.e. very low pH, low Olsen-P, low base saturation and low CEC) which enhance PR dissolution and thus indicates suitability for direct use of PR as a P fertiliser in these soils.

The plant-availability of P from PRs varies due to differences in PR dissolution, which depends on the chemical composition (e.g.  $\text{CaCO}_3$  content), physical properties (e.g. particle size) and chemical reactivity of the PR apatite (Rajan *et al.*, 1992; Hedley and Bolan, 1997).

As discussed in Section 3.1.1, MPR was not very soluble in 2% citric acid (5.5% of total P) nor 2% formic acid (7.7% of total P). Therefore this PR should be ranked as an unreactive PR because the literature shows that for direct application, more than 30% of the total P should dissolve in the 2% citric acid solution (Hedley and Bolan, 1997) and more than 50% in 2% formic acid (Syers *et al.*, 1986) to be classified as a reactive PR. The unreactive MPR dissolved very poorly in the Yellow Earth and did not increase plant-available P enough to significantly increase the DM yield of pigeon pea. Even after the addition of MPR at 30 and 60 kg P ha<sup>-1</sup>, available P (Olsen-P value) was not raised enough to meet the soil's optimum P status for short-term crop demand (refer to Experiments (1) and (2)).

The application of unreactive MPR may not give satisfactory results on acid soils (Yeates and Allen, 1987). The low agronomic effectiveness of MPR as indicated by low solubility in 2% citric acid or 2% formic acids was confirmed by the finding that MPR was only 23% as effective as TSP for increasing pigeon pea DM yield at the 60 kg P ha<sup>-1</sup> level.

In Experiment (2), where N was the primary factor limiting upland rice growth, in a composite Yellow Earth with an initial Olsen-P status of  $8 \text{ mg kg}^{-1}$  MPR applied at 15 or  $30 \text{ kg P ha}^{-1}$  and  $50 \text{ kg N ha}^{-1}$  as urea, upland rice yield were not greater than the N alone treatment. Triple superphosphate applied at  $15 \text{ kg P ha}^{-1}$  also failed to increase yield. These results may indicate that an Olsen-P of  $8 \text{ mg P kg}^{-1}$  in a Yellow Earth is adequate for upland rice growth. Thus the upland rice may not be a suitable test plant for the relative effectiveness of MPR on these Yellow Earths, unless upland rice is the focus crop to be grown in the field.

The relative agronomic effectiveness (RAE) of MPR was calculated using the equation of Rajan *et al.* (1992) derived for ryegrass grown on temperate acid soils:  $\text{RAE} = 11.62 - 0.198 \text{ formic-P} + 0.020 (\text{formic-P})^2$ . The RAE for MPR was 12.6%. Phosphate rocks with 2% formic acid and citric acid solubilities as low as MPR have been shown to have similarly low agronomic effectiveness e.g. Island PR (Yeates and Allen, 1987) and Duchess PR (6% of total P soluble in 2% formic acid) were much less effective than superphosphate or TSP (between 8 to 15% in pots and 5 to 22% in field trials, Bolan *et al.*, 1990a).

The agronomic value of MPR could be improved by partial acidulation with sulphuric acid and/or phosphoric acid (Braithwaite, 1987). The direct partial acidulation has proven to be an economically feasible method for improving the agronomic value of unreactive PR (Bolan *et al.*, 1990a). Using finely ground MPR for manufacturing PAPR may improve its agronomic value because the solubility of PAPR is affected by particle size of PR (Braithwaite, 1987; Bolan *et al.*, 1990a).

If the price of MPR was sufficiently low, a high rate of MPR (e.g.  $>2 \text{ t MPR ha}^{-1}$ ) application as a capital or annual application of MPR (e.g.  $>200 \text{ kg MPR ha}^{-1}$ ) may prove useful but would need to be verified first with field trials. This would have the added value of increasing or maintaining soil pH on these acid soils (Sinclair *et al.*, 1993; Loganathan *et al.*, 1995).

### ***Local dolomite as an effective liming agent***

The application of dolomite markedly raised the pH of the Yellow Earth in Experiment (1) (from pH 4.7 to pH 6.3). This indicates that local dolomite can be used as an effective liming material to correct the soil acidity. The optimum soil pH for crop production can be considered to be between pH 5.5 to 6.0 because little or no effect of  $\text{Al}^{3+}$  toxicity (Havlin *et al.*, 1999),  $\text{Mn}^{2+}$  and  $\text{H}^+$  toxicity (Kamprath, 1984) on plant growth is observed above pH 5.5.

Dolomite significantly increased the DM yield of pigeon pea on the Yellow Earth. Addition of TSP ( $15 \text{ kg P ha}^{-1}$ ) plus dolomite was more (13%) effective than TSP alone. In this case, raising soil pH in Yellow Earths by dolomite application may overcome Ca and Mg deficiency, which also limits plant growth (Jones and Fox, 1978). Similarly, Nurlaeny *et al.* (1996) showed in a glasshouse trial that liming with  $\text{CaCO}_3$  increased shoot dry weight in maize and soybean on two tropical acid soils (Oxisol and Ultisol) from Indonesia.

Based on the results of the Experiment (1), increasing soil pH by addition of dolomite increased nodule size and number on pigeon pea roots. This evidence indicates that soil pH plays an important role in the formation of nodules in tropical legumes. Other research has also shown that liming can improve the legume nodulation, such as nodule numbers and nodule growth (Andrew and Johnson, 1976; Munns *et al.*, 1977).

### ***Effect of N inputs on upland rice yield***

The addition of N either as urea or FYM ( $50 \text{ kg N ha}^{-1}$ ) significantly increased DM yield of upland rice, compared to zero N inputs to the Yellow Earth. Nitrogen application as urea was more effective than FYM. This result highlights that for growing cereal crops such as upland rice, N may be one of the main limiting factor for optimum crop growth in these acid upland soils. Therefore, to produce high yield of upland rice on the Red Earths and Yellow Earths, and to use P and K fertilisers efficiently, supplementary N must be added to every crop.

### 3.6 Conclusions

In this preliminary glasshouse study, the low available P status in Red Earths and Yellow Earths limited pigeon pea and rice bean growth. It indicates that the P availability is one of the serious problems for growing leguminous crops on the Red Earths and Yellow Earths in Southern Shan State, Myanmar and should be included as a major treatment effect examined in the subsequent field trials.

Chemical analysis shows that the locally available MPR was an unreactive PR because of its low level of 2% citric acid soluble P (5.5% of total P) and 2% formic acid soluble P (7.7% of total P). Consequently, MPR did not increase the P available status of the Yellow Earth. The pigeon pea growth in Experiment (1) showed that the relative agronomic effectiveness of MPR is very low compared with TSP. These experimental results indicate that MPR is not suitable as a direct application P fertiliser on the Red Earths and Yellow Earths for optimum yields of short-term crops. The recommendation would be not to use MPR in the subsequent field trials and other low cost P fertilisers need to be sourced.

The upland rice growth in Experiments (2) showed that the local FYM (at 15 and 30 kg P ha<sup>-1</sup>) did not markedly increase the P available status of the Yellow Earth. It is worth noting, however, that the application of TSP (at 30 kg P ha<sup>-1</sup>) in combination with FYM achieved greatest increase in the P available status (Olsen-P value) of the Yellow Earth.

The recommended soluble P fertiliser rate has to consider crop type and initial soil P status of the Red Earths and Yellow Earths. In this study, the rate of TSP required to raise the Olsen-P level from a low (8 mg P kg<sup>-1</sup>) to an optimum status (21 to 24 mg P kg<sup>-1</sup>) is 30 to 36 kg P ha<sup>-1</sup> in the Yellow Earth.

Locally produced dolomite in Shan State can be used as an effective liming materials to correct soil acidity for the Red Earth and Yellow Earth upland soils. This local dolomite applied with water-soluble P fertilisers (TSP) may further increase legume DM yield through significantly improving nodulation of legume roots in the highly weathered, P deficient Red Earths and Yellow Earths.

In addition, N fertiliser also limits the crop yield of non N-fixing crops on the Red Earths and Yellow Earths. The use of high N-fixing legumes as a green manure in crop rotations may be advantageous for building soil fertility in short-term.

## **CHAPTER 4    Evaluating Organic Amendments for Building Soil Organic Matter and Phosphorus Reserves in Red Earths and Yellow Earths**

### **4.1    Introduction**

The chemical characterisation of soils from the study area (Chapter 2) revealed that all the soils were low in SOM (Table 2.2). Low SOM contributes directly to the low fertility status of these soils.

It is likely that management practices that increase the SOM content will be beneficial for the long-term fertility status of these soils (see later discussion). In this section, the importance of SOM on the physical, chemical and biological fertility of soils is reviewed prior to designing experiments with the objective of building SOM reserves in Red Earths and Yellow Earths.

Each soil texture type and environmental regime has a range of SOM contents that are optimum for soil management and crop production. Soil organic matter can be classified into three fractions: (1) living organisms or biomass, (2) the remains of dead plant and animals, and (3) humified organic matter or humus (Foth and Ellis, 1997). The benefits of optimum levels of SOM are:

1. Improved soil physical properties, such as soil structure, soil strength, and less soil erosion (Oades, 1984; Fernandes and Sanchez, 1990; Cong, 2000)
2. Soil OM provides an energy source for soil organisms, which promote the soil aggregation process (Flaig *et al.*, 1977)
3. Store of N (Serna and Pomares, 1991), P (Hedley *et al.*, 1982a; Li *et al.*, 1990) and S (Iyamuremye *et al.*, 1996c)
4. Source of CEC to hold exchangeable cations in the plant root zone (Cong, 2000)
5. pH buffering and detoxification of Al in low pH soils (Naidu, 1985; Budianta, 1999)

### 4.1.1 Factors leading to change in SOM content

One method of raising the SOM status of a soil is to add organic amendments. Organic amendments include crop residues, mulches, plant litter (above and below ground), green manures, green wastes, animal effluents, animal manures, and sewage sludge. The use of organic amendments can result in increased N cycling but if it leads to increased SOM then N losses from cropped soils to the environment can also be reduced (Peoples and Craswell, 1992; Klausner *et al.*, 1994).

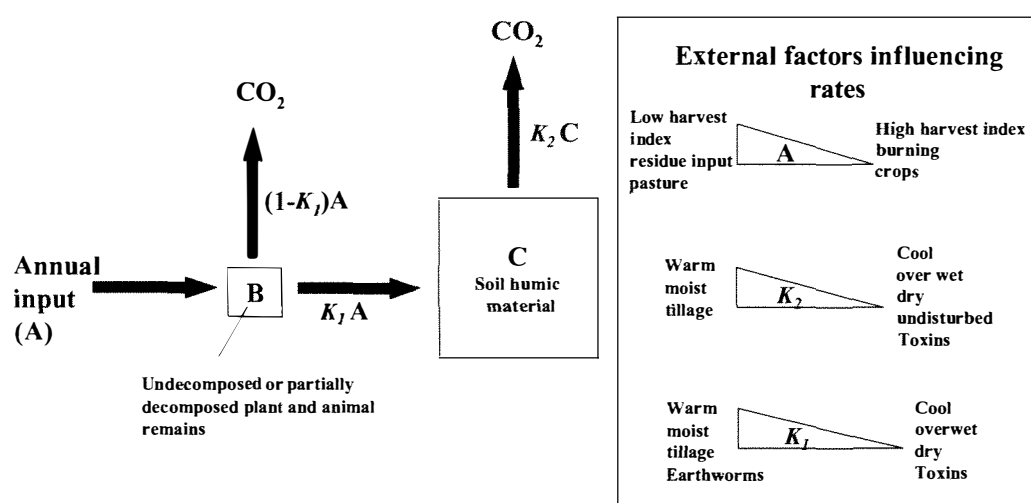


Figure 4.1 A simple model of soil organic matter dynamics (Massey University, 2000).

Organic amendments can be used as a source of nutrients for crop growth and organic carbon for soil micro-organisms. Organic materials are decomposed (mineralised) by a wide range of heterotrophic soil organisms that have a dietary need for both C and N. The rate of decomposition to inorganic solutes, water and gases depends on soil temperature, moisture content, clay mineralogy and soil fertility status. As shown in Figure 4.1 the rate of change in SOM is dependent on many factors. The amount of SOM present in soils mainly depends upon the rate of addition (A) of recently added organic amendments and their rate of decomposition (fraction decomposed per year), and the amount (C) and the rate of decomposition (fraction decomposed per year) of the older humic fraction of SOM (Figure 4.1). The amount of annual organic input left in partially or undecomposed form (B) at any one time under tropical conditions is small

compared to the amount of older humic materials. The rate of change in the amount of SOM is simply calculated as follows:

$$dC/dt = K_1 A - K_2 C \quad \text{Equation (4.1)}$$

In the Red Earths and Yellow Earths of Shan State, regular low-yield cropping with a high harvest index leads to low organic matter inputs (A), whilst warm moist soil conditions and frequent tillage lead to fast rates of decomposition.

Incorporation of organic amendments into soils at rates  $>30 \text{ t DM ha}^{-1}$  may be required to exceed the rate of C loss from SOM decomposition (see Figure 4.1) and increase the SOM content (Khaleel *et al.*, 1981; Darmody *et al.*, 1983; Hue, 1992; Falih and Wainwright, 1996).

#### **4.1.2 Beneficial effects of SOM**

##### ***Soil physical properties***

Soil organic matter is an essential component contributing to the structural properties of soil, predominantly acting as the 'glue' responsible for aggregate stability (Oades, 1984). A well aggregated soil has good porosity for storage of plant available water, and allows ready transportation of water, plant-available nutrients and gases. Aggregation of soil particles by OM reduces bulk density and improves plant root growth. In the humid tropics, the sudden changes of moisture and intense rainfall can easily destroy the aggregate stability of soils. Therefore, soil aggregation is one of the most important physical properties of tropical soils (Sanchez, 1976).

Organic matter binds clay and silt sized minerals into small stable microaggregates (2-20  $\mu\text{m}$ ). Polyvalent metal cations are involved in organo-metallic bonds that bind microaggregates to form a large microaggregates (20-250  $\mu\text{m}$ ) (Tisdall and Oades, 1982). If organic amendments are present, microaggregates may be bound together to form a macroaggregate (250-2000  $\mu\text{m}$ ) by transient organic matter components such as polysaccharides and temporary organic matter such as roots and fungal hyphae (Tisdall

and Oades, 1982). Increasing the amount of SOM in a mineral soil improves the water-stability of soil aggregates (Tisdall and Oades, 1982).

Lipiec and Stepniewski (1995) reported that soil compaction causes loss of nutrients from soils by accelerating of surface water runoff and soil erosion. Addition of FYM to compacted agricultural soils has been shown to decrease the bulk density, reduce soil compaction and shear strength (Ekwue and Stone, 1995). Cong (2000) reported that *Tithonia diversifolia* amendment improved soil porosity and aggregation, but reduced the specific surface area of Ferralsols and Cambisols in Vietnam. Reducing the specific surface area of a soil might be important as it might reduce phosphate sorption sites in high P-fixing soils (Budianta, 1999; Cong, 2000, see later discussion).

It is the decomposition products of SOM additions and the activities of soil organisms that lead to the formation of stable soil aggregates. As well as providing the raw materials to form the aggregates, SOM provides an energy source for soil flora and fauna. These include earthworms, other macro-fauna, meso- and micro-fauna, fungi and algae, bacteria and actinomycetes (Flaig *et al.*, 1977). The first three groups of living organisms participate more in mechanical processes to reduce plant and animal residues into smaller pieces, rather than biochemical processes. These organisms may create channels and burrows in the soil. The fungi and algae, and bacteria and actinomycete groups participate more in the biochemical processes. The addition of organic materials to soils has direct and indirect effects on the activity of soil flora and fauna.

Thus organic amendments placed on the soil surface as a mulch improves the soil organic matter content, the soil structure by simulating biological activity, and protects against erosion (De Boodt *et al.*, 1977). Mulching and/or incorporation of plant residues also improves soil macroporosity, water-retention capacity and infiltration rate, bulk density, and reduces rainfall impact and runoff velocity of soils (Fernandes and Sanchez, 1990; Cong, 2000). Reduced rainfall impact leads to conservation of soil aggregates.

### ***Nutrient source (N, P, S)***

Soil organic matter provides the sole reserves of soil N and major reserves of S and P (Cheng, 1977). Organic amendments can be important sources of N for crop production. Careful use of appropriate organic amendments to soils can increase the available N in soils (Serna and Pomares, 1991) and stimulate nitrification (Falih and Wainwright, 1996).

When organic materials are decomposed by soil organisms, mineralisation and immobilisation occur simultaneously in soils. The net amount of N produced by mineralisation depends on the 'quality' of organic amendments, particularly the carbon to nitrogen ratio (C:N ratio). The C:N ratio of organic inputs provides an indication of the amount of net N mineralisation, or net N immobilisation, when they are incorporated into soils. If there is a deficiency of N in the substrate for the microbes, during decomposition, they will utilise whatever available N is present in the immediate environment. Yadvinder-Singh *et al.* (1992) calculated that the critical C:N ratio for the N mineralisation of organic materials in soils was 19. The critical C:N ratio where zero net N mineralisation and immobilisation from decomposition of crop residues was about 40:1 (Virgil and Kissel, 1991) and from decomposition of animal manure was about 43:1 (van Faassen and van Dijk, 1987). In many cases the critical C:N ratio lies between 15:1 and 33:1 (Black, 1968). The critical values for the C:N ratio for zero net N mineralisation are not constant and depend upon factors such as moisture, temperature, and the length of time of adding organic materials in a soil. Organic amendments with a C:N ratio above 30:1 are not likely to contain enough N to cause net N mineralisation in the early stages of decomposition. Most residues of legumes, animal manures and composts have narrow C:N ratios (<20:1), favouring more rapid N mineralisation. Materials (such as wheat straw) with wide C:N ratios (>30:1) favour immobilisation when incorporated into soil. For materials with a C:N ratio between 20:1 and 30:1, the two processes (mineralisation and immobilisation) are approximately in balance (Glendinning, 1999). In general, the narrower the C:N ratio, the greater the likelihood of net mineralisation (Addiscott and Dexter, 1994), thus the greater the increase in short-term crop growth due to organic amendment addition. Table 4.1 shows C:N ratios of selected organic materials.

Table 4.1 Total N and P contents and C:N ratios of selected organic materials.

Organic material	Total concentration (% dry weight)		C:N ratio	Source
	N	P		
Cowpea ( <i>Vigna unguiculata</i> )	2.69	0.28	17.1	Yadvinder-Singh <i>et al.</i> (1992)
Gliricidia ( <i>Gliricidia maculata</i> )	3.49	0.22	10.42	Yadvinder-Singh <i>et al.</i> (1992)
Gliricidia ( <i>Gliricidia sepium</i> )	2.8	-	16.8	Aye (1994)
Leucaena ( <i>Leucaena leucocephala</i> )	3.15	0.20	12.7	Yadvinder-Singh <i>et al.</i> (1992)
Mucuna ( <i>Mucuna pruriens</i> )	4.49	0.17	11.79	Budianta (1999)
Mungbean ( <i>Vigna radiata</i> )	2.21	-	16.1	Yadvinder-Singh <i>et al.</i> (1992)
Pigeon pea ( <i>Cajanus cajan</i> )	1.94	0.15	21	Cong (2000)
Sesbania ( <i>Sesbania aculeata</i> )	2.62	0.32	16.4	Yadvinder-Singh <i>et al.</i> (1992)
Sunnhemp ( <i>Crotolaria juncea</i> )	2.86	0.34	16.1	Yadvinder-Singh <i>et al.</i> (1992)
Tree lucerne ( <i>Chamaecytisus palmensis</i> )	3.5	2.1	13	Trolove (2000)
Wheat straw ( <i>Triticum aestivum</i> )	0.53	0.9	87	Trolove (2000)
Wild sunflower ( <i>Tithonia diversifolia</i> )	3.83	0.29	14	Weerakoon (1983)
Composted goat manure	3.0	-	9.9	Aye (1994)
Fresh goat manure	1.8	-	23.3	Aye (1994)
Farmyard manure	1.1	-	20	Gaur (1983)
Grass compost	2.34	0.50	13.5	Teppoolpon and Wasinarat (1983)
Human Faeces	1.5	0.5	7.3	Flaig <i>et al.</i> (1977)
Rice straw compost	1.64	0.33	16.3	Teppoolpon and Wasinarat (1983)
Water hyacinth compost	3.88	2.28	9.4	Teppoolpon and Wasinarat (1983)

Use of legumes to increase soil fertility has been a common practice since ancient times. The importance of legumes in agriculture is due to their ability to fix large amounts of N and the narrow C:N ratio of their residues compared to other crop residues (Table 4.1). It must be remembered, however, that adequate growth of legume-based green manures requires adequate soil P status (see Chapter 3).

Organic materials decompose and release plant-available P into the soil solution when added to soil (Budianta, 1999; Cong, 2000). The mineralisation of P from an organic material during decomposition is closely analogous to the transformation of N (Thomson *et al.*, 1954) and depends on several factors, such as soil temperature, moisture and soil pH. The P concentration of organic materials is the most important factor governing the rapid release of plant-available P from those materials. The P concentration of organic materials varies depending upon their origin (i.e. plant or animal); in most agronomic plants, the P concentration will be between 0.1-0.4% (see Table. 4.1). The mineralisation of P from organic materials may depend on their C:P ratios, but the critical C:P ratio (for ready release of plant-available P) of those organic

materials varies between as low as 55:1 to as high as 300:1 (Yadvinder-Singh *et al.*, 1992).

Organic residues applied to soils may increase P availability for plant growth through mineralisation, but also by decreasing P fixation of soils (Li *et al.*, 1990). The decomposition of organic amendments can decrease the activity of Al and Fe in soil solution through precipitation and complexation reactions and thereby decreases P fixation (Iyamuremye *et al.*, 1996c).

In highly weathered acid soils, addition of organic amendments with a high P concentration such as steer manure and alfalfa (*Medicago sativa*) has been shown to increase soil pH and extractable P and decrease P fixing capacity by reducing exchangeable Al (Lee *et al.*, 1990; Iyamuremye *et al.*, 1996a).

Hedley *et al.* (1982a) suggested that for extremely P deficient soils, the addition of both organic matter and P fertiliser would be required to build-up plant-available P in the soil. The quantity of P mineralised may be positively related to the quantity of P initially present in the soil. They found that the addition of cellulose or P to soils changed the distribution of P amongst various soil P fractions with greater retention of P in labile SOM fractions. Thus adding P-rich organic amendments (e.g. animal manure and alfalfa) may cause the redistribution of P into plant-available fractions of soil organic P. Low P organic amendments (e.g. wheat straw) are unlikely to significantly increase the redistribution of soil inorganic P into labile organic P fractions (Iyamuremye *et al.*, 1996b). As described earlier, P transformation in soils also depends on the quality of added organic materials such as the content of C, N, P and the C:N:P ratio.

Organic manures also release plant-available S when they decompose. Organic S in a soil is decomposed by soil microbes to  $\text{SO}_4^{2-}$  under aerobic conditions, and  $\text{S}^{2-}$  under anaerobic conditions (Yadvinder-Singh *et al.* 1992). The appropriate conditions for S mineralisation from OM are similar to those for N and P mineralisations in soils. As with N and P, both mineralisation and S immobilisation can occur, depending on the C:S ratio of the OM plus the available  $\text{SO}_4^{2-}$  pool in the soil. For example, Falih and

Wainwright (1996) found that in soil with high  $\text{SO}_4^{2-}$  concentrations (20-25 mg S  $\text{kg}^{-1}$  soil), the concentration of  $\text{SO}_4^{2-}$  declined after the addition of sugar beet residues to soils. Those materials with a narrow C:S ratio (<200) tend to cause S mineralisation and those with a wide C:S ratio (>420) tend to cause S immobilisation (Barrow, 1960).

### ***Cation exchange capacity (CEC)***

In the plant root zone of a mineral soil (i.e. plough layer), OM can contribute to 50% or more of the soil negative charge (CEC). In mildly acidic soils, organic matter addition increases the negative surface charge of soils. In very acid soils, the phenols and carboxylic acid groups of OM become protonated and do not provide sites to retain nutrient cations. Cong (2000) reported that the organic amendment *Tithonia diversifolia* increased the CEC of Acrisols and Ferralsols in Vietnam. The weakly or non-specifically adsorbed cations of SOM are freely exchangeable. The quantities of exchangeable cations and anions absorbed by plants from the soil solution are often equal to the CEC and AEC (anion exchange capacity) (Foth and Ellis, 1997). Consequently, in mildly acidic or near neutral soils the higher the CEC of soils the more exchangeable cations they hold, this increases the supply of available of Ca, Mg, K and Na to plant roots.

### ***pH buffering and detoxification of Al in low pH soils***

Organic residues may have a liming effect, ameliorating the adverse effects of acid soils (Hue, 1992; Iyamuremye *et al.*, 1996a; Tang *et al.*, 1999; Cong, 2000; Haynes and Mokolobate, 2001). Also the decomposition of organic materials also produces soluble organic ligands, which can reduce Al toxicity to plant root growth in acid upland soils (Budianta, 1999; Haynes and Mokolobate, 2001). A wide range of Al species form in acid soils (Naidu, 1985), in particular, hydroxy forms of Al ( $\text{Al}(\text{OH})_3$ ,  $\text{Al}(\text{OH})_2^+$ ,  $\text{Al}(\text{OH})^{2+}$ ,  $\text{Al}^{3+}$ ) depending on the soil pH (Wright, 1989). Aluminium species have varying toxicity to plants (Foy, 1992) and the removal of the highly positively charged phytotoxic Al from soil solution improves plant root growth in acid soils. A significant negative relationship between soil pH and Al saturation was found in tropical Ultisols (Manrique, 1986; Haynes and Mokolobate, 2001).

The increase in pH with organic amendments may be important for decreasing P fixation in very acid soils (Yadvinder-Singh et al, 1992; Iyamuremye *et al.*, 1996a, Cong, 2000; Haynes and Mokolobate, 2001). One reason for this is that increasing the pH will cause precipitation of exchangeable Al and Fe, thus reducing the potential P precipitation in Acrisols.

Experiments conducted by Pocknee and Sumner (1997), Tang *et al.* (1999) and Tang and Yu (1999) using legume OM (2 to 4 t ha<sup>-1</sup>) have demonstrated that the increase in soil pH (0.6-0.7 unit) in an amended soil is mainly controlled by the cation-anion balance of the organic inputs and extent of decomposition of that organic amendment. A temporary increase in soil pH due to the production of NH<sub>4</sub><sup>+</sup> during the ammonification process of organic material decomposition also consumes H<sup>+</sup> from the soil solution (Trolove, 2000).

### ***Other positive effects***

Most organic materials are not a major source of micronutrients, but transformations of micronutrients in soils may occur as a result of oxidation-reduction reactions in soil caused by the addition of these organic materials to soils (Cheng, 1977; Yadvinder-Singh et al, 1992). For example, a healthy soil bacteria population is required to maintain manganese (Mn) oxidation and keep Mn in the non-toxic Mn (III) or Mn (IV) forms (Sparrow and Uren, 1986). Addition of easily decomposable OM to soils has been shown to enhance the reduction of toxic chromium Cr<sup>4+</sup> to non-toxic Cr<sup>3+</sup>.

Careful management of organic amendments can also reduce the amount of toxic agrochemicals (e.g. simazine, prometryne, atrazine, etc.) in the environment because organic ligands can bind these toxic ions to form non-toxic complexes (Addiscott and Dexter, 1994; Lefroy and Craswell, 1997).

### 4.1.3 Focus on soils of the study area

Given the low SOM content and low P availability of the Red Earths and Yellow Earths of the study area (Table 4.2), strategies attempting to raise the soil fertility status of these soils should include raising the SOM content. This may be achieved by crop rotations or use of organic amendments that return more OM to the soil per year than the rate of SOM decomposition. Addition of OM to the soil through green manures (e.g. rice bean) and housed animal manures (e.g. FYM) may also be a popular low cost alternative method of supplying nutrients needed for crop growth.

Table 4.2 The pH, organic C (OC %), total N, available P (Olsen-P) and P retention in the soils of the study area and similar soils from other regions.

Soil	Region	pH	OC (%)	Total N (%)	Olsen-P (mg kg <sup>-1</sup> )	P retention	Reference
Acrisol (Red Earth)	Southern Shan State, Myanmar	6.0	1.7	0.19	6.5	65	
Acrisol (Yellow Earth)	Southern Shan State, Myanmar	4.9	1.1	0.10	5.5	44	
Acrisol	Tra Co, Vietnam	4.49	0.71	0.04	5.9	-	Cong (2000)
Acrisol	Hoa Thanh, Vietnam	4.66	0.46	0.02	7.0	-	Cong (2000)
Ferralsol	Duc Lieu, Vietnam	4.45	2.34	0.20	2.6	-	Cong (2000)
Ferralsol	Phuoc Long, Vietnam	4.45	2.65	0.19	4.4	-	Cong (2000)
Ultisol	South Sumatra, Indonesia	4.72	1.47	0.13	1.33 (Bray-1)	-	Budianta (1999)
Ultisol	Kottawa, Sri Lanka	4.5	1.7	-	20	93	Zoysa (1997)
Ultisol	Sembawa, Indonesia	4.8	2.8	-	4.5	32	Tambunan (1992)

Research is required to determine whether OM addition to these and other tropical and subtropical soils is an effective soil fertility management strategy. For example, compared to temperate regions, the mineralisation of fresh plant residues and humified SOM is three to five times faster in humid tropical regions (Juo, 1990). Consequently the rate of C loss caused by cultivation is many times faster in tropical soils than temperate soils, with a considerable deterioration in soil quality often within a decade. Shang and Tiessen (1997) have stated that the organic matter of weathered tropical soils may be less stable than assumed, possibly because of the rapid degradation of SOM in

soils, thus SOM management research should be a priority for the investigation of sustainable agriculture practices in the tropics.

The ultimate goal of organic amendment management is to recycle the nutrients, so that the availability of nutrients can be enhanced, particularly N, S and P. Only a few studies on SOM dynamics, organic input quantity, quality and interaction with the mineral component of soil, have been published for the tropics (Fernandes and Sanchez, 1990). As recently as 1999, Martius *et al.* (1999), have stated that research is still required in SOM management, the importance of the quality of organic amendments in tropical soils, and in particular, on the fate and relative plant availability of nutrients added to soil in OM amendments.

In the following experimental section of this chapter, simple incubation experiments, using Red Earths and Yellow Earths from the study area, are conducted to test the influence of organic amendment type on SOM and nutrient content. Three different organic amendments (i.e. upland rice residues, pigeon pea residues, and FYM) are evaluated for building SOM and provision of labile P in Red Earths and Yellow Earths, using laboratory incubation. The incubation experiment has focused on evaluating organic amendments as nutrient sources, rather than considering the cost or environmental impacts of the amendments.

During these experiments the Walkley and Black (1934) procedure is evaluated as a 'low tech', portable method (see Section 4.4.4) for determining SOM change after soil amendment addition.

## **4.2 Experimental design**

The organic amendments, namely FYM, upland rice residue (UPR) and pigeon pea residue (PIP), were incubated with seven different Red Earths and Yellow Earths. Soils were also incubated without any amendment addition (control treatment, Con). A total of 28 treatments ( $7 \times 4$ ) were used in this experiment, with three replicates of each treatment.

### 4.3 Experimental Objectives

1. To compare the effect of the nature of organic amendments (FYM as animal manure, UPR and PIP as plant residues) for building SOM and nutrient reserves in Red Earths and Yellow Earths.
2. To use these soils to evaluate a method suitable for measuring changes in soil C in the field (i.e. the Walkley-Black method).

### 4.4 Materials and methods

#### 4.4.1 Soil samples

Soil samples were collected from the sites described in Section 2.1 (Chapter 2). Surface soil (0-15 cm) samples (air-dried and 2 mm sieved) of seven Red Earths and Yellow Earths were used in this incubation study. The soil materials were characterised and described in Section 2.4 (Chapter 2). The chemical characteristics of soil samples relevant to this study are presented in Table 4.3.

Table 4.3 Selected chemical characteristics of samples (0-15 cm depth) from cultivated (CU) and uncultivated (UN) Yellow (YE) and Red (RE) Earths.

Soil Type <sup>1</sup>	Soil sample	pH <sub>H2O</sub> (1:2.5)	OM (%) <sup>2</sup>	Total N (%)	Olsen-P (mg kg <sup>-1</sup> )	Total P (mg kg <sup>-1</sup> )	P-retention (%)
YE	SS0	4.9	2.53	0.15	6.6	410	53
YEUN I	SS31	5.2	2.30	0.14	8.4	315	46
YECU II	SS36	5.6	1.58	0.09	5.0	230	40
YECU II	SS38	6.5	1.29	0.08	2.2	205	38
RECU I	SS46	6.6	2.44	0.20	1.7	405	67
RECU II	SS51	6.1	2.75	0.21	6.7	530	66
REUN II	SS57	6.3	2.79	0.16	10.6	680	67

<sup>1</sup>Key to soil code in Table 2.2(Chapter 2).

<sup>2</sup>Determined by Leco C combustion  $\times 1.7$

#### 4.4.2 Organic amendments

Farmyard manure, UPR and PIP were obtained from farms in the Aungban locality of Shan State and used as organic amendments. Farmyard manure was air-dried at 35°C and plant residues were oven-dried at 60°C, they were then ground and sieved to <1 mm.

### *Ash-alkalinity of organic amendments*

The ash-alkalinity of organic amendments were determined by slowly heating 0.5 g samples in a muffle furnace to 400°C followed by 3 hours at 500° C. Then the ash was treated with 10 ml of 0.5 M HCl, and the residual acid titrated against 0.25 M NaOH (Jarvis and Robson, 1983b).

Some important chemical characteristics of the organic amendments are presented in Table 4.4.

Table 4.4 Selected chemical composition of organic amendments.

Amendment	Total concentration (% dry weight)			C:N	Ash-alkalinity cmol (-) kg <sup>-1</sup>
	C <sup>1</sup>	N	P		
FYM	21.0	1.9	0.72	11:1	55.5
UPR	38.4	1.7	0.21	23:1	77.7
PIP	39.7	2.1	0.19	19:1	109.6

<sup>1</sup> easily oxidizable organic C by Walkley-Black method (Walkley and Black, 1934).

#### **4.4.3 Incubation of soils**

The three organic amendments were incubated with the seven Red Earths and Yellow Earths (see later Section). Control soils were incubated without organic amendments. These soils also can be grouped into three groups (low P, medium P, and high P) based on their Olsen-P values.

Sixty grams of air-dry soil was mixed with each organic amendment (1.4 g of dry matter). The rate of addition of organic amendment to a soil was based on an application rate of 35 t DM ha<sup>-1</sup> mixed to 15 cm soil depth. The soil and organic amendment were mixed thoroughly. Deionised water was then added to bring the moisture content to 80% of field capacity. All soil treatments were incubated in partly opened, zip-top polythene plastic bags to allow gas exchange. Incubations were conducted in triplicate at room temperature (average 23°C). All bags were weighed monthly to check the moisture content and water was added to restore bags to the original weight if

necessary. This incubation study was undertaken in the Soil and Earth Sciences laboratory at Massey University for about 6 months (19 May 1998 to 30 November 1998).

After the end of incubation study all incubated soils were oven-dried at 35°C. Thereafter soils were ground and passed through a 1 mm sieve in preparation for chemical analysis.

#### ***4.4.4 Part 1. Evaluation of C in soils, organic materials and soils mixed with organic materials***

##### ***Brief review of methods***

The SOM content can be estimated by the determination of soil organic C that is a useful indicator of the degradation or improvement of soils for plant growth. The Walkley-Black procedure, which uses potassium dichromate ( $K_2Cr_2O_7$ ) and  $H_2SO_4$  oxidation to determine easily oxidizable carbon in soils, is commonly used in soil testing laboratories of Myanmar. It is commonly assumed that 77% of the organic C is oxidised by the Walkley-Black method and a conversion factor (1.3 to 1.33), has been used to calculate the total organic C. Olayinka *et al.* (1998) have argued that the Walkley-Black conversion factor is not applicable for determining organic C in tropical soils, but this procedure may be used without a correction factor, since tropical soils contain few strong organo-mineral complexes. There is a need to evaluate the Walkley-Black procedure on the Red Earths and Yellow Earths of Southern Shan State because the temperature of approximately 120°C, obtained by mixing the  $H_2SO_4$  with the sample, is not sufficient to totally oxidise all the soil organic compounds (Martin, 1999). Thus the method can result in a wide range of C recovery values due to interaction with different soils (Allison, 1960), different profiles of the same soil (Tabatabai, 1996), and different management systems (Martin, 1999).

In the present study, the C contents of soils, organic materials, dry soil mixed with organic materials and soils incubated for a short-term with organic materials were measured by both the Leco C analyser and the Walkley-Black method to test the

suitability of Walkley-Black method. The slopes of the regression equation relating the two C measurements were then compared with the conversion factor.

The C recovery factors were calculated by comparing the Walkley-Black C value with the C values determined by a dry combustion procedure (LECO FP 2000 automated C/N analyser). The loss of weight on ignition method (LOI) is also a simple and rapid method for assessing the organic matter content of all soil types (Ball, 1964; Goldin, 1987). The result, however, is also dependent upon soil type because ignition may cause losses in weight from the destruction of free carbonates and gains in weight through raising the oxidation state of Fe, Mn and Al oxides and hydroxides (Ball, 1964; Hesse, 1971; Goldin, 1987; Bluehen, 2001). It is suggested that this method can be widely applicable where a high degree of accuracy is not required. Ball (1964) showed that organic C in a range of soils, determined by LOI at the temperatures of 850°C and 375°C were highly correlated to values obtained by the Walkley-Black method. The lower temperature was deemed preferable because the accuracy is greater for LOI at the lower temperature (at 375°C) than the higher temperature (850°C) when compared with the Walkley-Black method (Hesse, 1971). The loss of structural water from clay minerals may occur at high temperature (Ball, 1964; Goldin, 1987). In non-calcareous soils, LOI and the Leco C analyser gave similar values of organic matter (Goldin, 1987).

#### ***Methods adopted for evaluation***

Carbon content in unincubated soils, organic materials, dry soil mixed with organic materials, and incubated soils was determined by the loss of weight on ignition method at 360°C (Storer, 1984), the chemical oxidation method (Walkley and Black, 1934) and the dry combustion method using a Leco C analyser (LECO FP 2000 automated C/N analyser)(Goldin, 1987). If the assumption is made that the ratio of organic matter to carbon is constant, organic matter content can be estimated from the C content of soil and manures. Two methods for determining C content in those samples (Leco and chemical oxidation) were compared with the loss on ignition (LOI) method to measure OM. Walkley-Black (1934) and LOI procedures are simple methods that could be conducted in the laboratory in Myanmar.

The LOI method used in the present study involved drying all soils materials at 105°C and organic materials at 70°C to determine moisture content, then heating samples in a muffle-furnace at 360°C for two hours, and reweighing. The value of LOI is calculated by the formula of Storer (1984) as follows:

$$\text{LOI (\%)} = (1 - \text{Weight at } 360^\circ\text{C} / \text{Weight at } 105^\circ\text{C (or } 70^\circ\text{C)}) \times 100$$

Organic matter was estimated by using the following equation (assuming OM contains 58% carbon):

$$\text{OM (\%)} = \% \text{ organic C} \times 1.72 \text{ (Helling } et al., 1964)$$

#### **4.4.5 Part 2. Effect of the organic matter amendments on soil C content**

At the end of the incubation, soil C was measured in the soils amended with organic materials, and compared to the initial soil C status of these soils and the soil C status of the unamended incubated soil.

#### **4.4.6 Part 3. Effect of the organic matter amendments on soil N and soil pH**

Total N in soils was determined by Kjeldahl wet digestion (Parkinson and Allen, 1975) using a Technicon Auto-Analyser and by dry combustion using a LECO FP 2000 automated analyser.

Soil pH was determined by using a soil:water ratio of 1:2.5 with a glass electrode (Farr, 1972). Changes in soil pH were measured before and after incubation with or without organic materials.

#### **4.4.7 Part 4. Effect of the organic matter amendments on soil P**

Total P in soils also was determined by Kjeldahl wet digestion (Parkinson and Allen, 1975) using a Technicon Auto-Analyser. Soil Olsen-P was determined by extraction

with sodium bicarbonate (Olsen *et al.*, 1954) and P retention (Blakemore *et al.*, 1987; Saunders, 1965) was also measured for the original soil samples. After incubation, soil P fractions were measured by the P fractionation procedure of Hedley *et al.* (1994).

### ***Sequential extraction of soil P fractions***

The soil samples were analysed for sequential P fractionations by a modified method of Hedley *et al.* (1994).

A 1 g soil sample was placed into a 50 ml polypropylene centrifuge tube and the following P fractions were sequentially analysed.

(1) Resin-P: by shaking end-over-end for 16 hours at 25°C in 27 ml of deionised water containing a Na<sup>+</sup> saturated cation exchange resin membrane strip and a HCO<sub>3</sub><sup>-</sup> saturated anion exchange resin membrane strip. At the end of the shaking, the strips were transferred into 35 ml vials using tweezers and P eluted by shaking end-over-end for 30 minutes with 10 ml of 0.5 M NaCl.

(2) 0.1 M NaOH-Pi: 3 ml of 1 M NaOH was added to the suspension from step (1) to make the final concentration 0.1 M NaOH, and shaken for a further 16 hours. Samples were then centrifuged at 8000 rpm for 10 minutes and the supernatant filtered through 0.45 µm Millipore filter.

(3) 0.1 M NaOH-Po: by digesting 2 ml of the 0.1 M NaOH extractant in 2 ml of concentrated H<sub>2</sub>SO<sub>4</sub> and then oxidising with 1 ml of H<sub>2</sub>O<sub>2</sub>. NaOH-Po was calculated by subtracting 0.1 M NaOH-Pi from digested P.

(4) 1 M NaOH-Pi: by adding 30 ml of 1 M NaOH to the soil pellet then shaking for 16 hours and analysing as step (2).

(5) 1 M NaOH-Po: by digesting 4 ml of the 1 M NaOH extractant in 2 ml of concentrated H<sub>2</sub>SO<sub>4</sub>, oxidising with 1 ml of H<sub>2</sub>O<sub>2</sub>, then subtracting 1 M NaOH-Pi from digested P.

(6) H<sub>2</sub>SO<sub>4</sub>-Pi: by adding 30 ml of 0.5 M H<sub>2</sub>SO<sub>4</sub> to the soil residue from step (4) and shaking for 16 hours, centrifuging and analysing as above.

(7) H<sub>2</sub>SO<sub>4</sub>-Po: by digesting 5 ml of the H<sub>2</sub>SO<sub>4</sub> extractant in 2 ml of concentrated H<sub>2</sub>SO<sub>4</sub>, oxidising with 1 ml of H<sub>2</sub>O<sub>2</sub>, then subtracting H<sub>2</sub>SO<sub>4</sub>-Pi from the digested P.

(8) Residual-P: the soil residue from step (6) was digested in 4 ml of concentrated H<sub>2</sub>SO<sub>4</sub> until residue was white. The digests were then made up to 50 ml with deionised water and filtered through a 0.45 µm Millipore filter. To avoid the precipitation of Fe-hydroxide and to minimise the use of NaOH in neutralisation, only a 5 ml aliquot was transferred into a 50 ml flask and neutralized with 5 M NaOH using Para-nitrophenol indicator.

The P concentrations of all the extracts and digests were measured by the colorimetric technique of Murphy and Riley (1962).

#### *Ion exchange membranes*

The ion exchange membranes used in this study were synthetic resins commercially manufactured and supplied by BDH Chemicals Ltd., England. The area of the membrane strips was 12.5 cm<sup>2</sup> (6.25 cm long and 2.5 cm wide). The original cation exchange resin (CER) strips are slightly lighter in colour than the anion exchange resin (AER) strips. The AER strips also have rounded corners to aid differentiation of these strips (Saggar *et al.*, 1990). The ion exchange capacity of the resin strips was determined by shaking the resin strips in 30 ml of 0.1 M KH<sub>2</sub>PO<sub>4</sub> for 30 minutes then measuring the amount of P and K retained by the strips. Each AER and CER strip retained 0.20-0.21 and 0.22-0.24 meq of charge, respectively. One AER and one CER strip were used to extract P from 1 g of air-dry soil in 27 ml of deionised water.

After extraction, P was eluted from both resin strip in a NaCl solution. After analysis for P in the NaCl eluant was completed, all cation and anion resin strips were recovered using tweezers and placed into (1 litre) plastic bottles. The cation and anion strips were

shaken in 0.5 M NaCl or 0.5 M NaHCO<sub>3</sub>, respectively, for 30 minutes. The solution was then discarded, and refilled with a fresh solution of NaCl or NaHCO<sub>3</sub> and shaken. Strips were washed three times. Finally, all membrane strips were thoroughly washed three times with deionised water and kept in deionised water for reuse.

The P fractions delineated by this procedure roughly correspond to the following soil P pools.

Resin-P: exchangeable inorganic P that is freely available to the plant;

0.1 M NaOH-Pi: predominantly inorganic P adsorbed to Fe and Al hydrous oxides;

0.1 M NaOH-Po: predominantly organic P adsorbed to Fe and Al hydrous oxides;

1 M NaOH-Pi: predominantly inorganic P from internal surfaces of soil aggregates (occluded P);

1 M NaOH-Po: dominantly organic P from internal surfaces of soil aggregates;

0.5 M H<sub>2</sub>SO<sub>4</sub>-Pi: predominately calcium phosphates or apatite-type P minerals. Some P occluded in Fe minerals. 0.5 M H<sub>2</sub>SO<sub>4</sub>-Pi was chosen over 1 M HCl because Tambunan *et al.* (1993) have shown better recovery of fertiliser residue P from tropical soils by 0.5 M H<sub>2</sub>SO<sub>4</sub>.

Residual-P: recalcitrant inorganic P or structural and stable organic P in organo-mineral complexes.

Plant uptake of Pi from soil has been shown to be from the resin-P and 0.1 M NaOH-Pi fractions (Hedley *et al.*, 1982a; Trolove *et al.*, 1996b). These two fractions can be grouped together and termed labile-Pi (see Section 4.8).

#### **4.4.8 Statistical analysis**

The experimental design was a randomised complete block factorial design with three replicates of each treatment. This study contained 28 treatments (4 amendments  $\times$  7 soils). All data were analysed using the SAS<sup>TM</sup>-GLM system for windows V6.12 programme. Analysis of variance was used to identify the impact of each main effect (i.e. organic amendment and soil factors) and any interactions (i.e. organic amendment sources  $\times$  soil types). Since all main effects and interactions significantly affected the soil organic C, soil pH and soil P fractions, Fisher's least significant difference test was used to assess their relative effects. Results were considered significant at  $\alpha = 0.05$ .

### **4.5 Part 1. Evaluation of the Walkley-Black procedure for a wide range of soils and organic amendments**

#### **4.5.1 Results**

##### ***Soils without amendments***

Results from the Walkley-Black digestion of Red Earths and Yellow Earths resulted in good reproducibility amongst the replicates (see Appendix 4.1).

The soil total C contents determined by Leco combustion and the Walkley-Black method were compared in 20 surface soil (0-15 cm) sub-samples from Red Earths and Yellow Earths (Figure 4.2). The recovery of C from the Walkley-Black method varied between 62 to 93%. The intercept of the relationship was non-significant. The inverse of the slope ( $1/0.76 = 1.32$ ) is similar to the correction factor (1.3) proposed in the original method of Walkley-Black (1934).

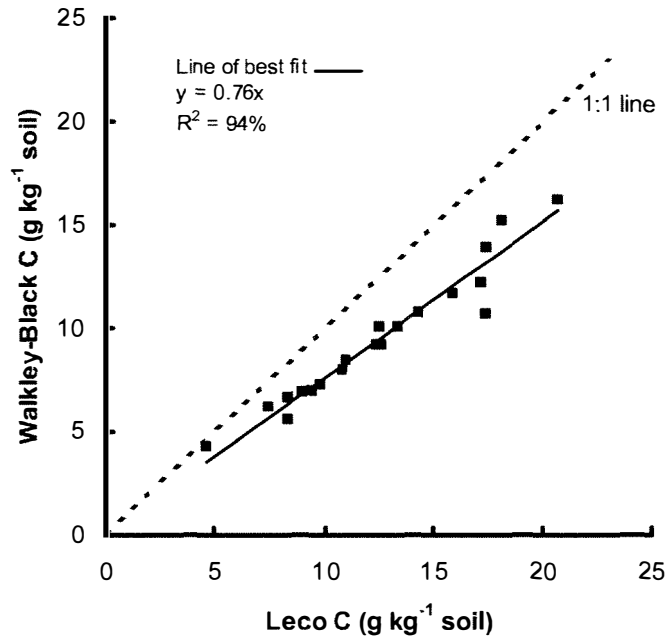


Figure 4.2 The relationship between C determined by the Leco and Walkley-Black methods for 20 samples of Red Earths and Yellow Earths (intercept is non-significant).

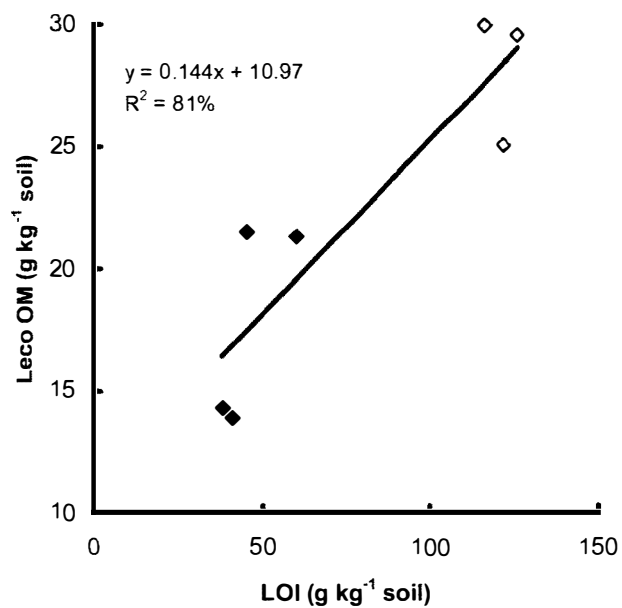


Figure 4.3 The relationship between weight loss on ignition and Leco OM for Red (◇) and Yellow (◆) Earths.

Table 4.5 The mean loss of weight ( $\text{g kg}^{-1}$ ) on ignition from seven soils and seven manures. The Standard error of the mean is in brackets.

Soil code	LOI ( $\text{g kg}^{-1}$ )	Manure	LOI ( $\text{g kg}^{-1}$ )
YE (SS0)	60.0 (0.7)	Farmyard manure (FYM)	624.7 (16.1)
YEUN I (SS31)	45.4 (0.7)	Tithonia diversifolia (TOA)	864.9 (3.5)
YECU II (SS36)	41.3 (0.1)	Horse (HEM)	767.3 (3.3)
YECU II (SS38)	38.1 (0.9)	Sheep (SPM)	799.7 (3.2)
RECU I (SS46)	116.0 (1.7)	Wheat straw (WSM)	930.4 (1.7)
RECU II (SS51)	121.7 (0.5)	Upland rice (UPR)	931.0 (5.1)
REUN II (SS57)	126.0 (0.3)	Pigeon pea (PIP)	928.7 (9.4)

The determination of OM content from weight lost on ignition (LOI,  $\text{g kg}^{-1}$ ) in the seven mineral soils is shown in Table 4.5. Loss on ignition values in Red Earths are 2 to 3 times greater than those of Yellow Earths but Leco OM values varied a lot between the two soils. The relationship that exists between LOI and Leco OM ( $\text{Leco C} \times 1.72$ ) (Figure 4.3) is:

$$\text{Leco OM (g kg}^{-1}\text{)} = 0.144 (\text{LOI}) \text{ g kg}^{-1} + 10.97 \text{ (R}^2 = 81\% \text{*)} \quad \text{Equation (4.2)}$$

However, considerable error exists in using this relationship to predict the Leco OM content of Yellow Earths. The LOI and Walkley-Black OM ( $\text{Walkley-Black C} \times 1.72$ ) are also poorly correlated for Red Earths and Yellow Earths ( $\text{R}^2 = 61\% \text{*$  in Figure.4.4).

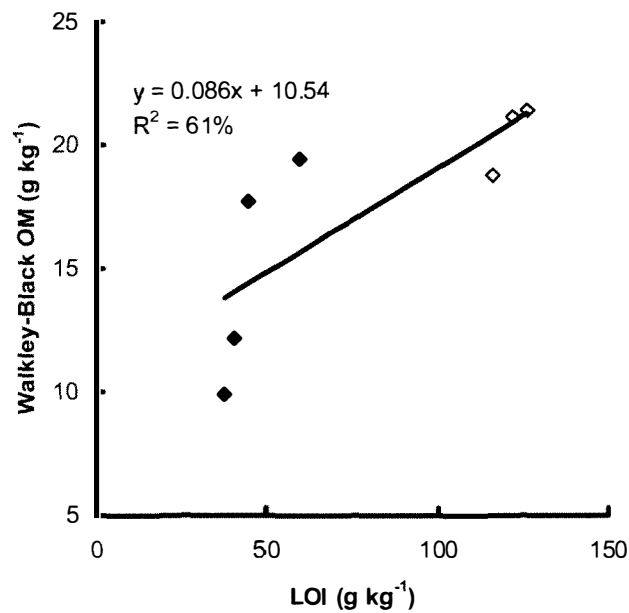


Figure 4.4 The relationship between weight loss on ignition (LOI) and Walkley-Black OM for Red (◇) and Yellow (♦) Earths.

#### *Dry soil mixed with organic materials*

The Walkley-Black C and Leco C methods were compared using 6 sub-samples of dry soil mixed with the organic inputs (Figure 4.5). Eighty-five to ninety-six percent C recovery was achieved by the Walkley-Black method. This generates a Walkley-Black correction factor of 1.08. Notably this relationship differs from that in Equation 4.2 for dry soil alone. The relationship between the Walkley-Black and Leco C contents in the dry soil mixed with the organic inputs can be expressed as the following regression equation:

$$\text{Walkley-Black C (g kg}^{-1}\text{)} = 0.92 (\text{Leco C}) \text{ g kg}^{-1} \text{ (R}^2 = 97\%^{**}\text{)} \quad \text{Equation (4.3)}$$

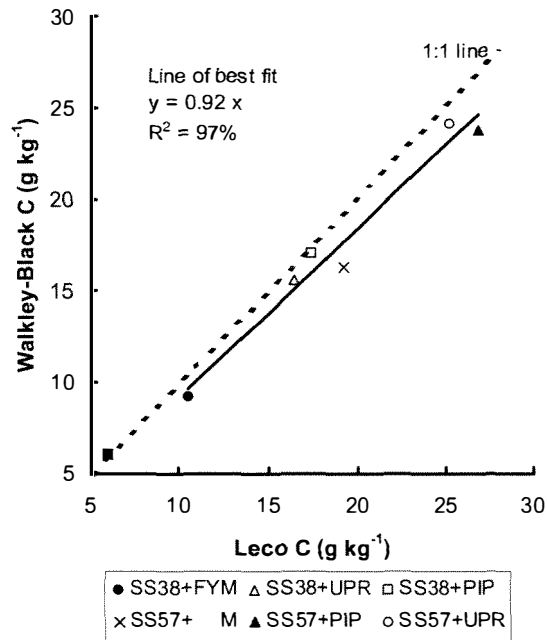


Figure 4.5 The relationship between C determined by the Leco and Walkley-Black methods from 6 samples (see Table 4.5 for treatment codes) of dry soils mixed with different organic materials (intercept is non-significant).

### *Soils after incubation with organic materials*

The relationship between Walkley-Black and Leco C was also compared using 16 subsamples of soils that had been incubated with organic inputs (Figure. 4.6). Carbon recoveries ranged between 74 to 94% by Walkley-Black method. This resulted in a mean Walkley-Black correction factor of 1.28. The relationship between the Walkley-Black and Leco C contents in the incubated soils with the organic inputs can be expressed as the following regression equation:

$$\text{Walkley-Black C (g kg}^{-1}\text{)} = 0.72 (\text{Leco C}) \text{ g kg}^{-1} + 1.20 \text{ (R}^2 = 97\%^{**}\text{)}$$

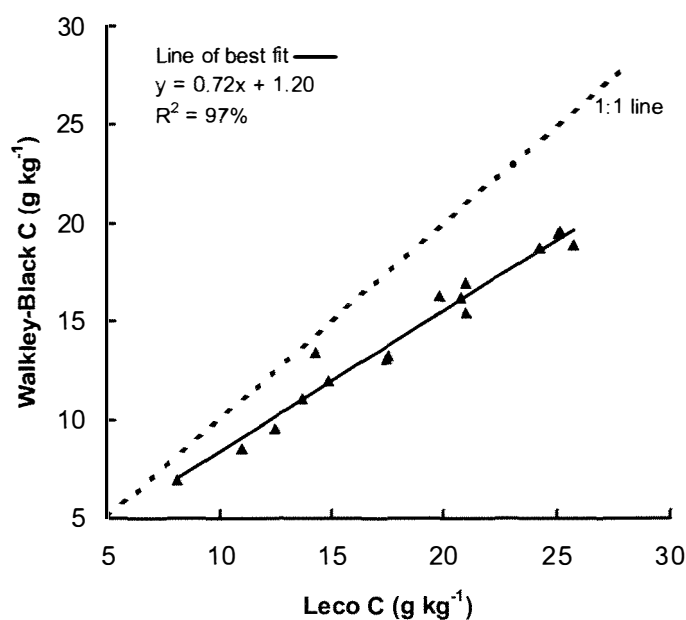


Figure 4.6 The relationship between C determined by the Leco and Walkley-Black methods for 16 samples of incubated soils with different organic materials (intercept is non-significant).

### ***Organic materials alone***

The total C content of organic materials measured by the Leco and Walkley-Black methods were compared in seven samples of FYM, UPR, PIP, *Tithonia diversifolia* (TOA), sheep manure (SPM), horse manure (HEM) and wheat straw (WSM) (Figure 4.7). Carbon recoveries ranged from 65 to 91%. In particular FYM shows a low percentage of Walkley-Black oxidisable C compared to total C determined by Leco (Figure 4.7). The average correction factor for the Walkley-Black method is 1.28. The relationship between the Walkley-Black and Leco C contents in the organic materials alone can be expressed as the following regression equation:

$$\text{Walkley-Black C (g kg}^{-1}\text{)} = 1.36 (\text{Leco C}) \text{ g kg}^{-1} - 247.22 \text{ (R}^2 = 82\% \text{*)}.$$

The weight lost ( $\text{g kg}^{-1}$ ) for the seven manures by LOI is presented in Table 4.5. The Leco OM can be estimated from weight loss on ignition in the manures by using the regression equation:

$$\text{Leco OM (g kg}^{-1}\text{)} = 0.7 (\text{LOI}) \text{ g kg}^{-1} + 140.56 \text{ (R}^2 = 88\% \text{*, Figure 4.8)}.$$

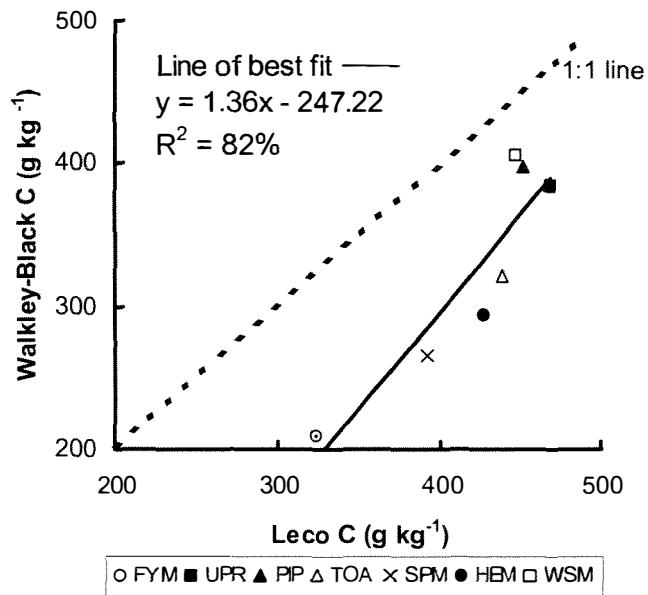


Figure 4.7 The relationship between C determined by the Leco C and Walkley-Black methods for seven samples of organic materials (see Table 4.5 for material code).

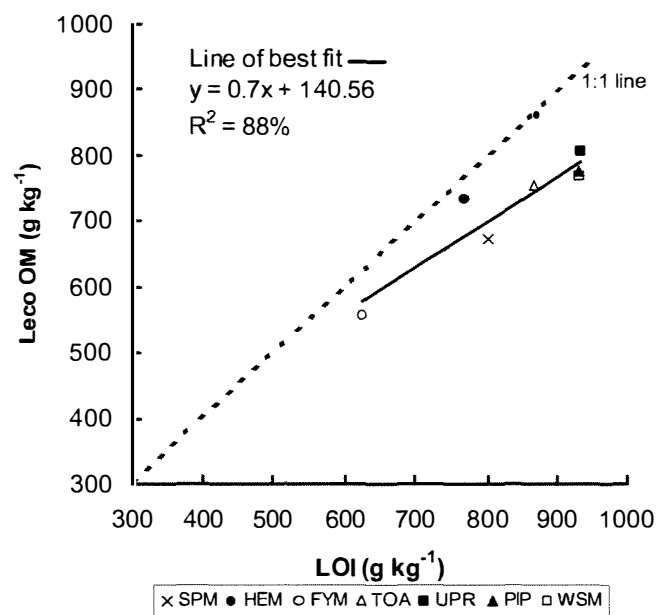


Figure 4.8 The relationship between weight loss on ignition (LOI) and Leco OM for a range of organic materials (see Table 4.5 for material code).

A slightly stronger linear relationship ( $R^2 = 91\%$ ) existed between Walkley-Black OM and LOI for the seven manures (Figure 4.9):

Walkley-Black OM ( $\text{g kg}^{-1}$ ) =  $1.07 (\text{LOI}) \text{ g kg}^{-1} - 332.63$  ( $R^2 = 91\%$ \*, Figure 4.9).

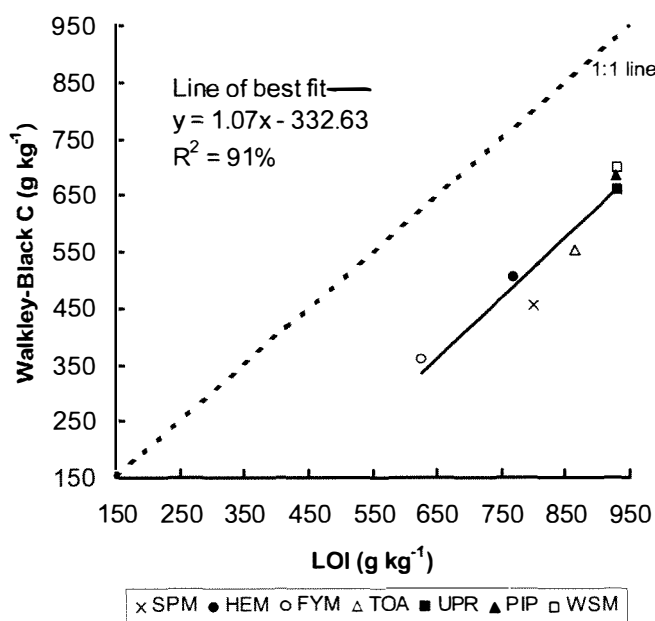


Figure 4.9 The relationship between weight loss on ignition (LOI) and Walkley-Black OM for a range of organic materials (see Table 4.5 for material code).

#### 4.5.2 Discussion

The results indicate that there were strong linear relationships between the Leco C and Walkley-Black C procedures for all soils and soil-organic matter mixtures ( $R^2 = 0.94^{**}$  to  $0.97^{**}$ ). A weaker correlation between the two methods of C determination was found for organic materials alone ( $R^2 = 82\%^*$ ). The percentage C measured by the Walkley-Black method from UPR, PIP, TOA and WSM plant residues or green manures was relatively high and consistent (73 to 91%), but C recovery from FYM, SPM and HEM were only 65%, 68%, and 69% respectively. The Walkley-Black oxidation of C in animal manure was much less complete than other C forms in plant residues. The reasons for this are unclear. This is probably related to greater amounts of recalcitrant C in animal manure, which has undergone the composting process. The Walkley-Black method generally oxidises easily oxidisable C. Further research found that the recovery

of charcoal C was very low (45%) by the Walkley-Black method. Sometimes, charcoal is generated by burning on-farm residues such as straw, leaves and twigs of crops and weeds, then incorporated into cattle manure during the making of FYM by farmers in Myanmar. It would seem reasonable therefore, that some charcoal could be present in FYM (Kerven *et al.*, 2000; Skjemstad and Taylor, 1999).

The results in Figure 4.5, however, indicate that the presence of a given amount of FYM incubated with soil had no influence on the recovery of C by the Walkley-Black method. Thus it is unlikely that presence of charcoal creates the low recovery, when FYM is oxidised by the Walkley-Black procedure. It remains unclear why FYM alone is incompletely oxidised by the Walkley-Black method. Three main sources of error can arise during the chromic acid digestion of the Walkley-Black method: (1) interfering inorganic constituents i.e. reducing agents, (2) sample induced differences in digestion conditions and reagent composition, and (3) from the variable composition of the organic matter itself (Bluehen, 2001).

The results from this study showed that the recovery of C using the Walkley-Black method varied with soil type (61 to 93%), with organic inputs (65 to 91%), in the dry mixed soils with organic inputs (85 to 96%), and the short-term incubated soils with organic inputs (74 to 94%). Thus a single recovery factor of 77%, giving a Walkley-Black correction factor of 1.3 may not be suitable to convert “easily oxidizable organic C” to total organic carbon in all cases.

The LOI method gives complete oxidation of organic C where as the Walkley-Black method only partially oxidises organic C, but the LOI method usually overestimates the amount of organic matter present in soils and organic materials, organic manures in particular (see Figures 4.3 and 4.8). The main weight loss in soils is due to the destruction of organic matter, further weight losses also occur due to loss of elemental C, and structural water from clay minerals (Ball, 1964; Goldin, 1987). Another positive error is due to the loss of H<sub>2</sub>O from hydroxyl groups in sequioxides.

The regression equations derived between Leco C and LOI, and Walkley-Black C and LOI would generate significant error in predicting the C content of the soils containing

low OM (Yellow Earths) (Figures 4.3 and 4.4). Loss on ignition appears to be a method better suited to determine the OM content of manures that contain large amounts of organic C (Figure 4.8).

### ***Common relationships for soils and soils incubated with organic materials***

The intercepts of the linear relationships between Leco C and Walkley-Black C presented for soils, incubated soils and organic materials (Figures 4.2, 4.6 and 4.7) were not significant. The slopes of the two relationships were also not significantly different.

The slopes of the relationship for the organic materials or dry mixed soils with organic inputs (Figure 4.5) were however significantly different from each other and the slope for soils alone ( $P < 0.01$ ). These results indicate that a common correction factor may not be suitable for organic materials alone, but that a common relationship may be suited for the determination of C for the soils and soil after short-term incorporation with organic inputs in these soils. The most appropriate Walkley-Black conversion factor for expressing the result as total C in these Red Earths and Yellow Earths with or without incubation with organic materials would be 1.29 (see Figure 4.10). This correction factor (1.29) is very closed to that reported (1.3) by Walkley and Black (1934).

In conclusion, for studies measuring the change in SOM over time in particular soil types, it would be better to report Walkley-Black results as “Walkley-Black C” rather than as total C using a correction factor. Nevertheless, in the absence of Leco combustion equipment, the Walkley-Black method will provide an adequate estimate of total organic C in these soils using a correction factor of 1.29.

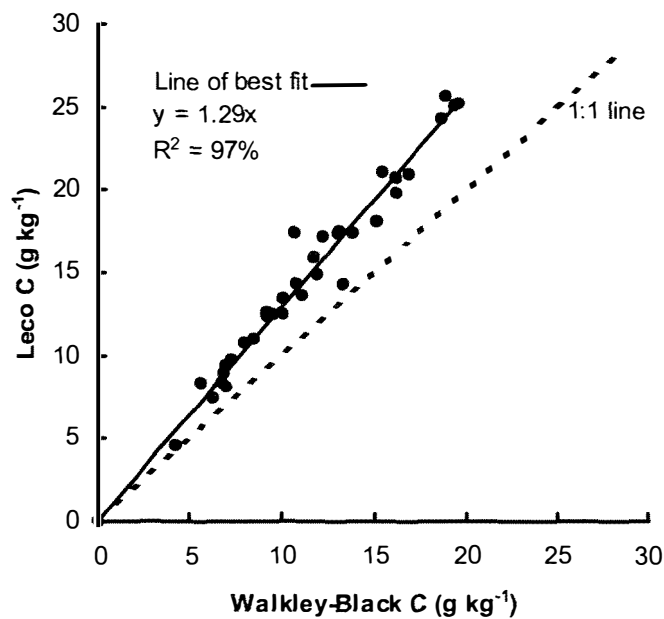


Figure 4.10 The relationship between determined C by Leco C and Walkley-Black C from 36 samples including incubated and initial soils.

## 4.6 Part 2. Use of the Walkley-Black method to measure changes in soil C after amendment of soil with organic materials

### 4.6.1 Results

#### *Initial soils*

The initial soil C contents in Red Earth samples were in general higher than in Yellow Earth samples. Within each soil type, uncultivated (xxUN) soil samples had a higher soil C content than cultivated (xxCU) soil samples (Table 4.6). Therefore, both soil type and previous management practice affected the soil organic C content.

#### *Effect of organic amendment*

Incubation of soil with FYM, UPR and PIP increased Walkley-Black C, compared to unamended soils (Figure 4.11). Increases in soil C were different despite similar amounts of C being added in each incubation. The PIP amended soil gave the highest increase in Walkley-Black C. In Figure 4.11, the ranking of Walkley-Black C increase

in soils was (from highest to lowest)  $PIP^a > UPR^b > FYM^c > CON$  at  $P < 0.01$  ( $SE = 0.1$ ,  $LSD = 0.3$ ).

Table 4.6 The effect of incubation (6 months) with or without organic amendments on the Walkley-Black C ( $g\ kg^{-1}$ ) content of Red Earths and Yellow Earths.

Soil type <sup>1</sup>	Soil sample	Initial soil C	After incubation			
			CON	FYM	UPR	PIP
YE	SS0 <sup>c</sup>	11.2	10.2	12.8	16.6	16.9
YEUN I	SS31 <sup>d</sup>	10.1	9.6	12.2	16.6	17.3
YECU II	SS36 <sup>b</sup>	6.9	7.8	10.3	14.8	15.0
YECU II	SS38 <sup>c</sup>	5.7	6.9	8.6	11.3	13.6
RECU I	SS46 <sup>a</sup>	10.8	13.2	16.3	18.6	18.9
RECU II	SS51 <sup>b</sup>	13.1	13.4	16.5	19.1	20.0
REUN II	SS57 <sup>bc</sup>	13.4	13.3	15.7	19.3	19.9
Mean		e	d	c	b	a

Means (in the last row for the main effect of organic material sources and means in the second column for the main effect of soil factor) which have the same letters are not significantly different ( $P < 0.05$ ).  
<sup>1</sup>see Table 2.2 for treatment code.

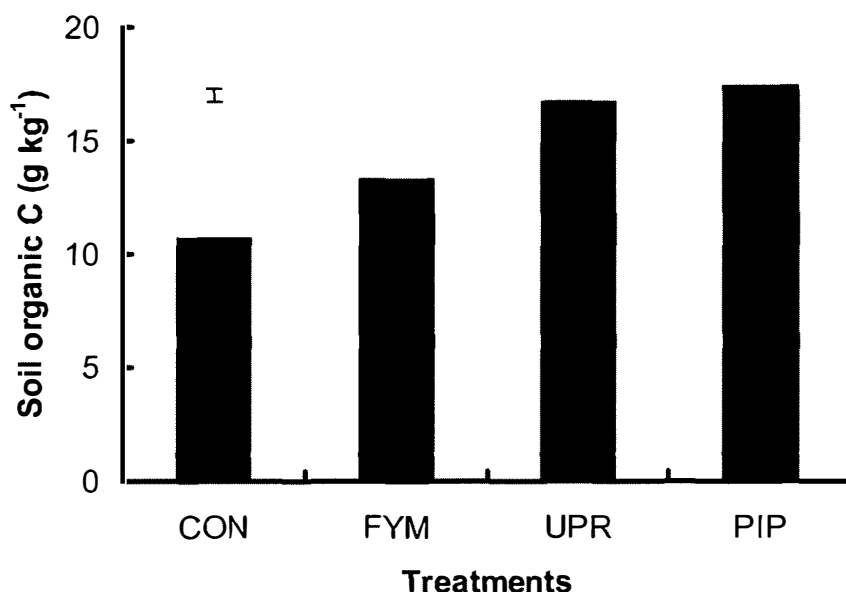


Figure 4.11 Effect of incubating (6 months) organic amendments with Red Earths and Yellow Earths on Walkley-Black C content (Main effect of adding organic amendment across all soils). The bar is the LSD of mean.

At the end of the incubation period, the organic C was determined in incubated control soils (CON) and compared with the initial soil organic C (Walkley-Black) of the given soils (Table 4.6). The organic C (Walkley-Black) decreased in SS0 (9%), SS31 (7%)

and SS57 (1%), however, the soil organic C (Walkley-Black) increased in SS36 (13%), SS38 (21%), SS46 (22%) and SS51 (2.3%) without organic material additions to soils (Table 4.6). An explanation for decrease in soil organic C (Walkley-Black) in incubated soils could be that some labile C (easily oxidisable C) was mineralised and converted to CO<sub>2</sub> (Jenkinson, 1977a and b). On the other hand, the increase in soil organic C (Walkley-Black) in soils could be explained if SOM not initially oxidised by Walkley-Black reagents was rendered oxidisable during the incubation. Alternatively, the presence of Fe<sup>2+</sup> in a Red Earth and Yellow Earth also may be involved in the oxidation reactions with chromate in the Walkley-Black method leading to overestimation of organic C (Bluehen, 2001). Ferrous iron (Fe<sup>2+</sup>) in dry soils is normally oxidised to ferric iron (Fe<sup>3+</sup>) during preparation of the soil sample, which minimises the amount of Fe<sup>2+</sup> present. Thus, after incubation Fe<sup>2+</sup> concentration may have increased resulting in the consumption of dichromate. In studies of SOM dynamics, similarly treated control soils may prove to be more appropriate comparisons with treated soils than initial soil versus treated soil comparisons.

Table 4.7 Recovery (%) of C added as organic amendments, and estimation of respired C (g kg<sup>-1</sup>) at the end of the incubation period in mineral soils with different organic amendments.

Soil sample	Recovery (%) <sup>1</sup> of added C in soils at the end of incubation with:			Estimation of C respired (g kg <sup>-1</sup> ) (Initial soil C + added C - final soil C) in soil amended with:		
	FYM <sup>a</sup>	UPR <sup>b</sup>	PIP <sup>b</sup>	FYM <sup>a</sup>	UPR <sup>b</sup>	PIP <sup>b</sup>
SS0	52.6	69.2	70.0	3.3	3.7	3.8
SS31	49.5	74.7	79.7	3.0	2.8	2.4
SS36	50.5	76.4	75.7	1.6	1.3	1.4
SS38	33.3	46.7	70.0	2.0	3.5	1.5
SS46	61.4	58.3	59.4	-0.4	1.4	1.4
SS51	60.5	61.4	68.7	0.7	2.3	1.7
SS57	48.8	64.7	68.7	1.6	2.3	2.0

<sup>1</sup>Recovery (%) of added C = 100 ((C in amended soil - C in control soil) / added C from organic materials) by Walkley-Black method.

The variation in the recovery of C added as organic amendments to soils, ranged from 33.3 to 61.4% in FYM, 58.3 to 76.4% in UPR, and 59.4 to 79.7% in PIP (Table 4.7). These differences were attributed to the difference in initial oxidisability of organic amendments, and subsequently their extent of microbial decomposition in these soils. An estimation of the amount of amendment C respired by microbial decomposition (Table 4.7) indicates that the amount of respired C was small relative to the amounts of

soil C and amendment C and that large errors are therefore associated with the calculation of respired C.

### *Effect of soil type on changes in soil C*

Soil characteristics also had a significant effect on soil C changes (i.e. initial soil C - final soil C), when soils were incubated with organic amendments although the changes were smaller than for organic amendment (Table 4.8). At the end of the incubation, the greatest increase of soil organic C in soil was found in SS46, a Red Earth, and the smallest increase in soil organic C was measured in SS0, a Yellow Earths. The results suggest that in short-term incubation with organic materials, Red Earths (i.e. SS46, SS51, and SS57) retain more C than Yellow Earths (i.e. SS0, SS31, and SS38).

Table 4.8 Change in soil Walkley-Black C (i.e. final C in soil - initial C in soil) after 6 months incubation with organic materials. (The standard error of the mean is in brackets).

Soil sample and treatment code <sup>1</sup>	Change in soil Walkley-Black C (g kg <sup>-1</sup> mineral soil) after incubation with:			
	CON <sup>d</sup>	FYM <sup>c</sup>	UPR <sup>b</sup>	PIP <sup>a</sup>
SS0 <sup>c</sup> (YE)	-1.0 (0.14)	1.7 (0.17)	5.9 (0.63)	5.5 (0.73)
SS31 <sup>d</sup> (YEUN I)	-0.5 (0.15)	2.0 (0.18)	6.9 (0.63)	6.5 (0.32)
SS36 <sup>b</sup> (YECU II)	0.8 (0.42)	3.4 (0.19)	8.2 (0.09)	8.0 (0.78)
SS38 <sup>c</sup> (YECU I)I	1.3 (0.25)	3.0 (0.31)	8.1 (0.14)	5.7 (0.44)
SS46 <sup>a</sup> (RECU I)	2.4 (0.36)	5.6 (0.43)	8.4 (0.19)	8.0 (0.97)
SS51 <sup>b</sup> (RECU II)	1.3 (0.17)	4.4 (0.62)	8.0 (0.71)	7.1 (0.72)
SS57 <sup>bc</sup> (REUN II)	1.0 (0.54)	3.4 (0.40)	7.7 (1.19)	7.1 (0.58)

<sup>1</sup> code defined in Table 2.2.

### **4.6.2 Discussion**

The C content in soils declines when no organic materials are added (Vitosh *et al.*, 1997), particularly in tropical soils under cultivation (Fernandes and Sanchez, 1990; Shang and Tiessen, 1997).

The Red Earths and Yellow Earths in the present study were very low in organic C and most of the labile C (easily oxidisable C) fraction had already been lost. Thus incubation for 6 months caused a large change in SOM content (Table 4.8, Figure 4.11). Incubation with organic amendments caused SOM to increase in all soils. Residues of upland rice (UPR) and pigeon pea (PIP) caused the greatest increases in oxidisable

SOM after incubation. Farmyard manure caused the smallest increases. This result is partially caused by the poor oxidisability of C in FYM by the Walkley-Black method (see Figure 4.7). This is shown by the fact that when FYM was added to dry soil, only 74% of the total C (Leco determined C) was recovered when measured by the Walkley-Black procedure.

#### 4.7 Part 3. Effect of organic amendments on changes in N and pH in soils

##### 4.7.1 Results

##### *Changes in soil N*

Determinations of total N in soils by Leco auto-analyser and wet digestion (Kjeldahl method) were not significantly different at  $P < 0.05$ . Total N results determined by the Kjeldahl method are presented in Table 4.9. The N in soils can be determined in three forms: nitrate ( $\text{NO}_3^-$ ), ammonium ( $\text{NH}_4^+$ ), and organically bound N (Table 4.9). Most N (>99% of total N) in surface soils is in organic forms and very little N (0.1 to 0.3% of total N) is in inorganic forms ( $\text{NO}_3^-$  and  $\text{NH}_4^+$ ) in air-dry conditions. The concentration of  $\text{NH}_4^+$  was greater than  $\text{NO}_3^-$  in these soils.

Table 4.9 Total N (Kjeldahl-N), organic N and mineral N content of air-dried Red Earth and Yellow Earth samples. (The standard error of the mean is in brackets).

Soil type	Soil sample	Total N (mg kg <sup>-1</sup> )	Forms of N (mg kg <sup>-1</sup> )		
			Organic N*	$\text{NH}_4^+$	$\text{NO}_3^-$
YE	SS0	1497 (253)	1495	1.37	0.71
YEUN I	SS31	1365 (154)	1363	1.16	0.71
YECU II	SS36	870 (127)	868	0.96	0.71
YECU II	SS38	820 (113)	818	1.37	0.71
RECU I	SS46	1747 (194)	1745	0.96	0.86
RECU II	SS51	2060 (325)	2058	1.37	0.71
REUN II	SS57	1628 (195)	1626	1.37	0.86

\*Organic N calculated by difference total N - ( $\text{NH}_4^+$  +  $\text{NO}_3^-$ ).

Total soil N (Kjeldahl) and soil organic C (Walkley-Black) were closely related in these soils ( $P < 0.05$ , Figure 4.12). Total C or organic matter content can be used as an index of total N content in these soils. The usual C:N ratio used for the conversion is between 10:1 and 12:1 (Stevenson and Cole, 1999). For the soils used in this study, the C:N ratio

(Walkley-Black C:Kjeldahl N) was between 6:1 and 8:1. However, using the correction factor for Walkley-Black C (1.29), the C:N ratio increased to between 8:1 and 10:1 (Figure 4.12).

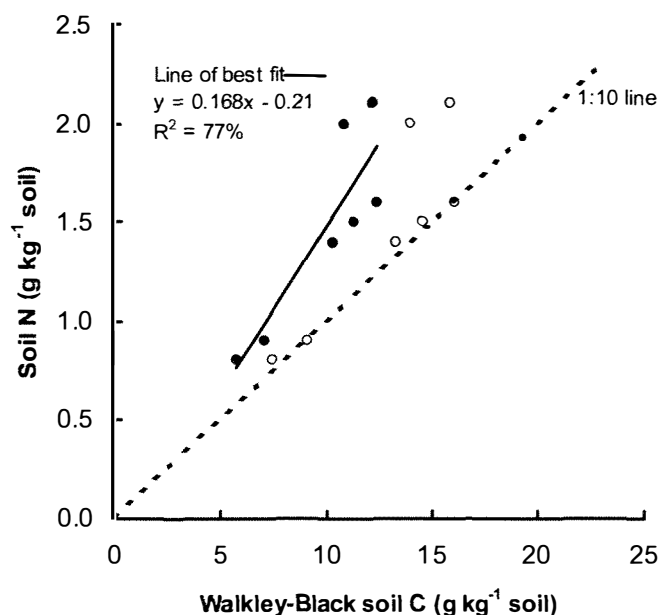


Figure 4.12 The relationship between soil organic C (● Walkley-Black) and soil N (Kjeldahl) in Red Earths and Yellow Earths (○ Walkley-Black values  $\times$  1.29 correction factor).

The incubation of soils alone caused little net change in the total N present in the soil (Table 4.10). The incorporation and incubation of organic materials with soils increased the total N content of soils in the current study (Table 4.10). As expected the largest increases were caused by the addition of organic materials with a high N content (i.e. PIP and FYM).

The incorporation of organic materials into soil influences the various mineral N dynamics in soils. For example, plant residues with a C:N ratio  $>30$  cause net mineral N immobilisation, and plant residues with a C:N ratio  $<24$  induce a release of mineral N (Trinsoutrot *et al.*, 2000). Therefore, the low C:N ratios of the organic amendments used in this study (Table 4.4) probably caused net N mineralisation. Also the C:N ratio of the residues (calculated as Walkley-Black C: Kjeldahl N) remaining in the incubated soil were also narrow (8:1 to 11:1) (Table 4.10) suggesting that N would be readily mineralised for plant growth. However, this may not always be the case. A study by

Aulakh *et al.* (2000) found that an accumulation of mineral N and the subsequent mineralisation of organic manures in upland soils was directly related to the N content of the manure and not inversely related the C:N ratio. The N concentration, plus the C:N ratio of the organic materials may be necessary to indicate the net effect of organic amendments on soil mineral N dynamics.

Table 4.10 Change in total soil N (i.e. final soil N - initial soil N) after 6 months incubation with organic materials, and the C:N ratio in the incubated soil.

Soil code and soil sample	Change in soil N (mg kg <sup>-1</sup> mineral soil) after incubation with:							
	CON <sup>d</sup>	(C:N) <sup>l</sup>	FYM <sup>a</sup>	(C:N) <sup>l</sup>	UPR <sup>c</sup>	(C:N) <sup>l</sup>	PIP <sup>b</sup>	(C:N) <sup>l</sup>
YEUN I (SS31)	-70	(8:1)	450	(9:1)	80	(10:1)	350	(11:1)
YECU II (SS38)	-50	(9:1)	550	(8:1)	190	(8:1)	410	(11:1)
RECU II (SS51)	20	(8:1)	710	(9:1)	270	(8:1)	630	(9:1)
REUN II (SS57)	-80	(8:1)	750	(8:1)	190	(8:1)	510	(9:1)

<sup>l</sup> C:N = Walkley-Black C: Kjeldahl N.

The ranking of increase in total soil N (from highest to lowest changes) with organic amendment was RECU II<sup>a</sup>>REUN II<sup>b</sup>>YECU II<sup>c</sup>>YEUN I<sup>d</sup> (means with the same letter are not significantly different at P<0.05). These results show that for a short-term incubation with organic materials, Red Earths (i.e. RECU II and REUN II) retained a higher total N status than Yellow Earths (i.e. YEUN I, and YECU II) due to the higher organic matter and higher total P status of Red Earths. The increase in total N in these soils was not significantly affected by soil pH and available P.

### ***Changes of soil pH***

Irrespective of soil type, the pH of control soils decreased at the end of the incubation period, compared with the initial pH of these soils (P<0.01, Table 4.11). The main reason for the soil pH decrease would be the mineralisation of major organic nutrients, particularly organic N, in soils during the aerobic incubation of soils. The pH decrease is probably caused by acid (H<sup>+</sup>) generated in soils by the oxidation of organic N to nitrate, and to a lesser extent, organic S to sulphate, during organic amendment decomposition.

Compared to the incubated unamended control soils, the soil pH of organically amended soils significantly increased (Table 4.11). In the organic amended soils, the amount of

$H^+$  consumed was greater than the amount of  $H^+$  released, resulting in a negative balance in the  $H^+$  budget. The PIP amendment, with its higher N content, caused the pH of the incubated soil to rise above that of the initial soil sample. Presumably, this is a direct result of greater ammonification than nitrification plus the respiration of organic matter with high ash alkalinity (see Table 4.4). These results support the view that organic material can have a liming effect, and this effect will be greatest with materials that have high ash alkalinity (Hue, 1992; Iyamuremye *et al.*, 1996a; Cong, 2000). The decarboxylation of organic anions balancing the mineral cation excess (total cations exceeds total anions) of the organic material will contribute the liming effect during decomposition (Tang and Yu, 1999). This hypothesis explains the long-term beneficial effect of organic amendments increasing soil pH (Olsen *et al.*, 1970; Vitosh *et al.*, 1997), which should be considered in acid upland soils. Farmyard manure and UPR materials with lower ash alkalinities had much smaller effects on soil pH (Figure 4.13, Table 4.11).

The decreases in pH of soils during incubation and the increases in pH on Yellow Earths after incubation with PIP were greater than on Red Earths (Table 4.11). This may indicate weaker pH buffering on Yellow Earths.

Table 4.11 The effect of organic amendments on soil pH of Red Earths and Yellow Earths under different management systems, after 6 months incubation.

Soil code	Soil sample	Initial pH <sup>b</sup>	Control <sup>c</sup>	FYM <sup>c</sup>	Upland rice <sup>d</sup>	Pigeonpea <sup>a</sup>
YE	SS0 <sup>e</sup>	4.91	4.64	4.77	4.63	5.26
YEUN I	SS31 <sup>f</sup>	5.20	4.41	4.56	4.50	5.22
YECU II	SS36 <sup>d</sup>	5.64	4.80	5.08	4.78	5.80
YECU II	SS38 <sup>b</sup>	6.53	5.97	6.22	6.22	6.63
RECU I	SS46 <sup>a</sup>	6.55	6.36	6.45	6.48	6.66
RECU II	SS51 <sup>c</sup>	6.13	6.20	6.14	6.16	6.35
REUN II	SS57 <sup>b</sup>	6.25	6.23	6.23	6.22	6.48

Means with the same letter are not significantly different ( $P < 0.01$ ).

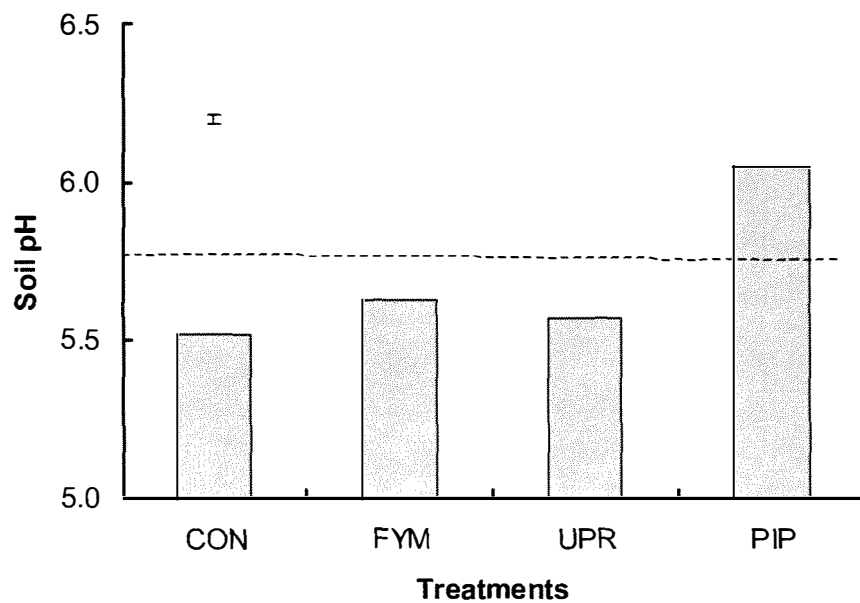


Figure 4.13 The effect of organic amendments on the pH (1:2.5 in water) of Red Earths and Yellow Earths at the end of the incubation period (The error bar is the LSD for main effect on soil means,  $\alpha=0.05$ ).

#### 4.7.2 Discussion

Addition of 396 to 490 mg kg<sup>-1</sup> soil of N as organic materials to Red Earths and Yellow Earths resulted in 48 to 100% of this N being retained in SOM. Therefore marked increases in soil N were achieved in Red Earths despite the fact that small losses of N through denitrification can be expected when soils are incubated in a moist condition, particularly with manures (Mahimairaja *et al.*, 1995ab). The addition and decomposition of the organic materials with a narrow C:N ratio (FYM) decreased the SOM.

Both organic amendment and soil type were factors affecting the pH changes in the soil when organic materials were incubated with soils. Thus van Breemen (1991) and van Breemen *et al.* (1983) stated the extent and cause of acidification or alkalization in soil varies considerably from ecosystem to ecosystem, but may be quantified for a given ecosystem by developing a proton (H<sup>+</sup>) budget. The chemical form and decomposition rate of plant materials are the most important processes determining the changes in pH (proton budget) of a soil amended with organic residues in the absence of plants (i.e. manures brought onto fallow land).

The results reported in this chapter illustrate that the addition of organic amendments does not necessarily cause soil acidification. Selection of additional organic amendments (brought in) with high ash alkalinity can be a management tool for correcting soil acidity.

## 4.8 Part 4. Effect of organic amendments on soil P fractions

### 4.8.1 Results

#### *Effect of amendments*

Short-term incubation of Red Earths and Yellow Earths with any organic amendment significantly increased total soil P and the P present in Resin-Pi, 0.1 M NaOH-Pi, 1 M NaOH-Po and Residual-Pi fractions (Table 4.12).

Table 4.12 The main effect of incubation with and without of organic amendments on P fractions ( $\mu\text{g P g}^{-1}$  soil) in Red Earths and Yellow Earths after a short-term (6 months) incubation.

Treat-ment	Resin-Pi	0.1 M NaOH-Pi	0.1 M NaOH-Po	1 M NaOH-Pi	1 M NaOH-Po	0.5 M H <sub>2</sub> SO <sub>4</sub> -Pi	Residua l-Pi	Total-P
FYM	32.4a	145.6a	79.5b	66.7bc	63.5a	49.8ab	111.6a	549.1a
UPR	22.3b	89.8b	69.0b	70.1ab	52.8b	52.7a	95.2b	451.6b
PIP	22.1b	94.6b	74.8b	62.3c	54.3b	25.3c	112.3a	448.8b
CON	17.2c	47.3c	97.0a	72.6a	37.5c	47.8b	87.4c	406.8c
LSD	1.9	8.4	10.9	5.2	5.3	3.2	5.2	5.0
SE	0.7	3.0	3.8	1.9	1.9	1.1	1.8	1.8

Means follow by the same letter within a column are not significantly different (*T* test,  $P < 0.05$ ).

See Table 4.5 for treatment code.

Across all soils, the largest increases in total P, and the more labile resin-Pi and 0.1 M NaOH-Pi fractions were caused by incubation with FYM (Table 4.12). This is consistent with FYM having the highest P content of all the manures (Table 4.4). Upland rice and PIP produced smaller but similar changes to total P and the resin-Pi and 0.1 M NaOH-Pi fractions (Table 4.12).

*Resin-Pi*

Figure 4.14 shows that the input of organic manures caused a large increase in labile resin-Pi in Yellow Earths with low initial resin values and low P retention values (Table 4.3). Increases were lower in Red Earths and the Yellow Earth with higher initial resin-Pi values and higher P retention values (Table 4.3). The small increase in labile-Pi in Red Earths indicates that more Pi may be fixed on soil surface and or within soil aggregates, in Red Earths compared with Yellow Earths.

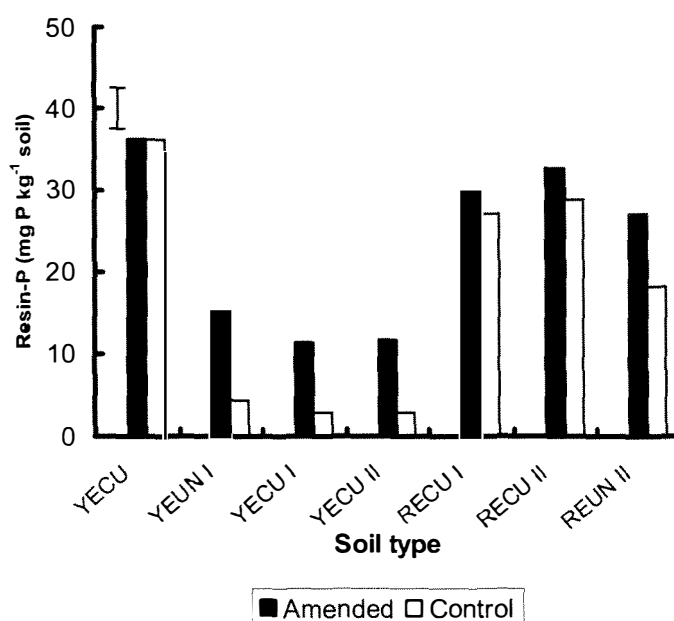


Figure 4.14 The amount of resin-Pi in Red Earths and Yellow Earths incubated alone (CON) or with organic amendment (See Table 4.5). The error bar is the LSD ( $\alpha=0.05$ ) between the soil means.

*0.1 M NaOH-Pi*

No consistent pattern emerged for the 0.1 M NaOH-Pi content of unamended (Control), cultivated and uncultivated Red Earths and Yellow Earths.

The addition of organic manures to the Red Earths and Yellow Earths caused increases of 26 to 64 mg P kg<sup>-1</sup> soil in the 0.1 M NaOH-Pi fraction of all soils (Figure 4.15 a). The percentage increase in 0.1 M NaOH-Pi in the Red Earths (52 to 68%) was greater than in the Yellow Earths (30 to 47%). This suggests that the reason for the lower resin P

values in the Red Earths is because P in the soil solution was absorbed to sesquioxide surfaces, i.e. solution P had moved into the 0.1 M NaOH-Pi fraction in the Fe-rich Red Earths.

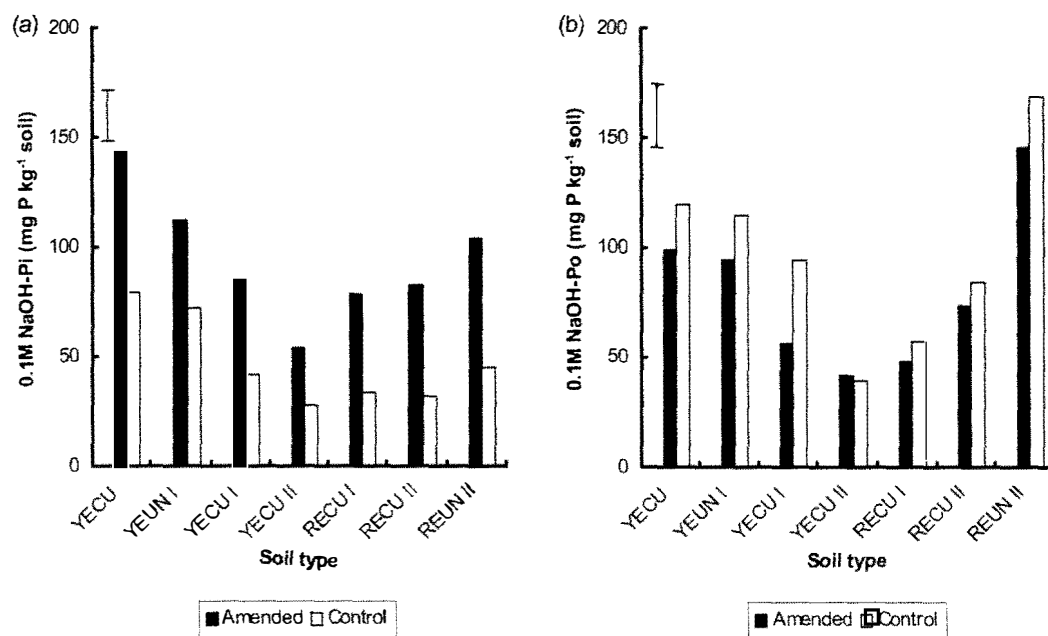


Figure 4.15 (a) The amount of 0.1 M NaOH-Pi and (b) the amount of 0.1 M NaOH-Po, in Red Earths and Yellow Earths incubated alone (CON) or with an organic amendment (See Table 4.5). The error bar is the LSD ( $\alpha=0.05$ ) between the soil means.

### 0.1 M NaOH-Po

The uncultivated Red Earth (REUN II) contained more 0.1 M NaOH-Po than the cultivated Red Earths. This trend was less apparent with the Yellow Earths (Figure 4.15 b). Incubation of all soils with organic amendments caused the amount of 0.1 M NaOH-Po to decline in all soils, except YECU II. This result suggests that either Po in the amendments is not soluble in weak alkali or that decomposition of the Po in the organic amendments has been almost complete leaving very little Po extractable in dilute alkali.

### 1 M NaOH-Pi

The uncultivated Red Earth (REUN II) contained more 1 M NaOH extractable Pi than cultivated Red Earth. Little difference in 1 M NaOH-Pi due to cultivation was evident in the Yellow Earths. Unlike 0.1 M NaOH-Pi, the amount of 1 M NaOH-Pi increased significantly only when amendments were incubated with Red Earths (Figure 4.16 a). This contrast may result from the higher P retention characteristics of the Red Earths than Yellow Earths.

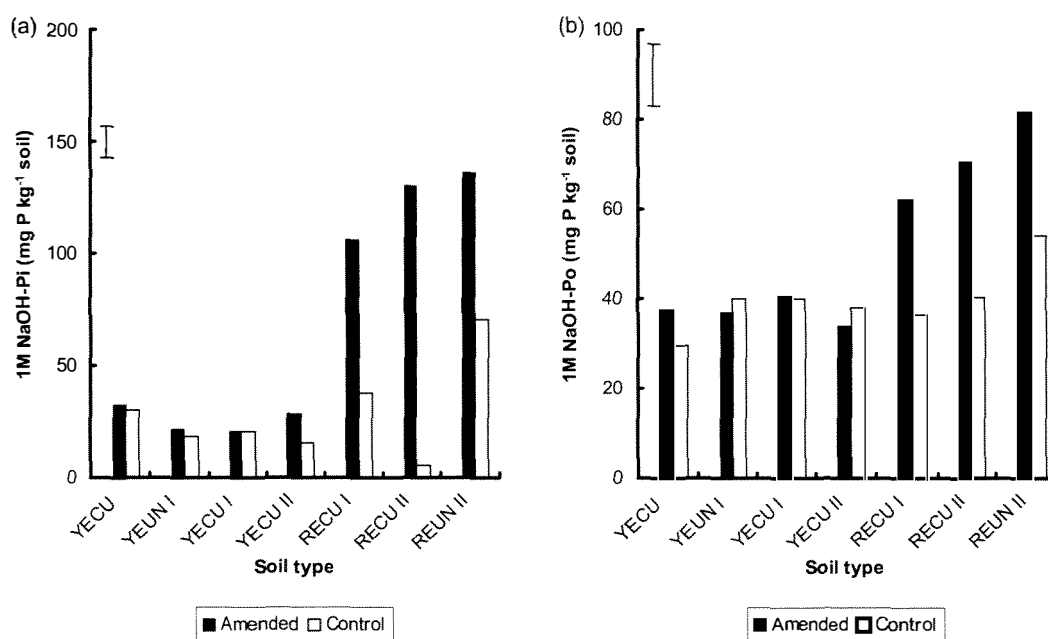


Figure 4.16 (a) The amount of 1 M NaOH-Pi, (b) the amount of 1 M NaOH-Po, in Red Earths and Yellow Earths incubated alone (CON) or with an organic amendment (See Table 4.5). The error bar is the LSD ( $\alpha=0.05$ ) between the soil means.

### 1 M NaOH-Po

Again the amounts of 1 M NaOH-Po were greatest in the uncultivated Red Earth (Figure 4.16 b). The lack of Po accumulation in the 1 M NaOH-Po fraction of Yellow Earths suggests that either amendment Po decomposition is complete in these soils or that the amendments contained little 1 M NaOH extractable Po. In contrast, amendment Po decomposition in Red Earths may produce a Po fraction soluble in strong alkali.

### 0.5 M H<sub>2</sub>SO<sub>4</sub>-Pi

The origins of this Pi are likely to be fertiliser residues and Pi occluded in hydrous oxides of Fe and their complexes with SOM. Notably, Red Earths contained markedly greater amounts of 0.5 M H<sub>2</sub>SO<sub>4</sub>-Pi than Yellow Earths (Figure 4.17) probably due to their higher Fe content (see Section 2.4.5, Chapter 2). Changes in the 0.5 M H<sub>2</sub>SO<sub>4</sub>-Pi fraction after incubation with OM amendments were not consistent across soils. Some of the larger increases in the 1 M NaOH-Pi fraction and decreases in the 0.5 M H<sub>2</sub>SO<sub>4</sub>-Pi may result from differences in P fractionation between batches of extraction.

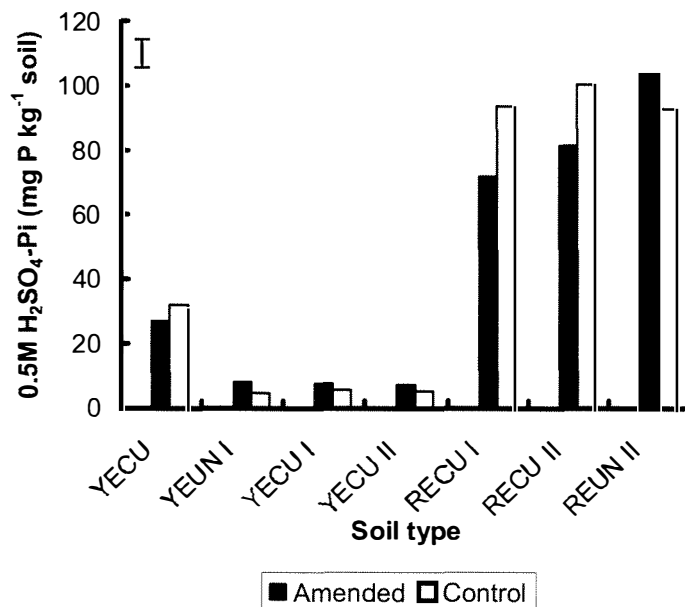


Figure 4.17 The amount of 0.5 M H<sub>2</sub>SO<sub>4</sub>-Pi in Red Earths and Yellow Earths incubated alone (CON) or with organic amendment (See Table 4.5). The error bar is the LSD ( $\alpha=0.05$ ) between the soil means.

### Residual-P

The residual-P concentration was generally higher in Red Earths than Yellow Earths (Figure 4.18). This is consistent with Red Earths containing more P in the less easily extracted 1 M NaOH-Pi, 1 M NaOH-P<sub>o</sub>, and 0.5 M H<sub>2</sub>SO<sub>4</sub>-Pi forms. Notably, OM amendments increased the residual-P component in each soil. Therefore the amount of the residual-P in soils also reflects the insoluble organic P forms in undecomposed plant

and animal residues as well as the amount and stage of decomposition of organic residues.

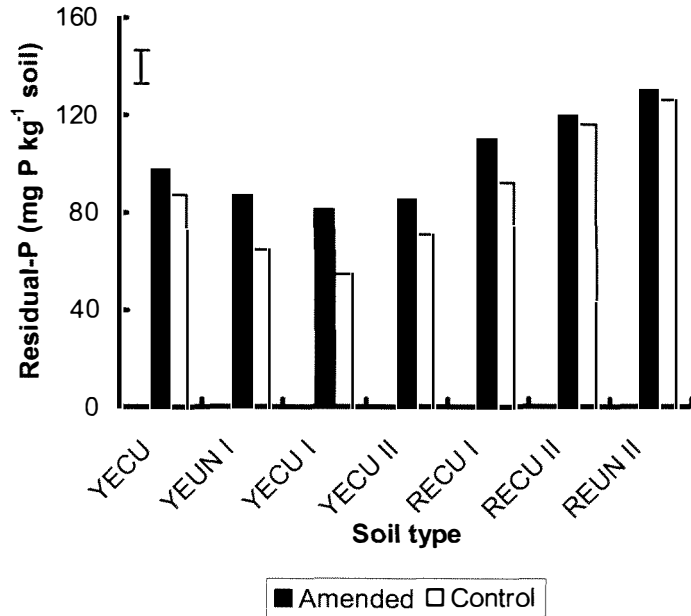


Figure 4.18 The amount of residual-P in Red Earths and Yellow Earths incubated alone (CON) or with organic amendment (See Table 4.5). The error bar is the LSD ( $\alpha=0.05$ ) between the soil means.

### *Total P*

The initial total P content in surface soils (0-15 cm) from southern Shan State is shown in Table 4.3. The Red Earths contained more total P than Yellow Earths (Figure 4.19). The highest amount of total P was found in the uncultivated Red Earth (680 mg P kg<sup>-1</sup>, REUN II) and the lowest amount of P was found in the cultivated Yellow Earth (205 mg P kg<sup>-1</sup>, YECU II). The difference in soil total-P could be due to different soil type and cultivation and management: long-time fallowed or non-cultivated soils tend to have a high P content, compared with short time fallow or continuously cultivated soils.

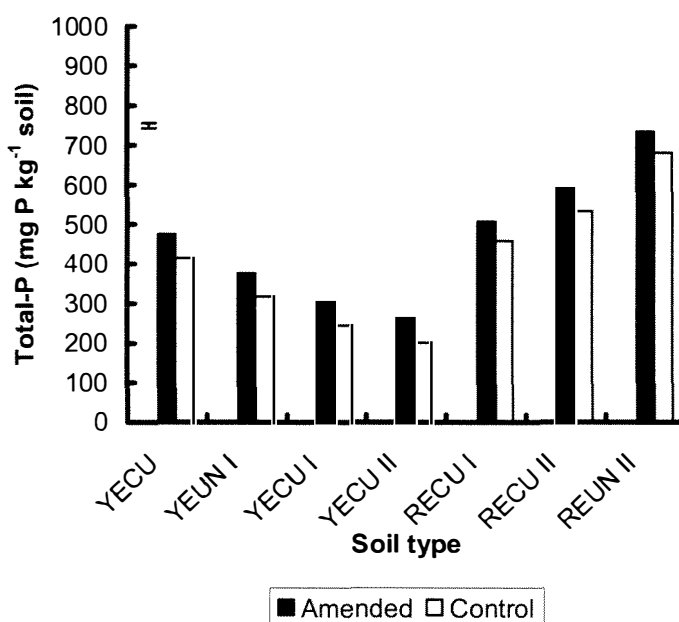


Figure 4.19 The amount of total-P in Red Earths and Yellow Earths incubated alone (CON) or with organic amendment (See Table 4.5). The error bar is the LSD ( $\alpha=0.05$ ) between the soil means.

At the end of the short-term incubation, the OM amendments significantly increased the total P content of these Red Earths and Yellow Earths (Table 4.12).

#### *Labile-Pi*

In order to examine the fate of the organic amendment P in these soils, the labile forms of Pi (resin + 0.1 M NaOH) have been summed. The main effect of organic amendment source on the labile-Pi fraction of the Red Earths and Yellow Earths are presented in Figure 4.20a.

The labile-Pi in these soils was significantly affected by the source of organic amendment ( $P<0.01$ ). The greatest amount of change in labile-Pi, expressed as % P added occurred in FYM treated soils (64% of added P). A similar percentage change in labile-Pi was found in PIP (45% of added P) and UPR (43% of added P) treated soils. The ranking, in ascending order was,  $FYM > UPR \geq PIP > CON$  (Figure 4.20a). The greater increase in labile-Pi with FYM is consistent with the higher P content of FYM (Table 4.4).

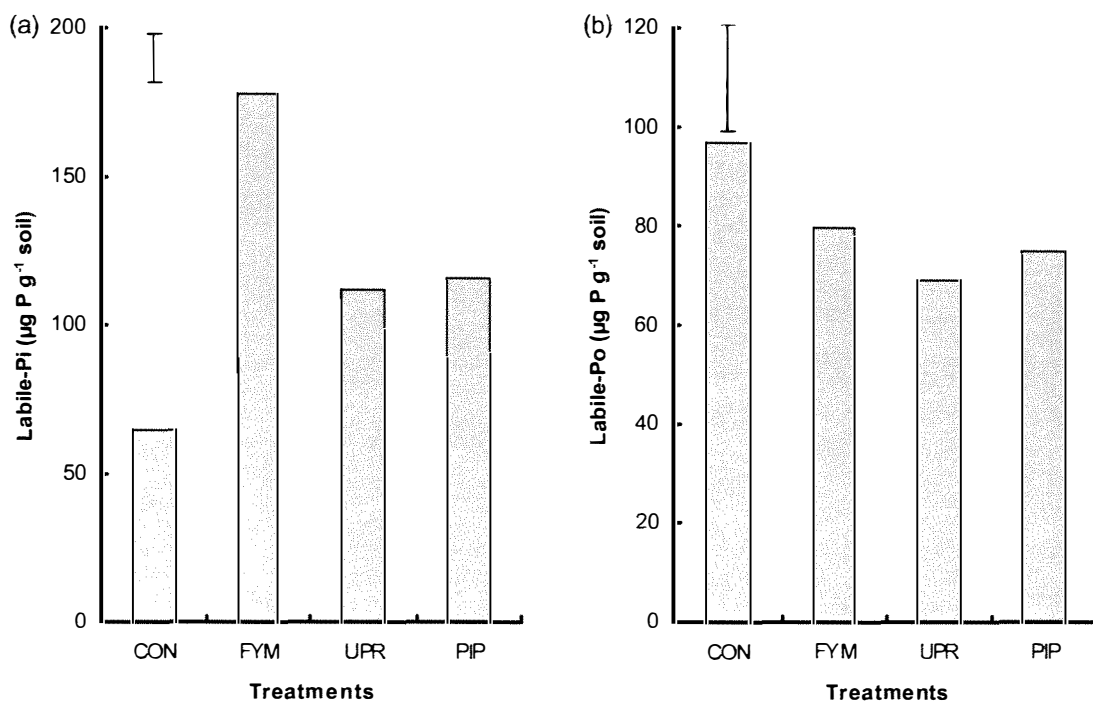


Figure 4.20 (a) The amount of labile-Pi (resin-Pi + 0.1 M NaOH-Pi) (b) The amount of labile-Po in Red Earths and Yellow Earths incubated with and without (CON) organic amendment (means of all soils). The error bar is the LSD ( $\alpha=0.05$ ) between the soil means. See Table 4.5 for treatment code.

### *Labile-Po*

Despite adding OM amendments to soils labile-Po decreased with incubation (Figure 4.20b). Thus, there is either little labile-Po in the OM amendments, or more likely, decomposition of the OM amendments has resulted in the creation of labile-Pi and less easily extracted Po (1 M NaOH-Po and residual Po) (Hedley *et al.*, 1982a).

The labile Po fraction can be transformed to the labile Pi fraction in soils. This means that labile Po may release available P for plants by mineralisation and this may be affected by soil type or type of organic matter. Regardless of soil type, a significant decrease ( $P>0.05$ , Figure 4.21b) in labile-Po was observed in all soils incubated with organic amendments compared with soil incubation alone. There was no significant ( $\alpha = 0.05$ ) soil type by OM interaction in these soils.

## Effect of soils

### Labile-Pi

The soil type significantly controlled the amount of labile-Pi (Figure 4.21 a). There was a greater variation in the increase in labile-Pi concentration (35 to 65 mg P kg<sup>-1</sup> soil) in Yellow Earths than in Red Earths (48 to 68 mg P kg<sup>-1</sup> soil). In general, the increase in labile-Pi was similar in the Yellow Earths compared to the Red Earths. This result indicates that greater increase in labile-Pi can be expected in low labile-Pi soils compared to the higher labile-Pi soils when organic amendments are added to Red Earths and Yellow Earths.

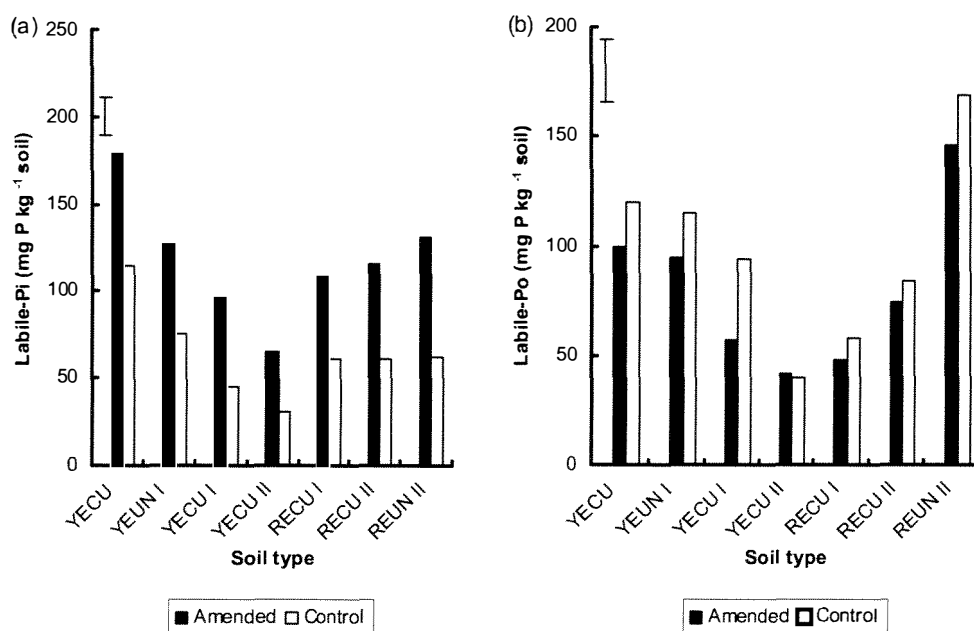


Figure 4.21 (a) The amount of labile-Pi (resin-Pi + 0.1 M NaOH-Pi) (b) The amount of labile-Po in Red Earths and Yellow Earths incubated alone (CON) or with organic amendment (See Table 4.5). The error bar is the LSD ( $\alpha=0.05$ ) between the soil means.

### Labile-Po

Figure 4.21b shows that the labile-Po in the Red and Yellow soils significantly decreased after incubation with organic amendments ( $P<0.05$ ). There was a greater decrease in the labile-Po in Yellow Earths (20 to 37 mg P kg<sup>-1</sup> soil) than in Red Earths

(10 to 23 mg P kg<sup>-1</sup> soil). This result suggests that Red Earths can retain labile-P<sub>o</sub> compared to Yellow Earths. The reason could be that Red Earths had higher organic matter status and P fixation capacity (see Table 4.3) than Yellow Earths.

#### **4.8.2 Discussion**

The short-term incubation of Red Earths and Yellow Earths with organic amendments produced a significant increase in total P over the control treatment. The major findings were that the largest increase in total P occurs in the more plant-available P fractions (resin-P<sub>i</sub> and 0.1 M NaOH-P<sub>i</sub>), and OM with high P content, such as FYM, did not release more labile-P<sub>i</sub> (Figure 4.22). However, incubation of OM amendments with these soils does not increase the labile-P<sub>o</sub> fraction, which appears to be readily mineralised to labile-P<sub>i</sub> in these Red Earths and Yellow Earths. There is no difference in the amount of decrease in 0.1 M NaOH-P<sub>o</sub> between cultivated and uncultivated soils (see Figure 4.21b).

Soil P retention characteristics significantly affected the release of labile-P<sub>i</sub> from Red Earths and Yellow Earths. In general increases in labile-P<sub>i</sub>, particularly resin-P, after incubation with OM amendments were greater in the Yellow Earths, which had a lower P fixation. Less of an increase in labile-P<sub>i</sub> can be expected in soils with higher P fixation (i.e. Red Earths). The reason is that more P<sub>i</sub> may be fixed on the soil surface and/or within soil aggregates in high P fixating soils compared with low P fixating soils.

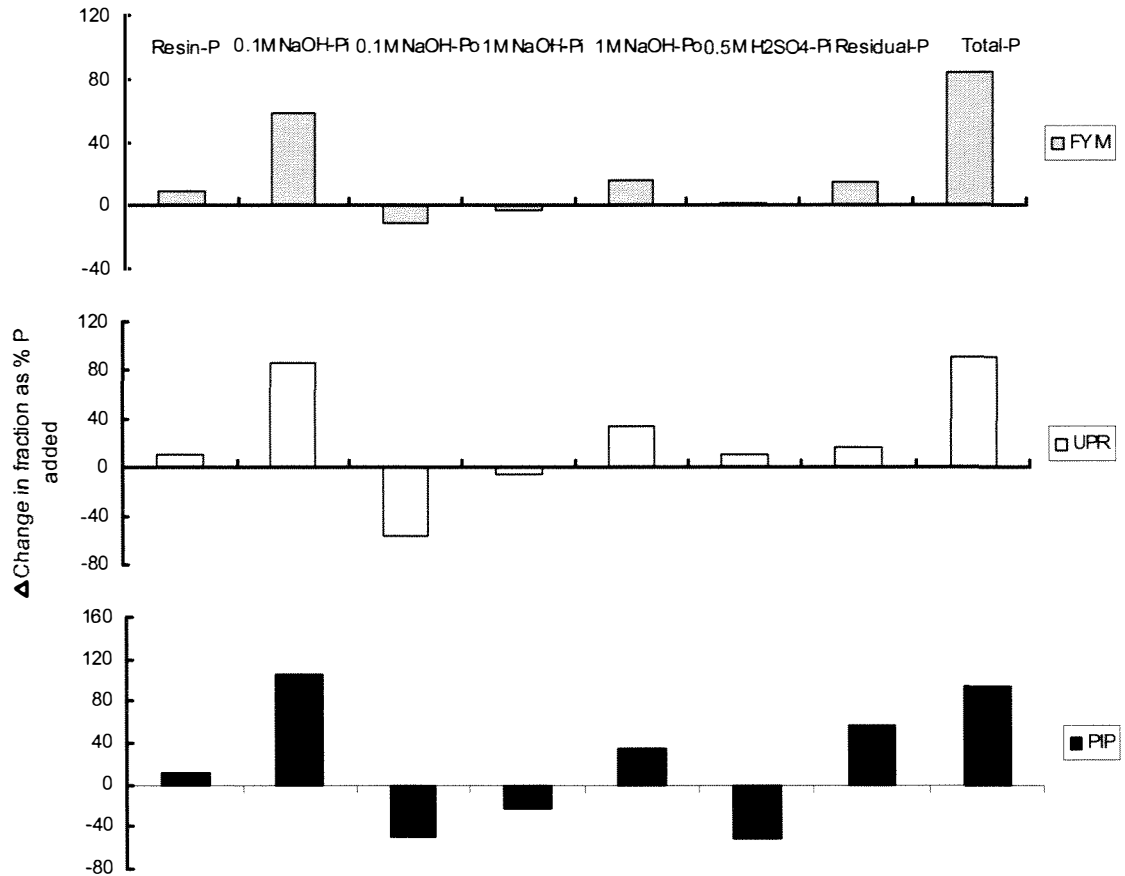


Figure 4.22 The amount of change in P fraction as % P added in Red Earths and Yellow Earths incubated with and without (CON) organic amendment (means of all soils). See Table 4.5 for treatment code.

## 4.9 Conclusions

### *Part 1*

The Walkley-Black method is adequate for the determination of organic C in the Red Earths and Yellow Earths with a common correction factor of 1.29, although for all soils and organic manures in situations where Leco combustion equipment is absent, it would be better to report Walkley-Black results as 'Walkley-Black C', particularly in studies following the SOM dynamics over time. This is because soil type does affect the correction factor, particularly in the lower OM content soils.

**Part 2**

Incorporating organic inputs such as FYM, UPR and PIP into the Red Earths and Yellow Earths at 37 t DM ha<sup>-1</sup> significantly increased the soil organic C content, particularly in the Red and Yellow soils with very low OM.

**Part 3**

Soil amended with organic materials markedly reduced the decrease in pH in soils in the short-term incubation. This effect was greater with pigeon pea (legume) residues, which had a high ash alkalinity. Thus, organic residues may partly substitute for conventional liming amendments. They could be used in ameliorating the adverse effects of acid soils on P availability by increasing pH and reducing the P sorption capacity of acid soils. However, correction of acidity in soils by adding highly ash alkalinity plant residues may not be suitable for long-term consideration in highly weathered soils, because during the growth phase these plants will acidify the rhizosphere soil through proton release from their roots (see Chapter 5).

The addition and incubation of organic materials with the Red Earths and Yellow Earths raised the soil total N content. The results indicate that the addition of organic materials with a high N content or narrow C:N ratio give the largest increase in total N in these soils.

**Part 4**

Amending with organic residues significantly increased the total P content of these Red Earths and Yellow Earths in this short-term incubation study. The results suggest that addition of organic amendments with a high P content can cause the greatest increase in total P in the soils.

The main effect of organic amendment P in the Red and Yellow soils is on labile P forms (i.e. Resin-Pi plus 0.1 M NaOH-Pi). The labile Pi in these soils can be raised by application of organic amendments that have a high P content. However, labile-Po

forms (a natural form of slow release P) do not increase significantly with the addition of organic amendments in these soils, presumably due to the rapid mineralisation of  $P_o$  to readily plant-available  $P_i$ .

The P concentration of the organic amendment markedly affected P fractions in the Red Earths and Yellow Earths, particularly the increase in readily-available  $P_i$ . This result showed that the source of organic amendment is very important in increasing the labile  $P_i$  in these soils.

In addition, soil P retention influenced the fate of organic amendment P. There was negative relationship between the percent P retention and increases in resin- $P_i$ . Thus lower P retaining soils can be expected to cause greater increases in readily-available P after being amended with organic material in these Red and Yellow soils.

## **CHAPTER 5    Plant-induced Changes to Rhizosphere Soil by Seven Sub-tropical Legume Species Grown in Low pH Red Earth**

### **5.1    Introduction**

In Myanmar, legumes are extensively used for food, fodder, shade, fuel wood, cover crops and/or green manure in different farming systems. Important legumes grown in Myanmar are described in the next section. The use of legumes in farming systems can increase N fertility of the soil and provide a direct economic return to the farmer in this developing region. The opportunities for growing legumes are greatest for the successful exploitation of N fixation because these Red Earths and Yellow Earths are particularly low in N (Peoples and Craswell, 1992). The contribution of legumes to sustainable agricultural systems, depends not only on how much N is fixed, but also how much N is removed at harvest. One disadvantage is that the establishment and improvement of legumes (e.g. legume-based pastures) has also been associated with accelerated soil acidification (Williams, 1980; Ridley *et al.*, 1990; Tang *et al.*, 1997). In some cases in Australia, soil acidification in legume-based farming systems has been reported to be responsible for significant decreases in crop and pasture yields (Coventry and Slattery, 1991). Soil acidification under legume-based farming systems has been attributed to short and long-term imbalances in the C and N cycles (Helyar and Porter, 1989; Bolan and Hedley, 2001).

As mentioned in Chapter 2, the upland Red Earths and Yellow Earths in Southern Shan State are highly leached and intensively weathered and, after clearing and continuous cultivation, soon become low in both total and plant-available nutrients particularly N, P and S. Soil acidity is another common problem in Red Earths and Yellow Earths, and it is usually corrected by using liming materials (see Section 1.8.2, Chapter 1).

The requirement for legume fixed N in these acid soils introduces the possibility that soft reactive phosphates could be used as the fertiliser P source. Such acid soluble

fertiliser may have enhanced dissolution in the legume rhizosphere (Trolove *et al.*, 1996a) and also assist in neutralising bulk soil acidity. No previous investigations have examined the combined role that direct application of RPRs can play in reducing soil acidification (Loganathan *et al.*, 1995) and improving soil P nutrition for plant growth in the Red Earths and Yellow Earths in Myanmar.

Numerous reviews of past investigations show clearly the agronomic value of direct application of RPRs in plant production in tropical and temperate soils (Khasawneh and Doll, 1978; Hammond *et al.*, 1986; Gregg *et al.*, 1989; Bolan *et al.*, 1990a; Bolland *et al.*, 1997; Hedley and Bolan, 1997). Often the agronomic value of directly applied RPR is less than similar rates of P applied as soluble P (Bolland *et al.*, 1997; Hedley and Bolan, 1997). Therefore new procedures should be explored to increase the efficiency of RPR-P use by plants. Improving the efficiency of P utilisation from RPR would assist adoption of RPR for use in the infertile Red Earths and Yellow Earths in Myanmar.

The agronomic effectiveness of RPRs may be influenced by their chemical reactivity, physical form, soil, plant, management and climatic factors (Gregg *et al.*, 1988; Hedley *et al.*, 1995). Based on this information, RPR research involving the root-soil interface has intensified (e.g. Trolove *et al.*, 1996a; Zoysa *et al.*, 1997) with the goal of selecting plants that can acidify their rhizosphere and enhance RPR dissolution. Legumes fall into this category and rhizosphere acidification and RPR dissolution has been shown to vary with legume species (Trolove *et al.*, 1996b). The low pH of Red Earths and Yellow Earths in Myanmar makes them suitable for the direct RPR application (see Section 3.5, Chapter 3). Several legumes, grown for cash crops in Myanmar, could also be grown in conjunction with RPR fertilisers.

In this chapter, a set of glasshouse trials was undertaken to investigate plant-induced changes to rhizosphere soils by various species of sub-tropical legume grown in low pH soils from Myanmar fertilised with Sechura reactive phosphate rock (SPR).

### ***5.1.1 Legumes grown in Myanmar***

Many different legume species are grown widely for food legumes as oilseeds (groundnut) and pulses (kidney bean, soybean, cowpea, pigeon pea, chickpea, green

gram, black gram, rice bean, lentil, etc.), and some for forage and green manure (rice bean) in upland cropping systems in Myanmar (Table 5.1). Growing of forage and green manure will be very important because the overall productivity in this region depends not only on food crops, but also on livestock production (see Section 1.8, Chapter 1). Therefore crop rotation with legumes could be included in existing farming systems (see Section 1.8.2, Chapter 1). Furthermore, these marginal farmers prefer to feed their animals at low or no external feed cost. However, low or no P fertilisation is a routine production practice for legumes on the Red Earths and Yellow Earths in Myanmar. Consequently, low yields of legume grain and biomass per unit land have resulted.

Table 5.1 Important legume species grown in Myanmar.

Common name	Botanical name	Common name	Botanical name
Black gram	<i>Vigna mungo</i>	Horse gram	<i>Macrotyloma uniflorum</i>
Butter bean	<i>Phaseolus lunatus</i>	Kidney bean	<i>Phaseolus vulgaris</i>
Chickpea	<i>Cicer arietinum</i>	Lablab bean	<i>Lablab purpureus</i>
Cowpea	<i>Vigna unguiculata</i>	Lentil	<i>Lens culinaris</i>
Garden pea	<i>Pisum sativum</i>	Pigeon pea	<i>Cajanus cajan</i>
Broad bean	<i>Vicia faba</i>	Rice bean	<i>Vigna umbellata</i>
Green gram	<i>Vigna radiata</i>	Soybean	<i>Glycine max</i>
Groundnut	<i>Arachis hypogaea</i>	Winged bean	<i>Psophocarpus tetragonolobus</i>

## 5.2 Objectives

The experimental objectives of this chapter are:

1. To measure changes in pH in the rhizosphere soil of seven legume species grown on a low pH Red Earth.
2. To determine whether plant ash-alkalinity can be used to predict the cation-anion balance in herbage and the likely pH change in legume rhizosphere.
3. To investigate RPR solubilisation and P uptake in the rhizosphere soil of seven legume species with potential as grain and oil seed crop plants or green manures.

## 5.3 Materials and methods

### 5.3.1 Soils

A composite Red Earth (0-30 cm) from Myanmar and Ramiha hill soil (0-7.5 cm) from New Zealand, were used in these experiments because these two soils were hill soils

and they had similar P retention values. The former soil was used for the legume growth experiment and the latter soil was used for the investigation of RPR solubilisation. The air-dried soils were passed through a 1 mm sieve. Some relevant properties of the two soils are presented in Table 5.2.

Table 5.2 Name, type and some chemical properties of the soils used.

Soil	Soil type	pH <sub>water</sub> (1:2.5)	Total C (%)	CEC cmol (+) kg <sup>-1</sup>	Olsen-P (mg kg <sup>-1</sup> )	P retention (%)
Red Earth	Paleustult	5.6	1.28	15	6.5	63
Ramiha	Andic Haplumbrept	6.0	5.62	23	19.5	57

### 5.3.2 Legume growth in rhizosphere study containers (RSC)

Seven species of sub-tropical legumes were chosen for this experiment (see Table 5.3). All legumes were tested for germination before starting of the experiment. The germination rates of the legumes are presented in Table 5.3.

Table 5.3 Percentage of seed germination and growing period of legume species grown in Red Earth.

Legume species	Germination (%)	Growth period (days)
Cowpea ( <i>Vigna unguiculata</i> )	98	50
Kidney bean ( <i>Phaseolus vulgaris</i> )	97	31
Soybean ( <i>Glycine max</i> )	86	42
Pigeon pea ( <i>Cajanus cajan</i> )	94	60
Black gram ( <i>Vigna mungo</i> )	80	50
Lentil bean ( <i>Culinaris lentil</i> )	93	60
Stylosanthes ( <i>Stylosanthes quyanensis</i> )	76	60
Control	NA	60

For the legume growth experiment rhizosphere study containers (RSC) were used. The RSC was made of 2 PVC cores (upper section: 82.5 mm internal diameter by 25 mm effective depth, basal section: 75 mm internal diameter by 50 mm depth), separated by a 22 µm polyester mesh (Figure 5.1 and Plate 5.1). A similar RSC technique was described by Hedley *et al.* (1994), Trolove *et al.* (1996a) and Zoysa *et al.* (1997). Legume plants were grown in the upper section of RSC and their roots spread throughout the soil in this section. The roots were unable to grow through the polyester mesh into the basal section of soil. Consequently roots could only spread horizontally along the mesh surface and root hairs grew through the polyester mesh forming a rhizoplane. Therefore, the soil immediately below the polyester mesh can be considered to be rhizosphere soil. The basal section of RSC was packed with 240 g of SPR-

fertilised (plus NK) soil for each section and the upper section was packed with 130 g of soil fertilised with N and K only.



Plate 5.1 Legumes growing in the rhizosphere study container (RSC).

### ***Soil and Fertiliser***

The composite Red Earth was used in this experiment. All treatments received  $20 \mu\text{g N g}^{-1}$  soil (as  $\text{KNO}_3$  and  $(\text{NH}_4)_2\text{SO}_4$ , 2:1 ratio) and  $290 \mu\text{g K g}^{-1}$  soil (as  $\text{KCl}$ ) as a basal fertiliser application. The N and K fertilisers were thoroughly mixed with the whole soil before adding SPR. A portion of this soil (240 g) was separated and SPR at  $125 \mu\text{g P g}^{-1}$  soil was mixed with it before packing into the basal section of the RSC (Section 5.3.2, Figure 5.1).

### ***Relative reactivity of SPR***

The P source used in this study was reactive Sechura phosphate rock (SPR),  $<250 \mu\text{m}$  particle sizes.

Prior to set up of this experiment, the particle size distribution of (as received) SPR from Peru was measured by sieve analysis and total P and soluble P determined by tri-acid digestion (concentrated  $\text{H}_2\text{SO}_4$ ,  $\text{HNO}_3$  and  $\text{HClO}_4$ , 1:1:1.4 ratio), water, 2% citric

and 2% formic acid extraction, respectively (Syers *et al.*, 1986). The physical and chemical properties of SPR are presented in Tables 3.1, 3.2 and 3.3.

As mentioned earlier, the plant availability of P from PR varies due to the variation in the chemical reactivity of the PR apatite (Rajan *et al.*, 1992; Hedley and Bolan, 1997). Sechura PR comprises a reactive francolite, which has 42% of total P soluble in 2% citric acid or 67% of total P soluble in 2% formic acid. It should be ranked as a highly reactive PR (a reactive PR should dissolve more than 30% of its total P in the 2% citric acid solution, Hedley and Bolan, 1997; and more than 50% in 2% formic acid, Syers *et al.*, 1986). The citric and formic acid solubility rankings were similar to those reported earlier by Udy (1981) and Gregg *et al.* (1988), and thus this SPR sample can be used for direct application.

### ***Seed preparation, pre-germination and sowing***

Seven varieties of sub-tropical legume were grown in RSCs during the glasshouse experiment (Table 5.3).

Undamaged clean seeds, of a reasonably uniform size were selected by sieving and hand sorting. Legume seeds were then treated with Thiram fungicide to prevent fungus diseases.

To give good emergence in the RSCs, the legumes were germinated between moist paper towels for 3 days before planting. After 3 days, >80% of most legume seeds had germinated, except stylosanthes seeds of which only 76%germinated.

Five germinated seeds were planted in each upper section of the RSC on 29<sup>th</sup> of December 1998. Legume seeds were not treated with any rhizobial inoculums at sowing time. Seedlings were later thinned to three plants per RSC 5 days after planting.

### ***Plant care***

The experiment was established as a completely randomised block design with three replications. There were 7 treatments for planted and one treatment for unplanted treatment. The total number of treatments was 8 treatments.

Rhizosphere study containers were placed on moist silica sand in plastic containers connected to a water container (Figure 5.1). The water level was held 20 cm below the sand surface, to maintain a moderate suction on the soil. Nutrient solution (N and P free solution, Middleton and Toxopeus, 1973) was applied 20 ml at planting to prevent any possible deficiencies of other nutrients.

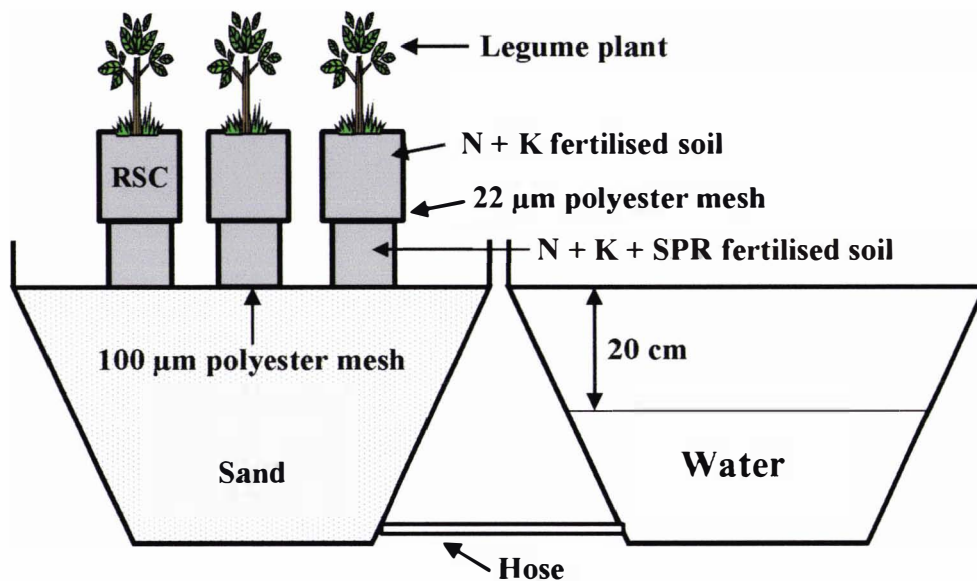


Figure 5.1 Schematic representation of the rhizosphere study container (RSC) technique.



Plate 5.2 Organisation of RSC's growing legumes species in the glasshouse experiment.

### 5.3.3 *Harvesting of legume crops and soil sectioning of RSC*

Depending on the growth rates, legumes were harvested at different times to achieve similar biomass. At harvest, plant shoots were cut 0.5 cm above the soil surface. The growing period of the different legumes is shown in Table 5.3.

At harvest, the upper section of the RSC was removed and sectioned 3 mm above the root boundary and the soil washed off and the roots collected for root length measurement. The polyester mesh was carefully removed from the basal section and the soil core was horizontally cut into thin slices using a piston microtome (Plate 5.3). The first four slices below the mesh were 0.5 mm thick (i.e. up to 2 mm from the rhizoplane) and a further four slices were cut 2 mm thick (2-10 mm). At slicing of the basal RSC section, all soil slices were weighed. All slices were then oven-dried at 35°C and re-weighed and the moisture content calculated. The slices were then ground and passed through a 1 mm sieve.



Plate 5.3 The piston microtome used for slicing soils from the lower RSC.

### 5.3.4 Nodule and root length measurements

Immediately after harvest, root nodules were counted on the washed roots from the upper section of the RSC. Only the number and the size of nodules could be measured by visual counting. After nodule counting, washed root samples were stored in sealed polyethylene bags for two days in a refrigerator. The root length in the 3 mm thick slice from the top section of RSC (Plate 5.4) was measured by the line intercept method (Newman, 1966; Tennant, 1975; and van Noordwijk, 1993). Roots were spread out with random orientation in a thin layer of water on a plastic plate (20 cm × 35 cm), water was removed and a grid sheet (photocopied on a transparency sheet) was put underneath the root sample. Intersections of roots with the horizontal (H) and vertical (V) grid lines were counted (N). The lengths of root samples were determined by using the formula as follows:

$$L = \pi ND/4$$

Where L = the length of roots (mm)

D = the grid size (mm)

Root counting was conducted manually by using a magnifying lens with a hand counter.



Plate 5.4 legume root mats formed on the 22  $\mu$ m polyester mesh above the SPR fertilised Red Earth.

### 5.3.5 *Plant analysis*

Shoot and root samples were dried at 60°C for 48 hours and weighed for dry matter yield. The dried legume shoots were finely ground to <1 mm. Then, shoot samples were digested by the Kjeldahl method (McKenzie and Wallace, 1954) and total N and P concentration in the digest measured by using a Technicon auto-analyser (Twine and Williams, 1971). For cation analysis shoot samples were digested with nitric acid (Jones and Case, 1990), then calcium ( $\text{Ca}^{2+}$ ) and magnesium ( $\text{Mg}^{2+}$ ) were determined by atomic absorption spectroscopy, and the potassium ( $\text{K}^+$ ) and sodium ( $\text{Na}^+$ ) were determined by flame emission spectroscopy. Legume shoot samples were extracted with hot water at 80°C for 1 hour, and the chloride ( $\text{Cl}^-$ ) content determined (Jarvis and Robson, 1983a) using a CORNING chloride analyser 925. Sulphur (S) was measured by the alkaline hypobromite oxidation method followed by automated turbidimetric analysis of sulphate concentrations in the diluted digest (Phimsarn, 1991).

#### *Ash-alkalinity of legume shoots*

The ash-alkalinity of legume shoots was determined by the Jarvis and Robson method (Chapter 4.4.2).

#### *Cation uptake excess*

The cation uptake excess by shoot and root was calculated from the sum of the charge from cation uptake  $\sum(\text{Ca}^{2+}, \text{Mg}^{2+}, \text{K}^+, \text{Na}^+)$  minus the sum of the charge from anion uptake  $\sum(\text{H}_2\text{PO}_4^-, \text{SO}_4^{2-}, \text{Cl}^-)$ , based on the equivalent (molar / charge on ion) concentrations of these nutrients in the shoot of legumes (Jarvis and Robson, 1983b; Monaghan *et al.*, 1998). The reason for not including N in the charge balance calculation is discussed in Section 5.4.

### 5.3.6 *Soil analysis*

#### *Preliminary standardisation of P fractionation*

Sechura PR was mixed with 20 g of soil sub samples at the rate of 125  $\mu\text{g P g}^{-1}$  soil (oven-dried at 35°C). Soil sub samples with no SPR added were also prepared.

Preliminary evaluation of the P fraction procedure (described in Section 4.4.7) was conducted using replicate samples of air-dry Red Earth and Ramiha soils, with and without SPR addition. In the fractionation experiment, all extraction steps were carried out at a soil to solution ratio of 1:60 with an extraction time of 16 hours. The P fractions from these soil samples were determined using the colorimetric procedure. This P fractionation procedure was then used to characterise soil P in slices of the rhizosphere soils (Section 5.5.2).

### ***Rhizosphere pH and sequential P fractionation***

The soil slice samples from legume rhizospheres were analysed for pH and sequential P fractionations by a modified method of Hedley *et al.* (1994), as described in Section 4.4.7 (Chapter 4). A 0.5 g soil sample was placed into a 50 ml polypropylene centrifuge tube. Next, 5 ml of deionised water was added and equilibrated for 4 hours, then the pH of the supernatant measured with a well-washed microelectrode. Following pH measurement, the Resin-P, 0.1 M NaOH-Pi and Po, 1 M NaOH-Pi and Po, 0.5 M H<sub>2</sub>SO<sub>4</sub>-Pi and Residual-P fractions were sequentially extracted and analysed (as described in Section 4.4.7). Soil pH and P fractionations were not measured in lentil bean RSCs due to very poor plant growth in the Red Earth.

### **5.3.7 *Statistical analysis***

Analysis of variance (ANOVA) was conducted by the general linear models (GLM) procedure (SAS, 1989). The F-test was used to test for differences among the means or effects of the treatments at the 95% confidence level. Fisher's least significant difference (LSD) was used for multiple comparison procedures of these treatment means.

## **5.4 Results and discussion**

### **5.4.1 *Dry matter yield, root length and nodule formation***

Cowpea and kidney bean produced significantly more dry matter (DM) yield than other legumes ( $P < 0.01$ ) (Table 5.4).

Table 5.4 The root length in upper 3 mm soil slice, number of nodules, shoot DM, Shoot N (%), Root DM, Root N (%), Seed weight, Seed N (%), Shoot + Root-Seed N, and estimate of symbiotically fixed-N in a range of sub-tropical legumes grown in RSCs filled with Red Earth.

Treatment	Root length (mm)	Nodules	Shoot DM (g)	Shoot N%	Shoot N (mg RSC <sup>-1</sup> )	Root DM (g)	Root N%	Root N (mg RSC <sup>-1</sup> )	3 Seeds (g)	Seed N%	N seed (mg RSC <sup>-1</sup> )	S+R-Seed N <sup>1</sup> (mg RSC <sup>-1</sup> )	N-fix <sup>2</sup> (mg RSC <sup>-1</sup> )
Cowpea	2243 <sup>a</sup>	11	3.63	1.49	54.09	1.06	1.45	15.43	0.50	3.45	17.4	52.1	10.9 to 49.2
Cowpea	2222 <sup>a</sup>	9	3.20	1.19	38.19	1.00	1.58	15.80	0.50	3.45	17.4	36.6	-4.7 to 33.7
Cowpea	2459 <sup>a</sup>	10	3.43	1.25	42.87	1.00	1.69	16.95	0.50	3.45	17.4	42.4	1.2 to 39.5
Kidney bean	1266 <sup>cd</sup>	0	3.42	2.03	69.34	1.57	0.75	11.74	1.58	3.15	49.8	31.3	
Kidney bean	746 <sup>d</sup>	0	2.13	2.09	44.40	0.98	0.85	8.30	1.58	3.15	49.8	2.93	
Kidney bean	1079 <sup>cd</sup>	0	3.42	1.49	50.98	1.69	0.75	12.66	1.58	3.15	49.8	13.9	
Soybean	1029 <sup>cd</sup>	3	2.51	1.64	41.28	0.99	1.45	14.28	0.46	3.55	16.3	39.2	-2.0 to 36.3
Soybean	1956 <sup>bc</sup>	4	2.71	1.55	41.91	0.92	1.55	14.20	0.46	3.55	16.3	39.8	-1.4 to 36.8
Soybean	1445 <sup>cd</sup>	0	1.84	2.09	38.39	0.88	1.50	13.17	0.46	3.55	16.3	35.2	
Pigeon pea	1732 <sup>bc</sup>	12	1.51	2.25	33.88	1.13	1.45	16.40	0.47	3.50	16.4	33.9	-7.3 to 30.9
Pigeon pea	1774 <sup>bc</sup>	16	1.79	2.38	42.55	1.09	1.65	18.02	0.47	3.50	16.4	44.2	3.0 to 41.2
Pigeon pea	1903 <sup>bc</sup>	17	1.61	2.24	35.99	1.13	1.60	18.08	0.47	3.50	16.4	37.7	-3.5 to 34.7
Black gram	2284 <sup>a</sup>	5	1.38	2.04	28.22	0.84	1.55	13.04	0.17	3.75	6.2	35.0	-6.16 to 32.1
Black gram	2158 <sup>ab</sup>	7	1.59	2.08	32.98	0.85	1.45	12.34	0.17	3.75	6.2	39.1	-2.10 to 36.2
Black gram	2212 <sup>a</sup>	10	1.87	1.69	31.49	0.83	1.40	11.58	0.17	3.75	6.2	36.8	-4.4 to 33.9
Lentil bean	202 <sup>f</sup>	0	0.39	4.70	18.37	0.03	1.05	0.26	0.06	3.30	1.9	16.8	
Lentil bean	239 <sup>f</sup>	0	0.34	4.80	16.36	0.03	1.10	0.33	0.06	3.30	1.9	14.8	
Lentil bean	218 <sup>f</sup>	0	0.40	4.60	18.21	0.02	1.00	0.23	0.06	3.30	1.9	16.6	
Stylosanthes	1001 <sup>cd</sup>	0	0.91	2.40	21.71	0.49	1.00	4.93	0.01	3.65	0.5	26.2	
Stylosanthes	1016 <sup>cd</sup>	0	1.57	2.14	33.54	0.78	1.05	8.14	0.01	3.65	0.5	41.2	
Stylosanthes	988 <sup>cd</sup>	0	1.50	2.19	32.92	0.67	1.00	6.71	0.01	3.65	0.5	39.2	

<sup>1</sup>Shoot N + Root N - Seed N = total soil derived N + fixed N or total soil derived N for unnodulated legumes.

<sup>2</sup>N-fix = estimate of range of symbiotically fixed N = [Nodulated legume (Shoot N + Root N - Seed N)] - [Range of unnodulated legume (Shoot N + Root N - Seed N)].

Irrespective of harvest time, soybean, pigeon pea, black gram and stylosanthes produced similar yields ( $P < 0.01$ ). Lentil bean growth was very poor, and little DM was harvested. Kidney bean, a short-term legume crop, produced a large amount of DM within a short period. However stylosanthes, a perennial forage, and pigeon pea, a long-term grain legume, produced less DM due to a slower rate of growth in the short study period. Similarly variable growth rates were found in ten grain legumes (Mclay *et al.*, 1997) and twelve pasture legumes (Tang *et al.*, 1997) grown in nutrient solution and four pasture legumes grown on low pH soils (Monaghan *et al.*, 1998).

Cowpea and black gram produced significantly longer roots than the other legume species. Amongst the species, lentil bean produced least root length and produced the lowest DM yield (Table 5.4). The length of legume roots was considered one of the important factors responsible for the observed changes in pH and soil P fractions in the 'rhizosphere' zone of the RSC (see discussion in later sections).

Nodulation occurred on roots of only some legume species grown in Red Earths (Table 5.4). Active nodules were formed on cowpea, pigeon pea, black gram and soybean roots, which indicated that these legumes could have utilised symbiotically fixed-N plus  $\text{NH}_4^+$  and  $\text{NO}_3^-$  taken up from mineralised soil N. The lack of nodules in kidney bean, lentil bean and stylosanthes indicated that only soil N was taken up as  $\text{NH}_4^+$  or  $\text{NO}_3^+$  by these species (Table 5.4). It is important to note that no artificial inoculation of rhizobium bacteria was carried out in this experiment. The differences in the nodulation between the legume species may be related to difference in the persistence native rhizobium bacteria.

### ***Nitrogen uptake***

Among the legume species, lentil bean had the highest N concentration in shoots partly because little dry matter was produced. Pigeon pea and stylosanthes contained significantly higher nitrogen concentrations in shoots than soybean and cowpea (Table 5.4). In terms of N content in legumes shoots, kidney bean had a higher nitrogen uptake per RSC than all other legumes except cowpea ( $P < 0.05$ ).

If it is assumed that unnodulated legumes took up only soil N and N derived from the seed, then the estimated soil N supply can be calculated as (shoot + root – seed) N/RSC (Table 5.4). This calculated amount, for non-nodulated legumes, had a large range (2.93 to 41.2 mg N RSC<sup>-1</sup>) partly because kidney bean has a very large seed N contribution, which could have supplied between 70 and 90% of the total N uptake by kidney bean at harvest. The small seed lentil bean was more consistent in soil N uptake, which ranged from 14.8 to 16.8 mg N RSC<sup>-1</sup>. Stylosanthes with the small seed N contribution gives soil N uptake estimates of between 26.2 and 41.2 mg of soil N RSC<sup>-1</sup>. Thus the estimate of soil N contribution to unnodulated legumes is highly variable. As a consequence when these values are used to make correction to the total N uptake by nodulated legume to calculate the likely amounts of N fixed, the result is a highly variable range of N estimates for the amounts of N fixed (N-fix, Table 5.4).

The process of NH<sub>4</sub><sup>+</sup> absorption by roots reduces Ca<sup>2+</sup>, Mg<sup>2+</sup> and K<sup>+</sup> uptake while increasing the absorption of HSO<sub>4</sub><sup>-</sup>, SO<sub>4</sub><sup>2-</sup> and Cl<sup>-</sup> (Curl and Truelove, 1985). Acidity generated by N fixation by legumes has been found to be proportional to the excess of cations over anions taken up by the legumes (Jarvis and Robson 1983c). This can vary from 0.2-0.7 mole H<sup>+</sup> per mol of fixed N (Jarvis and Robson 1983c). However some tropical legumes do not apparently acidify their rhizosphere as much as do temperate legumes when actively fixing N<sub>2</sub> by legumes. The reason is that the NH<sub>3</sub> assimilation products can be ureides (allantoin and allantoin acid), which have higher pKa values (Bolan and Hedley, 2001).

#### ***5.4.2 Plant nutrients and cation excess in legumes***

##### ***Cation uptake excess***

Ion uptake by plants can either reduce or increase the soil acidity. If a plant absorbs an excess of cations, it secretes H<sup>+</sup> into the rhizosphere to maintain electrical neutrality and thus acidifies the rhizosphere. The measured cation and anion concentrations of legume shoots are shown in Table 5.5. The dominant cations contributing to the charge balance in these legume shoots were: Ca<sup>2+</sup>>K<sup>+</sup>>Mg<sup>2+</sup>. Sodium made a small contribution to the charge balance of these legumes. The concentration of Ca<sup>2+</sup> was considerably lower in cowpea compared to the five other legumes. The concentrations of aluminium (Al) and

Table 5.5 Cation and anion composition, N concentration, cation excess (CE), ash-alkalinity (AA) and cation excess (CE) to N ratio in legumes shoots.

Legume	Ca <sup>2+</sup>	Mg <sup>2+</sup>	K <sup>+</sup>	Na <sup>+</sup>	Cations	H <sub>2</sub> PO <sub>4</sub> <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	Cl <sup>-</sup>	Anions	N	CE	AA	CE/N
	(cmol (±) kg <sup>-1</sup> )												
Cowpea	30.0	16.1	18.1	6.8	71	0.5	4.5	23.1	28	107	43	44	0.40
Cowpea	24.2	16.3	21.3	9.2	71	0.6	3.4	20.1	24	85	47	44	0.55
Cowpea	23.4	16.2	16.9	3.6	60	0.5	2.7	18.9	22	89	38	44	0.43
Kidney bean	33.1	23.9	31.7	4.2	93	1.1	2.7	34.9	39	145	54	44	0.37
Kidney bean	37.9	29.9	33.3	5.7	107	1.0	3.2	46.4	51	149	56	44	0.38
Kidney bean	42.0	28.4	26.3	3.7	100	0.9	2.9	43.7	48	106	53	44	0.50
Soybean	30.6	24.7	21.6	2.6	79	0.5	2.5	25.2	28	117	51	66	0.44
Soybean	39.1	30.4	28.1	4.9	102	0.6	3.4	20.6	25	111	78	66	0.70
Soybean	34.3	30.4	41.0	5.1	111	0.7	4.0	16.1	21	149	90	66	0.60
Pigeon pea	34.0	17.6	46.5	4.8	103	0.7	7.0	8.1	16	160	87	73	0.54
Pigeon pea	51.6	27.4	39.3	8.0	126	1.9	5.7	14.6	22	170	104	73	0.61
Pigeon pea	55.5	25.7	32.5	4.3	118	1.1	3.7	13.0	18	160	100	73	0.63
Black gram	52.6	35.1	24.7	17.2	130	0.7	3.9	48.2	53	146	77	73	0.53
Black gram	71.7	29.5	28.8	10.8	141	0.9	3.7	37.5	42	148	99	109	0.66
Black gram	52.6	26.4	25.0	9.4	113	0.8	3.4	46.8	51	121	62	88	0.52
Lentil bean	85.2	38.4	38.4	9.3	171	1.4	3.8	22.8	28	336	143	109	0.43
Lentil bean	97.8	38.8	39.5	9.0	185	1.3	4.0	19.2	25	343	161	105	0.47
Lentil bean	78.7	44.0	37.6	8.6	169	1.2	3.4	19.6	24	328	145	107	0.44
Stylosanthes	57.1	28.1	48.5	2.5	136	1.0	2.5	33.9	37	171	99	109	0.58
Stylosanthes	49.5	32.5	47.8	6.7	137	0.9	2.5	29.2	33	153	104	110	0.68
Stylosanthes	51.5	30.4	37.2	5.1	124	1.2	2.5	32.4	36	156	88	110	0.56

manganese (Mn) cations were not measured in this study because the form and the charge of the Al and Mn ions taken up were not known. Haynes and Ludecke (1981) found that Al and Mn uptake contributed a negligible amount to the charge balance of legumes. Also many workers have not included Mn and Al ions in the cation over anion balance (e.g. Gijsman, 1990; Jarvis and Robson, 1983b,c; Haynes and Ludecke, 1981). Chloride was the most dominant anion contributing to the balance of charge, followed by  $\text{SO}_4^{2-}$  and then  $\text{H}_2\text{PO}_4^-$  in all the legume shoots.

In this study, cation uptake excess (CE) is defined as total cation charge ( $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{K}^+$ , and  $\text{Na}^+$ ) minus total anion charge ( $\text{Cl}^-$ ,  $\text{SO}_4^{2-}$ , and  $\text{H}_2\text{PO}_4^-$ ) in plant shoots. The cation excess concentration (Table 5.5) was higher in lentil bean, stylosanthes and pigeon pea, but cowpea and kidney bean had significantly lower ( $P < 0.05$ ) cation excess concentrations. This was despite the absence of nodules on lentil bean and stylosanthes roots.

The balance of cations over anions did not include  $\text{NO}_3^-$  nor  $\text{NH}_4^+$  because of the uncertainty in the form of N uptake by legume roots (Table 5.4). However, the form of N taken up by the plant does play a major role in the overall cation-anion balance of the plant (Nye, 1981). If legumes take up N predominantly as  $\text{NO}_3^-$ , they need to take up additional cations to balance organate negative charge in shoots or  $\text{OH}^-$  could be released from roots to balance  $\text{NO}_3^-$  uptake. In the latter case rhizosphere pH could rise. The legumes fixing N could also have a large cation excess because N enters the plant as the neutral N molecule and cations from soil are taken up to balance negative charges on amino acid anions that are formed (Bolan and Hedley, 2001). In this case rhizosphere pH will decrease from the small amount of  $\text{H}^+$  ions released to balance cation uptake. If the legumes take up predominantly  $\text{NH}_4^+$  then mineral cation excess in the shoot may be smaller but rhizosphere pH will decrease as both mineral cation and  $\text{NH}_4^+$  uptake will cause  $\text{H}^+$  release.

### ***The relationship between dry matter and cation excess***

The absence of any relationship between legume species and cation excess  $\text{RSC}^{-1}$ , could have been due to the large variation in within species dry matter. Monaghan *et al.* (1998) found that dry matter yield and cation excess removal were almost linearly

related, and that plant yield was the dominant factor for cation excess uptake, rather than plant species. In this study a linear regression explained only 49% of the variation in the relationship between dry matter yield of plants and cation excess taken up by plants (Figure 5.2). The large unaccounted for variation probably indicates that the types of N nutrition ( $\text{NH}_4^+$  and/or  $\text{NO}_3^-$  and  $\text{N}_2$  fixation) varied between the legumes grown in this experiment.

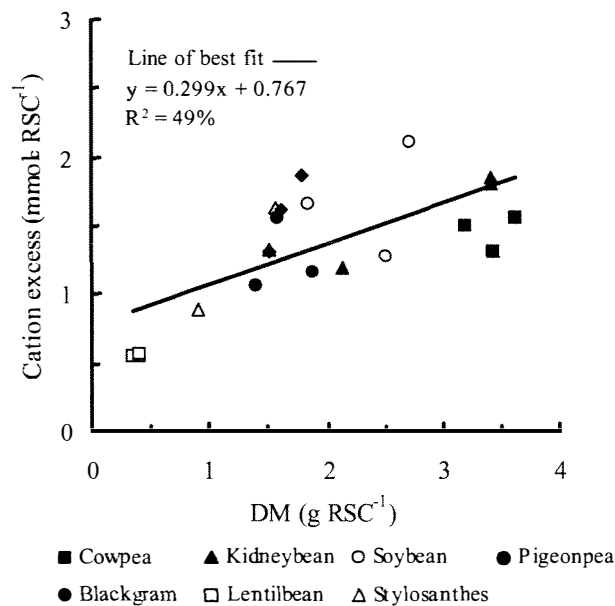


Figure 5.2 The relationship between DM yields  $\text{RSC}^{-1}$  (g) and cation excess ( $\text{mmol}_e \text{RSC}^{-1}$ ) of legume shoots (All three replications are included for each legume species).

### ***The relationship between cation excess and N concentration***

Figure 5.3 shows that the cation excess concentrations were closely related with N concentrations of shoots in the legume species ( $R^2 = 82\%$ ). But the relationship between cation excess and nitrogen content per RSC was weaker ( $R^2 = 60\%$ , Figure 5.4), which may partly be related to the poor relationship between cation excess and DM yield (Figure 5.2). Although the N concentration in lentil bean is very high the N uptake was low, primarily due to low DM yields. This was the main reason why the data for this legume species is an outlier in both figures.

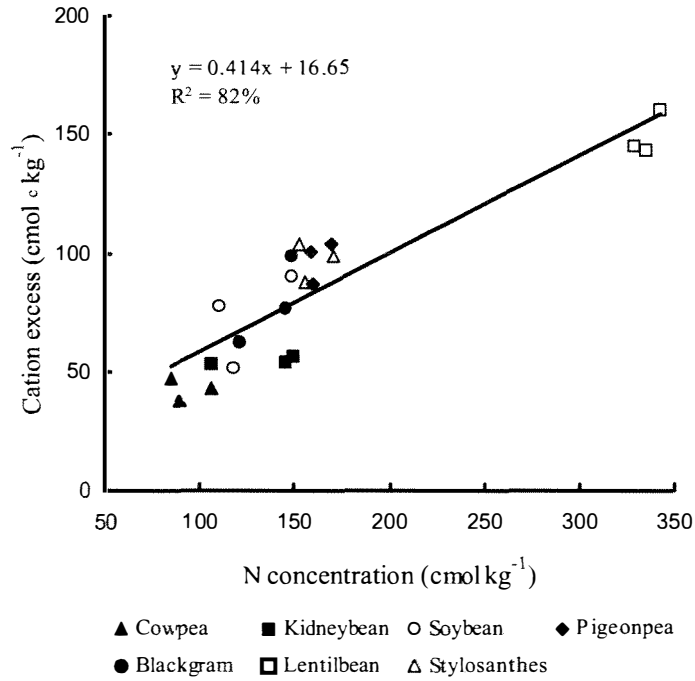


Figure 5.3 The relationship between N concentration ( $\text{cmol kg}^{-1}$ ) and cation excess ( $\text{cmol (+) kg}^{-1}$ ) of legume shoots.

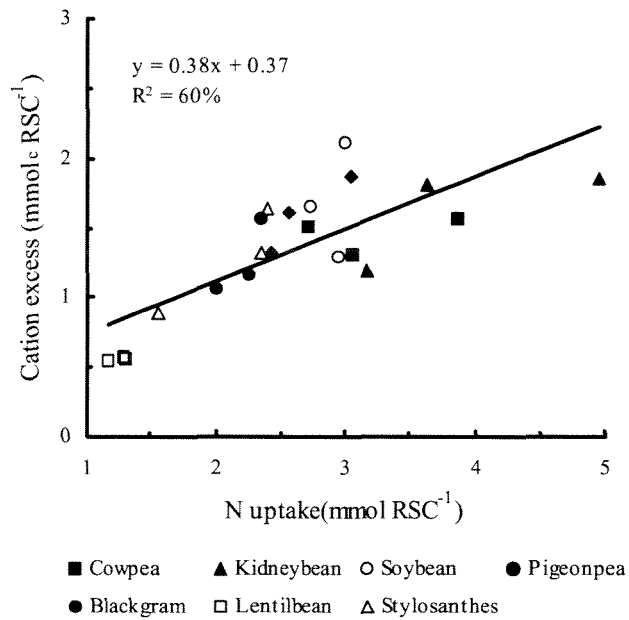


Figure 5.4 The relationship between N uptake ( $\text{mmol RSC}^{-1}$ ) and cation excess ( $\text{mmol (+) RSC}^{-1}$ ) of legume shoots.

The slope of the relationship between cation excess and N concentration which is the CE/N ratio averaged 0.41 for the seven legume species ( $R^2 = 82\%$ ). The determined CE/N ratios in the present study ranged from 0.37 in kidney bean to 0.70 in soybean. The higher CE/N concentration ratio in lentil bean is consistent with  $\text{NO}_3^-$  uptake from N mineralisation in the soil. Lentil bean had no nodules and fixed no N, thus the large soil N contribution (plant N – seed N, Table 5.4) was probably taken up as  $\text{NO}_3^-$  yielding a large cation excess per unit N taken up. Lower CE/N (around 0.4) values were generally supported by the data reported by Monaghan *et al.* (1998). The CE/N ratio, however, varies within plant type or species (0.35 to 0.41 in ryegrass) or among species of legume (0.41 in lotus and 0.77 in caucasian clover) (Pierre and Banwart, 1973).

Due to the large variation in the estimate of N fixed per RSC it was impossible to examine a relationship between CE and N fixed per RSC.

### 5.4.3 Ash-alkalinity

When plant samples are ashed at  $500^\circ\text{C}$  all organates are converted to  $\text{CO}_2$ , the decarboxylation yields oxides of the balancing metal cation. Similarly most organic S is lost and a large part of the organic N. The amount of acid required to neutralise the ash gives an estimate of the organate, and S containing amino acids loses on ignition. The alkalinity of the ash can be closely related to the CE of the plant (Monaghan *et al.*, 1998).

There were significant differences in the ash-alkalinity ( $\text{cmol (+) kg}^{-1}$  DM) of shoots between the legume species (Table 5.5). *Stylosanthes* had a significantly higher value of ash-alkalinity ( $110 \text{ cmol (+) kg}^{-1}$  DM), than the others five legumes, except black gram. The ash-alkalinity was significantly lower in cowpea and kidney bean ( $44 \text{ cmol (+) kg}^{-1}$  DM) compared to other species ( $P < 0.01$ ).

### *Ash-alkalinity compared to cation excess*

As expected, the ash-alkalinity and cation uptake excess of legume shoots were positively related ( $R^2 = 62\%$ , Figure 5.5). There was however much variation in the

relationship. There was as much variation within species (e.g. Soybean and black gram) as there was between species. Further more, the cation excess and ash-alkalinity relationship was poorer ( $R^2 = 26\%$ ), if the slow growing lentil bean is not included.

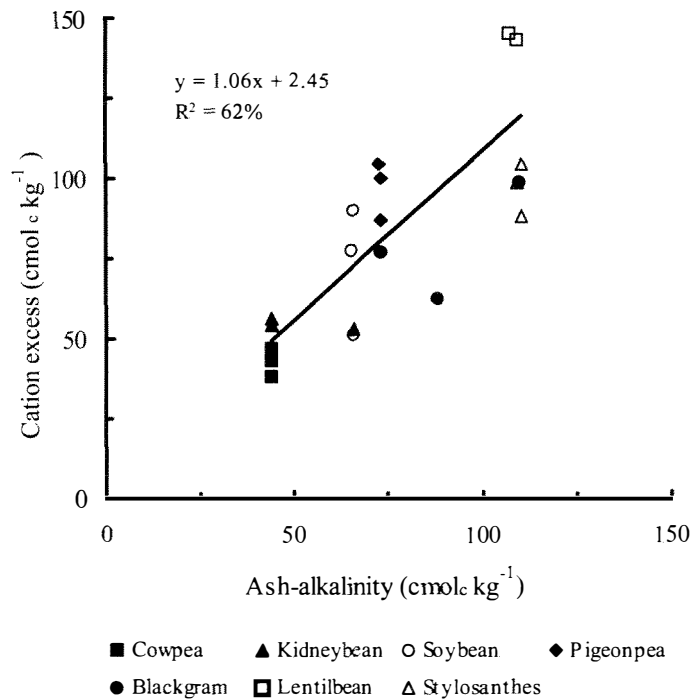


Figure 5.5 The relationship between ash-alkalinity (cmol (+) kg<sup>-1</sup>) and cation excess (cmol (+) kg<sup>-1</sup>) of legume shoots.

With the large variation in the relationship between legume species it was not possible to state that the slope of the relationship differed significantly from 1. Indeed it could be expressed that AA and CE may be similar because when N forms are excluded from the CE calculation then the excess cation charge balance in the ash accounted for by oxide is likely to be similar to the organate synthesised to balance the assimilation of  $\text{NO}_3^-$  into amino acids and strong amino acids that dissociate (Bolan and Hedley, 2001).

Significant  $\text{NO}_3^-$  uptake is possible in this experiment because, at the beginning of planting, the concentration of resin extractable soil  $\text{NH}_4^+$  ions was nearly double the concentration of  $\text{NO}_3^-$  ions. But by the end of experiment the concentration of  $\text{NO}_3^-$  was more than twofold higher than measured  $\text{NH}_4^+$  in resin extract solution in soil alone treatments whereas in planted soils  $\text{NO}_3^-$  concentration is same as  $\text{NH}_4^+$  concentration or lower than  $\text{NH}_4^+$  concentration (see Table 5.6).

Table 5.6 Probable calculated available-N depletion ( $\mu\text{g N RSC}^{-1}$ ) by different legumes in the planted and unplanted soil (from resin extraction solution at harvest).

Treatment	$\text{NH}_4^+$ ( $\text{mg N kg}^{-1}$ )	$\text{NO}_3^-$ ( $\text{mg N kg}^{-1}$ )	Total mineral N ( $\text{mg N kg}^{-1}$ )	Mineral N increase ( $\text{mg N kg}^{-1}$ )
Soil alone at planting	5.21	2.61	7.82	
Soil alone at harvest	5.70	13.53	19.23	11.41
Planted soils				Probable calculated N depletion ( $\text{mg N RSC}^{-1}$ ) <sup>1</sup>
Cowpea	5.63	4.80	10.43	3.26
Kidney bean	6.80	4.67	11.46	2.95
Soybean	5.47	2.96	8.43	4.00
Pigeon pea	5.79	4.06	9.85	3.47
Black gram	5.37	4.33	9.70	3.53
Stylosanthes	4.97	4.53	9.50	3.60

<sup>1</sup>Probable calculated N depletion ( $\text{mg N RSC}^{-1}$ ) =  $0.360 \text{ kg soil} \times \text{total soil mineral N at harvest (mg N kg}^{-1} \text{ soil)}$  (unplanted soil-planted soil).

The calculated probable depletion of mineral N by plant uptake (Table 5.6) ranged from 2.95 to 4.0  $\text{mg N RSC}^{-1}$  which is 6-10 fold lower than the estimate of soil N uptake from unnodulated legumes (Table 5.4). Thus net soil N mineralisation appears to be stimulated by the presence of plant roots and this contributes significantly to plant N uptake.

#### 5.4.4 Soil pH

Soil pH values in the unplanted control treatments (Figure 5.11) dropped 0.8 unit (pH 5.65 to 4.85) from the initial measured soil pH, however in planted soils (Figure 5.9) the pH increase in the rhizosphere soils from the initial pH 5.65 was much smaller 0.07 to 0.28 pH units. During the complete mineralisation and nitrification of organic nitrogen ( $\text{R-NH}_2$ ) to  $\text{NO}_3^-$ , one mole of  $\text{H}^+$  is produced for one mole of N mineralised (Equations 5.1 and 5.2).

Ammonification



Nitrification



In the ammonification process, R-NH<sub>2</sub> in the soil is mineralised to NH<sub>4</sub><sup>+</sup>-N by soil microbes (see Equation 5.1) and then nitrified to NO<sub>3</sub><sup>-</sup>.

Compared to the NO<sub>3</sub><sup>-</sup> concentration at planting, the measured NO<sub>3</sub><sup>-</sup> was five fold higher in the unplanted soils at harvest (Table 5.6), indicating that nitrification was probably a significant process in the N mineralisation in this soil. In the unplanted soil the net NO<sub>3</sub><sup>-</sup> production would have produced 0.81 mmol H<sup>+</sup> kg<sup>-1</sup> soil, plus approximately 0.08 mmol of H<sup>+</sup> kg<sup>-1</sup> soil would have been released from organic S mineralisation, because SOM contains approximately 10 times less S than N (Goh, 1988). The small pH increase in the planted soils (initial pH 5.65, c.f. Figure 5.11) is consistent with uptake of NO<sub>3</sub><sup>-</sup> (OH<sup>-</sup> release from root) derived from soil organic matter mineralisation / nitrification as well as the NO<sub>3</sub><sup>-</sup> added in KNO<sub>3</sub> at the start of trial (1mmol NO<sub>3</sub><sup>-</sup> kg<sup>-1</sup> soil added) with the little N derived from N fixation.

The buffer curve (Figure 5.7) indicates that a pH drop from 5.65 to 4.85 in the unplanted soil would involve a decrease of 8 mmol OH<sup>-</sup> kg<sup>-1</sup> soil. This is larger than the net H<sup>+</sup> generation from N mineralisation (0.81 mmol N kg<sup>-1</sup> soil). Decomposition of SOM, however, may yield decomposition products of lower molecular weight organic acids that dissociated at the soil pH of 5.65 causing the soil pH to decrease. In addition it is also possible that over the period of the trial the mineralisation of organic matter may have increased the ionic strength of soil solution causing a decreased soil pH measured in water. The measured decrease in pH, however, is not equivalent to the total amount of H<sup>+</sup> produced because SPR dissolution would have neutralized approximately 8 mmol H<sup>+</sup> kg<sup>-1</sup> soil of H<sup>+</sup> generated.

Table 5.7 Estimation of  $H^+$  consumption based on SPR dissolution and total  $H^+$  production in the rhizosphere (0-4mm from mesh) of legumes grown in RSCs fertilised with SPR.

Treatment	Observed pH decrease = pH (bulk - rhizosphere) <sup>1</sup>	Observed $H^+$ released in the rhizosphere <sup>2</sup> ( $\mu\text{mol } H^+ \text{ RSC}^{-1}$ )	SPR dissolution in the rhizosphere ( $\mu\text{g SPR g}^{-1} \text{ soil}$ )	SPR dissolution in the bulk soil 4-10 mm ( $\mu\text{g SPR g}^{-1} \text{ soil}$ )	Estimated acid consumption in SPR dissolution in rhizosphere over the bulk <sup>3</sup> ( $\mu\text{mol } H^+$ )	Root released $H^+$ in the rhizosphere <sup>4</sup> ( $\mu\text{mol } H^+$ )	Rhizosphere acid involved in SPR dissolution <sup>5</sup> ( $\mu\text{mol } H^+$ )	Total acid production in the rhizosphere ( $\mu\text{mol } H^+$ )
Cowpea	0.16	24	763	716	9	33	146	170
Cowpea	0.17	25	849	830	4	28	173	197
Cowpea	0.18	34	868	846	4	38	171	205
Kidney bean	0.15	24	840	830	2	25	157	180
Kidney bean	0.14	32	897	875	5	37	199	231
Kidney bean	0.15	26	840	830	2	28	165	191
Soybean	0.23	48	887	870	3	51	177	226
Soybean	0.28	59	887	869	4	63	185	244
Soybean	0.15	28	906	868	7	36	176	204
Pigeon pea	0.15	29	935	840	19	48	185	214
Pigeon pea	0.17	28	906	859	8	37	164	192
Pigeon pea	0.17	31	878	849	5	36	165	196
Black gram	0.10	24	897	821	14	39	171	195
Black gram	0.07	12	830	821	2	14	172	184
Black gram	0.14	25	926	792	27	52	186	211
Stylosanthes	0.11	23	935	840	17	40	172	195
Stylosanthes	0.20	54	954	897	12	66	198	252
Stylosanthes	0.18	34	935	868	13	47	177	211

<sup>1</sup>Difference in  $pH_{\text{water}}$  between the bulk soil (mean pH of slices within 4-10 mm of the root interface) and rhizosphere (mean pH of slices within 0-4 mm of the root interface).

<sup>2</sup>Sum total of (pH change in the slice of rhizosphere compared to the bulk soil  $\times$  soil pH buffering capacity ( $10 \mu\text{mol } H^+ \text{ g}^{-1} \text{ pH}^{-1} \text{ soil}$ )  $\times$  weight of that soil slice) for all slices in the rhizosphere

<sup>3</sup>Differences in SPR dissolved between the rhizosphere and bulk soil ( $\mu\text{g SPR g}^{-1} \text{ soil}$ )  $\times H^+$  required to dissolve  $1 \mu\text{g SPR}$  ( $0.00865 \mu\text{mol } H^+ \mu\text{g}^{-1} \text{ SPR}$ )  $\times$  soil weight in 0-4 mm

<sup>4</sup>Observed  $H^+$  released (column 3) plus the estimated  $H^+$  consumed in SPR dissolution (column 6) by plant root within 0-4 mm of the rhizosphere

<sup>5</sup>Amount of SPR dissolved ( $\mu\text{g SPR g}^{-1} \text{ soil}$ )  $\times H^+$  required to dissolve  $1 \mu\text{g SPR}$  ( $0.00865 \mu\text{mol } H^+ \mu\text{g}^{-1} \text{ SPR}$ )  $\times$  soil weight in 0-4 mm

In the planted treatments, the observed increase in bulk soil pH (Figure 5.11) (not rhizosphere pH) compared to the initial soil pH (5.65) was probably due to the consumption of protons during SPR dissolution (Loganathan *et al.*, 1995). Application of low reactive PR (Eppawala phosphate rock) also increased soil pH on acidic soil with low pH buffering (at pH 4 to 5, 21 mmol H<sup>+</sup> kg<sup>-1</sup> pH<sup>-1</sup>) but not on acidic Ultisols with high pH buffering and high P fixation (Zoysa, 1997). Manoharan *et al.* (1995) reported similar results on a New Zealand Yellow grey Earth (Pallic soil, Hewitt, 1992) under pasture.

In planted soil, it is possible that NO<sub>3</sub><sup>-</sup> uptake by the plant causes small changes in the rhizosphere pH if NO<sub>3</sub><sup>-</sup> assimilation in the shoot is balanced by organic anion release by roots rather than OH<sup>-</sup> release. This also depends on the pKa values of the released organic anions relative to the rhizosphere pH. Normally when NO<sub>3</sub><sup>-</sup> taken up by plant roots is assimilated into plant organic N, OH<sup>-</sup> is extruded into the rhizosphere soil, and soil pH is raised (Jarvis and Robson, 1983b). However in some studies, plants taking up NO<sub>3</sub><sup>-</sup> have been shown to excrete protons and acidify their rhizosphere (Hinsinger, 1998); this suggests organate excretion for NO<sub>3</sub><sup>-</sup> uptake or excessive active basic cation accumulation in the plant, resulting in the excretion of H<sup>+</sup> ions from the root.

In the planted treatments in this study, the rhizosphere pH (0-4 mm from root-soil interface) of the six legume species was lower by 0.08 to 0.3 pH units compared to bulk soil pH (4-10 mm from root-soil interface) (Table 5.7).

Stylosanthes and soybean had a significantly lower rhizosphere pH compared to black gram and cowpea (P<0.01). There was no relationship between rhizosphere pH and the dry matter weight of legume species (R<sup>2</sup>= 6%) (Figure 5.6). The ash-alkalinity and the cation excess of the shoot were not related to pH change in the rhizosphere soil (Figures 5.7 and 5.8).

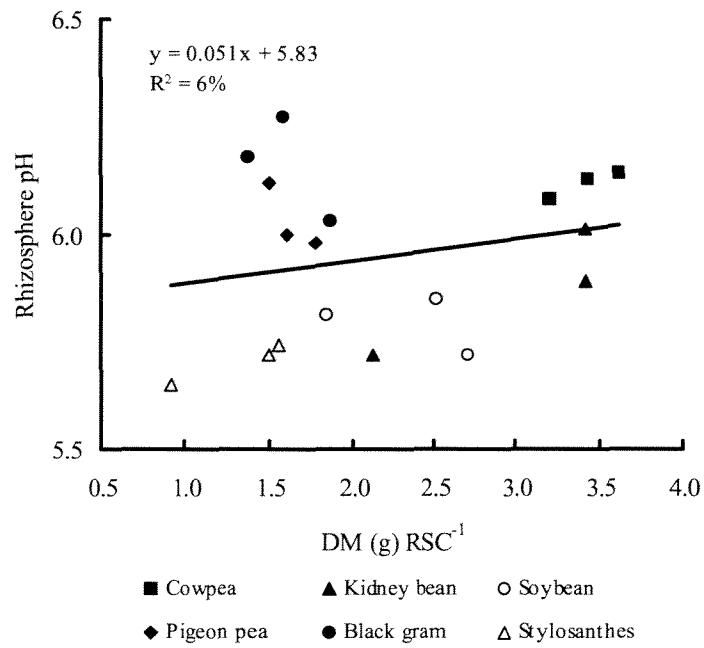


Figure 5.6 The relationship between DM of legume shoots and their rhizosphere pH.

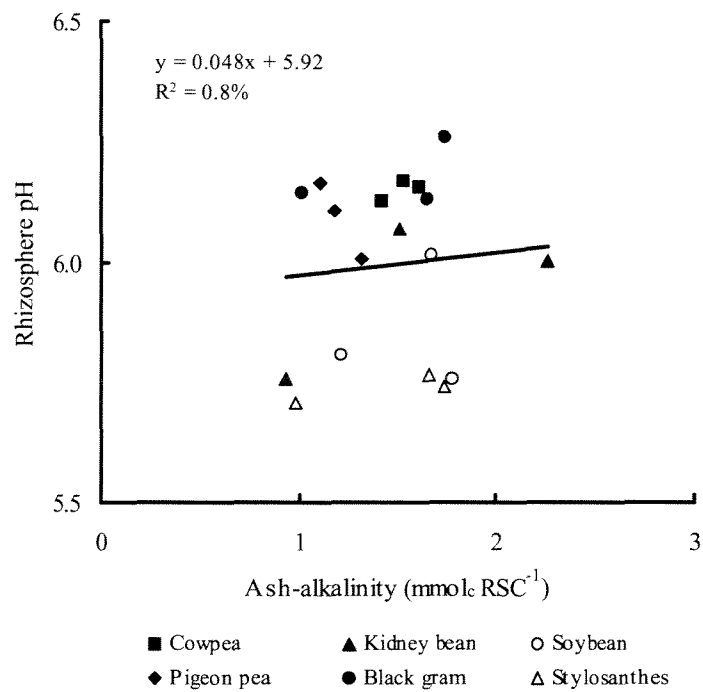


Figure 5.7 The relationship between ash-alkalinity (mmol RSC<sup>-1</sup>) of legume shoots and their rhizosphere pH.

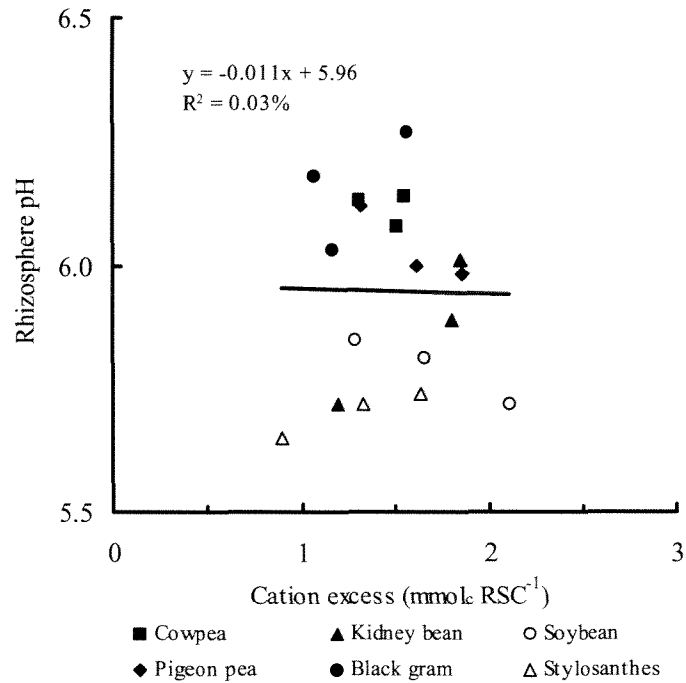


Figure 5.8 The relationship between cation excess (mmol RSC<sup>-1</sup>) of legume shoots and their rhizosphere pH

### *Observed acid or H<sup>+</sup> production*

In this section a quantitative explanation of the origins of the rhizosphere pH change is attempted.

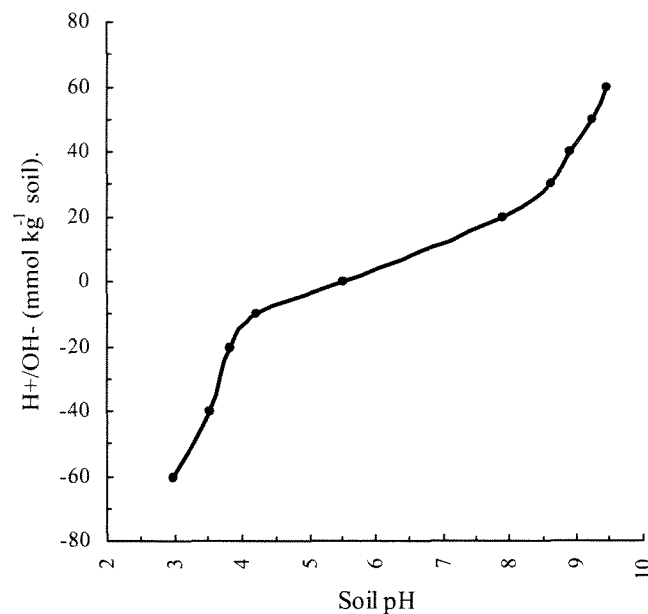
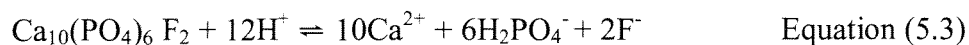


Figure 5.9 pH buffering curve of the composite Red Earth used in this study.

The amount of  $H^+$  production in the rhizosphere caused by legume roots was measured by comparing pH drop in the rhizosphere with the bulk soil, and allowing for the buffering capacity of soil (Figure 5.9). The observed  $H^+$  production within the rhizosphere soils, by legume roots, was calculated based on the difference in pH change in the rhizosphere soil slice compared with bulk soil  $\times$  soil pH buffering capacity ( $10 \mu\text{mol } H^+ \text{ g}^{-1} \text{ soil pH}^{-1}$ )  $\times$  weight of that slice. The total  $H^+$  production was summed for all slices in the rhizosphere (0 - 4 mm away from soil-root interface) (Table 5.7).

#### ***Acid ( $H^+$ ) consumption by SPR dissolution***

An additional amount of soil and rhizosphere acid would have been consumed by SPR dissolution. This can be calculated from the apparent SPR dissolution. Phosphate in RPRs is in the unprotonated form ( $\text{PO}_4^{3-}$ ) and phosphate in water-soluble P fertilisers (e.g. superphosphate) is doubly protonated ( $\text{H}_2\text{PO}_4^-$ ), which is equivalent to one mole of  $\text{CaCO}_3$  per mole of P (Sinclair *et al.*, 1993). The dissolution of phosphate rocks can be expressed by the following chemical reaction (Khasawneh and Doll, 1978):



The dissolution of PR requires acid ( $12 H^+$ ) and releases  $\text{Ca}^{2+}$  and  $\text{H}_2\text{PO}_4^-$  ions (Equation 5.3). Thus the amount of  $H^+$  consumed in dissolving SPR in the rhizosphere and the bulk soil was estimated based on the amount of SPR dissolved (see later P fractionation studies). During the dissolution of SPR, two moles of  $H^+$  were consumed for one mole of P dissolved (Loganathan *et al.*, 1995; Zoysa *et al.*, 1998). Thus the total amount of  $H^+$  consumed for SPR dissolution can be calculated from the amount of P dissolved and the amount of  $H^+$  consumed per unit P dissolved ( $0.066 \text{ mmol } H^+ \text{ mg P}^{-1}$ ). However total acids consumed in the dissolution of SPR includes both the acids reacted with the apatite in SPR plus the free carbonate in the PR. The total free carbonate content of the SPR was equivalent to 5.0%  $\text{Ca CO}_3$  (Sinclair *et al.*, 1993).

### ***Total acid (H<sup>+</sup>) production***

The effects of acid production in rhizosphere and bulk soils are reflected in both soil pH change and amounts of SPR dissolved. In this section the contributions to acid production in legume rhizosphere are estimated.

Total amount of acid released into the rhizosphere soil (0-4 mm away from soil-root interface) was calculated (Table 5.7) as a net effect of two processes: H<sup>+</sup> production by the legume roots, and amount of H<sup>+</sup> used for dissolving SPR. Both amounts were small with little extra dissolution of SPR in the rhizosphere soil slices.

The observed H<sup>+</sup> production calculated from the decrease in the soil pH and total acidity released in the rhizosphere in the lower RSC by the different legumes are given in Table 5.7. In this experiment, only 8-22% of the total acid is apparently contributed by the plant (Table 5.7). The bulk of the acid in the rhizosphere appears to be soil acid already present and that generated by oxidation processes like nitrification.

#### ***5.4.5 Interrelationship among N forms, cation excess and H<sup>+</sup> production into rhizosphere***

The cation excess calculated in Table 5.5 does not include the contributions that NH<sub>4</sub><sup>+</sup> ions make to cation uptake and NO<sub>3</sub><sup>-</sup> ions make to anion uptake. For legumes the cation - anion uptake charge imbalance resulting in H<sup>+</sup> extrusion from roots can be expressed as (Troelstra *et al.*, 1985):

$$\text{Root released H}^+ (\mu\text{eq}) = \sum(\text{Ca}^{2+} + \text{K}^+ + \text{Na}^+ + \text{Mg}^{2+} + \text{NH}_4^+) - \sum(\text{H}_2\text{PO}_4^- + \text{SO}_4^{2-} + \text{Cl}^- + \text{NO}_3^-) \quad \text{Equation (5.3)}$$

The  $\mu\text{eq}$  of NH<sub>4</sub><sup>+</sup> and NO<sub>3</sub><sup>-</sup> taken up are uncertain and can be expressed as:

$$\text{NH}_4^+ (\mu\text{eq}) = \alpha (\text{Plant total N}) \quad \text{Equation (5.4)}$$

Where  $\alpha$  is the fraction of plant total N derived from NH<sub>4</sub><sup>+</sup> uptake from soil

$$\text{Fixed N } (\mu\text{eq}) = \beta (\text{Plant total N}) \quad \text{Equation (5.5)}$$

Where  $\beta$  is the fraction of plant total N derived from biological N fixation

$$\text{NO}_3^- (\mu\text{eq}) = (1 - (\alpha + \beta)) \text{ Plant total N} \quad \text{Equation (5.6)}$$

To conduct a comparative analysis of the impact of legume N nutrition on the quantities of root released  $\text{H}^+$  values for  $\alpha$  and  $\beta$  must be estimated. This comparative analysis is made simpler when the legume species have not nodulated (kidney bean, stylosanthes and one soy bean plant) and  $\beta$  becomes 0, and the expression for root released  $\text{H}^+$  becomes:

$$\begin{aligned} \text{Root released } \text{H}^+ (\mu\text{eq}) = & \sum(\text{Ca}^{2+} + \text{K}^+ + \text{Na}^+ + \text{Mg}^{2+} + \alpha \text{ Plant N}^+) - \sum(\text{H}_2\text{PO}_4^- + \text{SO}_4^{2-} \\ & + \text{Cl}^- + (1 - \alpha) \text{ Plant N}^-) \end{aligned} \quad \text{Equation (5.7)}$$

or

$$\begin{aligned} \text{Root released } \text{H}^+ (\mu\text{eq}) = & \text{Cation excess} + \alpha \text{ Plant N}^+ - (1 - \alpha) \text{ Plant N}^- \\ = & \text{Cation excess} + \text{Plant N} (2\alpha - 1) \end{aligned} \quad \text{Equation (5.8)}$$

Soil contamination influencing the weights of root digested caused error in the determination of root cation and anion concentrations. This prevented calculation of total plant N and total plant cation excess. Experience from other experiments indicated that the root N contribution in RSC grown legumes ranges from 0.35-0.25 of total plant N. As total plant N could not be determined accurately the seed N contribution to plant N was also not corrected for.

The subsequent calculations in this section utilize shoot N and shoot cation excess values only. Thus while  $\alpha$  values are determined from shoot values only they will indicate the proportion of  $\text{NO}_3^-$  and  $\text{NH}_4^+$  taken up but underestimate the total amount of  $\text{NO}_3^-$  and  $\text{NH}_4^+$  taken up since they do not consider the root N pool. In addition the root released  $\text{H}^+$  will overestimate that generated by shoot CE alone. The calculation is continued for instructive purpose only. It is essential to obtain uncontaminated root samples if accurate calculations are required (Troelstra *et al.*, 1985).

The root release  $H^+$  in the rhizosphere of kidney bean was calculated to range from 25-37  $\mu\text{mol } H^+$  (Table 5.7). If this is considered to have been released by approximately 12-16% of the root mass within 3mm of the separating mesh then it is equivalent to approximately 50% of the acid released by these roots (The other 50% diffusing into the upper container rather than the lower container). Thus we can estimate that the whole kidney bean root system released  $H^+$  as:

$$\text{Root released } H^+ (\mu\text{eq}) = \text{Rhizosphere released } H^+ (\mu\text{eq}) / \text{Fraction of roots in rhizosphere} \times 2 \quad \text{Equation (5.9)}$$

Root released  $H^+$  ( $\mu\text{eq}$ ) estimates, the cation excess and plant N values were used in Equation (5.8) to estimate values for the portion of total N taken up as  $\text{NH}_4^+$ .

Example calculation for first kidney bean plant:

$$\text{Root released } H^+ (\mu\text{eq}) = 25 / 0.16 \times 2 = 313 (\mu\text{eq}) \text{ RSC}^{-1}$$

$$\text{Root released } H^+ (\mu\text{eq}) = \text{CE} + \text{Plant N} (2\alpha - 1)$$

$$\alpha = ((-\text{CE} + \text{root released } H^+) / \text{plant N} + 1) / 2$$

$$\alpha = ((-1850 + 313) / 4950 + 1) / 2$$

$$\alpha = 0.34$$

The estimates for all non-nodulated plants indicate that between 28 and 41 % of non-nodulated legume N would have to be taken up as  $\text{NH}_4^+$  for the cation – anion uptake balance to have generated the observed root released  $H^+$ .

The uncertainly  $\alpha = (0.28 \text{ to } 0.41)$  in the proportion of plant N taken up, leaves little value in trying to estimate  $\beta$  the proportion of total N fixed. Therefore these values have not been estimated for nodulated legumes.

Table 5.8 The excess of cations over anions in shoots, which correspond to the release of  $H^+$  from roots of different legume varieties into the rhizosphere soil ( $\mu\text{eq RSC}^{-1}$ ).

Legume Unnodulated ×	Shoot N ( $\mu\text{eq RSC}^{-1}$ )	Fraction of root mass within 3 mm above the mesh	Estimated root released $H^+$ in the rhizosphere ( $\mu\text{mol } H^+$ )	Total root released $H^+$ ( $\mu\text{eq RSC}^{-1}$ ) <sup>1</sup>	Observed cation excess for whole shoot ( $\mu\text{eq RSC}^{-1}$ )	$\alpha$	Estimated $NH_4^+$ taken up ( $\mu\text{eq RSC}^{-1}$ ) <sup>2</sup>	Estimated $NO_3^-$ taken up ( $\mu\text{eq RSC}^{-1}$ ) <sup>3</sup>
Cowpea	3860	0.34	33	194	1560			
Cowpea	2730	0.32	28	175	1510			
Cowpea	3060	0.32	38	238	1300			
Kidney bean ×	4950	0.16	25	313	1850	0.34	1706	3244
Kidney bean ×	3170	0.12	37	617	1190	0.41	1298	1872
Kidney bean ×	3640	0.13	28	431	1810	0.32	1148	2492
Soybean	2950	0.23	51	443	1290			
Soy bean	2990	0.28	63	450	2100			
Soybean ×	2740	0.17	36	424	1660	0.28	765	1975
Pigeon pea	2420	0.40	48	240	1310			
Pigeon ea	3040	0.40	37	185	1860			
Pigeon pea	2570	0.43	36	167	1610			
Black gram	2020	0.37	39	211	1060			
Black gram	2360	0.43	14	65	1570			
Black gram	2250	0.35	52	297	1160			
Stylosanthes ×	1550	0.34	40	235	890	0.37	580	970
Stylosanthes ×	2400	0.24	66	550	1630	0.39	935	1465
Stylosanthes ×	2350	0.29	47	324	1320	0.34	809	1541

<sup>1</sup>Total root released  $H^+$  ( $\mu\text{eq RSC}^{-1}$ ) = (Rhizosphere released  $H^+$  ( $\mu\text{eq}$ ) / Fraction of roots in rhizosphere) × 2

<sup>2</sup> $NH_4^+$  =  $\alpha$  (Shoot N).

<sup>3</sup> $NO_3^-$  = (1 -  $\alpha$ ) Shoot N.

## 5.5 Soil P fractionations of Red Earth and Ramiha hill soils

### 5.5.1 P fraction in native soils (without SPR added)

The strongly weathered soils of humid tropics are low in total P (Hedley *et al.*, 1994). Soil forming factors (climate, vegetation and fauna, topography, parent material and time span, soil management by humans) are quite different between the two mineral soils used in this study. These factors can explain why the Red Earth and Ramiha hill soil had markedly different in chemical P fractions (Figure 5.10).

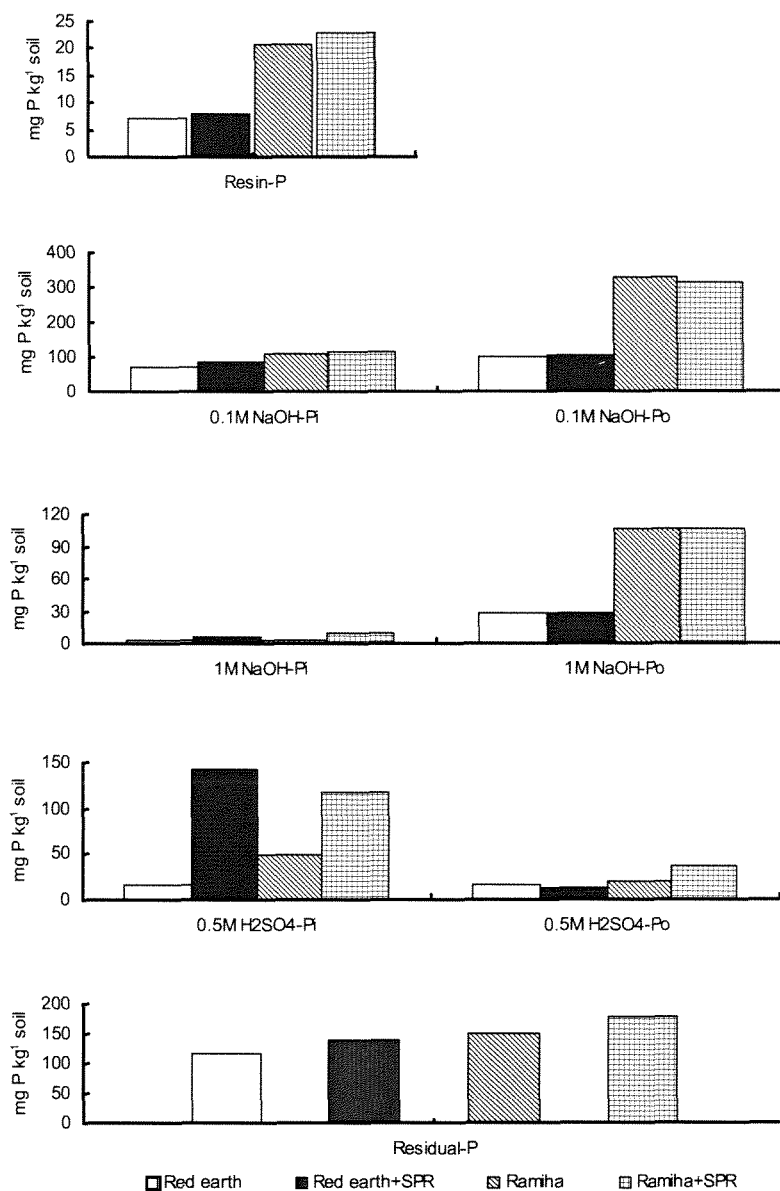


Figure 5.10 P fractions in SPR fertilised and unfertilised air-dried Red Earth and Ramiha soils immediately after the addition of RPR at the rate of  $125 \mu\text{g P g}^{-1}$  soil.

### *Resin-P*

Compared to the temperate Ramiha hill soil, the tropical Red Earth had three times less resin-P (readily plant-available P) for plant growth and development. The reason may be because the Ramiha soil came from pastureland, which had regularly received inorganic P fertilisers at least at maintenance rates for pasture growth, but the Red Earth came from arable land and had received none, or low quantities of inorganic P fertilisers.

### *Alkali-P*

Ramiha soil had markedly higher alkali soluble P (0.1 M and 1 M NaOH-Pi and Po), in particular the NaOH-Po fraction was significantly higher than the Red Earth. One reason is that Red Earth comes from an old and deeply weathered environment with a warm subtropical monsoon climate (see Chapters 1 and 2). It can be expected that the rate of SOM decomposition is more rapid than the rate of SOM accumulation in Red Earth, since it is found in the tropics and is a regularly cultivated soil (Hedley *et al.*, 1995). However, in the Ramiha soil the mineralisation rate of SOM may be low relative to the SOM accumulation rate under permanent pasture (Francis and Knight, 1993; Francis *et al.*, 1999) because it is found at ~300-400 m attitude, with a 1,400 mm annual rainfall and mean maximum temperature of 17.5°C.

### *H<sub>2</sub>SO<sub>4</sub>-P*

H<sub>2</sub>SO<sub>4</sub>-Pi fraction in the Ramiha soil was larger than the Red Earth. One explanation is that the native P in soil was derived from apatite in the soil-forming parent materials. Although apatite is highly insoluble in water, the P can be liberated and subsequently depleted by strong weathering processes over time. The primary apatite P is gradually mobilised and changed into organic P and secondary mineral P. Phosphate is then lost from the soil profile by erosion and leaching (Walker and Syers, 1976). Therefore the older, more strongly weathered, Red Earth contained very little P from apatite origins but the younger Ramiha soil may have more residual apatite and in addition has probably accumulated residual unacidulated apatite from regular dressings of superphosphate fertiliser (Quin and Rickard, 1983).

### *Residual-P*

Residual-P was the largest P fraction in both soils. This P fraction contains highly insoluble organic and inorganic compounds, containing P probably complexed with sesquioxides and silicate minerals. In temperate soils, this fraction is very stable and is not readily mineralised to labile plant-available P fractions (Hedley *et al.*, 1982a).

#### **5.5.2 P fractions in the Red Earth and Ramiha hill soils mixed with SPR**

Application of SPR to dry soil samples significantly increased the H<sub>2</sub>SO<sub>4</sub>-Pi pool (Figure 5.10, Table 5.9) compared to untreated soils.

There was no significant difference in alkali extractable-Pi and Po between SPR mixed and untreated Red Earth. This indicates that SPR did not dissolve to any great extent in dry mixed Red Earth. In comparison with untreated, the slightly higher value in the Resin-P and NaOH-Pi fractions of SPR-mixed soils is mainly due to a small amount of SPR dissolution in the 16-hour resin extraction procedure. This occurs especially when soils of low pH containing RPR are resin extracted (Zoyza *et al.*, 1997 and Trolove *et al.*, 1996b).

The main significant difference between SPR-mixed and untreated Red Earth is in the H<sub>2</sub>SO<sub>4</sub>-Pi, which was due to the SPR dissolution in 0.5 M H<sub>2</sub>SO<sub>4</sub> acid extraction. The quantity of residual-P, although raised slightly in the soil + SPR treatments, was not significantly different between SPR-mixed and without SPR treated soils. This indicates that 0.5 M H<sub>2</sub>SO<sub>4</sub> can dissolve all the apatite-bound P in SPR.

In the case of the Ramiha soil substantial amount of the SPR (22%) appeared in the residual fraction. The only explanation for this is that during the resin or H<sub>2</sub>SO<sub>4</sub> extractions some dissolved SPR-P was resorbed and complexed with non-alkali or non-acid soluble materials.

Recovery of P from added SPR was calculated as the difference between H<sub>2</sub>SO<sub>4</sub>-Pi extracted P from mixed-SPR and unmixed soils. The values are expressed as a percentage of the amount P added using the following formula:

Recovery of P from added SPR (%) =  $100[(\text{P fraction in SPR mixed soil} - \text{P fraction in untreated soil})/\text{SPR added P}]$

Table 5.9 P fractions in SPR-mixed dry Red Earth and Ramiha hill soil, and percent recovery of added SPR in the various P fractions.

P fraction	Red Earth			Ramiha hill soil		
	Untreated	SPR treated	P recovery (%)	Untreated	SPR treated	P recovery (%)
Resin-P	6.9	8.0	0.9	20.8	22.9	1.7
0.1 M NaOH-Pi	70.5	83.8	10.7	110.5	115.9	4.3
0.1 M NaOH-Po	3.7	6.5	2.4	3.7	9.3	4.5
1 M NaOH-Pi	100.6	103.9	2.6	326.8	313.2	10.9
1 M NaOH-Po	27.4	27.4	0.0	105.9	105.9	0.0
H <sub>2</sub> SO <sub>4</sub> -Pi	15.6	142.2	101.3	48.9	116.6	54.2
Residual-P	115.6	119.6	3.3	150.7	178.5	22.2
Total P	340.3	491.4	120.9	753.7	876.0	97.8

## 5.6 Effect of legumes on soil P fractions in Red Earth

### 5.6.1 Effect of plant species on rhizosphere pH

Irrespective of harvest time, all legume species caused slight acidification at their soil-root interface compared to non-rhizosphere soil at 8-10 mm away from the soil-root interface (Table 5.7). As discussed earlier the decrease in pH between planted and unplanted soils ( $\Delta$  pH) was considered to be due to nitrification (unplanted soil) and nitrate uptake (planted soil) (Figure 5.11). Zoysa *et al.* (2001) also observed a significantly lower pH in soils planted with tea compared to unplanted soils.

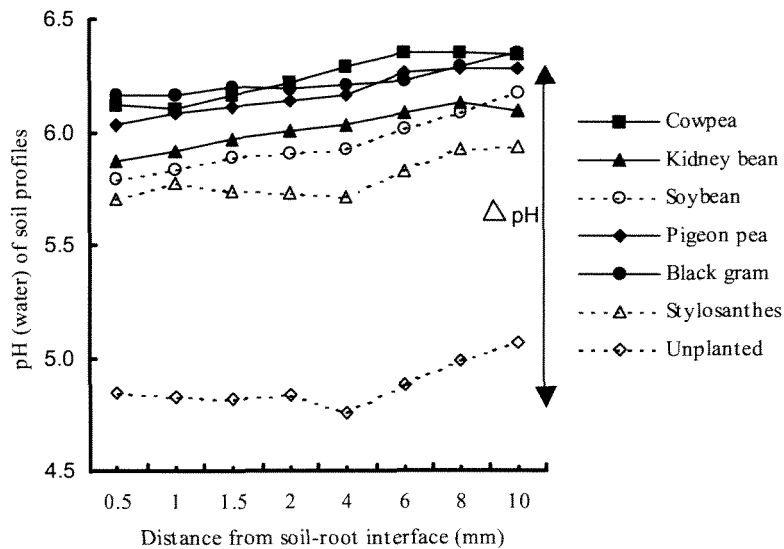


Figure 5.11 Effect of legume species on rhizosphere pH at harvest.

### 5.6.2 Depletion of P fractions

Different plant species or cultivars have different abilities to recover soil and fertiliser P. The legume roots altered the distribution of P in rhizosphere soils, compared to the unplanted control (Figure 5.12 and 5.13). The unplanted RSCs showed that there were no significant differences in any fractions of P in soil slice collected at various distances from the soil root interface, except resin-P. Thus, any difference observed in the P fractions between the rhizosphere and bulk soils was expected to be due to the effect of legume roots in the planted RSCs. The rhizosphere effect appears to extend 4 mm from the mesh and is most marked with the patterns of depletion of 0.1M NaOH (Figure 5.12), 1M NaOH (Figure 5.13) and the sum of all fractions (total P). To clarify the changes in soil and SPR fractions caused by time and rhizosphere effects the weighted mean amounts of fractions were calculated for rhizosphere soil (0-4 mm) from the mesh and bulk soil (4-10 mm) from the mesh.

A depletion in available-Pi (resin-P + 0.1 M NaOH-Pi) fractions was observed for all legume species in rhizosphere (0-4 mm) and bulk soils (4-10 mm), compared to the unplanted treatment. There was a slight change in available-Pi with distance from the mesh in the unplanted treatment (Figures 5.14 and 5.15). This may result from the soil being in a more oxidised state at the mesh boundary. This may inturn lead to higher P sorption, reducing resin-P concentration. In all legume treatments, available-Pi was

more depleted in rhizosphere than bulk soil. There is no doubt that soil Pi depletion is caused by uptake of P by legume plants.

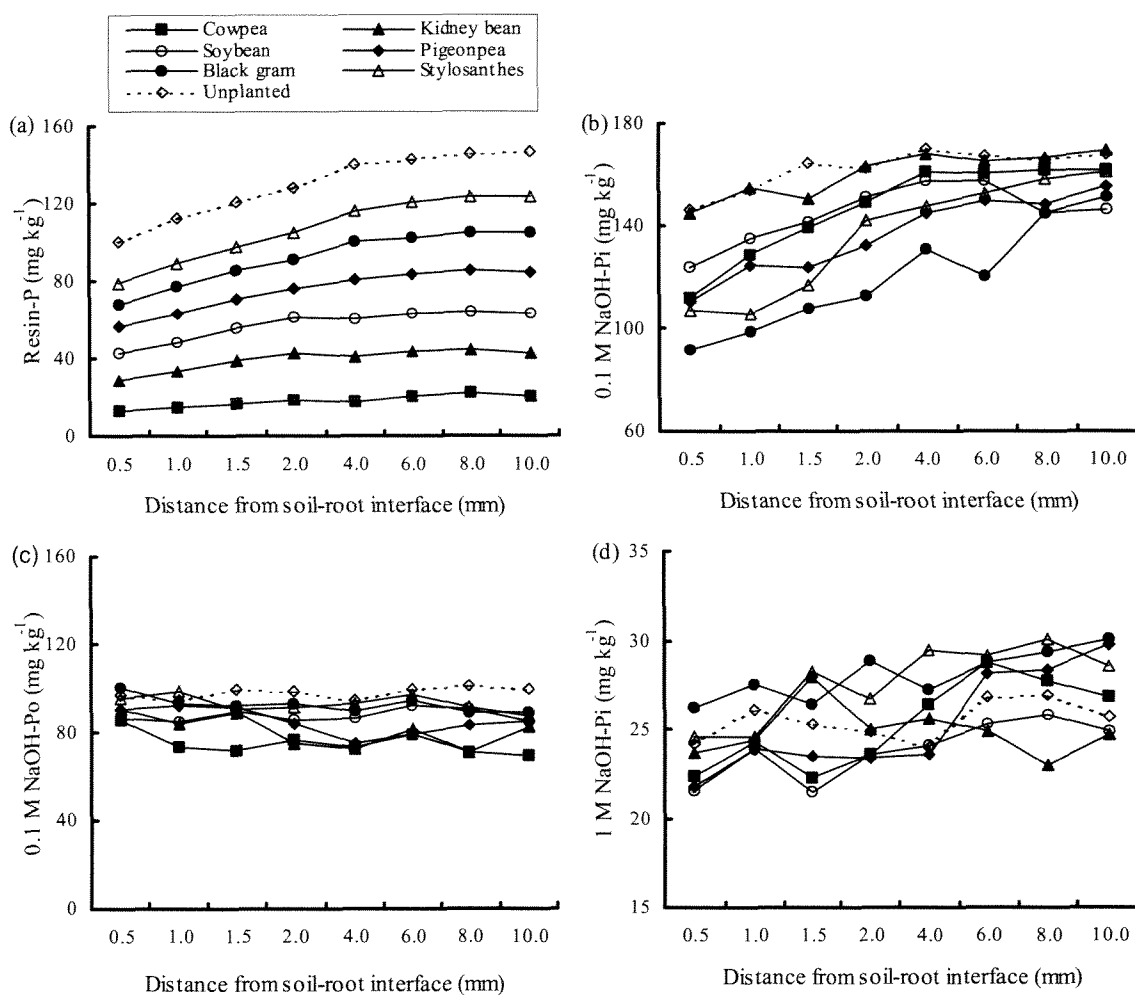


Figure 5.12 The effect of plant species on various P fractions in the rhizosphere (a) Resin-P, (b) 0.1 M NaOH-Pi, (c) 0.1 M NaOH-Po, (d) 1 M NaOH-Pi.

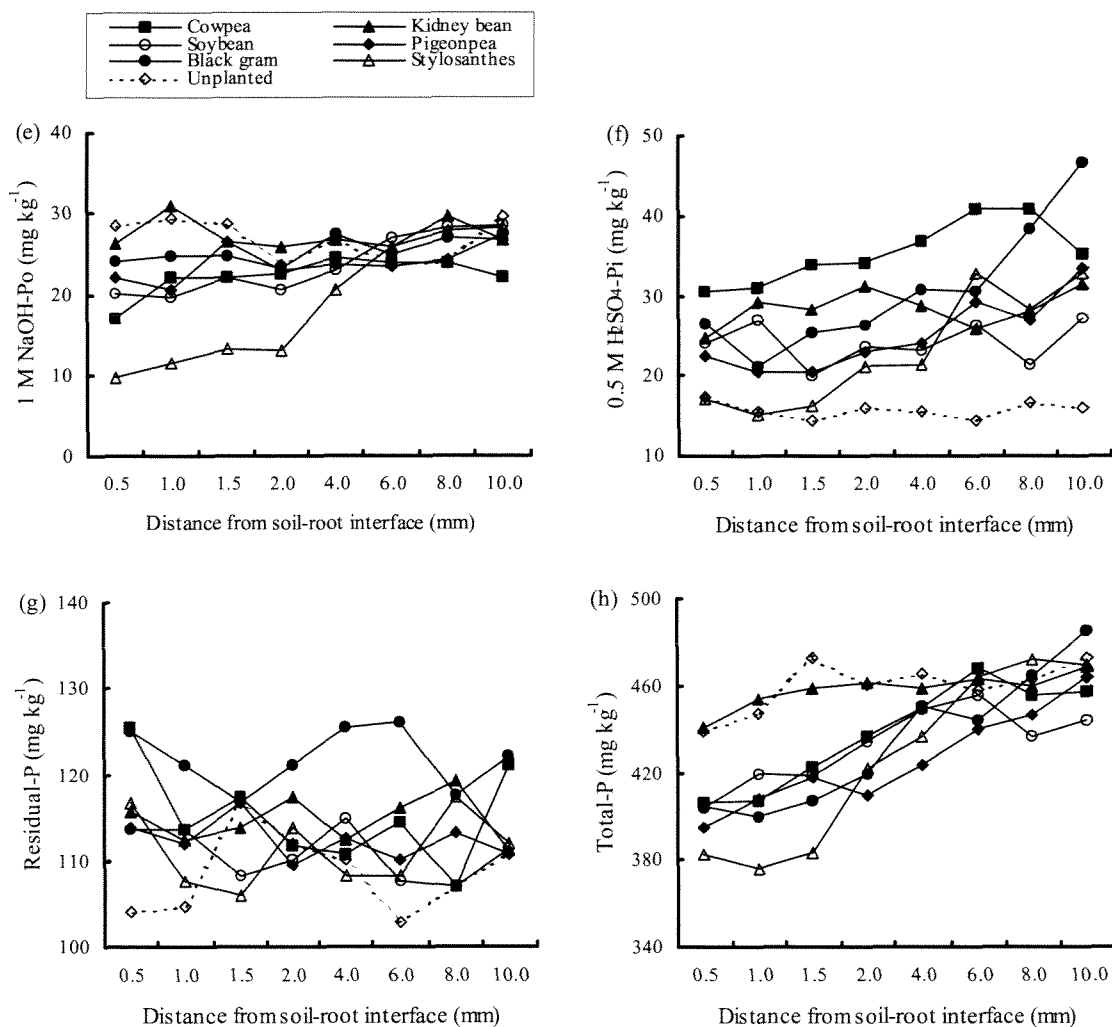


Figure 5.13 The effect of plant species on various P fractions in the rhizosphere: (e) 1 M NaOH-Po, (f) 0.5 M  $\text{H}_2\text{SO}_4$ -Pi (g) Residual-P, (h) Total-P.

All of the added SPR ( $125 \text{ mg P kg}^{-1}$  soil) to the legume treatments was recovered as shown by increases in sum of P fractions in the bulk soil (4-10 mm) compared to untreated Red Earth. Irrespective of bulk or rhizosphere soils, alkali-Pi fractions was the dominant fraction at harvest (Figures 5.14 to 5.17), showing a 32-95  $\text{mg P kg}^{-1}$  soil increase caused by SPR dissolution.

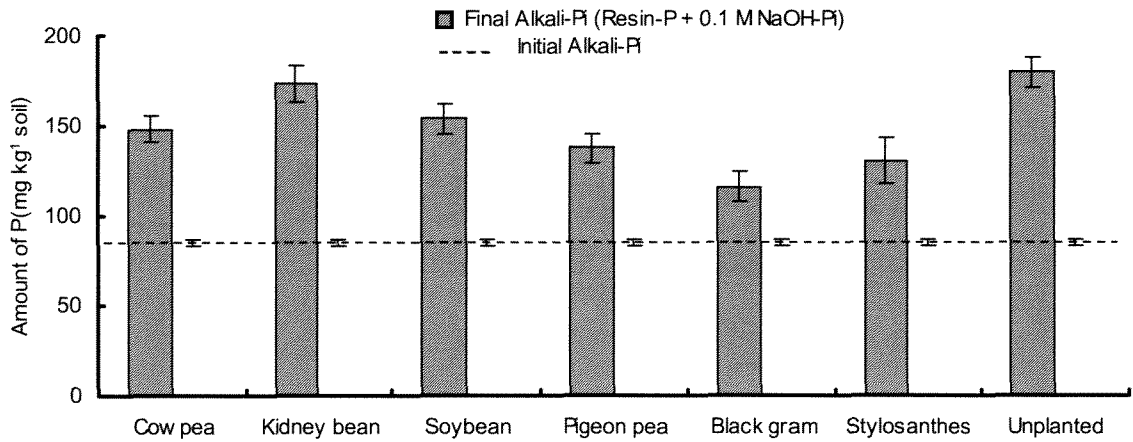


Figure 5.14 Weak Alkali-Pi (Resin-P+ NaOH-Pi) fraction of the rhizosphere soil and soil dry mixed with SPR (initial alkali-Pi).

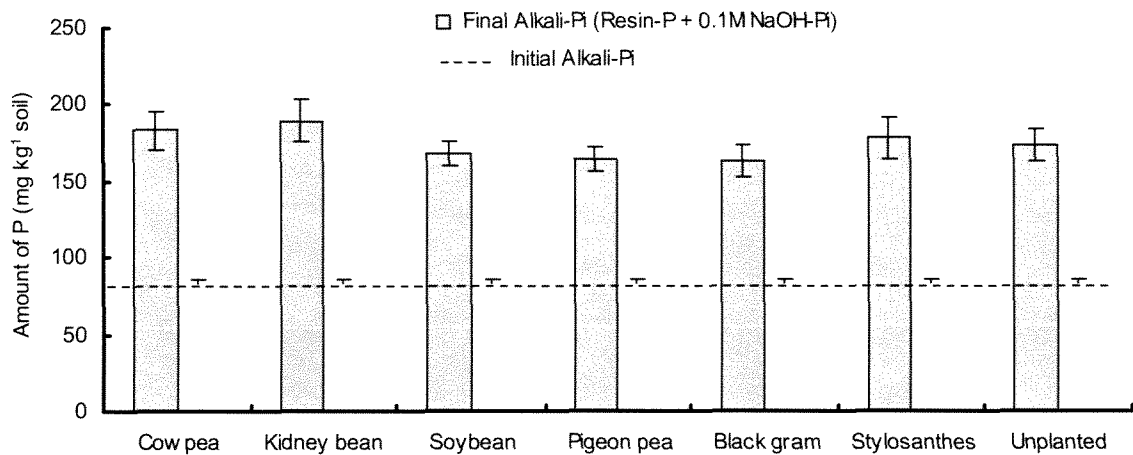


Figure 5.15 Weak Alkali-Pi (Resin-P+ NaOH-Pi) fraction of the bulk soil and soil dry mixed with SPR (initial alkali-Pi).

All legume species caused little depletion of alkali-P<sub>o</sub> in rhizosphere soil (Figure 5.16) and the extent of depletion was similar in bulk soil (Figure 5.17).

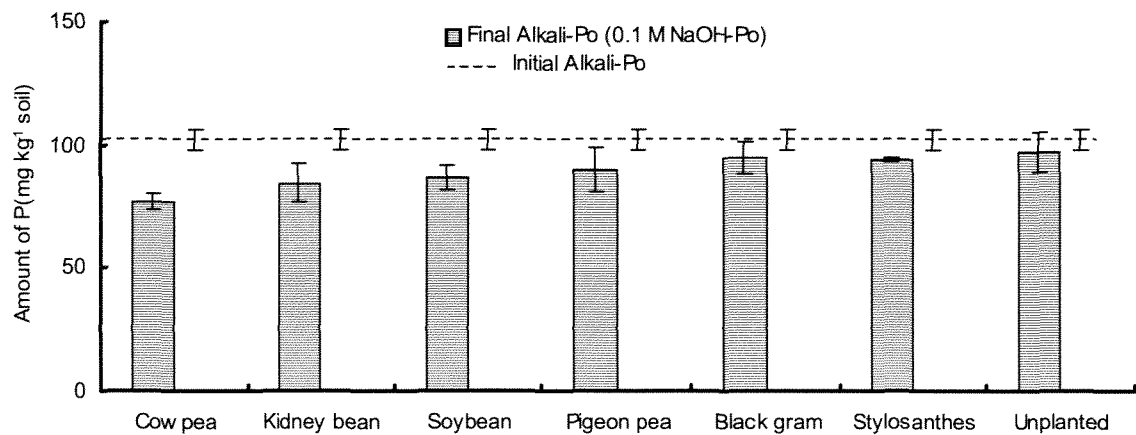


Figure 5.16 Weak Alkali-Po (NaOH-Po) fraction of the rhizosphere soil and soil dry mixed with SPR (initial alkali-Po).

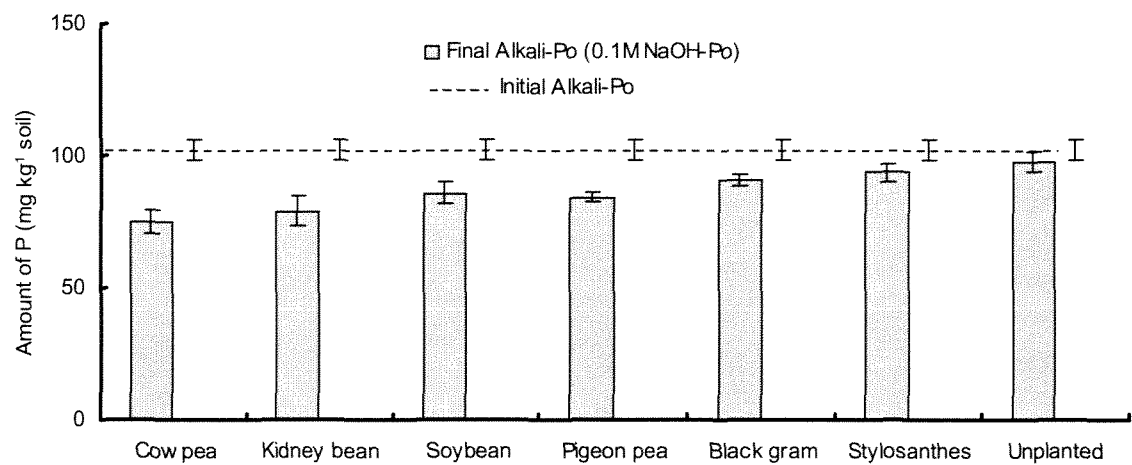


Figure 5.17 Weak Alkali-Po (NaOH-Po) fraction of the bulk soil and soil dry mixed with SPR (initial alkali-Po).

The  $H_2SO_4$ -Pi fraction was markedly decreased compared to initial  $H_2SO_4$ -Pi fraction and indicates that the majority of the added SPR dissolved in the Red Earth within a short-term (Figures 5.18 and 5.19). This contrasts with previous works (Trollove et al, 1996b; Zoysa, 1997) where the dominant P fraction in PR treated soil was still undissolved RPR in the  $H_2SO_4$ -Pi at harvest.

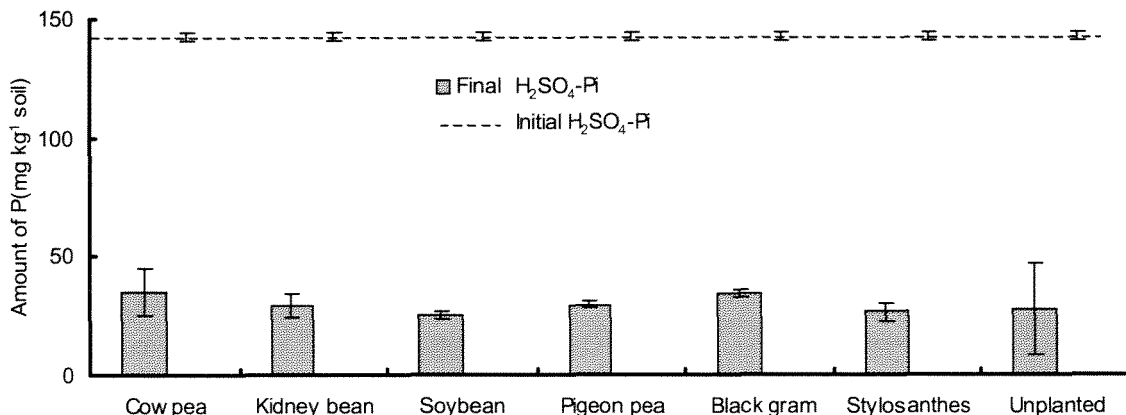


Figure 5.18 H<sub>2</sub>SO<sub>4</sub>-Pi fraction of the rhizosphere soil and soil dry mixed with SPR (initial H<sub>2</sub>SO<sub>4</sub>-Pi).

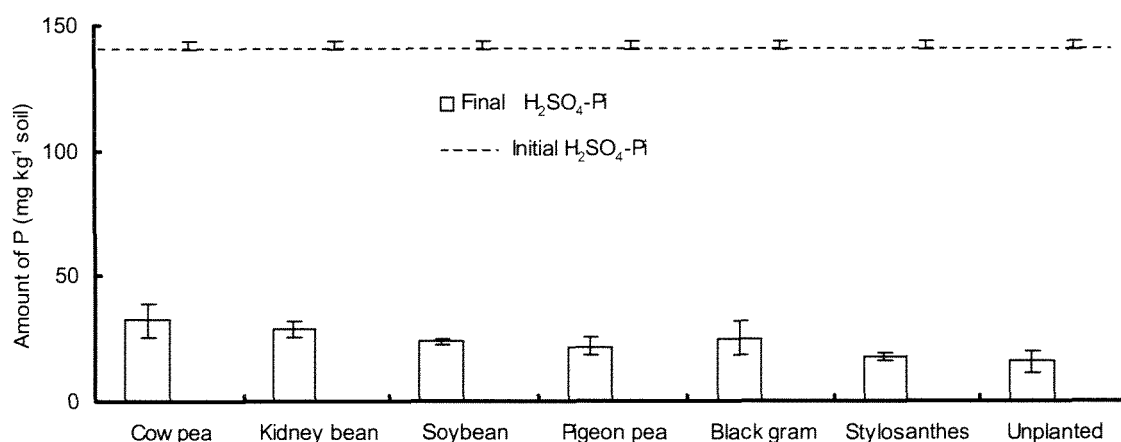


Figure 5.19 H<sub>2</sub>SO<sub>4</sub>-Pi fraction of the bulk soil and soil dry mixed with SPR (initial H<sub>2</sub>SO<sub>4</sub>-Pi).

### *Effect of legume species on P utilisation efficiency*

All legume P concentrations were very low showing marked P deficiency when grown on the Red Earth. Phosphate use efficiency can be categorised as external P efficiency and internal P efficiency. The external efficiency of P use corresponds to total P uptake by a plant from a unit volume of soil. The internal efficiency of P use is defined as the amount of plant biomass synthesised per a unit P taken up by that plant (g DM/mg P taken up: mg P taken up = (P concentration × DM) – seed P).

Table 5.10 The effect of legume species on external and internal P use efficiencies.

Name	Shoot P (mg g <sup>-1</sup> )	Shoot DM (g RSC <sup>-1</sup> )	Seed P (mg RSC <sup>-1</sup> )	External P <sup>1</sup> (mg)	Internal P <sup>2</sup> (mg)
Cowpea	0.45	3.63	1.01	0.62	5.89
Cowpea	0.55	3.20	1.01	0.74	4.30
Cowpea	0.45	3.43	1.01	0.54	6.40
Kidney bean	1.04	3.42	2.16	1.39	2.45
Kidney bean	1.20	2.13	2.16	0.39	5.44
Kidney bean	0.84	3.42	2.16	0.73	4.68
Soybean	0.50	2.51	0.92	0.33	7.60
Soybean	0.55	2.71	0.92	0.57	4.77
Soybean	0.65	1.84	0.92	0.27	6.86
Pigeon pea	0.70	1.51	0.94	0.12	12.91
Pigeon pea	1.88	1.79	0.94	2.43	0.74
Pigeon pea	1.04	1.61	0.94	0.74	2.17
Black gram	0.65	1.38	0.33	0.56	2.46
Black gram	0.89	1.59	0.33	1.08	1.47
Black gram	0.74	1.87	0.33	1.06	1.76
Lentil bean	1.31	0.39	0.11	0.40	0.98
Lentil bean	1.30	0.34	0.11	0.33	1.03
Lentil bean	1.20	0.40	0.11	0.36	1.09
Stylosanthes	1.00	0.91	0.03	0.88	1.03
Stylosanthes	0.84	1.57	0.03	1.30	1.21
Stylosanthes	1.20	1.50	0.03	1.77	0.85

<sup>1</sup>External P = (Shoot P × Shoot DM) – Seed P.

<sup>2</sup>Internal P = Shoot DM/External P.

Irrespective of harvest time, the large alkali-P depletions in rhizosphere soils of cowpea and black gram (Figures 5.12b or 5.14 c.f. Figure 5.15) were considered to be caused by their faster growth rate and greater external P efficiency of these species compared to stylosanthes and pigeon pea, which have slower growth. Therefore plant species vary in both their P needs and efficiency of P use. The external efficiency of P utilisation of the legume species tested followed: stylosanthes > pigeon pea > black gram > kidney bean > cowpea > lentil bean > soybean (Table 5.10). However the internal P use efficiency of legume species followed: cowpea > soybean > pigeon pea > kidney bean > black gram > stylosanthes ≥ lentil bean (Table 5.10). In the present study, stylosanthes showed greater external efficient utilisation of P and cowpea showed greater internal efficient utilisation of P than the other legume species.

## 5.7 Conclusions

All legumes grown in this experiment released H<sup>+</sup> into their rhizosphere soils and it caused a slight pH decrease in the Red Earth. The pH decrease was less than expected for legumes and may reflect the small plant biomass produced during the short growth

period. The pH decrease was greater, however in unplanted soils due to SOM mineralisation and nitrification of soil and fertiliser  $\text{NH}_4^+$ .

The small decrease in pH in the legume rhizosphere soil could be attributed mostly to 28-41 % of plant N being taken up as  $\text{NH}_4^+$  rather than caused by N fixation.

The ash-alkalinity and the cation excess of the shoot material were positively correlated, but neither was related to pH change in the rhizosphere soil.

The lack of relationship between cation excess and rhizosphere pH suggests that unless the source of legume N is solely fixed N then cation excess and ash-alkalinity measures are not useful in selecting legumes for their capability to acidify their rhizosphere.

SPR dissolution was almost complete in unplanted samples of Red Earth incubated for the same duration as legume growth. The presence of legumes did not increase the dissolution of RPR in this soil. It can be concluded that natural level of soil acidity present in Red Earths makes them suited to direct application of RPR irrespective of legume cultivation.

In selecting legumes as green manures ones with high external P efficiency would be suitable, i.e. they would recover more soil P into the green manure. For this purpose stylosanthes, pigeon pea and black gram seem most suitable.

For growth as food crops those legumes with greater internal P efficiency may be best, i.e. they would grow more DM per unit P taken up. For this purpose cowpea and soybean show more internal P efficiency than stylosanthes and black gram.

## **CHAPTER 6    Effect of Different Sources of Phosphorus Fertilisers on Maize Growth and their Residual Value**

### **6.1    Introduction**

As explained in Chapter 1, the fertility of Red Earths and Yellow Earths in the highlands of Southern Shan State are gradually degrading due to shifting cultivation with shortening fallow periods, and insufficient use of fertilisers, manures and restorative crops in current soil fertility management practices.

In this study, soil resources of the Red Earths and Yellow Earths were chemically characterised to select a representative area of low fertility soil for field experimentation in Southern Shan State (see Chapter 2). The results of the analyses confirmed that the chemical constraints to crop growth on the Red Earths and Yellow Earths at the research sites at Aungban, in Southern Shan State, are those common to the soils of the region. The major constraints of the Red Earths and Yellow Earths were very low available P status and low pH (see Table 2.3, Chapter 2). These Red Earths and Yellow Earths also have low SOM content that results in limited N, P and S reserves and low CEC resulting in poor retention of exchangeable basic cations.

The application of P fertilisers, especially water-soluble P (TSP), and local dolomite improved P availability and reduced acidity in the Red Earths and Yellow Earths, and increased plant yield under glasshouse conditions (Chapter 3). The indigenous Myanmar phosphate rock (MPR), characterised as an unreactive PR, was shown to be of little agronomic value in glasshouse experiments (Chapter 3) suggesting that it would be an ineffective P fertiliser for direct application to Yellow Earths in the field.

As mentioned in Section 1.8.1 (Chapter 1), Hammond *et al.* (1986) recommended partial acidulation of PR to convert less reactive phosphate rocks into suitable P sources (PAPRs) for crop production in the tropics. Sulphuric acid PAPR may have additional advantages in supplying available sulphate for plant growth. Gregg *et al.* (1988) mentioned that the products of sulphuric acid acidulated PAPR are often the most economic P fertilisers because they have immediately available soluble P, greater

residual P value and an agronomically useful S supply. As explained earlier, imported TSP is expensive, but it is the major P fertiliser used to correct P deficiency in Myanmar. A Chinese-manufactured PAPR is available, however, but its agronomic effectiveness has not been extensively evaluated for crops on Yellow Earths in Myanmar. In recent years, Myanmar farmers have realised that maximum returns per investment in fertiliser are required, rather than maximum production per hectare. In addition, in Myanmar price subsidies on imported fertilisers, based on their soluble P content, have been removed forcing farmers to purchase cheaper P fertilisers such as PR, PAPR and organic manures. The relative agronomic effectiveness of PAPR is briefly reviewed later in Section 6.3.3.

More recently there has been renewed research interest in using organic manures as alternatives to expensive chemical fertilisers to improve soil fertility and quality in the tropical regions (Budianta, 1999; Cong, 2000). Several workers (Khaleel *et al.*, 1981; Darmody *et al.*, 1983; Hue, 1992; Falih and Wainwright, 1996) reported that the addition of organic materials (plant residues and animal manures) play an important role in increasing SOM content and nutrient reserves in infertile soils. The benefits to soil fertility from optimum levels of SOM were discussed in Section 4.1.1 (Chapter 4). The agronomic values of the organic residues vary greatly with the quantity of biomass applied and its nutrient concentration. The effect of quantity and quality of legume green manures on plants and soil are discussed later in Chapter 8.

As mentioned in Chapter 1, FYM is the most commonly used conventional organic fertiliser in Myanmar. Glasshouse studies (Chapter 3) suggested that a typical FYM from Myanmar had poor agronomic value for upland rice on the Yellow Earths. In the field study described in this chapter the same source of FYM is evaluated on the Yellow Earth using the field grown maize.

As discussed in Chapter 1, the use of wild sunflower (*Tithonia diversifolia*) as a green manure has potential to provide a low cost source of organic N and P. This plant grows wild in Southern Shan State. The biomass of this plant has relatively high P and K concentrations (2 to 5.6 g P kg<sup>-1</sup> DM and 23 to 55 g K kg<sup>-1</sup> DM) and it has been used as a green manure for acid upland soils (Cong, 2000). Earlier workers (Palm *et al.*, 1999; Buresh *et al.*, 1997; Cong, 2000) indicated that the *Tithonia diversifolia* can grow easily

on low P status soils and it can mobilise soil P and increase P availability to subsequent crops. Improving P status by addition of *Tithonia diversifolia* residues is discussed further in Section 6.1.2. *Tithonia diversifolia* was included as a green manure treatment in this field trial to evaluate its agronomic effectiveness on the Yellow Earth in Southern Shan State. The field experiments were designed to evaluate methods of overcoming P limitations on crop growth that are economically viable for farmers in Myanmar.

## 6.2 Objective of this experiment

The main objective of this field trial was to establish relationships between soil P test values and crop yield response to different forms of P fertilisers on Yellow Earths in the Southern Shan State of Myanmar.

The specific objectives of this study were:

1. To develop soil test P response curves for maize production in the Yellow Earths in the Southern Shan State for freshly applied and residual fertiliser P.
2. To evaluate the relative agronomic effectiveness of partially acidulated phosphate rocks (CPAPR), local FYM and *Tithonia diversifolia* green manure compared to a water-soluble P fertiliser (TSP) on the acidic Yellow Earth.

## 6.3 Materials and Methods

### 6.3.1 Experimental site description

The maize field trial was first established in the growing season of 1998 in Southern Shan State, Myanmar. In the 1999 growing season plots were recultivated, fertilisers were reapplied to the same treatments and a second crop of maize was grown. Location, topography and climate of the experimental site are described in following section.

#### *Location*

The field trial was conducted at Aungban Research Farm (96° 39.43' East Longitude and 20° 40.75' North Latitude) in Kalaw Township, Southern Shan State, Myanmar. Aungban Research Farm is located about 5 km away from Aungban town on the road to

Taungyi City. The field trial site was located towards the rear of the Aungban Research Farm where less fertiliser had been used in the past.

### *Topography and climate*

As mentioned earlier in Section 1.3 (Chapter 1), the experimental site of the Kalaw and Pindaya areas are described as sub-tropical highlands with undulating landscapes. The elevation of the site is 1,280 m above mean sea level. The average annual rainfall of between 780 and 1,320 mm was concentrated within a growing period of only five months. Records of daily rainfall and temperature at Aungban were obtained from the Aungban Research Farm (Figure 6.1). In the Aungban area maximum temperature was between 31 to 33°C in March-April and minimum temperature was 2°C in January.

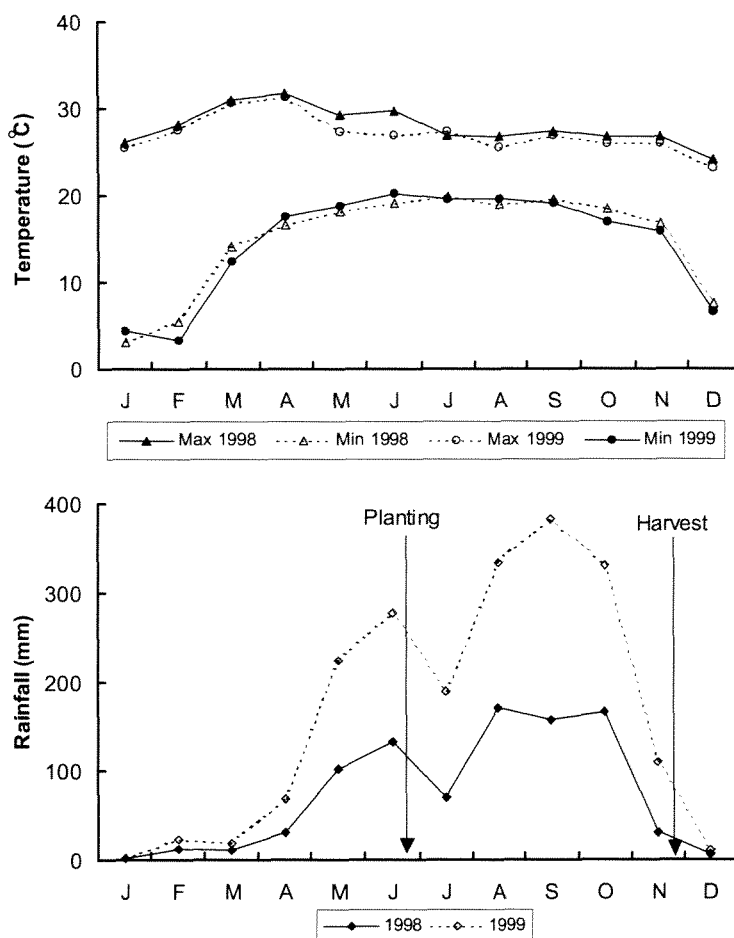


Figure 6.1 Temperature (maximum and minimum °C) and rainfall distribution (mm) for Aungban Research Station during January 1998 to December 1999.

### *Soil characteristics*

The soil was a Yellow Earth and is described as an Orthic Acrisol in the FAO/UNESCO system (see Section 2.4.1 in Chapter 2). Some of the relevant chemical characteristics of 30 soil samples from the field experimental site at Aungban Research Farm are presented in Table 6.1.

Table 6.1 Selected chemical characteristics of the Yellow Earth at the field trial site at Aungban, Southern Shan State (the average of 30 soil samples).

<b>Chemical characteristic</b>	<b>Value</b>	<b>Range</b>
pH (soil:water, 1:2.5)	4.9	4.1 to 5.5
Available P (Olsen-P)	8 mg kg <sup>-1</sup> (low)	5 to 9 mg kg <sup>-1</sup>
CEC	15 meq %	12 to 21 meq%
Total P	327 mg kg <sup>-1</sup> (low)	308 to 355 mg kg <sup>-1</sup>
P retention	53% (moderate, Saunders, 1965)	50 to 59%
C (Walkley and Black)	1.1% (low)	0.8 to 1.4%

### *6.3.2 Establishment of maize experiment*

#### *Experimental design and treatment*

Maize (*Zea mays*; local hybrid var. Yezin 3) was grown as the test crop in this experiment. The local maize hybrid variety was planted twice in June to September 1998 and subsequent year in June to September 1999.

The experiment was established as a completely balanced factorial design with four replications. A soluble, a partially soluble and two organic phosphate fertilisers were used in this maize experiment. There were 9 treatments for organic and inorganic sources and 7 treatments for P response with two common treatments ( $9 + 7 - 2 = 14$ ). The range of different rates of TSP was 0 to 120 kg P ha<sup>-1</sup> for the P response curve. The experiment included an additional treatment, which was soluble P (20 kg P ha<sup>-1</sup> as TSP) plus a dolomite rate of 2.5 t ha<sup>-1</sup> for assessing the liming effect of the local dolomite. The total number of treatments were 15. The each plot size was 5 m × 6 m, with 20 seed hills in 8 rows and maize plant spacing was 25 cm × 75 cm (Figure 6.2). The treatment description of this experiment is shown in Table 6.5.



Plate 6.1 Maize field experiment at Aungban Research Farm in Southern Shan State of Myanmar (Author pictured consoling P deficient plants!)

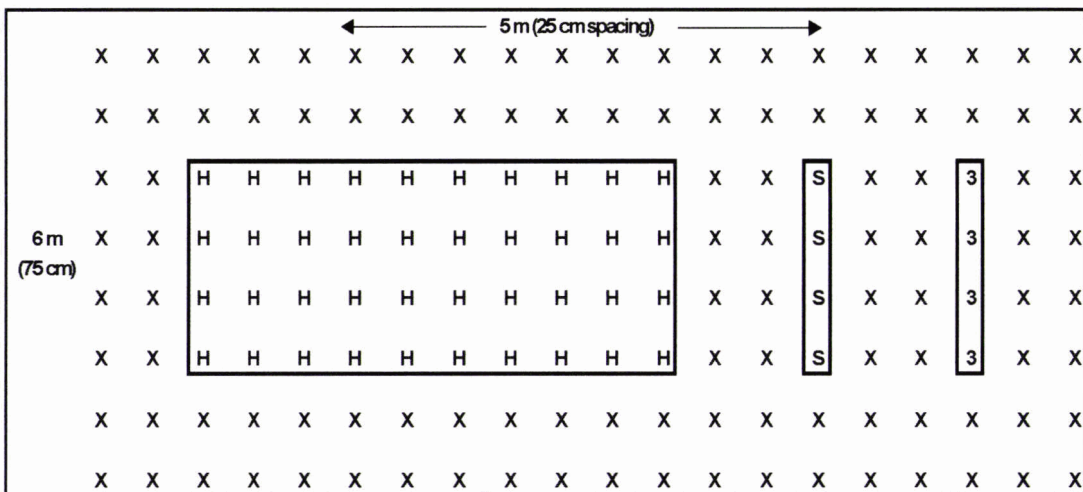


Figure 6.2 Planting spacing on an experimental plot (20 planting hills by 8 rows) and the key symbols of plants sampled at 21DAE (3), silking (S) and final harvest (H).

### 6.3.3 Review of P fertiliser sources

#### *Agronomic effectiveness of PAPR*

Directly acidulated PAPR is manufactured by direct partial acidulation of PRs with sulphuric ( $H_2SO_4$ ) and/or phosphoric acid (Harrison and Hedley, 1987; Braithwaite, 1987; Bolan *et al.*, 1990a; Rajan *et al.*, 1994). Partial acidulation is a lower cost method suitable for improving the agronomic value of unreactive PRs or for producing high analysis fertilisers that have been considered as alternatives to fully acidulated phosphate fertilisers (SSP and TSP) (Bolan *et al.*, 1990a; Rajan *et al.*, 1994; McLay *et al.*, 2000).

Partially acidulated phosphate rocks contain both, water-soluble monocalcium phosphate (MCP) and water-insoluble (mainly as unreacted apatite) forms of P. The chemical reactivity of PR, fineness of PR, composition and concentration of the acid used for acidulation, degree of acidulation and manufacture technology all influence the solubility of PAPR after application to a soil (Braithwaite, 1987; Bolan *et al.*, 1990a; Hagin *et al.*, 1990). Agronomic effectiveness of PAPRs is affected by the amount of water-soluble P (MCP) and the less water-soluble phosphate rock residue (Braithwaite, 1987; Bolan *et al.*, 1990a; Rajan *et al.*, 1994). Many workers (Harrison and Hedley, 1987; Rajan, 1987; Rajan *et al.*, 1994; Bolan *et al.*, 1990a; McLay *et al.*, 2000) have suggested that generally PAPRs are suitable for permanent pastures and perennial crops, but may not be efficient for quick growing crops. In acidic soils, the water insoluble residue of PAPRs may undergo rapid dissolution making them suitable for short-term crops that require higher P status. This may depend on the form of the PAPR applied. For example, granular forms of PAPRs have been found to have lower agronomic value compared to those PAPRs having nongranular or fine form (Engelstad and Terman, 1980). In very acid soils, fine (powder) form of PAPR has been shown to be more effective than fine fully water-soluble P fertiliser (McLean and Logan, 1970). The reason why particle size increases PAPRs effectiveness may be that the agronomic value of water-insoluble P compounds of PAPRs is a function of the surface area (Bouldin and Black, 1960) presented to soil acid.

It is usual to measure the solubility of PAPRs in water or neutral ammonium citrate and the solubility of the insoluble residue in either 2% formic or citric acid (Engelstad and

Terman, 1980, Bolan *et al.*, 1990ab). The decreased formic and citric acid solubility of the unacidulated PR portion of PAPRs acid corresponds to a decrease in the carbonate substitution level of the PR during acidulation (Charleston *et al.*, 1989). This means that the water insoluble residue from a PAPR is usually found to be less reactive than the PR used in manufacture.

The advantage of using PAPR instead of the direct use of RPR is that some P is supplied in a fast release P form, which can be consumed by short maturity crops and stimulates earlier crop growth which may lead to greater utilisation of the PR residue (Gregg *et al.*, 1988; Harrison and Hedley, 1987; Bolan *et al.*, 1990a). PAPRs acidulated with H<sub>2</sub>SO<sub>4</sub> are often the most economic P fertiliser because they also supply available S to plants (Friesen *et al.*, 1987). The PAPR can be as effective as a fully water-soluble P fertiliser under certain soil, plant and climatic conditions and the good agronomic performance of PAPRs can be expected in acid and high P retaining soils (McClean and Logan, 1970). The agronomic effectiveness of PAPRs in glasshouse and field trials increases with increasing level of nominal H<sub>2</sub>SO<sub>4</sub> acidulation (Rajan 1986 and 1987). IFDC (1985) reported that PAPR (unreactive Togo PR acidulated with H<sub>2</sub>SO<sub>4</sub> 50%) was found to be as effective as SSP or more cost-effective than SSP for maize and sorghum production on Ultisols in West Africa. In Colombia, similar results have been reported by Hammond *et al.* (1986), for PAPRs (acidulated with 40% and 50% H<sub>2</sub>SO<sub>4</sub>) used on potatoes and maize, which were inter-cropped with beans, grown on Andepts and rice grown on Oxisols. In addition, Menon and Chien (1990) reported that PAPRs (50% acidulation with H<sub>2</sub>SO<sub>4</sub>) were found to be as effective as TSP on maize in an acid soil (pH 4.5).

### ***Wild sunflower (Tithonia diversifolia) as a potential green manure***

In Southern Shan State of Myanmar, *Tithonia diversifolia* grows naturally along roadsides and farmers often plant the wild sunflower on farm boundaries as a fence because the *Tithonia diversifolia* tolerates regular pruning. Some of those farmers use its leaves for animal fodder, its stems for fuel wood and supporting sticks for climber and vine plants. *Tithonia diversifolia* can produce about 50 to 60 t DM ha<sup>-1</sup> year<sup>-1</sup> in the Kalaw and Pindaya areas (Table 6.2). *Tithonia diversifolia* propagates easily by seeds or vegetative propagation (stem cutting method). Buresh *et al.* (1997) and Cong (2000)

also mentioned that *Tithonia diversifolia* contains insect repellent substances and has been used for its anti-inflammatory properties.



Plate 6.2 *Tithonia diversifolia* plants in Southern Shan State.

Table 6.2 Dry matter production of *Tithonia diversifolia* at Kalaw-Pindaya area in Southern Shan State.

Harvest time	Dry matter yield (kg per m <sup>2</sup> )				DM yield (t ha <sup>-1</sup> )
	Sample 1	Sample 2	Sample 3	Mean	
First harvest	1.85	1.50	1.65	1.67	16.7
Second harvest	1.45	1.35	1.30	1.37	13.7
Accumulated yield	3.30	2.85	2.95	3.04	30.4

In general, the *Tithonia diversifolia* biomass contains higher P and K concentrations than many leguminous plants (Cong, 2000) with a high N (>3%) concentration and narrow C:N ratio (<20), which would hasten its decomposition in soils (Table 6.3). *Tithonia diversifolia* has in the past been used as a green manure, for example as a N source in flooded rice production in Sri Lanka (Nagarajah and Nizar, 1982) and as a P source in upland soils in Vietnam (Cong, 2000). In Western Kenya, incorporating *Tithonia diversifolia* at a rate of 5 t DM ha<sup>-1</sup> increased maize yield in low N and P soils and it has widely been recommended as a nutrient source for crop production (Gachengo *et al.*, 1999). Nziguheba *et al.* (1998) and Cong (2000) reported that the addition of *Tithonia diversifolia* either alone or in combination with TSP increased the available P pool (labile P fraction) and decreased the P adsorption capacity in the soil.

In addition, *Tithonia diversifolia* can be used as green manure K source in K deficient soils. It has shown similar effectiveness to KCl for maize (ICRAF, 1998). Apart from N, P and K, *Tithonia diversifolia* contains useful amounts of Ca and Mg as well (Table 6.3).

Table 6.3 Percent nutrient concentration in dry matter of *Tithonia diversifolia* from different sources (adapted from Cong, 2000).

Place	Nutrient concentration (%)					Reference
	N	P	K	Ca	Mg	
East Africa	3.1-4.0	0.24-0.56	2.7-4.8			Jama et al (2000)
Sri Lanka	3.2-5.5	0.2-0.5	2.3-5.5			Nagarajah and Nizar (1982)
West Africa	3.51	0.35	5.5	3.4	0.6	Tossah (2000)
Western Kenya	3.78	0.33	4.55	1.83	0.4	Gachengo <i>et al.</i> (1999)

### ***Nature of common FYM in Southern Shan State***

Farmyard manure is a traditional manure and contains N, P, K and other micro-nutrients. The majority of cattle and buffalo are the indigenous breeds, which are kept for draft power and manure in Southern Shan State. The cattle and buffalo graze on common grazing land. Rice straw, grass and crop residues are fed as supplementary feed to the ruminants in the dry season. Usually FYM is a decomposed mixture of cattle dung and urine combined with straw and litter, used as bedding material, and residues from the fodder fed to the cattle. The waste material of cattle sheds consisting of dung and urine is collected daily and placed in trenches or pits. If other animal manures (such as goat, sheep, pig and poultry manures), plant materials (weeds, leaves and twigs), kitchen wastes and wooden ashes are available, these are also added into the pit. A few farmers add urea and TSP in FYM making. Each trench or pit is filled up to a height of about 1 m above the ground level, the top of the heap is made dome shaped. The composting FYM becomes ready for use after 3-4 months.

### ***P fertiliser sources used in field trials (1998 and 1999)***

Prior to this experiment, all P sources were characterised and information on prices of the P sources were collected. The biomass yield of *Tithonia diversifolia* was measured per unit area from three places at the first harvest and then measured again at two

months after the first harvest (Table 6.2). The physical and chemical properties of the P fertilisers and the prices of P are shown in Table 6.4.

Table 6.4. Physical and chemical properties of the P fertilisers and the prices of P.

Fertiliser	Form	% of total P			Total P (%)	Price (kyat) kg <sup>-1</sup> P
		Water-soluble P	Citric-soluble P	Formic-soluble P		
TSP	Granular	93.5	94.1	97.6	20.6	420
CPAPR	Powder	47.2	58.3	94.0	11.6	345
FYM	Solid	-	-	-	1.1	450
<i>Tithonia diversifolia</i>	Wilted hay	-	-	-	0.1	500

In the maize field trial, manures were applied at a similar rate of P per hectare. FYM and *Tithonia diversifolia* used as a green manure, were used as organic P sources. Inorganic sources were Triple superphosphate (TSP) as soluble P source, and Chinese partially acidulated phosphate rock (CPAPR) as partially soluble P source (Table 6.4). Immediately after the P fertilisation of the plots, a maize crop was sown. The P sources and rate of P fertiliser used in this experiment in 1998 and reapplied in 1999 are shown in Table 6.5.

#### ***Nitrogen and K fertilisers (1998 and 1999)***

All treatments were supplied with urea (50 kg N ha<sup>-1</sup>) and KCl (50 kg K ha<sup>-1</sup>) as a basal application. Subsequent dressings of N fertiliser at a rate of 25 kg N ha<sup>-1</sup> as urea were applied to maize at 3 weeks after emergence and again at the silking stage.

#### ***Other fertilisers, rate and application (1999)***

In 1999 cropping season, zinc sulphate (5 kg Zn ha<sup>-1</sup>), MgSO<sub>4</sub> (15 kg Mg ha<sup>-1</sup>) and ammonium molybdate (50 g kg<sup>-1</sup> seed) were applied to prevent Zn, S, Mg and Mo deficiencies. Previously Zn, S and Mg deficiency symptoms have been seen on maize plants grown at Aungban Research Farm and farmers fields near by the experimental site.

### *Application method of fertilisers (1998 and 1999)*

Triple superphosphate, CPAPR, FYM and the basal fertilisers were applied in a band (width 25-30 cm) approximately 5 cm deep and incorporated, prior to seeding. *Tithonia diversifolia* and dolomite were broadcast over each plot and incorporated into the soil.

### *Soil samples*

Soil samples (0-15cm depth) were taken from each plot before treatments were applied, at 21 days after emergence, and again at silking, in both 1998 and 1999. Ten cores were collected from each plot between plants in a row and bulked for analysis. Bulk samples of 3 to 4 cores were also collected from the 15-30 cm soil layer. Soil samples were air-dried and stored in airtight plastic bags after sub-sampling.

### *Herbage samples*

Herbage samples (fully expanded young leaves and the whole plants) were collected from four maize plants from each plot at three weeks after emergence and again at silking (Figure 6.2). At harvest, herbage samples were collected from six representative plants and yields were measured using 40 plants from each plot. Herbage samples were oven-dried at 70°C and stored for chemical analysis.

### *Substitution ratio (SR) of P fertiliser*

The effectiveness of P fertilisers (i.e. CPAPR, FYM and *Tithonia*) was compared by calculating the amount of reference fertiliser (i.e. TSP) required to produce the same yield response. This is known as the 'Horizontal comparison' or substitution ratio (SR). The substitution ratio of P fertilisers relative to TSP was calculated using the following equation (Chien *et al.*, 1990):

$$SR = X_{RF}/X_{TF}$$

Where:  $X_{RF}$  = reference fertiliser rate (in this case TSP) and  $X_{TF}$  = test P fertiliser rate, required to produce the same yield response. It is to be remembered that all the test fertiliser were evaluated at one P level (20 kg P ha<sup>-1</sup> for CPAPR, FYM and *Tithonia*

*diversifolia*). Therefore to calculate the SR values, the P level required as TSP to achieve the maize yields obtained at 20 kg P ha<sup>-1</sup> for the test fertiliser was estimated from the TSP response curve.

### ***Statistical analysis***

Statistical analysis was completed by the general linear models (GLM) procedure (SAS, 1989). Results were tested for significant differences between treatment means. In an analysis of variance (ANOVA) the F-test provided the differences among the means or effects of the treatments at 95% confidence level and Fisher's least significant difference (LSD) was applied for multiple comparison procedures of the treatments.

### ***Biosecurity***

The soil and herbage samples were air freighted to New Zealand from Myanmar under the NZMAF Biosecurity Authority Control. After the completion of this study all these samples will be incinerated.

## **6.4 Results and Discussion**

### ***6.4.1 Maize field trial results in 1998***

#### ***6.4.2 Effect of P fertilisers on soil P test values***

The initial Olsen-P status of the soil and the effect of the various P fertilisers and dolomite addition on Olsen-P values of the Yellow Earth at 21 days after emergence (DAE) and at maize silking stage, in the 1998 field trial, are presented in Table 6.5.

The Olsen-P values for all treatment plots were not significantly different at the beginning of the field trial before the treatments were applied ( $P < 0.05$ ) (Table 6.5).

At 21 DAE, the Olsen-P values were significantly higher in P added treatments, except for FYM 20, *Tithonia diversifolia* 20, TSP 10 and FYM 20 + CPAPR 20 kg P ha<sup>-1</sup> ( $P < 0.05$ ). There was considerable variation between Olsen values for the TSP plot replicates (Figure 6.3) which was presumably caused by uneven mixing and sampling of

the TSP banded fertiliser within the soil. The TSP and CPAPR raised the Olsen-P values significantly higher, compared to the organic materials at 20 kg P ha<sup>-1</sup> rate (Table 6.5).

Table 6.5 Soil Olsen-P values at prior to fertiliser application (initial), 21 DAE and silking of maize grown on Yellow Earth fertilised with different P fertilisers and rates at the Aungban (1998).

Treatment	Soil Olsen-P (mg P kg <sup>-1</sup> soil)		
	Initial	21 DAE	Silking
Control 0 kg P ha <sup>-1</sup>	6.8	6.2g	4.7f
TSP 20 kg P ha <sup>-1</sup>	6.7	20.2de	22.4d
CPAPR 20 kg P ha <sup>-1</sup>	6.8	16.5ef	23.5d
FYM 20 kg P ha <sup>-1</sup>	6.9	6.6g	10.1e
FYM 20 kg P ha <sup>-1</sup> + TSP 20 kg P ha <sup>-1</sup>	6.2	15.9ef	23.4d
FYM 20 kg P ha <sup>-1</sup> + CPAPR 20 kg P ha <sup>-1</sup>	6.9	14.0efg	19.8d
<i>Tithonia diversifolia</i> 20 kg P ha <sup>-1</sup>	6.7	7.5g	13.2e
<i>Tithonia diversifolia</i> 20 kg P ha <sup>-1</sup> + TSP 20 kg P ha <sup>-1</sup>	6.3	21.3de	24.1d
<i>Tithonia diversifolia</i> 20 kg P ha <sup>-1</sup> + CPAPR 20 kg P ha <sup>-1</sup>	6.6	17.6def	23.6d
TSP 10 kg P ha <sup>-1</sup>	6.4	10.6fg	11.1e
TSP 40 kg P ha <sup>-1</sup>	7.2	24.9d	24.6d
TSP 60 kg P ha <sup>-1</sup>	6.7	35.4c	32.9c
TSP 80 kg P ha <sup>-1</sup>	6.5	55.9b	53.6b
TSP 120 kg P ha <sup>-1</sup>	7.5	103.9a	111.1a
TSP 20 kg P ha <sup>-1</sup> + Dolomite 2.5 t ha <sup>-1</sup>	6.9	19.14de	24.9d
	NS	LSD 7.9 (P<0.05)	LSD 5.3 (P<0.05)

Mean treatments followed by the same letter in a column are not significantly different at  $P < 0.05$ .

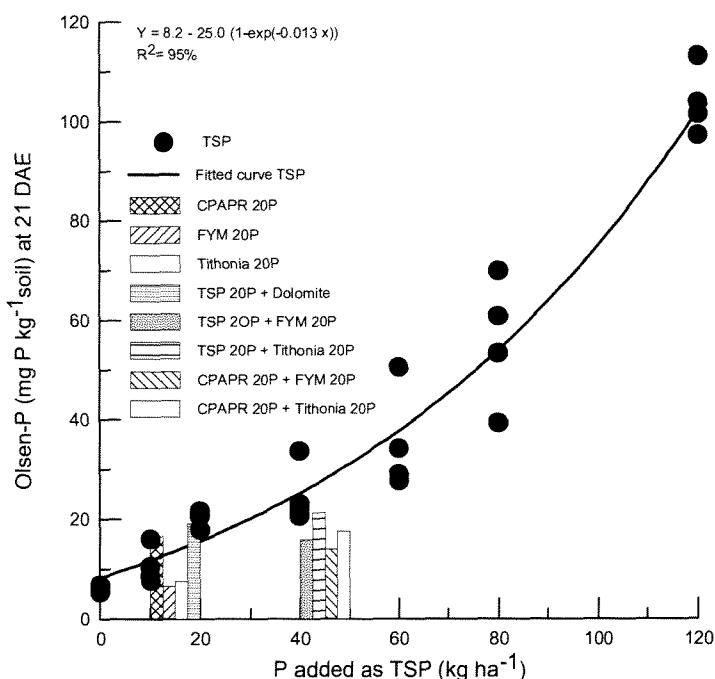


Figure 6.3 The effects of different P fertilisers of 20 and 40 kg P ha<sup>-1</sup> rate on Olsen-P test values at 21 DAE of maize (1998).

The major difference between samples taken at 21 DAE and silking (approximately 58 DAE) was that Olsen-P values at silking in all plots treated with fertilisers were all significantly higher than the control ( $P < 0.05$ ) (Table 6.5).

At both 21 DAE and at silking, combinations of TSP and CPAPR at  $20 \text{ kg P kg}^{-1}$  with organic materials at  $20 \text{ kg P ha}^{-1}$  (FYM and *Tithonia diversifolia*) caused similar increases in Olsen-P values ( $P < 0.05$ ) and these values were not significantly different from values in TSP and CPAPP plots alone. The addition of  $2.5 \text{ t ha}^{-1}$  of dolomite with TSP generated no difference in Olsen-P value, compared to TSP alone at  $20 \text{ kg P ha}^{-1}$ .

### *Effect of P fertilisers on soil pH*

The initial soil pH and the soil pH changes after application of various P fertilisers and dolomite on the Yellow Earth at 21 DAE and maize silking stage in the 1998 field trial are presented in Table 6.6.

Similar to soil Olsen-P values, the initial soil pH values in all plots were not significantly different ( $P < 0.05$ ) (Table 6.6).

Table 6.6 Soil pH values at prior to fertiliser application (initial), 21 DAE and silking stage of maize grown on Yellow Earth fertilised with different P fertiliser sources and rates at Aungban field trial in 1998.

Treatment	Soil pH <sub>water</sub> (1:2.5)		
	Initial	21 DAE	Silking
Control $0 \text{ kg P ha}^{-1}$	5.05	5.05	4.73e
TSP $20 \text{ kg P ha}^{-1}$	5.14	4.99	5.01bcde
CPAPR $20 \text{ kg P ha}^{-1}$	5.08	5.46	5.57ab
FYM $20 \text{ kg P ha}^{-1}$	5.03	5.39	5.40abcd
FYM $20 \text{ kg P ha}^{-1}$ + TSP $20 \text{ kg P ha}^{-1}$	4.92	5.24	5.32bcd
FYM $20 \text{ kg P ha}^{-1}$ + CPAPR $20 \text{ kg P ha}^{-1}$	4.91	5.42	5.40abcd
<i>Tithonia diversifolia</i> $20 \text{ kg P ha}^{-1}$	5.19	5.92	5.92a
<i>Tithonia diversifolia</i> $20 \text{ kg P ha}^{-1}$ + TSP $20 \text{ kg P ha}^{-1}$	5.18	5.56	5.51abcd
<i>Tithonia diversifolia</i> $20 \text{ kg P ha}^{-1}$ + CPAPR $20 \text{ kg P ha}^{-1}$	5.08	5.10	5.00cde
TSP $10 \text{ kg P ha}^{-1}$	5.23	5.13	4.99cde
TSP $40 \text{ kg P ha}^{-1}$	5.04	5.19	4.98de
TSP $60 \text{ kg P ha}^{-1}$	5.32	5.44	5.47abcd
TSP $80 \text{ kg P ha}^{-1}$	5.14	5.41	5.55abc
TSP $120 \text{ kg P ha}^{-1}$	5.29	5.33	5.35bcd
TSP $20 \text{ kg P ha}^{-1}$ + Dolomite $2.5 \text{ t ha}^{-1}$	5.02	5.37	5.51abcd
	NS	NS	LSD 0.57 ( $P < 0.05$ )

Mean treatments followed by the same letter in a column are not significantly different at  $P < 0.05$ .

Also, treatments did not significantly affect soil pH at 21 DAE ( $P < 0.05$ ).

By silking, however, treatments including dolomite applications and most combinations of organic materials, FYM, *Tithonia diversifolia* alone or in combination with inorganic P fertilisers (TSP), except *Tithonia diversifolia* plus CPAPR, significantly increased the soil pH above the control ( $P < 0.05$ ).

These differences were caused by a decrease in the control plot pH overtime plus increases in pH of plots receiving higher rates of P fertiliser, organic manures and dolomite.

### *Effect of P fertilisers on DM yield of maize*

Except for FYM and *Tithonia diversifolia* applied alone, the addition of P fertilisers increased the DM yield of maize at silking and harvest compared to the control treatment (Table 6.7).

At the earlier stage of 21 DAE, the lower rates of water-soluble P applied as TSP 10 and 20 kg P ha<sup>-1</sup> did not significantly increase DM yield of maize above the control.

Table 6.7 Dry matter maize yield at 21 DAE and silking stage, and stover and grain yields at harvest of maize grown on Yellow Earth fertilised with different P fertiliser sources and rates in June planting 1998.

Treatment	Dry mater yield			
	21 DAE (g plant <sup>-1</sup> )	Silking (g plant <sup>-1</sup> )	Stover (kg ha <sup>-1</sup> )	Grain (kg ha <sup>-1</sup> )
Control 0 kg P ha <sup>-1</sup>	1.2e	7f	3459h	424f
TSP 20 kg P ha <sup>-1</sup>	1.9cde	103d	6627ef	2583cd
CPAPR 20 kg P ha <sup>-1</sup>	2.4cd	112cd	5769g	2484d
FYM 20 kg P ha <sup>-1</sup>	0.8e	24ef	3481h	601f
FYM 20 kg P ha <sup>-1</sup> + TSP 20 kg P ha <sup>-1</sup>	2.4cd	105d	8113c	3111b
FYM 20 kg P ha <sup>-1</sup> + CPAPR 20 kg P ha <sup>-1</sup>	2.9c	119cd	7934cd	3103b
<i>Tithonia diversifolia</i> 20 kg P ha <sup>-1</sup>	1.0e	35e	3974h	1127e
<i>Tithonia diversifolia</i> 20 kg P ha <sup>-1</sup> + TSP 20 kg P ha <sup>-1</sup>	2.5cd	114cd	6332fg	2610cd
<i>Tithonia diversifolia</i> 20 kg P ha <sup>-1</sup> + CPAPR 20 kg P ha <sup>-1</sup>	2.4cd	132c	7646dc	3144b
TSP 10 kg P ha <sup>-1</sup>	1.9cde	44e	5607g	2317d
TSP 40 kg P ha <sup>-1</sup>	3.0c	130c	7293de	2735bcd
TSP 60 kg P ha <sup>-1</sup>	5.9b	167b	9939ab	4040a
TSP 80 kg P ha <sup>-1</sup>	7.6a	219a	10238a	4121a
TSP 120 kg P ha <sup>-1</sup>	6.5ab	204a	9427b	3877a
TSP 20 kg P ha <sup>-1</sup> + Dolomite 2.5 t ha <sup>-1</sup>	2.8c	116cd	7275de	3041bc
	LSD 1.3 ( $P < 0.05$ )	LSD 23 ( $P < 0.05$ )	LSD 748 ( $P < 0.05$ )	LSD 465 ( $P < 0.05$ )

Mean treatments followed by the same letter in a column are not significantly different at  $P < 0.05$ .

DM yields at silking as influenced by increasing rates of TSP applied (Plate 6.3) have been plotted as data points in Figure 6.4 and a soluble P fertiliser response curve has been obtained by least squares fitting of a Mitscherlich equation. The response curve explains 89% of the variation in DM yield caused by increasing rates of soluble P, and indicates near maximum (>90%) yields were obtained from applications of P varying from 80 to 120 kg P ha<sup>-1</sup>. The mean DM yields produced by other fertilisers are represented as bars. Figure 6.4 clearly shows that *Tithonia diversifolia* and FYM alone are ineffective in providing P for plants, being less than 30% as effective as TSP applied at the same rate (using a vertical comparison at 20 kg P ha<sup>-1</sup>). Substitution values calculated on the basis of the amount of TSP-P required to give the same yield suggest that by the time maize had reached silking stage FYM and *Tithonia diversifolia* were only 15 and 30% as effective as TSP.



Plate 6.3 The effects of P rates (0 to 120 kg P ha<sup>-1</sup> as TSP) on DM yield of maize at silking in June Planting 1998.

CPAPR applied at 20 kg P ha<sup>-1</sup> was as effective as TSP applied at the same rate and this similar (or slightly greater) agronomic effectiveness was also mirrored in grain yields (Figure 6.5) for CPAPR and TSP alone or in combination with FYM or *Tithonia diversifolia*.

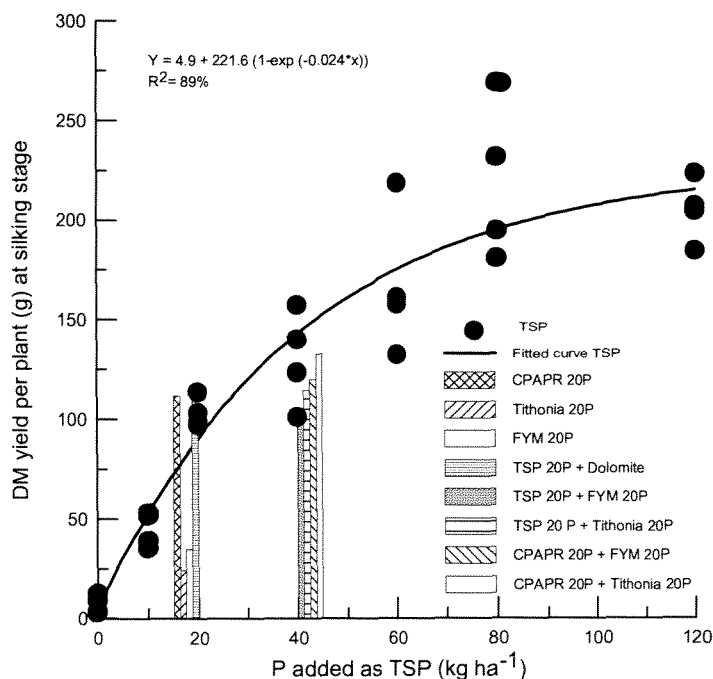


Figure 6.4 The effects of P rates on dry matter yield of maize at silking in June planting 1998.

There was a significant curvilinear relationship between P added as TSP and maize grain yield at harvest (Trend line in Figure 6.5). Greater than 90% of max grain yields were obtained with TSP applications of  $>49$  kg P ha<sup>-1</sup>. The trend line suggests that 95% of maximum maize grain yield occurs at approximately 64 kg P ha<sup>-1</sup> applied as TSP to the Yellow Earth. Substitution values calculated using the TSP response curve for grain yield indicated that both organic sources were  $<20\%$  as effective as P sources compared to TSP. FYM was particularly poor with a substitution value of  $<5\%$ .

A growth response curve using P fertiliser applied as the predictor (Figure 6.4) is not a portable model to use for determining the P fertiliser requirements in other locations (farmers fields) because soil contributions to plant P uptake may vary from site to site. The combined tools of soil testing, knowledge of how much P is required to raise the soil P test values and the P test values that are associated with optimum yields provide more portable diagnosis of P fertiliser requirements. For this reason the DM yields at silking and grain yields have been replotted against the Olsen-P soil test values from the soil sampling at 21 DAE.

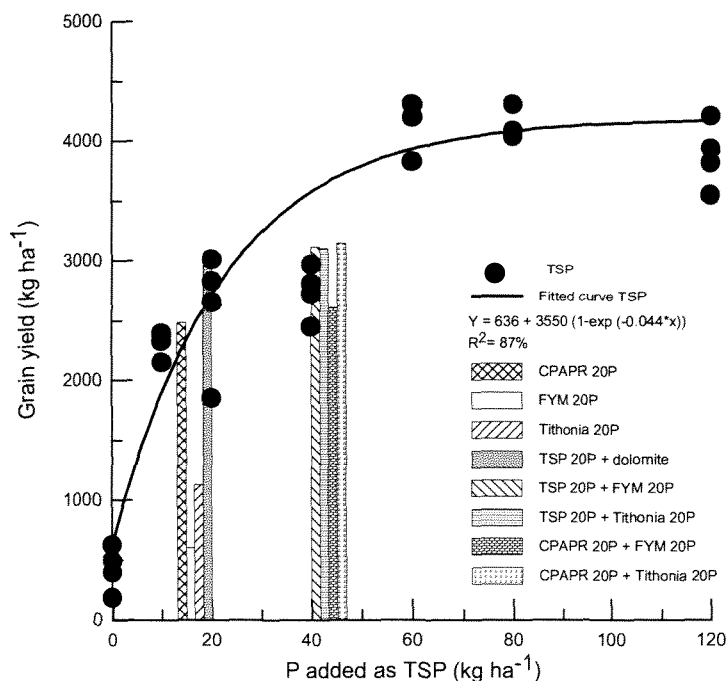


Figure 6.5 The effects of P rates on maize grain yield at harvest in June planting 1998.

### *Relationship between soil Olsen-P status and DM yield of maize in 1998*

There was a significant asymptotic relationship between soil Olsen-P values at 21 DAE and DM yield of maize at silking stage or grain yield at harvest (Figures 6.6 and 6.7). The trend line for DM yield at silking (Figure 6.6) suggests that 90% of maximum yield occurs at an Olsen-P value of 50 mg P kg<sup>-1</sup> at 21 DAE. The trend line for grain yield (Figure 6.7), however, indicates that 90% of max grain yield can occur with an Olsen value of 34 mg P kg<sup>-1</sup> soil. As grain yield provides the economic return to the farmer this is perhaps the better relationship to adopt for preliminary advice.

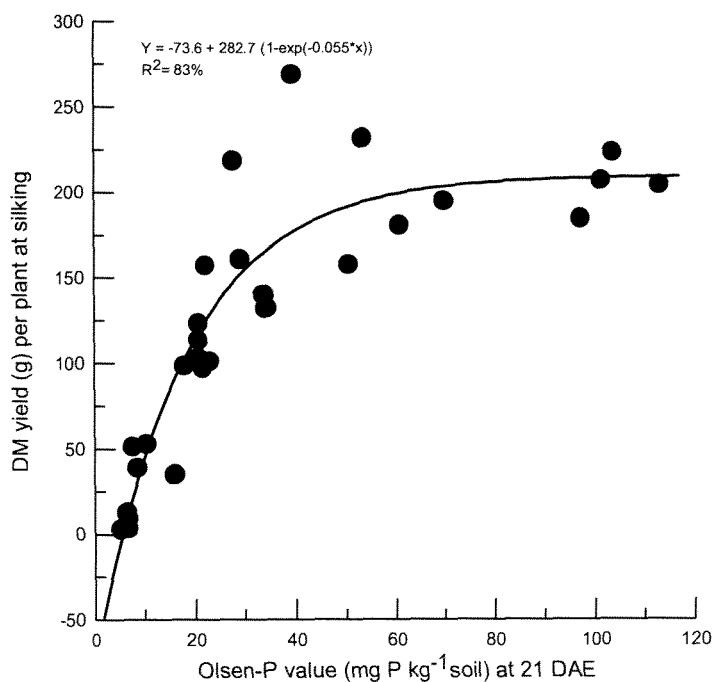


Figure 6.6 The relationship between soil Olsen-P value at 21 DAE and maize DM yield at silking in June planting 1998 (● = TSP response curve).

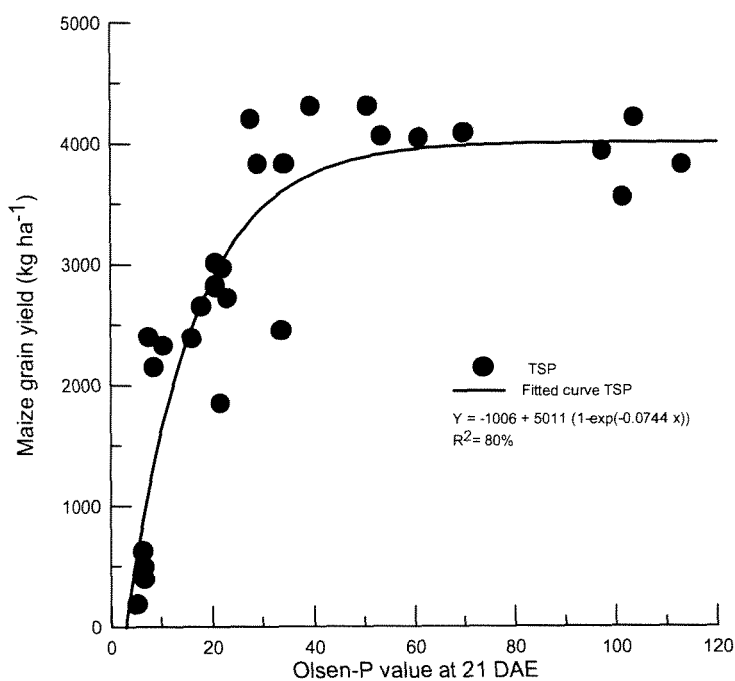


Figure 6.7 The relationship between soil Olsen-P value at 21 DAE and maize grain yield at harvest in June planting 1998 (● = TSP response curve).

### 6.4.3 Maize field trial results in 1999

#### *Effect of P fertilisers on soil P test values (1999)*

Prior to fertiliser application the initial Olsen-P tests show the effects of residual fertiliser value from the 1998 application. This residual effect will be discussed later (Section 6.4.4). After reapplication of fertiliser, the increasing rates of TSP significantly increased soil Olsen-P values (Table 6.8 and Figure 6.8) and maize DM yield (see Table 6.9). But organic materials, FYM and *Tithonia diversifolia* alone did not markedly increase either Olsen-P in the soil (Table 6.8) or maize DM yield (Table 6.9). Notably in the wetter 1999 season the Olsen-P values did not increase as markedly to the applied TSP, as was observed in 1998 (Table 6.9).

At the fertilisation rate of 20 kg P ha<sup>-1</sup>, CPAPR and TSP plus dolomite addition gave similar Olsen-P test values compared to TSP alone, thus they also produced similar amounts of maize DM yield at the silking stage. FYM failed to significantly raise Olsen-P values at 20 kg P ha<sup>-1</sup> rate and also did not increase the maize DM yield. This finding confirms the 1998 result that the local FYM rate of 20 kg P ha<sup>-1</sup> cannot supply enough immediately available P required for maize optimising growth in the short-term. *Tithonia diversifolia* was slightly better than FYM, in that by 21 DAE in 1999 the Olsen-P value had been increased significantly above the control. At silking in 1999 the Olsen-P value on the FYM plot were significantly different from the control plot (Figure 6. 8, Table 6.8).

#### *Relationship between Olsen-P values and maize yield in 1999*

Again there were significant asymptotic relationships between soil Olsen-P value at 21 DAE and DM yield of maize at silking stage (Figure 6.9) and grain yield (Figure 6.10). The trend line suggests that 90% of maximum DM yield at silking occurs at an Olsen-P of 44 mg P kg<sup>-1</sup> at 21 DAE (Figure 6.9).

The curvilinear relationship for 1999 grain yield suggests that 90% of maximum yields can be obtained at Olsen-P values of 28 mg P kg<sup>-1</sup> soil (Figure 6.10). This value is close to the value of 34 mg P kg<sup>-1</sup> soil obtained in 1998 (Figure 6.7). It should be noted that

relationships between Olsen-P values and plant yield at silking tend to overestimate the soil P fertilisation status that is required to produce 90% of maximum grain yield.

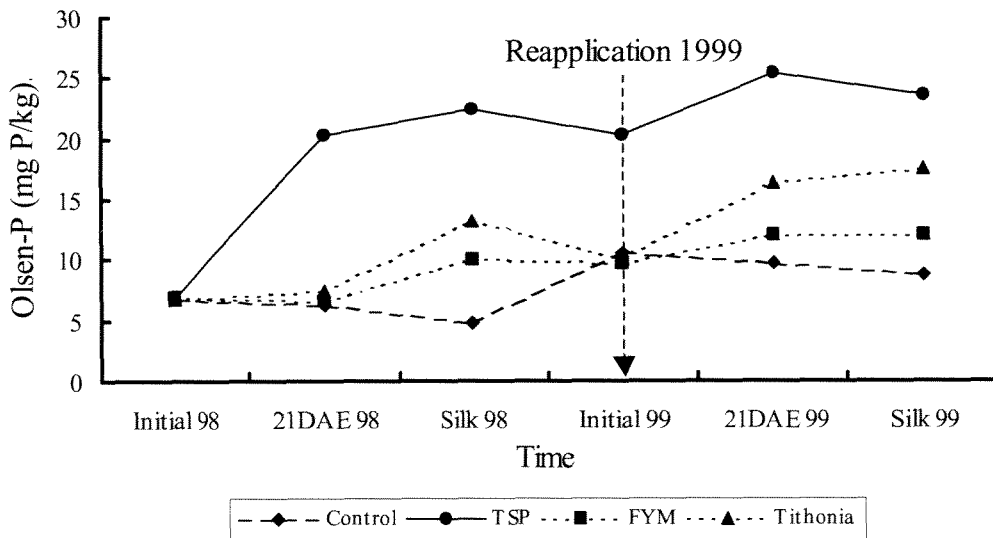


Figure 6.8 Long-term effect of organic manures and TSP applied at 20 kg P ha<sup>-1</sup> on Olsen-P soil test values.

Table 6.8 Soil Olsen-P values at initial, 21 days after emergence and silking stage of maize grown on Yellow Earth fertilised with different P fertiliser sources and rates in the 1999 field trial.

Treatment	Soil Olsen-P (mg P kg <sup>-1</sup> )		
	Initial	21 DAE	Silking
Control 0 kg P ha <sup>-1</sup>	10.5h	9.8j	8.8i
TSP 20 kg P ha <sup>-1</sup>	20.3ef	25.4e	23.5def
CPAPR 20 kg P ha <sup>-1</sup>	19.0efg	24.7ef	26.0de
FYM 20 kg P ha <sup>-1</sup>	9.8h	12.0ij	12.0h
FYM 20 kg P ha <sup>-1</sup> + TSP 20 kg P ha <sup>-1</sup>	16.5fg	22.3efg	22.8ef
FYM 20 kg P ha <sup>-1</sup> + CPAPR 20 kg P ha <sup>-1</sup>	16.3g	21.1fg	20.2fg
<i>Tithonia diversifolia</i> 20 kg P ha <sup>-1</sup>	10.1h	16.3ih	17.5g
<i>Tithonia diversifolia</i> 20 kg P ha <sup>-1</sup> + TSP 20 kg P ha <sup>-1</sup>	19.7efg	25.0ef	23.2ef
<i>Tithonia diversifolia</i> 20 kg P ha <sup>-1</sup> + CPAPR 20 kg P ha <sup>-1</sup>	22.3de	24.7ef	24.0def
TSP 10 kg P ha <sup>-1</sup>	20.0efg	19.8gh	16.5gh
TSP 40 kg P ha <sup>-1</sup>	25.8d	31.3d	28.7d
TSP 60 kg P ha <sup>-1</sup>	33.0c	37.4c	34.4
TSP 80 kg P ha <sup>-1</sup>	41.8b	46.8b	44.6b
TSP 120 kg P ha <sup>-1</sup>	47.5a	57.5a	75.3a
TSP 20 kg P ha <sup>-1</sup> + Dolomite 2.5 t ha <sup>-1</sup>	18.9efg	24.5ef	25.8de
	LSD 3.8 (P<0.05)	LSD 4.3 (P<0.05)	LSD 5.1 (P<0.05)

Mean treatments followed by the same letter in a column are not significantly different at P<0.05.

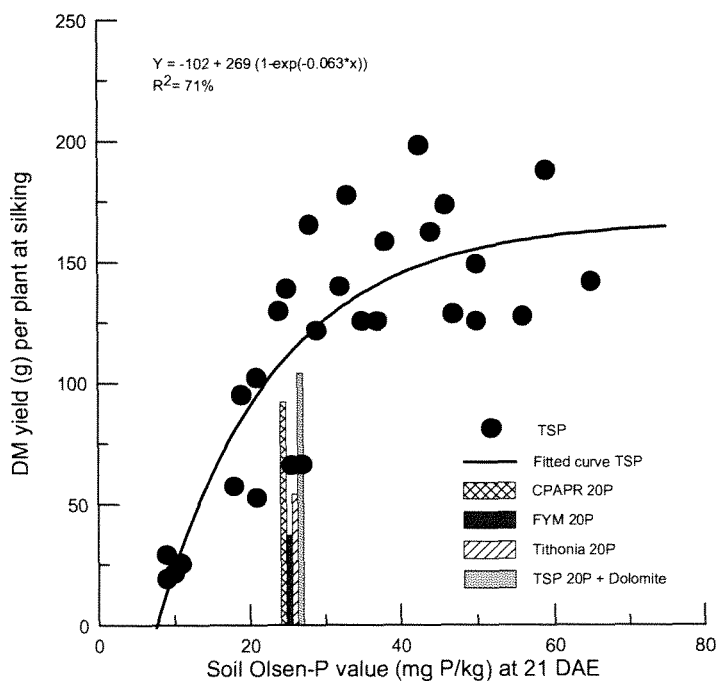


Figure 6.9 The relationship between soil Olsen-P value at 21 DAE and maize DM yield at silking in 1999 (● = TSP response curve).

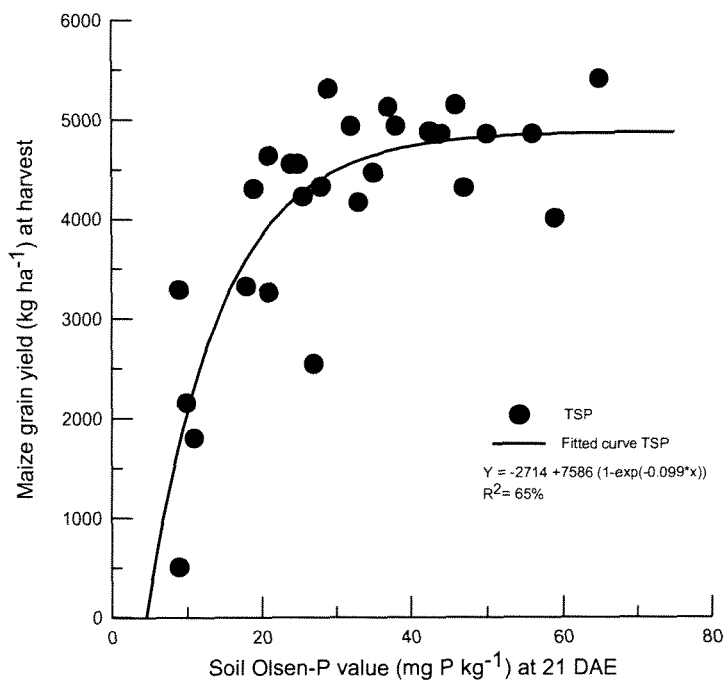


Figure 6.10 The relationship between soil Olsen-P value at 21 DAE and maize grain yield at harvest from June 1999 planting (● = TSP response curve).

### Effect of P fertilisers on DM yield of maize (1999)

At the early stage of 21 DAE, the maize DM yields were significantly increased by the application of P fertilisers ( $P < 0.05$ ) (Table 6.9). However, FYM and *Tithonia diversifolia* at rate of 20 kg P ha<sup>-1</sup>, *Tithonia diversifolia* 20 kg P ha<sup>-1</sup> + CPAPR 20 kg P ha<sup>-1</sup> applications did not significantly increase DM yield of maize compared to control treatment ( $P < 0.05$ ). Chinese PAPR applied at 20 kg P ha<sup>-1</sup> produced similar yield of maize to TSP ( $P < 0.05$ ).

Figure 6.11 shows the DM yields at silking for increasing rates of TSP (added soluble P) applied plotted as data points. Then, these data points were fitted by using the Mitscherlich equation to obtain a P response curve. The response curve indicates near maximum (90%) yields were obtained from soluble P applied at 40 kg P ha<sup>-1</sup>. This is much lower than the values of 80 to 120 kg P ha<sup>-1</sup> required in 1998 and presumably results from the residual value of TSP applied in 1998. Bars in the Figure 6.11 represent the mean DM yields produced by other fertilisers.

Table 6.9 Maize dry matter yield at 21 DAE and silking, and maize stover and grain yields at harvest when grown on a Yellow Earth and fertilised with different P fertiliser sources and rates in the 1999 field trial.

Treatment	Dry mater yield			
	21 DAE (g plant <sup>-1</sup> )	Silking (g plant <sup>-1</sup> )	Stover (kg ha <sup>-1</sup> )	Grain (kg ha <sup>-1</sup> )
Control 0 kg P ha <sup>-1</sup>	0.8e	24g	2435de	1935f
TSP 20 kg P ha <sup>-1</sup>	3.0cb	100cd	5418a	3965cde
CPAPR 20 kg P ha <sup>-1</sup>	2.7bcd	92cd	3743abcd	4178bcde
FYM 20 kg P ha <sup>-1</sup>	1.1e	37fg	1675e	1400f
FYM 20 kg P ha <sup>-1</sup> + TSP 20 kg P ha <sup>-1</sup>	3.4b	101cd	4798ab	5155ab
FYM 20 kg P ha <sup>-1</sup> + CPAPR 20 kg P ha <sup>-1</sup>	2.0cde	74def	3650de	3373bcde
<i>Tithonia diversifolia</i> 20 kg P ha <sup>-1</sup>	1.2e	54efg	2523cde	3120e
<i>Tithonia diversifolia</i> 20 kg P + TSP 20 kg P ha <sup>-1</sup>	3.5b	116bc	4498ab	4650abcd
<i>Tithonia diversifolia</i> 20 kg P + CPAPR 20 kg P ha <sup>-1</sup>	1.7de	95cd	4240abc	4148bcde
TSP 10 kg P ha <sup>-1</sup>	2.6bcd	77de	3180bcde	3878cde
TSP 40 kg P ha <sup>-1</sup>	5.4a	147ab	4025abcd	4560abcd
TSP 60 kg P ha <sup>-1</sup>	6.0a	155a	4538ab	4963abcd
TSP 80 kg P ha <sup>-1</sup>	6.1a	153a	3740abcd	5355a
TSP 120 kg P ha <sup>-1</sup>	6.0a	146ab	4685ab	4775abc
TSP 20 kg P ha <sup>-1</sup> + Dolomite 2.5 t ha <sup>-1</sup>	2.6bcd	104cd	3285bcde	4620abcd
	LSD 1.2 ( $P < 0.05$ )	LSD 37 ( $P < 0.05$ )	LSD 1770 ( $P < 0.05$ )	LSD1180 ( $P < 0.05$ )

Mean treatments followed by the same letter in a column are not significantly different at  $P < 0.05$ .

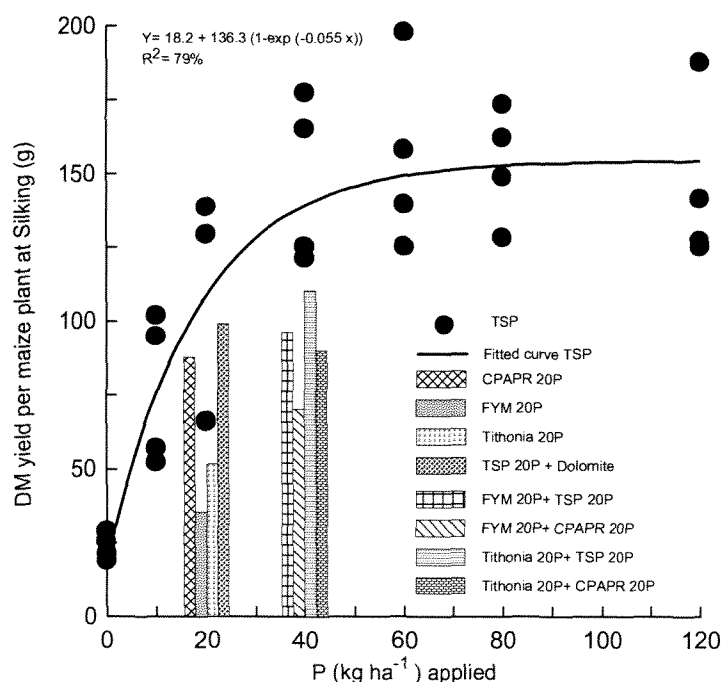


Figure 6.11 The effects of P rates on maize dry matter yield at silking from the June 1999 planting (● = TSP response curve).

As in the June 1998 planting, incorporation of FYM and *Tithonia diversifolia* at 20 P kg ha<sup>-1</sup> did not increase maize DM yield at silking ( $P < 0.05$ ), indicating that these materials are still ineffective P fertilisers, having TSP substitution values of 0.19 (19%) and 0.31 (31%) respectively (Table 6.10).

However, CPAPR produced a statistically similar maize DM yield compared to TSP at 20 kg P ha<sup>-1</sup> at silking stage in the 1999 field trial, with a substitution value averaging 0.71 (71%) in Table 6.10.

Addition of dolomite to TSP produced slightly more DM yield (4% more) than TSP alone at 20 kg P ha<sup>-1</sup>, however, this was not significantly different at  $P < 0.05$ .

Table 6.10 Substitution ratio values (SR)<sup>\*</sup> of P fertilisers with respect to TSP in the Yellow Earth

P fertiliser	Maize planting in 1998		Maize planting in 1999	
	Silking	Harvest	Silking	Harvest
CPAPR	1.38	0.84	0.71	0.93
FYM	0.19	-0.01	0.14	-0.14
<i>Tithonia diversifolia</i>	0.31	0.17	0.28	0.33

$$SR = X_{RF} / X_{TF}$$

### Grain yield of maize at harvest 1999

Table 6.9 shows that the maize grain yield was significantly increased by all P fertilisers ( $P < 0.05$ ) except FYM alone and *Tithonia diversifolia*. *Tithonia diversifolia*, however, produced better maize grain yields than FYM and was 33% (0.33) as effective as TSP applied at the same rate (Table 6.10, Figure 6.12).

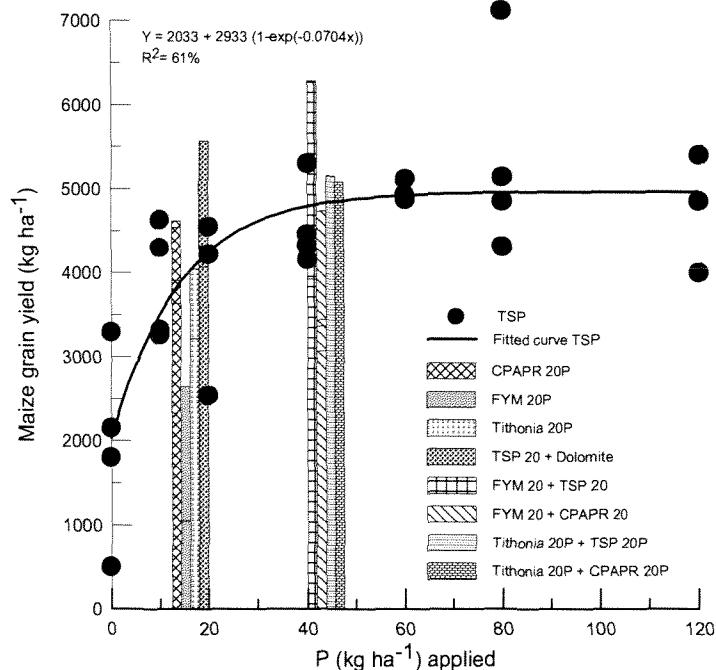


Figure 6.12 The effects of P rates on grain yield at harvest from June 1999 planting (● = TSP response curve).

Compared to the water-soluble P fertiliser TSP, the less water-soluble P fertiliser, CPAPR, produced slightly more maize grain yield (105%) at the 20 kg P ha<sup>-1</sup> rate, however, this was not significantly different ( $P < 0.05$ ) (Table 6.9). This result suggests that CPAPR was as effective as TSP. However TSP applied at rates of 10, 20, 40 and 60 kg P ha<sup>-1</sup> raised maize grain yields but were not significantly different (Table 6.9). This illustrates that caution must be used in the interpretation of variable field trial results with P fertiliser treatments that produce near maximum yields (Figures 6.5 and 6.12). Thus based on observations from this one trial it is not possible to conclusively say that CPAPR is as effective as TSP applied at the same rate. In addition, in Chapter 7 evidence is provided, that despite basal S dressings, CPAPR application may cause an additional S response.

The water-soluble P fertiliser, TSP, applied at 20 or 40 kg P ha<sup>-1</sup> and CPAPR applied at 20 kg P ha<sup>-1</sup> gave similar grain yields to the combination of TSP at 20 kg P ha<sup>-1</sup> plus 20 kg P ha<sup>-1</sup> as organic P fertilisers. These results suggest that combined application of TSP or CPAPR at 20 kg P ha<sup>-1</sup> with FYM or *Tithonia diversifolia* at 20 kg P ha<sup>-1</sup>, may have similar effectiveness to TSP alone in their second year of application.

Dolomite addition to TSP at 20 kg P ha<sup>-1</sup> produced similar yields to TSP alone (Table 6.9).

#### 6.4.4 General discussion

In both the growing seasons of 1998 and 1999, different P treatments resulted in significant differences in maize growth and vigour which became visible at an early crop growth stage. Generally, maize growth in the second year (1999) was healthier than the first year maize growth (1998) in all plots. This had more to do with differences in rainfall between seasons than residual effects from P fertiliser, as Olsen-P test values varied little between years (Figure 6.13).

In the sub-tropical highland of Southern Shan State, availability of soil moisture relies on climatic factors (rainfall pattern, temperature, etc.) and thus maize growth is highly dependent upon the rainfall distribution during the early growth stages of the crop. Due to land slope, intensive rain readily runs off the Red Earths and Yellow Earths of Myanmar, which dry quickly after rain. The June 1999 planting of maize received higher rainfall, which was evenly distributed during the first two weeks after maize sowing. However the June 1998 planting received the lower, unevenly distributed rainfall, which affected early maize growth (Figure 6.1).

The control treatment that received no P had poor growth and vigour with serious P deficiency symptoms. Similarly, maize grown with the low rate of TSP at 10 kg P ha<sup>-1</sup>, and FYM and *Tithonia diversifolia* at 20 kg P ha<sup>-1</sup> were visually less vigorous and grew leaves with P deficiency symptoms. This was clearly due to the low P availability status of the soil in these treatments (Table 6.5). These observations were confirmed by differences in soil Olsen-P test values and maize DM production at 21 DAE and silking stage.

### ***Residual effect of TSP fertilisers***

#### *Olsen-P values and yields*

Once P fertiliser as TSP is applied to the Yellow Earth, an apparent 5 to 30% of the P in TSP becomes available to plants. The remaining P converts to insoluble compounds, adsorbed P and organic P, in the soil and the residual effects of these sources may influence plant growth in later years. Colwell (1985) suggested that the residual effects of P are better measured by soil analysis data compared to biological measurement data because of uncontrolled seasonal variations in the experiment.

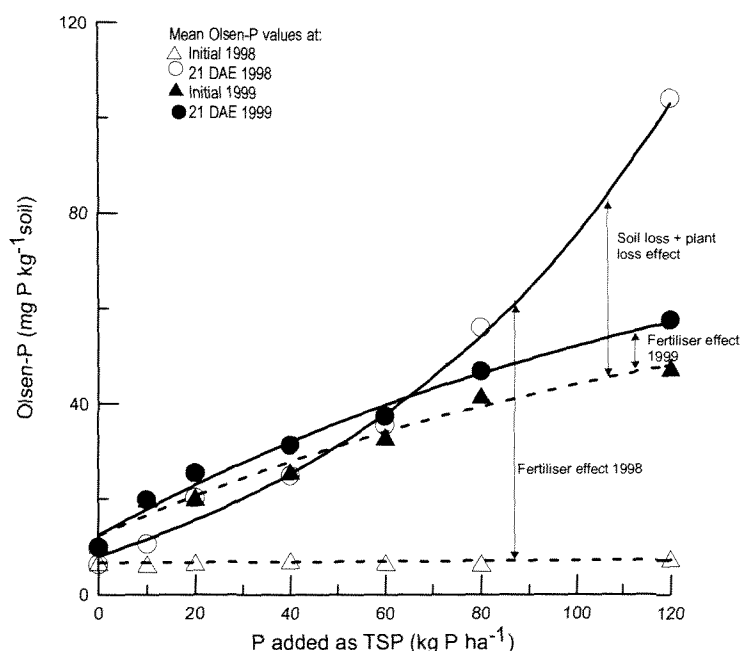


Figure 6.13 The effects of P added as TSP rates on Olsen-P values at initial and 21 DAE of maize planting in 1998 and 1999.

For reasons which are unclear the 80 and 120 kg P ha<sup>-1</sup> TSP applications created much higher Olsen-P values at 21 DAE in 1998 than those caused by reapplication of TSP at 80 and 120 kg P ha<sup>-1</sup> in 1999 (Figure 6.13). For all other rates of application ( $\leq 60$  kg P ha<sup>-1</sup>) Olsen-P values were higher at 21 DAE in 1999 than in 1998. Possibly the drier soil conditions in 1998 may have caused more unreacted TSP to have remained in the soil at 21 DAE causing elevated Olsen-P values. In 1999, the wetter year, these reactions may have been more rapid. The elevated Olsen-P values for the 80 and 120 kg P ha<sup>-1</sup> rates in

1998 quickly returned to lower levels by the 1999 cultivation period (initial 1999) and were more consistent with the Olsen-P values measured at 21 DAE in 1999.

The repeated applications of TSP in 1999, increased Olsen-P values by 21 DAE (Figure 6.13). The increase per unit P applied, however, was much lower than the 1998 effect. The reason for this is also unclear, however, P fractionation of these soils may have established the fate of the applied TSP-P, if time had permitted. Trials involving regular annual application of P fertiliser may be required to confirm relationships for increasing and maintaining the P status in the Yellow Earth.

#### *Residual fertiliser P effects on maize yields*

Residual effect of P fertilisers is defined as the effect on growth (P uptake) of the current crop resulting from P applied to previous crops. The fertiliser response effect on a given crop per unit quantity P applied is usually lower for residual P fertiliser than for freshly applied P fertiliser (Barrow, 1980). The effect on successive crops per unit P generally decreases less rapidly for a residual P nutrient than for the same P nutrient freshly applied, thus the total cumulative effect over a number of years on the present and future crop yields may be expected to be greater with the residual P nutrient than with the freshly applied P nutrient (Black, 1993). This was confirmed with the reapplication of TSP in the 1999 trial. Less freshly applied TSP was required to obtain maximum yield. In both seasons the relative maize grain yield response curves plotted against applied TSP are similar (Figure 6.14), showing how plant growth is dependent on the soil plus fertiliser P pool. Figure 6.13 shows the effect of TSP fertiliser application and time on the Olsen-P levels from trial initiation to 21 DAE of the maize for the next year (1999). Thus the larger Olsen-P values at 21 DAE (1999) for any one rate of TSP applied are consistent with reapplication of fertiliser having greater residual value.

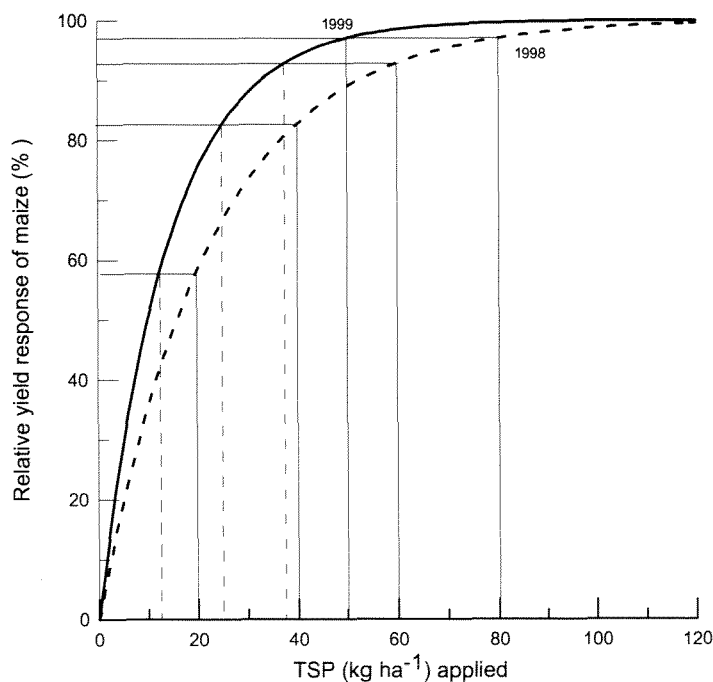


Figure 6.14 The percentage relative yield response of maize to P applied as TSP in 1998 and 1999.

The two maize grain response curves for 1998 and 1999 are plotted for applied TSP (Figure 6.15), where yield responses can be fitted by the Mitscherlich equation:

$$Y = A + B (1 - \exp^{-cx})$$

Where  $Y$  = Maize grain yield ( $\text{kg ha}^{-1}$ )

$x$  = Rate of P applied ( $\text{kg P ha}^{-1}$ )

$B$  = Yield response (Maximum yield – yield at 0)

$A$  = Yield for a P application rate of 0 (Predicted control yield)

$c$  = Curvature coefficient

$$Y (1998) = 636 + 3550 (1 - \exp^{-0.044x}) \quad \text{Equation (6.1) (1998 Trial)}$$

$$Y (1999) = 2033 + 2933 (1 - \exp^{-0.0704x}) \quad \text{Equation (6.2) (1999 Trial)}$$

The equations 6.1 and 6.2 suggest that near maximum (90%) yield were obtained from  $48.6 \text{ kg P ha}^{-1}$  in 1998 and  $25.2 \text{ kg P ha}^{-1}$  in 1999 (Figure 6.15).

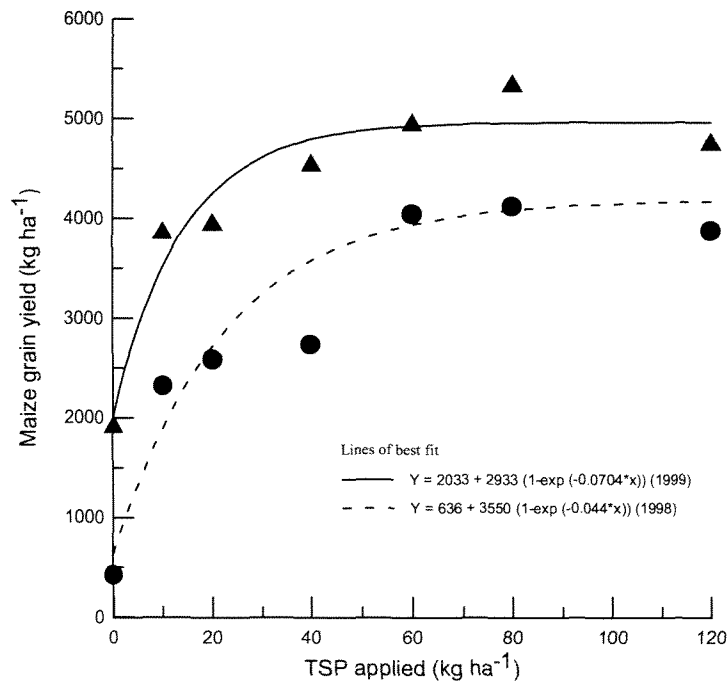


Figure 6.15 The maize grain yield produced by different rates of TSP in 1998 and 1999.

The relative yield (% of maximum yields) response to applied P can be calculated as:

$$\text{Relative yield (\%)} = A + B (1 - \exp^{-cx}) / (A + B) \times 100$$

Where  $A + B = \text{Maximum yield}$

Where the difference between A values (i.e. Predicted control yields) in 1998 and 1999 is probably caused by a seasonal climate difference (wetter in 1999). The effect of climate on the differences in calculated relative yield was reduced by removing A and calculating relative yield response as follows:

$$\text{Relative yield response (\%)} = B (1 - \exp^{-cx}) / B \times 100$$

The relative yield responses of each year are plotted against applied TSP (Figure 6. 14). These relative yield curves can then be used to calculate apparent residual values for TSP applied in year 1 (1998). This is achieved by expressing the residual value of TSP applied in 1998 as the difference between TSP required in 1998 and 1999 to produce the same relative yield response (Figure 6.14). The values are presented in Table 6.11. The difference between the residual value of 38% at 80 kg P ha<sup>-1</sup> and 46% at 120 kg P ha<sup>-1</sup> suggests that residual value kg<sup>-1</sup> P increases with higher rates of P application in the

Yellow Earth (Table 6.11 and Figure 6.16). This suggests that an increase in rate of applied P is not leading to greater P fixation.

Useful fertiliser P at the end of year 1 is that deemed to have been used by the crop plus that which has residual value for the 1999 crop.

Table 6.11 The rate of TSP applied and relative maize grain yields (%) in year 1 (1998) and application rate of TSP to give the same relative yield in year 2 (1999) and percent relative residual value of year 1 (1998).

TSP rate in year 1 (kg ha <sup>-1</sup> )	Relative yield in year 1 (%)	TSP rate in year 2 (kg ha <sup>-1</sup> )	Apparent residual value (kg ha <sup>-1</sup> )	Residual value of year 1 (%) of application rate	P removed in grain in year 1 (kg ha <sup>-1</sup> )	% efficiency of fertiliser use
10	36	6.3	3.6	36.0	3.7	73
20	59	12.7	7.3	36.5	6.1	67
40	83	25.2	14.8	37.0	6.0	52
60	93	37.8	22.2	37.0	9.7	53
80	97	49.8	30.2	37.8	10.1	50
120	99	65.4	54.6	45.5	9.5	53

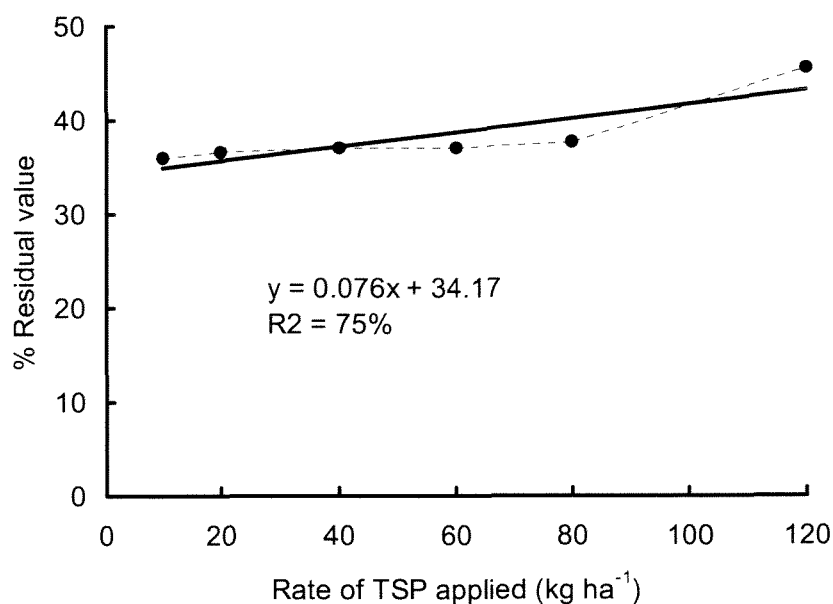


Figure 6.16 The relationship between the rate of TSP applied (kg ha<sup>-1</sup>) and percent residual value of TSP.

Percentage efficiency of fertiliser use in year 1 was calculated using the formula as follows.

Percentage efficiency of use fertiliser in year 1 (%) =  $100 \times [\text{P removed in crop (kg ha}^{-1}) + \text{residual value (kg ha}^{-1})] / \text{rate of P applied (kg ha}^{-1})$

The greater efficiency of fertiliser use in year 1 was found at the rates  $<40 \text{ kg ha}^{-1}$  of P applied (Table 6.11 and Figure 6.17). These are the rates that are used most efficiently. However, they produced sub-maximum yields. As mentioned earlier, the near maximum yield was obtained by TSP applied at  $49 \text{ kg P ha}^{-1}$  in year 1 (1998). It is around this value ( $40 \text{ kg P ha}^{-1}$ ) that fertiliser efficiency decreases to around 50% (Table 6.11). Thus if near maximum yields are to be produced the calculated value (%) suggests that for each  $1 \text{ kg P ha}^{-1}$  of TSP applied to the Yellow Earth, only  $0.5 \text{ kg}$  of P will contribute to crop yields in the year 1 plus have some residual value in year 2. Residual value will contribute to subsequent crops because soil test values have been raised (Figure 6.13) but longer term trials are required to measure that residual value. Mendoza (1992) reported that the residual value of P in soils was varied with soil P retention values and the soil Olsen-P test reflected the decrease of P availability with time.

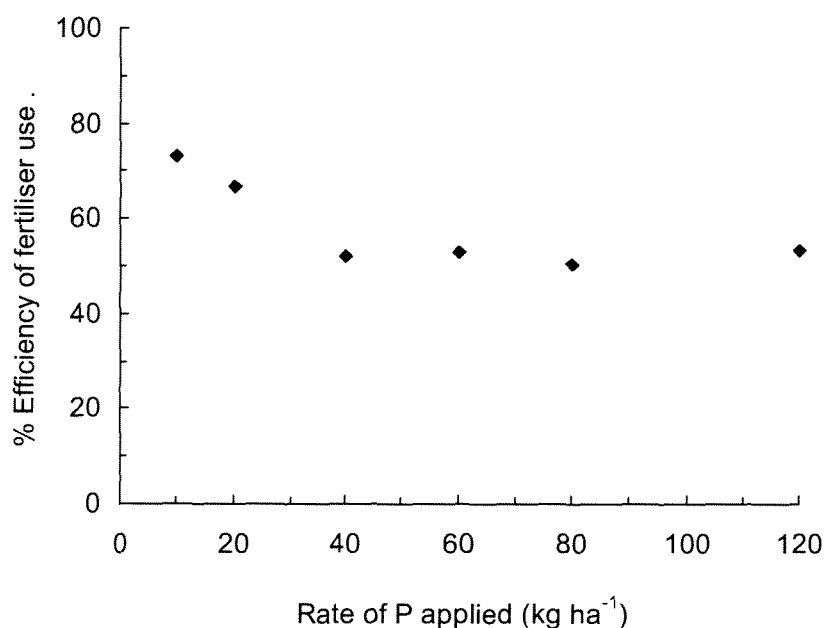


Figure 6.17 The relationship between the application rate of P ( $\text{kg ha}^{-1}$ ) and percentage efficiency of P fertiliser use (TSP).

### ***Residual effect of organic fertilisers***

#### *Organic fertiliser effects on maize yield*

Repeated additions of organic materials such as FYM and *Tithonia diversifolia* residues to Yellow Earth increased the maize DM yield at silking and again at grain yield in 1999, compared to the maize yields in 1998. The improvement in yield response above the control is presumably due to residual effects of the organic manures (see Tables 6.7 and 6.9). However, the maize crop can benefit from these sources only when P is released as these organic materials decompose. This result indicates that yield increases may occur quite slowly over years and it will take several years of FYM and *Tithonia diversifolia* applications before the combined P release from residues meets the P uptake demand of the maximum yield of maize.

Tables 6.7 and 6.9 show that the combination of FYM or *Tithonia diversifolia* with TSP or CPAPR was as effective as TSP applied at an equivalent P rate for grain yields in years 1999 and 1998. When organic fertiliser alone is added to soil the residual fertility is low and yield increases cannot be expected in the short-term. Thus the results indicate that increased nutrient recovery and improved residual values may occur with combined nutrient additions (i.e organic plus inorganic) compared with inorganic fertilisers applied alone in long-term. Similar results have been reported by Palm *et al.* (1997), who found that the optimum combined use of organic and inorganic nutrient sources increase the nutrient recovery and residual soil fertility in African soils.

#### *Organic fertiliser effects on Olsen-P*

Tables 6.5 and 6.8 demonstrate that soil Olsen-P values at 21 DAE in 1998 were not increased by applications of FYM or *Tithonia diversifolia* residues. However, by 21 DAE in the 1999 season Olsen-P values increased markedly above the control after FYM and *Tithonia diversifolia* reapplications. Some of this increase is caused by P release from the decomposing residues left in the soil from 1998 and some from their reapplication in 1999 (Figure 6.8).

Notably in the 1999 cropping season the Olsen-P values increased markedly to the applied *Tithonia diversifolia* residues (from 8 to 16 mg P kg<sup>-1</sup>) but the Olsen-P values

still showed slow response to the applied FYM (from 7 to 12 mg P kg<sup>-1</sup>). The reason may be that the organic P in FYM is more resistant to degradation than *Tithonia diversifolia* residues in the Yellow Earth (Blair *et al.*, 1976).

### ***Effect of local dolomite***

In this field situation neither soil pH nor Olsen-P rose significantly with dolomite application to the Yellow Earth. In contrast, liming acid soils can alter the availability and use of P by crop plants in three major ways: (1) P sparing effect: reducing the surface adsorption of P by soil colloids; (2) enhancing the mineralisation of soil organic P; and (3) improved root growth enhancing the absorption and translocation of P within the plant (Haynes, 1988). Net P sorption by the acidic Yellow Earth can decrease by addition of local dolomite (Haynes, 1988; Miles and Farina, 1988). However, increases in crop yield can be expected for acid intolerant plants (e.g. legumes) through dolomite addition and this can be at least partially attributed to an effect of applied Mg and Ca in the Yellow Earth (Bolan *et al.*, 1988). It is important to stress that P sparing effect of dolomite application occurs only when the soil is having an adequate reserve of native P and also in situation where high concentrations of Al and Mn inhibit the uptake of P.

## **6.5 Conclusion**

The information from two years of field experiments (1998 and 1999) confirms that soil fertility, particularly P availability, is the major constraint to optimising maize crop yields in the Yellow Earth.

However, large variations in harvested grain yields for the same treatment do not allow precise predictions of how much soluble P equivalent should be applied to maximise P yields. In 1998, applications of TSP  $\geq 45$  kg P ha<sup>-1</sup> produced near maximum yields, whereas in 1999 this could be achieved with a reapplication of  $\geq 25$  kg P ha<sup>-1</sup> on top of the residual value of the 1998 application.

Olsen-P test values of individual plots are useful predictors of yield and effectiveness of fertilisers in the Yellow Earth. Plotting grain yields against Olsen values generally explains 65% (1999) to 80% (1998) of the variation in grain yields on the Yellow Earth.

The combined data from 1998 and 1999 suggests that 90% of maximum grain yields can be obtained by raising the Olsen-P to 30-35 mg P kg<sup>-1</sup> soil. The data consistently showed that fertilisers effective in raising Olsen-P values produced higher maize yields. Therefore, the Olsen-P test can be used as an effective tool for predicting the degree of soil P constraint to crop production in Southern Shan State of Myanmar.

The residual value for TSP applied in 1998 ranged from 36% (0.36) to 46% (0.46) increasing with higher rates of P application. Further long-term trials are required to establish residual values of fertiliser P at maintenance P rates for crops.

Chinese PAPR contains 11.6% of total P with 47.2% in water soluble P, which has immediate value to maize crops in P deficient of Yellow Earths of Southern Shan State. In this trial the CPAPR applied at 20 kg P ha<sup>-1</sup> was statistically as effective as TSP at relieving P stress on maize growth in the Yellow Earth. This result needs further confirmation because the grain yield variability in this trial did not allow clear mean yield separation on plots receiving 10, 20 and 40 kg P ha<sup>-1</sup>.

However, these results highlight that at the right price CPAPR could prove to be an economically feasible fertiliser for improving the P status of Red Earths and Yellow Earths.

Local dolomite did not affect maize yield significantly and its addition with water-soluble P fertilisers (TSP) did not further increase yields in the Yellow Earth, compared to TSP alone.

Local FYM and *Tithonia diversifolia* are poor sources of plant-available P in short-term in the Yellow Earth. However, this field trial shows that the *Tithonia diversifolia* amendment (20 kg P ha<sup>-1</sup>) will significantly increase the available P (Olsen-P test value) compared with either the untreated control or FYM addition (20 kg P ha<sup>-1</sup>) in the Yellow Earth, particularly if time is allowed for its decomposition in the soil. For a long-term approach, repeated annual applications of *Tithonia diversifolia* can be considered as a potential P source for improving soil P status in the Yellow Earth of Shan State.

The data in years 1999 and 1998 suggests that the combination of FYM (20 kg P ha<sup>-1</sup>) or *Tithonia diversifolia* (20 kg P ha<sup>-1</sup>) with TSP (20 kg P ha<sup>-1</sup>) or CPAPR (20 kg P ha<sup>-1</sup>) was as effective as TSP (40 kg P ha<sup>-1</sup>) applied at an equivalent P rate for optimum grain yields of maize.

As P sources alone both FYM and *Tithonia diversifolia* applied at 20 kg P ha<sup>-1</sup> had low TSP substitution values of -0.14 and 0.33 respectively. This may prohibit the purchase of such materials because of their handling cost. Use as a local on-farm resource should, however, be encouraged.

## **CHAPTER 7    The Effect of Phosphate Fertiliser Form and Application Rate on the Yield Response of Maize Grown in a Yellow Earth**

### **7.1    Introduction**

As characterised earlier in Chapter 2, the Yellow Earths in Southern Shan State had low pH levels and were low in available P, Ca and S. The results from the glasshouse experiments (Chapter 3) and the two years field experiments (Chapter 6) confirmed that available P rather than soil pH was the major constraint to plant growth on the Yellow Earth at Aungban Research Farm in Southern Shan State.

In the previous maize trials (Chapter 6) alternative fertilisers to TSP were evaluated only at single, low rates of application. The relative (to soluble P fertilisers) agronomic value of sparingly soluble P fertilisers, which require soil acid for dissolution, can decrease markedly with increased rate of application (Gregg *et al.*, 1989; White *et al.*, 1989; Bolan *et al.*, 1990b; Hedley *et al.*, 1995). Thus this field trial examines the RAE of alternatives to TSP at a range of application rates. The alternatives to be evaluated are the Chinese partially acidulated phosphate rock (CPAPR) and a known reactive phosphate rock from Sechura in Peru (SPR).

As mentioned earlier in Chapter 6, an advantage of using PAPR instead of the direct use of PR is that some P is supplied in a soluble P form that can be immediately utilised by short-term maturity crops. This will stimulate earlier crop growth, which may lead to greater utilisation of the PR residues. The application of CPAPR improved P availability in the Yellow Earth, and increased plant yield under the field conditions (see Chapter 6).

The low pH Yellow Earth was a suitable soil for direct PR application and PR dissolution (see Section 3.5 in Chapter 3 and Section 5.5 in Chapter 5). The chemical assessment of PRs reactivity for direct application was also discussed in Section 3.3.1 (Chapter 3). On the basis of the criteria reported by Quin *et al.* (1987) the RPR chosen

for this trial, SPR, would be ranked as one of the most reactive rocks and best suited for direct application (see Table 3.2, Chapter 3).

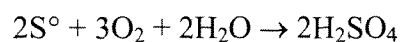
In Chapter 5, which described the short-term RSC glasshouse study, the SPR dissolved well in the composite Red Earth from Southern Shan State. The P-sorption capacity of an acid soil can influence the rate and extent of a PR dissolution (Chien *et al.*, 1980). Mackay *et al.* (1987) investigated the soil reactions that dominate the dissolution of SPR, and found that a high P-sorbing soil dissolved more P from SPR than a low P-sorbing soil under glasshouse study conditions. Whilst the P sorption power may assist RPR dissolution, the same property may reduce the plant availability of the dissolved P. Therefore, 'soil or site specific' field trials are required to fully test the RAE of RPR. Gregg *et al.* (1989) reported that highly reactive SPR applied directly to established pastures on low pH soils (range pH 5 to pH 6) in New Zealand has been found to be as effective as a soluble P fertiliser (SSP). Sinclair *et al.* (1990) have also reported that SPR is a useful source of molybdenum (Mo), containing 43 mg Mo kg<sup>-1</sup> SPR. The agronomic effectiveness of SPR under field condition on the Yellow Earth has not previously been tested.

Apart from the major constraint of P availability, the Red Earths and Yellow Earths are low in available S, however, little or no S fertiliser is used to correct S deficiency on these soils. Elemental S (S<sup>0</sup>) has been used as a S fertiliser in agriculture and the important role of S<sup>0</sup> used in agriculture is reviewed in a following section. One of objectives of the experiments discussed in this chapter is to provide useful data (information) on the direct use of RPRs and the role of S<sup>0</sup> in crop production on the Red Earths and Yellow Earths in Southern Shan State, Myanmar.

### ***The important role of elemental S (S<sup>0</sup>) used in agriculture***

Elemental S fertiliser is insoluble in water and requires biological oxidation to form the readily available soluble sulphate (SO<sub>4</sub><sup>2-</sup>) for plant growth (Watkinson, 1988; Goh, 1988). The great advantage of S<sup>0</sup> is its 100% S content, which reduces storage and transport costs over the soluble S fertilisers.

A range of factors affect the biological oxidation of S<sup>o</sup> in a soil, some of these are temperature, moisture and aeration, soil reaction, microbial population, fertiliser and management practices (Goh, 1988). The genus *Thiobacillus* is the most important of the S-oxidizing micro-organisms in a soil (Lee *et al.*, 1987); recent studies, however, have shown as actinomycetes is also involved in the oxidation of S<sup>o</sup> (Watkinson and Bolan, 1998). In the presence of S<sup>o</sup> oxidising micro-organisms, the rate of S-oxidation is controlled by the surface area of the S<sup>o</sup> (i.e. particle size) exposed for attachment of soil microbes. The microbial oxidation of S<sup>o</sup> in a soil generates H<sub>2</sub>SO<sub>4</sub> as shown below:



Incubation studies (Rajan and Edge, 1980; Lee and Watkinson, 1987) showed that addition of S<sup>o</sup> to RPRs caused small increases in soluble P in soil. The reason is that oxidation of S<sup>o</sup> increases the RPR dissolution rate through an increase in soil acidity in the vicinity of RPR particles (Chatupote, 1990). Rajan (1983) reported that mixtures of SPR and S<sup>o</sup> applied into a low pH soil increased the availability of P to plants under glasshouse conditions. The low ratio of PR:S (SPR:S ratio, 5:1) used in his study was found to be as effective as a soluble P fertiliser (SSP).

It is expected that crops grown on the soils of the study area will be S responsive. It has been reported that mixing of S<sup>o</sup> and P fertilisers increased maize yield on a highly weathered Red Earth in Indonesia (Santoso *et al.*, 1995).

As well as a useful S source, the studies mentioned above indicate that the agronomic value of SPR may be improved by the addition of S<sup>o</sup>. Therefore, the effect of S<sup>o</sup> addition to SPR was evaluated using a maize crop grown in a Yellow Earth on the Aungban Research Farm.

## 7.2 Objectives

1. To evaluate the relative agronomic effectiveness of CPAPR and SPR compared to the fully soluble TSP at a range of application rates in Yellow Earth.

2. To examine the influence of elemental S addition to SPR on maize growth in the Yellow Earth.
3. To investigate the agronomic effectiveness of combinations of FYM with CPAPR or TSP.

### **7.3 Materials and Methods**

#### **7.3.1 *Experimental site description***

##### ***Location***

The field trial was conducted at Aungban Research Farm (96° 39.43' East Longitude and 20° 40.75' North Latitude) in Kalaw Township of Southern Shan State, Myanmar. The location of the field trial site was described in Section 6.3.1 (Chapter 6). This trial was near to the maize trials described in Section 6.3.1, on the same soil type, but at a slightly lower elevation.

##### ***Topography and climate***

The topography and climate of the experimental site was described earlier in Section 1.3 (Chapter 1) and Section 6.3 (Chapter 6). The temperature and rainfall at the experimental site at Aungban were presented in Chapter 6 (see Figure 6.1).

##### ***Soil type and characteristics***

The soil type and classification are described in Chapter 2 (see Section 2.4.1) and the important chemical characteristics of the topsoil are presented in Chapter 6 (see Table 6.2).

##### ***P fertiliser sources***

The physical and chemical properties of the TSP, CPAPR and FYM fertilisers are reported in Table 6.4 (Chapter 6) and the properties of SPR are presented in Table 3.2 (Chapter 3).

### ***Elemental S***

The S<sup>o</sup> used was carefully ground to pass through a 500 µm sieve, and stored in airtight plastic bags. All plots received S<sup>o</sup> at the rate of 20 kg S ha<sup>-1</sup>, except treatment 9, which received SPR at the rate of 80 kg P ha<sup>-1</sup> without S treatment.

### ***Nitrogen, K and other fertilisers***

Nitrogen (100 kg N ha<sup>-1</sup>) was supplied as Urea, in three split applications (50 kg N ha<sup>-1</sup> at planting, 25 kg N ha<sup>-1</sup> at three weeks after emergence and 25 kg N ha<sup>-1</sup> at silking) with no allowance made for the N content of the FYM. Potassium, as KCl, was applied at 50 kg K ha<sup>-1</sup> and other nutrients such as zinc sulphate (5 kg Zn ha<sup>-1</sup>) and ammonium molybdate (50 g kg<sup>-1</sup> seed) were also applied at seeding.

### ***7.3.2 Experimental design and treatments***

This maize experiment was established during June to September 1999. The local variety of Maize (*Zea mays*; local hybrid var. Yezin 3) was used as the test crop. The treatment descriptions and codes are presented in Table 7.1.

Table 7.1 Fertiliser treatments for the Maize Field Trial 2 on a Yellow Earth at Aungban Research Farm.

No.	Treatment description	Code
1	Control (0 kg P ha <sup>-1</sup> )	Con 0 P
2	TSP 20 kg P ha <sup>-1</sup>	TSP 20 P
3	CPAPR 20 kg P ha <sup>-1</sup>	CPAPR 20 P
4	CPAPR 40 kg P ha <sup>-1</sup>	CPAPR 40 P
5	CPAPR 80 kg P ha <sup>-1</sup>	CPAPR 80 P
6	SPR 20 kg P ha <sup>-1</sup>	SPR 20 P
7	SPR 40 kg P ha <sup>-1</sup>	SPR 40 P
8	SPR 80 kg P ha <sup>-1</sup>	SPR 80 P
9	SPR 80 kg h <sup>-1</sup> (-Sulphur)	SPR 80 P (-S)
10	FYM 40 kg ha <sup>-1</sup>	FYM 40 P
11	FYM 40 kg P ha <sup>-1</sup> + TSP 20 kg P ha <sup>-1</sup>	FYM 40 P + TSP 20 P
12	FYM 40 kg P ha <sup>-1</sup> + TSP 40 kg P ha <sup>-1</sup>	FYM 40 P + TSP 40 P
13	FYM 40 kg P ha <sup>-1</sup> + CPAPR 20 kg P ha <sup>-1</sup>	FYM 40 P + CPAPR 20 P
14	FYM 40 kg P ha <sup>-1</sup> + SPR 20 kg P ha <sup>-1</sup>	FYM 40 P + SPR 20 P
15	TSP 10 kg P ha <sup>-1</sup>	TSP 10 P
16	TSP 40 kg P ha <sup>-1</sup>	TSP 40 P
17	TSP 60 kg P ha <sup>-1</sup>	TSP 60 P
18	TSP 80 kg P ha <sup>-1</sup>	TSP 80 P
19	TSP 120 kg P ha <sup>-1</sup>	TSP 120 P
20	TSP 20 kg P ha <sup>-1</sup> + Dolomite 2.5 t ha <sup>-1</sup>	TSP 20 P + Dolomite

This experiment was conducted in a completely balanced factorial design. There were seven rates of P (0, 10, 20, 40, 60, 80, 120 kg P ha<sup>-1</sup>) used for the TSP response curve. Comparative CPAPR and SPR response curves were generated at the 0, 20, 40 and 80 kg P ha<sup>-1</sup> rates of application. The basal treatment of Urea (50 kg N ha<sup>-1</sup>), KCl (50 kg K ha<sup>-1</sup>), Zinc Sulphate (ZnSO<sub>4</sub>; 5 kg Zn kg<sup>-1</sup>) and S<sup>o</sup> (20 kg S ha<sup>-1</sup>) were applied to all plots. Elemental S was omitted from treatment 9 (SPR 80 kg P ha<sup>-1</sup>) to test whether S<sup>o</sup> addition enhanced the agronomic value of SPR.

In addition, the treatments TSP, CPAPR and SPR at 20 kg P ha<sup>-1</sup> and TSP at 40 kg P ha<sup>-1</sup> were applied in combination with FYM at 40 kg P ha<sup>-1</sup>. Also, an application of TSP at 20 kg P ha<sup>-1</sup> with dolomite at 2.5 t ha<sup>-1</sup> was made to assess whether soil pH was limiting maize growth. The total number of the treatments in this experiment was 20. All treatments were replicated thrice.

### ***7.3.3 Cultivation and crop establishment***

The experimental plot was a sited towards the rear of the Aungban Research Farm in Southern Shan State of Myanmar. All three replications of this experiment were established on one contour and blocks and plots were laid out. This experimental site was ploughed by an ox and then levelled with a hoe. In this experiment each plot size was 5 m × 6 m, with 20 hills in 8 rows and spacing of 25 cm × 75 cm, as described in the first maize trials in Chapter 6 (see Figure 6.2). Fertiliser treatments were applied on 25 June 1999 and then maize was sown by hand in all plots on the same day.

#### ***Application of fertilisers***

As described in Chapter 6, TSP, CPAPR, FYM and other fertilisers were applied in a band (width 25-30 cm) approximately 5 cm deep, while SPR was spread and incorporated by hand, prior to seeding. Dolomite was broadcast over each plot and incorporated into the soil.

#### ***Soil samples***

Soil samples (0-15 cm and 15-30 cm) were taken from each plot before treatments were applied, at 21 DAE and silking stage of maize. Ten cores from the 0-15 cm soil layer

were collected from each plot and bulked for analysis. A bulked sample of 3 to 4 cores per plot of the 15-30 cm layer were also collected. The soil core samples (0-15 cm) were taken from the P fertiliser banded area across the plot. The soil samples from each plot were air dried and crushed to pass through a 2-mm sieve, and stored in airtight plastic bags after sub-sampling.

### **Herbage samples**

Herbage samples (leaves and the whole plants) were collected from 4 plants from each plot at 21 DAE and at silking stage of maize. At harvest, herbage samples were collected from 6 representative plants from each plot. Herbage samples were oven-dried at 70°C and stored for chemical analysis.

### ***Chemical analysis of soil and herbage***

The soil and herbage samples were air freighted to New Zealand from Myanmar under the NZMAF Biosecurity Authority Control. After completion of the study all samples will be incinerated. Total N and P contents of maize leaves were determined using a Technicon auto-analyser (McKenzie and Wallace, 1954; Blakemore *et al.*, 1987) following Kjeldahl digestion. Soil samples were analysed using the following methods: soil pH using a 1:2.5 soil to water ratio and available P by Olsen-P method (Olsen *et al.*, 1954).

### ***Relative agronomic effectiveness of CPAPR, SPR and FYM***

The agronomic effectiveness of P fertilisers (i.e. CPAPR, SPR and FYM) at different rates relative to TSP were calculated using the following equation (Mnkeni *et al.*, 2000):

$$\text{RAE (\%)} = (Y_F - Y_C) / (Y_T - Y_C) \times 100$$

Where:  $Y_F$  = yield from P fertiliser,  $Y_T$  = yield from reference fertiliser (in this case TSP), and  $Y_C$  = yield from the control treatment. Substitution values, which indicated the rates of TSP required to give the same yields as CPAPR or SPR, were calculated using the fitted maize growth response curves (Chien *et al.*, 1990; Lewis *et al.*, 1997).

Although the CPAPR and SPR were tested at various rates of P, the response curves for these P sources did not follow that of the TSP. Hence the substitution ratios for these sources at various P rates were calculated from the ratio of the P required to achieve similar yields between TSP (estimated from the response curve) and the test fertilisers added at different rates.

### Statistical analysis

The differences among the means or effects of the treatments were tested for statistical analysis using the general linear models (GLM) procedure (SAS, 1989) to conduct an analysis of variance (ANOVA). Fisher's least significant difference (LSD at 95% confident level) was applied for multiple comparison procedures of the treatments, unless otherwise stated.

## 7.4 Results and discussion

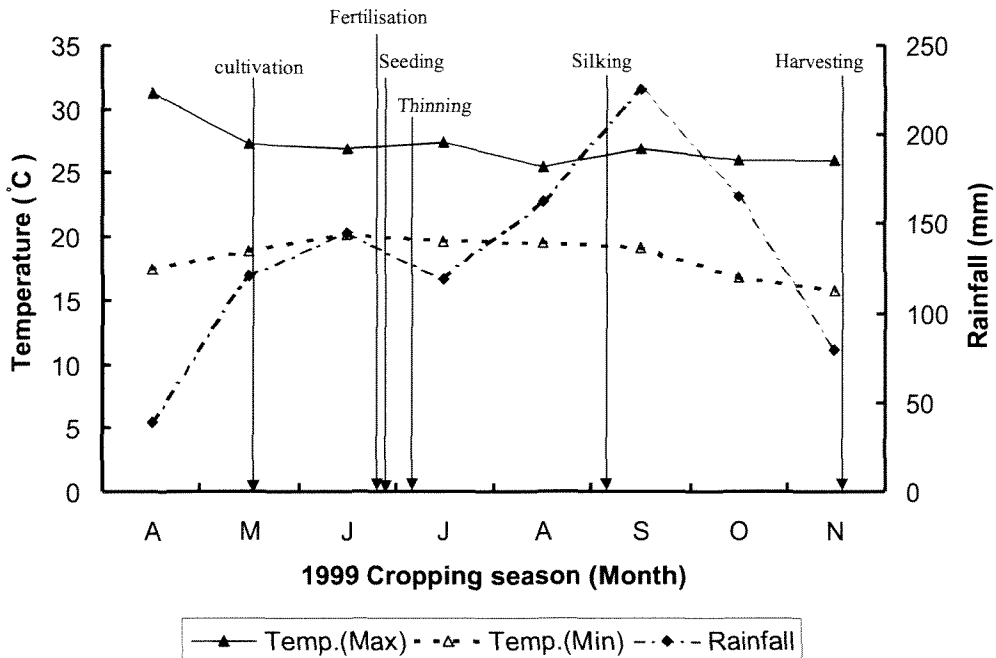


Figure 7.1 Temperature (maximum and minimum °C) and Rainfall (mm) for the Maize Field Trial 2 growing periods at Aungban Research Farm (1999).

Average rainfall distribution through Southern Shan State in Myanmar for 1999 suggested large areas of Kalaw and Pindaya received more than 1,000 mm per year with seasonal variation (Figure 7.1), with the wetter season occurring from May to November. The average maximum and minimum temperature ranged between 16 to 31 °C during the cropping season and was suitable for growing sub-tropical and tropical crops (Figure 7.1).

The results from the Maize Field Trial 1 (1998 and 1999) and this Maize Field Trial 2 (1999) pointed out that delays in planting maize at the start of the cropping season (monsoon season) bring risks of significant reductions in maize grain yield due to lower water availability at the early stages (usually drought in July) and heavy rain at the silking of maize. Similarly, soil moisture must be conserved as it is received at early stages of maize growth, and population of maize plants must be restricted to maximize the potential seasonal production in Southern Shan State.

The final maize grain yield may depend upon management practices, thus, many improvements or innovative techniques by farmers in Southern Shan State are needed including; timing of cultivation and seeding (i.e. before middle of June); timing of fertiliser application; planting density and moisture conservation; adoption of early maturity crop (i.e. maize); balanced use of fertilisers (i.e. N, P, K and S fertilisers); use of pesticides (i.e. to control rodent) and insecticides (i.e. to control wire worm *Agriotes spp*).

#### **7.4.1 Effect of P fertilisers on Olsen-P test values**

Before the treatments were applied, the initial soil Olsen-P values in all plots were similar averaging 8 mg P kg<sup>-1</sup> with a range at 7 to 10 mg P kg<sup>-1</sup>. Thus, the available P status was evenly distributed in this experiment and soil P fertility of this area was relatively homogenous (Table 7.2).

By 21 DAE, the soils' initial Olsen-P status (average initial) was increased significantly by additions of TSP, CPAPR and SPR treatments (Table 7.2), except the SPR treatment applied at 20 kg P ha<sup>-1</sup>.

The soluble P fertiliser TSP raised the Olsen-P values significantly higher than CPAPR and SPR applied at 20, 40 and 80 kg P ha<sup>-1</sup> rates (Figure 7.2). This is consistent with the lower solubility of the CPAPR and SPR fertilisers. There were strong relationships between P added and the Olsen-P increase when P applied is expressed as the amount of water-soluble P or citric-soluble P applied (Figure 7.3a and b). These results indicate that either water-soluble P content (i.e. for TSP) or citric-soluble P content (i.e. for SPR) of P fertilisers could be used to predict the rates of P fertiliser required to raise Olsen-P values to target levels.

Table 7.2 The soil Olsen-P status at cultivation (initial), 21 days after emergence and silking stage of maize grown in a Yellow Earth fertilised with different P sources (Field Trial 2).

Treatment	Initial	21 DAE	Silking
Con 0 P	8.	9l	9k
TSP 20 P	7	19ghi	19hij
CPAPR 20 P	10	17ij	23ghi
CPAPR 40 P	7	22fg	26fg
CPAPR 80 P	7	25ef	33de
SPR 20 P	8	11kl	19hij
SPR 40 P	7	19ghi	24ghi
SPR 80 P	9	21fgh	27fg
SPR 80 P (-S)	8	15jk	17j
FYM 40 P	8	18hij	17j
FYM 40 P + TSP 20 P	8	21gh	23ghi
FYM 40 P + TSP 40 P	10	26e	30ef
FYM 40 P + CPAPR 20 P	9	19ghi	17j
FYM 40 P + SPR 20 P	8	17ij	17j
TSP 10 P	7	17ij	19ij
TSP 40 P	7	33d	36d
TSP 60 P	7	47c	46c
TSP 80 P	8	54b	71b
TSP 120 P	7	70a	84a
TSP 20 P + Dolomite	8	22fgh	24gh
	NS	LSD 4 P<0.05	LSD 5 P<0.05

Mixing S<sup>o</sup> with SPR at the 80 kg P ha<sup>-1</sup> treatment significantly increased Olsen-P above the value of SPR alone at 80 kg P ha<sup>-1</sup> (Table 7.2). It is possible that there was sufficient oxidation of S<sup>o</sup> by 21 DAE to produce sulphuric acid, which enhanced SPR dissolution (Lee *et al.*, 1987; Lee *et al.*, 1988).

The Olsen-P values in the TSP (10 to 60 kg P ha<sup>-1</sup>) plots, control plots and plots containing FYM changed little between 21 DAE and silking (Table 7.2). However, in the SPR and CPAPR plots, Olsen-P values increased between 21 DAE and silking. This may be explained by continued dissolution of the SPR and PR residues in the CPAPR.

Olsen values in soils where TSP applied at 80 and 120 kg P ha<sup>-1</sup> rates also increased soil Olsen-P values markedly. The reason for this is unclear but may be caused by non-uniform sampling of the fertiliser band in the TSP plots. In this case uneven sampling cannot be ruled out as a cause for the Olsen increase in the CPAPR plots between 21 DAE and silking. Sechura PR was broadcast over the whole plot area thus uneven sampling is less likely to have occurred for this treatment.

In this trial it took 1.6 to 1.7 kg P ha<sup>-1</sup> of TSP, 2.7 to 4.4 kg P ha<sup>-1</sup> of CPAPR and 3.3 to 6.6 kg P ha<sup>-1</sup> of SPR to raise the Olsen-P value by one unit from planting to 21 DAE. The differences in the rates between P fertilisers is consistent with their initial P solubilities in water for the more soluble P fertilisers (TSP 93.5%, CPAPR 47.2% water-soluble P). But it is not consistent with the solubility of the less soluble P fertiliser (SPR 0.3% water-soluble P). These differences are consistent, however, with their initial solubility in 2% citric acid solution (TSP 94.1%, CPAPR 58.3% and SPR 42% citric-soluble P).

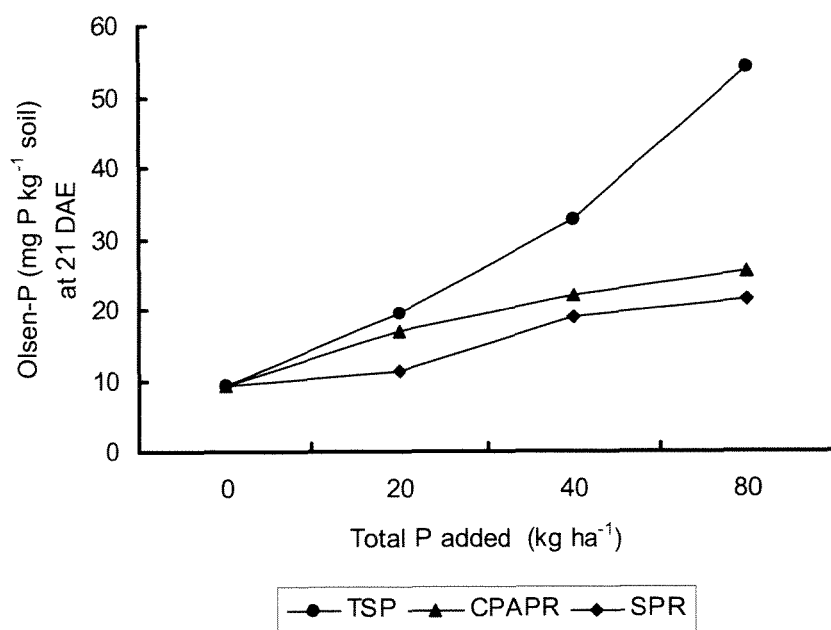


Figure 7.2 The effects of P fertiliser forms and rates on soil Olsen-P at 21 DAE of maize in June planting 1999 (Field Trial 2).

### 7.4.2 Effect of P fertilisers on maize yield

At the earlier stage of 21 DAE, low rates of TSP at 10 and 20 kg P ha<sup>-1</sup>, CPAPR at 20 kg P ha<sup>-1</sup>, SPR at 20 and 40 kg P ha<sup>-1</sup>, SPR at 80 kg P ha<sup>-1</sup> without S, FYM at 40 kg P ha<sup>-1</sup>, and FYM at 40 kg P ha<sup>-1</sup> combined with SPR 20 kg P ha<sup>-1</sup>, did not significantly increase DM yield of maize more than the control ( $P < 0.05$ ) (Table 7.3). Although the addition of dolomite with TSP 20 kg P ha<sup>-1</sup>, produced more maize DM yield at 21 DAE compared to the control treatment, the yield was not significantly different compared to the 20 kg P ha<sup>-1</sup> TSP alone treatment (Table 7.3).

Table 7.3 The effects of different P fertilisers on the maize DM yield (g plant<sup>-1</sup>) at 21 DAE and silking stage, and maize grain and stover yield (kg ha<sup>-1</sup>) at harvest.

Treatment	21 DAE (g plant <sup>-1</sup> )	Silking (g plant <sup>-1</sup> )	Stover (kg ha <sup>-1</sup> )	Grain (kg ha <sup>-1</sup> )
Con 0 P	1.9i	76.5i	2260k	520j
TSP 20 P	3.8fghi	110.5defg	3590hi	2213fg
CPAPR 20 P	3.3ghi	101.3efgh	3600hi	1353h
CPAPR 40 P	5.5cdef	113.7def	7187a	2777e
CPAPR 80 P	7.0bcd	164.8a	7010a	4803a
SPR 20 P	2.0i	92.8ghi	2423k	500j
SPR 40 P	2.7hi	100.3defgh	3803h	927i
SPR 80 P	7.5abc	157.5ab	5807def	2303f
SPR 80 P (-S)	3.1hi	108.2defg	2987j	1057hi
FYM 40 P	2.9hi	94.9fghi	3247ij	1100hi
FYM 40 P + TSP 20 P	4.7efgh	122.8cd	6143bcd	2183fg
FYM 40 P + TSP 40 P	5.3defg	137.3bc	6517b	3457cd
FYM 40 P + CPAPR 20 P	4.2fgh	102.7defgh	5443f	1927g
FYM 40 P + SPR 20 P	3.1ghi	108.4defg	4700g	2157fg
TSP 10 P	2.9hi	87.17hi	3677h	1977g
TSP 40 P	8.0ab	137.3bc	5777def	3167d
TSP 60 P	9.5a	177.7a	6280bc	4210b
TSP 80 P	7.9ab	162.3a	6050cde	4026b
TSP 120 P	6.8bcde	120.8cde	5670ef	3647c
TSP 20 P + Dolomite	4.4fgh	136.0c	4597g	2647e
	LSD 2.2	LSD 20.5	LSD 424	LSD 324
	$P < 0.05$	$P < 0.05$	$P < 0.05$	$P < 0.05$

By silking stage, (Figure 7.4), there was a marked visual response to soluble P applied as TSP (Plate 7.1) and, more treatments (see Table 7.3) began to produce yields significantly greater than the control. This trend continued until final harvest when all treatments except SPR applied at 20 kg P ha<sup>-1</sup> produced significantly greater stover and grain yields compared to the control.

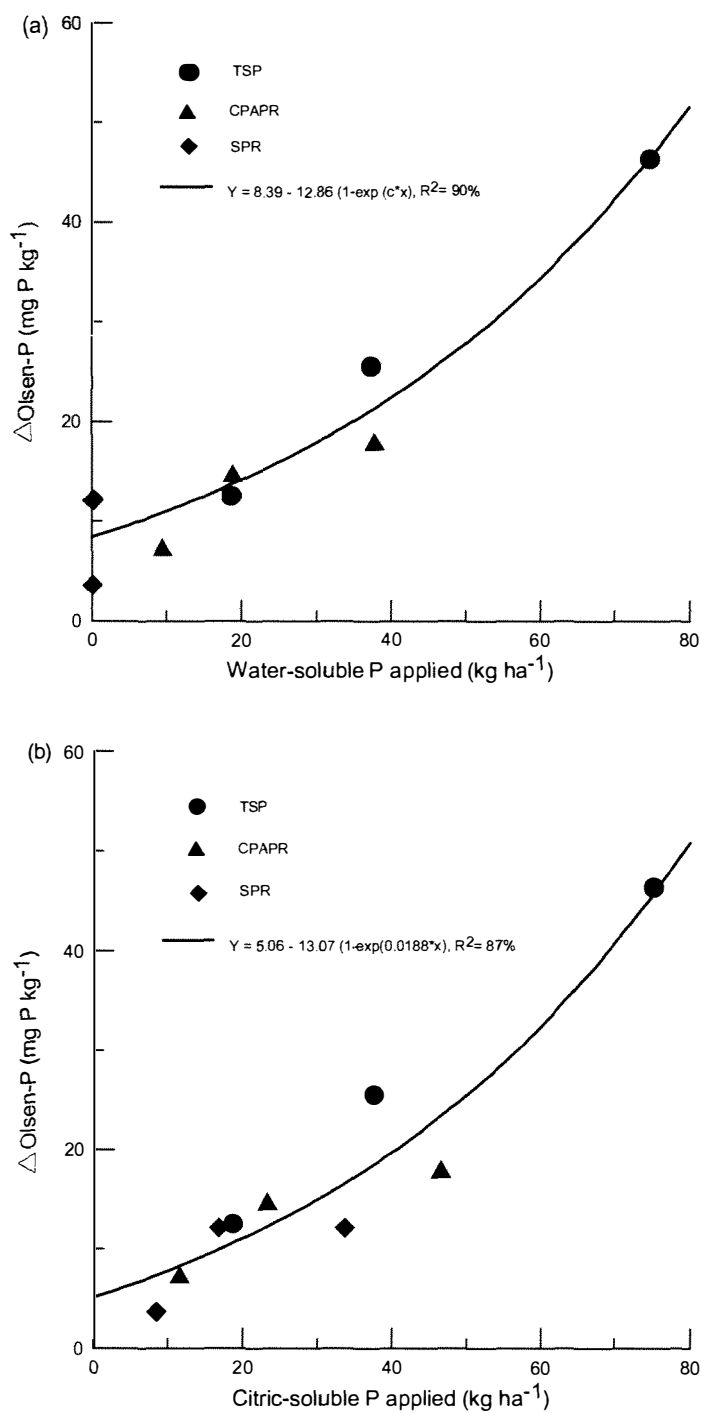


Figure 7.3 The increase in  $\Delta$ Olsen-P values at 21 DAE caused by the addition of P as (a) water-soluble applied P (kg P ha<sup>-1</sup>) and (b) citric-soluble applied P (kg P ha<sup>-1</sup>) (Field Trial 2).

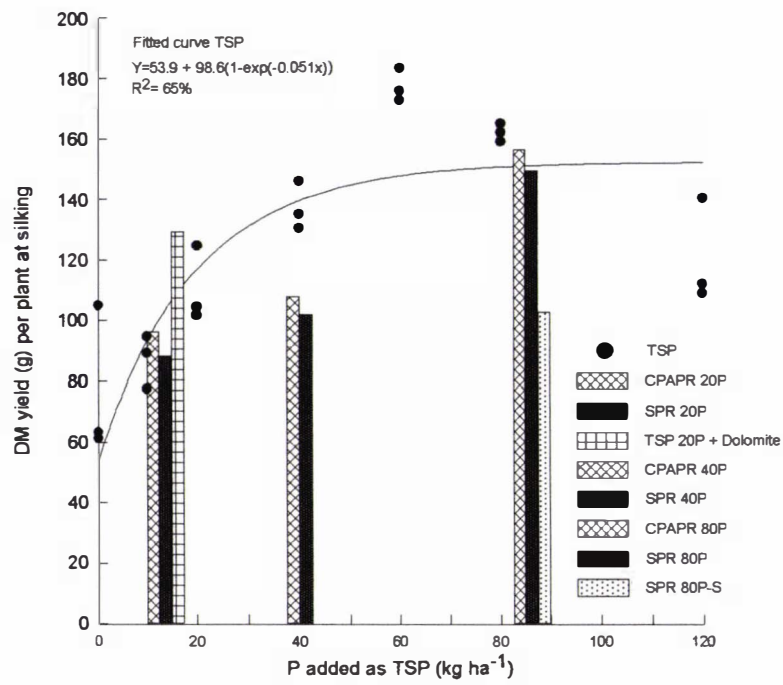


Figure 7.4 The effects of P rates on dry matter yield of maize at silking in Field Trial 2 June 1999 planting.

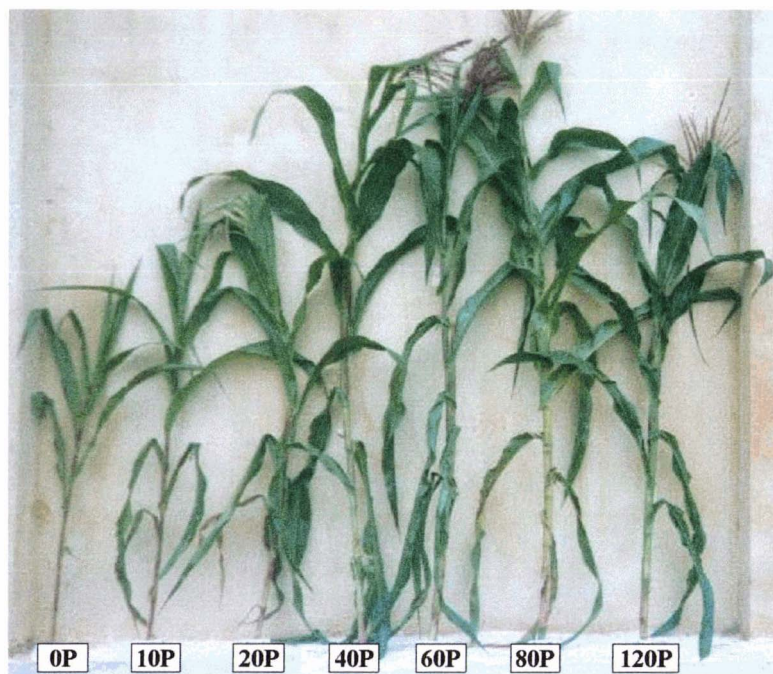


Plate 7.1 The effect of TSP rates (0 to 120  $\text{kg P ha}^{-1}$ ) on maize DM yield at silking stage.

At harvest time, the highest stover yields were achieved by application of CPAPR at 40 and 80 kg P ha<sup>-1</sup> (Figure 7.5 and Table 7.3). It is likely that the unexpectedly high stover yield at CPAPR 40 kg P ha<sup>-1</sup> treatment was caused by variations in plot fertility, probably differences in localised N or S availability. This effect was not evident in grain yields (Figure 7.6), which increased linearly with CPAPR application. This increased grain yield more than CPAPR addition suggests that there is an additional growth response to the soluble S present in the sulphuric acid acidulated fertiliser. Evidence for this S responsiveness comes from the dramatically lower yields of grain and stover produced when S<sup>o</sup> was omitted from the SPR applied at 80 kg P ha<sup>-1</sup> (Table 7.3).

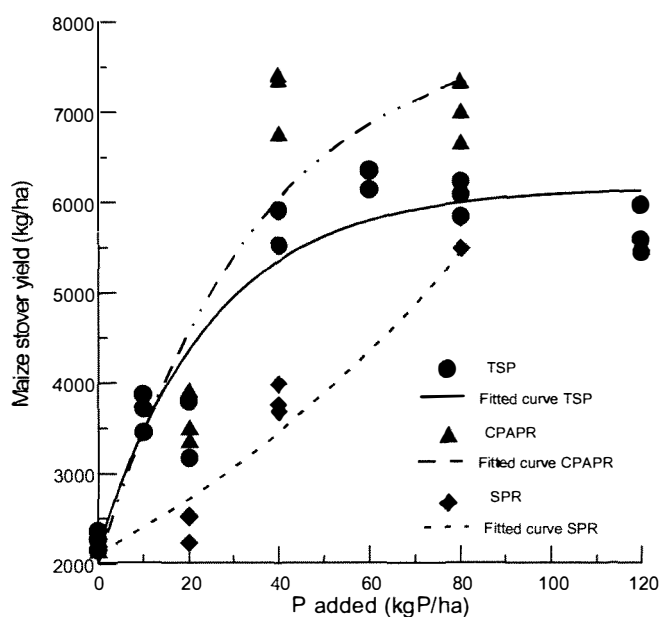


Figure 7.5 The effects of P rates on maize stover yield at harvest in June planting 1999 (Field Trial 2).

Sechura PR consistently produced lower grain yields than TSP and CPAPR per unit P applied, but stover yields at the 80 kg P ha<sup>-1</sup> application rate were similar.

The combination of FYM at 40 kg P ha<sup>-1</sup> with TSP at 20 kg P ha<sup>-1</sup> improved the maize stover yield, but FYM at 40 kg P ha<sup>-1</sup> with CPAPR 20 kg P ha<sup>-1</sup> or SPR 20 kg P ha<sup>-1</sup> produced significantly lower maize stover yield, compared to TSP 60 kg P ha<sup>-1</sup> alone.

The addition of dolomite with TSP at 20 kg P ha<sup>-1</sup> produced greater maize stover and grain yields (125 and 120%) than TSP alone at 20 kg P ha<sup>-1</sup> in this field trial (Table 7.3).

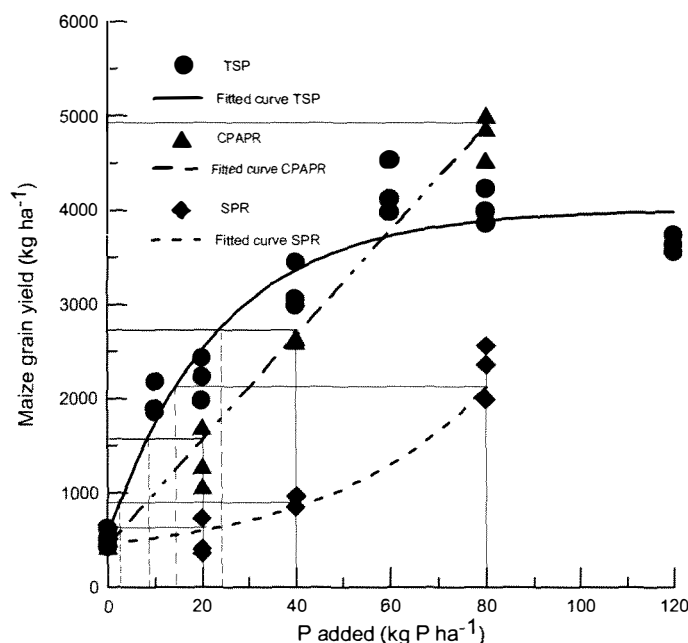


Figure 7.6 The effects of P rates on maize grain yield at harvest in June planting 1999 (Field Trial 2). Lines in this figure are estimated for SR values of P fertilisers.

The asymptotic relationship between the soluble P added as TSP and maize grain yield at harvest (Figure 7.6), was fitted by Mitscherlich equation as follows:

$$Y = 553.48 + 3451(1 - \exp^{-0.042x}), R^2 = 92\%$$

The above equation suggests that 90% of maximum maize grain yield was produced by applying 51 kg P ha<sup>-1</sup> added as TSP.

The grain yields produced by different rates of total P applied as CPAPR and SPR did not fit this relationship, indicating that not all their total P was plant available and perhaps CPAPR had an additional S effect at higher rates of application. When P added is expressed as the amount of citric-soluble P applied or water-soluble P applied this relationship changed (Figures 7.7 and 7.8). All plotted data points were fitted with a common Mitscherlich relationship as a line of best fit for all P fertilisers. The water-soluble P trend line (Figure 7.7) indicated that the application of 48 kg P ha<sup>-1</sup> as water-soluble P produced a near maximum grain yield of maize. Yields produced by SPR treatments are underestimated by the line of best fit because of its negligible water-soluble P content. The citric-soluble P trend line (Figure 7.8) suggest that 90% of maximum grain yield can be produced by the addition of 66 kg P ha<sup>-1</sup> as citric-soluble P in the Yellow Earth for all P fertilisers. However, the line of best fit now overestimates

yields produced by SPR. These relationships should prove useful in making decisions on the rates of application of partially soluble P fertilisers.

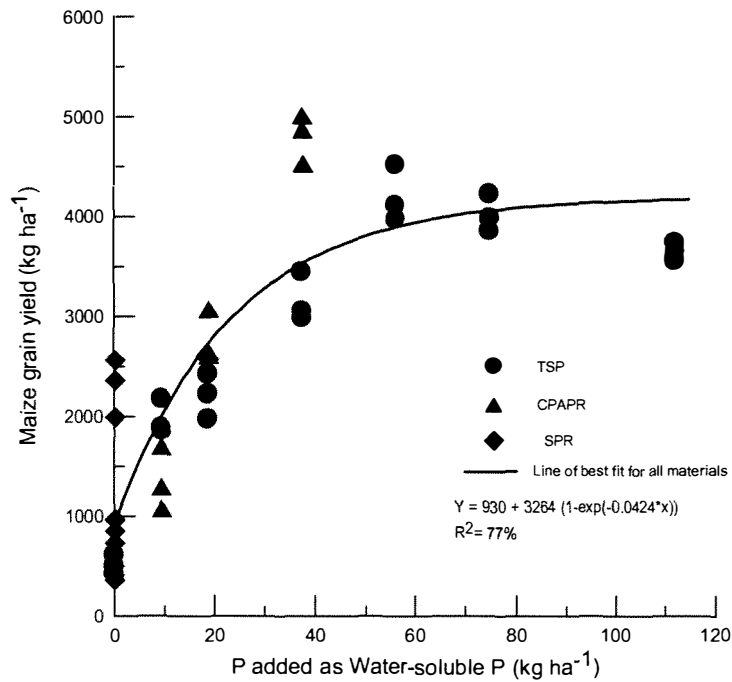


Figure 7.7 The effects of P added as water-soluble P (kg P ha<sup>-1</sup>) on maize grain yield (kg ha<sup>-1</sup>) in Field Trial 2.

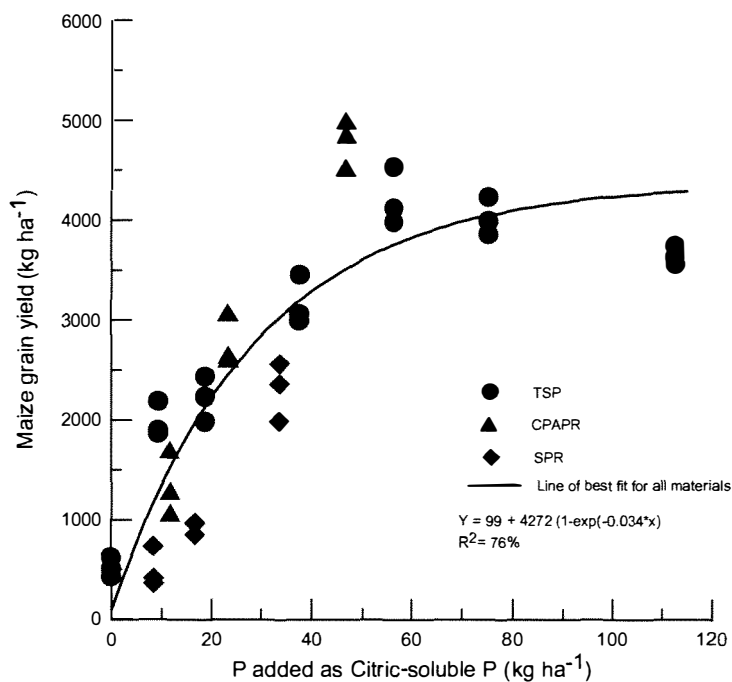


Figure 7.8 The effects of P added as citric-soluble P (kg P ha<sup>-1</sup>) on maize grain yield (kg ha<sup>-1</sup>) in Maize Field Trial 2.

Consistently, applications of FYM at 40 kg P ha<sup>-1</sup> with TSP or CPAPR or SPR at 20 kg P ha<sup>-1</sup> gave lower maize grain yields than TSP at 60 kg P ha<sup>-1</sup> alone (Table 7.3).

The addition of FYM at 40 kg P ha<sup>-1</sup> with TSP at 20 and 40 kg P ha<sup>-1</sup>, however, produced a similar amount of maize grain yield to TSP at 20 and 40 kg P ha<sup>-1</sup> alone (Table 7.3). This combination did not enhance the value of TSP in the short-term. FYM addition at 40 kg P ha<sup>-1</sup> with CPAPR and SPR at 20 kg P ha<sup>-1</sup> produced yields that were significantly greater than each fertiliser applied alone at the same application rate and in the case of SPR the combination effect was greater than the sum of grain yields produced by SPR 20 kg P ha<sup>-1</sup> and FYM 40 kg P ha<sup>-1</sup>. Thus FYM appears to have a significant interaction with the P availability from SPR.

Grain yield of maize was increased significantly (125%) when dolomite was added with TSP at 20 kg P ha<sup>-1</sup>. There was no increase in Olsen-P (Table 7.2) with dolomite application, a similar result to the glasshouse trial (see Section 3.4, Chapter 3), thus the maize yield increase may be caused by the P sparing effect of lime, or improved root growth through improved Ca and Mg nutrition with dolomite. It is not uncommon for liming to depress Olsen-P values, which is an artefact of the Olsen-P test (Sorn-Srivichai *et al.*, 1988).

### ***Relationships between Olsen-P values and maize yield***

Water-soluble P (Figure 7.7) or citric-soluble P (Figure 7.8) applied provided better predictions of maize grain yield than total P applied (Figure 7.6). However, these relationships did not include FYM and varied from site to site depending on the initial soil P status. This is because the plant growth P response is due to both soil P + P released from the fertiliser during the growing season. Results previously presented in Figure 7.1 and Table 7.2 show the variable effect of fertiliser form on the available soil P pool, as reflected in the Olsen-P test. Relationships between soil P test value and grain yield (or relative yield) may be more spatially portable. In this section the relationship between yield and Olsen-P at 21 DAE is examined.

There were highly significant relationships between soil Olsen-P value at 21 DAE and maize DM yield at silking or maize grain yield at harvest (Figures 7.9 and 7.10). The relationships were of the diminishing return type (asymptotic, trend lines in Figures 7.9 and 7.10). The TSP trend lines suggest that 90% of maximum maize DM yield at 21 DAE is achieved at an Olsen-P value of 34 mg P kg<sup>-1</sup> soil. Ninety percent of maximum grain yield (Figure 7.10) is achieved at an Olsen-P of 40 mg P kg<sup>-1</sup> soil.

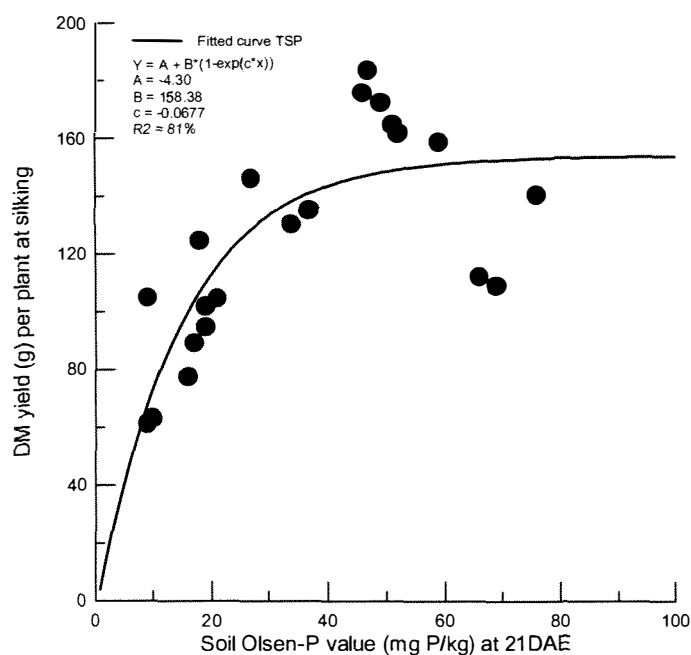


Figure 7.9 The relationships between Olsen-P values at 21 DAE and maize DM yield at silking stage in June planting 1999 (Field Trial 2) (● = TSP data point for every plot).

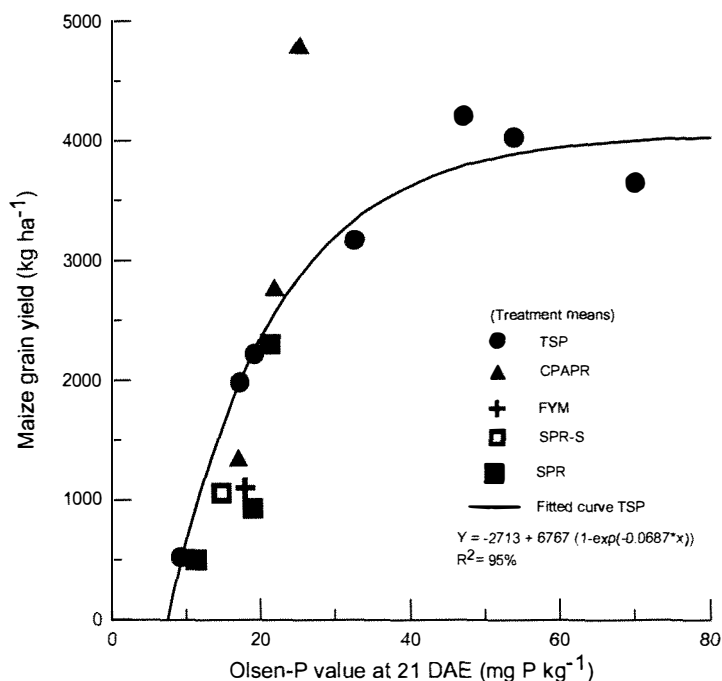


Figure 7.10 The relationships between Olsen-P values at 21 DAE and maize grain yield at harvest in June planting 1999 (Field Trial 2).

The 'TSP' Olsen trend line gives close predictions of the grain yields on the SPR treatments and most of the CPAPR treatments except the 80 kg P ha<sup>-1</sup> rate, which would have had a total S input of (20 kg S<sup>o</sup> ha<sup>-1</sup> + 70 kg SO<sub>4</sub><sup>2-</sup> ha<sup>-1</sup> from the CPAPR) which is probably responsible for the higher grain yields.

### General discussion

In this maize field trial, the different rates and forms of P fertilisers markedly affected maize growth and vigour even in the early growth stages. Plants in the control treatment (0P) showed visual P deficiency symptoms compared to P added treatments. Maize plant growth with low rates of TSP at 10 kg P ha<sup>-1</sup>, SPR at 20 kg P ha<sup>-1</sup>, FYM at 40 kg P ha<sup>-1</sup> and the high rate of SPR at 80 kg P ha<sup>-1</sup> without S<sup>o</sup>, also exhibited poor growth. Thus the RAE of these fertilisers relative to TSP applied at the same rate (Table 7.4) is poor. The problem appears to be that these P treatments cannot increase the pool of P available to maize plants in the Yellow Earth in the short-term. This observation was confirmed by the low Olsen-P test values at 21 DAE (Table 7.2) for these treatments plus the strong relationships between grain yield and Olsen-P confirm the importance of P being available by 21 DAE.



Plate 7.2 The effect of S with SPR on maize growth at silking.

Notably the addition of S appears essential for producing harvestable yields. Omitting S from the SPR treatment reduced the grain yield by 54%. Also, the high rate of S ( $90 \text{ kg S ha}^{-1}$ ) applied in the CPAPR  $80 \text{ kg P ha}^{-1}$  treatment, which supplied a near optimal  $38 \text{ kg water-soluble P ha}^{-1}$ , appears to stimulate higher yields than TSP at  $80 \text{ kg P ha}^{-1}$ . Similarly, although the amount of water-soluble P in the CPAPR at  $40 \text{ kg P ha}^{-1}$  was equivalent to that in the TSP at  $20 \text{ kg P ha}^{-1}$ , the grain yield from the CPAPR at  $40 \text{ kg P ha}^{-1}$  was much greater than that of TSP applied at  $20 \text{ kg P ha}^{-1}$  (See discussion of the effects of S° in the following section.)

### ***Relative agronomic effectiveness of CPAPR, SPR and FYM***

The yield response curves for the three P fertilisers (TSP, CPAPR and SPR) were obtained (Figures 7.5 and 7.6). The maize grain yield data for TSP followed the Mitscherlich type response curve (Figure 7.6) whereas the data for the other two fertilisers did not follow the Mitscherlich curve (Figure 7.6). From the Mitscherlich curve for TSP the amounts of P (added as TSP) required to achieve similar yields obtained at various levels of other P fertilisers were estimated. From these values, the SR values were calculated. For example, CPAPR at  $40 \text{ kg P ha}^{-1}$  produced  $2.8 \text{ t ha}^{-1}$  of maize grain. The TSP response curve shows that to produce  $2.8 \text{ t ha}^{-1}$  maize grain from

40 kg P ha<sup>-1</sup> for CPAPR, 24.6 kg P ha<sup>-1</sup> is required from TSP. Therefore the SR value for the CPAPR at 40 kg P ha<sup>-1</sup> is 0.61 (24.6/40).

Some key points are shown in the calculated RAE (%) and substitution values (Table 7.4) relative to TSP. If RAE values are calculated early in the growth of maize (silking) then the values for SPR are optimistically high, presumably because of the contribution from the initial soil P supply. At harvest, however, the SPR RAE's have decreased indicating that SPR has been unable to provide sufficient available P at grain filling. This pattern also occurs for rates of CPAPR that supply sub-optimal P (rates >48 kg water-soluble P ha<sup>-1</sup> are required for 90% maximum yield, Figure 7.9). For example, 20 kg P ha<sup>-1</sup> produces a higher RAE at silking than for grain yield. The high RAE for CPAPR at 80 kg P ha<sup>-1</sup>, as explained earlier, is considered to result from the additional S supply.

Farmyard manure at 40 kg P ha<sup>-1</sup> consistently shows a low RAE and low substitution value and again RAE is lower at the final harvest. These RAE of FYM results were consistent with the previous maize trials (Chapter 6) as well as the pigeon pea glasshouse trial.

Table 7.4 The RAE % and substitution value (kg P ha<sup>-1</sup>) of CPAPR, SPR and FYM at different rates with respect to TSP.

Rate of P fertiliser	CPAPR		SPR		FYM	
	RAE %	TSP <sup>1</sup> substitution value (kg P ha <sup>-1</sup> ) and substitution ratio in brackets	RAE %	TSP <sup>1</sup> substitution value (kg P ha <sup>-1</sup> ) and substitution ratio in brackets	RAE %	TSP <sup>1</sup> substitution value (kg P ha <sup>-1</sup> ) and substitution ratio in brackets
Based on DM yield at silking stage of maize						
20 kg P ha <sup>-1</sup>	74	12.9 (0.65)	48	9.8 (0.49)	-	-
40 kg P ha <sup>-1</sup>	61	18.3 (0.46)	39	12.5 (0.31)	30	10.5 (0.26)
80 kg P ha <sup>-1</sup>	103	>120 (>1.50)	94	58.7 (0.73)	-	-
Based on grain yield at harvest maize						
20 kg P ha <sup>-1</sup>	49	6.3 (0.31)	-1	-	-	-
40 kg P ha <sup>-1</sup>	85	24.6 (0.61)	15	2.7 (0.07)	22	4.1 (0.10)
80 kg P ha <sup>-1</sup>	122	>120 (>1.50)	51	16.8 (0.21)	-	-

<sup>1</sup>calculated as TSP substitution value (kg P ha<sup>-1</sup>) / rate of P applied (kg P ha<sup>-1</sup>) in bracket

Calculation of RAE% by vertical comparison can be misleading if the objective is to compare cost effectiveness of fertiliser materials (Chien *et al.*, 1990; Ratkowsky *et al.*, 1997). For purposes of cost comparison the 'Horizontal' substitution value is more

appropriate and gives the quantities of fertilisers required to give the same yields. Substitution values for CPAPR and SPR treatments, except CPAPR 80 kg P ha<sup>-1</sup>, are considerably lower than RAE% values. Due to the differences in the shape of response curves in Figure 7.6, substitution values vary with rate of fertiliser applied. For P application rates of  $\leq 40$  kg ha<sup>-1</sup> the substitution values for grain production with CPAPR range from 0.31 to 0.61 at 20 and 40 kg P ha<sup>-1</sup> rates of CPAPR application. Thus, to be cost-effective the price for CPAPR would need to be 1/3 to 2/3 cheaper than TSP. The TSP substitution values for SPR for maize grain production are less than 0.10. Thus SPR is not a cost-effective option for short-term crops.

### ***Effect of elemental S***

At the 80 kg P ha<sup>-1</sup> rate of SPR applied with S<sup>o</sup> significantly increased soil Olsen-P values (Table 7.3) and the DM (Figure 7.4 and Plate 7.2) of stover and grain yield of maize (Figure 7.11) above the yields of SPR applied without S<sup>o</sup> (SPR 80 P (-S)). Maize yield was reduced (46%) by omitting the S<sup>o</sup> from the SPR. The increased P availability is probably due to the interaction of SPR with the sulphuric acid produced by the microbial oxidation of S<sup>o</sup> (Rajan, 1983).

Despite the interaction of S<sup>o</sup> with SPR to increase yields, the substitution value of SPR 80 kg P ha<sup>-1</sup> plus S<sup>o</sup> was only 0.21, based on grain harvest. Nevertheless, these results indicate that S<sup>o</sup> is required for SPR to be more effective and thus the RAE of SPR can be improved by S<sup>o</sup> applied with SPR. Notably the substitution value of 0.21 is approximately halfway the water-soluble and citric-soluble P content of SPR (expressed as fraction of TSP).

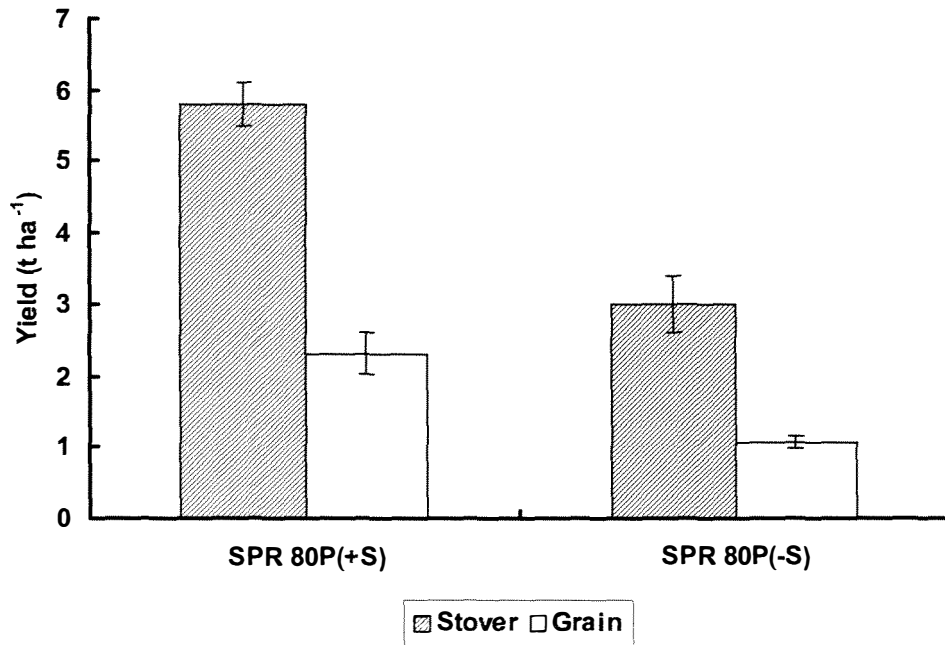


Figure 7.11 The effect of S with SPR on stover and grain yield of maize. (The error bar is the LSD ( $\alpha=0.05$ ) between three replicates).

## 7.5 Conclusion

The observations from this maize field experiment (1999) also confirm that soil fertility, particularly P, is the major constraint to the maize yield in the Yellow Earth.

This field trial consistently showed that the fertilisers that are effective in raising Olsen-P values and produced higher maize yield than those ineffective in raising Olsen-P values. Thus, the Olsen-P test can be used as an effective soil P test for predicting the degree of soil P constraint to the maize crop.

In this experiment, applications of TSP  $>50$  kg P ha<sup>-1</sup> produced near maximum yields. Expressing the amount of fertiliser P applied as citric-soluble P provides a useful index to compare the RAE of different P fertiliser materials.

The Olsen-P data from the TSP treatments suggests that 90% of maximum grain yields can be obtained by raising the Olsen-P to 40 mg P kg<sup>-1</sup> soil.

As mentioned in Chapter 6, CPAPR contains about half of its P is in water-soluble P, which has immediate value to maize crops in P deficient Yellow Earths. Applied on a water-soluble P or citric-soluble P basis the CPAPR was more effective than TSP in relieving P stress in the Yellow Earth but this was probably partly due to the S effect of CPAPR. In this case CPAPR contains 10% S as  $\text{SO}_4^{2-}$  which may be responsible for the higher crop yield. Sulphur may limit crop yields and S should be applied with the P fertiliser in the Yellow Earth.

If RPRs are to be used, combined application with  $\text{S}^\circ$  will help to increase the dissolution rates and raise soil test P status. Despite enhanced dissolution of P with  $\text{S}^\circ$ , reactive SPR was a poor P fertiliser for short-term crops like maize, having a TSP substitution values of only 0.21.

Local dolomite addition with water-soluble P fertilisers (TSP) markedly increased maize grain yields in the Yellow Earth.

This field trial confirmed the earlier result that local FYM was a poor source of plant-available P for short-term crop grown in the Yellow Earth.

## **CHAPTER 8    Managing of Phosphorus Fertilisers and Legume Crop Management on a Yellow Earth**

### **8.1    Introduction**

Field trials conducted in Chapters 6 and 7 have identified P fertiliser materials and application rates capable of relieving the P fertility constraints of Yellow Earths. One of the aims (Section 1.1) of this research work is to identify economically sustainable crop rotations with legumes that will allow significant N input and more sustainable permanent cultivation of these Red Earths and Yellow Earths.

The short-term N and P availability from legume green manures for subsequent crops depends largely on the characteristics of the legumes, soil properties, residue management practices and climate (Peoples and Craswell, 1992; Yadvinder-Singh *et al.*, 1992). The earlier glasshouse trials in Chapter 3, demonstrated that legume growth responded to P fertilisation on the Red Earths and Yellow Earths. Pigeon pea and rice bean gave increased dry matter yield after application of the water-soluble P fertiliser TSP. Also the local dolomite applied with TSP improved legume root nodulation in these Red Earths and Yellow Earths. In Chapter 6, the agronomic effectiveness of a green manure (*Tithonia diversifolia*) was greater than that of local FYM. Based on these results, in this chapter the effect of P sources (with or without the local dolomite) on P response of legume green manures and a subsequent crop of wheat is evaluated under field conditions.

It is important to evaluate the amount of plant-available N and P the green manure crop releases and whether release of available N from the green manure during decomposition coincides with subsequent N and P demands of wheat in the short-term.

The economic value of green manures is also discussed in terms of comparing their value as forage or cash crops with their value as green manures.

The following section of the literature review first aims to review the use of legume green manures and secondly, considers the N and P requirements of a subsequent wheat crop.

### 8.1.1 Legume green manure

Crop rotation with legumes plays a very important role in sustainable farming systems because of their ability to biologically fix N from atmosphere (Ebelhar *et al.*, 1984). Legumes vary in their amount of N fixation depending on legume species, soils and climate. In general, tropical legumes can accumulate N in the range of 25 to 116 kg N ha<sup>-1</sup>, and produce 1.3 to 4.9 t ha<sup>-1</sup> of biomass within 40 to 49 days (Yadvinder-Singh *et al.*, 1992). The quantity of N fixation by some tropical and sub-tropical legumes is presented in Table 8.1. In Chapter 5, the important food legumes produced in Myanmar are given (see Table 5. 1).

#### *Green manure N and P contribution to subsequent crop*

Table 8.1 Amount of total crop N and N derived from N<sub>2</sub> fixation for some tropical and sub-tropical legumes.

Species	Total crop N (kg ha <sup>-1</sup> )	N <sub>2</sub> -fixed (kg ha <sup>-1</sup> )	Reference
Pigeon pea ( <i>Cajanus cajan</i> )	77-92	68-88	Rao (1990)
Common bean ( <i>Phaseous vulgaris</i> )	128-183	17-57	Ssali and Keya (1986)
Soybean ( <i>Glycine max</i> )	121-643	17-450	Rennie <i>et al.</i> (1988)
Groundnut ( <i>Arachis hypogaera</i> )	126-165	109-152	Giller <i>et al.</i> (1987)
Green gram ( <i>Vigna radiata</i> )	71-74	64-66	Peoples and Craswell (1992)
Black gram ( <i>Vigna mungo</i> )	125-143	119-140	Peoples and Craswell (1992)
Rice bean ( <i>Vigna umbellata</i> )	135	49	Rerkaesem <i>et al.</i> (1988)
<i>Centrosema pubescens</i>	299	150	Agamuthu and Broughton (1985)

Several studies have reported that incorporation and decomposition of legumes in soils can supply considerable N to subsequent crops (Yadvinder-Singh *et al.*, 1992). The availability of P for crops can also be increased through the application of legume green manures to soils (Blair and Boland, 1978; Yadvinder-Singh *et al.*, 1992; Budianta, 1999). The availability of N and P from legume green manures depends on their N and P mineralisation rate and pattern, which apart from the amount and quality of added legume, is controlled by temperature, moisture, soil physical and chemical properties as well as the method of placement in the soil (Fernandes and Sanchez, 1990; Yadvinder-Singh *et al.*, 1992). The application and incorporation of a green manure should be

timed such that maximum nutrient release is synchronised with crop demand (Myers *et al.*, 1997).

### 8.1.2 Nitrogen and phosphorus requirements of wheat

The total amount of N and P that is accumulated by a wheat variety provides a minimum indication of its N and P requirement provided the crop did not show N and P deficiency symptoms. The amount of N and P requirement varies within varieties of wheat and over the season. This is because, most of the N and P in the straw mobilise into the grain as the plant matures (Glendinning, 1999).

It can be estimated that a green manure crop needs to supply a minimum of 220 kg N ha<sup>-1</sup> (assuming a 50% recovery in the plant) and 65 kg P ha<sup>-1</sup> (assuming the substitution value of 0.3 *Tithonia diversifolia* for TSP observed in Chapter 6) for a wheat crop growing on Yellow Earths producing 4 t of grain ha<sup>-1</sup> (Table 8.2). This N requirement appears to be a higher than can be provided by most of the legume crops listed in Table 8.1 if used as green manures.

Table 8.2 Nitrogen and P concentration and requirement of wheat (grain yield 4 t ha<sup>-1</sup>) (adapted from Glendinning, 1999)

Wheat	N (%)	P (%)	N (kg ha <sup>-1</sup> )	P (kg ha <sup>-1</sup> )
Grain	2.1-3	0.42	84	16.8
Straw	0.67	0.12	26	4.8

## 8.2 Experimental Objectives

The objective of this study was to evaluate the growth of two green manure legumes compared to fallow plus FYM as systems for fertilising a subsequent wheat crop on a Yellow Earth in Southern Shan State.

The specific objectives of this chapter are:

1. To investigate the effects of water-soluble P fertiliser rates on soil P test value and biomass yield of two legume crops grown on a Yellow Earth.
2. To determine the effect of the local dolomite on the yield of legumes grown on a Yellow Earth and,

3. To evaluate the agronomic value of two legume green manures and local FYM addition on wheat yield.

### ***Site of field experiment***

The field experiment was conducted at the Aungban Research Farm, Southern Shan State, Myanmar. The locality of the Aungban Research Farm, soil type, topography and climate were presented earlier in Section 6.3.1 (Chapter 6). The field trial site was selected for its low soil P status and low SOM. Some properties of the soil are presented in Table 6.1 (Chapter 6).

### ***Treatments***

The experiment was conducted in a balanced split plot design. There were two parts to this experiment. The first part evaluated the P responsiveness of the legume biomass production. Test crops were rice bean (*Vigna umbellata*) and black gram (*Vigna mungo*). Three rates of P as TSP, namely 0, 20, 40 kg P ha<sup>-1</sup>, with or without dolomite, were assessed using three different systems such as growing rice bean and mowings returned, growing black gram pod removed and biomass returned, and fallow (no legume, only weeds) until wheat was sown. There were three replications of each treatment in this experiment.

The second part of the experiment was to use the green manure to fertilise a subsequent cereal test crop (wheat; *Triticum aestivum*; variety UP 262). The legume rotation was continued for a season. After legume growth the legume biomass was cultivated in and a wheat crop grown. Three treatments left fallow, which at cultivation for wheat received either 20 kg P ha<sup>-1</sup> as TSP, with and without dolomite, or 20 kg P ha<sup>-1</sup> as FYM. All wheat treatments received a basal dressing of N and K at the rate of 50 kg N ha<sup>-1</sup> as Urea and 25 kg K ha<sup>-1</sup> as KCl. The treatment descriptions and treatment codes are illustrated in Table 8.3. The total treatments were 15 (2 × 3 × 2 + 3) and the total number of plots were 45 (15 × 3).

Table 8.3 The code and description of the different treatments used on legumes, fallow and the wheat crop.

Code	Treatment description	
	Part (1): Green manure crop (26/6/1999)	Part (2): Subsequent crop (26/9/1999)
RB 0P	Rice bean with 0 kg P ha <sup>-1</sup>	Wheat (50 N + 25 K kg ha <sup>-1</sup> )
RB 20P	Rice bean with 20 kg P ha <sup>-1</sup>	Wheat (50 N + 25 K kg ha <sup>-1</sup> )
RB 40P	Rice bean with 40 kg P ha <sup>-1</sup>	Wheat (50 N + 25 K kg ha <sup>-1</sup> )
BG 0P	Black gram with 0 kg P ha <sup>-1</sup>	Wheat (50 N + 25 K kg ha <sup>-1</sup> )
BG 20P	Black gram with 20 kg P ha <sup>-1</sup>	Wheat (50 N + 25 K kg ha <sup>-1</sup> )
BG 40P	Black gram with 40 kg P ha <sup>-1</sup>	Wheat (50 N + 25 K kg ha <sup>-1</sup> )
RB 0P+DO	Rice bean with 0 kg P + Dolomite 2.5 t ha <sup>-1</sup>	Wheat (50 N + 25 K kg ha <sup>-1</sup> )
RB 20P+DO	Rice bean with 20 kg P + Dolomite 2.5 t ha <sup>-1</sup>	Wheat (50 N + 25 K kg ha <sup>-1</sup> )
RB 40P+DO	Rice bean with 40 kg P + Dolomite 2.5 t ha <sup>-1</sup>	Wheat (50 N + 25 K kg ha <sup>-1</sup> )
BG 0P+DO	Black gram with 0 kg P + Dolomite 2.5 t ha <sup>-1</sup>	Wheat (50 N + 25 K kg ha <sup>-1</sup> )
BG 20P+DO	Black gram with 20 kg P + Dolomite 2.5 t ha <sup>-1</sup>	Wheat (50 N + 25 K kg ha <sup>-1</sup> )
BG 40P+DO	Black gram with 40 kg P + Dolomite 2.5 t ha <sup>-1</sup>	Wheat (50 N + 25 K kg ha <sup>-1</sup> )
F-TSP	Fallow	Wheat (20 P TSP, 50 N, 25 K kg ha <sup>-1</sup> + Dolomite 2.5 t ha <sup>-1</sup> )
20P+DO		
F-TSP 20P	Fallow	Wheat (20 P TSP, 50 N, 25 K kg ha <sup>-1</sup> )
F-FYM 20P	Fallow	Wheat (20 P FYM, 50 N, 25 K kg ha <sup>-1</sup> )

### ***Fertiliser treatments***

Phosphorus fertilisers used in this field experiment were TSP from Tunisia and local FYM. The physical and chemical properties of these P fertilisers are presented in Tables 3.1, 3.2 and 3.3 (Chapter 3).

#### *Part (1): Green manure crop production*



















A single application of water-soluble P fertiliser (rates 0, 20 and 40 kg P ha<sup>-1</sup> as TSP) was banded at the sowing time of both rice bean and black gram. These treatments were designed to evaluate the P responsiveness of different legumes to water-soluble P fertiliser.

The land was ploughed and levelled using bullock drawn implements. At first, the experiment was designated for three blocks within the same contour line. Then each block was divided into 15 plots. Each plot represented a fertiliser treatment and measured 4.8 m × 4.8 m with 30 cm legume row spacing. The application methods of N, P and K fertilisers, and dolomite were explained in Section 6.3.3 (Chapter 6). The legumes, which were weeded by hand, were sown on 26 June 1999 and mowed on 17 September 1999 (Table 8.4).

*Part (2): Wheat crop production*

Rice bean and black gram biomass were incorporated into the soil at cultivation on 17 September 1999, 2 weeks before sowing the wheat crop. Farmyard manure, TSP and dolomite ( $2.5 \text{ t ha}^{-1}$ ) and any weeds grown on the plots were incorporated into the fallow plots at the same cultivation. The row spacing of the wheat crop was 30 cm. The basal fertiliser application for the wheat crop was urea ( $25 \text{ kg N ha}^{-1}$ ) and KCl ( $25 \text{ kg K ha}^{-1}$ ). A subsequent dressing of N fertiliser was applied as urea ( $25 \text{ kg N ha}^{-1}$ ) at 3 weeks after wheat emergence. The activities of crop management practices are illustrated in Table 8.4.

Table 8.4 The activity of green manure and wheat crop management practices.

Activity	June	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb
Green manure									
Wheat									
Rainfall (mm)	159	124	162	230	165	79	20	5	0
Sowing time									
Incorporating of green manure									
Harvest time of wheat									
Time of fertiliser application	1  2 			1  2  3  4 					

1 TSP 20 or 40 kg P ha<sup>-1</sup>2 Dolomite 2.5 t ha<sup>-1</sup>3 FYM 20 kg P ha<sup>-1</sup>4 Urea 50 kg N ha<sup>-1</sup> plus KCl 25 kg K ha<sup>-1</sup>*Sowing and harvesting of wheat*

The wheat crop was grown from 26 September 1999 to 3 February 2000 (Table 8.4). Two weeks prior to wheat sowing, the legume biomass was cut and returned and incorporated to the plots. After the application of P to fallow plots and basal fertilisers, wheat was sown in rows on the same day. Thinning and weeding were done by hand when necessary. Wheat straw and grain were harvested, and then the straw and grain yields measured.

*Soil sampling*

Soil samples were taken on five occasions over the duration of the experiment. There were three samplings in Part (1) of the experiment: prior to sowing of legume crop at

the beginning of the experiment, at 45 days after emergence (45 DAE) of legume crops and at harvesting of the legume crops. In Part (2) of the experiment soil sampling times were: at 21 DAE and at heading stage of wheat. At each sampling 10 cores from 0-7.5 cm soil depth were taken per plot. These soil samples were bulked for each plot, air-dried and sieved to pass through a 2 mm sieve for further chemical analysis.

### ***Plant and grain sampling***

As mentioned earlier, rice bean, black gram, weed, wheat straw and grain samples were collected at harvest. These samples were oven-dried at 70°C and milled to <1mm particle size for chemical analysis.

### ***Soil analysis***

Soil samples (0-15 cm) were analysed for pH (soil:water ratio, 1:2.5) and Olsen-P (Olsen *et al.*, 1954).

### ***Plant analysis***

The total N and P content of the legume green manures (rice bean and black gram), the weeds from fallow plots, wheat straw and grain samples were determined following Kjeldahl digestion as described in Section 3.3.2 (Chapter 3). Carbon content in these plant samples was measured by the method of Walkley and Black (1934).

### ***Climatic data***

Daily rainfall and maximum and minimum temperature were collected at Aungban Research Farm. The rainfall and temperature distribution for Aungban Research Farm during the experimental periods (May 1999 to February 2000) are illustrated (see Figure 6.1, Chapter 6).

### 8.3 Results

#### 8.3.1 Part (1): Green manure crops production

##### *Establishment of legume green manures*

Rice bean and black gram germinated and emerged uniformly five days after sowing. The legumes established well in all plots. However, the vigour of the legumes varied reflecting P fertiliser rate and dolomite addition. There was also a major species difference. The rice bean growth was more vigorous than the black gram (see Plate 8.1). The fallow plots developed a weed cover, particularly Shan-pyay (*Richardia brasiliensis*) (see Plate 8.1).



Plate 8.1 Plant growth and vigour of rice bean and black gram in the field trial at 67 DAE.

Prior to legume green manure incorporation into the soil, their biomass yields were measured at harvest time, including the weeds in the fallow plots. Biomass yield (i.e. fresh and dry weight), total N and P uptake of legume green manures were measured, and are discussed in the following sections.

### *Yield of legume green manures*

The fresh biomass yields of rice bean per ha were similar to the weed biomass on the fallow plots and both were significantly larger than the black gram biomass.

Increasing P application only increased the rice bean DM yield significantly ( $P < 0.05$ ) (Table 8.5 and Figure 8.1).

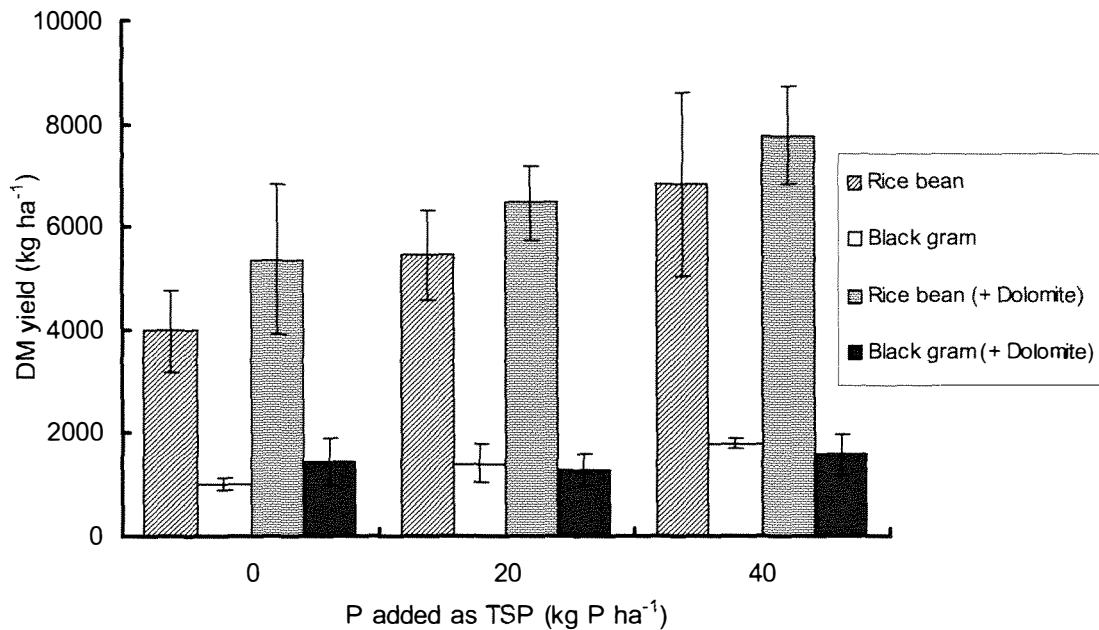


Figure 8.1 Rice bean and black gram DM yields influenced by rate of TSP and dolomite application to a Yellow Earth in Southern Shan State, Myanmar. The error bar is the standard error between the replicates.

The dry matter yield of rice bean ranged from 3.9 t ha<sup>-1</sup> for the control (0P) to 6.8 t ha<sup>-1</sup> for TSP at 40 kg P ha<sup>-1</sup> alone, and 7.8 t ha<sup>-1</sup> for TSP at 40 kg P ha<sup>-1</sup> plus dolomite. Rice bean yields were up to 4 times higher than black gram yields for the same fertiliser treatments. Dolomite addition with the P fertiliser caused small and mostly non-significant increases in the rice bean yields, but the black gram yields were commonly reduced. The result for rice bean was similar to the small increase in pigeon pea DM yield caused by dolomite application to the Yellow Earth under glasshouse conditions (see Chapter 3).

Nilnond *et al.* (1999) reported that the highest yield of mungbean [*Vigna radiata*] was obtained from the application of inorganic fertilisers (N, P, K and Mg) and lime on acid upland soils in Thailand.

Table 8.5 The fresh biomass, dry matter and bean yield of legumes at harvest prior to incorporation of green manures.

Treatment	Fresh biomass (kg ha <sup>-1</sup> yr <sup>-1</sup> )	DM yield (kg ha <sup>-1</sup> yr <sup>-1</sup> )	Legume bean yield (kg ha <sup>-1</sup> )
RB 0P	14091d	3974d	0
RB 20P	19314c	5447c	0
RB 40P	24175ab	6817ab	0
BG 0P	4993e	1009ef	68d
BG 20P	6973e	1409e	127c
BG 40P	8869e	1792e	166ab
RB 0P + DO	19025c	5365c	0
RB 20P + DO	22888abc	6454bc	0
RB 40P + DO	27546a	7768a	0
BG 0P + DO	7089e	1432e	146bc
BG 20P + DO	6293e	1272e	164ab
BG 40P + DO	7841e	1584e	176a
F-TSP 20P <sup>1</sup> + DO	21586bc <sup>2</sup>	5332bc <sup>2</sup>	0
F-TSP 20P <sup>1</sup>	25058ab <sup>2</sup>	6189b <sup>2</sup>	0
F-FYM 20P <sup>1</sup>	23003abc <sup>2</sup>	5682b <sup>2</sup>	0
	LSD 4847 (P<0.1)	LSD1535 (P<0.05)	LSD 24 (P<0.05)

Treatment code (RB = rice bean, BG = black gram, F = fallow) (P rate) (DO = dolomite).

<sup>1</sup>Fertiliser applied when weeds were incorporated prior to wheat seeding.

<sup>2</sup>Weed yields during the fallow period.

### Legume grain yield

The growing period (three months) was not sufficient for rice bean to produce beans. Black gram was a shorter maturing crop and produced beans within three months. Although, bean yields of black gram were low, they increased with increased P application and dolomite application significantly increased bean yield in the absence of P and at the lower rate of P application (20 kg P ha<sup>-1</sup>) (Table 8.5 and Figure 8.2).

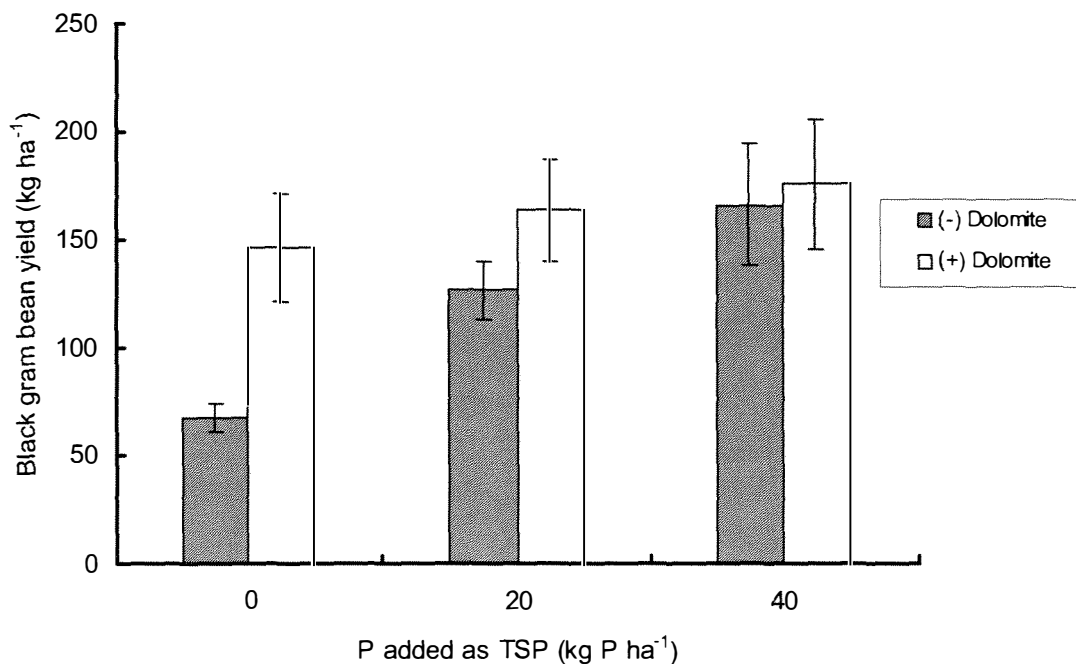


Figure 8.2 The effect of dolomite and P application on black gram bean yields on a Yellow Earth in Southern Shan State, Myanmar. The error bar is the standard error between the replicates.

### ***Green manure N and P status and C:N ratio***

As mentioned earlier in Section 8.1.1, the ability of green manures to be effective sources of N and P for a subsequent crop mainly depends on the total amount of N and P, the N, P and C concentration and/or C:N ratio of green manures applied to the soil.

Rice bean and black gram N and P concentration increased with both P application rate and dolomite application (Table 8.6).

The N and P accumulation in black gram was low because it produced low DM yield in this study, and for most P treatments had a lower P concentration than rice bean. For rice bean, application of P and dolomite caused a marked increase in N uptake over P treatment alone but dolomite addition had a similar effect on P uptake (Table 8.6). The weeds growing on the fallow plot had a lower N concentration than both legume treatments, and a lower N and P uptake compared with rice bean, whilst producing similar biomass C per ha.

Table 8.6 The effect of treatments on the concentration and uptake of N, P and C in the green manures grown on a Yellow Earth in Southern Shan State, Myanmar.

Treatment	Total N (%)	Total P (%)	Total C (%)	N-uptake (kg ha <sup>-1</sup> )	P-uptake (kg ha <sup>-1</sup> )	Biomass-C (kg ha <sup>-1</sup> )
RB 0P	2.39efgh	0.138fg	40.6e	95d	5.5ef	1609d
RB 20P	2.59cde	0.176bcd	41.9bcd	141c	9.5cd	2283bc
RB 40P	2.75bc	0.180abcd	41.1de	188b	12.5b	2798ab
BG 0P	2.23h	0.136g	42.6ab	23e	1.4g	429e
BG 20P	2.41efgh	0.149efg	42.2bc	34e	2.1g	594e
BG 40P	2.48efg	0.192ab	42.3abc	45e	3.4fg	757e
RB 0P + DO	2.69cd	0.167cde	40.8e	145c	9.0cd	2182c
RB 20P + DO	2.92ab	0.181abcd	40.8e	188b	11.7bc	2635bc
RB 40P + DO	3.02a	0.201a	41.3cde	234a	15.5a	3212a
BG 0P + DO	2.32gh	0.144fg	42.5ab	33e	2.0g	608e
BG 20P + DO	2.37fgh	0.172bcd	42.6ab	30e	2.2g	541e
BG 40P + DO	2.54def	0.184abc	42.7ab	41e	2.9fg	677e
F-TSP 20P + DO*	1.92i	0.177bcd	42.7ab	102d	9.5cd	2279bc
F-TSP 20P*	1.82i	0.160def	42.2bc	113cd	9.8bcd	2613bc
F-FYM 20P*	1.77i	0.143fg	43.2a	100d	8.1de	2459bc
	LSD 0.20 P<0.05	LSD 0.023 P<0.05	LSD 0.95 P<0.05	LSD 33 P<0.05	LSD 2.9 P<0.05	LSD 534 P<0.05

\*Dry matter yield of weeds during the fallow period.

### ***Relationship between soil Olsen-P test and DM yield of green manures***

The Olsen-P test values for all plots were determined at cultivation (initial), at 45 DAE and at harvest of legume green manures. Soil Olsen-P test values at 45 DAE (Table 8.7) were used to explain the green manure DM yields (Figures 8.3 and 8.4).

Increasing rates of TSP applied at cultivation significantly increased Olsen-P at 45 DAE of green manures (Table 8.7, Figures 8.3 and 8.4). As in earlier experiments (Chapters 3, 6 and 7), the application of TSP at a rate of 20 kg P ha<sup>-1</sup> raised the Olsen-P value to above 20 mg P kg<sup>-1</sup> soil. However, a further 20 kg P ha<sup>-1</sup> increase (40 kg P ha<sup>-1</sup> as TSP treatment) in P applied caused only a 5 unit or lower increase in Olsen-P value. This result has been repeated in 2 field trials (Chapters 6 and 7), but remains unexplainable without further analysis of the P fertilised soil. Both rice bean and black gram DM yields increased with increasing Olsen values, but the relationships were not particularly strong ones (Figures 8.3 and 8.4). The addition of dolomite changed the nature of the DM response tending to produce larger legume yields at lower Olsen-P values, but not at higher Olsen-P values. The change in the shape of trendlines suggests some P sparing effect of dolomite at lower Olsen-P values.

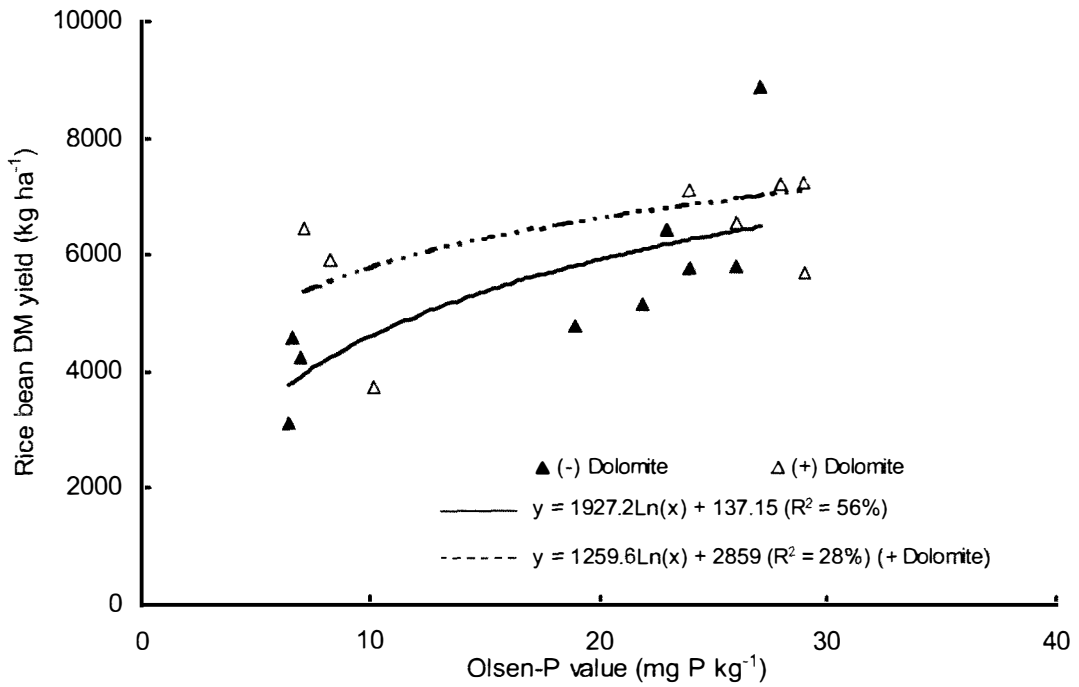


Figure 8.3 The relationships between Olsen-P values at 45 DAE and DM yield of rice bean grown in the field trial.

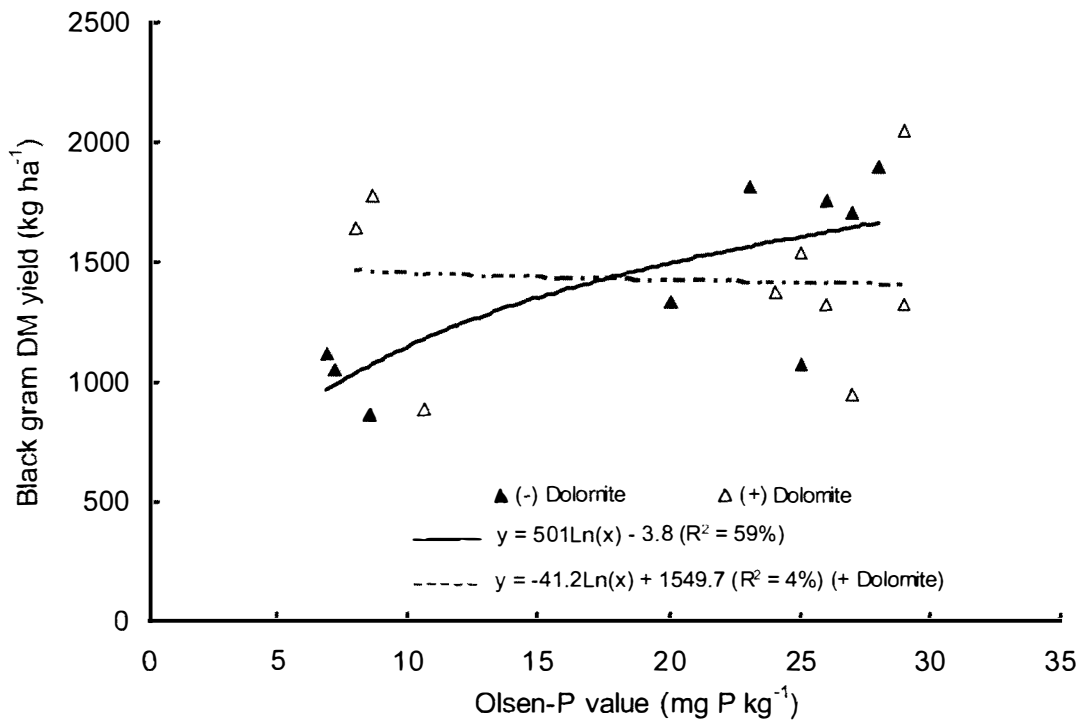


Figure 8.4 The relationships between Olsen-P values at 45 DAE and DM yield of black gram in the field trial.

The incorporation of green manure and weeds caused the Olsen-P values to increase between green manure harvest and 21 DAE of the wheat (Table 8.7). This effect is discussed in a later section.

Table 8.7 Soil Olsen-P values at initial, 45 days after emergence and harvest of green manure crops, and at 21 days after emergence and heading of wheat.

Treatment	Green manure			Wheat	
	Initial	45 DAE	At harvest	21 DAE	Heading
RB 0P	7	7c	7g	11fg	11e
RB 20P	6	21b	26abc	29c	28ab
RB 40P	7	26a	26abc	30bc	30a
BG 0P	8	8c	7g	10g	9e
BG 20P	7	23b	24bc	28c	23c
BG 40P	7	27a	27ab	32ab	27b
RB 0P + DO	7	9c	10f	13f	8e
RB 20P + DO	7	26a	26abc	34a	24c
RB 40P + DO	7	28a	27ab	34a	29ab
BG 0P + DO	8	9c	10fg	13f	9e
BG 20P + DO	7	26a	24bc	31bc	27b
BG 40P + DO	7	27a	28a	33ab	28ab
F-TSP 20P + DO	8	8c	8g	23d	22c
F-TSP 20P	9	8c	9fg	22d	18d
F-FYM 20P	7	7c	8g	17e	16d
	NS	LSD 2.9 P<0.05	LSD 2.8 P<0.05	LSD 3 P<0.05	LSD 3 P<0.05

### *Effect of P fertiliser and dolomite on soil pH at different times of green manure growth*

Prior to fertiliser and dolomite application, initial pHs in all pots were not significantly different, except the rice bean with TSP at 40 kg P ha<sup>-1</sup> alone had the lowest initial pH, (4.8) and rice bean with TSP at 40 kg P ha<sup>-1</sup> plus dolomite (2.5 t ha<sup>-1</sup>) had the highest initial pH (5.13).

At the application rates used, TSP did not change soil pH significantly, compared to the control treatment. However, irrespective of TSP rates and green manure treatment, the addition of dolomite to soil markedly raised soil pH (Table 8.8 and Figure 8.5). The results support the conclusion that local dolomite (2.5 t ha<sup>-1</sup>) can be used as an effective liming agent in the practical field condition.

Table 8.8 Soil pH values at cultivation (initial), 45 days after emergence and harvest of green manure crops, and at 21 days of emergence and heading stage of wheat.

Treatment	Green manure crops			Wheat	
	Initial	45 DAE	At harvest	21 DAE	Heading
RB 0P	5.10ab	4.93de	4.77def	4.83gh	4.83fg
RB 20P	5.06abc	5.00d	4.77def	5.07f	5.00de
RB 40P	4.80e	4.73f	4.66ef	5.00fg	4.90ef
BG 0P	4.83de	4.77ef	4.70def	4.73h	4.67h
BG 20P	5.03abcd	4.93de	4.77def	5.00fg	4.80fgh
BG 40P	5.10ab	5.03cd	4.80de	5.13ef	4.73gh
RB 0P + DO	4.93abcde	5.20bc	5.23c	5.37cd	5.13bcd
RB 20P + DO	4.83de	5.27ab	5.50ab	5.57ab	5.40a
RB 40P + DO	5.13a	5.30ab	5.47ab	5.53abc	5.23b
BG 0P + DO	4.93abcde	5.37ab	5.27c	5.27de	5.13bcd
BG 20P + DO	5.07abc	5.43a	5.37bc	5.47bc	5.07cd
BG 40P + DO	4.87cde	5.37ab	5.53a	5.70a	5.40a
F-TSP 20P + DO	5.03abcd	4.90def	4.83d	5.03f	5.20bc
F-TSP 20P	4.93abcde	4.77ef	4.73def	4.83gh	4.90ef
F-FYM 20P	4.90bcde	4.80ef	4.63f	5.00fg	5.07cd
	LSD 0.22 P<0.05	LSD 0.19 P<0.05	LSD 0.15 P<0.05	LSD 0.17 P<0.05	LSD 0.14 P<0.05

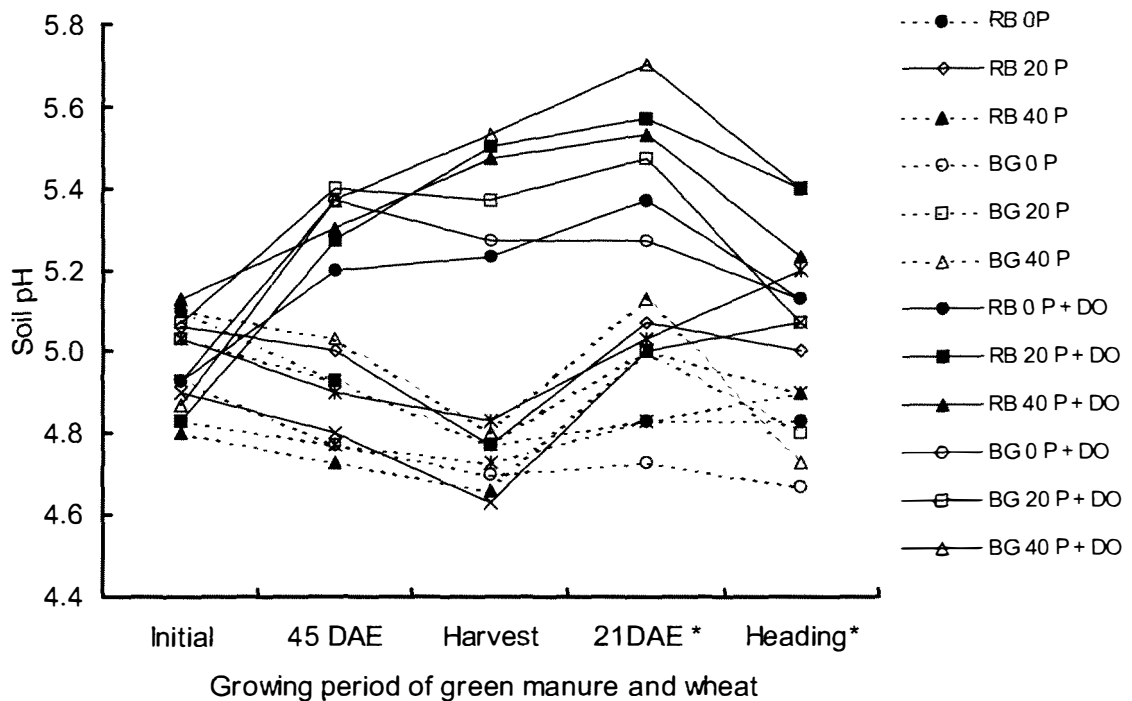


Figure 8.5 The effect of P fertiliser and dolomite on soil pH during green manure (at initial, at 45 DAE and at harvest) and wheat growth (at 21 DAE and at heading).

### 8.3.2 Part (2): Wheat crop production

#### *Effect of incorporating green manures on wheat yield at 21 DAE, at heading and at harvest*

The effects on wheat yields from the incorporation of green manures, and weeds only became evident at wheat heading stage (Table 8.9). Significantly greater DM yields of wheat occurred where rice bean and black gram residues had been treated with 40 kg P ha<sup>-1</sup> as TSP alone and/or with dolomite, with the exception of the rice bean grown with TSP at 40 kg P ha<sup>-1</sup> plus dolomite. The result supports the view that residual P have a major influence on subsequent crop yield. There was no residual effect of dolomite on wheat yields at heading.

The residual value of 40 kg P ha<sup>-1</sup> as TSP, applied to the rice bean green manure produced greater DM yields at the heading stage than the yields produced by the incorporation of a fresh 20 kg P ha<sup>-1</sup> into the fallow plots before wheat seeding.

Table 8.9 Dry matter yield of wheat at 21 days after emergence, heading stage and wheat straw and grain yields at harvest.

Treatment	21 DAE (kg ha <sup>-1</sup> )	Heading (kg ha <sup>-1</sup> )	Straw (kg ha <sup>-1</sup> )	Grain (kg ha <sup>-1</sup> )
RB 0P	73	358f	767h	578e
RB 20P	87	410f	1281def	823bcd
RB 40P	188	913a	1976ab	1118a
BG 0P	94	462ef	1052fgh	714bcde
BG 20P	174	733bcd	1580cd	790bcde
BG 40P	143	872ab	1533cd	587e
RB 0P + DO	80	323f	1007fgh	663de
RB 20P + DO	94	427f	1444cde	773bcde
RB 40P + DO	104	483ef	1917ab	922ab
BG 0P + DO	69	462ef	1028fgh	712bcde
BG 20P + DO	128	722bcd	1120efg	918ab
BG 40P + DO	135	830abc	2137a	894bc
F-TSP 20P + DO	118	684cd	1743bc	655de
F-TSP 20P	143	622de	1118efg	760bcde
F-FYM 20P	101	382f	889gh	672cde
	NS	LSD 209 P<0.05	LSD 330 P<0.05	LSD 223 P<0.1

Wheat grain yields were poor (<1,200 kg ha<sup>-1</sup>) and variable preventing differences between many treatments to be distinguished. Increasing P rate on rice bean plots resulted in increasing wheat grain and straw yields. Rice bean plots fertilised with 40 kg

P ha<sup>-1</sup> as TSP produced the largest wheat grain yields. For black gram plots, increasing the P application rate did not have a consistent effect on wheat grain yield.

***Relationship between green manure N and P accumulation and wheat straw and grain yields at harvest***

There was no relationship between the wheat straw yield, and the amount of N or P in the legume green manures or weeds (Figures 8.6 and 8.7). There was also no relationship between the wheat grain yield and the amount of N or P in the legume green manure treatments (Figures 8.8 and 8.9).

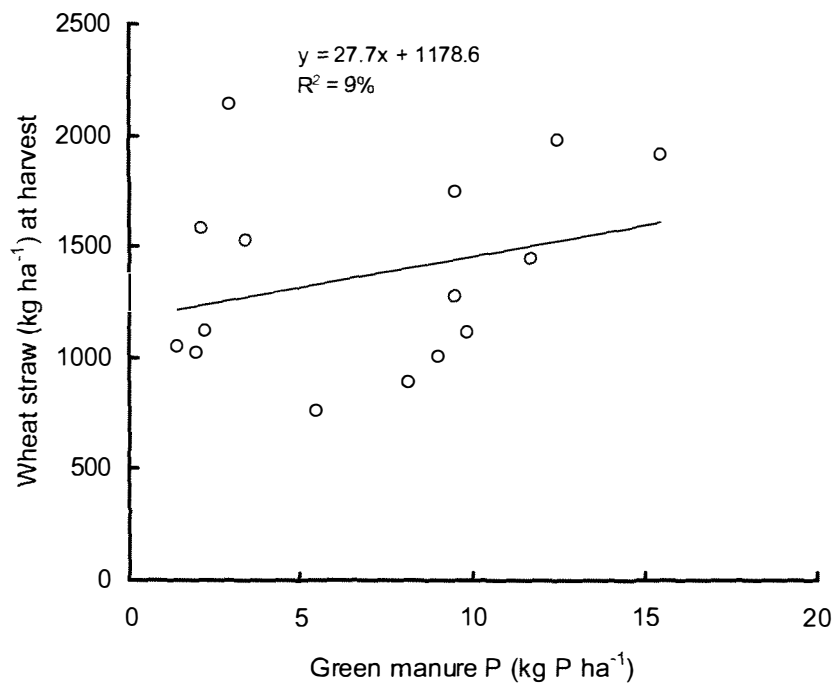


Figure 8.6 The wheat straw yield (kg ha<sup>-1</sup>) at harvest plotted against the amount of P applied (kg P ha<sup>-1</sup>) in green manure.

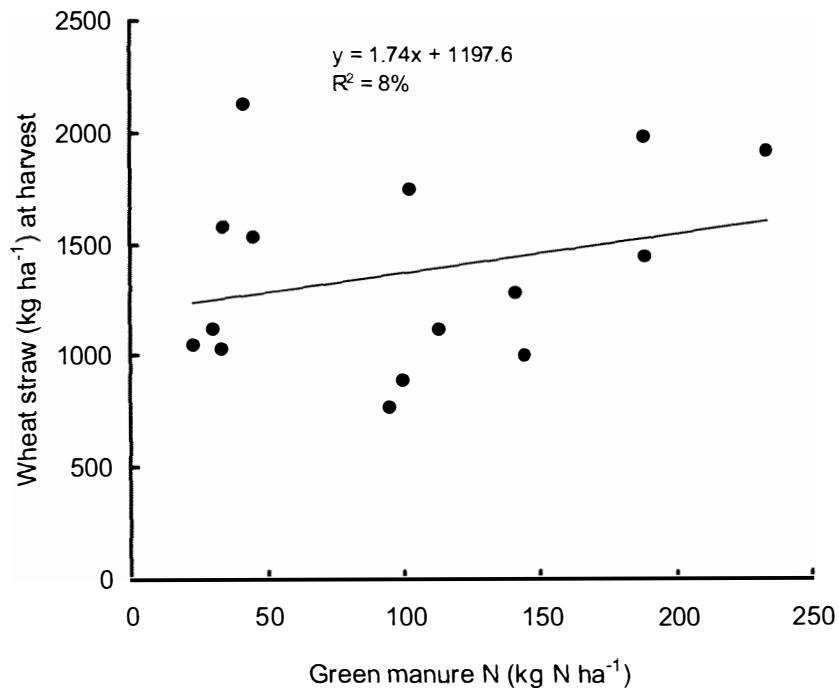


Figure 8.7 The wheat straw yield (kg ha<sup>-1</sup>) at harvest plotted against the amount of N applied (kg N ha<sup>-1</sup>) in green manure.

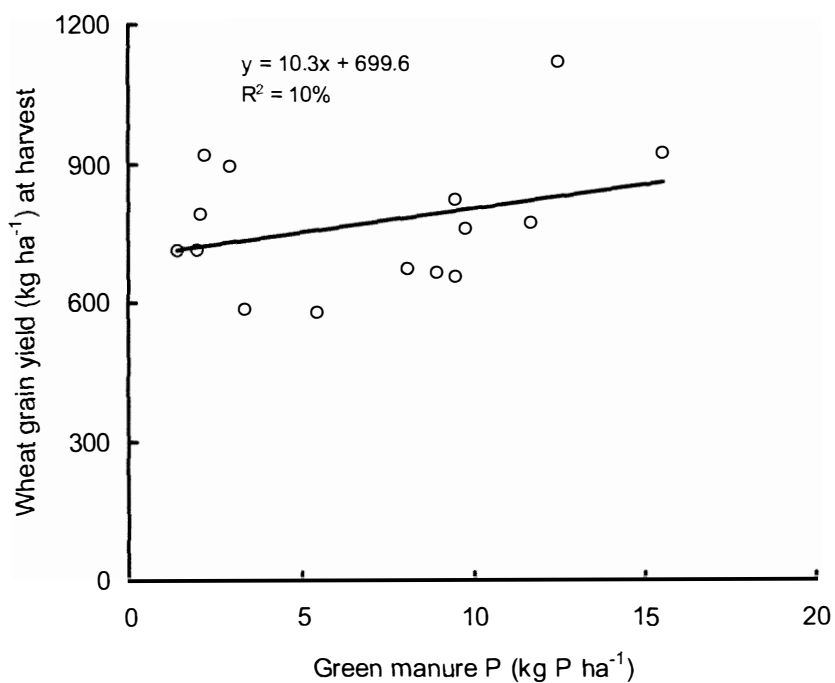


Figure 8.8 The wheat grain yield (kg ha<sup>-1</sup>) at harvest plotted against the amount of P applied (kg P ha<sup>-1</sup>) in green manure.

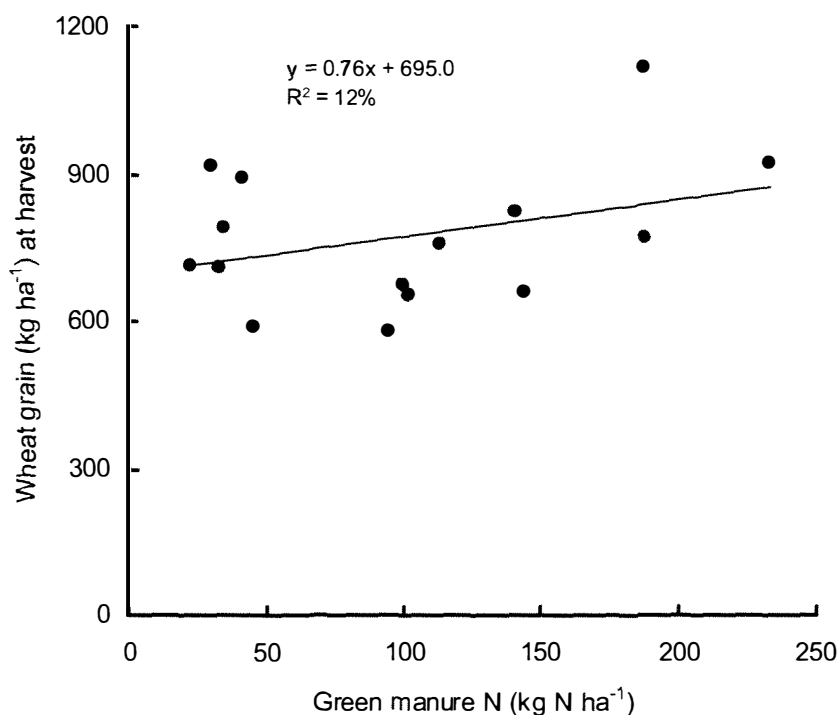


Figure 8.9 The wheat grain yield (kg ha<sup>-1</sup>) at harvest plotted against the amount of N applied (kg N ha<sup>-1</sup>) in green manure.

A reason for the weak relationships between the amounts of P in green manures and the wheat straw and grain yields results may be that P concentration in the green manures did not differ greatly (i.e. total P in the green manures <0.2%, Table 8.6) and then the amount of P applied in these green manure residues were small (ranging from 1.4 to 15.5 kg P ha<sup>-1</sup>, Table 8.6).

A explanation for the weak relationships between the amounts of N in green manure treatments and wheat straw and grain yields may be that the application of urea (50 kg N ha<sup>-1</sup>) at wheat sowing time was adequate to produce the 2 t ha<sup>-1</sup> of wheat straw and 1 t ha<sup>-1</sup> of grain (see Table 8.2).

Treatment effects resulted in significant differences between wheat straw P and N content and grain P content but not grain N content (Table 8.10). The RB 20 P treatment resulted in the highest wheat straw P and N concentrations being 67% and 51% higher than the lowest treatment effect (F-FYM 20P), respectively. The RB (20P), BG (0, 20 P), and F-TSP (20 P) treatment effects on wheat straw P concentration were not

significantly different from the highest treatments (RB 40 P  $\pm$  DO and BG 40 P  $\pm$  DO) (Table 8.10).

Table 8.10 Percentage of total P and N content in wheat straw and grain.

Treatment	Straw		Grain	
	Total P (%)	Total N (%)	Total P (%)	Total N (%)
RB 0P	0.042bcd	0.54cdef	0.282e	2.35
RB 20P	0.060a	0.68a	0.324abcd	2.29
RB 40P	0.049abcd	0.62abc	0.344ab	2.21
BG 0P	0.056ab	0.65ab	0.324abcd	2.32
BG 20P	0.056ab	0.60abcd	0.349a	2.23
BG 40P	0.052abc	0.56bcdef	0.325abcd	2.24
RB 0P + DO	0.043bcd	0.56bcdef	0.308de	2.29
RB 20P + DO	0.037cd	0.47ef	0.313cd	2.22
RB 40P + DO	0.047abcd	0.55bcdef	0.316bcd	2.25
BG 0P + DO	0.037cd	0.49def	0.338abc	2.22
BG 20P + DO	0.042bcd	0.55bcdef	0.313cd	2.22
BG 40P + DO	0.052abc	0.57bcde	0.311cde	2.33
F-TSP 20P + DO	0.053ab	0.56bcdef	0.345a	2.30
F-TSP 20P	0.045bcd	0.51cdef	0.331abcd	2.23
F-FYM 20P	0.036d	0.45f	0.310cde	2.07
	LSD 0.015 P<0.05	LSD 0.11 P<0.05	LSD 0.03 P<0.05	NS

### ***Effect of P fertiliser and the incorporation of green manures on available P status in soil***

Increasing rates of TSP significantly raised soil Olsen-P by 45 DAE of legumes (Figures 8.10 and 8.11). The TSP alone applied at 40 kg P ha<sup>-1</sup> markedly raised the Olsen-P values more than that of the TSP at 20 kg P ha<sup>-1</sup>. In contrast, TSP at 40 kg P ha<sup>-1</sup> plus dolomite did not increase Olsen-P status significantly greater than TSP applied at 20 kg P ha<sup>-1</sup> plus dolomite (see Table 8.7). As mentioned in the glasshouse trials (Chapter 3), the application of dolomite reduced the Olsen-P values at all TSP rates of application in this field trial. This reduction may be partly due to a co-precipitation of Ca-P in the Olsen extract (Sorn-Srivichai *et al.*, 1988) and may not reflect a decrease in soil P status.

The 0P treatment (+/- dolomite) and fallow plots showed little change in the Olsen-P values during legume growth (Figures 8.10, 8.11 and 8.12). The incorporation of the green manures, however, elevated the Olsen-P status in the Yellow Earth.

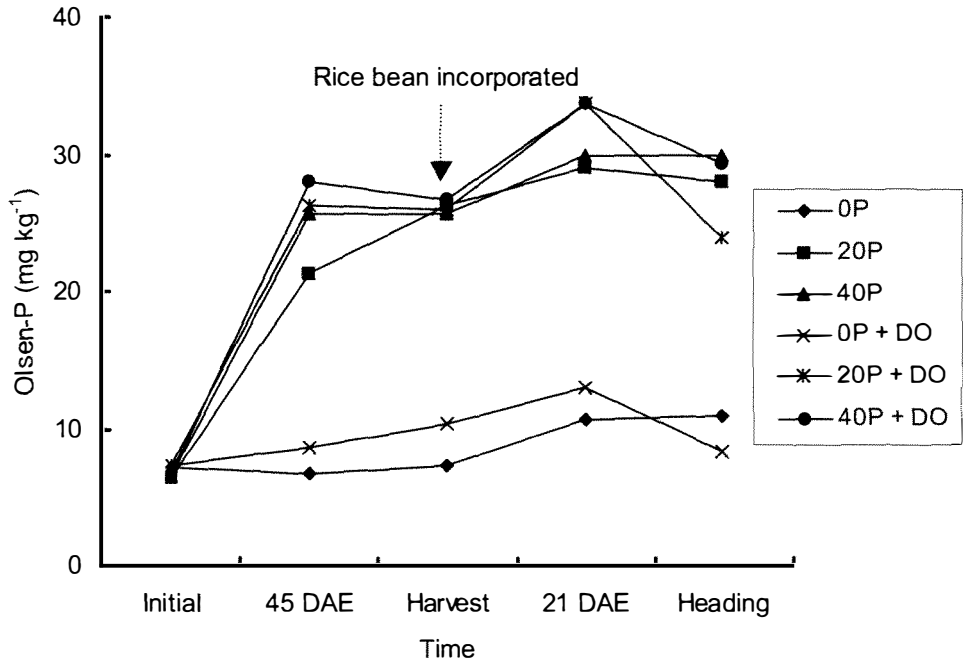


Figure 8.10 Effect of P applied (with or without dolomite) and the seedbed incorporation of rice bean on soil Olsen-P status at the different times.

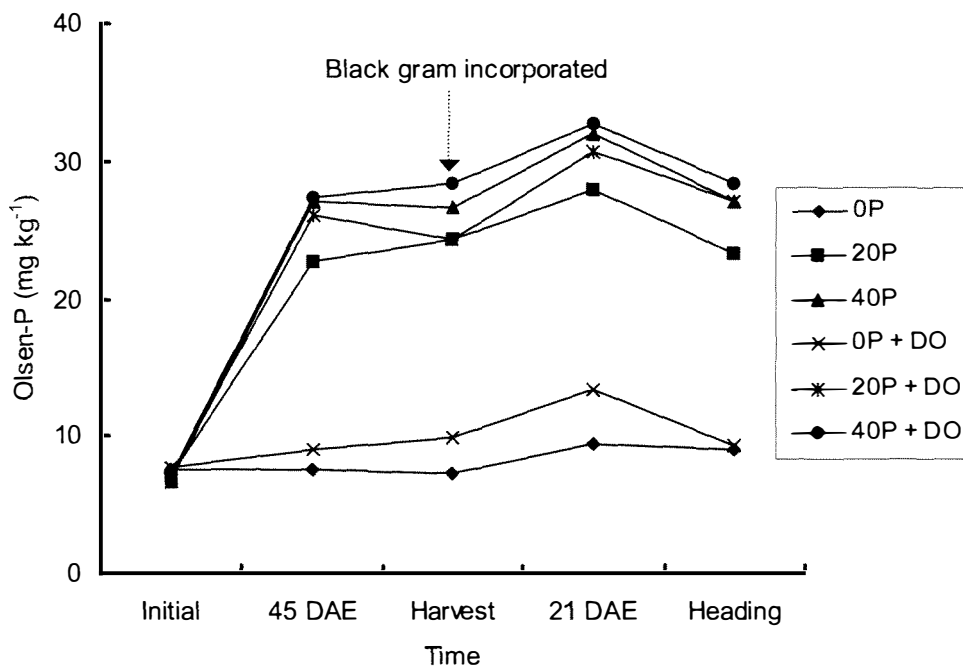


Figure 8.11 Effect of P applied (with or without dolomite) and the seedbed incorporation of black gram on soil Olsen-P status at the different times.

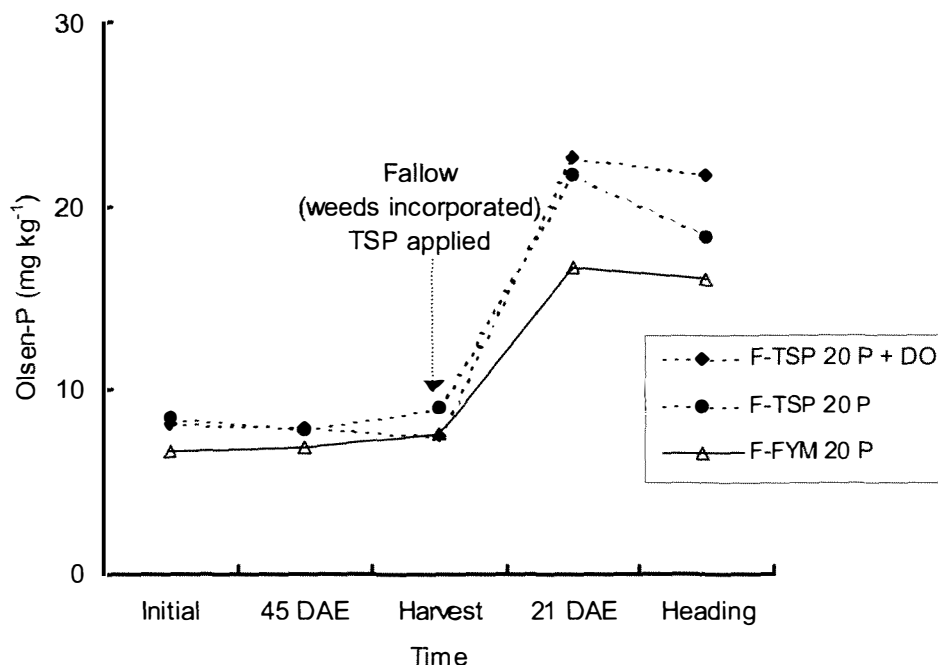


Figure 8.12 Effect of fallow and P applied after weed incorporation on soil Olsen-P status at the different times.

The application of TSP at  $20 \text{ kg P ha}^{-1}$  plus incorporated weeds in the fallow plots markedly increased the Olsen-P values, however, the FYM applied at  $20 \text{ kg P ha}^{-1}$  to the fallow plots caused smaller increases in Olsen-P values (Figure 8.12). Results from this study indicated that the soil available P (Olsen-P) can be raised by both the application of water-soluble P and the incorporation of green manures.

At the same rate of P application ( $20 \text{ kg P ha}^{-1}$ ), Olsen-P values were slightly higher after TSP application, and growth of a green manure compared to TSP application to fallow.

Although, incorporation of green manures and weeds raised Olsen-P values. There was no relationship between P added in green manures and elevation of Olsen-P values (Figure 8.13). This result suggests that the P added in green manure treatments (ranging from  $1.4$  to  $15.5 \text{ kg P ha}^{-1}$ ) was not a main factor influencing soil P availability in the Yellow Earth in the short-term. This could indicate that the extent of decomposition of the green manure was small.

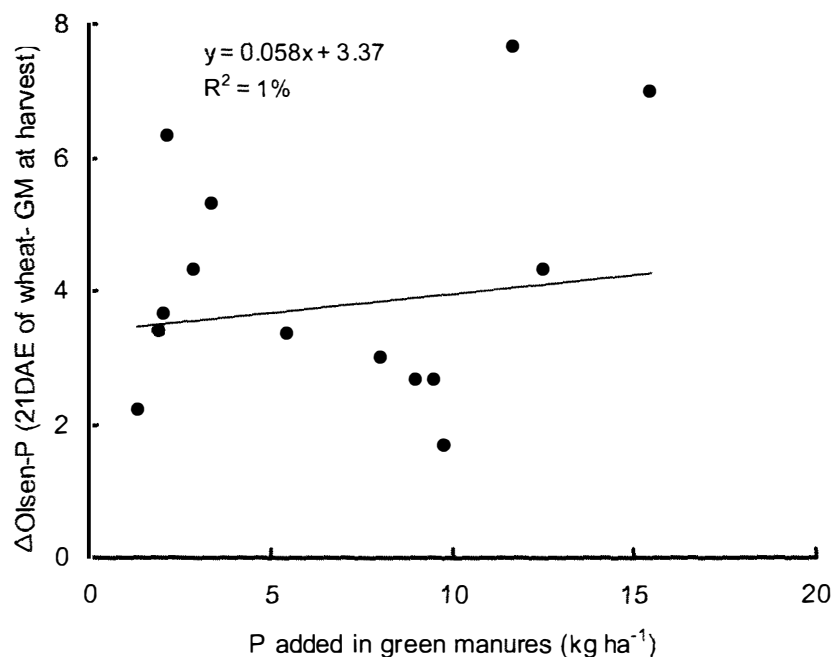


Figure 8.13 The relationship between P added ( $\text{kg P ha}^{-1}$ ) in green manure and elevation of Olsen-P ( $\text{mg P kg}^{-1}$ ) during the period between the green manure harvest and 21 DAE of wheat.

### ***Effect of incorporating green manures on soil pH during the wheat growth***

Irrespective of fertiliser P or dolomite treatment, incorporating green manures increased the soil pH values by 21 DAE of wheat (Figure 8.5). The pH increase is probably caused by the ammonification of green manure N and the decarboxylation of negatively charged carboxylates (Bolan *et al.*, 1991).

The application of FYM at  $20 \text{ kg P ha}^{-1}$  also significantly increased the soil pH compared to the same rate of TSP application at the wheat heading stage (Table 8.8).

### ***Relationship between total N and P uptake of wheat and available Olsen-P status at 21 DAE of wheat***

There were weak linear relationships between the total N and P uptake and the Olsen-P values at 21 DAE of wheat growth (Figures 8.14 and 8.15). The positive relationships indicate that the soil available P status (Olsen-P) at 21 DAE of wheat was an important factor controlling the total N and P accumulation of wheat in the Yellow Earth.

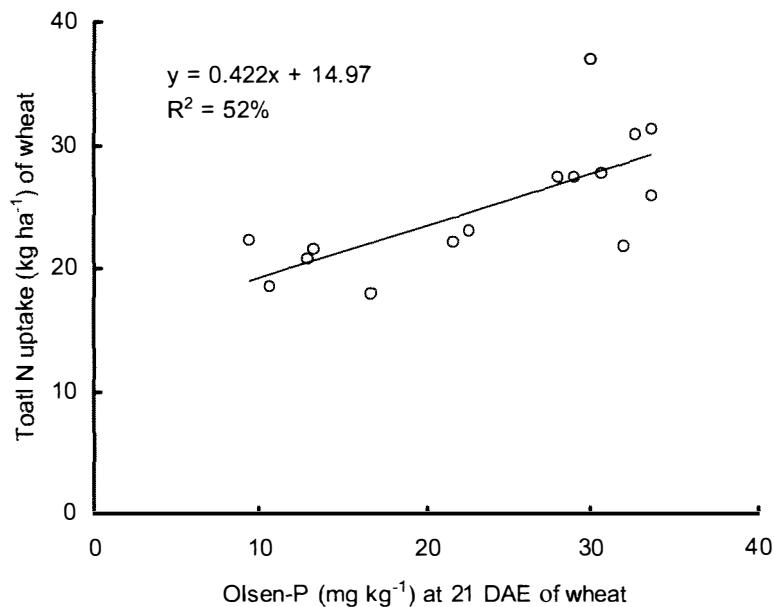


Figure 8.14 The relationship between total N uptake (kg N ha<sup>-1</sup>) of wheat and Olsen-P status (mg P kg<sup>-1</sup> soil) at 21 DAE of wheat, grown in a Yellow Earth.

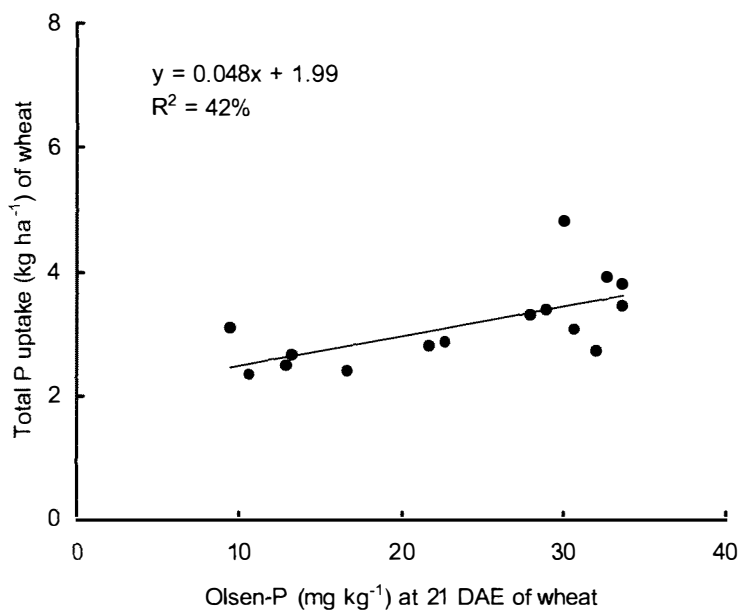


Figure 8.15 The relationship between total P uptake (kg P ha<sup>-1</sup>) of wheat and Olsen-P status (mg P kg<sup>-1</sup> soil) at 21 DAE of wheat, grown in a Yellow Earth.

### *Effect of green manure N and C:N ratio on wheat N uptake at harvest*

The N accumulation of wheat at harvest (Figure 8.16) was weakly related to the quantity of green manure N incorporated. Stronger relationships are observed when only rice bean and weeds (Fallow) N uptake and the paired wheat N uptake are evaluated separately (Figure 8.16). This result suggests that the larger biomass and N uptake in rice bean and weeds influenced total N uptake of wheat at harvest. However, Figure 8.16 shows that there was no relationship between added N in black gram and the total N uptake of wheat. This is not surprising because the incorporation of black gram supplied 5 times less N than the incorporation of rice bean or weeds. The rice bean fresh biomass, of around 28 t ha<sup>-1</sup>, supplied 240 kg N ha<sup>-1</sup>, which had been estimated to be sufficient for a 4 t of grain wheat crop.

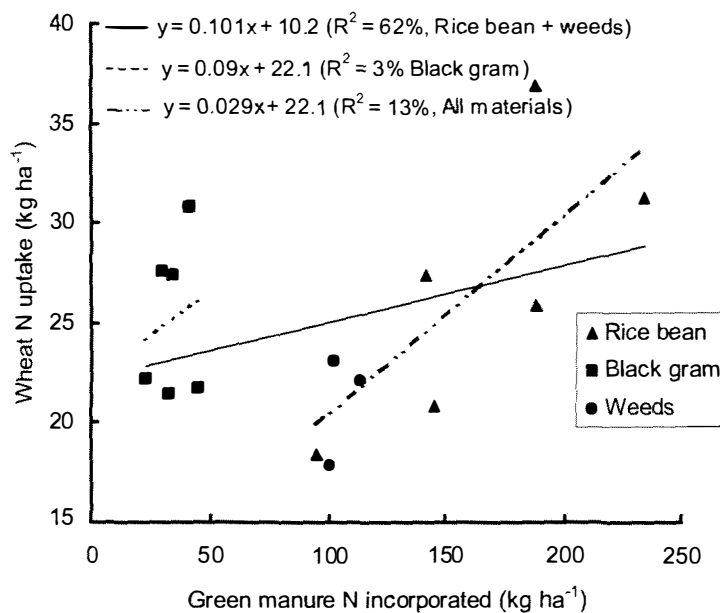


Figure 8.16 Relationship between green manure (rice bean, black gram and weeds) N uptake (kg N ha<sup>-1</sup>) and wheat N uptake (kg N ha<sup>-1</sup>).

The C:N ratio of green manure residues negatively correlated with total N uptake of wheat in this study (Figure 8.17). Kumar and Goh (2000) reported that the higher the C:N ratio of green manure residues the slower their decomposition rates in soil compared green manures with lower C:N ratios. This appears to have occurred in this experiment despite the fact that the C:N ratio was not related to the total amount of N supplied in the green manure.

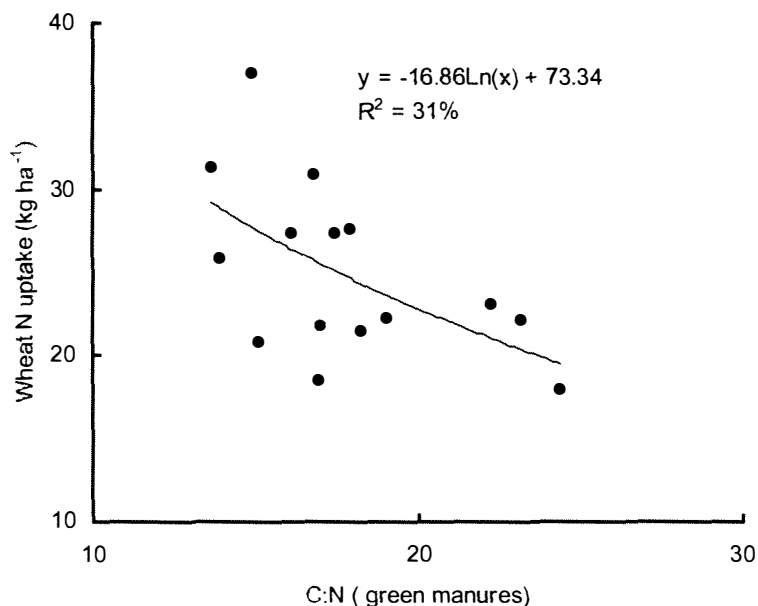


Figure 8.17 Relationship between C:N ratio of green manure and wheat N uptake (kg N ha<sup>-1</sup>).

To evaluate this influence of green manure biomass and C:N ratio further the N mineralisation model discussed by Sakadevan *et al.* (1993) is used for the green manure treatments.

The model considers that the N mineralised ( $N_{\min}$ ) from SOM (green manure (g) in this case) can be described as the amount of N that is not required by the decomposer microorganisms for growth. During growth of soil microbial biomass (m), which is approximately 20% bacterial and 80% fungi (Shields *et al.*, 1974) with a combined  $C_m/N_m$  ratio of 8 respire 0.6 of their substrates C (green manure,  $C_g$ ) as  $CO_2$  whilst assimilating 0.4 of the substrate  $C_g$ . Therefore a simple expression for the amount of N mineralised can be derived:

$$N_{\min} \text{ (kg ha}^{-1}\text{)} = \alpha C_g (N_g/C_g - 0.4 N_m/C_m) \quad \text{Equation (8.1)}$$

Where  $\alpha$  = proportion of green manure C (g) decomposed

$C_g$  = Green manure C (kg ha<sup>-1</sup>)

$N_g$  = Green manure N (kg ha<sup>-1</sup>)

$N_m/C_m$  = Microbial N/Microbial C, estimated as 0.125

Equation 8.1 was rearranged to the form:

$$\text{Total potential } N_{\min} (\text{kg N ha}^{-1}) = \alpha C_g(N_g/C_g - 0.05)$$

and was plotted against wheat N uptake to produce a combined constants that would reflect both the extent of green manure mineralisation and the % recovery of mineralised N by the wheat crop (Figure 8.18).

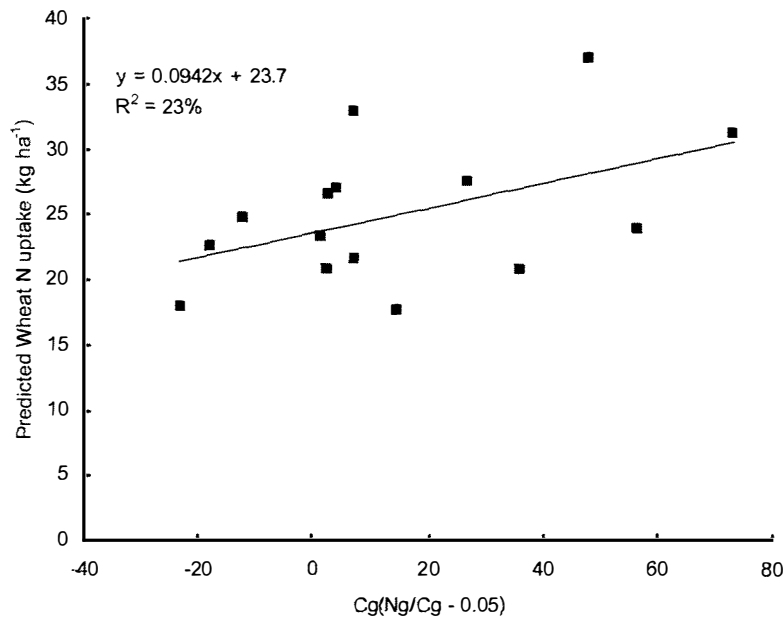


Figure 8.18 Relationship between predicted wheat N uptake ( $\text{kg N ha}^{-1}$ ) and the total potential amount of N mineralised ( $C_g(N_g/C_g - 0.05)$ ) derived from equation 8.1.

The linear regression analysis yielded the following relationship.

$$\text{Wheat N uptake} = 0.0942 \text{ total potential } N_{\min} + 23.7 \quad \text{Equation (8.2)}$$

If we assume that the recovery of the soil mineral N by the wheat is 60%, then the slope of the relation suggest that green manure decomposition is  $0.0942/0.6 = 0.157$  and the soil mineral contribution is  $23/0.6 = 39.4 \text{ kg N}_g \text{ ha}^{-1}$ .

$$\text{Wheat N uptake (kg N ha}^{-1}) = 0.6 (39.4 + 0.157[C_g(N_g/C_g - 0.05)]) \quad \text{Equation (8.3)}$$

Equation 8.3 was used to predict wheat N uptake (Figures 8.18 and 8.19). The model, however, only explains 22% of the variation in wheat yield with green manure

decomposition. No other variable, soil Olsen-P, green manure N/C ratio, green manure P/C ratio was capable of explaining the residual variation from this model.

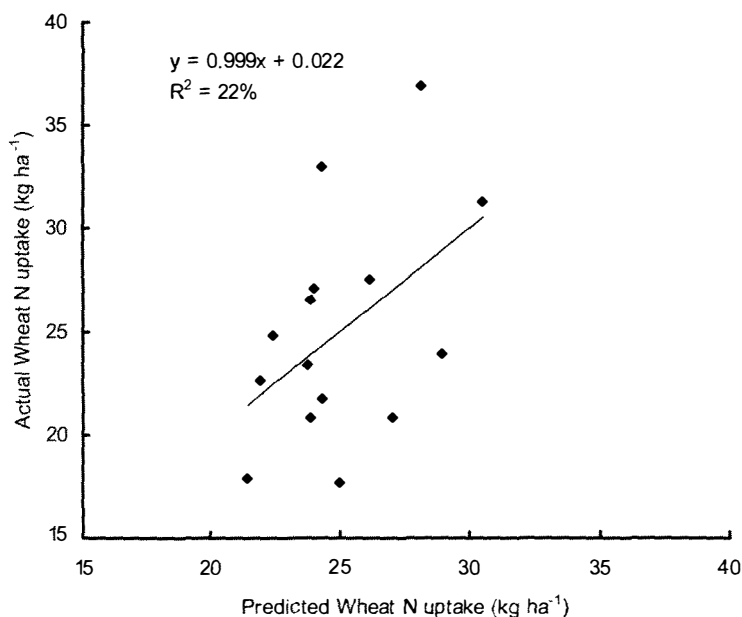


Figure 8.19 Relationship between actual wheat N uptake (kg N ha<sup>-1</sup>) and predicted wheat N uptake (kg N ha<sup>-1</sup>).

### ***Economic consideration of alternative use of legume green manure***

There was sufficient evidence in the literature (Section 8.1.1) and from the rice bean yields in this field trial to support the view that legume green manure crops can fix adequate amounts of N when grown on Yellow Earths. The rice bean contributed between 23 to 234 kg N ha<sup>-1</sup>. In economic terms, this result suggests that the farmer could save money on N fertiliser values in the range of K 7,199 to 1,429 ha<sup>-1</sup> crop<sup>-1</sup> by growing rice bean with applied P fertiliser and dolomite in the Yellow Earth.

As explained in Section 1.8.5 (Chapter 1), there are opportunities for the production of meat and milk products and potential market for small farmers in Southern Shan State. These farmers are faced with very limited production capacity due to a lack of dedicated forage or existing pastures. Therefore, it may be possible to demonstrate to farmers that the potential income from legume forage crop could be greater than its cash crop or green manure value. For example, in one season equivalent to rice bean green manure production, it is possible to grow 6.5 to 7.8 t of DM forage per ha (see Table 8.11). Assuming 80% utilisation of the legume forage crop by a dairy cow, a yield of 6 litres

of milk per 16 kg DM per day is expected, which equals to 1,316 to 1,584 litres per ha (for a lactation of 0.68 of a year). The gross return from milk production is expected to be K 65,800 to 79,200 per ha (milk production in litres per ha × K 50 per litre of milk). The equivalent amount of DM forage utilised by beef cattle, based on an expected yield of 0.4 kg of meat from 1 kg of live weight per 10 kg DM, would be 258 to 310 kg meat per ha. The gross return from meat production is expected to be K 154,900 to 186,400 per ha (meat production per ha × K 600 per kg of meat). Comparing these values with the gross return for rice bean used highlights that raising of livestock, particularly beef and dairy (ruminant animals) would generate more income than their value as green manures supply P and N for a subsequent cash crop.

Table 8.11 Production of DM yield of green manures, N and P fertiliser value of green manures and forage values of green manures in one season.

Treatment	Green manure yield (kg ha <sup>-1</sup> crop <sup>-1</sup> )			Green manure value (K** ha <sup>-1</sup> crop <sup>-1</sup> )			Forage value (K** ha <sup>-1</sup> crop <sup>-1</sup> )	
	DM	N	P	N	P	N and P	Beef	Dairy
RB 0P	3974	95	5.5	12635	2310	14945	95376	40535
RB 20 P	5447	141	9.5	18753	3990	22743	130728	55559
RB 40 P	6817	188	12.5	25004	5250	30254	163608	69533
BG 0 P	1009	23	1.4	3059	588	3647	24216	10292
BG 20 P	1409	34	2.1	4522	882	5404	33816	14372
BG 40 P	1792	45	3.4	5985	1428	7413	43008	18278
RB 0 P + DO	5365	145	9	19285	3780	23065	128760	54723
RB 20 P + DO	6454	188	11.7	25004	4914	29918	154896	65831
RB 40 P + DO	7768	234	15.5	31122	6510	37632	186432	79234
BG 0 P + DO	1432	33	2	4389	840	5229	34368	14606
BG 20 P + DO	1272	30	2.2	3990	924	4914	30528	12974
BG 40 P + DO	1584	41	2.9	5453	1218	6671	38016	16157
F-TSP20P+DO	5332*	102	9.5	13566	3990	17556	127968	54386
F-TSP 20 P	6189*	113	9.8	15029	4116	19145	148536	63128
F-FYM 20 P	5682*	100	8.1	13300	3402	16702	136368	57956

\*weed yields

\*\*Kyat (Myanmar currency)

Indeed, there is a great additional benefit from feeding legumes as folder crops to animals, because of the forage N and P ingested 70% N returns from their dung and urine and 85% P returns from their dung because animals use only a small portion of the N and P in growth (Haynes and Williams, 1993).

This result supports the view that integrating livestock production with crops and green manures for forage would allow a general improvement in soil fertility, leading to

higher crop yields and generate income for farmers to purchase the necessary fertilisers to raise soil fertility.

#### **8.4 Conclusion**

The current study has confirmed that low soil P status is one of the major constraints to producing viable legume yields in the Yellow Earth.

Application of water-soluble P fertilisers as TSP (up to 40 kg P ha<sup>-1</sup>) will increase the rice bean biomass yield in either the presence or the absence of dolomite. Although, TSP at 20 and 40 kg P ha<sup>-1</sup> did not increase the biomass yield of black gram, it did significantly increase its bean yield. However, black gram is not a suitable test crop for this climate because its unfavourable nature in the low temperature.

Use of the indigenous rice bean as a green manure has been shown to increase N status of a subsequent cereal crop (in the case wheat).

The N accumulation in a subsequent crop (i.e. wheat) was weakly related to the amount of green manure N incorporated and further research is required to quantify the rate of N release from green manures in the Red Earths and Yellow Earths.

Incorporation of green manures also raises soil pH and will improve the plant-available P status (Olsen-P) in the Red Earths and Yellow Earths.

Considerable economic potential exists to use green manures as animal forage before return to the soil as FYM. Such mixed farming systems should be evaluated further.

## **CHAPTER 9 Summary, Conclusions and Suggestions for Future Work**

This thesis reports on the investigation of soil fertility constraints preventing the development of sustainable agriculture practices on the major soil type around Kalaw and Pindaya townships in Southern Shan State of Myanmar. Kalaw and Pindaya townships have soil resources and climate typical of much of Shan Plateau in Myanmar. The studies presented in this thesis are summarised below:

### **9.1 Current farming practice**

In Chapter (1), review of a farmer survey concluded that the current farming systems are unsustainable for crop production on the Red Earths and Yellow Earths in Southern Shan State, Myanmar. Low soil P status, low SOM and soil acidity are serious constraints to crop growth on these Red Earths and Yellow Earths.

Many farmers in Southern Shan State are threatened by encroaching poverty. One of the major findings of the farmer survey was that plant nutrients removed by crops are not replaced with fertiliser applications, resulting in soil nutrient depletion and unsustainable crop yields from the existing farming systems. If P limitations to production are not fully recognised, resource-poor farmers will continue on the downward spiral to the poverty trap and soil infertility in Southern Shan State of Myanmar will remain.

The fertility of farmers' land should be improved through increased inputs of cost-effective P fertilisers, by improvement in SOM through managed legume crop rotation. These three topics are investigated in this thesis.

### **9.2 Soil resources**

In Chapter (2), the current study confirmed that Red Earths and Yellow Earths of Southern Shan State are Acrisols. Red Earths are Ferric Acrisols and Yellow Earths are Orthic Acrisols in FAO/UNESCO system. The Red Earths and Yellow Earths are

infertile acid upland soils. Soil analysis showed that the soils within the study area have moderate soil acidity, low available P status ( $<11 \text{ mg P ha}^{-1}$  Olsen-P) with moderate P retention and low Al toxicity, low SOM ( $<2\%$  Leco C), low ECEC ( $<5 \text{ cmol (+) kg}^{-1}$ ) and contain low reserves of N, P and S, and low concentration of basic cations such as  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ .

These soil fertility characteristics were considered to be the major constraints to crop growth, but can be relieved by introducing modified farming systems involving targeted use of fertiliser and lime. Subsequent research concentrated on evaluating suitable materials and practices to ameliorate low P status and soil acidity.

### 9.3 Preliminary soil fertility research

During the farmer survey samples of the study soils were taken and freighted to New Zealand for glasshouse and laboratory studies. These preliminary studies demonstrated:

- (a) In glasshouse studies, the growth of pigeon pea and rice bean were very responsive to P application in these soils. However upland rice growth did not respond markedly to P application to the Yellow Earth (Chapter 3).
- (b) The amounts of water-soluble P fertiliser (TSP) required to raise Olsen-P test values to  $17 \text{ mg P kg}^{-1}$  appeared adequate for pigeon pea growth (Chapter 3).
- (c) The nodulation of some legumes (pigeon pea and rice bean) was promoted by liming the study soils with a local dolomite from Southern Shan State, Myanmar (Chapter 3). A subsequent legume-wheat rotation field trial (Chapter 8) was designed to field test the agronomic value of the local dolomite.
- (d) Glasshouse trials in Chapter 3 confirmed that the indigenous MPR, which had low solubility in 2% citric acid solution, was an unreactive PR and was probably not an effective P source for crops on Red Earths and Yellow Earths in the short-term. It is worth noting that the relative agronomic effectiveness (RAE) of MPR could be improved by partial acidulation with sulphuric acid of finely ground MPR, but this was

not tested in the present study. This may be an economically feasible method for improving the agronomic value of PR materials of low chemical reactivity.

(e) A laboratory soil incubation study demonstrated that incorporation of FYM, pigeon pea and upland rice residues into the Red Earths and Yellow Earths markedly increased soil organic C, increased soil pH buffering, increased the total P content and increased labile-P fractions that could be used for plant growth. In particular, labile-Pi in these soils can be raised by application of P rich organic materials (Chapter 4). The determination of soil organic C is a useful index of the soil quality for plant growth in tropical soils, and the studies demonstrated that Walkley-Black method is suited for the determination of organic C in Red Earths and Yellow Earths and organic amendments.

It was concluded from the glasshouse studies that lack of P rather than soil acidity was likely to be the major soil fertility constraint in these Red Earths and Yellow Earths in Southern Shan State, Myanmar.

The following research strategy was developed for field trials to be conducted at Aungban Research Farm in Southern Shan State, Myanmar.

Field trials using increasing rates of P fertiliser would be used to produce relationships describing the crop growth response both to P fertiliser added and soil test P values.

Soil test values at which optimum crop growth occurred would be defined. In addition the relationship between form of P fertiliser, rate of P application and change in soil test value would be developed.

#### **9.4 Maize trials (1998 and 1999)**

Maize plant growth and grain yield response to increasing rates of applied water-soluble P and increasing soil test P (Olsen-P) values were measured and used:

- (a) To establish optimum soil P test values for growing maize
- (b) To evaluate alternative locally available sources of P.

### ***Optimum Olsen-P test values***

The Olsen-P values at 21 DAE of maize responsible for 90% maximum DM yield at silking ranged from 47 and 44 mg P kg<sup>-1</sup> for Maize Field Trial (1) in 1998 and 1999, and 34 mg P kg<sup>-1</sup> for Maize Field Trial (2) in 1999 (Table 9.1). The Olsen-P values required to give 90% maximum grain yield at final harvest ranged 34 and 28 mg P kg<sup>-1</sup> for Maize Field Trial (1) in 1998 and 1999, and 40 mg P kg<sup>-1</sup> for Maize Field Trial (2) in 1999 (Table 9.1).

It can be concluded that 90% maximum yield of maize can be expected at Olsen-P values between 28 to 40 kg P ha<sup>-1</sup> in the Red Earths and Yellow Earths.

Table 9.1 A summary of critical Olsen-P test values (mg P kg<sup>-1</sup>) estimated to produce 90% maximum maize yields at silking and grain harvest.

<b>Crop</b>	<b>Olsen-P values at 21 DAE required for 90% maximum DM yield at silking (mg P kg<sup>-1</sup>)</b>	<b>Olsen-P values at 21 DAE required for 90% maximum grain yield (mg P kg<sup>-1</sup>)</b>	<b>Chapter</b>
Maize (Field Trial 1, 1998)	47	34	6
Maize (Field Trial 1, 1999)	44	28	6
Maize (Field Trial 2, 1999)	34	40	7

### ***Agronomic value of alternative P sources***

Maize yield growth response was poor when local FYM, *Tithonia diversifolia* and Sechura reactive phosphate rock were used as P sources compared to TSP (Chapters 6 and 7). It was concluded that this resulted from these materials failing to substantially increase plant-available P status (Olsen-P) during the short-growing season in the Yellow Earths. A partially (sulphuric acid) acidulated rock phosphate (CPAPR), however, was a useful P and S source, and it may be used as a cost-effective fertiliser for short season crops in these Red Earths and Yellow Earths.

Through regular long-term applications, despite low substitution values when compared to TSP in the short-term, FYM, and *Tithonia diversifolia* will raise soil P test levels. Family farmers where labour is not charged may be able to use these organic materials cost effectively.

### **9.5 Legume trials**

Evaluation of rice bean and black gram as green manures confirmed that low P status was again the major constraint to producing viable legume yields in the Yellow Earth. The Olsen-P values above 25 mg P kg<sup>-1</sup> at 45 DAE of legumes (rice bean) produced the highest biomass yield.

At harvest the indigenous rice bean contained adequate amounts of N for utilisation by a subsequent wheat crop, if all biomass decomposed before wheat growth. However, apparent decomposition was approximately 16% in this study. Thus, further research should be carried out to quantify the rate of N release from green manures in these soils.

### **9.6 Summary of amounts of P required to raise Olsen-P test to optimum levels for crop growth**

The Red Earths and Yellow Earths in Southern Shan State are inherently deficient in P, it is necessary to raise their P fertility level in order to sustain crop production.

In order to design improved P fertiliser recommendations for sustainable crop production on Red Earths and Yellow Earths, the soil P test is a very important tool. There are many different methods used for soil P testing to obtain indices of soil P availability to crops. In this study, the Olsen-P test consistently served as a useful index of the soil P status required for maximum plant growth in both glasshouse (Chapter 3) and field trials (Chapters 6, 7 and 8).

For three field trials, the two maize trials (1998 and 1999) and the legume-wheat rotation trials, there was a consistent relationship (Figure 9.1) between P added as TSP (kg P ha<sup>-1</sup>) and Olsen-P values (mg P kg<sup>-1</sup>) measured at 25 to 35 days after application (a period when crop demand for P begins).

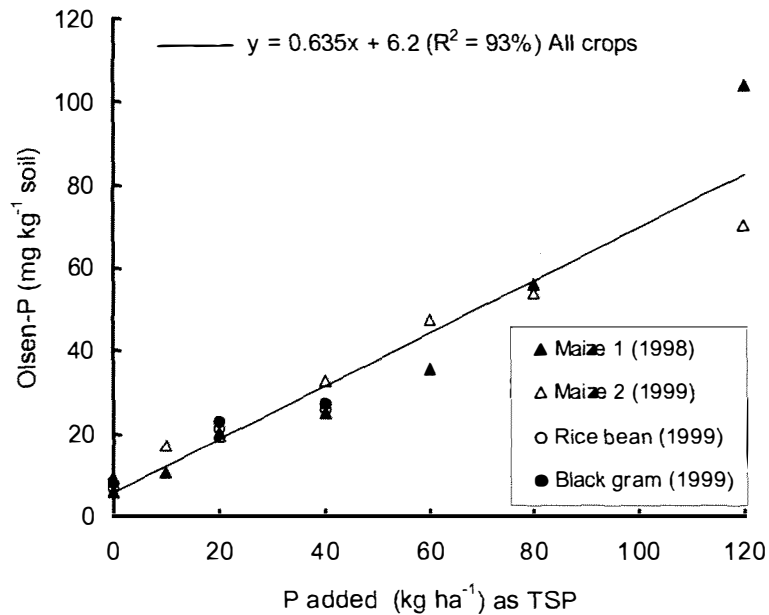


Figure 9.1 The effect of amount of P added as TSP ( $\text{kg ha}^{-1}$ ) to cultivated soils for periods of 25 (maize trials) to 35 (legume-wheat rotation trial) days before measurement of Olsen-P values ( $\text{mg kg}^{-1}$ ) in the field trials (1998 and 1999) on Yellow Earths.

The relationship (Figure 9.1) indicates that approximately  $1.6 \text{ kg ha}^{-1}$  of soluble P in fertiliser are required to raise Olsen-P by one unit in this short period (25 to 35 days) prior to crop demand for available P. In the Yellow Earth with an initial Olsen-P of  $8 \text{ mg P kg}^{-1}$ , between 35 to  $51 \text{ kg P ha}^{-1}$  as TSP are required to raise Olsen-P levels to optimum values of  $30\text{-}40 \text{ mg P kg}^{-1}$  soil.

During the development phase of Red Earths which have higher P retention it is expected that more P may be required to increase the Olsen-P by one unit than on the lower P retaining Yellow Earths.

Alternative P fertiliser materials such as FYM and the green manures (rice bean, *Tithonia diversifolia*) were used to raise soil P status (Figure 9.2). Their ability to raise Olsen-P values was very variable in the short-term. For example, changes in Olsen-P ranged from 0 to  $6 \text{ mg P kg}^{-1}$  when  $20 \text{ kg P ha}^{-1}$  was applied as *Tithonia diversifolia* or FYM. The change in Olsen-P is presumably dependent upon extent of decomposition, which was shown to be related to the N:C ratio of the organic materials.

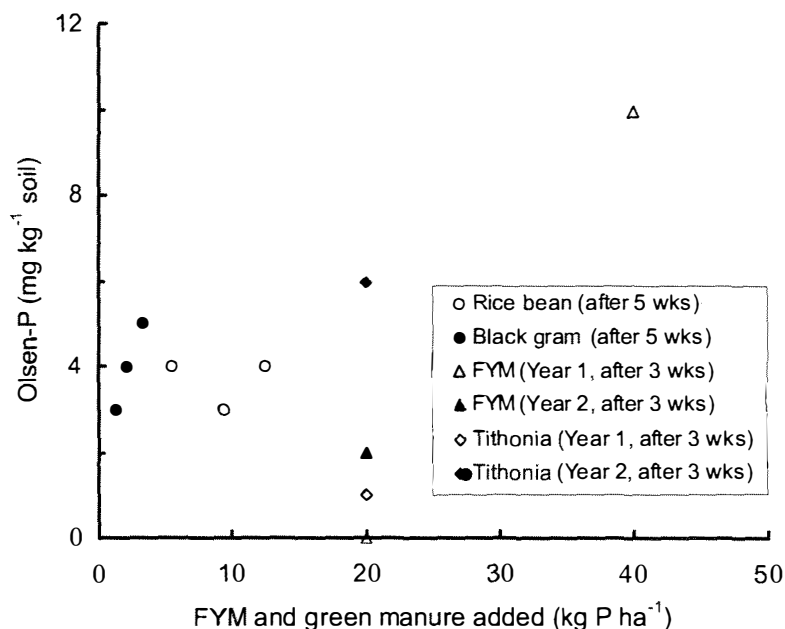


Figure 9.2 The change in Olsen-P values (3-5 weeks) after FYM and green manure application to field trials.

It was concluded that manures and green manures should be used in long-term strategies for raising soil P status and that where short-term increases in P status are required soluble inorganic P fertilisers should be used.

### 9.7 Dolomite responsive of crops

Use of the local dolomite increased soil pH and improved legume (pigeon pea and rice bean) nodulation. The application of water-soluble P fertiliser (TSP 40 kg P ha<sup>-1</sup>) plus dolomite (2.5 t ha<sup>-1</sup>) increased the rice bean DM and black gram bean yields.

Cost of liming is disadvantage for resource poor farmers if a liming material is not a local resource. The local dolomite can be a cost-effective liming material but efforts need to be directed towards cost-effective methods of providing it in suitable fine particle range.

### 9.8 Sulphur responsive of crops

The application of CPAPR at 80 kg P ha<sup>-1</sup> to a Yellow Earth gave as good or greater maize yields than TSP applied at the same rate (Chapter 7). However, CPAPR applied

at low rates (20 and 40 kg P ha<sup>-1</sup>) gave lower TSP substitution ratio values of 0.31 (31%) and 0.61 (61%). This provided evidence that at the 80 kg P ha<sup>-1</sup> rate the extra S applied above the basal S dressing gave an additional maize growth response to S. This evidence of a S response was confirmed when maize yields decrease by 46% when S<sup>o</sup> was omitted from the SPR treatment (Chapter 7).

Based on these findings, further trials should be undertaken to quantify the S responsiveness of crops, particularly legumes on Yellow Earth. Relief of S deficiency may allow other nutrients N, P and K to be utilised more efficiently.

### **9.9 Alternative use of legume green manure**

The potential amount (41 to 130 kg N ha<sup>-1</sup>) of N that can be fixed by correctly managed legumes is sufficient to use as a green manure for a subsequent cereal crop and can save expenditure on N fertiliser. However, it was demonstrated that the potential income from using the legume as a forage crop is greater than when growing a cereal cash crop. Comparing these values with the gross return for green manure (e.g. rice bean), suggests that keeping of ruminants, would generate more income than the value of N and P in the green manure. Considerable economic potential exists to use green manures as animal forage before returning the dung and urine, as FYM, to the soil. Such mixed farming systems should be developed in Southern Shan State, Myanmar.

### **9.10 Future work**

The research findings on soil P testing in this thesis indicates the inherent P deficiency can be corrected by application of 35 to 50 kg P ha<sup>-1</sup> in the Red Earths and Yellow Earths.

This raises two issues in the developing of a sustainable soil fertility strategy.

The combined tools of soil testing and knowledge of how much P is required to raise the soil P test values to optimum value will provide methods for diagnosis of P fertiliser requirements and fertiliser recommendations to farmers. One of the key problems, however, is that farmers in Southern Shan State do not know the available P status

(Olsen-P value) of their croplands. Therefore soil P testing (including N, K, S and etc.) must be implemented in Southern Shan State, Myanmar.

In the absence of soil testing, farmers need simple clear advice on rate and frequency of fertiliser and manure application. For example, if one basket of maize (55 kg) is removed from a farm, farmer has to apply either TSP 1.25 kg at seeding or fresh green manure biomass 800 kg at 3-6 weeks before seeding maize. Such simple instructions should be extended to cover N, K and S replacement.

Alternative cost-effective P fertilisers are still required for farmers to improve these acid infertile soils to productive soils in Southern Shan State. Research on cost-effective fertiliser sources should focus on methods of improving the agronomic value of the local Myanmar PR. This research should address novel methods of low cost acidulation with sulphuric acid.

Production of forage provides income from animal products and can produce an N, P and K rich FYM in mixed legume-based forage farming systems. These local on farm manures can be used over the long-term to improve soil fertility in particularly building OM and P reserve in the Red Earths and Yellow Earths. Future research on a long-term approach to the use of organic amendments should be considered (e.g. growing *Tithonia diversifolia* as hedge row or contour band systems).

## References

- Adams, F. and C.E. Evans (1962) A rapid method for measuring lime requirements of Red-Yellow Podzolic soils. *Proceedings of Soil Science Society of America* 26:355-357.
- Addiscott, T.M. and A.R. Dexter (1994) Tillage and crop residue management effects on losses of chemicals from soils. *Soil and Tillage Research* 30:(2-4)125-168.
- Agamuthu, P. and W.J. Broughton (1985) Nutrient cycling within the developing oil palm - legume ecosystem. *Agriculture Ecosystems and Environment* 13:(2)111-123.
- Allison, L.E. (1960) Wet-combustion apparatus and procedure for organic and inorganic C in soil. *Proceedings of Soil Science Society of America* 24:36-40.
- Anderson, D.L., W.R. Kusow and R.B. Corey (1985) Phosphate rock dissolution in soils: Indication from plant growth studies. *Soil Science Society of America Journal* 49:918-925.
- Anderson, J.M. and J.S.I. Ingram (1993) *Tropical soil biology and fertility: a handbook of methods* (2<sup>nd</sup> Edition). Wallingford, Oxon: CABI.
- Andrew, C.S. and A.D. Johnson (1976) Effect of calcium, pH and nitrogen on the growth and chemical composition of some tropical and temperate pasture legumes. II. Chemical composition (calcium, nitrogen, potassium, magnesium, sodium and phosphorus). *Australian Journal of Agriculture Research* 27:625-636.
- Armstrong, R.D. and K.R. Helyar (1992) Changes in the soil phosphate fractions in the rhizosphere of semi-arid pasture grasses. *Australian Journal of Agriculture Research* 30:131-143.
- Aulakh, M.S., T.S. Khera and J.W. Doran (2000) Mineralisation and denitrification in upland, nearly saturated and flooded subtropical soil. II. Effect of organic manures varying in N content and C:N ratio. *Biology and Fertility of Soils* 31:168-174.
- Aye, T.M. (1994) A comparative study on N-mineralisation of fertiliser materials and their influence on growth and yield of maize. M.Sc. Thesis, Asian Institute of Technology, Thailand.
- Ball, D.F. (1964) Loss-on-ignition as an estimate of organic matter and organic carbon in non-calcareous soils. *Soil Science* 15:84-92.
- Barrow, N.J. (1960) A comparison of the mineralisation of nitrogen and of sulphur from decomposing organic materials. *Australian Journal of Agricultural Research* 11:960-969.
- Barrow, N.J. (1980) Evaluation and utilization of residual phosphorus in soils. *In* F.E. Khasawneh, E.C. Sample and E.J. Kamprath (eds.) *The role of phosphorus in agriculture*. (Proceedings of a symposium held 1-3 June 1976 at the National

- Fertiliser Development Centre, Tennessee Valley Authority, Muscle Shoals, Alabama). American Society of Agronomy, Crop Science Society of America, Soil Science Society of America, Madison, Wisconsin, USA. Pp 333-359.
- Black, C.A. (1968) *Soil-Plant Relationships* (2<sup>nd</sup> Edition). Wiley, New York.
- Black, C.A. (1993) *Soil fertility evaluation and control*. Lewis Publishers, USA.
- Blair, G.J. and O.W. Boland (1978) The release of phosphorus from plant material added to soil. *Australian Journal of Soil Research* 16:(1)101-111.
- Blair, G.J., A.R. Till and R.C.G. Smith (1976) The phosphorus cycle – What are the sensitive areas? *In* J.G. Blair (ed.) *Prospects for improving efficiency of phosphorus utilization*. Proceedings of a symposium held at the University of New England, Australia. August 1976. *Reviews in Rural Science* Number III. Pp 9-19.
- Blakemore, L.C., P.L. Searle and B.K. Daly (1987) *Method of chemical analysis of soils*. NZ Soil Bureau Scientific Report 80.
- Blamey, F.P.C. (1983) Acid soil infertility effects on peanut yields and yield components. *Communications in Soil Science and Plant Analysis* 14:373-386.
- Blamey, F.P.C. and D.G. Edwards (1989) Limitations to food crop production in tropical acid soils. *In* van der Heide, J. (ed.) *Nutrient management for food crop production in tropical farming systems*. Institute for Soil Fertility, Haren, Netherlands and University Brawijaya, Malang, Indonesia. Pp 73-94.
- Bluehen (2001) [http://bluehen.ags.udel.edu/deces/prod\\_agric/chap8-95.htm](http://bluehen.ags.udel.edu/deces/prod_agric/chap8-95.htm)
- BOB (2001) BOP Fertiliser Limited. *In* D. Edmeades (ed.) *Fertiliser Handbook*. Northland Fertiliser, New Zealand. Pp31-34.
- Bolan N.S. and M.J. Hedley (2001) Role of carbon, nitrogen and sulphur cycles in soil acidification. *In* Zed Rengel (ed.) *Handbook on soil acidity*. Marcel and Dekker, INC (in press).
- Bolan N.S., M.J. Hedley, R. Harrison and A.C. Braithwaite (1990a) Influence of manufacturing of variables on characteristics and the agronomic value of partially acidulated phosphate fertilisers. *Kluwer Academic Publishers, Netherlands*. *Fertiliser Research* 26:119-138.
- Bolan, N.S., J. Elliott, P.E.H. Gregg and S. Weil (1997) Enhanced dissolution of phosphate rocks in the rhizosphere. *Biology and Fertility of Soils* 24:169-174.
- Bolan, N.S., J.K. Syers and R.W. Tillman (1988) Effect of pH on the adsorption of phosphate and potassium in batch and column experiments. *Australian Journal of Soil Research* 26:165-170.
- Bolan, N.S., M.J. Hedley and R.E. White (1991) Processes of soil acidification during nitrogen cycling with emphasis on legume based pastures. *Plant and Soil* 134:(1)53-63.

- Bolan, N.S., R.E. White and M.J. Hedley (1990b) A review of the use of phosphate rocks as fertilisers for direct application in Australia and New Zealand. *Australian Journal of Experimental Agriculture* 30:297-313.
- Bolland, M.D.A., D.C. Lewis, R.J. Gilkes and L.J. Hamilton (1997) Review of Australian phosphate rock research. *Australian Journal of Experimental Agriculture* 37:845-859.
- Bouldin, D.R. and C.A. Black (1960) Fertiliser evaluation. IV. Use of  $^{32}\text{P}$  labelled fertiliser. *Proceedings of Soil Science Society of America* 24:491-496.
- Bouton, J.H., J.K. Syers and M.E. Sumner (1981) Alfalfa, *Medicago sativa* L., in highly weathered, acid soils. I. Effect of lime and P application on yield and acetylene reduction ( $\text{N}_2$ -fixation) of young plants. *Plant and Soil* 59:455-463.
- Brady, N.C. (1974) *The nature and properties of soils* (8<sup>th</sup> Edition). MacMillan Publishing Co., New York. Pp 58-62.
- Braithwaite, A.C. (1987) Partially acidulated phosphate rock fertilisers - An FMRA research review. *In* R.E. White and L.D. Currie (eds.) *The use of reactive phosphate rocks and their derivatives as fertilisers*. Proceedings of the workshop, organised by FLRC in cooperation with MAF, Occasional Report No.1, Fertiliser and Lime Research Centre, Massey University, Palmerston North, New Zealand. Pp 18-26.
- Bremner, J.M. and M.A. Tabatabai (1971) Use of automated combustion techniques for total carbon, total nitrogen, and total sulphur analysis of soils. *In* L.M. Walsh (ed.) *Instrumental methods for analysis of soils and plant tissue*. Soil Science Society of America, Madison, Wisconsin, USA.
- Budianta, D. (1999) Reclamation of an Utisol from South Sumatra using *Mucuna* L. and Lime. PhD Thesis, University of Ghent, Belgium.
- Budianta, D. and J. Vanderdeelen (2000) Short-term evolution of phosphorus in an Ultisol. *Communications in Soil Science and Plant Analysis* 31:(19-20)3135-3146.
- Buresh, R.J., P.C. Smithson and D.T. Hellums (1997) Building soil phosphorus capital in Africa. *In* R.J. Buresh, P.A. Sanchez and F. Calhaun (eds.) *Replenish Soil fertility in Africa*. SSSA Special Publication 51, SSSA and ASA, Madison, Wisconsin, USA. Pp 111-149.
- Charleston, A.G., L.M. Condon and I.W.M. Brown (1989) The nature of the residual apatites remaining after partial acidulation of phosphate rocks with phosphoric and sulphuric acids. *Fertiliser Research* 18:257-274.
- Chatupote, Wichien (1990) An investigation of some factors influencing the rate of oxidation of elemental sulphur fertilisers. PhD Thesis, Massey University, Palmerston North, New Zealand.
- Cheng, B.T. (1977) Soil organic matter as a plant nutrient. *In*: *Soil organic matter studies*, Proceedings of a symposium on soil organic matter studies, Jointly organised by the International Atomic Energy Agency and The Food and

- Agriculture Organisation of the United nations in co-operation with Agrochimica and held in Braunschweig, 6-10 September 1976. Pp 31-39.
- Chien, S.H. and R.G. Menon (1995) Factors affecting the agronomic effectiveness of phosphate rock for direct application. *Fertiliser Research* 41:227-234
- Chien, S.H., L.A. Leon and H.R. Tejada (1980) Dissolution of North Carolina phosphate rock in acid Columbia soils as related to soil properties. *Soil Science Society of America Journal* 44:1267-1271.
- Chien, S.H., L.L. Hammond and L.A. Leon (1978) A comparison of various laboratory methods for predicting the agronomic potential of phosphate rock for direct application. *Soil Science Society of America Journal* 42:935-939.
- Chien, S.H., P.W.G. Sale and D.K. Friesen (1990) A discussion of the methods for comparing the relative effectiveness of phosphate fertilisers varying in solubility. *Fertiliser Research* 24:149-157.
- Coleman, N.T. and G.W. Thomas (1967) The basic chemistry of soil acidity. *In* R.W. Peason and F. Adams (eds.) *Soil acidity and liming*. Soil Science Society of America, Madison, Wisconsin, USA. Pp 4-49.
- Coleman, N.T., S.B. Weed and R.J. McCracken (1959) Cation-exchange capacity and exchangeable cation in Piedmont soils of North Carolina. *Proceedings of Soil Science Society of America* 23:146-149.
- Colwell, J.D. (1985) Fertilising programs. I. Variability in responses of successive crops to fresh and previous applications of phosphorus fertiliser in Australia and Brazil. *Fertiliser Research* 8:(1)21-38.
- Cong, P.T (2000) Improving phosphorus availability in selected soils from the uplands of Southvietnam by residue management. PhD Thesis, Katholieke Universiteit Leuven, Belgium.
- Cornforth, I. (1998) *Practical soil management*. Lincoln University Press, New Zealand. Pp 111-119.
- Costa, F.P. and T. Rehman (1999) Exploring the link between farmers objectives and the phenomenon of pasture degradation in the beef production systems of Central Brazil. *Agricultural Systems* 61:135-146.
- Coventry, D.R. and J. Evans (1989) Symbiotic nitrogen fixation and soil acidity. *In* A.D. Robson (ed.) *Soil acidity and plant growth*. Academic Press Australia. Pp103-128.
- Coventry, D.R. and W.J. Slattery (1991) Acidification of soil associated with lupins grown in a crop rotation in north-eastern Victoria. *Australian Journal of Agriculture Research* 42:391-397.
- Coventry, D.R., J.R. Hirth, T.G. Reeves and V.F. Burnett (1985) Development of *Rhizobium trifolii* and nodulation of subterranean clover following the cropping phase in crop-pasture rotation in south-eastern Australia. *Soil Biology and Biochemistry* 17:17-22.

- Craswell, E.T., C. Niamskul and F.W.T. Penning de Vries (1998) Catchment approach to combating soil erosion in Asia - the managing soil erosion consortium. Soil erosion at multiple scales: principles and methods for assessing causes and impacts. CAB International, Wallingford, UK. Pp 161-173.
- Cregan, P.D., J.R. Hirth and M.K. Conyers (1989) Amelioration of soil acidity by liming and other amendments. *In* A.D. Robson (ed.) Soil acidity and plant growth. Pp 205-264.
- Curl, E.A. and B. Truelove (1985) The rhizosphere. Advance series in Agricultural Sciences 15.
- Current, D. (1988) Agroforestry practices in selected areas of Burma: Preliminary recommendation. *In*: Multipurpose-Tree-Species-Network-Research-series: Report.1988, No.5, Arlington, USA, Winrock International Institute for Agricultural Development, Forestry/Fuelwood Research and Development (F/FRED) Project.
- Curtin, D., H.P.W. Rostad and P.M. Huang (1984) Soil acidity in relation to soil properties and lime requirement. *Canada Journal of Soil Science* 64:545-554.
- Dabin, B. (1980) Phosphorus deficiency in tropical soils as a constraints on agricultural output. *In*: Priorities for alleviating soil-related constraints to food production in the tropic. International Rice Research Institute, Manila, Philippine. Pp 217-232.
- Darmody, R.G., J.E. Foss, M. McIntosh and D.C. Wolf (1983) Municipall sewage sluge compost-amended soils: some spatiotemporal treatment effects. *Journal of Environmental Quality* 12:231-236.
- De Boodt, M., D. Gabrield and J. Lenvain (1977) Mulching as protection against erosion *In*: Soil Organic Matter Studies, Proceedings of a symposium on soil organic matter studies, Jointly organised by the International Atomic Energy Agency and The Food and Agriculture Organisation of the United nations in co-operation with Agrochemica and held in Braunscheweig, 6-10 September 1976. Pp 117-122.
- Dent, F.J. (1980) Major production systems and soil-related constraints in Southeast Asia. *In*: Priorities for alleviating soil-related constraints to food production in the tropic. International Rice Research Institute, Manila, Philippine. Pp 79-106.
- Dissanayake, S.T.B., J.D.H. Wijewardena and L. Samarappulli (1999) Management of Wet Zone Soils. *In* R.B. Mapa, S. Somasiri and N. Nagarajah (eds.) Soils of the wet zone of Sri Lanka. Pp 160-175.
- Driessen, P.M. and R. Dudal (1989) The major soils of the world. Lecture notes on their geography, formation, properties and use. Agricultural University Wageningen and Katholieke Universiteit Leuven.
- Dudal, R. (1980) Soil-related constraints to agricultural development tin the tropics. *In*: Priorities for alleviating soil-related constraints to food production in the tropic. International Rice Research Institute, Manila, Philippine. Pp 23-40.

- Ebelhar, S.A., W.W. Frye and R.L. Blevins (1984) Nitrogen from legume cover crops for no-tillage corn. *Agronomy Journal* 76:51-55.
- Edmeades, D.C., R.M. Pringle, P.W. Shannon and G.P. Mansell (1985) Optimum pH for Grassland Soils. Proceedings of a workshop on lime in New Zealand Agriculture, New Zealand Ministry of Agriculture and Fisheries. Pp 65-67.
- Ekwue, E.I. and R.J. Stone (1995) Organic matter effects on the strength properties of compacted agricultural soils. *Transactions of the ASAE* 38:357-365.
- Engelstad, O.P. and G.L. Terman (1980) Agnomic effectiveness of phosphate fertilisers. *In* F.E. Khasawneh, E.C. Sample and E.J. Kamparth (eds.) *The Role of Phosphorus in Agriculture*. American Society of Agronomy, Madison, Wisconsin, USA. Pp 311-332.
- FADINAP-Fertiliser Advisory, Development and Information Network for Asia and Pacific (1994) *Agrochemical News in Brief*. Vol.20 ESCAP/FAO/UNDP.
- Falih, A.M.K. and M. Wainwright (1996) Microbial and enzyme activity in soils amended with a natural source of easily available carbon. *Biology and Fertility of Soils* 21:177-183.
- FAO (1974) *FAO/UNESCO Soil Map of the world Volume I Legend*, The United Nations Educational, Scientific and Cultural Organization, Place de Fontenoy, 75700 Paris.
- FAO (1977) *Guidelines for soil profile description (2<sup>nd</sup> Edition)*. Soil Resources Development and Conservation Service, Land and Water Development Division, Food and Agriculture Organization of United Nations, Rome.
- FAO (1987) *Fertiliser Strategies*. FAO Land Use and Water Development Series No. 10.
- FAO (1988) *Tropical forage legume (2<sup>nd</sup> Edition)*. FAO Plant Production and Protection Series No. 2. Pp 1-13.
- FAO (2001) <http://www.fao.org/waicent/faoinfo/agricult/agl/agll/prosoil/acri.htm>
- Farr, E. (1972) An investigation on laboratory and field methods of determining the pH of soil suspensions. *Journal of the Science of Food and Agriculture* 23:1089-1092.
- Fernandes, E.C.M and P.A. Sanchez (1990) The role of organic inputs and soil organic matter for nutrient cycling in tropical soils. *In: Organic matter and tillage in Africa*. Pp 169-187.
- Flaig, W., B. Nagar, H. Söchtig and C. Tietjen (1977) Organic materials and soil productivity. *Soil resources development and conservation service land and water development division, FAO Soils Bulletin*.
- Foth, H.D. and B.G. Ellis (1997) *Soil fertility (2<sup>nd</sup> Edition)*. CRC press, Inc. USA. Pp 145-147.

- Foy, C.D. (1992) Soil chemical factors limiting plant root growth. *Advances in Soil Science* 19:97-149.
- Francis G.S., F.J. Tabley and K.M. White (1999) Restorative crops for the amelioration of degraded soil conditions in New Zealand. *Australian Journal of Soil Research* 37:1017-1034.
- Francis, G.S. and T.L. Knight (1993) Long-term effects of conventional and no-tillage on selected soil properties and crop yields in Canterbury, New Zealand. *Soil and Tillage Research* 26:(3)193-210.
- Frear, D.E. (1930) A method for the estimation of the acid-base balance in the ash of plants. *The journal of Biological Chemistry* 88:675-681.
- Friesen, D.K., M.H. Miller and A.S.R. Juo (1980) Liming and lime-phosphorus-zinc interactions in two Nigerian Ultisols. II. Effects on maize root and shoot growth. *Soil Science Society of America Journal* 44:1227-1232.
- Friesen, D.K., P.W. Sale and G.J. Blair (1987) Long-term greenhouse evaluation of partially acidulated phosphate rock fertilisers. II. Effect of co-granulation with elemental S on availability of P from two phosphate rocks. *Fertiliser Research* 13:45-54.
- Gachengo, C.N., C.A. Palm, B. Jama and C. Othenio (1999) Tithonia and Senna green manures and inorganic fertilisers as phosphorus sources for maize in Western Kenya. *Agroforestry Systems* 44:21-36.
- Gaur, A.C. (1983) Organic fertilisers: Appraisal and outlook. *In: Recycling organic matter in Asia for fertiliser use*, Asian Productivity Organisation, Japan. Pp 197-216.
- Gijsman, A.J. (1990) Nitrogen nutrition of Douglas-fir (*Pseudotsuga menziesii*) on strongly acid sandy soil. I. Growth, nutrient uptake and ionic balance. *Plant and Soil* 126:53-61.
- Giller, K.E., P.T.C. Nambiar, B. Srinivasa Rao, P.J. Dart and J.M. Day (1987) A comparison of nitrogen fixation in genotypes of groundnut (*Arachis hypogaea* L.) using <sup>15</sup>N isotope dilution. *Biology and Fertility of Soils* 5:23-25.
- Glendinning, J.S. (1999) Australian soil fertility manual. Fertiliser Industry Federation of Australia, Inc. CSIRO publishing, Australia.
- Goh, K.M (1988) Sulphur transformations in field soil – A review summary. *In* R.E. White and L.D. Currie (eds.) *Proceedings of the workshop on Towards the more efficient use of soil and fertiliser sulphur*. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. Pp 78-94.
- Gohoonia, T.S. and N.E. Nielsen (1992) The effect of root induced pH changes on the depletion of inorganic and organic phosphorus in the rhizosphere. *Plant and Soil* 143:185-191.

- Goldin, A. (1987) Reassessing the use of loss-on-ignition for estimating organic matter content in noncalcareous soils. *Communications in Soil Science and Plant Analysis* 18:1111-1116.
- Greenland D.J. and P.H. Nye (1959) Increase in the carbon and nitrogen contents of tropical soils under natural fallow. *Journal of Soil Science* 10:284-299.
- Greenland, D.J., A. Wild and D. Adams (1992) Organic matter dynamics in soils of the tropics-from myth to complex reality. *Myths and science of soils of the tropics: Proceedings SSSA, Las Vegas, Nevada, 17 October 1989*. Soil Science Society of America, Madison, Wisconsin, USA. 17-33:61.
- Gregg, P.E.H., A.D. Mackay, L.D. Currie and J.K. Syers (1988) Application strategies for Senchura phosphate rock use on permanent pasture. *Fertiliser Research* 17:219-243.
- Gregg, P.H.E., N.S. Bolan, M.J. Hedley and R.E. White (1989) Reactive phosphate rocks-Potential as a direct use fertiliser and as a component of other phosphorus fertilisers. *Proceedings of the Phosphorus Symposium September 1988*. Published by the Phosphorus Symposium Organising Committee, SIRI, Private Bag x79, Pretoria 0001. Republic of South Africa. Pp 6-20.
- Hagin J., S.S.S. Rajan, M.K. Boyes and M.C. Upsdell (1990) Partially acidulated phosphates rocks: phosphorus release characteristics. *Kluwer Academic Publishers, Netherlands. Fertiliser Research* 22:109-117.
- Hammond, L.L., S.H. Chien and A.U. Mkwunye (1986) Agronomic value of unacidulated and partially acidulated phosphate rocks indigenous to the tropics. *Advances in Agronomy* 40:89-140.
- Harrison, R. and M.J. Hedley (1987) Phosphate rock dissolution during the manufacture and hydrolysis of partially acidulated phosphate rocks. *In R.E. White and L.D. Currie (eds.) The use of reactive phosphate rocks and their derivatives as fertilisers. Occasional Report No.1, Fertiliser and Lime Research Centre, Massey University, Palmerston North, New Zealand. Pp 3-17.*
- Havlin, J.L., J.D. Beaton, S.L. Tisdale and W.L. Nelson (1999) *Soil fertility and fertilisers. An Introduction to Nutrient Management (6<sup>th</sup> Edition)*. Prentice-Hall, Inc. Upper Saddle River, New Jersey 07458. Pp 47-63.
- Haynes, R.J. (1982) Effect of liming on phosphate availability in acid soils: A critical review. *Plant and Soil* 68:289-308.
- Haynes, R.J. (1983) Effect of lime and phosphate applications on the adsorption of phosphate, sulfate, and molybdate by a Spodosol. *Soil Science* 135:(4)221-227.
- Haynes, R.J. (1988) Effect of liming on phosphate availability-an overview. *Proceedings of the Phosphorus Symposium September 1988*. Published by the Phosphorus Symposium Organising Committee, SIRI, Private Bag x79, Pretoria 0001. Republic of South Africa. Pp 49-56.

- Haynes, R.J. (1992) Relative ability of a range of crop species to use phosphate rock and monocalcium phosphate as P sources when grown in soil. *Journal of the Science of Food and Agriculture* 60:205-211.
- Haynes, R.J. and M.S. Mokolobate (2001) Amelioration of Al toxicity and P deficiency in acid soils by additions of organic residues: a critical review of the phenomenon and the mechanisms involved. *Nutrient Cycling in Agroecosystems* 59:47-63.
- Haynes, R.J. and P.H. Williams (1993) Nutrient cycling and soil fertility in the grazed pasture ecosystem. *Advances in Agronomy* 49:119-199.
- Haynes, R.J. and R. Naidu (1991) Effects of lime additions on the availability of phosphorus and sulphur in some temperate and tropical acid soils. *In: Plant-Soil interactions at Low pH. Proceedings of the 2<sup>nd</sup> International Symposium on Plant-Soil Interaction at Low pH, 24-29 June 1990, Beckley, West Virginia, USA. Kluwer Academic Publishers, Netherlands. Pp 267-274.*
- Haynes, R.L. and T.E. Ludecke (1981) Yield, root morphology and chemical composition of two pasture legumes as affected by lime and phosphorus application to an acid soil. *Plant and Soil* 62:241-254.
- Hedley M.J., J.W.B. Stewart and B.S. Chauhan (1982a) Changes in inorganic and organic soil phosphorus fractions induced by cultivation practices and by laboratory incubations. *Soil Science Society of America Journal* 46:970-976.
- Hedley, M.J. and N.S. Bolan (1997) Developments in some aspects of reactive phosphate rock research and use in New Zealand. *Australian Journal of Experimental Agriculture* 37:861-884.
- Hedley, M.J. and P. Loganathan (1999) An Introduction to: Soil nutrients and plant availability. *In: Soil fertility assessment and fertiliser recommendations. A short course for laboratory managers, Fertiliser and Lime Research Centre, Massey University, Palmerston North, New Zealand. 28 September-1 October 1999.*
- Hedley, M.J., G.J.D. Kirk and M.B. Santos (1994) Phosphorus efficiency and the forms of soil phosphorus utilized by upland rice cultivars. *Plant and Soil* 158:53-62.
- Hedley, M.J., J.J. Mortvedt, N.S. Bolan and J.K. Syers (1995) Phosphorus fertility management in Agroecosystems. *In H. Tiessen (ed.) Phosphorus in the Global Environment. Pp 59-92.*
- Hedley, M.J., R.E. White and P.H. Nye (1982b) Plant induced changes in the rhizosphere of rape (*Brassica napus* var. Emerald) seedlings. III. Changes in L. Value, soil phosphate fractions and phosphatase activity. *New Phytologist* 91:(1)45-46.
- Helling, C.S., G. Chesters and R.B. Corey (1964) Contribution of organic matter and clay to soil cation exchange capacity as affected by the pH of the saturating solution. *Proceedings of Soil Science Society of America* Pp 517-520.
- Helyar, K.R. and W.M. Porter (1989) Soil acidification, its measurement and the process involved. *In A.D. Robson (ed.) Soil Acidity and Plant Growth. Academic Press Australia. Pp.61-101.*

- Hesse, P.R. (1971) A text book of soil chemical analysis. John Murray Publishers Ltd, London. Pp 88-105.
- Hewitt, A.E. (1992) Soil classification in New Zealand: legacy and lessons. Australian Journal of Soil Research 30:(6)843-854.
- Hinsinger, P. (1998) How do plant roots acquire mineral nutrients? Chemical processes involved in the rhizosphere. Advances in Agronomy 64:225-265.
- Holmgren, G.G.C. (1967) A rapid citrate-dithionite extractable iron procedure. Proceedings of Soil Science Society of America 31: 210-211.
- Hue, N.V. (1992) Correcting soil acidity of a highly weathered Ultisol with chicken manure and sewage sludge. Communications in Soil Science and Plant Analysis 23:241-264.
- IBSRAM (International Board for Soil Researchh and Management) (1994) Methodological guidelines for IBSRAM's soil management networks (2<sup>nd</sup> Edition), Bangkok, IBSRAM, Thailand.
- ICRAF (1998) Annual report for 1997. International Centre for Research in Agroforestry, Nairobi, Kenya.
- IFDC (1985) Fertiliser Research Programme for Africa. Rep. Int. Fund. Agric. Dev. International Fertiliser Development Centre, Muscle Shoals, Alabama, USA.
- IRRI (1996) Community-based natural resources management in Myanmar, International Rice Research Institute, September 1996.
- Iyamuremye, F., R.P. Dick and J. Baham (1996a) Organic amendments and phosphorus dynamics. I. Phosphorous chemistry and sorption. Soil Science 161:426-435.
- Iyamuremye, F., R.P. Dick and J. Baham (1996b) Organic amendments and phosphorus dynamics. II. Distribution of soil phosphorous fractions. Soil Science 161:(7)436-443.
- Iyamuremye, F., R.P. Dick and J. Baham (1996c) Organic amendments and phosphorus dynamics. III. Phosphorous speciation. Soil Science 161:444-451.
- Jama, B., C.A. Palm, R.J. Buresh, A. Niang, C. Gachengo, G. Nziguheba and B. Amadalo (2000) *Tithonia diversifolia* as a green manure for soil fertility improvement in western Kenya: A review. Agroforestry Systems 49:(2)201-221.
- Jarvis, S.C. and A.D. Robson (1983a) The effects of nitrogen nutrition of plants on the development of acidity in Western Australian soils. I. Effects with subterranean clove grown under leaching conditions. Australian Journal of Agriculture Research 34:341-343.
- Jarvis, S.C. and A.D. Robson (1983b) A comparison of the cation/anion balance of ten cultivars of *Trifolium subterraneum* L., and their effects on soil acidity. Plant and Soil 75:235-243.

- Jarvis, S.C. and A.D. Robson (1983c) The effects of nitrogen nutrition of plants on the development of acidity in Western Australian soils. II. Effects of differences in cation/anion balance between plant species grown under nonleaching conditions. *Australian Journal of Agricultural Research* 34:355-365.
- Jenkinson, D.S. (1977a) Studies on the decomposition of plant material in soil. V. The effects of plant cover and soil type on the loss of carbon from  $^{14}\text{C}$  labelled ryegrass decomposing under field conditions. *Soil Science* 28:424-434.
- Jenkinson, D.S. (1977b) Studies on the decomposition of plant material in soil. IV. The effect of rate of addition. *Soil Science* 28:417-423.
- Jones, J. and Jr. Benton (1972) Plant Tissue Analysis for micronutrients. *In* J.J. Mortvedt, P.M. Giordano and W.L. Lindsay (eds.) *Micronutrients in Agriculture*. Soil Science Society of America, Madison, Wisconsin, USA.
- Jones, J.B. and V.W. Case (1990) Sampling, handling, and analyzing plant tissue samples. *In: Soil Testing and Plant Analysis (3<sup>rd</sup> Edition)*. Soil Science Society of America, Madison, Wisconsin, USA. Pp 389-427.
- Jones, J.P. and R.L. Fox (1978) Phosphorus nutrition of plants influenced by manganese and aluminium uptake from an oxisol. *Soil Science* 126:230-236.
- Juo, A.S.R (1990) Maintenance and management of organic matter in tropical soils. *In: Organic matter and tillage in Africa*. Pp 199-212.
- Kabata-Pendias, A. and H. Pendias (1984) Trace elements in soils and plants. CRC press, Inc. USA. Chapter 3:15-31.
- Kamprath, E. (1980) Soil acidity in well-drained soils of the tropics as a constraint to food production. *In: Priorities for alleviating soil-related constraints to food production in the tropic*. International Rice Research Institute, Manila, Philippines. Pp79-106
- Kamprath, E. J. (1984) Crop response to lime on soils in the tropics. *In: Soil acidity and liming – Agronomy Monograph No.12 (2<sup>nd</sup> Edition)*. ASA-CSSA, Madison, USA. Pp349-368.
- Kamprath, E.J. and M.E. Watson (1980) Conventional soil and tissue tests for assessing the phosphorus status of soils. *In: Soil and tissue tests for P in soils*. Soil Science Society of America, Madison, Wisconsin, USA. Pp 433-469.
- Keeney, D.R. and J.M. Bremner (1966) Comparison and Evaluation of Laboratory Methods of Obtaining and Index of Soil Nitrogen Availability. *Agronomy Journal* 58:498-503.
- Kerven, G.L., N.W. Menzies and M.D. Geyer (2000) Soil Carbon Determination by High Temperature Combustion – A Comparison with Dichromate Oxidation Procedure and the Influence of Charcoal and Carbonate Carbon on the Measured Value. *Communications in Soil Science and Plant Analysis* 31:1935-1939.

- Khaleel, R., K.R. Reddy and M.R. Overcash (1981) Changes in soil physical properties due to organic waste application: A review. *Journal of Environmental Quality* 10:133-141.
- Khasawneh, F.E. and E.C. Doll (1978) The use of phosphate rock for direct application to soils. *Advances in Agronomy* 30:159-206.
- Klausner, S.D., V.R. Kanneganti and D.R. Bouldin (1994) An approach for estimating a decay series for organic nitrogen in animal manure. *Agronomy Journal* 86:897-903.
- Kumar, K. and K.M. Goh (2000) Crop residues and management practices: effects on soil quality, soil nitrogen dynamics, crop yield, and nitrogen recovery. *Advances in Agronomy* 68:197-319.
- Lal, R. and B.A. Stewart (1992) Need for land restoration. *Advances in Soil Science* 17:1-11.
- Le Mare, P.H. (1991) Rock phosphates in agriculture. *Experimental Agriculture* 27:413-422.
- Lee, A. and J.H. Watkinson (1987) Effect of some soil properties and elemental sulphur on the dissolution of Jordan phosphate rock in some New Zealand soils. In R.E. White and L.D. Currie (eds.) *The use of reactive phosphate rocks and their derivatives as fertilisers. Occasional Report No.1, Fertiliser and Lime Research Centre, Massey University, Palmerston North, New Zealand.* Pp 90-94.
- Lee, A., C.G. Boswell and J.H. Watkinson (1988) Effect of particle size on the oxidation of elemental sulphur, *thiobacilli* numbers, soil sulphate, and its availability to pasture. *New Zealand Journal of Agricultural Research* 31:(2)179-186.
- Lee, A., J.H. Watkinson, G. Orbell, J. Bagyaraj and D.R. Lauren (1987) Factors influencing dissolution of phosphate rock and oxidation of elemental sulphur in some New Zealand soils. *New Zealand Journal of Agricultural Research* 30:(3)373-385.
- Lee, D., X.G. Han and C.F. Jordan (1990) Soil phosphorus fractions, aluminium and water retention affected by microbial activity in an ultisols. *Plant and Soil* 121:125-136.
- Lefroy, R.D.B. and E.T. Craswell (1997) Soil as a filter for nutrients and chemicals: sustainability aspects. Food and Fertiliser Technology Centre for the Asian and Pacific Region, Taiwan. Technical Bulletin No.146.
- Lefroy, R.D.B., G.J. Blair and A. Conteh (1995) Chemical fractionation of soil organic matter and measurement of the breakdown rates of residues. Soil organic matter management for sustainable agriculture: A workshop held in Ubon, Thailand, 24-26 August 1994. Australian Centre for International Agricultural Research (ACIAR), Canberra, Australia. Pp 149-158.
- Lewis, D.C., P.W.G. Sale and D. Johnson (1997) Agronomic effectiveness of a partially acidulated reactive phosphate rock fertiliser. *Australian Journal of Experimental Agriculture* 37:985-993.

- Li, G.C., R.L. Mahler and D.O. Everson (1990) Effects of plant residues and environmental factors on phosphorus availability in soils. *Communications in Soil Science and Plant Analysis* 21:471-491.
- Lipiec, J. and W. Stepniewski (1995) Effects of soil compaction and tillage systems on uptake and losses of nutrients. *Soil and Tillage Research* 35:37-52.
- Logan, T.J. (1992) Reclamation of chemically degraded soils. *Advances in Soil Science* 17:13-35.
- Loganathan, L., M.J. Hedley and S. Saggar (1995) Liming effect of reactive phosphate rocks: A laboratory evaluation. *In* R.A. Date *et al.* (eds.) *Plant Soil Interactions at low pH*. Pp 641-645.
- MacKay, A.D., J.K. Syers and P.E.H. Gregg (1984a) Ability of chemical extraction procedures to assess the agronomic effectiveness of phosphate rock materials. *New Zealand Journal of Agricultural Research* 27:219-230.
- Mackay, A.D., M.W. Pritchard and J.K. Syers (1987) Effect of the growing plant on the dissolution of a reactive phosphate rock in soil. *In* R.E. White and L.D. Currie (eds.) *The use of reactive phosphate rocks and their derivatives as fertilisers*. Occasional Report No.1, Fertiliser and Lime Research Centre, Massey University, Palmerston North, New Zealand. Pp 95-101.
- Mackay, A.D., P.E.H. Gregg and J.K. Syers (1984b) Field evaluation of Chatham Rise phosphorite as a phosphatic fertiliser for pasture. *New Zealand Journal of Agricultural Research* 27:65-82.
- MAFF/ADAS (1981) Lime and liming. Reference Book 35, Ministry of Agriculture, Fisheries and Food, London.
- Mahimairaja, S., N.S. Bolan and M.J. Hedley (1995a) Agronomic effectiveness of poultry manure composts. *Communications in Soil Science and Plant Analysis* 26:1843-1861.
- Mahimairaja, S., N.S. Bolan and M.J. Hedley (1995b) Dissolution of phosphate rock during the composting of poultry manure: an incubation experiment. *Fertiliser Research* 1994/1995. 40:(2)93-104.
- Manoharan, V., P. Loganathan and R.W. Tillman (1995) Effects of long-term application of phosphate fertilisers on soil acidity under pasture in New Zealand. *In*: *Plant-soil interactions at low pH: principles and management*. Proceedings of the 3<sup>rd</sup> International Symposium, Brisbane, Queensland, Australia, 12-16 September 1993. Kluwer Academic Publishers, Dordrecht, Netherlands. Pp 85-91.
- Manrique, L.A. (1986) The relationship of soil pH to aluminium saturation and exchangeable aluminium in ultisols and oxisols. *Communications in Soil Science and Plant Analysis* 17:439-455.
- Martin Diaz-Zorita (1999) Soil Organic Carbon Recovery by the Walkley-Black Method in a Typic Hapludoll. *Communications in Soil Sciences and Plant Analysis* 30:739-745.

- Martius, C., H. Tiessen and P. Vlek (1999) The challenge of managing soil organic matter in the tropics. Bonn University, Germany, Centre for Development Research, ZEF News No.2. September 1999. Pp 3-4.
- MAS-LUD (1994) Soil Map of Myanmar. Myanma Agriculture Service, Land Use Division, Myanmar.
- Massey University (2000) 189.251, Soil Fertility and Fertilisers Study Notes, Topic 8.1 effects of cultivation on nutrient cycles, Institute of Natural Resources, Open University Study Extramural, Massey University, Palmerston North, New Zealand.
- Maung, Than U. (1966) Research on mineral resources. Mining Corporation, 1<sup>st</sup> Myanmar Research Conference, 1966 March 4, Union of Burma, Journal of Science and Industry (in Burmese) Pp 296-327.
- McClellan, G.H. and J.R. Lehr (1969) Crystal chemical investigation of natural apatites. *American Mineralogist* 54:1374-1391.
- McClellan, G.H. and L.R. Gremillion (1980) Evaluation of phosphatic raw materials. *In* F.E. Khasawneh, E.C. Sample and E.J. Kamprath (eds.) The role of phosphorus in agriculture. ASA-CSSA-SSSA, Madison, Wisconsin, USA. Pp 43-80.
- McKenzie, H.A. and H.S. Wallace (1954) The Kjeldahl determination of nitrogen: A critical study of digestion conditions-temperature, temperature, catalyst, and oxidising agent. *Australian Journal of Chemistry* Pp 55-70.
- McLay, C.D.A., L. Barton, and C. Tang (1997) Acidification potential of ten grain legume species grown in nutrient solution. *Australian Journal of Agriculture Research* 48:1025-1032.
- McLay, C.D.A., S.S.S. Rajan and Q. Lui (2000) Agronomic Effectiveness of Partially Acidulated Phosphate Rock Fertilisers in an Allophanic Soil at Near-Neutral pH. *Communications in Soil Science and Plant Analysis* 31:423-435.
- McLean, E.O. and T.J. Logan (1970) Source of phosphorus for plants grown in soils with different phosphorus fixation tendencies. *Proceedings of Soil Science Society of America* 34:907-911.
- Mendoza, R.E. (1992) Phosphorus effectiveness in fertilised soils evaluated by chemical solutions and residual value for wheat growth. *Fertiliser Research* 32:185-194.
- Mengel, K. and E.A. Kirkby (1979) *Principles of Plant Nutrition* (2<sup>nd</sup> Edition). International Potash Institute Berne, Switzerland. Pp 203-210.
- Menon, R.G. and S.H. Chien (1990) Phosphorus availability to maize from partially acidulated phosphate rocks and phosphate rocks compacted with triple superphosphate. *Plant and Soil* 127:123-128.
- Middleton, K.R. and M.R.J. Toxopeus (1973) Diagnosis and measurement of multiple soil deficiencies by a subtractive technique. *Plant and Soil* 38:219-226.
- Miles, N. and M.P.W. Farina (1988) Effects of lime on extractable and soluble phosphorus in highly weathered soils. *Proceedings of the Phosphorus Symposium*

- September 1988. Published by the Phosphorus Symposium Organising Committee, SIRI, Private Bag x79, Pretoria 0001. Republic of South Africa. Pp 66-71.
- Mnkeni, P.N.S., S.H. Chien and G. Carmona (2000) Effectiveness of Panda Hills phosphate rock compacted with triple superphosphate as source of phosphorus for rape, wheat, maize, and soybean. *Communications in Soil Science and Plant Analysis* 31:(19-20)3163-3175.
- Moir, J.L., M.J. Hedley, A.D. Mackay and C.B. Garland (1995) Climate, Soil Fertility and Pasture Production in Wairarapa hill country. *In* L.D. Currie and P. Loganathan (eds.) *Fertiliser Requirements of Grazed Pasture and Field Crops: Macro- and Micro-nutrients. Proceedings of the Workshop, Fertiliser and Lime Research Centre in conjunction with AgResearch, Massey University, Palmerston North, New Zealand.* Pp 254-259.
- Monaghan, R.M., J.D. Morrison and A.G. Sinclair (1998) Soil acidification through carbon cycling in legumes: a pot experiment examining the contributions from white clover, lotus, caucasian clover, and lucerne. *New Zealand journal of Agricultural Research* 41:(2)243-250.
- Moody, P.W. and M.D.A. Bolland (1999) Phosphorus. *In* K.I. Peverill *et al.* (eds.) *Soil Analysis an Interpretation Manual.* CSIRO, Australia. Pp 187-220.
- Moormann, F.R. and D.J. Greenland (1980) Major production systems related to soil properties in humid tropical Africa. *In: Priorities for alleviating soil-related constraints to food production in the tropics.* International Rice Research Institute, Los Banos, Laguna, Philippines. Pp 55-77.
- Munns, D.N. (1965) Soil acidity and growth of a legume. I. Interactions of lime with nitrogen and phosphate on growth of *Medicago sativa* L. and *Trifolium subterraneum* L. *Australian Journal of Agriculture Research* 16:733-741.
- Munns, D.N. and R.L. Fox (1977) Comparative lime requirements of tropical and temperate legumes. *Plant and Soil* 46:533-548.
- Munns, D.N., R.L. Fox and B.L. Koch (1977) Effect of lime on nitrogen fixation in tropical and temperate legumes. *Plant and Soil* 46:591-601.
- MUNSELL® Soil Color Charts (1994) (Revised Edition) Macbeth Division of Kollmorgan Instruments Corporation, 405 Little Britain Road, New Windsor, NY 12553.
- Murphy, J. and J.P. Riley (1962) A modified single solution method for the determination of phosphate in natural waters. *Analytica Chimica Acta* 27:31-36.
- Myers R.J.K. and E.De Pauw (1995) Strategies for the management of soil acidity. *In* R.A. Date, *et al.* (eds.) *Plant soil interaction at low pH.* Kluwer Academic Publishers, Netherlands. Pp 729-741.
- Myers, R.J.K., M. Noordwijk, P. van. Vityakon (1997) Synchrony of nutrient release and plant demand: plant litter quality, soil environment and farmer management options. *Driven by nature: plant litter quality and decomposition.* CAB International, Wallingford, UK. Pp 215-229.

- Myrold, D.D. (1987) Relationship between microbial biomass nitrogen and a nitrogen availability index. *Soil Science Society of America Journal* 51:1047-1049.
- Nagarajah, S. and B.M. Nizar (1982) Wild sunflower as a green manure for rice in the mid-country wet zone. *Tropical Agriculture* 138:69-80.
- Naidu, R. (1985) Lime-aluminium-phosphate interactions in selected acid soils from Fiji. PhD Thesis, Massey University, Palmerston North, New Zealand.
- Newman, E.I. (1966) A method for estimating the total length of root in a sample. *Journal of Applied Ecology* 3:139-145.
- Nilmond, C., S. Suthipradit, L. Nualsri, D.G. Edwards, R.J.K. Myers and N.J. Grundon (1999) Management of tropical acid upland soil for sustainable food crop production in southern Thailand. *Thai Journal of Agricultural Science* 32:(1)19-30.
- Nurlaeny, N., H. Marschner and E. George (1996) Effect of liming and mycorrhiza colonization on soil phosphate depletion and phosphate uptake by maize (*Zea mays* L.) and soybean (*Glycine max* L.) grown in two tropical acid soils. *Plant and soil* 181:275-285.
- Nye, P.H. (1981) Changes of pH across the rhizosphere induced by roots. *Plant and Soil* 61:7-26.
- Nziguheba, G., C.A. Palm, R.J. Buresh and P.C. Smithson (1998) Soil phosphorus fractions and adsorption as affected by organic and inorganic sources. *Plant and Soil* 198:159-168.
- Oades, J.M. (1984) Soil organic matter and structural stability: mechanisms and implication for management. *Plant and Soil* 76:319-337.
- Official Journal of the European Communities (1977) No.L212/63, Regulation No.77/535/EEC.
- Olayinka, A., A. Adebayo and A. Amusan (1998) Evaluation of organic carbon oxidation efficiencies of a modified wet combustion and Walkley-Black procedures in Nigerian soils. *Communications in Soil Sciences and Plant Analysis* 29:2749-2756.
- Olsen, R.J., R.F. Hensler and O.J. Attoe (1970) Effect of manure application, aeration, and soil pH on soil N transformations and certain soil test value. *Proceedings of Soil Science Society of America* 34:222.
- Olsen, S.R., C.V. Cole, F.S. Watanabe and L.A. Dean (1954) Estimation of available phosphorus in soils by extraction with sodium bicarbonate. USDA Circular 939. U.S. Government Printing Office, Washington D.C.
- Palm, C., G. Nziguheba, C. Gachengo, E. Gacheru and M.R. Rao (1999) Organic materials as sources of phosphorus. *Agroforestry Forum* 9:30-33.
- Palm, C.A., R.J.K. Myers and S.M. Nandwa (1997) Combined use of organic and inorganic nutrient sources for soil fertility maintenance and replenishment. Replenishing soil fertility in Africa. *Proceedings of an international symposium,*

- Indianapolis, USA, 6 November 1996. Soil Science Society of America, Madison, Wisconsin, USA. Pp 193-217.
- Parkinson, J.A. and S.E. Allen (1975) A wet oxidation procedure suitable for the determination of nitrogen and mineral nutrients in biological material. *Communications in Soil Science and Plant Analysis* 6:1-11.
- People, M.B. and E.T. Craswell (1992) Biological nitrogen fixation: Investments, expectations and actual contributions to agriculture. *Plant and Soil* 141:13-39.
- Perrott, K.W. and B.E. Kerr (1994) Determination of phosphate rock residues in acid soils. *Transaction 15<sup>th</sup> International Soil Science Congress* 5:230-243.
- Peverill K.I. (1993) Soil testing and plant analysis in Australia. *Australian Journal of Experimental Agriculture* 33:963-971.
- Phimsarn, S. (1991) A comparison of the fate of elemental sulphur and sulphate sulphur based fertilisers in pasture soils. PhD Thesis, Massey University, Palmerston North, New Zealand.
- Pierre, W.H. and W.L. Banwart (1973) Excess-base and excess-base/nitrogen ratio of various crop species and parts of plants. *Agronomy Journal* 65:(1)91-96.
- Pingali, P.L., M. Hossain and R.V. Gerpacio (1997) Erosion, pollution and poison: externalities and rice. *In: Asian Rice Bowls: The Returning Crisis?* CAB International, Published associated with IRRI. Pp 91-125.
- Pocknee, S. and M.E. Sumner (1997) Cation and nitrogen contents of organic matter determine its soil liming potentials. *Soil Science Society of American Journal* 61:86-92.
- Ponnamperuma, F.N. and A.K. Bandyopadhyaya (1980) Soil salinity as a constraint on food production in the humid tropics. *In: Priorities for alleviating soil-related constraints to food production in the tropic.* International Rice Research Institute, Manila, Philippine. Pp 203-216.
- IBSRAM (International Board for Soil Research and Management)(1994) *Methodological guidelines for IBSRAM's soil management networks*, 2<sup>nd</sup> ed. Bangkok. Pp 171.
- Quin, B.F. and D.S. Rickard (1983) Pasture production and changes in soil fertility on a long-term irrigated superphosphate trial at Winchmore, New Zealand. *Proceedings of the 14<sup>th</sup> International Grassland Congress*, held at Lexington, Kentucky, U.S.A., June 15-24, 1981. Westview Press, Boulder, Colorado, USA. Pp 323-326.
- Quin, B.F., C.B. Dyson and Y.S. Chiao (1987) Agronomic and economic aspects of the use of phosphate rock for pasture-development of a predictive model. *In* R.E. White and L.D. Currie (eds.) *The use of Reactive Phosphate Rocks and Their Derivatives as Fertilisers.* Occasional Report No.1, Fertiliser and Lime Research Centre, Massey University, Palmerston North, New Zealand. Pp147-163.

- Raij, B.van. and J.A. Quaggio (1990) Extractable phosphorus availability indexes as affected by liming. *Communications in Soil Science and Plant Analysis* 21:1267-1276.
- Rajan, S.S.S (1983) Effect of sulphur content of phosphate rock/sulphur granules on the availability of phosphate to plants. *Fertiliser Research* 4:(3)287-296.
- Rajan, S.S.S. (1986) Partial acidulation of 'unground' phosphate rock. II. Plant availability of phosphate. *Fertiliser Research* 8:219-229.
- Rajan, S.S.S. (1987) Partially acidulated phosphate rocks-agronomic evaluation. *In* R.E. White and L.D. Currie (eds.) *The use of reactive phosphate rocks and their derivatives as fertilisers. Occasional Report No.1, Fertiliser and Lime Research Centre, Massey University, Palmerston North, New Zealand.* Pp 103-114.
- Rajan, S.S.S. and E.A. Edge (1980) Dissolution of granulated low grade phosphate rocks phosphate rocks/sulphur (Biosuper) and superphosphate in the soil. *New Zealand Journal of Agricultural Research* 23:451-456.
- Rajan, S.S.S., M.B. O'Connor and A.G. Sinclair (1994) Partially acidulated phosphate rocks: controlled release phosphorus fertilisers for more sustainable agriculture. *Fertiliser Research* 37:(1)69-78.
- Rajan, S.S.S., M.W. Brown, M.K. Boyes and M.P. Upsdell (1992) Extractable phosphorus to predict agronomic effectiveness of ground and unground phosphate rocks. *Fertiliser Research* 32:291-302.
- Rao, J.V.D.K.K (1990) Pigeonpea: nitrogen fixation. *The pigeonpea.* CAB International, Wallingford, UK. Pp 233-256.
- Ratkowsky, D.A., S.B. Tennakoon, P.W.G. Sale and P.G. Simpson (1997) The use of substitution values for characterising fertiliser performance. *Australian Journal of Experimental Agriculture* 37:(8)913-920.
- Rennie, R.J, D.A. Rennie, C. Siripaibool, P. Chaiwanakupt, N. Boonkerd and P. Snitwongse (1988) N<sub>2</sub> fixation in Thai soybeans: Effects of tillage and inoculation on <sup>15</sup>N-determined N<sub>2</sub> fixation in recommended cultivars and advanced breeding lines. *Plant and Soil* 112:183-193.
- Rerkasem, B., K. Rerkasem, M.B. Peoples, D.F. Herridge and F.J. Bergersen (1988) Measurement of N fixation in maize (*Zea mays* L.) - ricebean (*Vigna umbellata* [Thunb.] Ohwi and Ohashi) intercrops. *Plant and Soil* 108:(1)125-135.
- Ridley, A.M., K.R. Helyar and W.J. Slattery (1990) Soil acidification under subterranean clover (*Trifolium subterraneum* L.) pastures in north-eastern Victoria. *Australian Journal of Experimental Agriculture* 30:195-201.
- Ritchie, G.S.P. (1989) The chemical behaviour of aluminium, hydrogen and manganese in acid soils. *In* A.D. Robson (ed.) *Soil acidity and plant growth.* Academic Press Australia. Pp 1-49.
- Roazanov, B.G. and I.M. Rozanova (1963) Soil of the mountainous subtropics and high mountains of Burma. *Vestnik Moskovskogo Universiteta Bulletin* 3:71-78.

- Runge, M. and M.W. Rode (1991) Effects of soil acidity on plant association. *In* B. Ulrich and M.E. Sumner (eds.) Soil acidity. Pp 183-202.
- Saggar, S., M.J. Hedley and R.E. White (1990) A simplified resin membrane technique for extracting phosphorus from soils. *Fertiliser Research* 24:173-180.
- Saggar, S., M.J. Hedley and R.E. White (1992a) Development and evaluation of an improved soil test for phosphorus. I. The influence of phosphorus fertiliser solubility and soil properties on the extractability of soil P. *Fertiliser Research* 33:81-91.
- Saggar, S., M.J. Hedley, R.E. White, K.W. Perrott and I.S. Cornforth (1992b) Development and evaluation of an improved soil test for phosphorus. II. Comparison of Olsen and mixed cation-anion exchange resin test for predicting the yield of ryegrass grown in pots. *Fertiliser Research* 33:135-144.
- Saggar, S., M.J. Hedley, R.E. White, K.W. Perrott, P.E.H. Gregg and I.S. Cornforth (1993) Assessment of the relative agronomic effectiveness of phosphate rocks under glasshouse conditions. *Fertiliser Research* 34:141-151.
- Saggar, S., M.J. Hedley, R.E. White, K.W. Perrott, P.E.H. Gregg, I.S. Cornforth and A.G. Sinclair (1999) Development and evaluation of an improved soil test for phosphorus. III. Field comparison of Olsen, Colwell and Resin soil P tests for New Zealand pasture soils. *Nutrient Cycling in Agroecosystems* 55:35-50.
- Sakadevan, K., M.J. Hedley and A.D. Mackay (1993) Sulphur cycling in New Zealand hill country pastures. I. Laboratory sulphur, nitrogen and carbon mineralisation studies. *Journal of Soil Science* 44:(1)73-83.
- Samithisawad, R. (1992) Dairy farming industry. *Bangkok Bank Monthly Review* 33:34-38.
- Sanchez, P.A. (1976) Clay Mineralogy and Ion Exchange Process. Properties and Management of soils in the tropics. Pp 135-158.
- Sanchez, P.A. and G. Uehara (1980) Management considerations for acid soils with high phosphorus fixation capacity. *In* F.E. Khasawneh (ed.) The role of phosphorus in agriculture. ASA, Madison, Wisconsin, USA. Pp 471-514.
- Santoso, D., R.D.B. Lefroy and G.J. Blair (1995) Sulphur and phosphorus dynamics in acid soil/crop system. *Australian Journal of Soil Research* 33:135-151.
- SAS institute Inc. (1989) The system for windows v6.12, 1989-1996 by SAS Institute Inc., Cary, NC, USA.
- Saunders, W.M.H. (1965) Phosphate retention by New Zealand soils and its relationship to free sesquioxides, organic matter and other soil properties. *New Zealand Journal of Agricultural Research* 8:30-57.
- Searle, P.L. (1967) Determining of carbon, calcium carbonate and sulphur in soil using high-frequency induction furnace equipment. *New Zealand Soil News* 5:168-180.

- Serna, M.D. and F. Pomares (1991) Comparison of biological and chemical methods to predict nitrogen mineralisation in animal wastes. *Biology and Fertility of Soils* 12:89-94.
- Shang, C. and H. Tiessen (1997) Organic matter lability in a tropical oxisol: evidence from shifting cultivation, chemical oxidation, particle size, density, and magnetic fractionations. *Soil Science* 162:795-807.
- Shields, J.A., E.A. Paul and W.E. Lowe (1974) Factors influencing the stability of labelled microbial materials in soils. *Soil Biology and Biochemistry* 6:(1)31-37.
- Sinclair, A.G., P.D. Johnstone, A.H.C. Roberts, M.B. O'Connor and J.D. Morton (1997) Relationship between pasture dry matter and Olsen P from a series of long term field trials. *New Zealand Journal of Agriculture Research* 40:559-567.
- Sinclair, A.G., P.D. Johnstone, L.C. Smith, W.H. Risk, M.B. O'Connor, A.H. Roberts, J.D. Morton, L. Nguyen and P.W. Shannon (1993) The effect of reactive phosphate rock on the pH of soil under pasture. *New Zealand Journal of Agricultural Research* 36:(3)381-384.
- Sinclair, A.G., P.W. Shannon and W.H. Risk (1990) Sechura phosphate rock supplies plant-available molybdenum for pastures. *New Zealand Journal of Agricultural Research* 33:(3)499-502.
- Skjemstad J.O. and J.A. Taylor (1999) Does the Walkley-Black Method Determine Soil Charcoal? *Communications in Soil Sciences and Plant Analysis* 30:2299-2310.
- Slattery, W.J., M.K. Conyers and R.L. Aitken (1999) Soil pH, aluminium, manganese and lime requirement. *In* K.I. Preverill, L.A. Sparrow and D.J. Reuter (eds.) *Soil analysis an interpretation manual*. CSIRO publishing. Pp 103-128.
- Smartt, J. (1976) The Economic Importance of Pulse Crops. *In*: *Tropical Pulses, Tropical Agriculture series*, Longman Group Ltd, London. Pp 293-317.
- Smartt, J. (1990) The role of grain legume in the human economy. *In*: *Grain Legumes, Evolution and Genetic resources*. Cambridge University Press. Pp 9-29.
- Sorn-Srivichai, P., J.K. Syers, R.W. Tillman and I.S. Cornforth (1988) An evaluation of water extraction as a soil-testing procedure for phosphorus. I. Glasshouse assessment of plant-available phosphorus. *Fertiliser Research* 15:211-223.
- Sparrow, L.A. and N.C. Uren (1986) Oxidation and reduction of Mn in acidic soils: effect of temperature and soil pH. *Soil Biology and Biochemistry* 19:143-148.
- Ssali, H. and S.O. Keya (1986) The effects of phosphorus and nitrogen fertiliser level on nodulation, growth and dinitrogen fixation of three bean cultivars. *Tropical Agriculture (Trinidad)* 63:105-109.
- Stangel, P.J. and H.R. von Uexküll (1990) Regional food security; demographic and geographic implications. *In*: *Phosphorous Requirements for Sustainable Agriculture in Asia and Oceania*, IRRI, Manilla, Philippines. Pp 21-43.

- Stevenson, F.J. and M.A. Cole (1999) Cycles of soil: carbon, nitrogen, phosphorus, sulphur, micronutrients. John Wiley Publishing, New York.
- Storer, D.A. (1984) A simple high sample volume ashing procedure for determining soil organic matter. *Communications in Soil Sciences and Plant Analysis* 15:759-772.
- Sudjadi, M. (1984) Problem soils in Indonesia and their management. *In: Ecology and management of problem soils in Asia*. Food and Fertiliser Technology Centre for the Asian and Pacific Region, Taiwan. Pp 58-73.
- Sumner, M.E. (1979) Response of alfalfa and sorghum to lime and P on highly weathered soils. *Agronomy Journal* 71:763-766.
- Syers, J.K., A.D. Mackay, M.W. Brown and L.D. Currie (1986) Chemical and physical characteristics of phosphate rock materials of varying reactivity. *Journal of Science, Food and Agriculture* 37:1057-1064.
- Tabatabai, M.A. (1996) Soil organic matter testing: An overview. *In: Soil Organic Matter: Analysis and Interpretation*. SSSA Special Publication No.46. Soil Science Society of America, Madison, Wisconsin, USA. Pp 1-9.
- Tabatabai, M.A. and J.M. Bremner (1970) An alkaline oxidation method for determination of total sulphur in soils. *Proceedings of Soil Science Society of America* 34:62-65.
- Tambunan, D. (1988) A laboratory assessment of the pH buffering capacity and lime requirements of selected New Zealand soils. The Post-Graduate Diploma Thesis, Massey University, Palmerston North, New Zealand.
- Tambunan, D. (1992) Dissolution and plant availability of phosphate rocks in selected New Zealand and Indonesian soils. PhD Thesis, Massey University, Palmerston North, New Zealand.
- Tambunan, D., M.J. Hedley, N.S. Bolan and M.A.A. Turner (1993) Comparison of sequential extraction procedures for measuring phosphate rock residues in soils. *Fertiliser Research* 35:(3)183-191.
- Tang, C. and Q. Yu (1999) Impact of chemical composition of legume residues and initial soil pH on pH change of a soil after residue incorporation. *Plant and Soil* 215:29-38.
- Tang, C., C.D.A. McLay and L. Barton (1997) A comparison of proton excretion of twelve pasture legumes grown in nutrient solution. *Australian Journal of Experimental Agriculture* 37:563-570.
- Tang, C., C.P. Sparling, C.D.A. McLay and C. Raphael (1999) Effect of short-term residue decomposition on soil acidity. *Australian Journal of Soil Research* 37:561-573.
- Tennant, D. (1975) A test of a modified line intersect method of estimating root length. *Journal of Ecology* 63:995-1001.

- Teppoolpon, M. and S. Wasinarat (1983) Country reports: Thailand. *In: Recycling organic matter in Asia for fertiliser use*, Asian Productivity Organisation, Japan. Pp 217-225.
- Tha Tun Oo (1990) Problem soils: country report, union of Myanmar. *Problem Soil of Asia and the Pacific*. FAO, RAPA. Pp 125-138.
- The department of settlement and land records (1998) The land use in Southern Shan State, Taunggyi, Shan State (in Myanmar).
- Thomson, L.M., C.A. Black and J.A. Zoellner (1954) Occurrence and mineralisation of organic P in soil with particular reference to association with N, C and pH. *Soil Science* 77:185-196.
- Tisdall, J.M. and J.M. Oades (1982) Organic matter and water-stable aggregates in soils. *Soil Science* 33:141-163.
- Tossah, B.K. (2000) Influence of soil properties and organic inputs on phosphorus cycling in herbaceous legume-based cropping system in the West Africa derived savanna. PhD Thesis, Katholieke Universiteit Leuven, Belgium.
- Trinsoutrot, I., S. Recous, B. Bentz, M. Lineres, D. Cheneby and B. Nicolardot (2000) Biochemical quality of crop residues and carbon and nitrogen mineralisation kinetics under nonlimiting nitrogen conditions. *Soil Science Society of American Journal* 64:918-926.
- Troelstra, S.R., van K. Dijk and T. Blacquiere (1985) Effects of N source on proton excretion, ionic balance and growth of *Alnus glutinosa* (L.) Gaertner: comparison of N<sub>2</sub> fixation with single and mixed sources of NO<sub>3</sub> and NH<sub>4</sub>. *Plant and Soil* 84:361-385.
- Trolove, S.N. (2000) Root-soil-phosphate interactions in rice growing in aerobic soil. PhD Thesis, Massey University, Palmerston North, New Zealand.
- Trolove, S.N., M.J. Hedley, J.R. Caradus and A.D. Mackay (1996a) Uptake of phosphorus from different sources by *Lotus pedunculatus* and three genotypes of *Trifolium repens*. I. Plant yield and phosphate efficiency. *Australian Journal of Soil Research* 34:1015-1026.
- Trolove, S.N., M.J. Hedley, J.R. Caradus and A.D. Mackay (1996b) Uptake of phosphorus from different sources by *Lotus pedunculatus* and three genotypes of *Trifolium repens*. II. Forms of phosphate utilised and acidification of the rhizosphere. *Australian Journal of Soil Research* 34:1027-1040.
- Twine, J.R. and C.H. Williams (1971) The determination of phosphorus in kjeldahl digests of plant materials by automatic analysis. *Communications in Soil Science and Plant Analysis* 2:485-489.
- Udy, D.J. (1981) Sechura phosphate rock. *In* J.K. Syers and P.E.H. Gregg (eds.) *Proceedings of the technical workshop on Potential of phosphate rock as a direct application fertiliser in New Zealand*. Department of Soil Science, Massey University, Palmerston North, New Zealand. Pp 123-128.

- Uehara, G. and G. Gillman (1981) *The Mineralogy, Chemistry, and Physics of Tropical Soils with Variable Charge Clays*. Westview Press, Boulder, CO.
- UNDP (2001) <http://www.undp.org/hrd2001>.
- USDA (1975) Ultisols. *In: Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys*, Soil Survey Staff. Soil Conservation Service U.S. Department of Agriculture. Pp 349-373.
- van Breemen, N. (1991) Soil acidification and alkalization. *In* B. Ulrich and M.E. Sumner (eds.) *Soil Acidity*. Pp 1-7.
- van Breemen, N., J. Mulder and C.T. Driscoll (1983) Acidification and alkalization of soils. *Plant and Soil* 75:283-308.
- van Faassen, H.G. and H. van Dijk (1987) Manure as source of nitrogen and phosphorus in soils. *In* H.G. van Der Meer, R.J. Unwin, T.A. van Dijk, and G.C. Ennik (eds.) *Animal manure on grassland and fodder crops. Fertiliser or waste? Proceedings of an International Symposium of the European Grassland Federation, Wageningen, Netherlands, 31 August-3 September 1987*. Pp 27-45.
- van Noordwijk, M. (1993) Roots: length, biomass, production and mortality. *In* J.M. Anderson and J.S.I. Ingram (eds.) *Tropical soil biology and fertility, a handbook of methods*. Pp 179-184.
- van Raij, B., H. Cantarella, J.A. Quaggio, L.I. Prochnow, G.C. Vitti and H.S. Pereira (1994) Soil testing and plant analysis in Brazil. *Communications in Soil Science and Plant Analysis* 25:739-751.
- Virgil, M.F. and D.E. Kissel (1991) Equations for estimating the amount of nitrogen mineralised from crop residues. *Soil Science Society of American Journal* 55:757-761.
- Vitosh, M.L., R.E. Lucas and G.H. Silva (1997) Long-term effects of fertiliser and manure on corn yield, soil carbon, and other soil organic chemical properties in Michigan. *In: Soil Organic Matter in Temperate Agroecosystems*. Chapter 8:129-139.
- von Uexküll, H.R. (1986) Efficient Fertiliser Use in Acid Upland Soils of the Humid Tropics. *FAO Fertiliser and Plant Nutrition Bulletin* 10.
- von Uexküll, H.R. (1989) The fertiliser situation in Asia and its effects on small-scale farms. *In: Transfer of technology to small-scale farms. The 9<sup>th</sup> meeting of the Technical Advisory Committee*. Food and Fertiliser Technology Centre for the Asian and Pacific Region, Taiwan. Pp 11-19.
- von Uexküll, H.R. and E. Mutert (1995a) Global extent, development and economic impact of acid soils. *In* R.A. Date, *et al.* (ed.) *Plant soil interaction at low pH*. Kluwer Academic Publishers, Netherlands. Pp 5-19.
- von Uexküll, H.R. and E. Mutert (1995b) Rehabilitation of anthropic savana. *In: Phosphorus in the Global Environment*. Pp 149-154.

- von Uexküll, H.R. and R.P. Bosshart (1989) Management of Acid Upland Soils in Asia. *In* E.T. Craswell and E. Pushparajah (eds.) Management of acid soils in the humid tropic of Asia. 1984 Co-published by Australian Centre for International Agricultural Research and IBSRAM, ACIAR Monograph No.13.
- von Uexküll, H.R., Y.C. Woo and J.S. Adiningsih (1992) Use of phosphate in land reclamation for agricultural use. Workshop on phosphate sources for acid soils in the humid tropic of Asia, 6-7 November 1990, Kuala Lumpur, Malaysia. Malaysian Society of Soil Science, Kuala Lumpur, Malaysia. Pp 163-169.
- Vries, W.D.E. and A. Breeuwsma (1987) The relation between acidification and element cycling. *Water, Air, and Soil Pollution*. D. Reidel Publishing Co. 35:293-310.
- Walker, T.W. and J.K. Syers (1976) The fate of phosphorus during pedogenesis. *Geodermatology* 15:1-19.
- Walkley, A. and I.A. Black (1934) An examination of Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Science* 37:29-38.
- Wang, H. (1996) Potential uses of fluidised bed boiler ash as a liming material, soil conditioner and sulphur fertiliser. PhD Thesis, Massey University, Palmerston North, New Zealand.
- Watkinson J. and N.S. Bolan (1998). Modelling the dissolution of elemental sulphur in soils. *In* D.G. Maynard (ed.) Sulphur in the environment. Marcel and Dekker, INC. Pp 135-172.
- Watkinson, J.H. (1988) Rate equations for the oxidation of elemental sulphur in soil. *In* R.E. White and L.D. Currie (eds.) Proceedings of the workshop on Towards the more efficient use of soil and fertiliser sulphur. Fertiliser and Lime Research Centre, Massey University, Palmerston North, New Zealand.
- Weerakoon, W.L. (1983) Country reports: Sri Lanka. *In*: Recycling organic matter in Asia for fertiliser use, Asian Productivity Organisation, Japan. Pp 53-79.
- Whitbread, A., G. Blair, K. Naklang, R. Lefroy, S. Wonprasaid, Y. Konboon and D. Suriyaarunroj (1999) The management of rice straw, fertilisers and leaf litters in rice cropping systems in Northeast Thailand. *Plant and Soil* 209:29-36.
- White, R.E., M.J. Hedley, N.S. Bolan and P.E.H. Gregg (1989) Recent development in the use of phosphate fertilisers on New Zealand pastures. *Journal of the Australian Institute of Agricultural Science* 20:26-32.
- Williams, C.H. (1980) Soil acidification under clover. *Australian Journal of Experimental Agriculture and Animal Husbandry* 20:561-567.
- Wright, R.J. (1989) Soil aluminium toxicity and plant growth. *Communications in Soil Sciences and Plant Analysis* 20:1479-1497.
- Yadvinder-Singh, Bijay-Singh and C.S. Khind (1992) Nutrient transformations in soils amended with green manures. *Advances in Soil Science* 20:238-298.

- Yeates, J.S. and D.G. Allen (1987) Low effectiveness of three rock phosphates as phosphorus fertilisers and liming materials on an acid clay-loam. *Australian Journal of Agriculture Research* 38:1033-46.
- Zoysa, A.S.K, P. Loganathan and M.J. Hedley (1998) Effect of forms of nitrogen supply on mobilisation of phosphorus from a phosphate rock and acidification in the rhizosphere of tea. *Australian Journal of Soil Research* 36:373-387.
- Zoysa, A.S.K. (1997) The influence of phosphorus fertiliser forms and rhizosphere process on the phosphorus nutrition of tea (*Camellia sinensis* L.) PhD Thesis, Massey University, Palmerston North, New Zealand.
- Zoysa, A.S.K., P. Loganathan and M.J. Hedley (1997) A technique for studying rhizosphere processes in tree crops: soil phosphorus depletion around camellia (*Camellia japonica* L.) roots. *Plant and Soil* 190:253-265.
- Zoysa, A.S.K., P. Loganathan and M.J. Hedley (2001) Comparison of the agronomic effectiveness of a phosphate rock and triple superphosphate as phosphate fertilisers for tea (*Camellia sinensis* L.) on a strongly acidic Ultisol. *Nutrient Cycling in Agroecosystems* 59:95-105.

### Appendix 4.1

Calculation of Walkley-Black C (organic C).									
No.	Soil	Soil wt (mg)	Blank used (FeSO <sub>4</sub> ) ml	Start	End	Soil used (FeSO <sub>4</sub> ) ml		Walkley-Black C	
								(mg)	(%)
1	Std.1	497	20.3	0	11.1	11.1	0.45	13.87	2.79
2	Std.1	499	20.3	0	11.1	11.1	0.45	13.87	2.78
3	YE Exp.	477	20.3	8.2	25	16.8	0.17	5.28	1.11
4	YE Exp.	480	20.3	7.2	24	16.8	0.17	5.28	1.10
5	YE Exp.	492	20.3	3	20	17	0.16	4.97	1.01
6	YE Exp.	490	20.3	2.5	19.5	17	0.16	4.97	1.02
7	YE Exp.	531	20.3	0.1	17.4	17.3	0.15	4.52	0.85
8	YE Exp.	525	20.3	1.2	18.4	17.2	0.15	4.67	0.89
9	YE Exp.	520	20.3	0.1	17.5	17.4	0.14	4.37	0.84
10	YE Exp.	517	20.3	0.1	17.5	17.4	0.14	4.37	0.85
11	YE Exp.	489	20.3	2	19.6	17.6	0.13	4.07	0.83
12	YE Exp.	491	20.3	0	17.7	17.7	0.13	3.92	0.80
13	YE Exp.	530	20.3	0	17	17	0.16	4.97	0.94
14	YE Exp.	528	20.3	1	18	17	0.16	4.97	0.94
15	YE Exp.	518	20.3	0.6	17.6	17	0.16	4.97	0.96
16	YE Exp.	521	20.3	0.5	17.5	17	0.16	4.97	0.95
17	YE Exp.	511	20.3	0.5	17.6	17.1	0.16	4.82	0.94
18	YE Exp.	506	20.3	1.5	18.6	17.1	0.16	4.82	0.95
19	YE Exp.	507	20.3	5	22.6	17.6	0.13	4.07	0.80
20	YE Exp.	512	20.3	3	20.6	17.6	0.13	4.07	0.79
21	YE Exp.	515	20.3	0.6	17.3	16.7	0.18	5.43	1.05
22	YE Exp.	507	20.3	1	17.7	16.7	0.18	5.43	1.07
23	Std.2	530	20	4.7	18.5	13.8	0.31	9.49	1.79
24	Std.2	518	20	4.5	17.8	13.3	0.34	10.25	1.98
25	YE Exp.	521	20	1.8	18.8	17	0.15	4.59	0.88
26	YE Exp.	510	20	2.5	19.5	17	0.15	4.59	0.90
27	YE Exp.	498	20	0.1	17.1	17	0.15	4.59	0.92
28	YE Exp.	492	20	1.1	18.1	17	0.15	4.59	0.93
29	YE Exp.	508	20	2.5	19	16.5	0.18	5.36	1.05
30	YE Exp.	501	20	1.1	17.6	16.5	0.18	5.36	1.07

Calculation of Walkley-Black C (organic C).									
No.	Soil	Soil wt (mg)	Blank used (FeSO <sub>4</sub> ) ml	Start	End	Soil used (FeSO <sub>4</sub> ) ml		Walkley-Black C	
								(mg)	(%)
31	YE Exp.	513	20	1.4	18.1	16.7	0.17	5.05	0.98
32	YE Exp.	509	20	5.4	22.1	16.7	0.17	5.05	0.99
33	YE Exp.	527	20	1.5	18.2	16.7	0.17	5.05	0.96
34	YE Exp.	524	20	5.5	22.2	16.7	0.17	5.05	0.96
35	YE Exp.	551	20	0.1	16.5	16.4	0.18	5.51	1.00
36	YE Exp.	545	20	0.5	17	16.5	0.18	5.36	0.98
37	YE Exp.	521	20	1.9	17.2	15.3	0.24	7.19	1.38
38	YE Exp.	519	20	3	18.3	15.3	0.24	7.19	1.39
39	YE Exp.	518	20	2.4	19	16.6	0.17	5.20	1.00
40	YE Exp.	516	20	0.4	17	16.6	0.17	5.20	1.01
41	YE Exp.	535	20	1.5	18.3	16.8	0.16	4.90	0.92
42	YE Exp.	531	20	2.5	19.3	16.8	0.16	4.90	0.92
43	YE Exp.	514	20	0	16.7	16.7	0.17	5.05	0.98
44	YE Exp.	509	20	0	16.7	16.7	0.17	5.05	0.99
45	Glucose	51	20	3.6	10.5	6.9	0.66	20.04	39.30
46	Glucose	50	20	3.5	10.6	7.1	0.65	19.74	39.47
47	Std.1	520	20.1	0	10.5	10.5	0.48	14.61	2.81
48	Std.1	531	20.1	0	10.6	10.6	0.47	14.46	2.72
49	YE Exp.	527	20.1	0.2	16.5	16.3	0.19	5.79	1.10
50	YE Exp.	524	20.1	0.1	16.5	16.4	0.18	5.63	1.07
51	YE Exp.	489	20.1	1	17.6	16.6	0.17	5.33	1.09
52	YE Exp.	492	20.1	1	17.6	16.6	0.17	5.33	1.08
53	YE Exp.	509	20.1	0.6	16.7	16.1	0.20	6.09	1.20
54	YE Exp.	506	20.1	1.5	17.7	16.2	0.19	5.94	1.17
55	YE Exp.	511	20.1	0.2	16.5	16.3	0.19	5.79	1.13
56	YE Exp.	514	20.1	2.2	18.5	16.3	0.19	5.79	1.13
57	YE Exp.	521	20.1	3.9	19.9	16	0.20	6.24	1.20
58	YE Exp.	525	20.1	5.9	21.9	16	0.20	6.24	1.19
59	YE Exp.	515	20.1	4	20.5	16.5	0.18	5.48	1.06
60	YE Exp.	513	20.1	2	18.5	16.5	0.18	5.48	1.07

Calculation of Walkley-Black C (organic C).									
No.	Soil	Soil wt (mg)	Blank used (FeSO4) ml	Start	End	Soil used (FeSO4) ml		Walkley-Black C	
								(mg)	(%)
61	YE Exp.	499	20.1	3.5	19.4	15.9	0.21	6.39	1.28
62	YE Exp.	494	20.1	1.5	17.4	15.9	0.21	6.39	1.29
63	YE Exp.	511	20.1	0.9	16.3	15.4	0.23	7.16	1.40
64	YE Exp.	514	20.1	0.6	16	15.4	0.23	7.16	1.39
65	YE Exp.	516	20.1	0.3	15.9	15.6	0.22	6.85	1.33
66	YE Exp.	510	20.1	1.5	17.2	15.7	0.22	6.70	1.31
67	YE Exp.	512	20.1	0.1	16.4	16.3	0.19	5.79	1.13
68	YE Exp.	505	20.1	1.5	17.8	16.3	0.19	5.79	1.15
69	Std.2	528	20.2	1	14.1	13.1	0.35	10.76	2.04
70	Std.2	514	20.2	0	13.2	13.2	0.35	10.60	2.06
71	YEUN I	524	20.2	0	16.7	16.7	0.17	5.30	1.01
72	YEUN I	527	20.2	2	18.6	16.6	0.18	5.45	1.03
73	YEUN I	549	20.2	0.9	17.4	16.5	0.18	5.60	1.02
74	YEUN I	545	20.2	5	21.5	16.5	0.18	5.60	1.03
75	YEUN I	528	20.2	0.3	16.4	16.1	0.20	6.21	1.18
76	YEUN I	525	20.2	1.5	17.5	16	0.21	6.36	1.21
77	YEUN I	499	20.2	0	16.4	16.4	0.19	5.76	1.15
78	YEUN I	494	20.2	5	21.6	16.6	0.18	5.45	1.10
79	YECU II	513	20.2	1	18.8	17.8	0.12	3.64	0.71
80	YECU II	517	20.2	5	22.7	17.7	0.12	3.79	0.73
81	YECU II	522	20.2	0.1	17.9	17.8	0.12	3.64	0.70
82	YECU II	526	20.2	2.1	19.9	17.8	0.12	3.64	0.69
83	YECU II	524	20.2	3.5	22	18.5	0.08	2.58	0.49
84	YECU II	529	20.2	3.6	22	18.4	0.09	2.73	0.52
85	YECU II	515	20.2	1.8	20.1	18.3	0.09	2.88	0.56
86	YECU II	512	20.2	5.8	24	18.2	0.10	3.03	0.59
87	YEUN II	523	20.2	0.5	18.2	17.7	0.12	3.79	0.72
88	YEUN II	529	20.2	5.4	23.2	17.8	0.12	3.64	0.69
89	YEUN II	526	20.2	1.1	18.8	17.7	0.12	3.79	0.72
90	YEUN II	521	20.2	1.6	19.4	17.8	0.12	3.64	0.70

Calculation of Walkley-Black C (organic C).									
No.	Soil	Soil wt (mg)	Blank used (FeSO <sub>4</sub> ) ml	Start	End	Soil used (FeSO <sub>4</sub> ) ml		Walkley-Black C	
								(mg)	(%)
91	Glucose	52	20.2	0.7	7.3	6.6	0.67	20.60	39.62
92	Glucose	55	20.2	0.5	7	6.5	0.68	20.75	37.73
93	Std. I	527	20.3	2.7	12.8	10.1	0.50	15.38	2.92
94	Std. I	520	20.3	7	17	10	0.51	15.53	2.99
95	YEUN II	512	20.3	0.5	18.5	18	0.11	3.47	0.68
96	YEUN II	517	20.3	2.5	20.5	18	0.11	3.47	0.67
97	YEUN II	511	20.3	0	17.6	17.6	0.13	4.07	0.80
98	YEUN II	506	20.3	6	23.6	17.6	0.13	4.07	0.80
99	RECU I	519	20.3	4	22.6	18.6	0.08	2.56	0.49
100	RECU I	516	20.3	0	18.6	18.6	0.08	2.56	0.50
101	RECU I	514	20.3	0.1	18.3	18.2	0.10	3.17	0.62
102	RECU I	519	20.3	2.1	19.4	17.3	0.15	4.52	0.87
103	RECU I	523	20.3	0.2	19	18.8	0.07	2.26	0.43
104	RECU I	527	20.3	2.02	21	18.9	0.07	1.99	0.38
105	RECU I	507	20.3	0.3	17	16.7	0.18	5.43	1.07
106	RECU I	505	20.3	1.5	18.2	16.7	0.18	5.43	1.07
107	REUN I	510	20.3	1.8	19.7	17.9	0.12	3.62	0.71
108	REUN I	500	20.3	2.5	20	17.5	0.14	4.22	0.84
109	REUN I	529	20.3	0.5	18	17.5	0.14	4.22	0.80
110	REUN I	521	20.3	1.5	19.1	17.6	0.13	4.07	0.78
111	REUN I	525	20.3	1.6	18.7	17.1	0.16	4.82	0.92
112	REUN I	521	20.3	5.6	22.7	17.1	0.16	4.82	0.93
113	REUN I	507	20.3	1.9	19.9	18	0.11	3.47	0.68
114	REUN I	501	20.3	5.9	23.9	18	0.11	3.47	0.69
115	Glucose	56	20.2	0.4	5.9	5.5	0.73	22.27	39.76
116	Glucose	50	20.2	0.9	7.9	7	0.65	20.00	39.99
117	RECU II	521	20.2	2.9	19	16.1	0.20	6.21	1.19
118	RECU II	517	20.2	4.8	21	16.2	0.20	6.06	1.17
119	RECU II	513	20.2	2.6	17.7	15.1	0.25	7.73	1.51
120	RECU II	509	20.2	3.5	18.7	15.2	0.25	7.57	1.49

Calculation of Walkley-Black C (organic C).									
No.	Soil	Soil wt (mg)	Blank used (FeSO <sub>4</sub> ) ml	Start	End	Soil used (FeSO <sub>4</sub> ) ml		Walkley-Black C	
								(mg)	(%)
121	RECU II	522	20.2	5	20.4	15.4	0.24	7.27	1.39
122	RECU II	519	20.2	5.5	21	15.5	0.23	7.12	1.37
123	RECU II	514	20.2	6	24.3	18.3	0.09	2.88	0.56
124	RECU II	510	20.2	0.2	18.3	18.1	0.10	3.18	0.62
125	REUN II	507	20.2	3.8	18.5	14.7	0.27	8.33	1.64
126	REUN II	504	20.2	5.7	20.5	14.8	0.27	8.18	1.62
127	REUN II	512	20.2	0	15.1	15.1	0.25	7.73	1.51
128	REUN II	518	20.2	0	15.1	15.1	0.25	7.73	1.49
129	REUN II	527	20.2	0.2	16.2	16	0.21	6.36	1.21
130	REUN II	523	20.2	7.2	23.2	16	0.21	6.36	1.22
131	REUN II	511	20.2	2.4	17.6	15.2	0.25	7.57	1.48
132	REUN II	508	20.2	5.4	20.5	15.1	0.25	7.73	1.52