



# **Lime requirement in acidifying cropping soils in South Australia**

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## List of Abbreviations

AEC	anion exchange capacity
Al <sub>Ca</sub> or Mn <sub>Ca</sub>	Al or Mn extracted in 0.01 M CaCl <sub>2</sub>
Al <sub>K</sub> or Mn <sub>K</sub>	Al or Mn extracted in 1M KCl
APSIM	agricultural production system simulator
AR	acidification rate
C-cycle	carbon cycle
CEC	cation exchange capacity
CSIRO	commonwealth scientific & industrial research organisation
DUL	volumetric water content at Drained Upper Limit
ECEC	effective cation exchange capacity
ES	exchangeable sodium percentage
ESW	extractable soil water
GR	gypsum requirement
L	lime requirement
LL15	volumetric water content at Crop Lower Limit
LMWOA	low molecular weight organic acid
N-cycle	nitrogen cycle
OC	organic carbon
OM	organic matter
pHBC	pH buffering capacity
pH <sub>Ca</sub>	pH measured 1:5 soil into 0.01M CaCl <sub>2</sub> solution
pH <sub>SS</sub>	pH soil solution
pH <sub>w</sub>	pH measured in 1:5 soil:water
S	sulfur treatment
SW	soil water
SARDI	South Australian Research and Development Institute
TEC	total exchangeable cations
W-B	wheat-faba bean rotation
W-L	wheat-lupins rotation
W-F	wheat-fallow rotations
W-W	wheat-wheat rotations

# Table of Contents

1. General introduction .....	1
2. Review of literature.....	4
2.1 Introduction.....	4
2.1.1 Soil acidity and soil acidification.....	4
2.1.2 Soil pH .....	6
2.1.3 Soil acidity and aluminium .....	7
2.1.4 Soil acidity and manganese.....	9
2.2 Soil acidification processes.....	10
2.2.1 Nitrogen cycle .....	11
2.2.2 Carbon cycle .....	13
2.2.3 Other cycles.....	14
2.3 Measurement of acidity/alkalinity inputs to soil.....	15
2.3.1 Indirect measurement of acidification.....	15
2.3.2 Modified indirect method .....	16
2.3.3 Difference in profile acidification.....	23
2.3.4 Direct measurement of acidification .....	23
2.3.5 Simulation of acidification.....	24
2.4 Soil acidity and Australian agriculture.....	25
2.5 South Australian soil acidity and liming.....	26
2.6 Lime use in South Australia.....	29
2.7 Liming impacts on crop production .....	30
2.8 Longevity of liming.....	33
2.9 Liming materials .....	34
2.10 Lime Requirement (LR) methods .....	35
2.11 Hochman's model for lime prediction .....	36
2.12 Sodic soils in South Australia.....	37
2.13 Managing soil acidification.....	38
2.13.1 Efficient use of soil N, C and water .....	38
2.13.2 Controlling plant removal .....	39
2.13.3 Fertiliser selection .....	39
2.13.4 Plant selection .....	40
2.13.5 Crop rotation .....	40
2.13.6 Managing soil acidification in South Australia.....	41
2.14 Conclusions and experimental chapter aims.....	42
3. General materials and methods .....	46
3.1 Introduction.....	46
3.2 Site selection .....	46
3.3 Climatic information.....	50
3.4 Experimental design.....	51
3.5 Statistical analysis .....	52
3.6 Hochman model for lime calculation.....	52
3.7 Gypsum calculation.....	56
3.8 APSIM program for measuring carbon, N and water dynamics .....	56
4. Effect of lime and sulfur application on soil properties and crop yields .....	60
4.1 Introduction.....	60
4.2 Materials and methods .....	61

4.2.1 Site selection and soil description.....	61
4.2.2 Experimental treatments .....	62
4.2.3 Crop management .....	63
4.2.4 Crop measurements.....	64
4.2.5 Soil sampling and measurements.....	65
4.2.5.1 Field pH buffer capacity.....	65
4.2.5.2 Soil chemical characteristics .....	67
4.2.6 Statistical analysis .....	67
4.3 Results .....	68
4.3.1 Yield data .....	68
4.3.2 Soil chemical parameters .....	76
4.3.2.1 Soil pH .....	76
4.3.2.2 Soil pH buffer capacity .....	76
4.3.2.3 Soil cation properties .....	81
4.4 Discussion .....	89
4.4.1 Efficacy of LR model.....	89
4.4.2 Relationship between yield and soil properties.....	93
4.4.3 Prediction of yield and field lime requirement .....	95
4.5 Conclusions.....	100
5. Aspects of management for high-input intensive cropping systems that may be involved in the acidity complex on red brown earth soils .....	103
5.1 Introduction.....	103
5.2 Materials and methods .....	104
5.2.1 Site selection, soil description and experimental design .....	104
5.2.2 Protein and N content measurement .....	105
5.2.3 Exchangeable sodium percentage (ESP) measurement .....	105
5.2.4 Statistical analysis .....	105
5.3 Results .....	105
5.3.1. Yield and soil treatments .....	105
5.3.2 Soil solid phase chemical parameters .....	106
5.3.2.1 Soil pH .....	106
5.3.2.2 Soil solid phase properties .....	106
5.3.3 Protein .....	111
5.3.4 ESP of the soil.....	112
5.4 Discussion .....	113
5.5 Conclusions.....	116
6. Effects of crop rotations, stubble management and application of nitrogenous fertiliser on soil pH and other soil properties at Tarlee, South Australia.....	118
6.1 Introduction.....	118
6.2 Materials and methods .....	119
6.2.1 Site selection and soil description.....	119
6.2.2 Soil sampling .....	120
6.2.3 Soil solid phase chemical analysis.....	120
6.2.4 Field pH buffer capacity.....	120
6.2.5 Soil acidification rates.....	120
4.2.6 Statistical analysis .....	124
6.3 Results.....	124
6.3.1 Grain yield.....	124
6.3.2 Soil solid phase chemical parameters .....	125

6.3.2.1 Soil pH .....	125
6.3.2.2 Soil Al, Mn and other solid phase properties.....	136
6.3.3 Acidification rates.....	144
6.3.3.1 Total acidification rates.....	144
6.3.3.2 Carbon cycle acidification rates .....	146
6.3.4 Soil organic matter properties .....	148
6.4 Discussion .....	154
6.4.1 Soil acidification .....	154
6.4.2 Soil properties .....	160
6.5 Conclusions.....	163
7. Effects of different management practices on soil solution, soil organic acids and complexation of toxic Al forms in soil solution .....	165
7.1 Introduction.....	165
7.2 Materials and methods .....	166
7.2.1 Site specification.....	166
7.2.2 Soil solution phase chemical parameters .....	166
7.3 Results.....	168
7.3.1 Soil Solution chemistry.....	168
7.3.1.1 Soil solution pH .....	168
7.3.1.2 Soil solution cations.....	168
7.3.1.3 Sum of the activities of monomeric species of Al .....	171
7.3.3 Low molecular weight organic acids .....	177
7.4 Discussion .....	181
7.5 Conclusions.....	187
8. Testing APSIM against the long-term (1977-1996) Tarlee data as part of understanding the behaviour of soil water, nitrogen and carbon dynamics under different management practices .....	190
8.1 Introduction.....	190
8.2 Materials and methods .....	192
8.2.2 The models.....	192
8.2.3 Modeling the experiment .....	194
8.3 Results.....	195
8.3.1 Grain yield.....	195
8.3.2 Soil water .....	200
8.3.3 Rainfall and drainage .....	200
8.3.4 Soil organic related components .....	205
8.4 Discussion .....	221
8.4.1 Soil changes .....	221
8.4.2 The accuracy of the model .....	223
8.5 Conclusion .....	225
9 General discussion .....	227
9.1 Conclusion .....	229
References .....	230

## Abstract

Soil acidification is a serious problem in terms of land degradation and crop-yield reduction in many countries and in all states in Australia as well as in South Australia. Cropping on red-brown earth soils in South Australia has become more intensive in the past decade, with increase in N-fertiliser inputs, rotation of cereals with pulse crops and canola, and retention of stubble. These high-input systems have the potential to decrease soil pH and increase soil acidification. In this thesis field sites and soils from cropping studies in the mid-north of South Australia have been used to address the questions of soil responses to lime and the influence of acidifying inputs.

Lime use is the principal management option available to ameliorate problems associated with soil acidification. These short-term field trials and one long-term field experiment have been used as part of understanding processes behind soil acidification and its lime equivalent calculation. The lime requirement calculated using a published model provided very good estimates of final pH change. Field studies have shown that the lime treatments always increased pH, with the extent of increase depending on site and lime rates. The lime treatment decreased Al% of ECEC to lower than 0.2% or 5 mg/kg, and sulfur treatment increased Al to around 8% or 55 mg/kg. Using lime at rates calculated by the model generally increased yield of field crops by 30-60% compared to the controls at all sites.

Analysis of soils from the long-term site has shown that acidification is occurring in this medium rainfall-cropping region (400-500mm). The site at Tarlee after 19 years of continuous cropping had OM improved with inclusion of legumes and higher N-fertiliser rates, but these treatments also increased soil acidification and soil pH<sub>Ca</sub> declined from 6.4 to 4.2. Soil acidification rates ranged between 3.15 and 6.33 kmol H<sup>+</sup>ha<sup>-1</sup>·year depending on year and management. Soil acidification increased the Al level to 2.71 mg/kg with stubble retained and 80 kg/ha N-fertiliser through the period of the experiment. However it is not possible to conclude from this Al level or the related yield data on whether this acidification is affecting grain yield.

The study showed that LMWOAs associated with different stubbles can help to ameliorate toxicity through complexation with Al. The presence of specific organic acid ligands in soil solution could play an important role in Al detoxification through complexation. The key organic acid (as observed in this study) responsible for complexation with Al would seem to be succinic, malic and fumaric for the faba bean stubble and succinic and fumaric for wheat and lupin stubbles.

Soil process modeling with data from the long-term cropping sequences was also used in describing soil profile acidification. A key finding from using the APSIM model is that the high concentration of the  $\text{NO}_3^-$  and  $\text{NH}_4^+$  leached from the soil profiles are the likely reason for soil acidification in this study, especially for stubble retained and 80 kg/ha N-fertiliser practices. Also the export of the stubble as part of the C-cycle (stubble and grain removal) has more potential to produce acidification in plots where the stubbles were removed. The model predicted an extensive range of field data very well.

## **Declaration**

This work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

I give consent to this copy of my thesis, when deposited in the University Library, being made available for loan and photocopying.

  
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## **Publications**

Part of the work described in this thesis has been published:

Xu, R.K., Coventry, D.R., Farhoodi, A., and Schultz, J.E. (2002). Soil acidification as influenced by crop rotations, stubble management and application of nitrogenous fertiliser, Tarlee, South Australia. *Australian Journal of Soil Research*. 40, 483-494.

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# Chapter 1

## 1. General introduction

Soil acidity is a major limitation to crop production in many countries (Greenland *et al.* 1994). As soils become more acidic then soil factors associated with low pH may cause plant yields to decline. Globally, about 26% (or 37.8 million km<sup>2</sup>) of agricultural land is constrained for crop production by soil acidity (Ritchey and Sousa 1997; Sumner 1997). Large areas of land in semi-arid zones have become acidic, both naturally and influenced mostly by agriculture. Acidic soils tend to have low fertility, induced by Al and Mn toxicities. Other soil chemical restrictions to plant growth on acid soils can be associated with toxicities of other metal ions (Zn, Cu, Cd, Ni), low pH (H<sup>+</sup> toxicity), and deficiencies of Ca, Mg, P, Mo, and other elements (including N, K, Zn, Fe) (Foy 1984; Edmeades *et al.* 1995). However, the influence of these factors varies with the plant (differences in tolerance) and the soil (differences in Al and Mn solubility with pH changes) (Myers and De Pauw 1995).

Soil acidification is a substantial soil degradation problem encountered on about 30 million hectares of Australian soils, associated with most types of agriculture (Chartres *et al.* 1992; Cregan and Scott 1998). Soil acidification is occurring in all states, with large areas in the eastern states, Western Australia and the high rainfall parts of South Australia (Merry *et al.* 1996 and 1997; Cregan and Scott 1998). In Australia, generally the areas that are receiving greater than 500 mm rainfall are those with extensive evidence of accelerated acidification (Coventry 1992; Cregan and Scott 1998; Scott *et al.* 2000).

Soil acidification is recognised as a serious form of land degradation associated with farming systems involving crop and pasture production. Acidification in farming systems that use rotations of crops and pastures is well studied, particularly in higher rainfall areas. In these crop rotations, the N cycle and C cycle are contributing most to the acid input (Coventry and Slattery 1991; Helyar *et al.* 1997). However, the extent that acidity is affecting crop production in the medium rainfall regions (400-500 mm) is not so well understood, and little work has been done to understand any unique characteristics of acidification on South Australian soils. Recent studies show surface soil pH is rapidly declining in the mid-north and other cropping regions of South Australia (Jeffrey and Hughes 1995; Merry *et al.* 1996; Xu *et al.* 2002), and

there is now concern that acidity is affecting field crop production. Some of these soils are strongly acidic ( $\text{pH}_{\text{Ca}}$  4.2-4.4) in the top 10cm, and may be beginning to show a strong presence of Al (Xu *et al.* 2002). The farming systems in the 400-500 mm cropping region of South Australia are likely to be rapidly acidifying. Here some farmers do use lime and gypsum, but little is known on what benefits accrue and the pattern of change in the soil chemistry.

Application of lime is the main management option used for correcting soil acidity caused by acidification. Whilst lime can change the chemistry of the top 5-8cm of the soil, and provide immediate benefits to crop production, it is also important that the crop-pasture rotation is managed so that further acid addition to the soil is minimised. In particular, attention has to be given to the way N and C are managed within the crop rotation. Many of the commonly used management practices such as stubble retention, N-fertiliser use, as well as using rotations of legumes are integral in the N and C cycles, and therefore can impact on soil acidification. Thus it is desirable to understand all components of production systems, as well as how these components impact on these cycles, so that less acidifying agricultural approaches can be used along with specific lime application. It is also necessary to calculate the right amount of lime for use in crop production as well as having information associated with liming material quality.

It has been well documented that soils respond to lime differently based upon their intrinsic characteristics, and that the lime responsiveness varies considerably between crop species and cultivars (Robson 1981). Based on data from Victoria, New South Wales and Western Australia, lime responses commonly amount to 15-80%, and with this information and also international information, various lime requirement models have been developed (eg. Kamprath 1970; Edmeades *et al.* 1985; Conyers *et al.* 1991). An agreed conclusion from this work is that these models are not universal or portable. The most useful models are those field derived for specific soil types and farming systems. Little information is available on the measure of lime responses on acidic soils in South Australia, and no scientific approach for lime requirement model development has been undertaken in South Australia.

Questions remain as to whether soil liming has the potential to realise crop yield gains in South Australia, and also the extent of the risk of acidification and whether a

'no liming' strategy poses any potential risk for these soils. No detailed research has been conducted in any cropping regions of South Australia to define the extent of acidity prone soils, or the adverse affects caused by soil acidity, which may influence crop growth. Also, little work had been undertaken to develop reliable procedures for lime prediction to ameliorate soil acidity problems. At present no technically supported strategies exist to inform farmers on the need for liming and of the likely consequences, be they beneficial or otherwise. Also the effects of intensive rotational cropping systems on soil acidification and crop yield are largely undocumented. Therefore the hypothesis of this thesis is that the high-input cropping systems practiced in the 450-500 mm rainfall region are contributing to permanent acidification of the soil.

To test this hypothesis the four aims of the study were to:

1. Use predictive methodologies for lime requirement with acidic soils in South Australia to establish lime responsiveness of these soils.
2. Discriminate amongst the impact/influence of different acidity related factors on crop yield for several crop species.
3. Determine the effect of associations of crop rotations and different tillage treatments on pH and other soil properties in red-brown earths of South Australia.
4. Utilise a soil process model (APSIM) with data from long-term cropping sequences as a means of describing soil profile acidification.

# Chapter 2

## 2. Review of literature

### 2.1 Introduction

The purpose of this review is to provide background information to later chapters, clarify our current understanding of acidic soils, and to determine the areas of soil acidification in which our understanding is lacking, especially in South Australia.

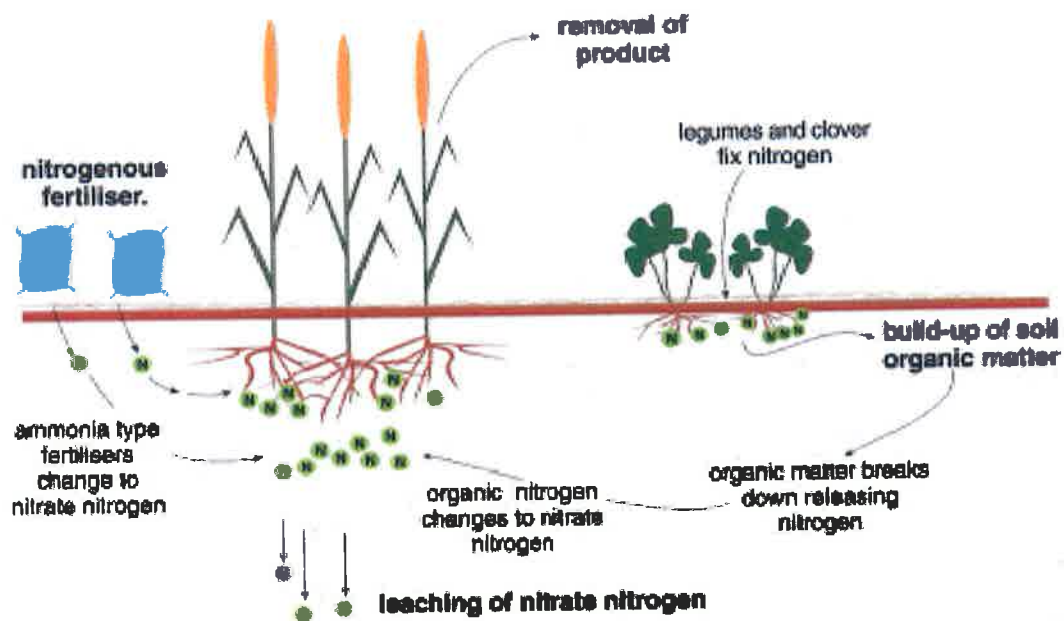
#### 2.1.1 Soil acidity and soil acidification

For the purpose of influence on plant production a soil is described as strongly acidic when it has an excessive acid reaction throughout some of the soil profile associated with plant roots, and generally when the  $\text{pH}_{\text{Ca}}$  measure is lower than 5.0. The process of soil acidification is the change in the amount of acid in the soil, which in the long term results in a decline in soil pH. Soil acidification is a natural process that occurs as the result of processes of weathering and leaching of exchangeable cations (especially Ca and Mg) from upper horizons in a soil profile. Soil acidification has been accelerated by changes associated with agriculture (Helyar 1976; Helyar and Porter 1989). Generally the factors causing soil acidification are classified into direct and indirect inputs of  $\text{H}^+$ . The direct inputs are from the dissociation of water and carbonic acid, and from nitric and sulphuric acids in acid rain. The indirect inputs of  $\text{H}^+$  are mainly associated with carbon and nitrogen cycles, and these are the dominant influences in the Australian agricultural situation (Helyar 1976; Helyar and Porter 1989).

The typical contributors to soil acidification from agricultural practices in Australia are illustrated in Figure 2.1, and the nature and impacts of these components are described later in this review (Section 2.2). For example, acidification can involve a series of chemical reactions in the soil that cause N from organic materials, or from ammonium based fertilisers, to convert to ammonium, which in turn converts to nitrate. Anions such as sulfate, chloride, bicarbonate and in particular nitrate can be leached and leave an over-abundance of  $\text{H}^+$  ions in the topsoil. As  $\text{H}^+$  ions increase and the soil becomes more acid, concentrations of Al and Mn may enter the soil

water solution (Cregan and Scott 1998). Many plants can only tolerate small quantities of these elements before their growth is affected (Black 1992).

To describe soil acidity, three factors are normally used; these are the intensity of acidity, the total acidity of the system, and the buffer capacity. The activity of  $H^+$  in solution (not including  $Al^{3+}$ ) is called the intensity of acidity (or active acidity) and is measured on a pH scale where  $pH = -\log_{10}H^+$ . Total acidity is made up of residual acidity (non-exchangeable Al bound by OM) and exchangeable acidity that includes exchangeable  $Al^{3+}$  and  $H^+$  which is extracted by a neutral unbuffered salt solution such as KCl or  $CaCl_2$  (Bache 1980).



**Figure 2.1 Causes of soil acidification in dryland farming systems in Australia**  
(Source: Fenton *et al.* 1996).

Associated with these factors, the pH buffering of the soil is important as this indicates the soils capacity to resist against pH change caused by acidifying processes. The usual way to measure pHBC is by a titration method (Helyar and Porter 1989; Aitken and Moody 1994; Nobel *et al.* 1997). Field pHBC as measured in a titration method can be approximated as an increase in the ECEC (Van Raij and Peech 1972), the precipitation of Al ions from solution and exchange sites, precipitation of  $Mn^{2+}$  from solution and from exchange sites which is slow at  $pH < 7$  (Conyers *et al.* 2000).

Furthermore, by multiplying pHBC by the change in soil pH ( $\Delta\text{pH}$ ) during a period of study, the acidification rate can be predicted for an agricultural system. This is done by measuring (or estimating) the amount of acid added to a soil for an individual depth (please refer to section 2.3 for more detailed descriptions). Then the soil profile acid addition is divided by the time period over which the acidification has occurred to give the soil acidification rate ( $\text{kmol H}^+/\text{year}$ ). These measurements are important, as the values for acidification rates and pHBC of soil are both useful for estimating lime requirement of soil (Conyers *et al.* 2000). It is noteworthy to mention that the approach described in Conyers *et al.* (2000) was used in the models developed by Hochman *et al.* (1989) for calculating buffer capacity, and these models are used for pHBC measurements in this thesis.

### 2.1.2 Soil pH

Soil pH is measured simply as the index of acidity and alkalinity in the soil solution and is the primary indicator of potential soil acidifying processes. Soil pH data also can provide information on the solubility of plant nutrients as the availability of many essential or toxic elements for plant growth vary in the different pH ranges. So knowledge about soil pH does to some extent provide information about availability of nutrients in soil solution for crop uptake (Adams 1978). Also, soil pH is a necessary value for an understanding of natural soil weathering, buffering and the response of a soil to inputs of lime and acid forming nitrogen fertilisers.

Soil pH is determined by measuring the pH after equilibrating soil with pure water ( $\text{pH}_W$ ) or in dilute salt solutions (Glossary of Soil Science Terms 1997). The  $\text{pH}_W$  can be subject to large variation within a field because of seasonal changes in the soil moisture and ionic concentration of the soil solution (Adams 1978). In contrast soil pH measured in salt solution is less affected by temporal variations. In Australia soil pH is most commonly measured in 0.01M  $\text{CaCl}_2$  ( $\text{pH}_{\text{Ca}}$ ) as 1:5 soil to extractant (Slattery *et al.* 1995). When pH is measured using a water extraction rather than a dilute salt extraction, the values may be higher by 0.6 to 1.2 units in low salinity soils and higher by 0.1 to 0.5 units in high salinity soils. Soils with extremely acidic pH values would be expected to be close to the point of zero salt effect (PZSE), where there is little difference between  $\text{pH}_W$  and  $\text{pH}_{\text{Ca}}$  (Ahern *et al.* 1995). For soils further from the PZSE, a greater difference between  $\text{pH}_W$  and  $\text{pH}_{\text{Ca}}$  would be expected. This pH variation was explained on the basis of the buffering effect of Al (Little 1992),

and variable charge theory (Aitken and Moody 1991), and at high pH by the presence of carbonate (Little 1992). To avoid this variation in soil pH, it is often recommended that pH be measured in 0.01 M CaCl<sub>2</sub> (Bloom 2000).

Some authors suggest that soil solution pH (pH<sub>SS</sub>) is also an appropriate measure for describing pH of soil, as this more closely resembles the pH that plant roots are exposed to at any time (Bruce *et al.* 1988; Bessho 1990; Bessho and Bell 1992). Menzies *et al.* (1994) and Moody *et al.* (1995) suggest from plant growth studies that pH<sub>SS</sub> is a better indicator of acidity than other soil pH measurements. Practically, the closest measurement to pH<sub>SS</sub> in a soil extract measure is a 0.002M CaCl<sub>2</sub> extraction, with exception of high ionic strength soils in which case 0.01M CaCl<sub>2</sub> extraction may be closer to pH<sub>SS</sub> (Aitken and Moody 1991). However Dolling and Ritchie (1985) have shown that pH values measured in 0.01M CaCl<sub>2</sub> or 0.005M KCl are closer to pH<sub>SS</sub> than pH<sub>w</sub>. The pH<sub>w</sub> values when the measure was less than 6.5 was similar to pH<sub>SS</sub> and was lower than pH<sub>SS</sub> at values above 6.5 (Menzies *et al.* 1994). Because the ionic strength (I<sub>s</sub>) of the soil has a very important influence on the value of measured pH, some authors have suggested that soil pH should be measured in concentrations equivalent to the measured I<sub>s</sub> for the soil in question (Dolling and Ritchie 1985; Munns *et al.* 1992).

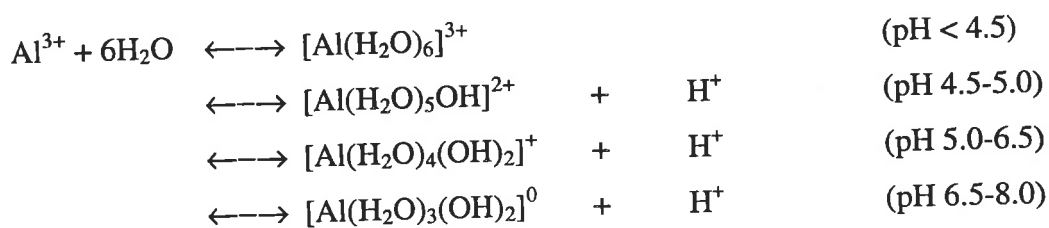
### 2.1.3 Soil acidity and aluminium

Acidity itself is not responsible for restricting crop growth, but the associated chemical changes in acidic soil can restrict the availability of some beneficial plant nutrients and increase the availability of toxic elements. For example, the recognition of the relationship between Al activity and the pH level of acidic soils led to the suggestion that Al toxicity per se could be a major factor of acid soil infertility (Adams 1981). Soil contains an abundant amount of Al but it has no impact on plant productivity unless the soil pH drops to levels where Al toxicity can be a factor. To identify Al toxicity in soil, it is essential to understand Al activity between the solid (adsorbed Al, organically complexed Al) and liquid (soil solution) phases of a soil.

Soluble Al species can be broadly divided into two groups: monomers and polymers (Ritchie 1989). In acid soils the soluble Al mainly is in monomeric forms. Monomeric Al species are divided into inorganic Al, organic Al (Al-OM) and acid-soluble Al. Distinguishable forms of the monomeric inorganic Al are Al<sup>3+</sup>, Al-F

complexes ( $\text{AlF}^{2+}$ ,  $\text{AlF}_2^+$ ,  $\text{AlF}_3^0$ ), Al-SO<sub>4</sub> complexes and the Al-OH complexes ( $\text{Al}(\text{OH})^{2+}$ ,  $\text{Al}(\text{OH})_2^+$  and  $\text{Al}(\text{OH})_3^0$ ). Under strongly acid conditions,  $\text{Al}^{3+}$  is the major form of inorganic Al.

The concentration of Al-OM,  $\text{Al}^{3+}$ , Al-F and Al-OH complexes are influenced by pH. So knowledge of the different Al species in soil solution at a certain pH can provide information on the toxicity effects on plants (Hodges 1987). The sequence of hydrolysis reactions on  $\text{Al}^{3+}$  as the pH increases from 4 to 6.5 progresses according to the following stages:



Usually the hydration states shown above are not indicated, and the ions are simply written as  $\text{Al}^{3+}$ ,  $\text{Al}(\text{OH})^{2+}$ ,  $\text{Al}(\text{OH})_2^+$  or  $\text{Al}(\text{OH})_3$ . The proportion of Al-OH complexes to monomeric inorganic Al is small, because the concentration of  $\text{OH}^-$  is very low under acid conditions. At higher pH, this proportion is very small due to the low solubility of Al but at pH near 8, two new soluble Al species ( $\text{Al}(\text{OH})_3$  and  $\text{Al}(\text{OH})_4$ ) can become available and cause toxicity in excessively basic soils.

Given the importance of the relationship of Al species in soil, and their toxic or non-toxic levels and subsequent effects on plants, the methods of analysis for differentiating Al species is very important. Many methods have been introduced to measure Al (Kerven *et al.* 1989; Kamprath 1970; Juo and Kamprath 1979; Bromfield *et al.* 1983). Some may overestimate the monomeric Al or some in plant growth studies have not shown toxicity responses. The realistic concentration of Al that is available to plants as determined by a 0.01M  $\text{CaCl}_2$  extraction, may be the closest estimate of monomeric Al activity. As monomeric Al dominates in strongly acid soils ( $\text{pH}_{\text{Ca}} < 4.5$ ), it is this form that is likely to be toxic to plant growth (Coleman and Thomas 1984). The sum of the activity of monomeric Al ( $\text{Al}^{3+}$  and the hydroxy-Al species) in soil solution is considered by some authors as the best Al measure to describing relationships between plant growth and phytotoxicity of Al (Pavan *et al.* 1982; Alva *et al.* 1987).

In contrast, organically complexed forms of Al produce less toxicity compared to  $\text{Al}^{3+}$  and monomeric Al-hydroxy species (Hue *et al.* 1986; Ritchie 1989). OM complexes with Al and lowers the Al concentration in the soil solution (Evan and Kamprath 1970; Thomas 1975; Helyar 1978; Cameron *et al.* 1986; Hue *et al.* 1986). Similarly, many researchers (Kwong and Huang, 1979; Violante and Violante 1980; Kodama and Schnitzer 1980; Hue *et al.* 1986; Inoue and Huang 1986) have confirmed that detoxification of monomeric Al was related to strong complexes formed between organic acids with Al. So to measure the complexed Al, it is necessary to determine the amount of Al total ( $\text{Al}_{\text{Tot}}$ ) as exchangeable Al and non-exchangeable Al (both represent the potential reactive Al pool of soils) and Al monomers ( $\text{Al}_{\text{Mono}}$ ), then the difference between  $\text{Al}_{\text{Tot}}$  and  $\text{Al}_{\text{Mono}}$  could reveal the amount of Al complexed with organic acids.

#### **2.1.4 Soil acidity and manganese**

The second major toxicity factor affecting plant growth in acid soils is the uptake of  $\text{Mn}^{2+}$ . But Mn availability in acidic soils is less widespread as a toxicity factor compared to Al, and depends on the extent of Mn losses due to leaching during soil formation and mineralogy of the parent material (degree of weathering) (Helyar 1987). At low pH in weakly weathered soil, Mn concentration is high so Mn can become toxic to plant growth (Table 2.1). This is opposite in highly weathered soils, which tend to have large amounts of Al and lesser amounts of Mn.

Reduced Mn ( $\text{Mn}^{2+}$ ) is the form that plants can absorb and its availability depends on oxidation/reduction reactivity, which occurs both chemically and microbially from unavailable forms ( $\text{Mn}^{3+}$  and  $\text{Mn}^{4+}$ ) in the soil. Production of  $\text{Mn}^{2+}$  depends on prevailing moisture, temperature conditions and presence of Mn oxides (Bromfield 1974; Pankow and Morgan 1981). Under dry and hot conditions, biological activity is minimised and chemical reduction takes place. Thus an unavailable form of Mn changes to a plant-available form (Payne and Fenton 1995). In contrast, Mn becomes less available at warm and moist conditions (especially water-logged and anaerobic) that favour microbial activity and thus changes Mn to a non-available form. Increasing soil pH by lime application will increase microbial activity and makes Mn less available, but if hot and dry conditions return, Mn becomes more available. Availability of Mn by chemical oxidation is limited in acidic soil and under low pH conditions (Ritchie 1989). Available Mn ultimately is controlled by

buffering from solid phase (i.e. adsorption) and only modified by redox reactions which both may be affected by soil pH.

**Table 2.1 Groups of soil types that release similar amounts of Al and Mn, when they are acid (Fenton *et al.* 1996).**

Group	Soil type
Weakly weathered (high Mn, low Al)	Red, black and red-brown earths, grey and brown cracking clay soils, prairie soils, chocolate soils.
Moderately weathered (moderate Mn and Al)	Podsolised earths, solodic soils.
Highly weathered (low Mn, high Al)	Podsollic soils, podsols, acid sands.
Highly weathered (high Mn, high Al)	Krasnozems, euchrozems, and other soils with high levels of Fe and Mn, and very high levels of Al oxides.

Plant growth can be affected by Mn toxicity in soil (Siman *et al.* 1974; Helyar 1978; Adams 1981; Foy 1983; Evans *et al.* 1987; Hochman *et al.* 1990). Similar to  $Al_{Ca}$ ,  $Mn_{Ca}$  (both measured in 1:5 soil:0.01M  $CaCl_2$ ) is a good indicator for Mn toxicity for plants (Ritchie 1989). The level of plant tolerance to toxic Mn is important in the toxicity responses. However, the potential for Mn toxicity in acid soils may only exist at certain times of the year since the level of toxic Mn can vary up to five fold throughout a year (Fenton *et al.* 1996).

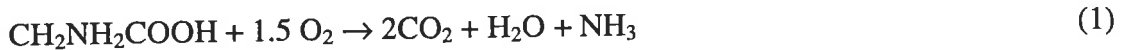
## 2.2 Soil acidification processes

The main processes contributing to acidification within an ecosystem have generally been categorised in terms of the  $H^+$  production or consumption associated with soil nutrient cycles (Helyar 1976; Kennedy 1986; Reuss and Johnson 1986; Binkley and Richter 1987; Helyar and Porter 1989; Bolan *et al.* 1991). The overall rate of acidification is dependent on the initial soil pH and buffering capacity, the time period involved and the particular management system (Haynes 1983). The N and C cycles contribute most to the acid and alkaline reactions in agricultural systems, and understanding these processes is important as they provide background for development of non-acidifying management strategies (Helyar 1976; Helyar and Porter 1989; Bolan *et al.* 1991; Kennedy 1992; Helyar *et al.* 1997). As well as these

major causes of soil acidification, other important processes influencing acidification include reactions involving S, P, Mn, Fe and direct inputs of H<sup>+</sup>.

### 2.2.1 Nitrogen cycle

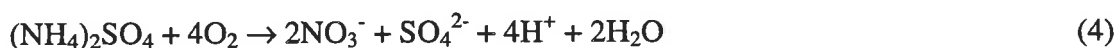
Various N inputs, outputs or accumulations of inorganic forms as part of the N cycle, affect the net balance of H<sup>+</sup> for the ecosystem (Binkley and Richter 1987; Helyar and Porter 1989). Ammonia (NH<sub>3</sub>) from N mineralisation (Equation 1) dissolves in soil water and gives a net gain of one OH<sup>-</sup> per mole of ammonia (Equation 2); ammonium (NH<sub>4</sub><sup>+</sup>) is absorbed (microbe or plant without equivalent anion uptake) and equivalent H<sup>+</sup> is transferred into the soil and therefore balances the H<sup>+</sup> consumed in forming NH<sub>4</sub><sup>+</sup> from NH<sub>3</sub>. Also, nitrification yields one net H<sup>+</sup> for each NO<sub>3</sub><sup>-</sup> ion formed, as one H<sup>+</sup> may be considered to balance the H<sup>+</sup> consumed in protonating NH<sub>3</sub> (Equation 3).



The soil acidification accelerates when N inputs into farming systems are in excess of the needs of plants, and has led to NO<sub>3</sub><sup>-</sup> leaching (Williams 1980; Helyar and Porter 1989; Black 1992; Poss *et al.* 1995). The main form of nitrogen for plant uptake is NO<sub>3</sub><sup>-</sup>-N, formed from nitrification of ammonia either during the mineralisation of organic matter or from fertiliser addition. The acidity formed from the production of NO<sub>3</sub><sup>-</sup>-N can be neutralised by OH<sup>-</sup> excretion from plant roots during NO<sub>3</sub><sup>-</sup> take-up, or conversion of NO<sub>3</sub><sup>-</sup>-N to N<sub>2</sub> under waterlogged conditions. If uptake of NO<sub>3</sub><sup>-</sup> does not occur by any source (plant or microbial), then the NO<sub>3</sub><sup>-</sup> may be leached from the rooting zone, resulting in a net H<sup>+</sup> production for each NO<sub>3</sub><sup>-</sup> leached (Helyar 1976; Binkley and Richter 1987; Bolan *et al.* 1991).

The use of ammonia-based fertilisers, such as monoammonium phosphate (MAP) and diammonium phosphate (DAP), also causes a net addition of acidity as they generate 2 or 1.5 mole of protons respectively for every mole of N, resulting in an excess balance of protons. Net acid addition can result from the leaching and loss of NO<sub>3</sub><sup>-</sup> from this cycle. Table 2.2 illustrates how the type of N fertiliser and leaching can influence acidification rate. For example, ammonium sulphate has an acid

reaction in addition to any acidity that may result from leaching of  $\text{NO}_3^-$ -N. In contrast, urea does not affect soil acidity when it is applied unless leaching of  $\text{NO}_3^-$ -N occurs. Ammonium nitrate (Equation 3) based fertilisers have a lower potential effect than ammonium sulphate (Equation 4) based fertilisers for acidification.



**Table 2.2 Soil acidifying effect of various forms of nitrogenous fertilisers (kg of lime per kg of N added) (Cregan and Helyar 1986).**

Fertilisers and acidification rates	No leaching of nitrate formed	100% of nitrate formed is leached
Most acidifying: ammonium fertilisers such as ammonium sulphate and MAP (monoammonium phosphate).	3.7	7.1
Medium acidification: DAP (diammonium phosphate).	1.8	5.3
Low acidification: urea, ammonium nitrate, aqua ammonia, anhydrous ammonia and biologically fixed (legume) N.	0	3.6
Alkaline fertilisers: sodium and calcium nitrate.	-3.6	0

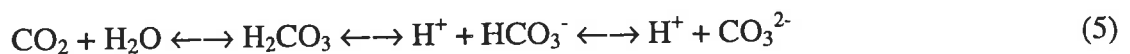
Soil environmental and management factors do influence the inputs and outputs of the N cycle within the whole system. These influences are summarised below as:

- 1) Lighter soil texture with higher rainfall, where under such conditions the  $\text{NO}_3^-$ -leaching rate is higher (Helyar *et al.* 1990).
- 2) More N input by a higher proportion of crop- or pasture-legumes in the rotation can lead to greater amounts of N available for nitrification and leaching (Coventry and Slattery 1991; Loss 1992; Dolling *et al.* 1994a).
- 3) Using perennial and deep rooting species, may increase  $\text{NO}_3^-$  uptake as this neutralises up to 78% of the acid generated from nitrification (Black 1992).
- 4) Grazing or higher stocking rate, trimming and hay removal may reduce  $\text{NO}_3^-$  uptake by plant then  $\text{OH}^-$  excretion will be decreased and results in more acidification.

- 5) The return of crop residues and mineralization of organic anions may generate enough alkalinity to balance the acidity generated as a consequence of  $\text{NO}_3^-$  production and leaching.
- 6) The level of N fertiliser (N fertilization) previously applied on top of that crop, and the oxidation of urinary N (from beef cattle or sheep) to  $\text{NO}_3^-$ -N, and then leaching of these nitrates.
- 7) The amount of water stored in the soil profile has a dominant effect on water drainage beyond the root zone and  $\text{NO}_3^-$ -N uptake as in a wet year (especially after  $\text{NO}_3^-$  accumulation), the soil profile can reach its drained upper limit and accelerate the leaching processes.

### 2.2.2 Carbon cycle

The carbon cycle processes contribute acidity and alkalinity into the soil system through inorganic and organic carbon pools. Water in soil holds carbonic acid ( $\text{H}_2\text{CO}_3$ ) (Equation 5) in equilibrium with  $\text{CO}_2$  in the soil air (Russell 1973). In neutral or alkaline soils  $\text{HCO}_3^-$  can be leached as water percolates through soil (bicarbonate leaching) (Kennedy 1986; Binkley and Richter 1987), therefore acidification occurs. Below pH 5.4,  $\text{HCO}_3^-$  is no longer a significant constituent of the soil solution, being converted to  $\text{H}_2\text{CO}_3$  or  $\text{CO}_2$ .



When organic anions export is higher than organic anions addition, the effect on the overall organic carbon pool will be more soil acidification. The effect of organic anion addition appears to depend on the initial soil pH and final OM levels of the soil (Tang and Yu 1999) and may cause soil pH to increase, decrease or remain unchanged. Some studies (Robertson *et al.* 1982; Nelson and Oades 1998; Tang and Yu 1999) suggest that adding OM to moderately acidic and alkaline soils could decrease soil pH. In contrast, other studies (Noble *et al.* 1996; Yan *et al.* 1996; Pocknee and Sumner 1997; Tang and Yu 1999) suggest that the net effect of adding OM to acidic soil could be an increase in pH values to some extent. Helyar (1976) and Ritchie and Dolling (1985) describe situations where OM has a  $\text{pK}_a$  of its weak acid groups higher than that of the soil pH, then there can be an association of  $\text{H}^+$  from the soil solution with organic anions resulting in an increase in soil pH. Generally, decarboxylation of organic anions and ammonification of plant residue-N

are major causes for soil pH to increase, while nitrification of mineralised residue N causes soil pH to decrease (Pocknee and Sumner 1997; Tang and Yu 1999).

When OM is lost from the system, soil can significantly lose its capacity to buffer against pH decline, for example by about 3.94 cmol (+)/kg for every 1% in OC in the surface 10cm of soil as reported by Slattery *et al.* (1998). If soil C level decreases lower than 0.5%, a more rapid decline of pH may result (Slattery *et al.* 1998). So the C cycle can contribute substantially to the total calculated acid additions (or acidification) in a farming system, the contributions being as low as 15% and to higher level of 100% (Ridley *et al.* 1990b; Coventry and Slattery 1991; Dolling 1996; Moody and Aitken 1997; Slattery *et al.* 1998).

### 2.2.3 Other cycles

Fluxes of sulphur (S cycle) are less important compared to N and C cycles in Australia (Helyar and Porter 1989). However, if sulphate ( $\text{SO}_4^{2-}$ ) from oxidation of organic S is not adsorbed in soils, acidification could occur. Normally, oxidation of organic S to  $\text{SO}_4^{2-}$  results in the production of  $\text{H}^+$  ions ( $2\text{H}^+$  for every  $\text{SO}_4^{2-}$  formed), which is balanced through uptake and assimilation of  $\text{SO}_4^{2-}$  by plants and microorganisms. In agricultural systems the main sources for the S cycle are acid sulphate soils, acid rain, elemental S and finely divided sulphides in fertilisers. Direct inputs of  $\text{H}^+$  as acid rain will impact on the soil in the same way as acids from other sources (Kennedy 1986), but in Australia acid rain is not an important source of soil acidification and normally not counted in calculation of acidification rates. Atmospheric deposition is normally estimated using rainfall pH values.

The P cycle usually does not influence  $\text{H}^+$  fluxes in Australian agricultural systems, due to phosphate ( $\text{PO}_4^{3-}$ ) being readily fixed with Al or Fe oxides, and these are mostly not susceptible to leaching. The reaction of superphosphate [ $\text{Ca}(\text{H}_2\text{PO}_4)_2$ ] in soil results in production of  $\text{CaHPO}_4$ ,  $\text{H}^+$  and  $\text{H}_2\text{PO}_4^-$  usually within a short time; then  $\text{H}_2\text{PO}_4^-$  reacts with Al and Fe oxides (and a reaction product of  $\text{OH}^-$ ) precipitating the phosphate (Leeper and Uren 1993).

The  $\text{H}^+$  production from Mn and Fe cycles also does not usually have a significant effect on soil acidification in Australia (Kennedy 1987; Helyar and Porter 1989). The reduction and oxidation of Mn consumes and releases protons respectively and can

result in seasonal pH changes. Also, some substances can turn to a strong acid source such as elemental S and finely divided sulphides (as aluminium and iron sulphides) in moist aerobic soils, when oxidised to sulphuric acid.

### 2.3 Measurement of acidity/alkalinity inputs to soil

To measure different sources of acid or alkali input to the overall rate of acidification, the contribution of each nutrient cycle needs to be measured. The relative contribution of different proton sources to the total H<sup>+</sup> pool in a soil profile was initially developed by Helyar and Porter (1989). The basis of methods for quantifying soil acidification rates are the rate of pH change ( $\Delta\text{pH year}^{-1}$ ) (examples are: Williams and Donald 1957; Russell 1960; Barrow 1964; Watson 1969; Williams 1980; Bromfield *et al.* 1983; Lewis *et al.* 1987; Chartres *et al.* 1990; White 1990) and the rate of proton addition ( $\text{kmol}_C \text{H}^+ \text{ha}^{-1} \text{year}^{-1}$ ) (examples are: Helyar *et al.* 1990; Ridley *et al.* 1990a, b, c; Coventry *et al.* 1992; Loss 1992; Dolling *et al.* 1993 a, b).

#### 2.3.1 Indirect measurement of acidification

Soil acidification rates can be estimated as absolute change. This is either a comparison of acid addition rates of soils before and after a period of acidification, or comparison of acidification rates of a site under study relative to a reference control site (eg. a fenceline). Acidification rates (or rates of proton addition as  $\text{kmol}_C \text{H}^+ \text{ha}^{-1} \text{year}^{-1}$ ) are calculated as pH increase in a site under study compared to a control site ( $\Delta\text{pH year}^{-1}$ ) and multiplying by the soil pH buffer capacity ( $\text{kmol}_C \text{ha}^{-1} \text{pH}^{-1}$ ) (eg. Donald and Williams 1954; Barrow 1969; Williams 1980; Bromfield *et al.* 1983; Chartres *et al.* 1990; Helyar *et al.* 1990; Ridley *et al.* 1990b; Loss 1992; Dolling *et al.* 1991). Rates of acidification then can be calculated according to the Equation given by Helyar and Porter (1989) (Equation 6):

$$A = (\text{pH}_1 - \text{pH}_2)(\text{pHBC} \times \text{BD} \times V) / T \dots \dots \dots \text{kmol H}^+ \text{ha}^{-1} \text{year}^{-1} \quad (6)$$

pH<sub>1</sub> is pH in year1 and pH<sub>2</sub> is pH in year2, pHBC is the buffer capacity ( $\text{kmol H}^+ \text{kg}^{-1} \text{pH}^{-1}$  unit) of the soil which is calculated for year2 (Aitken and Moody 1994), BD is the soil bulk density ( $\text{kgm}^{-3}$ ) of year1, V is the volume ( $\text{m}^3 \text{ha}^{-1}$ ) of the depth interval of soil for each soil depth increment and T is the time in years over which the acidification rate is calculated.

Across different permanent pasture and crop rotation studies in south-eastern New South Wales, north eastern Victoria, north Queensland, Western Australia and South Australia the rate of acid addition and lime required to balance acid additions are quite different (Table 2.3). Acidification rates for agricultural soils determined with this approach vary from 0.16 to 3.6 kmol (H<sup>+</sup>) ha<sup>-1</sup> year<sup>-1</sup> for pastures (Helyar *et al.* 1990; Ridley *et al.* 1990 a, b & c; Loss *et al.* 1993; Conyers *et al.* 1996; Dolling 1996), from 0.12 to 4.1 for continuous wheat and N fertiliser (Coventry and Slattery 1991; Slattery *et al.* 1998; Xu *et al.* 2002) and from -1.0 to 7.5 kmol (H<sup>+</sup>) ha<sup>-1</sup> year<sup>-1</sup> for cereal-legume rotations, depending upon the frequency of legume use in the rotation (Helyar *et al.* 1990; Coventry and Slattery 1991; Loss *et al.* 1993; Poss *et al.* 1995; Moody and Aitken 1997) (Table 2.3).

### 2.3.2 Modified indirect method

This method is similar to the method discussed above but the approach is changed with the aim of taking into account changes in buffer capacity over time by the term  $\Delta\text{pH} \times \text{final pHBC}$ . Results based on acid addition relative to a control site (Equation 6) may result in an underestimate of acidification influenced by short-term measure of pHBC in laboratory. Ridley (1995) considered that the most useful way to express soil acidification is to calculate the rate of acid addition, which must be neutralised to maintain the soil pH at a constant value (mol ha<sup>-1</sup> period<sup>-1</sup>). With this approach (Equation 7) it is possible to compare one agricultural system relative to another at the same time, or to compare them at two different times (Ridley 1995). The advantage of this approach is the keeping track of all parameters that affect soil pHBC by measuring the initial and final pHBC. Therefore the model given as Equation 6 has been modified to Equation 7:

$$A_i = [A_u \times T / (\text{pHBC}_u \times \text{BD}_u \times V_u) + \text{pH}_u - \text{pH}_i] \times \text{pHBC}_i \times \text{BD}_i \times V_i \quad (7)$$

A is acidification rate (kmol H<sup>+</sup> ha<sup>-1</sup> year<sup>-1</sup>), i is improved site and u is unimproved site and others are similar to the main formula of Helyar and Porter (1989) as given in Equation 6. A<sub>u</sub> (the acidification of reference site) has been assumed because soil data recorded for the system at the beginning of the study period are rarely available.

Table 2.3. Acidification rates for different crop and pasture rotations and the amount of CaCO<sub>3</sub> required neutralising that acidification.

Author	Rotation	Initial soil pH <sub>Ca</sub>	Soil type	Location	Acid addition mechanism (%)	Soil depth (cm)	Acidification (kmol (H <sup>+</sup> )/ha/year)	CaCO <sub>3</sub> equivalent (t/ha/year)
Coventry and Slattery (1991)	Continuous wheat	6.0	Podsollic earth	NE Victoria, Rutherglen		0-20	3.22	0.16
	Continuous lupins	6.0				0-20	5.26	0.26
	Wheat-lupin	6.0		Rutherglen Vic.	N=100	0-20	4.11	0.21
Coventry and Slattery (1991)	Continuous lupins	6.0		Rutherglen Vic.	N=100	0-20	4	0.21
	Continuous lupins	6.0		NE Victoria	N=100	0-20	5.26	0.26
Coventry (1992)	Crop-pasture	4.2				0-20	0.62-1.69	0.03-0.08
	Wheat-wheat	4.2	Solodic soil	Rutherglen Vic.		0-20	3.22	0.161
	Wheat-lupin	4.2				0-20	4.11	0.205
	Lupin-lupin	4.2				0-20	5.26	0.263
Coventry <i>et al.</i> (1992)	Continuous wheat		Sandy loam podsolics	NE Victoria			3.22	0.161
	Wheat-lupin						4.11	0.205
	Continuous lupin						5.26	0.263
Conyers <i>et al.</i> (1996)	Annual crop-pasture	4.9	Chromic luvisol	Wagga NSW	N	0-20	1.42 (0.92-1.9)	0.07
Dolling <i>et al.</i> (1994b)	Cereal-subclover		Deep yellow sands			0-80	0.19-0.23	0.01-0.115
	Cereal-subclover		sandy			0-50	0.15	0.008
Dolling <i>et al.</i> (1994a)	Continuous wheat + fertiliser		Duplex soils			0-50	0.35	0.018
	Pasture-wheat					0-50	0.41	0.02
	Pasture-pasture-wheat					0-50	0.82	0.041
	Continuous pasture					0-50	0.92	0.046



Table 2.3. (continued).

Author	Rotation	Initial soil pH <sub>Ca</sub>	Soil type	Location	Acid addition mechanism (%)	Soil depth (cm)	Acidification (kmol (H <sup>+</sup> )/ha/year)	CaCO <sub>3</sub> equivalent (t/ha/year)
Helyar and Porter (1989)	Subterranean clover	5.2	Granite soil	Crookwell NSW	C=59, N=40	0-60	3.46	0.17
	Grass	5.5	Basalt soil		C=47, N=51	0-60	4.22	0.21
Helyar <i>et al.</i> (1990)	Pasture/crop	5.2		North coast NSW		0-30	6.18-7.44	0.31-0.37
Helyar <i>et al.</i> (1990)	Grazed kikuyu perennial pasture						0	0
	0-300 kg/ha/year (NH <sub>4</sub> ) <sub>2</sub> NO <sub>3</sub> -N				N		8	0.4
	700 kg/ha/year (NH <sub>4</sub> ) <sub>2</sub> NO <sub>3</sub> -N							
Helyar <i>et al.</i> (1990)	White clover			North coast NSW	(N, C)		1.24	0.062
	125 kg/ha/year superphosphate					2.58	0.129	
	250 kg/ha/year superphosphate					3.64	0.182	
	500 kg/ha/year superphosphate							
Helyar <i>et al.</i> (1990)	Perennial pasture			Northern tablelands NSW	(N, C)		2.76	0.138
	188 kg/ha/year superphosphate					2.5	0.125	
	375 kg/ha/year superphosphate							

Table 2.3. (continued).

Author	Rotation	Initial soil pH <sub>Ca</sub>	Soil type	Location	Acid addition mechanism (%)	Soil depth (cm)	Acidification (kmol (H <sup>+</sup> )/ha/year)	CaCO <sub>3</sub> equivalent (t/ha/year)		
Helyar <i>et al.</i> (1997)	Pasture-cereal rotations	5.2-5.5	Red earth	Wagga Wagga NSW						
	wwpwwp (33% pasture)				C=21, N=79		2.28	0.114		
	wwwwpp (33% pasture)				C=20, N=80		2.52	0.126		
	wpwpwp (50% pasture)				C=29, N=71		2.48	0.124		
	wwwppp (50% pasture)				C=28, N=72		2.84	0.142		
	wppwpp (67% pasture)				C=35, N=65		2.52	0.126		
	wwpppp (67% pasture)				C=36, N=66		2.48	0.124		
Loss <i>et al.</i> (1993)	Wheat-lupin	>4.5	Sandy soil	West. Australia		0-60	0.29-0.55	0.01-0.03		
	Pasture paddocks	>4.5				0-60	0.16-0.21	0.01		
Loss (1992)	Subclover-wheat	>4.5	Sandy soil	West. Australia		0-60	0.16-0.21	0.01		
	Lupin-wheat	>4.5				0-60	0.29-0.55	0.01-0.03		
Moody and Aitken (1997)	Sugarcane	3.8-4.1		Tropical and subtrop. Queensland	C=58, N=42	0-90	2.8-4.7	0.14-0.24		
	Tobacco	5.5-5.8				0-70	-0.5 to -5.2	-0.03 to -0.26		
	Grapes	4.2-5.1			C=30, N=70	0-50	1.3-2.5	0.07-0.13		
	Bananas	5.9			C=20, N=80	20-30	36.7	1.84		
	Bananas	5.6-6.4				0-100	28.0-39.8	1.40-1.99		
	Crop-pasture	5.1				0-50	1.7	0.09		
	Summer crop/winter fallow	4.0-5.3			C=19, N=81	0-50	0.8-3.5	0.04-0.18		
	Grass-legume (hay)	4.1-5.5					0-90	1.0-11.0	0.05-0.55	
	Noble and Jones (1997)	Leucaena based pasture				North Queensland	N=78%		2.7	0.135

Table 2.3. (continued).

Author	Rotation	Initial soil pH <sub>Ca</sub>	Soil type	Location	Acid addition mechanism (%)	Soil depth (cm)	Acidification (kmol (H <sup>+</sup> )/ha/year)	CaCO <sub>3</sub> equivalent (t/ha/year)
Noble <i>et al.</i> (1998)	Leucaena pasture based	5.5	Haplic Eutrophic Red Kandosol	Samford, south eastern Queensland	N=20%, C=80%	0-90	1.0	0.05
	Pasture system + N fertiliser						5.1	0.255
Noble <i>et al.</i> (2000)	Continuous pasture						0.5-3.1	0.03-0.16
Poss <i>et al.</i> (1995)	Wheat annual cycle	4.5	Red Kandosol	South eastern Australia			-1.0 to 1.4	-0.05 to -0.07
	0-25 cm				N=100		-1.7 to -2.3	0.09-0.12
	25-90 cm				N=100		0.8	0.04
	Burning wheat straw						4.68	0.23
Ridley <i>et al.</i> (1990a)	Annual pasture	4.6				0-60	3.72	0.19
	Phalaris pasture	4.6				0-60	1.42	0.07
Ridley <i>et al.</i> (1990b)	Fertilised pasture	5.5	Strongly acid alfisols	NE Victoria	C=65, N=35	0-60	2.37	0.12
	Fertilised + lime	5.9			C=42, N=25	0-60	0.16	0.01
	Unfertilised	5.9			C=100	0-60	0.77	0.04
Ridley <i>et al.</i> (1990c)	Annual pasture	4.2-5.0	Strongly acid alfisols	NE Victoria		0-60		
	Red earth			Wagga Wagga NSW		0-90		
Smith <i>et al.</i> (1998)	Wheat-lucerne				N=100		0.3	0.015
	Wheat phase				N=100		0.9	0.045
	Lucerne phase							

Table 2.3. (continued).

Author	Rotation	Initial soil pH <sub>Ca</sub>	Soil type	Location	Acid addition mechanism (%)	Soil depth (cm)	Acidification (kmol (H <sup>+</sup> )/ha/year)	CaCO <sub>3</sub> equivalent (t/ha/year)
Slattery <i>et al.</i> (1998)	Continuous wheat	6.00	Solodic or yellow dermosol	NE Victoria Rutherglen	N=100	0-60	4.1	0.2
	Continuous lupins	6.0			N=100	0-60	12.5	0.63
Xu <i>et al.</i> 2002	W-Wheat, remove, 0	6.3	Red earth	Tarlee South Australia		0-10	0.5	0.03
	W-Wheat, remove, 80						2.06	0.10
	W-Wheat, retain, 0						1.34	0.07
	W-Wheat, retain, 80						2.03	0.10
	W-Beans, remove, 0						1.26	0.06
	W-Beans, remove, 80						0.73	0.04
	W-Beans, retain, 0						1.76	0.09
	W-Beans, retain, 80						2.16	0.11
	W-Lupins, remove, 0						1.36	0.07
	W-Lupins, remove, 80						1.85	0.09
	W-Lupins, retain, 0						1.78	0.09
	W-Lupins, retain, 80						2.22	0.11
	W-Fallow, remove, 0						0.92	0.05
	W-Fallow, remove, 80						1.08	0.05
	W-Fallow, retain, 0						0.94	0.05
	W-Fallow, retain, 80						1.78	0.09

Notes on the Table 2.3: Most data (except Ridley *et al.* 1990b and Helyar *et al.* 1997) are based on acid addition relative to a control site this may result in an underestimate of acidification. In some places acid addition mechanisms have not been shown, because the mechanism was not available.

### 2.3.3 Difference in profile acidification

Early studies (Williams and Donald 1957; Barrow 1964; Watson 1969) reporting pH declines only observed the declines for topsoil (0-10 cm, or up to 15 cm depth). More recent studies (Bromfield *et al.* 1983; Ridley *et al.* 1990b; Coventry and Slattery 1991; Dolling 1992; Loss 1992; Dolling *et al.* 1994 a & b; Dolling *et al.* 1993; Slattery *et al.* 1998) have shown considerable acidification evident below the surface 10 cm. But most of these studies have measured the acidification rates for the entire root zone and ignored any differences between rates of acidification within the profile. Acidification and alkalisations studies within surface and subsoil from soil columns (Black 1992), and under field conditions (McLaughlin *et al.* 1990), suggest that bulk assessment of acidification for an entire soil column (or entire root zone) can mask the overall acidification, due to differences of acidity and alkalinity inputs within each individual profile.

Poss *et al.* (1995) suggested that with acidification studies for long-term rotational experiments it is much better to have more specific knowledge of the fluxes (direct measurement) for acidification measurements in soil layers than to temporally separate the overall proton balance (indirect measurement) between, for example, two phases of a rotation. Smith *et al.* (1998) show that monitoring soil profile down to 90 cm can reveal the importance of crop uptake of  $\text{NO}_3^-$ -N from the deeper soil layers by an active root system. The difference between acidification rate at the depth of 0.25 and 0.9 m could reveal the crop uptake of  $\text{NO}_3^-$ -N, and the significant role of that event in  $\text{H}^+$  consumption and overall soil acidification. Similarly, as given in Slattery *et al.* (1998) and Poss *et al.* (1995), the inclusion of measuring of soil acidification rates for deeper profiles increased the accuracy in measurement of overall acidification compared to rates calculated for only surface soil.

### 2.3.4 Direct measurement of acidification

Only a few of the studies given in Table 2.3 directly measured the effect of C and N processes on acidification rates. Many assumptions have been used with indirect methods to estimate contribution of C and N processes to acidification, compared with approaches that directly measure each individual process. In contrast, in a direct approach, attempts

are made to measure the contribution of each process to overall acidification directly. For example, the inputs and outputs of organic acids, ammonification, nitrification, ammonium and nitrate accumulation and export are calculated on overall acidification. Verburg *et al.* (1998) suggest that the results of most acidification studies under different management and weather condition are not similar. It is ideal to use this individual information to include the temporal effect of weather and account for different management or soil type using an agricultural model simulator such as APSIM (Agricultural Production Systems SIMulator) (Probert *et al.* 1998 a&b). Subsequently, soil acidification can be calculated directly and daily for each soil depth layer by a proton budget (APSIM SOILpH).

Noble *et al.* (1998) and Smith *et al.* (1998), using a similar experimental approach, have shown that the direct measurement of  $\text{NO}_3^-$ -N within the soil profile is a good predictor of soil N transformation and  $\text{NO}_3^-$ -N redistribution and leaching in a soil profile, as part of N cycle for measuring acidification. Having access to direct measurements of leaching  $\text{NO}_3^-$  and  $\text{H}^+$  produced for individual depths provided the advantage of having a better perspective in terms of the fate of the  $\text{H}^+$  pool.

### **2.3.5 Simulation of acidification**

As has shown in the above studies, where given complex environmental conditions, there are many things that can influence the estimation of acidification rates. APSIM is a software system that can be easily formatted to simulate various production systems (McCown *et al.* 1995). At the same time, the APSIM can be empowered by the SOILpH module to simulate the major processes that contribute to soil acidification (Probert *et al.* 1998a; Verburg *et al.* 1998).

The SOILpH module, which tracks the production and consumption of protons, weak acids and alkalis in the N and C cycles can be plugged into APSIM, and give capability to APSIM to calculate the rate and distribution of acidification in cropping systems. This approach can be used as a modelling framework for research and management of soil acidification (Hochman *et al.* 1998). In the SOILpH module, a proton budget is calculated daily for each soil depth layer and the crop is treated as a separate component of the

overall system (Hochman *et al.* 1998). The SOILpH module employs empirical functions to calculate pH buffer capacity through time. Also, it uses standard solubility constants to allow for reactions of CO<sub>2</sub>, CaCO<sub>3</sub>, Al silicates and pH-Al relationships to update its value over time to keep up with changes in factors that modify buffering.

Therefore the SOILpH module gives APSIM extra potential to be used for investigating the effects of management options such as cropping rotations and fertiliser use on long-term acidification rates and productivity, and the evaluation of the susceptibility of different environments (soil climate combinations) to acidification by alternative cropping systems (Hochman *et al.* 1998). Also, the accurate information on rates of soil acidification, with different intensive cropping practices, can be used to estimate the lime required to increase soil pH to ensure no crop yield losses due to acidity.

#### **2.4 Soil acidity and Australian agriculture**

There is clear evidence that cropping soils in higher rainfall areas (>500 mm) in north eastern Victoria and southern New South Wales are affected by soil acidification (Coventry 1992; Cregan and Scott 1998). In Western Australia acidification is affecting the medium rainfall (400-500mm) cropping areas where the soils are sand over clay and sand plain soils (Dolling *et al.* 1994a; Dolling 1995). Soil pH has also declined with crop-based farming systems in the medium rainfall cropping zone in Victoria, New South Wales and South Australia, but with little evidence of effects on crop production (Coventry *et al.* 1989b; Chartres *et al.* 1990; Schultz 1995). In the semi-arid cropping regions (250-400 mm rainfall) acidity is not usually a problem, but some cropping practices have been identified as affecting soil pH in New South Wales (Young *et al.* 1999). The distribution of pH on a statewide basis (Table 2.4) shows that NSW has the largest area of land affected by soil acidity in Australia.

**Table 2.4 Extent of acid soils in Australia (ha×10<sup>6</sup>) (Cregan and Scott 1998).**

State	Highly acidic (pH <sub>Ca</sub> <4.8)	Moderate acidity (pH <sub>Ca</sub> <4.9-5.5)	Slight acidity (pH <sub>Ca</sub> <5.6-6.0)
New South Wales	13.5	5.7	5.1
Victoria	3.0	5.6	5.5
Western Australia	4.7	4.7	n/a
South Australia	2.8	n/a	n/a
Queensland	8.4	32.0	n/a
Tasmania	1.0	n/a	n/a

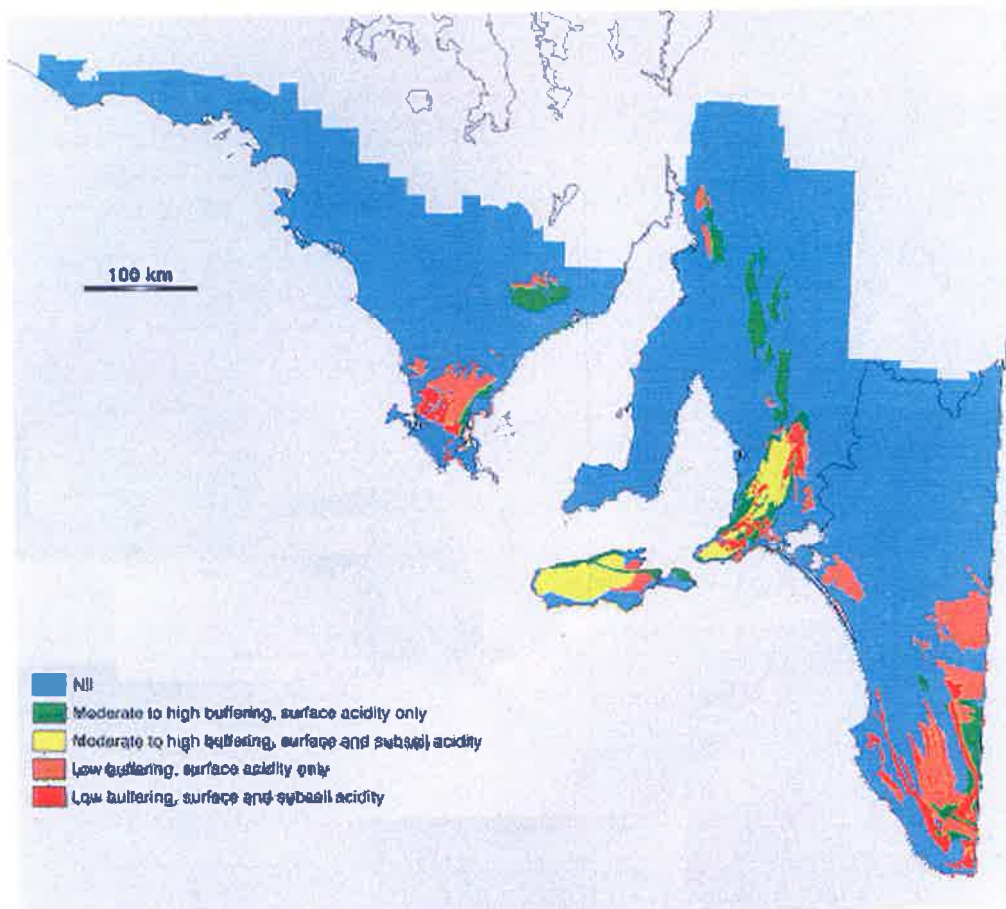
n/a: not available

### 2.5 South Australian soil acidity and liming

In South Australia approximately 2.2 million hectares of soil are prone to surface soil acidification and about 750,000 hectares to subsurface acidification (B. Hughes pers comm. 2001). The distribution of soil acidity in South Australia (Figure 2.2 and Table 2.5) shows that more than 30% of the agricultural areas have pH<sub>Ca</sub><4.5. Land classes have been used to differentiate between: 1) land where surface soils only are acidic, and land where acidity extends below 50 cm, and 2) soils with moderate to high buffering capacity surfaces and soils with low buffering capacity surfaces.

The most common acidic soils in the cropping region are solodised brown soils and red brown earths, each normally with low phosphate and nitrogen content. The second most common soil is the solodised solonetz and solodic, again with a low phosphate and nitrogen content. All these soils are susceptible to acidification, especially the second group where there are sandy surfaces and low buffering capacity (LWRRDC 1995). Notwithstanding this acidification risk, most soils in South Australia are naturally and strongly alkaline in all layers apart from the high rainfall (>600mm) areas (Naidu *et al.* 1993).

Soil acidification was first highlighted by Cook (1925) in the higher rainfall areas of South Australia at Kybybolite. Further evidence of acidification occurring in pasture soils came from 3 soil surveys; by Lewis (1978), Hodge and Lewis (1989) and Richards (1992) respectively. Generally, for acidic areas, the distribution of profile acidity within soil layers often proceeds faster in top layers than in others.



**Figure 2.1** Distribution of acidic soils at risk from acidity in South Australia. Each colour represents the extent of acidity in that specified area (Source: B. Hughes from PIRSA).

**Table 2.5 Areas prone to acidification, in relation to the region with a  $pH_{Ca} < 5.5$  in South Australia (ha) (Source: B. Hughes from PIRSA).**

Category and region	Eyre Peninsula	Northern Agricultural Districts	Mount Lofty Ranges	Kangaroo Island	South east	Total
Moderate to high buffering surface only	70,142	209,558	148,875	65,565	129,833	623,973
Moderate to high buffering surface and subsurface only		878	166,915	216,014		383,807
Low buffering surface only	169,718	40,706	61,803	40,083	494,932	807,242
Low buffering surface and subsurface only			119,622		258,057	377,679
<b>Total by region</b>	<b>239,860</b>	<b>251,142</b>	<b>497,215</b>	<b>321,662</b>	<b>882,822</b>	<b>2,192,701</b>

More recently Merry *et al.* (1996) analysed data of 2 soil samplings (1966, 1993) from 64 permanent sites in South Australia. These data showed that the soils were acidifying irrespective of production systems (Table 2.6). The Table (2.6) also gives amounts of lime required to neutralise the acid produced in each production system. Recent surveys by Hughes (B. Hughes pers. comm. 2001) show that acidity is quite widespread in many regions in South Australia. For example,  $pH_{Ca}$  ranged from 4.6-6.1 for lower Eyre Peninsula, 4.1-6.8 for Mount Lofty Ranges, 4.3-6.8 for South East, 4.6-5.9 for Kangaroo Island and 4.4-7.2 for Northern Districts (Mid-North), and that in these regions under study, most have more than 60% of samples below  $pH_{Ca}$  5.5. In some districts such as the South-East and the Mount Lofty Ranges, more than 50% of the samples had  $pH_{Ca}$  less than 5.0 (B. Hughes pers. comm. 2001).

Merry *et al.* (1992) have categorised soil acidification in South Australia into three distinct groups. These are low intensity grazing or cropping, high intensity grazing and cropping, and high intensity on sodic/calcareous soils. Data in Table 2.7 show the annual acidification rate and an estimation of the lime required to return the soil to its original pH level. Acidification rates in this study were calculated using the model of Helyar and Porter (1989). The third group, with the highest acidification rate, was always on alkaline sodic soils, where large pH decreases were recorded (up to 2 pH units). The study by Merry and others clearly demonstrates pH reduction in South Australian agricultural soil,

with most acidification occurring near the surface (up to 20-30 cm depth). Soil acidification was only observed in the B horizon where soils were alkaline sodic and prone to carbonate ( $\text{Na}_2\text{CO}_3$  or  $\text{NaHCO}_3$ ) leaching, and this effect increased with increasing annual rainfall and for high intensity/sodic pasture and cropping systems (Merry *et al.* 1996). The various survey studies have shown that the cropping regions with higher rainfall and high production potential are prone to acidification.

**Table 2.6 Rates of acidification and lime required to neutralise this acidity in South Australia (1966- 1993) (Merry *et al.* 1996).**

Rotation	Mean acidification ( $\text{kmol H}^+/\text{ha}/\text{year}$ )	$\text{CaCO}_3$ equivalent ( $\text{t}/\text{ha}/\text{year}$ )
Continuous crop + high N	4.64	0.232
Crop-pasture + high N	3.98	0.199
Crop-pasture	1.68	0.084
Low intensity grazing Mt. Lofty ranges	0.68	0.034
Low intensity grazing south east	0.74	0.037
Medium to high intensity grazing and hay cutting Adelaide Hill	2.14	0.107
High intensity grazing and regular hay cutting South East	2.32	0.116

### 2.6 Lime use in South Australia

In order to increase productivity on soils affected by acidity, lime application has been recommended as a primary means of amelioration. Soils respond to lime in different ways and Cregan *et al.* (1989) have summarised the many lime responses recorded in Australian soils. Mechanisms of lime responses and the effects of soil acidity amelioration on plant growth have been reviewed by Edmeades *et al.* (1995). Recent data suggest that the rate of lime use in South Australia is quite small with about 200,000 tonnes used between 1998-99 (B. Hughes pers. comm. 2001). These data have been used by Hughes to suggest that this amount of lime is less than 40% of the total lime required for soil amelioration in South Australia.

**Table 2.7 Summary of annual acidification rates (kg CaCO<sub>3</sub>/ha/year) for different farming systems in South Australia (Merry *et al.* 1996).**

Farming systems		Low intensity	High intensity	High intensity/sodic
Pasture systems	Mean acidification (kmol (H <sup>+</sup> )/ha/year)	0.62	2.28	5.46
	CaCO <sub>3</sub> equivalent (t/ha/year)	0.031	0.114	0.273
Cropping systems	Mean acidification (kmol (H <sup>+</sup> )/ha/year)	0.88	2.18	4.52
	CaCO <sub>3</sub> equivalent (t/ha/year)	0.044	0.109	0.226

An important factor in the use of lime by farmers is the estimation of the amount of lime that an acid soil might need. In areas affected by acidity, there often is little documented evidence or scientific basis for liming strategies. A 'rule of thumb' approach is used to estimate lime rates in much of South Australia. This mostly involves estimates based on local knowledge rather than use of objective data such as acidification rates (Merry *et al.* 1997). Generally there is no suitable laboratory test for liming recommendation. The determination of soil buffer capacity by batch equilibration with Ca(OH)<sub>2</sub>, which is supposed to simulate field liming, has been used in South Australia but, as demonstrated in Section 2.3, this approach often underestimates the liming requirement of the soil. Even calculation of liming requirement from the rate of soil acidification using the Helyar and Porter (1989) method may underestimate the liming requirement (Merry *et al.* 1997).

### **2.7 Liming impacts on crop production**

Liming experiments have shown consistent plant responses to lime on soils affected by acidity (Table 2.8). In the higher rainfall cropping regions of Victoria these lime responses are well documented (Ellington 1986; Coventry *et al.* 1987; Brooke *et al.* 1989). In Western Australia on duplex soil types, various lime responses have been reported (Dolling *et al.* 1991). In some studies on acidic soils there is no clear growth

benefit after liming (Scott 1982; Ellington 1986; Coventry *et al.* 1989 a&b; Coventry 1991) or some times negative growth effects (Carr *et al.* 1991). But in most studies (north east Victoria and southern NSW) where the soil  $pH_{Ca}$  was less than 4.7, yield responses of the order of 20-100% with wheat have been obtained after liming the soil (Cregan *et al.* 1989; Coventry 1992).

However, soil environmental and management factors do influence the liming impacts on crop production. These influences are summarised below as 1) Soil types with different Al level may not respond to inactivation of Al (Bromfield *et al.* 1983; Hoyt and Nyborg 1987; Conyers *et al.* 1991), but may respond to additional Ca as increasing total ECEC after liming (Edmeades 1982; Hochman *et al.* 1992); 2) Subsoil acidity might mask the influence of surface liming (Helyar 1991; Loss *et al.* 1993; Dolling *et al.* 1994 a & b; Dolling 1995); 3) Depths of lime incorporation (Scott *et al.* 1997); 4) Soil nutrient factors (Ritchie 1989; Suthipradit *et al.* 1990); 5) Dependent on the delay in lime dissolution; 6) The critical level of soil Al for various crop and pasture (microbial activity) could be different, thus may show different responses to liming (Ritchie 1989; Robson and Abbot 1989; Slattery and Coventry 1993).

To have better crop indicators to liming it is better to have combined soil information such as field buffering capacity, exchangeable bases and pH (Hochman *et al.* 1989) and to discriminate between these responses to lime on the basis of soil type and crop species (Slattery and Coventry 1993). Also for strongly acid soils ( $pH_{Ca}$  4.5-4.7), Al-buffering (Kamprath 1970; Reeve and Sumner 1970; Farina *et al.* 1980) and Mn-buffering (Conyers *et al.* 2000), the binding of Al (Al monomers) by organic acid ligands (Hargrove and Thomas 1981; Hue *et al.* 1986) and exchangeable Ca activity (Edmeades 1982; Hochman *et al.* 1992) are likely to be important on plant responses. So the understanding and partitioning of soil differences with plant responses could be useful in understanding the buffering reactions that control pH, and may contribute to more accurate lime prediction for different soil types.

**Table 2.8 Liming impacts on crop production in Australia depending on soil type and crop species**

Author	Location	Soil type	Plant type	Responses	Suspected factor
Brooke <i>et al.</i> (1989)	Rutherglen Victoria		Wheat, triticale, oats, barley canola safflower, field pea chickpea & lupin	Yield increased for all crops (9-29%) except lupins	
Coventry <i>et al.</i> (1985) and Coventry <i>et al.</i> (1992)	north east Victoria		Subterranean clover	15-30% yield increase	Mo deficiency
Coventry <i>et al.</i> (1989b)	north east Victoria	Duplex soils	Wheat and barley	All barley responded but only sensitive wheat responded	
Coventry <i>et al.</i> (1992) and Coventry <i>et al.</i> (1987, 1989a)	north east Victoria		Wheat	31-103% yield responses	
Coventry <i>et al.</i> (1997)	north east Victoria	Sodosols sandy clay loam.	Wheat	24-79% for acid tolerant & acid sensitive respectively	
Dolling <i>et al.</i> (1991)	south west of WA	Yellow brown sandy clay loam Sodosols.	Barley	Yield increase by 9-30% at all sites	
Heenan <i>et al.</i> (1998)	Wagga Wagga NSW	Red earth.	Wheat	Yield increases in most acidified rotations especially on Wheat-Wheat + N	Al toxicity
Hochman <i>et al.</i> (1990)	Southern NSW		Subterranean clover	18-22% yield response	High exchan- geable Al and reducible Mn
Scott (1982)	Wagga Wagga NSW		Wheat, barley & triticale	Responded to lime and large yield increase	Acid tolerant used
Scott and Cullies (1992)	Wagga Wagga NSW		Subterranean clover	3-50% yield increase	
Scott <i>et al.</i> (1997 &1999)	Southern NSW	Yellow chromosol or yellow podsolic. Red brown, red podsolic and podsolised red earth.	Wheat & barley	Yield responses especially for 0-10 cm depth	Al & Mn and subsoil acidity
Slattery and Coventry (1993)	north east Victoria		Wheat, triticale, barley & canola	Various responses dependent on soil type	

## 2.8 Longevity of liming

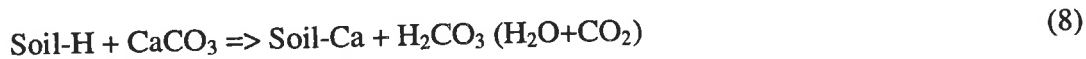
After initial lime application in an agricultural system, soil reliming may be necessary if inputs of acids are continuing from the various acidifying processes (Helyar and Porter 1989; Coventry and Slattery 1991). Liming is expensive in some regions (eg. Victoria and New South Wales) and here information on the longevity of liming responses is needed as part of the decision-making process in farm management (Coventry *et al.* 1997). The rate of soil pH decline can vary between 0.1 pH<sub>Ca</sub> units/year (after 5 t/ha lime) to 0.02 pH<sub>Ca</sub> units/year (after 0.5 t/ha) (Scott *et al.* 1999), so, with progressive acidification of soils, reliming cropping soils at or about 10 years after the initial application of lime is recommended (Coventry *et al.* 1997).

However, longevity of applied liming depends on many factors including the quantity of lime applied (Sumner 1995), the neutralizing value of liming materials which determine its rate of dissolution in soil, soil reactivity with liming materials, the rate of acidification of the soil after liming (acidification rate increases after liming)(Ridley 1995; Coventry *et al.* 1997), soil types (Coventry *et al.* 1989; Coventry 1992; Slattery and Coventry 1993; Slattery *et al.* 1995) and on the pH achieved after liming and rates of subsequent lime dissolution (Cregan *et al.* 1989; Ridley *et al.* 1990b).

Coventry *et al.* (1997) have shown that with higher rates of lime application (5 t/ha) and by mechanical tillage, there was more downward movement of the neutralising effect of lime and better yield responses compared to lower lime rates (2.5 t/ha). Even the small movement of lime was very important for sensitive crops, even after 12 years of original lime application to improve crop yield. The rate of lime re-creation also increased with increasing application rate and soil pH in the studies of Conyers and Scott (1989), Scott *et al.* (1999) and Scott *et al.* (2000). As subsurface soil pH declines, so does the potential yield. In contrast, as subsurface soil pH increases after a few years of lime application, the lime response can be greater where there has been long-term movement of lime into an acidic subsurface (Conyers *et al.* 1995).

## 2.9 Liming materials

Lime addition changes the soil pH due to the  $\text{CO}_3^{2-}$  ion reacting with  $\text{H}^+$  to form  $\text{HCO}_3^-$  and  $\text{H}_2\text{CO}_3$  (Equation 8).



There are large differences in quality among liming materials and lime reactions among soils (Venter *et al.* 2001). Liming materials are compared and characterised by three factors of purity (calcium carbonate content), Ca and Mg content and fineness, which all influence the amount of pH change and plant responses. Neutralising value (NV) describes the chemical purity of liming materials and their ability to neutralise acidity, and is the measure of purity of the product. Pure lime has 100% NV, but purity of liming materials could vary from 47% to 99% (Haby and Leonard 2002). Normally good liming materials should have a NV greater than 80%. Another consideration of liming material quality is the level of alkalinity, which is measured by pH and varies between alkaline (i.e. 9) to very alkaline (i.e. 12).

Other factors may influence the reaction of liming materials in soil, including 1) Highly reactive surface carbonates decompose rapidly leaving less reactive carbonates to maintain soil buffering (Henderson *et al.* 2000); 2) Clay rich soil with fine close-packed grains and substantial surface area protecting soil carbonate grains against acids compared to sandier soils; 3) Tillage is accelerating the lime dissolution as well as shortening the period of soil liming requirement (reliming); 4) Reduced tillage is likely protecting lime particles against dissolution and stretches the time in which carbonates will stay in soil. However the source of liming materials is important, as lime derived from calcic clay or silt clay deposits may need to be applied in higher rates to be effective. In addition, some liming materials have a higher NV value than 100 such as slaked, burnt (calcium oxide) and semi-burnt limes with NV value of 130-140.

The most common liming materials used in South Australia are the agricultural limes (mainly  $\text{CaCO}_3$ ), as well as dolomites (a mixture of calcium and magnesium carbonates) and a small amount of magnesite-based products. Other types of neutralising agents available are lime sand (this is mainly calcium carbonate but is coarser and slower

reacting than agricultural lime), neutral or alkaline clays on water repellent sands, alkaline irrigation water as addition of lime or sodium bicarbonate within the water and returning hay or stock feed as an alkaline source to soil (B. Hughes pers. comm. 2001).

### **2.10 Lime Requirement (LR) methods**

The LR of a soil is the amount of lime or other basic materials required to bring the pH of an acidic soil to a value that is favourable for the soil and crop (Thomas and Hargrove 1984; Edmeades *et al.* 1995; Sims 1996; Sumner 1997). Historically, 'target pH' has been used for soil samples to simulate field conditions (Shoemaker *et al.* 1961; Adams and Evans 1962; Curtin *et al.* 1984; Edmeades *et al.* 1985). By using target pH, soluble and toxic Al may disappear (Ritchey and Sousa 1997) but at the same pH toxic concentrations of  $Mn^{2+}$  may still be present (Sumner 1997). Some authors have used the elimination of Al as the basis for liming, since Al is the main cause of loss in crop and pasture production (Kamprath 1970; Reeve and Sumner 1970; Webber *et al.* 1976; Farina *et al.* 1980). Lime applications to highly weathered lateritic soils with high Al concentrations, even though eliminating Al toxicity may also induce Mn toxicity (Richards and Merry 1988).

Because of such difficulties, most of the methods mentioned above cannot provide precise information on LR, possibly related to differences in the pH buffer capacity (pHBC) of the soils. As the pHBC is related to many soil factors (clay content and type, OM content, CEC and initial soil pH) it is unlikely that such measures can be extrapolated to soils of entirely different characteristics (Sumner 1997). The determination of soil pHBC by batch equilibration with  $CaCO_3$ , which is supposed to simulate field liming, has often been considered to be the most reliable method of estimating LR. Edmeades *et al.* (1985) demonstrated that incubation with  $CaCO_3$  and titration with  $Ca(OH)_2$  often underestimated the field LR. Not only this method, but also ranges of other laboratory methods have underestimated the LR to reach a target pH of 6.0 as determined from field trials (field LR) (Edmeades *et al.* 1985).

Therefore a major difficulty in obtaining a 'right LR' with analytical methods is the lack of calibration against observed crop responses in the field. This would suggest that the

only true standard against which rapid methods for the estimation of LR can be calibrated is the LR determined based on the results of field experimentation on the crops and soils of interest. When such calibrations are carried out, meaningful estimates of LR can be obtained from laboratory methods (Sumner 1997).

Slattery and Coventry (1993) adopted the approach taken by Hochman *et al.* (1989) to produce such calibrations for LR requirement, and demonstrated good estimates of the predetermined final soil pH. However, occasionally final pH was underestimated caused by the laboratory measurement of pHBC, which could not account for the soil response to liming in the field. Slattery and Coventry (1993) suggested that further consideration of responses from tolerant and susceptible species to Al, Mn and maximum yield need to be included in any LR method. So the rate of lime required (field determined lime requirement) can be modelled using relative yield percent against soil pH, Al and Mn to reach 90% of maximum yield for each crop species.

Hochman *et al.* (1995) summarised many LR studies and correlated pH buffering with various soil chemical factors such as pH, ECEC, Al and organic matter percent (OM%). In conclusion, considering all mentioned approaches, the best way to measure buffer capacity with the regard to liming requirements, considering acidification rates and pH changes would seem to be an empirical approach such as used by Hochman *et al.* (1995). No such empirical approach has been taken for the acidic soils in South Australia. Thus in a similar approach, this study has used an empirical model to calculate and predict LR of cropping soils.

### **2.11 Hochman's model for lime prediction**

The opportunity to develop methodology for the estimation of lime requirement for cropping soils in South Australia arose from the lime prediction research of Hochman *et al.* (1989, 1992 and 1995), which was developed for acid soils of the southern slopes of New South Wales and adopted elsewhere by Slattery and Coventry (1993). In these studies soil information on field buffering capacity, exchangeable bases, and pH were used to predict lime rates required to raise soil pH to a predetermined level for specific soil types.

Generally the complex nature of soil acidity makes it hard to use individual soil information from acidic soil for lime calculation. Thus many soil properties are required to build a strong background for such analyses. When this information is available, then modelling can provide the tool needed to integrate and quantify knowledge and understanding of the relevant chemical and biological processes and present it with a simple decision oriented model for farm decisions. The purpose of such a model is not to predict yields but to give an overall view and summary of how yields may be affected by soil acidity in terms of the interacting underlying processes. The information gained by this approach can be applied rapidly in forming a liming strategy and produce tailor-made advice for a particular soil and crop situations.

This method (called the Hochman model in this thesis) can be used to predict changes in soil pH, exchangeable aluminium and CEC in response to liming. The advantages of this method are: "(1) that it requires no laboratory tests other than those required for routine soil diagnosis, and; (2) that it is not limited by preconceived 'target' levels of either pH or exchangeable aluminium" (Hochman *et al.* 1989). Detail of the soil components and underlying relationships of this model are given in Chapters 3 and 4 of this thesis.

In this thesis the relationship between soil pH, and individual soil properties in lime-amended soils will be investigated. Then the model proposed by Hochman *et al.* (1989 and 1995) will be validated for predicting the rate of change of ECEC and Al with pH to allow calculation of LR for soils in the mid-north region of South Australia.

## **2.12 Sodic soils in South Australia**

The majority of soils in Australia consist of different types of alkaline and sodic soils (Northcote and Skene 1972). A high proportion of soils in South Australia are sodic, but only a small proportion (1.9% out of 32.9%) of these soils are sodic-acid soils (Naidu *et al.* 1993). Sodic soils vary in their pH values, ranging from 4 to 10 (Szabolcs 1989). In sodic soils, exchangeable sodium percentage (ESP) is high. Soils with an ESP in the root zone greater than 5 (McIntyre 1979) are considered sodic and those with an ESP > 15 are classified as highly sodic (Northcote and Skene 1972; Chartres 1993).

To reclaim soils with a sodicity problem, using an amendment such as gypsum is necessary. The purpose of gypsum application on the target soil needs to be known (Loveday 1984). For example if gypsum is used in order to maintain high permeability at the soil surface during irrigation or rainfall, then improving the electrolyte effect, as measured by electrical conductivity (EC), is the more important requirement. In contrast in soils where the high ESP of the soil profile needs to be reduced and permanent improvements in soil physical properties are desired then improving CEC of the soil is of greater significance. In this thesis, the gypsum was used to reduce sodicity, and the gypsum requirement (GR) was calculated using the method suggested by Gupta and Abrol (1990) for improving CEC of the soil.

### **2.13 Managing soil acidification**

Lime application is a key approach in managing soil acidity in most acidified areas. Applying lime to increase soil pH is the most practical option to manage acid soils especially in South Australia, where lime application is likely to be cheaper compared to other Australian states. Other management practices can be used alone or combined with liming practices to keep the soil from further acidification. Generally, these management techniques can be classified from those that avoid the problem (alternative crop plants, using tolerant crops, alternative land use), to those that treat the problem (correcting the soil via inputs of organic materials, lime, mineral fertilisers, etc.). The most important issues and alternative approaches available in cropping system to minimise soil acidification will be discussed here.

#### **2.13.1 Efficient use of soil N, C and water**

Because C and N cycles and their leaching by rainfall are the most important acidifying causes in Australia, thus the efficient use of these sources in agricultural systems is essential for managing soil acidification. For example, perennial species (lucerne, cocksfoot and phalaris) can be used to reduce N leaching during summer rather than annual species (Cregan and Helyar 1986). The longer growing season of such perennial species with their deep rooting systems make them capable of taking up excess water and nitrate (Ridley *et al.* 1998), especially in regions where annual rainfall is greater than

500mm and causing leaching (Helyar *et al.* 1997; Passioura and Ridley 1998; Verburg *et al.* 1998). Also, early sowing of crops can lead to more complete absorption of soil  $\text{NO}_3^-$  before it is leached below the root zone with heavy winter rains (Helyar 1991).

### **2.13.2 Controlling plant removal**

Controlling crop removal for some plants is unavoidable because some crops like wheat obviously need to be harvested, but losses associated with the burning of stubble are avoidable. The removal of products low in organic anions such as cereal grain is less acidifying (Coventry and Slattery 1991) compared to the removal of products high in organic anions such as lucerne hay (Helyar 1991). Other possible management options are returning stubble back to the soil, adoption of grazing rather than hay cutting and returning dung and urine waste products to the donor ground (Helyar 1991). However, the addition of OM to soil (eg. stubble retention) as was discussed earlier can result in increases or decreases in soil pH depending on the influence that the addition has on the balance of the various processes that consume and release protons. The intensity of grazing also is an important concern. This can be controlled by fencing to minimise camping behaviour given that heavier grazing can result in greater amounts of N mineralisation, and the potential for either more plant N uptake or soil N accumulation (Unkovich *et al.* 1998).

### **2.13.3 Fertiliser selection**

Nitrogen fertilisers acidify the soil but actual acidification depends on the form, type and fate of applied nitrogen (Cregan and Helyar 1986; Baldock 1999). Acidification rates can be reduced by avoiding the use of strongly acidifying ammonium based fertilisers such as ammonium sulphate and monoammonium phosphate (MAP), and it may be better to use less acidifying fertilisers such as urea and ammonium nitrate. Other fertilisers such as potassium nitrate, calcium nitrate and composted poultry manure do not acidify the soil but the higher cost per unit will limit their use. Similarly slow releasing forms of N-fertiliser (eg. metal ammonium phosphate, guanidylurea, polyolefin-coated fertilisers), and inhibitors of nitrification in soils (eg. 2-chloro-6 (trichloromethyl) pyridine) also can have positive effects by slowing acid input, but these are not used in crop rotations because of high price (Kennedy 1992).

The best management option with fertiliser application is to avoid accumulating mineral N, by targeting minimum N-fertiliser use for optimum yield and establishing target crop yields, such as the approaches that define a potential yield based on growing season rainfall (French and Shultz 1984). Also, timing of application and placement of N-fertilisers could effectively increase N uptake by the plant. These strategies are using N-fertiliser in the early stage of growth or deep placement with the seed at sowing and continuing supply of N to at least the boot stage with wheat to ensure an established yield potential (Angus *et al.* 1998). Therefore in favourable years the rate of N can be increased or used as topdressing, whereas in dry years it could be decreased or not applied at all (Angus *et al.* 1998).

#### **2.13.4 Plant selection**

The option of using crop and pasture plants with tolerance to acidic soils compared with less-tolerant plants may be essential for some cropping areas in Australia. There is a risk however that reliance on crop choice alone, and not liming to correct acidity, will ultimately result in productivity losses as the soils acidify (Scott and Fisher 1989). Meanwhile, the choice of suitable plants (perennial and deep rooting varieties) with tolerance to acidity could offset acidification, as a result of using water through better root growth and accessing more  $\text{NO}_3^-$  deeper into the soil profile. Also, the use of tolerant plants is important where subsoil acidity exists, particularly as the amelioration of acidity in the subsoil (below the depth of incorporation) following liming is slow (Conyers and Scott 1989; Coventry *et al.* 1997).

#### **2.13.5 Crop rotation**

Differences between plant sequences in their acidifying effect on soil can be used, for example, employing a sequence where species tending towards alkalinity follow acidifying sequences. For instance, using pasture legumes or grain legumes (specially lupin and faba bean) in rotations is more likely to acidify soil than is wheat (Loss *et al.* 1993; Schultz 1995; Dolling 1995 & 1996; Slattery *et al.* 1998; Xu *et al.* 2002). Using perennial species instead of annual species can provide a better scope for retarding acidification with their more efficient use of soil N and water (Cregan and Helyar 1986). Also decreasing the proportion of legume-based pasture in rotations may have to be

considered, as shown by Heenan *et al.* (1995). Organic matter accumulation and product removal can increase from 20 to 36% as the proportion of pasture in the rotation increases from 33 to 67%. But importantly, prior to any decision on crop sequences, the farmer has to match the current soil N to the N requirements of a targeted crop to ensure minimal N is left in the profile and thus prone to leaching.

#### **2.13.6 Managing soil acidification in South Australia**

Whilst some of the management options mentioned in the last section could be applied in the cropping regions in South Australia to reduce soil acidification, the most obvious management option is lime application. Some issues related to low lime application in South Australia have been identified from a survey conducted by Hughes (B. Hughes pers. comm. 2001); these are: soil acidity is not recognised as a land degradation issue; causes of acidity are poorly understood and; erroneous belief that gypsum can be used to treat acidity. Furthermore, there is a lack of information about the degree of economic return, and the levels of crop response to liming. These are given as the most important issues that are keeping farmers away from adoption of a liming strategy.

Little research has been undertaken in cropping areas of South Australia on lime application rates, crop responses and any adverse affect of the nutrient processes which could have impacts on yield properties. Most of the management options given in this review are derived from interstate data and from different environments and soils. Therefore there is a requirement for measurements of LR, and an understanding of components of soil acidification specific for South Australia. By considering the main causes of soil acidification in South Australia, and integrating such data with the proven ability of computer models such as APSIM to achieve more accuracy with LR rates, then this could facilitate the adoption of management options. Also the understanding of acidifying processes is important as this provides background for development of non-acidifying management strategies including minimising the need for lime use (Cregan *et al.* 1989).

#### 2.14 Conclusions and experimental chapter aims

There are large areas of low pH soils in the medium rainfall cropping regions in South Australia, but to date there is little information on whether this acidity is affecting crop production. To enhance crop productivity on acid soils lime application is usually recommended, but in South Australia little is known for these cropping areas whether yield responses will be obtained following lime application. Little research has been undertaken on lime application rates, crop responses and any possible adverse effects on nutrient processes that could affect yield. There have been no attempts to discriminate any responses to lime on the basis of soil type, or to evaluate methods for determining the amount of lime to be applied to soils affected by acidity. **Therefore, in chapter 4, a lime prediction approach (Hochman *et al.* 1989) is field validated for a commonly found soil type of South Australia to establish lime responses and requirements based on a relative grain yield response.**

In South Australia a high proportion of the cropping soils are sodic, and a small percentage of these (1.9% out of 32.9%) are sodic-acid soils (Naidu *et al.* 1993). Sodicity can influence soil structure and nutrient availability in a way that eventually can affect plant growth and plant productivity (Gupta and Abrol 1990; Naidu and Rengasamy 1993). The standard practice in managing a soil sodicity problem is the use of an amendment such as gypsum. Where sodic-acid situations exist, simultaneous application of gypsum and lime to soil has been practiced by some farmers in South Australia. But there is little known from field studies on what mutual or additive benefits accrue from using these two soil amendments together and the associated change in the soil chemistry. With these management practices, associated with a combination of gypsum use, stubble management and reduced tillage, farmers have adopted a more high input approach to cropping. Given such management, it has been possible to improve crop production but such management could also increase the opportunity for soil acidification. **Therefore in chapter 5 aspects of management such as nitrogen use and gypsum use are investigated with respect to any influence on the soil acidity complex.**

The two most important sources of soil acidification out of many causes in cropping systems are acid production from the C and N cycles (Helyar and Porter 1989). The understanding of these N and C cycle processes is important as they provide background

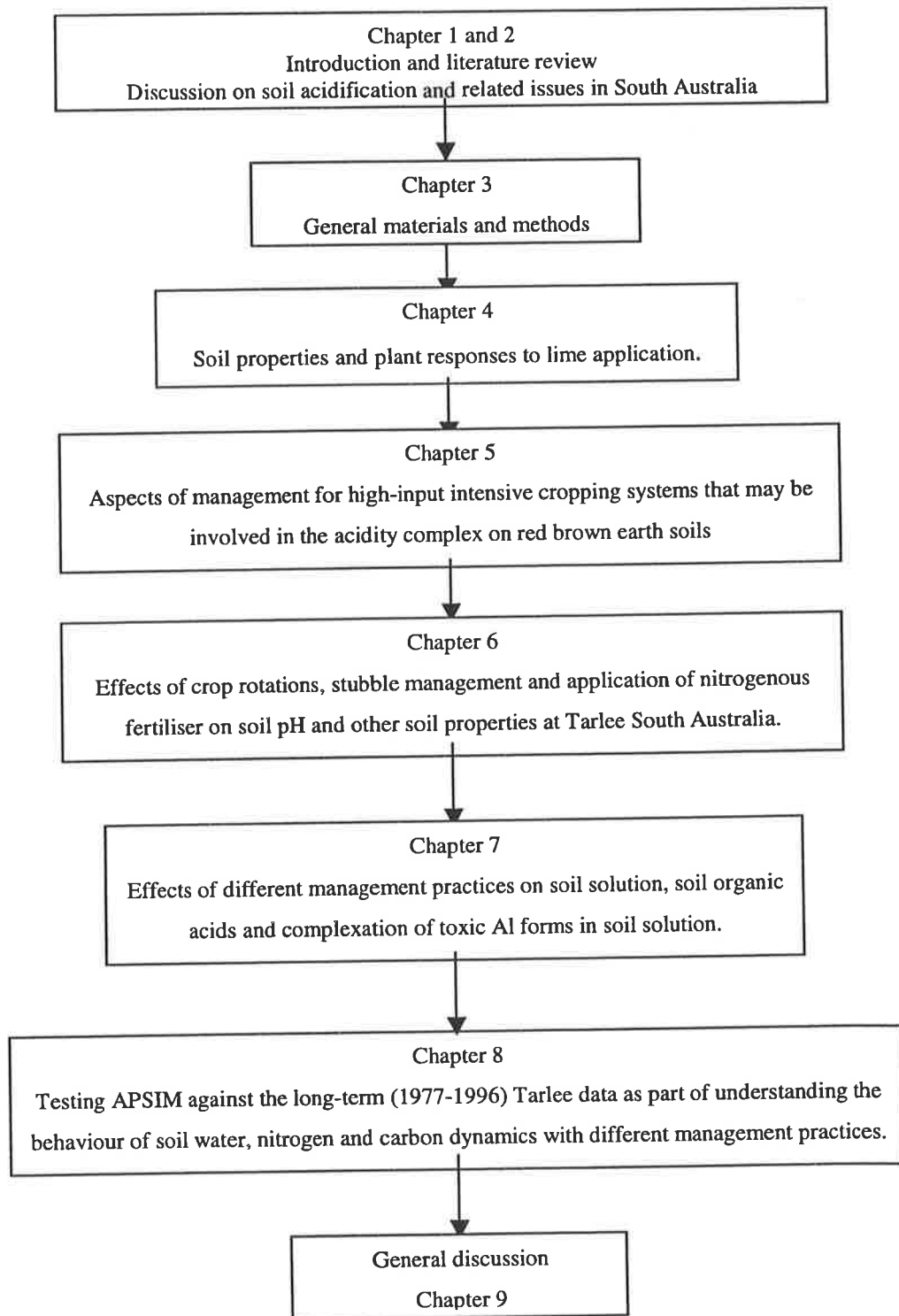
for the development of non-acidifying management strategies or developing techniques to minimise the need for lime (Cregan *et al.* 1989). The amount of N-fertiliser used in crop systems throughout Australia has increased in recent years, and generally in the high rainfall cropping areas, this agricultural practice is likely to accelerate soil acidification. Similarly, using legumes in cropping systems can contribute to soil acidification. Soil acidification is important, not only because of its current impacts on the growth of plants, but because the areas affected and the intensity of the problem can rapidly increase with time. In a recent study, Xu *et al.* (2002) have shown that the overall soil acidification was increased by some intensive cropping systems (1978-1992). **In chapter 6, soil samples from a long-term rotation trial at Tarlee (1978-1996), South Australia, are used to estimate the soil acidification rates under different management practices. Also, effects of crop rotations, stubble management and application of nitrogenous fertiliser on soil pH and other soil properties will be investigated.**

Some studies suggest that using soil solution measure (such as  $pH_{SS}$ ) as a more appropriate direct measure on the influence of acidity factors on the plant growth (Bruce *et al.* 1988; Bessho and Bell 1992; Slattery *et al.* 1995). With the  $pH_{Ca}$  drop at the Tarlee (described in chapter 6) to a value of about 4.2, then it is possible that the soil there may be dominated by monomeric forms of Al, which may be toxic to plant growth (Coleman and Thomas 1984). In cropping systems, the type of rotation and thus the vegetative residues present under different crop rotations may be important in influencing the concentration and type of organic acids in the soil solution (Huang and Violante 1986). So the reduction in the toxicity of Al through complexation with organic acids in cropping systems may occur with a process for retaining residues, and equally this process may be an important factor in sustaining crop yields. **Therefore in chapter 7, effects of different management practices on soil solution, soil organic acids and complexation of toxic Al forms in soil solution will be investigated.**

As has been described in the literature review, where given the complex conditions of a soil-plant-environment, there are many things that can influence the estimation of acidification rates (Ridley 1995; Verburg *et al.* 1998). Only a few studies (eg. Poss *et al.* 1995) have attempted to determine rates of acidification by measuring direct values for

separate depths, and understand processes behind the causes of acidification. To date, there has been no attempt to explain or simulate the nutrient processes behind soil acidification for South Australian environment. The Tarlee data will be used against the APSIM model to monitor fluxes both at the surface and at the depth, and compare these outcomes (predicted) with real data (observed) from the field studies (eg. chapter 6). By testing APSIM against the Tarlee data set, it may be possible to determine the accuracy of these simulated data in explaining the processes behind soil acidification and, importantly, it may be possible to make predictions on the future change in soil pH with various farming systems. **Thus in chapter 8, APSIM will be tested against the long-term (1977-1996) Tarlee data as part of understanding the behaviour of soil water, nitrogen and carbon dynamics with different management practices.**

A flow chart, indicating the organisation of the thesis outline and the order in which the key issues outlined above are addressed in this study is provided in Figure 2.3.



**Figure 2.3** Outline and key issues of chapters in this thesis.

# Chapter 3

## 3. General materials and methods

### 3.1 Introduction

This chapter outlines the broad base of materials and methods used for this study on acidic soils in the mid-north of South Australia. A major part of the research conducted during this study included site selection, field experimentation and extensive soil analysis. For this work the general information is reported here. This includes site description, climatic information, experimental design and general statistical methods, calculation of lime treatments (similar to Hochman *et al.* 1989 and 1995), calculation of gypsum treatment and some background on the APSIM program for measuring C, N and water dynamics. More detailed individual soil analysis and agronomic procedures are covered in the relevant experimental chapter.

### 3.2 Site selection

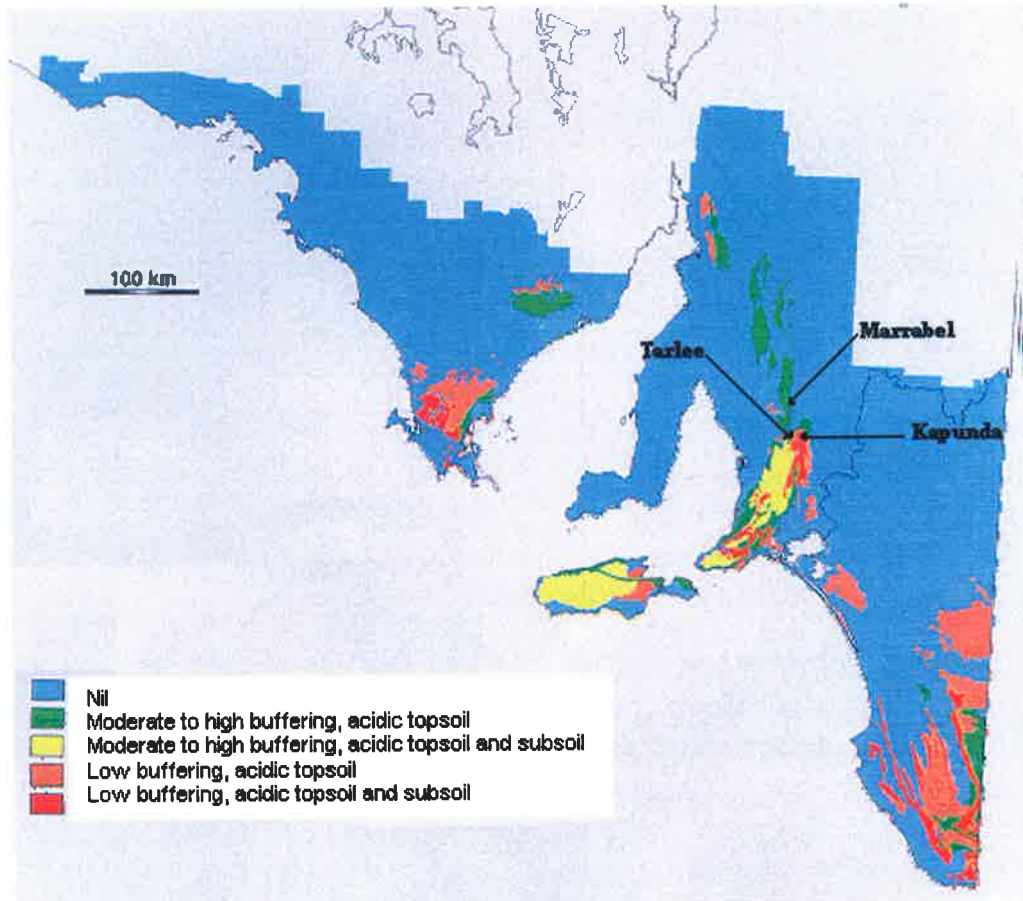
Initially many acidity-affected farms were located and visited to choose the experimental sites. A survey was conducted during September-November 1998 and many potential farms, based on past and present soil surveys from SARDI and CSIRO (Division of Soil and Water), were investigated as potential experimental sites. Twenty farmers in the mid-north region were contacted regarding possible project collaboration. Subsequently soil samples were taken from various fields on these farms to guide the selection of the experimental site. The criteria for site selection was low soil pH, uniform soil type and rotation history. Finally the 3 field experimental sites were selected in the mid-north region on soil types common to this cropping area of South Australia (Figure 3.1). These locations were at Marrabel on the property of Mr. Geoff Rowett (GR), the northern side of Kapunda on the property of Mr. David Shannon (DS) and on the eastern side of Kapunda on the property of Mr. Mick Ryan (MR). The information on the rotation history for the selected 3 sites is shown in Table 3.1, and this information was the basis for choosing the rotation sequence on each experimental site. A more detailed soil chemical characterisation was undertaken at these sites to establish the soil treatments. The sampling protocol involved taking soil samples (0-10cm intervals to 50cm depth) at 3 m

intervals over two 150 transects. Some of the detailed chemical characteristics of the soil at these sites (before application of lime treatments) are given in Table 3.2. The soil across each site was homogeneous (uniform) with respect to soil pH<sub>Ca</sub> in the surface 10cm with a standard deviation of less than 0.15 of a pH unit.

**Table 3.1 Crop rotations for previous years and for 1999 and 2000 season for 3 sites**

Site	1995	1996	1997	1998	1999	2000
MR	Sub clover	Wheat	Sub clover	Sub clover	Wheat, durum, canola	Wheat, durum, barley
GR	Peas	Barley	Canola	Pasture	Wheat, barley, durum	Wheat, barley, faba
DS	Lucerne	Wheat	Lucerne	Durum	Wheat, barley, canola	Wheat, barley, faba

Another study in this thesis involved using data (re-analysis of historical and stored soil samples) from a field experiment started in 1977 at Tarlee, South Australia. The Tarlee site has been described in detail by Schultz (1995). The selected treatments used from this experiment are described in Chapter 6. The trial site is located at Tarlee, 80 km north of Adelaide, on hard setting red brown earth with a sandy loam texture on the property of Mr. John Rohde. Some soil properties at the start of the trial are given in Table 3.3. The long-term site at Tarlee is unique in that the management treatments initiated in 1977 mostly reflect the current cropping practices of the 1990s (eg. continuous cropping, high N rates, no-till and stubble management). Data from this long-term trial are used in this thesis to provide an understanding of the causes and rates of development of soil acidification in this type of environment, thus assisting with recommendation for acidification control or amelioration.



**Figure 3.1 The location of experimental sites in the mid-north of South Australia: DS (20 km north of Kapunda) MR (15 km, south of Kapunda), GR (10 km, north of Marrabel) and Tarlee (30 km north of Gawler).**

**Table 3.2 Soil properties and standard deviation (sd) for 50 (0-50cm) soil samples taken in August 1998 across 3 sites (check chapter 4 for methodology)**

	Site GR		Site DS		Site MR	
	Mean	sd	Mean	sd	Mean	sd
<b>pH (CaCl<sub>2</sub>)</b>						
0-10cm	4.62	0.15	4.32	0.12	4.69	0.15
10-20cm	5.57	0.16	4.73	0.15	5.09	0.10
20-30cm	6.20	0.12	5.60	0.15	6.30	0.10
30-40cm	7.70	0.15	6.30	0.11	7.00	0.13
40-50cm	8.00	0.15	7.35	0.10	7.90	0.12
<b>pH (H<sub>2</sub>O)</b>						
0-10cm	5.71	0.18	5.44	0.18	5.86	0.15
10-20cm	6.78	0.21	5.98	0.12	6.60	0.15
20-30cm	7.45	0.20	7.10	0.21	7.45	0.14
30-40cm	8.45	0.20	7.45	0.18	8.00	0.21
40-50cm	8.95	0.11	8.35	0.12	8.80	0.13
<b>EC (dS/m)</b>						
0-10cm	0.11	0.15	0.07	0.04	0.04	0.02
10-20cm	0.08	0.04	0.06	0.05	0.03	0.01
20-30cm	0.07	0.10	0.09	0.06	0.10	0.02
30-40cm	0.22	0.05	0.20	0.04	0.19	0.01
40-50cm	0.22	0.04	0.49	0.03	0.29	0.02
Al (cmol+/kg) 0-10cm	0.11	0.08	0.14	0.03	0.04	0.03
Mn (cmol+/kg) 0-10cm	0.07	0.01	0.09	0.02	0.04	0.02
Cu (mg/kg) 0-10cm	1.08	0.13	0.78	0.10	0.77	0.13
Fe (mg/kg) 0-10cm	114.25	14.10	125.00	6.93	54.45	12.82
Total N %	0.15	0.02	0.11	0.02	0.10	0.02
Total C %	1.89	0.2	1.30	0.1	1.39	0.2
Mn (mg/kg) 0-10cm	21.75	4.57	21.75	4.57	11.50	1.73
Zn (mg/kg) 0-10cm	0.90	0.55	1.08	0.13	1.80	0.96
Ca (cmol+/kg) 0-10cm	4.84	0.50	2.50	0.14	4.12	0.52
Mg (cmol+/kg) 0-10cm	1.46	0.41	0.66	0.04	0.91	0.13
Na (cmol+/kg) 0-10cm	0.31	0.15	0.23	0.04	0.31	0.05
K (cmol+/kg) 0-10cm	0.88	0.12	1.35	1.36	0.39	0.06
ECEC 0-10cm	7.67	1.08	4.97	1.28	5.81	0.60
	4%		4%		6.7%	
<b>B (mg/kg)</b>						
0-10cm	2.30	0.20	1.70	0.20	1.70	0.25
10-20cm	3.70	0.13	1.60	0.25	3.10	0.21
20-30cm	10.00	0.15	5.20	0.12	5.80	0.14
30-40cm	12.20	0.10	13.90	0.10	5.60	0.10
40-50cm	12.50	0.10	17.70	0.10	9.00	0.10

**Table 3.3 Soil properties at the start of the Tarlee experiment in 1977 (check chapter 6 for methodology).**

Attribute	Unit					
Soil depth	cm	0-10	10-30	30-60	60-90	90-120
OC	%	1.04	0.75	0.39	0.20	0.17
Total N	%	0.112	0.085	0.039	0.020	0.016
EC (1:5 extract)	ds/m	0.25	0.60	0.87		
Total soluble salts	%	0.087	0.209	0.304	0.300	0.304
pH <sub>w</sub>		6.8	8.5	9.2	9.4	9.3
Clay	%	14	41	37		
Silt	%	8	9	16		
Sand	%	78	50	47		
Total P	ppm	310	250	200	170	210
NaHCO <sub>3</sub> extractable P	mg/kg	54	15	2	3	2
NaHCO <sub>3</sub> extractable K	mg/kg	430	340	200		

### 3.3 Climatic information

A Mediterranean type of environment is the typical climate in the cropping regions of South Australia, with cool, wet winters and hot dry summers (Aschmann 1973). Annual average rainfall in these regions is usually between 250-500 mm (Webber *et al.* 1976). The mean annual rainfall with growing season rainfall for 1998 and 1999 growing season for the GR, MR and DS sites, and from 1978 to 1996 at Tarlee for designated years, are shown in Table 3.4. In the 2 years of experimentation for the GR, DS and MR sites different rainfall patterns were experienced, with the 2000 season having above average rainfall compared to the 1999 season. However for 1999, the opening rain for the season was higher for all 3 sites compared to 2000 season. The MR and DS sites are approximately 20km apart and these sites had a similar pattern of rainfall to that of the GR site, which is almost 50 km apart from the other 2 sites. At the Tarlee site the long-term average annual rainfall was measured as 479 mm.

**Table 3.4 Monthly and long-term monthly rainfall (mm) averages with season and April-October sub-total (growing season) at GR, DS, MR and Tarlee sites.**

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Apr-Oct	Total
<b>GR site</b>														
1998	38.6	36.8	12.0	61.6	16.2	80.0	57.6	31.8	45.0	64.8	44.4	18.0	357	507
1999	22.4	11.2	56.8	10.0	72.0	33.8	35.2	39.0	52.2	63.0	65.9	26.0	305	487
2000	0.0	93.4	18.8	48.6	54.2	59.0	66.2	48.4	55.8	66.0	25.6	7.8	398	544
<b>DS site</b>														
1998	8.0	35.0	10.0	69.0	15.0	62.0	70.0	29.0	44.0	56.0	73.0	9.0	345	480
1999	9.0	11.0	62.0	5.0	79.0	35.0	44.0	41.0	61.0	49.0	57.0	25.0	314	478
2000	0.6	111.0	19.5	44.8	63.2	67.9	71.1	52.6	53.4	55.0	31.8	7.0	408	578
<b>MR site</b>														
1998	4.0	36.2	9.6	68.4	15.0	61.8	74.6	29.0	45.8	56.8	44.6	9.6	351	455
1999	9.2	10.6	62.2	5.6	78.2	36.6	45.8	43.2	61.2	48.4	56.4	22.6	319	480
2000	0.6	118.2	18.6	46.8	66.0	69.2	72.2	51.0	52.2	54.0	33.9	6.6	411	589
<b>Tarlee site</b>														
1978	9.0	5.0	6.0	42.0	53.0	87.0	101.0	69.0	95.0	23.0	41.0	17.0	470	548
1984	42.0	2.0	15.0	52.0	26.0	31.0	89.0	94.0	59.0	47.0	33.0	5.0	398	495
1986	7.0	3.0	0.0	28.0	24.0	30.0	94.0	85.0	72.0	83.0	27.0	20.0	416	473
1992	1.0	7.0	61.0	57.0	67.0	49.0	54.0	123.0	128.0	80.0	80.0	103.0	558	810
1996	41.0	19.0	42.0	9.0	7.0	99.0	100.0	84.0	63.0	9.2	15.0	19.0	371	506
20-year avg.	22.0	12.0	21.0	33.0	39.0	58.0	66.0	63.0	59.0	49.0	35.0	23.0	366	479

### **3.4 Experimental design**

The experimental design for the 3 sites (GR, MR and DS) was a split plot of 3-crop species within 7 treatment rates of lime, gypsum or sulfur, randomized within 4 replicates. An example of the experimental design (2000 season for DS site) used for this study is shown in Figure 3.2, with 4 replicates (84 plots) at each site and treatment and crop species indicated in each specific plot.

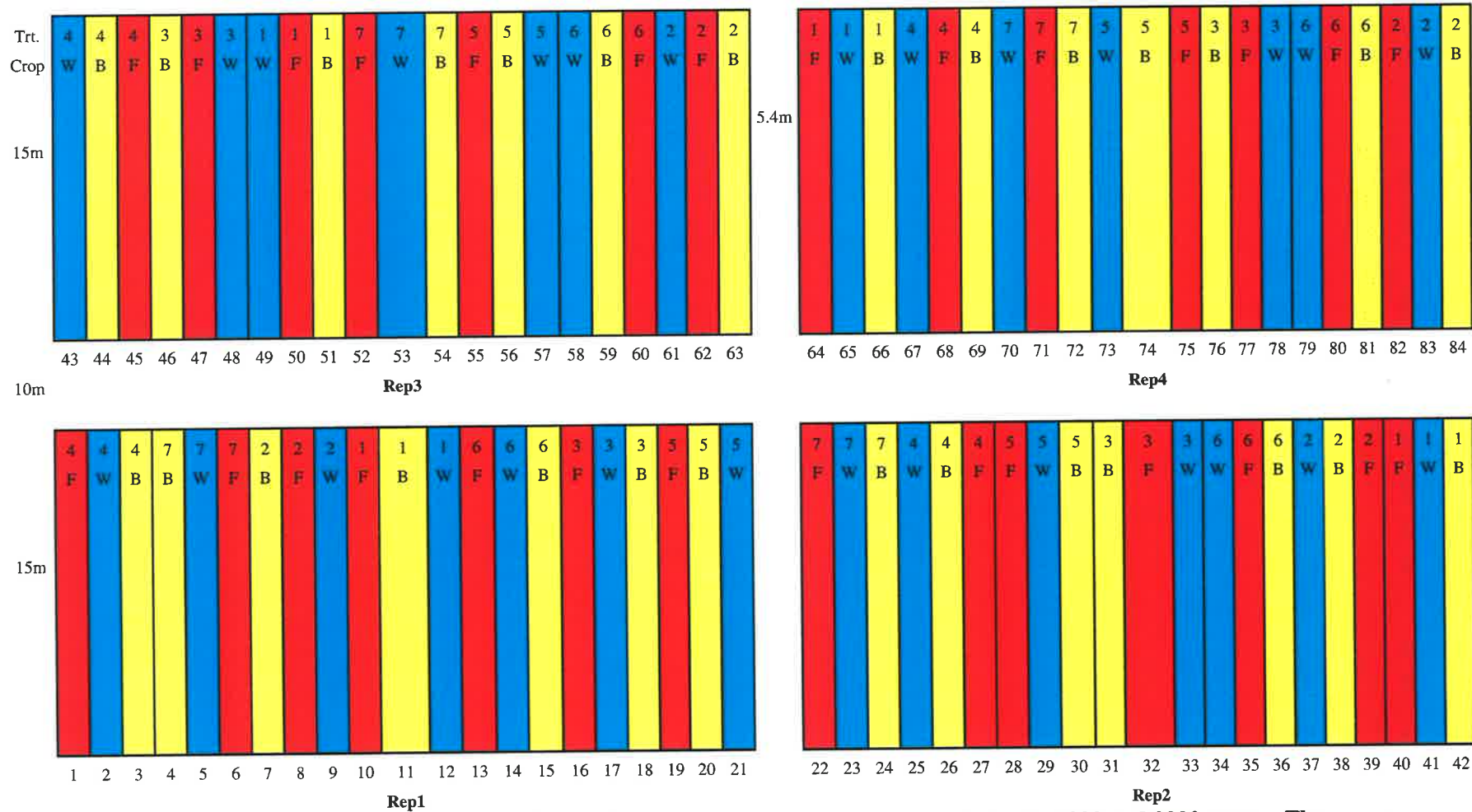
The experimental design at Tarlee has been described in detail by Schultz (1995). However, selected rotations were used in this study and there were 4 two-year rotations (wheat-wheat, wheat-bean, wheat-lupins and wheat-fallow) that were applied continuously up to 1996; two stubble treatments (removed and retained); and 2 rates of nitrogen (0, 80 kg /ha N as ammonium nitrate) applied to the wheat phase. There were 2 phases to allow each crop to be grown each year, and 2 replicates.

### **3.5 Statistical analysis**

Analysis of variance (AOV) was applied to all data, which have been measured over 2 growing seasons to determine significant differences between treatments and sites. Also analysis of variance was used to determine the least significant differences between treatments for soil extraction analysis and between yields for the seven treatments at the three sites. All statistical analyses developed least significant differences calculated from the standard error of difference and the t-test distribution at  $P=0.05$  for the degrees of freedom for each determination. Standard errors were calculated from AOV at the 95% confidence level. Regression analysis also was performed between different soil properties and the coefficient of determination ( $R^2$ ) and the probability (P) as not significant (ns), significant at 0.05 (\*), significant at 0.01 (\*\*), and significant at 0.001 (\*\*\*), where used, are shown. All data were analysed using Genstat 5 statistical analysis software, release 5, 2001 (Lawes Agricultural Trust, Rothamstead, UK) and using SUPER ANOVA statistical analysis software version 1.1 (Abacus Concepts Incorporation 1991).

### **3.6 Hochman model for lime calculation**

A lime requirement model (Hochman *et al.* 1989) developed for the southern slopes of New South Wales was used in the present study. This model is a decision support system tool that can be used for lime prediction for a specific soil. The model takes into account soil properties that affect pH buffering. In the study where the 3 new sites were established the model was used initially for predicting the change in soil pH for these mid-north South Australia soils as an outcome of adding various rates of lime.



**Figure 3.2** Example of experimental design (DS site) used for the field experiments on 3 sites in 1999 and 2000 season. These were 4 replicates and 84 plots, with the treatments (seven soil amendment treatments) and crop (wheat, barley and faba beans).

The Hochman approach uses the combined soil information of field buffering capacity, exchangeable bases, pH and Al to predict lime rates required to raise soil pH to a predetermined level (Hochman *et al.* 1989). Thus this model is used as a means of determining the lime rates required to obtain approximate pH ranges for the soil types being studied.

Equation (9) was used to describe the rate of change in soil pH due to liming.

$$\Delta\text{pH} = B_S (\sqrt{L+1} - 1) \text{ or } L = (\Delta\text{pH}/B_S + 1)^2 - 1 \quad (9)$$

In this formula, where  $\Delta\text{pH}$  is pH increase due to liming,  $B_S$  is buffering capacity of the soil and  $L$  is lime ( $\text{tha}^{-1}$ ).

The relationship between degree of change in soil pH and the initial cation exchange capacity (CEC) of the soil can be described as a possible index for pH buffering capacity and  $SL_S$  as the soil specific variable which determines the slope of the line (Equation 10).

$$\text{TEC} = SL_S (\text{pH} - 2.043) - 0.957 \quad (10)$$

The value of  $SL_S$  can then be predicted from measured pH and TEC values for unlimed soils by using Equation (10a), which is derived from Equation (10).

$$SL_S = (\text{TEC}_i + 0.957)/(\text{pH}_i - 2.043) \quad (10a)$$

The potential use of  $SL_S$  as an index of pH buffering capacity was investigated by its correlation with  $B_S$ . The correlation obtained provides a basis for prediction of pH change for any rate of lime added (Equation 11).

$$B_S = (34.24/(SL_S + 9.5)) - 1.741 \quad (11)$$

The calculation routine for predicting a change in soil pH in response to lime rates is as follows:

Derive a value for  $SL_s$  using Equation (10a)

Use the  $SL_s$  value in Equation (11) to predict  $B_s$

Use the  $B_s$  value in Equation (9) to predict the change in soil pH.

Also to predict the Al level of the soil after lime application, the relationship between pH (expressed as  $H^+$  concentration) and exchangeable aluminium needs to be defined (Equation 12)

$$SLAl_s = (Al \times 90 - 1.0273) / ([H^+] - 3.7 \times 10^{-6}) \quad (12)$$

Where  $SLAl_s$  is the slope of the line relating exchangeable aluminium (Al) to  $[H^+]$  for soil s. Therefore, pH and exchangeable aluminium of an unlimed soil are sufficient data to predict the slope of the  $[H^+]/Al$  line for that soil. Since both pH and TEC can be predicted from equations (9) and (10), percentage aluminium saturation (%Al) can now be predicted for any lime rate (Equation 13).

$$\%Al = 100 \times (-1.233 + SLAl_s / 10pH_L) / (TEC_L \times 90) \quad (13)$$

Where  $pH_L = pH + \Delta pH$ ; and from Equation (10):  $TEC_L = SL_s \times (pH_L - 2.043) - 0.957$

Thus we can use this method to predict changes in soil pH, exchangeable Al and TEC in response to liming. The advantages of this method are: (1) that it requires no laboratory tests other than those required for routine diagnosis; and (2) that it is not limited by preconceived "target" levels of either pH or exchangeable aluminium (Hochman *et al.* 1989). In acid soils, Al exchange by  $H^+$  and hydrolysis of  $Al^{3+}$  ions on organic matter exchange sites are important factors in pH buffering (Bloom *et al.* 1979). But Hochman (pers com. 1998) has shown that organic matter under the range of 5-6% (Hochman *et al.* 1992, 1995) has no significant effect on the buffering capacity of the soil and when considering that the soil used here has OM content of less than 2%, it is better to use the original method of Hochman *et al.* (1989) for LR calculations.

### 3.7 Gypsum calculation

The amount of gypsum requirement (GR) is calculated by the method of Gupta and Abrol (1990), as shown in Equation 14:

$$GR \text{ (t/ha)} = 0.172 \times 104 \times pb \times ds \times n \times (CEC) (ENa_i - ENa_f) \quad (14)$$

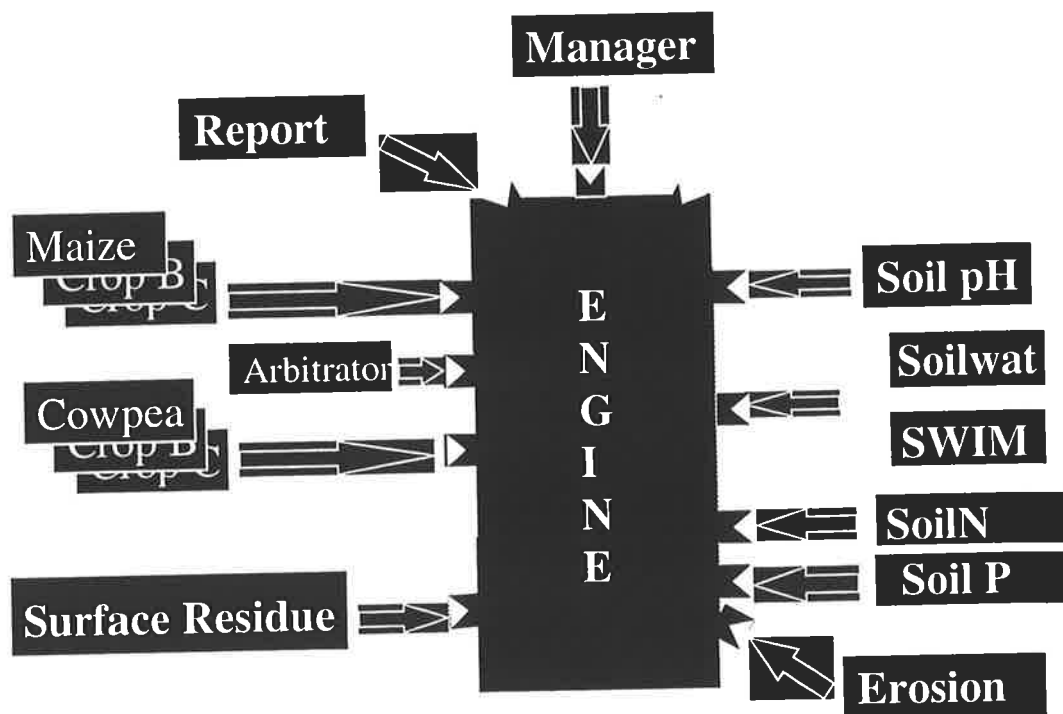
Pb is the bulk density ( $t/m^3$ ), ds is the depth of soil (m), CEC is the cation exchange capacity of the soil (mol (+)/tonne of soil),  $ENa_i$  and  $ENa_f$  are initial and desired final fractions of exchangeable Na, and n is the Na-Ca exchange inefficiency factor, and is usually taken as 1.20 (US Salinity Laboratory Staff 1954). The amount of gypsum calculated was 3.29 t/ha for each site, but the final GR is 20% higher, because gypsum used in this experiment was 80% pure. So the final calculated GR rate for all experimental sites was 4 t/ha. However, notwithstanding this calculation, the amount of gypsum used for the lime+gypsum treatment plots was 2.5 t/ha.

Two important parameters are generally used to define sodic soils, including the exchange Na percentage (ESP) and sodium adsorption ratio (SAR). In this study only ESP was used to describe some of the changes influenced by gypsum application on soil properties. The ESP describes the level of adsorbed Na in the soil and is defined as:  $ESP = 100(\text{exchangeable Na}/CEC)$ . Na was extracted in 0.1 M  $BaCl_2$  and 0.1 M  $NH_4Cl$  (Rayment and Higginson 1992) and then measured by atomic adsorption (Gillman and Sumpter 1986), and is expressed as  $cmol (+) kg^{-1}$ . CEC was determined by summing the concentrations of Ca, Mg, Na, K, Mn and Al (1 M KCl) (Slattery *et al.* 1995).

### 3.8 APSIM program for measuring carbon, N and water dynamics

The APSIM is a modular modelling framework that has been developed by the APSRU group in Australia. APSIM is a software system that easily can be formatted to simulate various production systems (McCown *et al.* 1995) and estimate related processes. APSIM is a modelling framework that allows individual modules of key components of the farming system to be 'plugged in' (McCown *et al.* 1995). The structure of the APSIM (Figure 3.3) software environment (McCown *et al.* 1995) shows that this model consists of elements of a system (as modules), which handle the various sub-systems. Modules are

grouped in biological modules, environmental modules and program management (manager, report and arbitrator) modules (Probert *et al.* 1998a; Keating *et al.* 1997; McCown *et al.* 1995). Output reports done by report module performed from all the rules set by the three mentioned modules, which then allow construction of complex rules to simulate a hypothetical system of actual situations (Carberry *et al.* 1996; McCown *et al.* 1995; Probert *et al.* 1998a). The communication system in APSIM (engine and modules interfaces) allows modules to share information and work as a central control unit (Verburg 1995). This works as a 'plug-in plug-out' system of sharing information to the main engine, so they are able to permit the simulation by minimal changes to existing code (McCown *et al.* 1995) as shown in Figure 3.3.



**Figure 3.3** Diagrammatic representation of the APSIM simulation framework with separate modules, interfaces and simulation engine (Keating *et al.* 2001).

APSIM can simulate farming systems with information on yield estimation in response to management and also prediction of the long-term consequences of farming practice on the soil resources (e.g. soil organic matter dynamics, erosion, acidification etc.). In each simulation, different modules of soil-state variables such as soil water balance, nutrient

flow (nutrient dynamic, which includes soil C and N balances), residue decomposition, and soil erosion are integrated dynamically, flexibly and continuously by an engine to describe processes in crop and pasture growth and development in response to weather and management options (Carberry *et al.* 1996; McCown *et al.* 1995; Probert *et al.* 1998b). Also region-based information with various soil processes are simulated, which differ between users, to get a description of the crop, with yield as the output (Verburg 1995; Carberry *et al.* 1996; McCown *et al.* 1995; Probert *et al.* 1998b).

SOILWAT has been described by Probert *et al.* (1998b), as a cascading layer model that originally as a concept was taken from CERES (Jones and Kiniry 1986) and PERFECT (Littleboy *et al.* 1989, 1992). SOILWAT operates on a daily-time step. The water characteristics of the soil are specified in terms of the lower limit (ll15), drained upper limit (dul) and saturated (sat) volumetric water contents of a sequence of soil layers. SOILN is the module that simulates the mineralisation of nitrogen and thus the N supply available to a crop from the soil and residues/roots from previous crops (Probert *et al.* 1998a). SOILN originated from the CERES (eg. Jones and Kiniry 1986) and PAPRAN models (eg. Seligman and van Keulen 1981). The surface residue module (RESIDUE) has been described by Probert *et al.* (1998a). Much of the tillage incorporation and cover relationships are retained from PERFECT (Littleboy *et al.* 1989, 1992, 1996). A more mechanistic basis for the decomposition of surface residue to maintain the carbon and nitrogen balances in the SOILWAT module was described by Carberry *et al.* (1996).

The SOILpH module can be plugged into APSIM and give the capability to calculate the rate and distribution of acidification in cropping systems and used as a modelling framework for research and management of soil acidification (Hochman *et al.* 1998). The APSIM SOILpH module can provide a representation of the acidification of soil, and how pH changes are distributed through the profile, as a consequence of the imbalance in uptake of cations and anions, the leaching of nitrate, and changes in soil organic matter content. SOILpH is based on the proton balance of Helyar and Porter (1989), where the balance of hydrogen ions in the soil-plant system can be calculated and related to changes in soil pH. Accordingly SOILpH uses the simulation of N and C to predict changes in soil pH (Hochman *et al.* 1998). The SOILpH module employs empirical functions to calculate pH buffer capacity and pH-Al relationships. SOILpH module uses standard solubility

constants to allow for reactions of CO<sub>2</sub>, CaCO<sub>3</sub>, Al silicates and others. The need to simulate changes in pHBC through time is resolved using empirical relationships as described by Hochman *et al.* (1995). The pH buffering in this approach has been categorised as a function of hydrogen ion concentration, effective cation exchange capacity, exchangeable aluminium and percent organic carbon. So the SOILpH module can keep track of all the parameters used to calculate pHBC, and it can update its value over time to keep up with changes in factors that modify buffering (Hochman *et al.* 1998).

In the present study, however, only some modules from the APSIM program have been used to describe the dynamics of C, N and water in plant-soil ecosystems and response to management practices. These modules are used for the Tarlee experimental site as explained in chapter 6. The modules from APSIM that are used in this study are, carbon, nitrogen, residue, legumes, wheat, manager and report. Each module was specified to simulate the various treatments as continuous runs (1978-1996) and was initialised only at the start of the experiment before the 1978 crop. The SOIL pH module has not been used in simulation of data in this thesis and the reason for this decision will be explained in chapter 8. For other modules, however, there was no difficulty in specifying APSIM to mimic the management practices of the Tarlee data.

## Chapter 4

### 4. Effect of lime and sulfur application on soil properties and crop yields

#### 4.1 Introduction

As soils become more acidic then soil factors associated with low pH, especially Al, can cause plant yields to decline. There is clear evidence that cropping soils in the higher rainfall areas (>500 mm) of Australia (north eastern Victoria, southern New South Wales) are affected by acidity (Coventry 1992; Cregan and Scott 1998), and in Western Australia acidification is affecting the medium rainfall (400-500mm) cropping areas (Dolling *et al.* 1994 a&b; Dolling 1995). There are large areas of low pH soils in the medium rainfall cropping areas in South Australia, but to date there is little information on whether this acidity is affecting crop production.

To enhance crop productivity on acid soils lime application is usually recommended, but soils can respond to lime application in different ways. In most studies (eg. north eastern Victoria and southern NSW) where the soil pH<sub>Ca</sub> was less than 4.7, yield responses of the order of 20-100% with wheat have been obtained after liming the soil (Cregan *et al.* 1989; Coventry 1992). In Western Australia on duplex soil types, various lime responses have been reported (Dolling *et al.* 1991), including sometimes negative growth effects (Carr *et al.* 1991). In some studies on acidic soils in the eastern states of Australia there also was no clear growth benefit after liming (Scott 1982; Ellington 1986; Coventry *et al.* 1989 a&b; Coventry 1991).

In South Australia little is known for the cropping areas on whether yield responses will be obtained following lime application. Little research has been undertaken in these areas on lime application rates, crop responses and any possible adverse affects on nutrient processes that could affect yield. There have been no attempts to discriminate any responses to lime on the basis of soil type, or to evaluate methods for determining the amount of lime to be applied to soils affected by acidity.

Various methods have been tried and used for estimating lime requirement and crop responses; for example target pH (Shoemaker *et al.* 1961; Adams and Evans 1962; Curtin *et al.* 1984; Edmeades *et al.* 1985) or toxic Al removal (Kamprath 1970; Reeve and Sumner 1970; Webber *et al.* 1976; Farina *et al.* 1980; Ritchey and Sousa 1997) and a soil buffer capacity method (Edmeades *et al.* 1985). However this latter method and also a range of other laboratory methods underestimate the lime required to reach a target pH as determined from field trials (Edmeades *et al.* 1985). For liming requirement estimation it appears to be better to use combined soil information such as field buffering capacity, exchangeable bases, Al and pH (Hochman *et al.* 1989), and to discriminate responses to lime on the basis of soil type, crop species and relative grain yield response (Slattery and Coventry 1993). The approach for estimating lime requirement used in this thesis arose from the lime prediction research of Hochman *et al.* (1989, 1995), and was subsequently adapted by Slattery and Coventry (1993). In this chapter such a lime prediction approach (Hochman *et al.* 1989) is field validated for a commonly found soil type of South Australia to accurately establish lime requirements based on a relative grain yield response. Further, the calculated lime rates are used in field experiments to investigate the lime responsiveness of a range of field crops, and to provide information on soil acidity factors as part of lime prediction models and plant responsiveness.

## **4.2 Materials and methods**

### **4.2.1 Site selection and soil description**

Three field sites were established in 1998 on acidic soils in the lower and mid-north regions of South Australia. Soil description for these sites and mean annual rainfall for these areas are given in Table 4.1 and Table 3.4. The criteria for site selection were low soil pH, uniform soil type and rotation history (Table 3.1). The rotations chosen for this experiment were based on the study objectives, field history and farmer preference. These locations are selected to also represent medium-high rainfall regions of South Australia. Some of the chemical characteristics of the soil at these sites before the treatments were imposed are given in Table 3.2.

#### 4.2.2 Experimental treatments

The information obtained for site chemical analysis (Table 3.2) was required so that the lime (to increase pH) and sulphur (to decrease pH) rates could be estimated from models developed by Hochman *et al.* (1989) and Slattery and Coventry (1993). In February of 1999 the 3 sites were treated with 7 soil amendment treatments, which were randomised within 4 replicates in a split plot design. The plots were 1.8 × 15 m long and the seven amendment treatments were as follows: Control (nil lime), Sulfur (0.3 t/ha), Gypsum (4 t/ha), Lime + Gypsum (2.5+2.5 t/ha), Lime1 (1 t/ha), Lime 2 (2 t/ha) and Lime 3 (4 t/ha), and crop species as the sub-plots within the main soil treatments. Data for Lime 1 (L1), Lime 2 (L2), Lime 3 (L3), Sulfur (S) and the Control (C) are given in this chapter. Data for the 2 gypsum treatments and source of the other soil treatments are given in the next chapter. In each year (1999, 2000), each site was sown with 3 crop varieties out of 5 chosen species. Table 4.2 shows the crop varieties used in these experiments.

**Table 4.1 Description of the 3 soils in South Australia used in this study**

Site and location <sup>A</sup>	Texture of A horizon	Handbook of Australian soils <sup>B</sup>	Factual key <sup>C</sup>	World soil map <sup>D</sup>	The Australian Soil Classification <sup>E</sup>
1. Marrabel (Geoff Rowett - GR)	Clay loam	Sodic red-brown earth	Dr2.23	Calcic luvisol	Eutrophic Subnatric, Red Sodosol; medium, non-gravelly, clay loamy/clayey, shallow.
2. Kapunda (David Shannon - DS)	Fine sandy loam	Non-calcic brown soil (sodic)	Db1.12	Chromic luvisol	Eutrophic, Subnatric, Brown Sodosol; medium, non-gravelly, sandy/clayey, deep.
3. Kapunda (Mick Ryan -MR)	Light sandy clay loam	Sodic red-brown earth	Dr2.13	Calcic luvisol	Eutrophic, Subnatric, Red Sodosol; thin, non-gravelly, loamy/clayey, shallow.

<sup>A</sup>Farmer cooperator in parentheses <sup>B</sup>Stace *et al.* 1968; <sup>C</sup>Northcote 1979; <sup>D</sup>Northcote *et al.* 1975; <sup>E</sup>Isbell (1996). Note: GR site overlies 15 cm of highly calcareous saprolite at 50cm; DS site overlies salty, blocky, calcareous, heavy clay at 105 cm; and MR site overlies slightly calcareous saprolite at 40cm.

Lime and sulphur rates were estimated using field buffering capacity, calculated from the sum of the exchangeable cations (ECEC), and the pH for each site (Table 4.3). The 'target' lime rate as estimated by the Hochman model was designated as L2, and L3

represented a higher and L1 a lower rate respectively than the target rate. The sulfur treatment was included to induce Al toxicity, and determine the crop responses to additional soil acidity. The S rate was calculated assuming that 1 mole CaCO<sub>3</sub> equals 3.125 mole S. Lime was spread with a 1.5m-drop spreader (Scott and Rodham 1987) and powdered S was spread by hand on the surface soil. After the materials were spread, the soil was cultivated and treatments were incorporated to a depth of 10cm by one pass with a scarifier. The lime was ground agricultural limestone containing 40% Ca (98% CaCO<sub>3</sub>) and 0.3% Mg (mainly as MgCO<sub>3</sub>), with an effective neutralizing value of 96%, with 100% of the product less than 250 µm in particle size. The gypsum was 80% pure containing 21.15% Ca, 16.18% S, 0.02% soluble chloride and 2% free moisture. The lime was supplied by Omya Southern (Linfield, New South Wales-Mr. Bob Macoun) and gypsum supplied by Processed Gypsum in South Australia (Mr. Andrew Newland).

**Table 4.2 Crop varieties and agronomic information used for 3 sites.**

Crop	Cultivars	1000 grain weight (g)	Target plant density (plants/m <sup>2</sup> )	Seeding rate (kg/ha)
Wheat ( <i>Triticum aestivum</i> )	Janz	34	180	72
Barley ( <i>Hordeum vulgare</i> )	Franklin	41	180	83
Canola ( <i>Brassica napus</i> )	Dunkeld	4	80	3.5
Durum ( <i>Triticum turgidum</i> )	Yallaroi	52	180	104
Faba beans ( <i>Vicia faba</i> )	Fiesta	650	40	180

#### 4.2.3 Crop management

In 1999 all sites were sown on 27 and 28 of May and in 2000 the crops were sown on 3 and 4 of June (Plate 1). Depths of sowing were 3-4 cm for wheat, durum and barley, 2 cm for canola and 4-5 cm for faba beans. Crops were sown with a cone-seeder with narrow points and a press wheel. The crop species and cultivars and seeding rate and densities are shown in Table 4.2. Fertiliser for barley at sowing was in the form of triple superphosphate, as 25 kg P/ha, and 40 kg/ha N as urea. An overall 80 kg/ha of 18:20:0, N:P:K, with 2.5% Zn was applied to canola, faba, durum and wheat in 1999 and 2000, but an extra 25 kg/ha N at tillering stage was applied with these crops only in the 1999

season. The objective with fertiliser choice was to use product and rates as close as possible to the current farmer practice.

**Table 4.3 Soil properties used to calculate the lime requirement.**

Site	Exchangeable cations (cmol/kg)										
	pH <sub>Ca</sub>	Ca	Mg	Na	K	Al	Mn	ECEC	B <sub>s</sub>	SL <sub>s</sub>	Organic C%
DS	4.32	2.5	0.66	0.23	1.23	0.14	0.09	4.83	1.09	2.59	1.30
GR	4.62	4.85	1.46	0.32	0.32	0.11	0.07	7.59	0.92	3.35	1.88
MR	4.69	4.12	0.72	0.31	0.31	0.04	0.04	5.77	1.1	2.56	1.38

ECEC (effective cation exchange capacity), Field buffering capacity (B<sub>s</sub>), and slope of the regression of pH and total exchangeable bases (SL<sub>s</sub>) were calculated from the model of Hochman *et al.* (1989). Each site represents a bulked 0-10 cm sample from 20 cores taken randomly over the site in February 1998.

Before sowing in both years each site was sprayed for emerged weeds with Glyphosate (2 L/ha). Post emergent weeds were controlled during the growing season according to district recommendations, and the constraint provided by having the mix of crop species within the experiment. Where possible, Glean (18 g/ha) or Achieve (380 g/ha) was used for ryegrass control. In July 1999 Omethoate (50mL/ha) was sprayed for lucerne-flea and red-legged earth mites on sites coming out from pasture (GR and MR sites). In the 2000 season Mancozeb (2.5 kg/ha) was used to prevent chocolate spot on the faba bean plots. At mid-late tillering the pathways between plots and reps were sprayed with Glyphosate (2 L/ha) using a shielded boom sprayer.

#### 4.2.4 Crop measurements

Whole plots were machine harvested at maturity using a KEW harvester on 29 December 1999 and 4 December 2000 to measure grain yield. The harvested yield of each plot area (19.7 m<sup>2</sup>) was then converted to t/ha using a conversion factor of 0.5072. Destructive sampling was performed only in the 2000 season and involved pulling 2×0.5 m rows of plants intact, from 3 random spots/plot, so as to measure dry matter (DM). These data are only shown for the wheat crop at DS site (2000), where grain yield data are not reliable due to frost damage.

#### **4.2.5 Soil sampling and measurements**

Soils samples were collected from the 0-10 cm soil depth during September of 1998, 1999 and 2000. Each plot was randomly sampled by taking 15 soil cores that were cut into increments before bulking into plastic bags. Sub-samples to be used for solid phase chemical determinations were dried immediately after field sampling, in a fan forced oven at 40°C for 24 hours. The soil was then ground between rollers to pass through a 2 mm sieve, and stored in sealed 500 ml plastic containers at room temperature for further analyses.

##### **4.2.5.1 Field pH buffer capacity**

Soil pH Buffer Capacity was measured involving the reaction of two buffer solutions  $\text{Ca}(\text{OH})_2$  and  $\text{NaOH}$  (the method similar to that of Aitken and Moody 1994). In brief, titration curves were established by adding incremental amounts of  $\text{Ca}(\text{OH})_2$  or  $\text{NaOH}$  to soil suspended (1:5) in water (Noble *et al.* 1997). For each titration, 5g of soil were weighed into each of 6 polyethylene tubes, and appropriate amounts of deionised water added to a final volume of 25ml. The concentration of  $\text{Ca}(\text{OH})_2$  or  $\text{NaOH}$  was 0.04 mol/L (standardised) and, for each soil, additions of 0, 0.15, 0.25, 0.5, 1.0 and 2.0 ml were made. To minimise variations in ionic strength, additions of 1.0 mL of 0.05 mol/L  $\text{CaCl}_2$ , as well as 0.25 mL of chloroform, were made to each tube and the suspensions were shaken for 24 h at 25°C (end-over-end shaker). The suspensions were then equilibrated for a further 6 days at 25°C, followed by re-suspension by shaking the samples for 2 minutes daily for a total 7 days, then EC and  $\text{pH}_w$  was determined at day eight. Finally 0.5 mL of 0.5 M  $\text{CaCl}_2$  was added to each solution and  $\text{pH}_{\text{Ca}}$  was recorded. Then linear regressions were fitted to titration data with pH values versus mmol/kg of buffer used and the slopes of these lines were used as a measure of pHBC.



**Plate 4.1 Photographs of the DS (top) and GR (bottom) sites illustrates the canola and wheat crops grown in 1999.**

#### 4.2.5.2 Soil chemical characteristics

The soil  $pH_w$  and EC were measured in 1:5, soil to water, mixed by end-over-end shaking for 1 hour, rotating at 30rpm. EC and  $pH_w$  was first measured then 0.5 mL of 0.5 M  $CaCl_2$  was added to each container and  $pH_{Ca}$  was measured. Soil extractable (extracted by 0.01 mol/L  $CaCl_2$  using 1:5 soil:solution) and exchangeable Al (extracted by 1mol/L KCl using 1:10 soil:solution) were determined by a modification of the method of Wilson and Sergeant (1963), where Al was measured colorimetrically by catechol violet, and hexamethylene-tetramine was used to maintain the solution pH at 6.1 – 6.2 and as the colour-developing reagent. All reagents were prepared fresh on the day of assay. Mn was determined in the same extracts as Al by atomic absorption spectroscopy. Al and Mn extracted in 0.01 M  $CaCl_2$  are both expressed as mg per kg soil. Al was also extracted in 1 M KCl and analysed colorimetrically as above and expressed as  $cmol (+) kg^{-1}$ . Ca, Mg, Na and K were extracted in 0.1 M  $BaCl_2$  and 0.1 M  $NH_4Cl$  (Rayment and Higginson 1992) and then measured by atomic absorption (Gillman and Sumpter 1986), and are expressed as  $cmol (+) kg^{-1}$ . ECEC was determined by summing the concentrations of Ca, Mg, Na, K, Mn and Al (1 M KCl) (Slattery *et al.* 1995). Boron was measured similarly to the method (12C1) in Rayment and Higginson (1992). The DTPA extractable method similar to method 12A1 in Rayment and Higginson (1992) has been used to determine Cu, Fe, Mn and Zn.

#### 4.2.6 Statistical analysis

A linear and nonlinear regression analysis was applied to the means of the yield data, plotted with the mean soil pH collected over 2 growing seasons, for wheat, durum, barley and one growing season for canola and faba bean. Backward elimination was used to calculate the relationship between relative yield, and means of pH and extractable Al and Mn for each species at each site to predict yield. The coefficient of variation ( $R^2$ ) was calculated for each relationship from the analyses. Analysis of variance (ANOVA) was applied to the relative yields of the crops over 2 growing seasons to determine significant differences between these sites. Also ANOVA was used to determine the least significant differences between treatments for soil extraction analysis and between yields for the seven treatments at three sites. Also, to determine whether sites used in this experiment

are uniform, mean and standard deviation (Sd) were calculated for each soil property and depths at each site.

### 4.3 Results

#### 4.3.1 Yield data

The analysis of variance for the data in year 2000 is shown in Table 4.4. This table clearly shows that there were significant differences between lime treatments on yield and also between crop species at all 3 sites. Table 4.5, 4.6 and 4.7 show the yield data for all crops for the 1999 and 2000 experimental seasons. Grain yield data for the DS site in the 1999-growing season for wheat and barley showed no significant changes with the lime treated plots compared with nil-lime plots, with the exception of canola, and this only happened for L1 and L2 treatments. At the GR site for the 1999 season, only the S treatment produced a significant change ( $P < 0.05$ ) with reduced yield for all species; the lime treatments did not improve yield. At the MR site for the 1999 season, only wheat showed a significant increase in yield and only for the highest lime treatment (L3).

**Table 4.4 Summary of analysis of variance for the effect of treatment and crop species on yield at all sites for year 2000 season.**

Source	DS site			GR site		MR site	
	df	MS	P	MS	P	MS	P
Rep	3	0.005	ns	0.00	ns	0.000	ns
Lime treatment	4	3.600	***	3.46	***	5.490	***
Rep×treatment	12	0.003	ns	0.00	ns	0.002	ns
Crop	2	30.890	***	1.94	***	0.760	***
Lime×Crop	8	0.020	***	0.16	***	0.270	***
Residual	30	0.003		0.002		0.002	

\*\*\* Significant at  $P=0.001$  and ns= not significant, P= probability, MS= mean square and df is the degrees of freedom.

In the 2000 growing season (Table 4.5, 4.6, 4.7 and Figure 4.1), the S treatment at all sites decreased yield ( $P > 0.001$ ) compared with all other treatments. Generally, at each site the L1, L2 and L3 treatments produced higher yields ( $P > 0.001$ ) compared to the C

treatment. The L2 treatment produced significantly higher yield response compared to L1 and L3 treatments for all species at the MR site. At the GR site the trend was similar and L2 had higher yield compared to L1 and L3, but only for durum and barley. At the DS site, increasing lime rates significantly ( $P>0.001$ ) improved yield for all crop species. The photograph reproduced in Plate 4.2 shows the dramatic effect of soil acidity (S and nil lime plots) on faba bean, compared with medium lime rate (L2), at the GR site in 2000.

**Table 4.5 Mean yield data for 2 growing seasons at DS site. The effect of treatment on crop yield has been shown. Note that yield is the mean data for all species over each growing season 1999 and 2000.**

Site	Treatment	Crop (1999)	Crop (2000)	Mean yield 1999 (t/ha)	Mean yield 2000 (t/ha)	±s.e. for	
						yield 1999	yield 2000
DS	C	B	B	2.46	2.56	0.02	0.02
DS	L1	B	B	2.48	3.12	0.03	0.04
DS	L2	B	B	2.35	3.36	0.02	0.02
DS	L3	B	B	2.17	3.69	0.02	0.01
DS	S	B	B	2.40	1.97	0.01	0.02
DS	C	C	F	1.94	0.75	0.03	0.02
DS	L1	C	F	1.87	1.39	0.01	0.01
DS	L2	C	F	1.92	1.73	0.01	0.02
DS	L3	C	F	1.99	1.79	0.03	0.01
DS	S	C	F	1.88	0.25	0.04	0.02
DS	C	W	W	2.29	0.67(10.58) <sup>1</sup>	0.03	0.01
DS	L1	W	W	2.33	0.53(10.66)	0.01	0.05
DS	L2	W	W	2.44	0.50(11.08)	0.02	0.04
DS	L3	W	W	2.38	0.62(12.25)	0.02	0.02
DS	S	W	W	2.46	0.80 (9.86)	0.02	0.01

<sup>1</sup>data in parenthesis indicate DM production (t/ha) because wheat yield lost due to frost damage

**Table 4.6 Mean yield data for 2 growing seasons at GR site. The effect of treatment on crop yield has been shown. Note that yield is the mean data for all species over each growing season 1999 and 2000.**

Site	Treatment	Crop (1999)	Crop (2000)	Mean yield 1999 (t/ha)	Mean yield 2000 (t/ha)	±s.e. for yield 1999	±s.e. for yield 2000
GR	C	B	B	2.13	1.70	0.04	0.03
GR	L1	B	B	2.15	2.27	0.03	0.01
GR	L2	B	B	2.11	2.74	0.06	0.02
GR	L3	B	B	2.03	2.29	0.04	0.03
GR	S	B	B	2.00	1.37	0.13	0.02
GR	C	D	F	2.51	1.20	0.05	0.01
GR	L1	D	F	2.69	1.57	0.02	0.03
GR	L2	D	F	2.55	2.10	0.03	0.03
GR	L3	D	F	2.67	2.01	0.03	0.04
GR	S	D	F	2.29	0.74	0.05	0.01
GR	C	W	W	1.75	1.52	0.03	0.01
GR	L1	W	W	1.85	2.67	0.03	0.01
GR	L2	W	W	1.90	2.56	0.02	0.03
GR	L3	W	W	1.98	2.11	0.04	0.03
GR	S	W	W	1.36	1.42	0.03	0.01

**Table 4.7 Mean yield data for 2 growing seasons at MR site. The effect of treatment on crop yield has been shown. Note that yield is the mean data for all species over each growing season 1999 and 2000.**

Site	Treatment (1999)	Crop (1999)	Crop (2000)	Mean yield 1999 (t/ha)	Mean yield 2000 (t/ha)	±s.e. for yield 1999	±s.e. for yield 2000
MR	C	C	B	2.00	2.20	0.02	0.02
MR	L1	C	B	2.12	2.94	0.01	0.03
MR	L2	C	B	2.12	3.89	0.04	0.03
MR	L3	C	B	2.07	3.51	0.03	0.01
MR	S	C	B	1.95	1.88	0.04	0.03
MR	C	D	D	2.39	2.47	0.04	0.01
MR	L1	D	D	2.78	2.41	0.02	0.02
MR	L2	D	D	2.83	3.18	0.03	0.02
MR	L3	D	D	2.59	2.74	0.03	0.05
MR	S	D	D	2.75	1.68	0.02	0.01
MR	C	W	W	2.72	2.12	0.01	0.09
MR	L1	W	W	2.68	2.33	0.05	0.07
MR	L2	W	W	2.76	3.45	0.05	0.10
MR	L3	W	W	2.51	3.35	0.03	0.11
MR	S	W	W	2.56	1.99	0.03	0.09

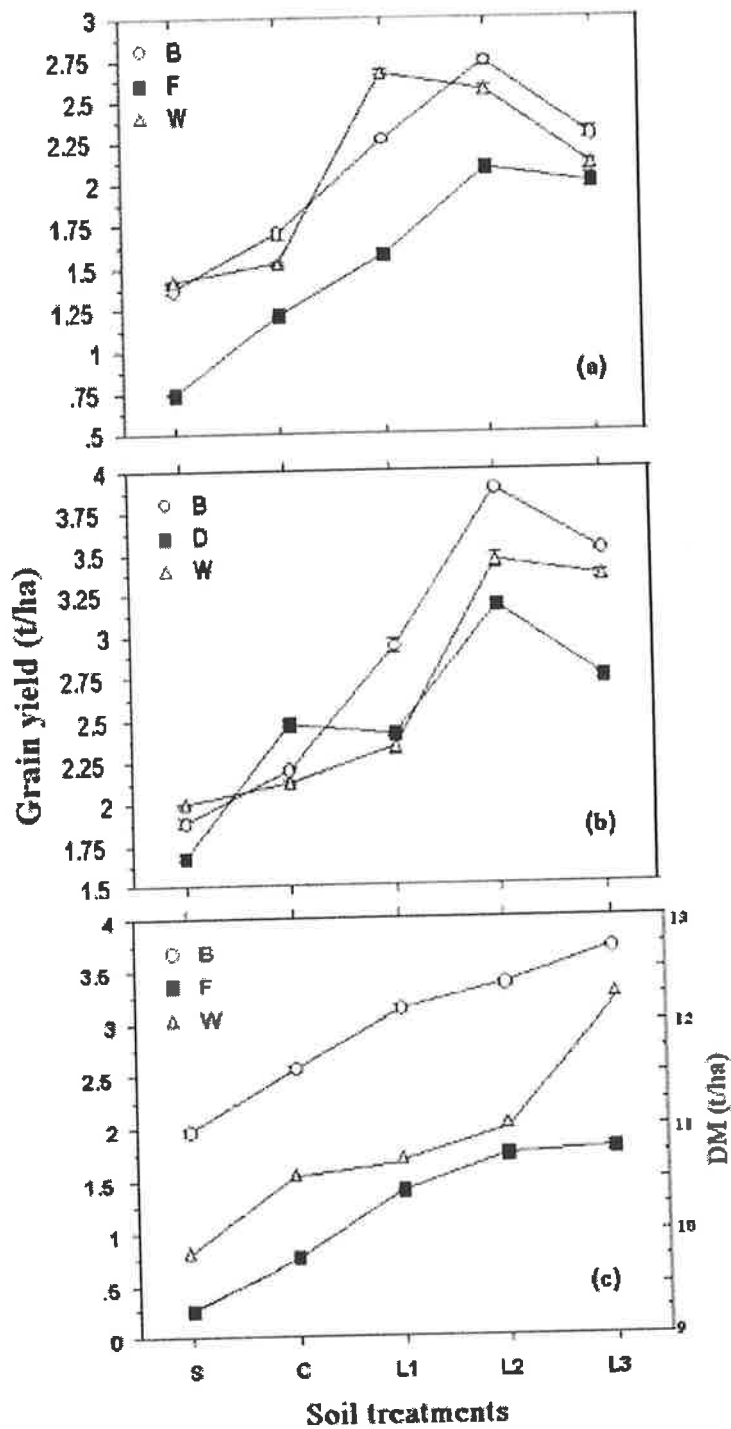


Figure 4.1 Relationship between crop × lime treatment for grain yield at GR (a), MR (b) and DS (c) sites respectively in 2000. The data shown in section c for wheat is DM (t/ha) production.



Plate 4.2 Photographs of the GR site showing the effect of nil lime, Lime 2 and Sulfur on faba beans taken on June 2000

The regression analyses between grain yield and pH are calculated for all sites (Table 4.8), and show that almost 90% of variability in yield was accounted for by variations in pH for all species. In all sites increasing lime rates increased pH but the nature and extent of yield responses differed slightly at the different sites. These relationships (from Table 4.8) are shown in Figure 4.2, with all data points shown and regression lines fitted. The regression for the GR site indicated quadratic responses with barley and wheat, but for faba beans the response was linear. At this site (GR site) with the barley and wheat the yield started to decrease at higher soil pH. At the MR site increasing soil pH improved yield for wheat and barley, but the yield for durum decreased with more increase in soil pH. However, for the DS site this yield improvement continued to increase as a linear response with increasing lime rates and soil pH. Unfortunately the wheat at the DS site was frost damaged and no meaningful yield harvest was possible.

**Table 4.8 Regression equations for the relationship between grain yield of each crop species and  $pH_{Ca}$ ; the data are presented in Figure 4.2 for 3 sites.**

Site	Regression equation	A ( $\pm$ s.e.)	B ( $\pm$ s.e.)	C ( $\pm$ s.e.)	R <sup>2</sup>
Wheat					
GR	Yield= $A \times pH + B \times pH^2 + C$	$7.54 \pm 3.12$	$-0.68 \pm 0.31$	$-18.49 \pm 7.81$	0.89
MR	Yield= $A \times pH + B$	$0.97 \pm 0.13$	$-2.32 \pm 0.64$		0.88
Barley					
GR	Yield= $A \times pH + B \times pH^2 + C$	$5.98 \pm 2.15$	$0.53 \pm 0.22$	$-14.43 \pm 5.29$	0.85
MR	Yield= $A \times pH + B$	$1.29 \pm 0.16$	$-3.75 \pm 0.82$		0.89
DS	Yield= $A \times pH + B \times pH^2 + C$	$2.35 \pm 0.85$	$-0.16 \pm 0.08$	$-4.66 \pm 2.12$	0.92
Durum					
MR	Yield= $A \times pH + B \times pH^2 + C$	$5.22 \pm 2.24$	$-0.45 \pm 0.22$	$-12.37 \pm 5.61$	0.85
Faba					
GR	Yield= $A \times pH + B$	$0.92 \pm 0.10$	$-3.14 \pm 0.52$		0.91
DS	Yield= $A \times pH + B \times pH^2 + C$	$4.27 \pm 1.01$	$-0.35 \pm 0.10$	$-11.27 \pm 2.49$	0.92
Canola					
DS	Yield= $A \times pH + B$	$0.02 \pm 0.02$	$1.84 \pm 0.12$		ns
MR	Yield= $A \times pH + B$	$-0.05 \pm 0.05$	$2.28 \pm 0.24$		ns

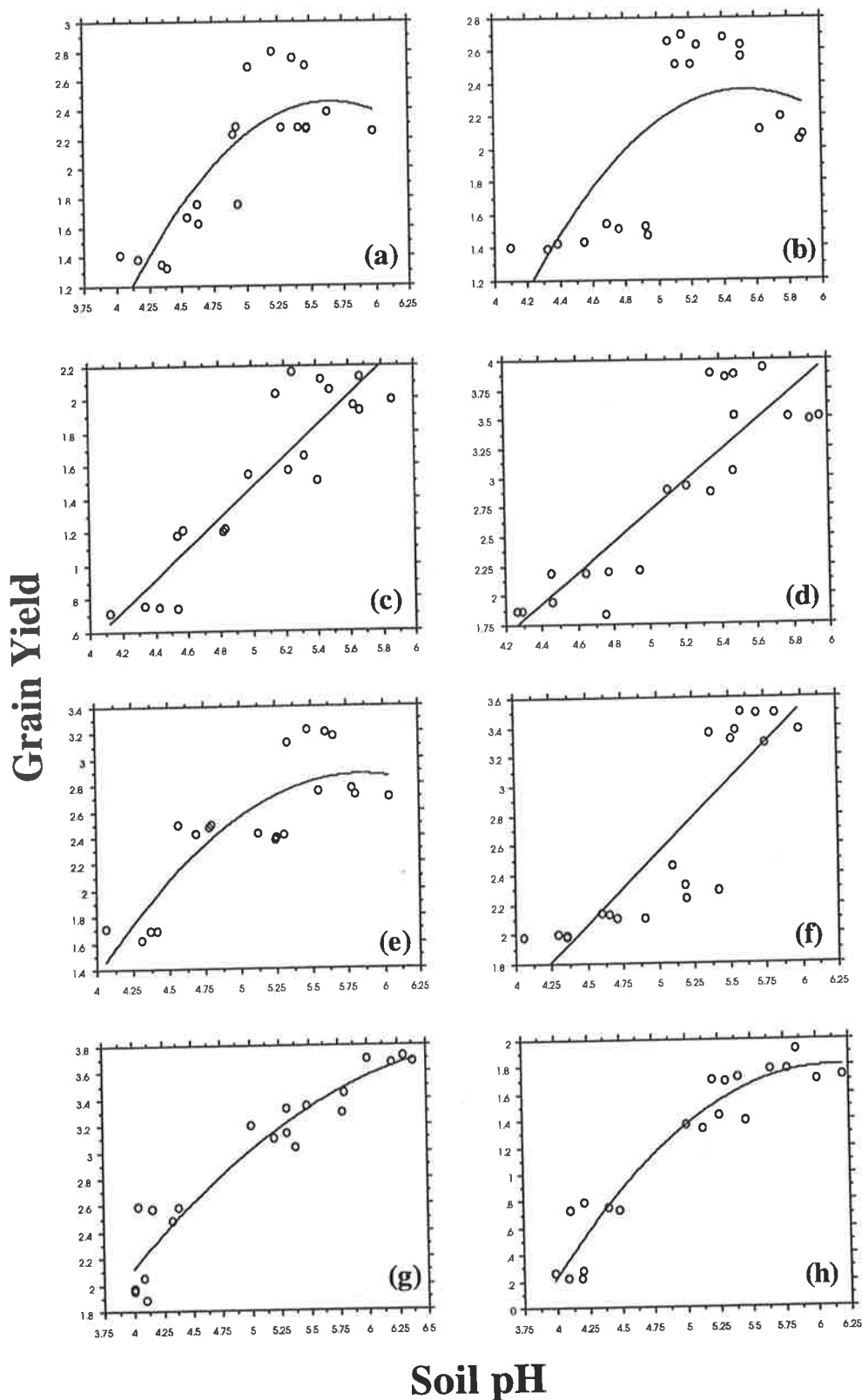


Figure 4.2 Relationship between grain yield (t/ha) and  $\text{pH}_{\text{Ca}}$  for GR; barley (a), wheat (b) and faba beans (c); for MR barley (d), durum (e) and wheat (f); and for DS barley (g) and faba beans (h) on 3 experimental sites in 2000 season. The dark line indicates the best fitted line and the formula is shown in Table 4.8.

## 4.3.2 Soil chemical parameters

### 4.3.2.1 Soil pH

Soil pH<sub>w</sub> and pH<sub>Ca</sub> are presented for all the soil treatments in 1999 (Table 4.9) and 2000 (Table 4.10). The relationships between soil pH<sub>Ca</sub> for each treatment and crop species, after 12 months in the 2000 growing-season are shown at each site (Figure 4.3). The data show that pH has been increased linearly as the lime rates were increased at all sites. Sulphur treatment decreased pH level significantly compared with the control and lime treatments at all 3 sites. There was a significant increase in pH also from the 1999 season and the 2000 season, possibly because of delay in lime dissolution. There was no difference in soil pH change associated with the different crop species (Figure 4.3). Figure 4.4 shows the relationship between the lime applied and the change in soil pH<sub>Ca</sub> at 3 sites (GR, MR and DS sites) in 1999 and 2000 season. For all 3 sites the measured pH data from the field (in 2000) are very close to the pH values that are predicted from the Hochman model. The change in soil pH values for each individual soil treatment from 1999 towards 2000 season can be clearly seen in Figure 4.4. This model provided a very good estimate of the final pH for soil treatments at each of the 3 sites.

### 4.3.2.2 Soil pH buffer capacity

The value of pHBC measured for each site and each method (using Ca(OH)<sub>2</sub> or NaOH ) varied and the amounts of lime required to neutralize acidity were not similar when calculated by the different methods (Table 4.11). The high coefficient of variation (R<sup>2</sup>) for all 3 sites shows the accuracy of the measurement used for all these methods. The lime required to neutralize acidity is calculated to be 50 kg CaCO<sub>3</sub>/ha/10 cm for each mmolc/kg/ha. To account for soil bulk density for each layer, this number (50) needs to be multiplied by 1.3, which comes to 65. So the data in the pHBC column are thus multiplied, which then gives lime requirement for each site and buffer method. The GR site has the highest pHBC amongst all sites and consequently the highest estimate of lime required to neutralise its acidity. The variability between the values of pHBC at the different sites measured by Ca(OH)<sub>2</sub> method is higher compared to the NaOH method (Table 4.11). However the lime requirement calculated by these two methods is much lower than the LR rate calculated from the model (Hochman *et al.* 1989) used in this study.

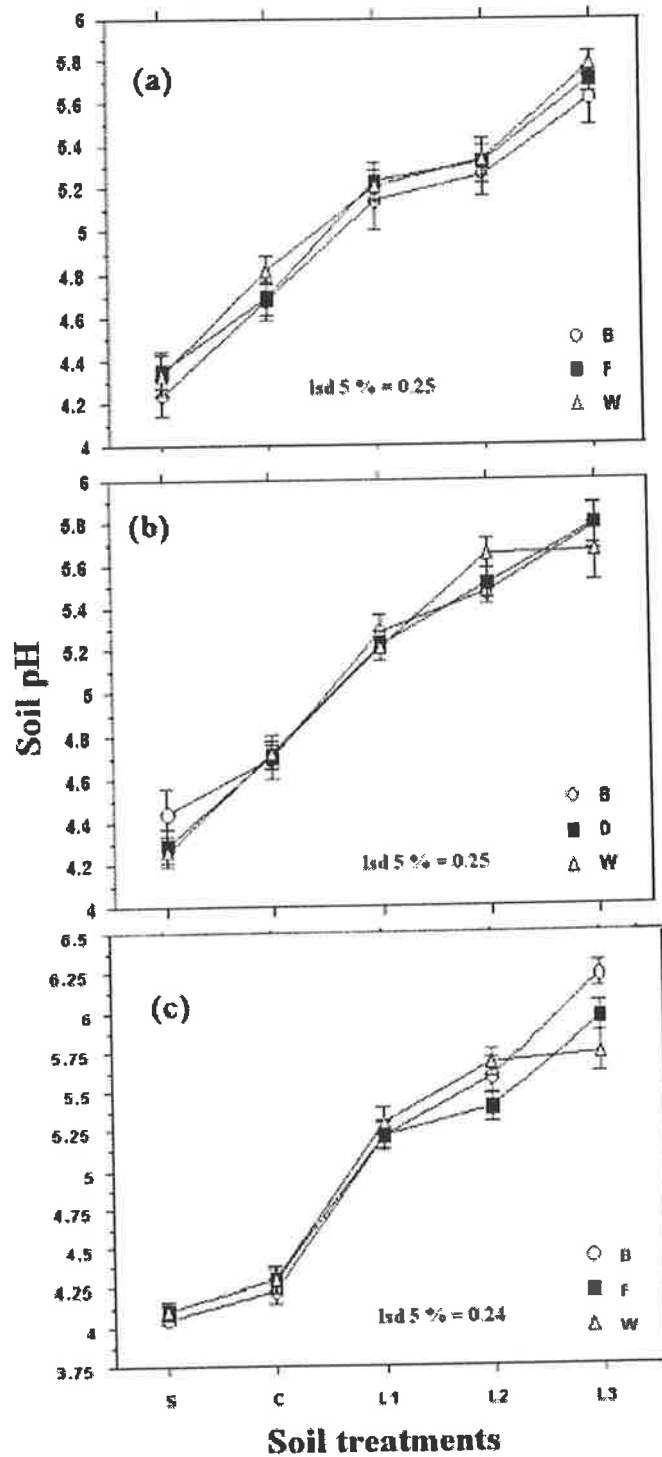


Figure 4.3 Relationship between crop x lime treatment for soil pH<sub>Ca</sub> at GR (a), MR (b) and DS (c) respectively for the 2000 season. S, C, L1, L2 and L3 are soil treatments as sulphur, control, lime1, lime2 and lime3 respectively. Error bars indicate standard error.

**Table 4.9 Effect of treatment on some soil characteristics (solid phase measures) at each site used in this study for 1999 season.**

**The data are the mean for all species for each treatment.**

Site	Trt.	pH <sub>w</sub>	pH <sub>Ca</sub>	Ca (cmol+/kg)	Mg (cmol+/kg)	Al <sub>Ca</sub> (mg/kg)	Mn <sub>Ca</sub> (mg/kg)	Al <sub>K</sub> (cmol+/kg)	Mn <sub>K</sub> (cmol+/kg)	ECEC	%Al of ECEC	Ca:Al ratio	Ca:Mg ratio	S(mg/kg)
GR	C	5.73	4.74	4.70	1.70	1.70	24.75	0.06	0.08	7.84	0.81	143.16	2.76	24.50
GR	L1	5.82	5.04	5.50	1.40	1.23	21.25	0.03	0.07	8.13	0.33	224.70	3.93	23.75
GR	L2	5.96	5.15	5.00	1.60	0.85	23.50	0.02	0.08	7.91	0.29	247.37	3.12	28.50
GR	L3	6.01	5.37	5.90	1.50	1.05	23.00	0.03	0.08	8.64	0.39	278.44	3.93	39.75
GR	S	5.30	4.58	4.60	1.60	4.72	62.65	0.14	0.18	7.71	1.75	115.39	2.88	130.25
DS	C	5.31	4.31	2.20	0.50	7.20	38.75	0.17	0.10	4.13	4.10	13.17	4.40	14.75
DS	L1	5.90	5.13	3.80	0.60	2.15	22.25	0.03	0.07	5.65	0.48	150.45	6.33	16.75
DS	L2	6.07	5.32	4.40	0.60	1.40	19.25	0.02	0.06	6.21	0.30	251.35	7.33	15.50
DS	L3	6.30	5.75	5.50	0.60	1.83	15.25	0.02	0.05	7.27	0.22	350.25	9.17	16.75
DS	S	4.94	4.21	2.10	0.50	9.90	57.75	0.25	0.15	4.06	6.15	8.62	4.20	86.75
MR	C	5.47	5.08	3.80	0.70	2.22	12.33	0.03	0.05	5.22	0.58	131.76	5.43	20.50
MR	L1	5.78	4.92	5.20	0.70	1.55	7.95	0.02	0.02	6.61	0.27	340.36	7.43	18.25
MR	L2	5.82	5.30	5.70	0.70	1.15	6.75	0.01	0.02	7.10	0.20	419.28	8.14	22.25
MR	L3	5.47	4.76	6.00	0.90	1.10	6.85	0.01	0.02	7.61	0.20	417.69	6.67	18.25
MR	S	5.67	5.02	3.70	0.70	3.62	37.50	0.07	0.11	5.17	1.35	56.44	5.29	97.25
<b>Lsd 5%</b>		<b>0.46</b>	<b>0.53</b>	<b>1.05</b>	<b>0.53</b>	<b>2.86</b>	<b>14.92</b>	<b>0.04</b>	<b>0.05</b>	<b>1.58</b>	<b>1.16</b>	<b>112</b>	<b>2.23</b>	<b>120.00</b>

**Table 4.10 Effect of treatment on some soil characteristics (solid phase measures) at each site used in this study for 2000 season. The data are the mean for all species for each treatment.**

Site	Trt.	Mean pH <sub>w</sub> (2000)	Mean pH <sub>Ca</sub> (2000)	Ca (cmol+/kg)	Mg (cmol+/kg)	Al <sub>Ca</sub> (mg/kg)	Mn <sub>Ca</sub> (mg/kg)	Al <sub>K</sub> (cmol+/kg)	Mn <sub>K</sub> (cmol+/kg)	ECEC	%Al of ECEC	Ca:Al ratio	Ca:Mg ratio	Ca:K ratio	S (mg/kg)
GR	C	6.06	4.73	4.80	1.15	1.93	24.00	0.04	0.07	7.35	0.50	130.91	4.17	5.22	2.50
GR	L1	6.27	5.19	6.50	1.07	0.73	13.00	0.01	0.04	8.75	0.08	975.00	6.08	7.74	2.20
GR	L2	6.31	5.31	5.95	1.23	0.57	13.33	0.01	0.04	8.43	0.07	1071.00	4.82	7.08	1.70
GR	L3	6.63	5.70	6.80	1.15	0.77	8.50	0.001	0.03	9.11	0.01	6800.00	5.90	8.61	0.01
GR	S	5.38	4.30	4.15	1.07	7.13	45.33	0.20	0.11	6.74	3.00	20.52	3.88	4.77	239.0
DS	C	5.53	4.27	2.45	0.36	7.97	30.67	0.17	0.07	4.21	4.01	14.51	6.77	2.78	0.70
DS	L1	5.98	5.24	3.65	0.40	1.67	16.67	0.01	0.03	5.24	0.21	328.50	9.24	4.40	1.70
DS	L2	6.24	5.55	4.30	0.43	1.33	11.77	0.01	0.03	5.90	0.11	645.00	10.05	5.18	1.10
DS	L3	6.35	5.97	4.30	0.40	1.20	11.20	0.01	0.03	5.84	0.10	774.00	10.66	5.12	2.30
DS	S	4.88	4.08	2.25	0.34	14.67	56.00	0.31	0.11	4.07	7.70	7.18	6.67	2.71	579.00
MR	C	5.93	4.71	4.20	0.59	1.63	14.00	0.01	0.03	5.48	0.26	290.77	7.09	10.00	0.60
MR	L1	6.24	5.24	4.95	0.58	0.83	7.20	0.004	0.02	6.22	0.07	1113.75	8.59	10.76	1.00
MR	L2	6.48	5.55	5.45	0.60	0.53	4.83	0.001	0.01	6.72	0.02	4905.00	9.07	12.67	0.00
MR	L3	6.59	5.74	5.70	0.64	0.33	3.90	0.0006	0.01	7.02	0.01	5510.00	8.88	14.25	0.00
MR	S	5.38	4.33	3.65	0.50	4.47	27.00	0.09	0.06	4.89	1.88	39.58	7.27	9.86	199.00
<b>Lsd 5%</b>		<b>0.28</b>	<b>0.26</b>	<b>1.30</b>	<b>0.35</b>	<b>1.45</b>	<b>4.75</b>	<b>0.09</b>	<b>0.03</b>	<b>1.50</b>	<b>2.55</b>	<b>112</b>	<b>2.23</b>	<b>120</b>	<b>0.02</b>

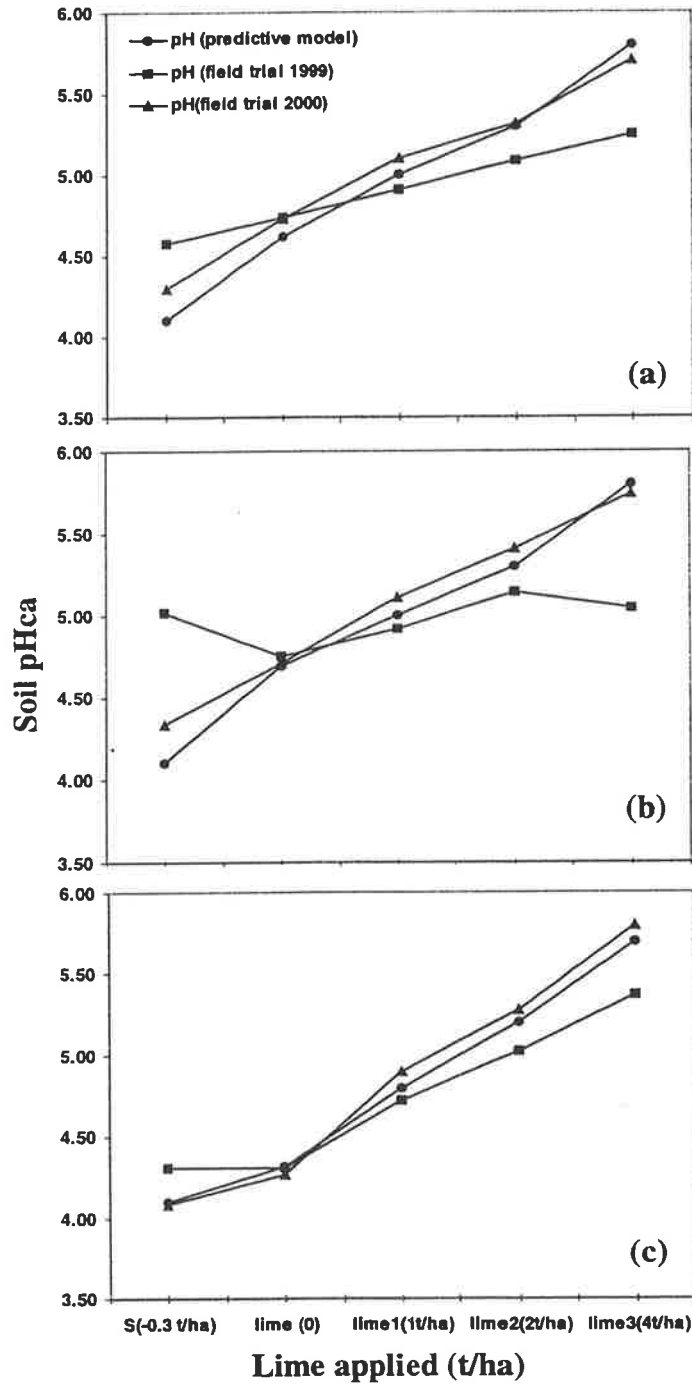


Figure 4.4 Relationship between the lime applied and the change in soil pH<sub>Ca</sub> at 3 sites used in this study GR (a), MR (b) and DS (c) in 1999 and 2000 season. Lime rates were determined from the Hochman *et al.* (1989) predictive model.

**Table 4.11 Soil pHBC and lime requirement rates for surface soil (0-10 cm) for 3 sites, measured by titration at the beginning of the experiment in 1998.**

Site	pHBC Measurement Method	pHBC (mmolc/kg/pH)	R <sup>2</sup>	Lime Requirement (kg CaCO <sub>3</sub> /ha/10cm)
GR	Ca (OH) <sub>2</sub>	28.3	0.99	1839
	NaOH	10.69	0.99	695
DS	Ca (OH) <sub>2</sub>	19.05	0.99	1238
	NaOH	11.31	0.99	735
MR	Ca (OH) <sub>2</sub>	18.23	0.99	1185
	NaOH	10.53	0.99	684

#### 4.3.2.3 Soil cation properties

The soil extractable (0.01 M CaCl<sub>2</sub> shown as Al<sub>Ca</sub> or Mn<sub>Ca</sub>) and exchangeable (1 M KCl shown as Al<sub>K</sub> or Mn<sub>K</sub>) Al and Mn data in Table 4.9 (1999) and Table 4.10 (2000), are presented as the mean soil values (including measures from plots with different species) at each site. There was no difference in soil Al or Mn associated with the different plots with the crop species (data not shown). The Al<sub>Ca</sub> and Mn<sub>Ca</sub> measures decreased with lime application, from the control (nil lime), and these values were not significantly changed within the lime rates (Table 4.10 and Figure 4.5). But these values, in all sites, decreased significantly (P>0.01) with time, from 1999 towards 2000. Also, levels of both extractable and exchangeable Al and Mn increased for all S treatments in all sites in 1999 season and again this level had increased when the soils were sampled from the S plots in season 2000. These overall data show that pH<sub>Ca</sub> 4.7 is the 'break of curve' value where there is a significant increase in the Al<sub>Ca</sub> and Mn<sub>Ca</sub> values (Figure 4.6). For example, the overall Al<sub>Ca</sub> and Mn<sub>Ca</sub> values increased to 12 and 60 mg/kg from the starting value of 2 and 25 after the sharp decrease in pH, mostly due to the S treatment. Also these overall values decreased from control to L3 treatments, from 2 to 1.2 mg/kg for Al<sub>Ca</sub> and from 25 to 9 mg/kg for Mn<sub>Ca</sub>.

Similarly Al saturation percentage of the ECEC showed (Table 4.10 and Figure 4.7) an increase with S and a decrease with increasing lime rate at all sites. There was a negative

relationship between the Al saturation % of the ECEC and  $\text{pH}_{\text{Ca}}$  (Figure 4.7 section b). Where  $\text{pH}_{\text{Ca}}$  increased to above 5.0 then %Al saturation of the ECEC was observed to decrease to less than 0.5%, and where the soil  $\text{pH}_{\text{Ca}}$  decreased below 4.7 then Al saturation % of ECEC increased up to 7%.

The sum of exchangeable cations (ECEC) decreased with S application at all sites. But ECEC was increased ( $P < 0.05$ ) by increasing rates of lime for all sites (Table 4.10 and Figure 4.8). Similarly, lime application increased ( $P < 0.05$ ) exchangeable Ca, and the S treatment decreased exchangeable Ca ( $P < 0.01$ ) at all sites (Figure 4.8). The regression equations between pH and all individual cations (Table 4.12) showed that there are significant ( $P < 0.01$ ) positive correlations with Ca and negative relationships with Al and Mn. The coefficients of determination ( $R^2$ ) for a linear model of the Ca at all sites ranged between 0.85 and 0.92. The data in Table 4.12 is suggesting that the exchange sites vacated by  $\text{H}^+$ , Al and Mn were almost all taken up by Ca after liming. Both Al and Mn had significant ( $P < 0.01$ ) negative correlations with pH, with slopes very similar for all sites (Table 4.12). Mg, Na and K were not changed ( $P < 0.05$ ) after the addition of S for any site. The correlation between K and Na was not significant with pH for any site.

The regression equations for the overall relation for pH and yield with  $\text{Al}_{\text{Ca}}$  and  $\text{Mn}_{\text{Ca}}$  are presented in Table 4.13. These relationships for Al and Mn with yield are also graphically presented for all 3 sites (GR, MR and DS) in Figure 4.9. These relationships for yields indicate that with increasing Al or Mn there is a significant decline in yield (Figure 4.9). This decline in yield starts to show its effect after the value for Al and Mn increases to higher than 1 and 10 mg/kg respectively (Figure 4.9). Also, the coefficient of variation ( $R^2$ ) values in Table 4.13 show that Al and Mn have explained the variation in pH values much better than in yield. This especially is more apparent at the DS site by almost 60%, with the inclusion of Al, and 29% with the inclusion of Mn. However the soil pH still is a better factor to explain the variation in yield compared to Al and Mn.

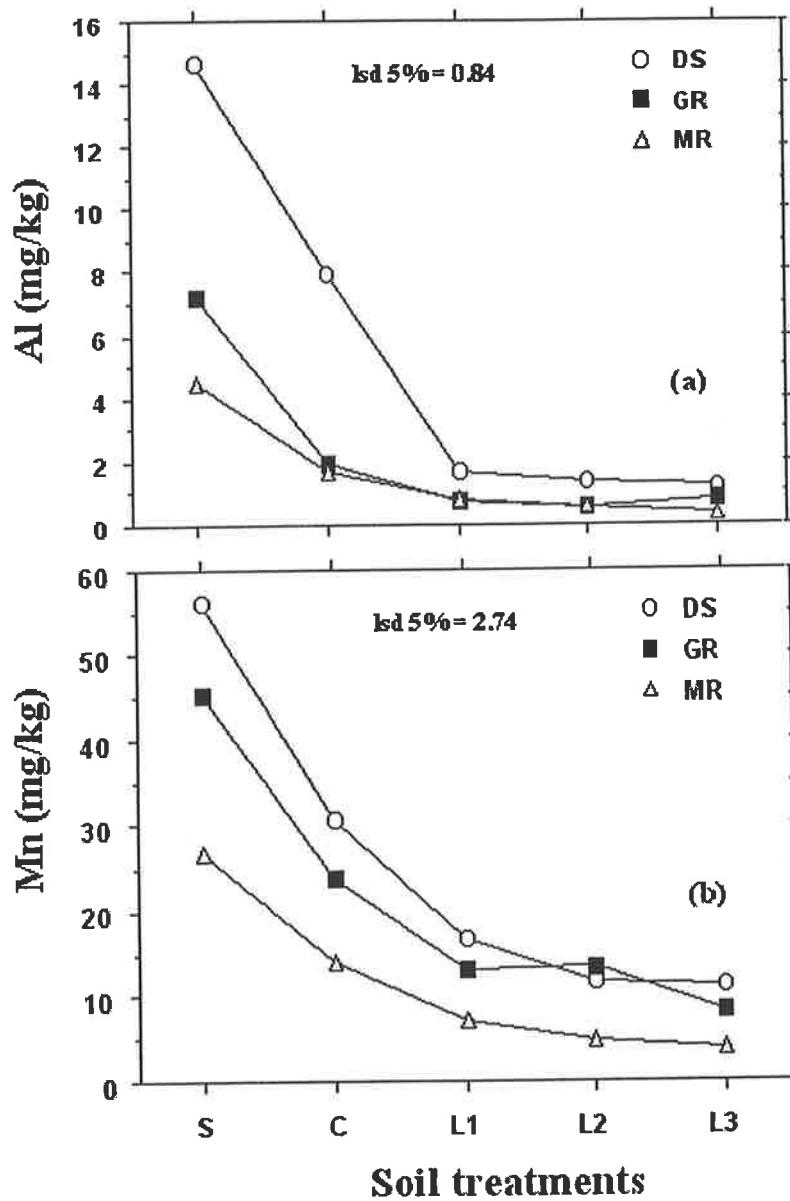


Figure 4.5 Relationship between extractable (0.01 M CaCl<sub>2</sub>) Al (a) and Mn (b) with soil treatments used for GR, MR and DS sites in 2000 season.

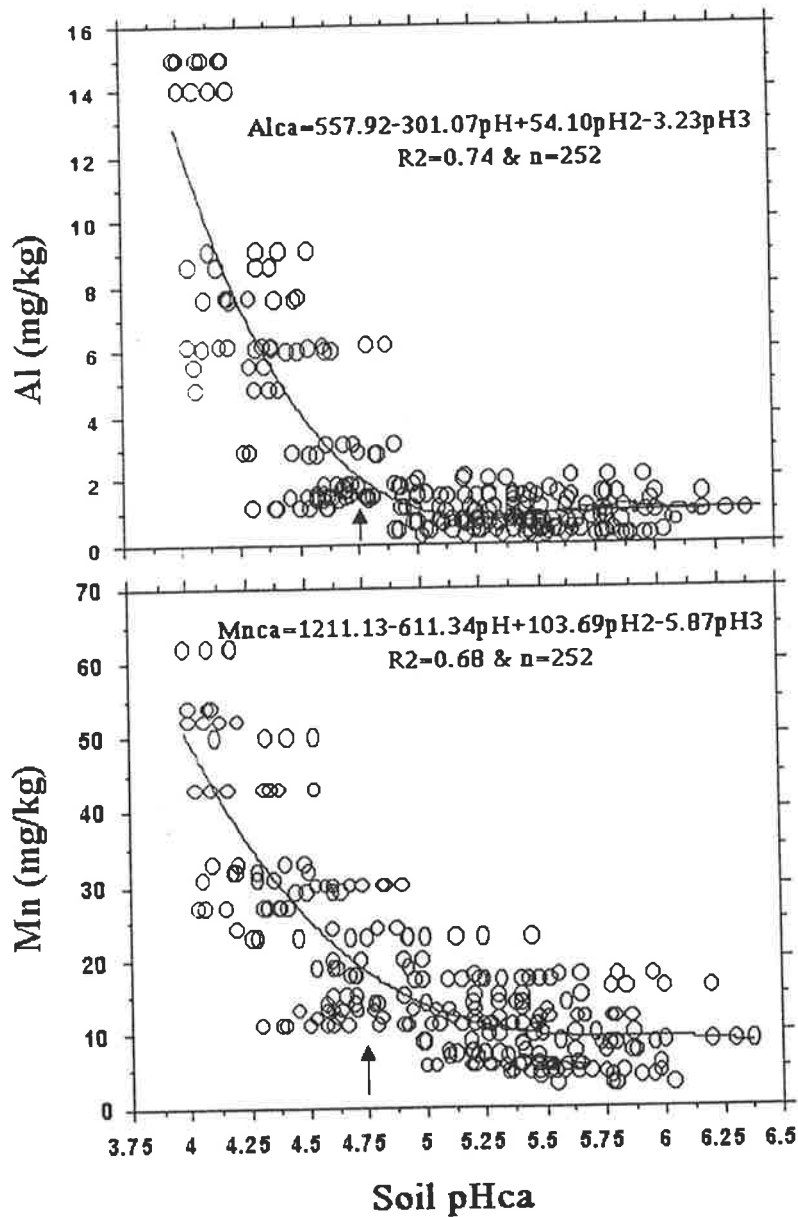


Figure 4.6 Relationship between pH<sub>Ca</sub> and 0.01 M CaCl<sub>2</sub> extractable Al and Mn for all 3 sites. Arrow indicates 'break of curve'.

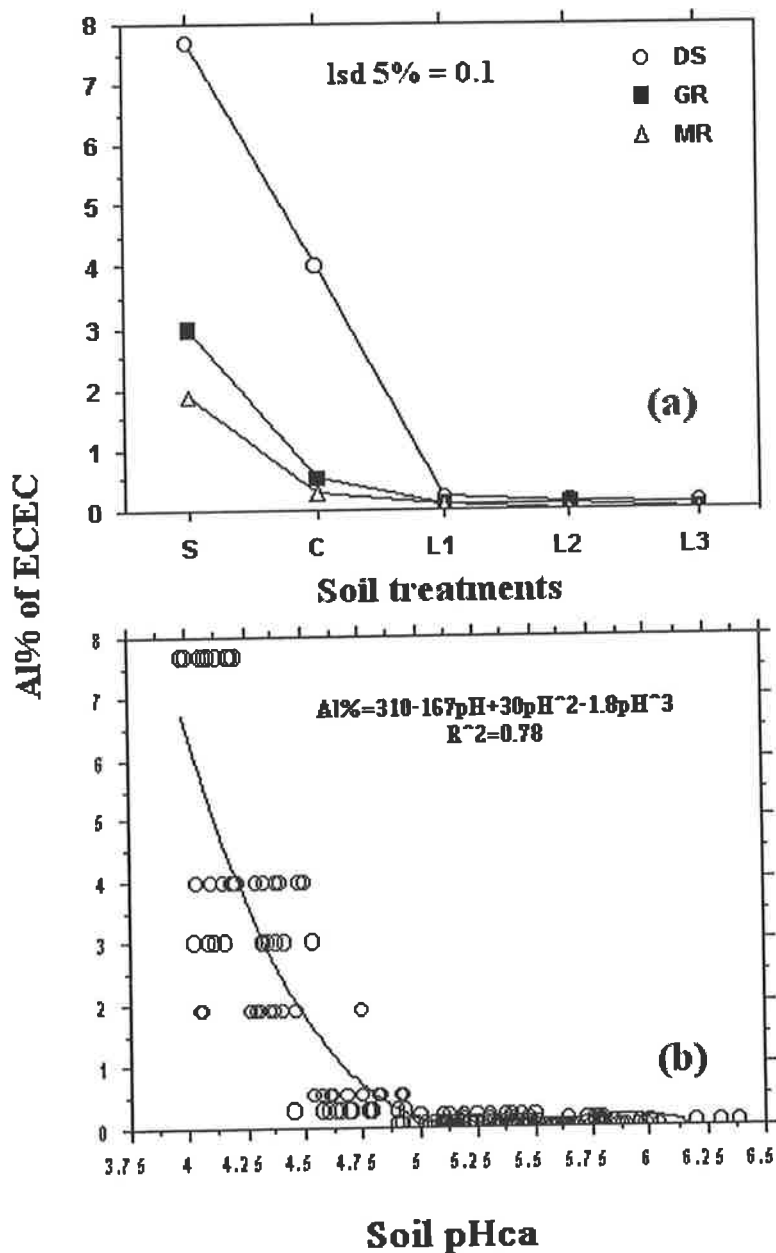


Figure 4.7 Relationship between Al% of ECEC with soil treatments for GR, MR and DS sites (a) and between Al% of ECEC with soil pH<sub>ca</sub> (b) for overall data at 3 sites in 2000.

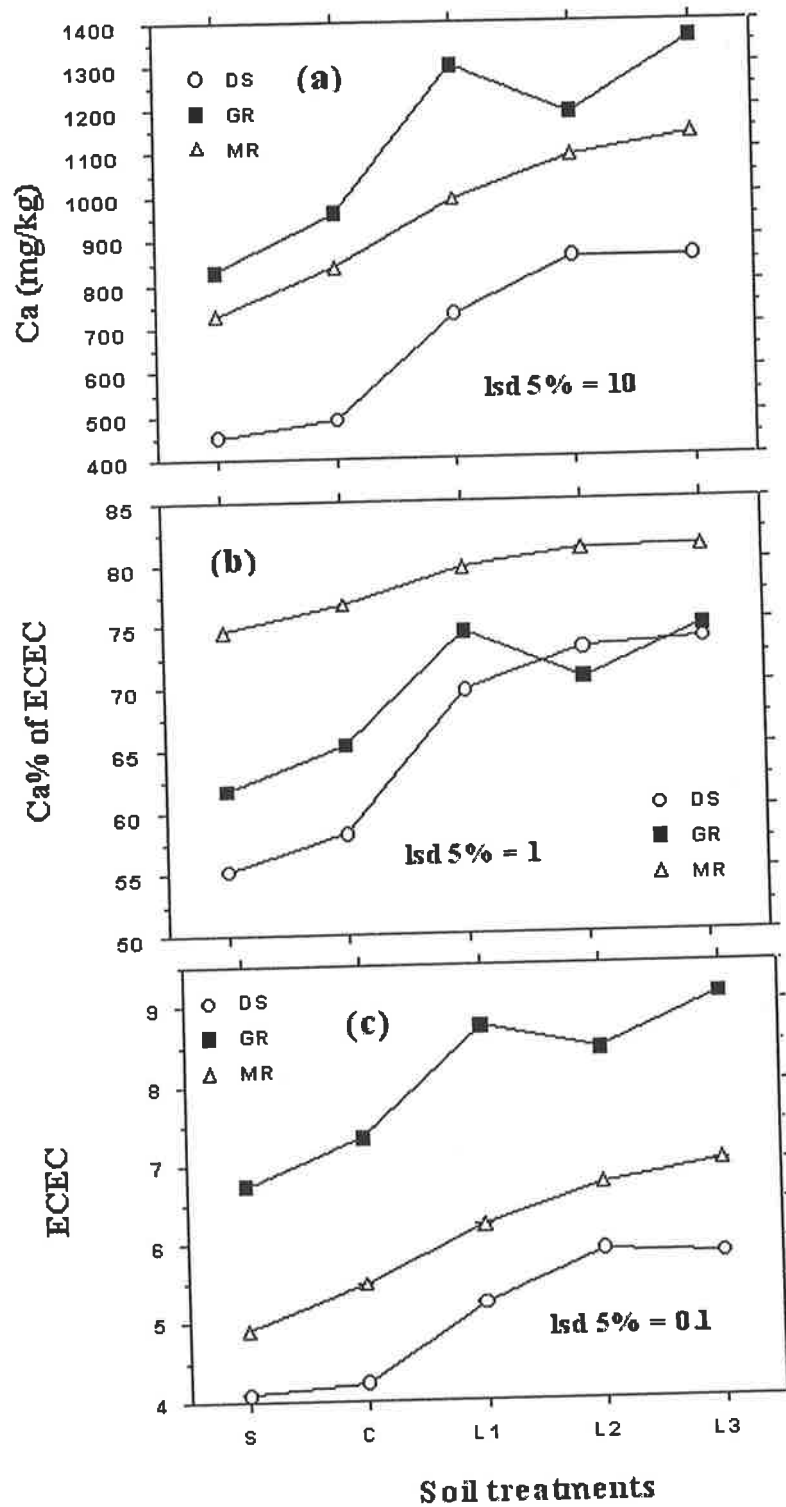


Figure 4.8 Relationship between Ca (a), Ca% of ECEC (b) and ECEC (c) with soil treatments for GR, MR and DS sites in 2000.

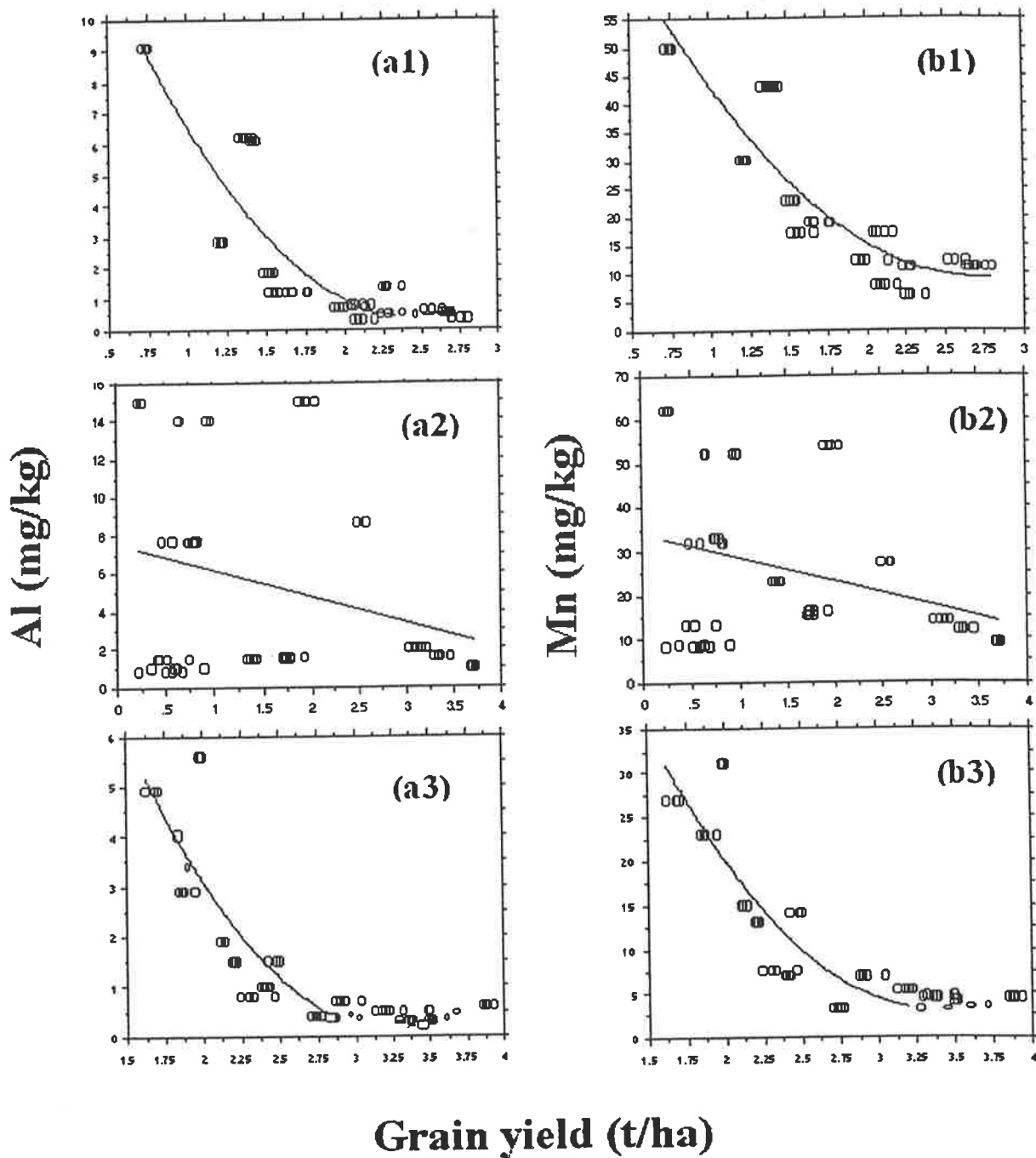


Figure 4.9 Correlations between Al (a1, a2, a3) and Mn (b1, b2, b3) (0.01 M extractable) with yield (t/ha) for GR (a1 and b1) for DS (a2 and b2) and MR (a3 and b3). Lines represent the best-fitted line for all crops for each site.

**Table 4.12 Coefficients of determination ( $R^2$ ) and slopes ( $b = \text{cmol}(+) \text{ kg}^{-1}/\text{pH unit}$ ) for relationship between exchangeable cations and soil pH for all sites.**

Site	Ca		Mg		K		Na		Al		Mn	
	$R^2$	b	$R^2$	b	$R^2$	b	$R^2$	b	$R^2$	b	$R^2$	b
MR	0.92	1.34	ns <sup>A</sup>	0.07	ns	0.02	ns	0.02	0.63	-0.05	0.86	-0.03
GR	0.82	1.79	ns	0.05	ns	-0.06	ns	-0.003	0.65	-0.12	0.84	-0.06
DS	0.91	1.12	ns	0.04	ns	-0.01	ns	0.02	0.78	-0.14	0.77	-0.04

<sup>A</sup> Not significant ( $P < 0.05$ )

**Table 4.13 Regression equations for the relationship between yield and  $\text{pH}_{\text{Ca}}$  with 0.01 M extractable  $\text{Al}_{\text{Ca}}$  and  $\text{Mn}_{\text{Ca}}$  for 3 sites in year 2000.  $R^2$  is the coefficient of the variation.**

Regression equation	A ( $\pm$ s.e.)	B ( $\pm$ s.e.)	C ( $\pm$ s.e.)	$R^2$
<b>GR site</b>				
Yield= $A \times \text{Al} + B \times \text{Al}^2 + C$	$-14.64 \pm 1.78$	$3.01 \pm 0.48$	$18.19 \pm 1.59$	0.78
Yield= $A \times \text{Mn} + B \times \text{Mn}^2 + C$	$-61.84 \pm 9.15$	$11.34 \pm 2.47$	$93.47 \pm 7.99$	0.78
pH= $A \times \text{Al} + B \times \text{Al}^2 + C$	$-41.22 \pm 6.85$	$3.73 \pm 0.88$	$114.17 \pm 16.99$	0.73
pH= $A \times \text{Mn} + B \times \text{Mn}^2 + C$	$-156.73 \pm 30.34$	$13.39 \pm 3.03$	$467.37 \pm 75.22$	0.81
<b>DS site</b>				
Yield= $A \times \text{Al} + B$	$-2.67 \pm 0.69$	$11.03 \pm 1.61$		0.28
Yield= $A \times \text{Mn} + B$	$-11.14 \pm 1.91$	$49.46 \pm 4.43$		0.47
pH= $A \times \text{Al} + B \times \text{Al}^2 + C$	$-48.46 \pm 5.32$	$6.35 \pm 0.63$	$140.39 \pm 15.74$	0.89
pH= $A \times \text{Mn} + B \times \text{Mn}^2 + C$	$-122.56 \pm 29.49$	$10.31 \pm 2.92$	$375.80 \pm 73.13$	0.76
<b>MR site</b>				
Yield= $A \times \text{Al} + B \times \text{Al}^2 + C$	$-12.68 \pm 1.55$	$1.97 \pm 0.28$	$20.56 \pm 2.05$	0.75
Yield= $A \times \text{Mn} + B \times \text{Mn}^2 + C$	$-63.15 \pm 7.47$	$9.50 \pm 1.34$	$108.26 \pm 9.91$	0.80
pH= $A \times \text{Al} + B \times \text{Al}^2 + C$	$-23.20 \pm 3.29$	$2.05 \pm 0.33$	$65.89 \pm 8.24$	0.82
pH= $A \times \text{Mn} + B \times \text{Mn}^2 + C$	$-103.74 \pm 13.73$	$8.85 \pm 1.36$	$307.81 \pm 34.35$	0.91

## 4.4 Discussion

### 4.4.1 Efficacy of LR model

In this study field experimental data have been used to test and validate a chosen model's ability to predict changes in soil pH with variable rates of lime. Whilst there was a difference in pH measured in 1999 and 2000, indicating a delay in S and lime dissolution in these soil types, after a time period of almost 12 months the target pH was achieved. The lime requirement calculated using the model of Hochman *et al.* (1989) provided very good estimates of the final pH changes obtained in the 3 sites (Figure 4.4). Also the high  $R^2$  (0.91) values for the overall data at the 3 sites indicates that the predicted values from the model explained the observed values very well (Figure 4.10). The accuracy estimated here in this study (Figure 4.10) is very similar to the accuracy obtained by Hochman *et al.* (1995) ( $R^2=0.86$ ).

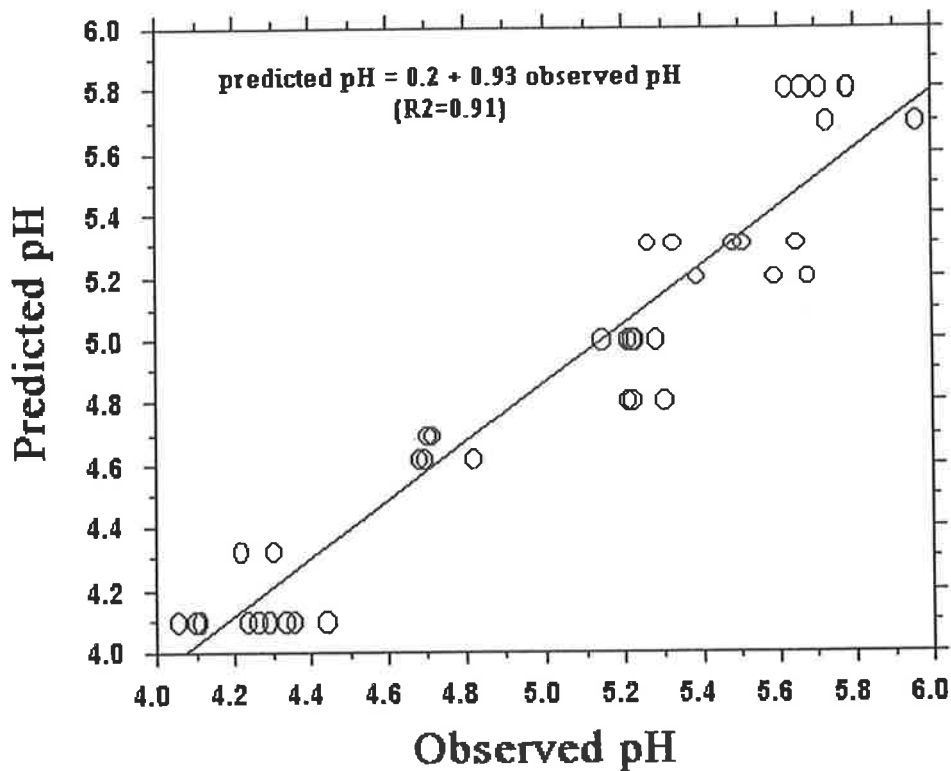


Figure 4.10 Plot of field-observed pH versus predicted values from Hochman model for all soil treatments in 2000 season at 3 sites. Best-fitted line is shown by solid line.

Also the buffering capacity ( $B_s$ ) (Table 4.3) and the slope of the regression of pH and total exchangeable bases ( $SL_s$ ) for all 3 sites correlated well with the Hochman predicted data (Figure is not shown here). This good correlation between observed and predicted pH values would indicate that the values associated with pH buffering are likely to be important in lime reaction in these soils. The parameters that are affecting the pH buffering and that have been used here to predict the effects of lime rates are soil TEC, Al and pH of unlimed soil. There is evidence that these reactions are the main pH buffering reactions between pH 4.5 and 6.5 (Helyar *et al.* 1993). Also, this corresponds well with the study of Magdoff and Bartlett (1985), that the soil titrations for many different soil types cover a pH range from less than 4.5 to over 6.5 and over this range follow a straight line. Because over this pH range (4.5-6.5) the soil pH is mainly buffered by association/dissociation reactions of  $H^+$  ions, but dissolution/precipitation processes are relatively remain slow (Helyar and Porter 1989). Therefore in this range often the pHBC is approximately constant (Magdoff and Bartlett 1985). Thus in this study those factors that affect lime requirement have worked well, especially where the  $pH_{Ca}$  was in the range between 4.0 and 6.0 (Figure 4.4).

At lower pH values, the pHBC increases due to increase in the dissolution of soil minerals (Bloom and Grigal 1985) and mainly due to the Al hydrous oxides (Hartikainen 1986; Bailey *et al.* 1989 a & b). In all sites, the measured value was not met by the predicted value where the target pH was lower than 4.0. This buffering effect of Al is consistent with the current data (Figure 4.4) that an increase in Al would reduce the predicted change in soil pH for a given rate of S added (Figure 4.4). This is consistent with the equations of Bailey *et al.* (1989a & b) and the observation of Magdoff and Bartlett (1985) that the increased buffering is due to the effect of having more exchangeable Al in the soil solution as pH falls from 5.0 to 4.0. Data in this study show that the pH outcome is predicted to be 3.6 with 0.3 t/ha S applied to the soil, but the lowest pH observed was 4.1.

According to Hochman *et al.* (1995), addition of an equal amount of lime to different sites with the same TEC, Al and Mn, though with different pH values, yielded a smaller pH change in the soil wherever there were higher initial pH values. This prediction is consistent with the equation of Bailey *et al.* (1989a & b) but not with the observation of

Magdoff and Bartlett (1985) that soils are least buffered in the pH range 5.0-5.6. This outcome was also obtained here where the DS site with a lower initial pH value, compared with GR and MR sites with higher pH values, almost reached the same final pH level with the same lime rates. The buffering capacity of the GR and MR was higher than the DS soil (Table 4.11). For example at the MR and GR sites the pH values increased by 0.9 of a  $\text{pH}_{\text{Ca}}$  unit after addition of 4 t/ha of lime, whereas increases of 1.7 of  $\text{pH}_{\text{Ca}}$  unit was obtained for the DS site for the same lime rate. This suggests that the GR and MR soils were buffered by reactions involving carbonate minerals. The higher soil ECEC at the GR and MR sites will account for a difference in the observed buffering capacity when compared with the DS site.

The reaction of different buffer solutions as titrations methods ( $\text{Ca}(\text{OH})_2$  and  $\text{NaOH}$ ) on soils from the different sites have also been used to calculate LR in this study. The results demonstrate that pHBC measured with either  $\text{NaOH}$  or  $\text{Ca}(\text{OH})_2$  is unsuitable to calculate LR rates, as they underestimated the lime to achieve best pH and yield responses compared to the values obtained in this study from the model. As indicated in other studies, using single or double buffer methods (Shoemaker et al. 1961; Yuan 1976; Adams and Evans 1962; Mehlich 1976; Woodruff 1948), which was previously used in the study by Richards (1992) in South Australia, has produced discrepancies in predicting a final pH. The report by Richards (1992) indicates that poor relationships were obtained for the estimation of LR for  $\text{pH}_{\text{Ca}}$  5.0 and 5.5 for all buffers, but more accurate measures were found near neutrality (pH 6.5-7.0).

Whilst the lime requirement calculated by titrations methods may ameliorate toxicity due to the effect of Al and Mn, they may not be enough to achieve 90% of potential yield as shown in this study. Many Australian studies have reached a similar conclusion that, on determining LR to reduce exchangeable Al to a predetermined level, they did not then maximise plant growth (Aitken *et al.* 1990; Aitken 1992; Slattery and Coventry 1993). This is especially important here in mid-north South Australia, as in this soil type, the levels of Al are very low compared with other soil types and studies in Australia. So the best option here could be increasing pH, and subsequently Ca and ECEC of the soil to reach higher yield, rather than would be indicated just by removing Al toxicity. This study shows that predicting pHBC from soil properties (such as OM, exchangeable Al and

ECEC), and using initial soil pH to predict LR to any target pH, is likely to be more suitable to the soil type used in this study. However, the OM could act as a source for hydrolysis of  $\text{Al}^{3+}$  ions on OM exchange sites and exchange by  $\text{H}^+$  on the strongly acidic carboxyl groups (Magdoff and Bartlett 1985), and could play an important role in pH buffering (Bloom *et al.* 1979). OM is considered very important in estimating lime requirement (Helling *et al.* 1964; Magdoff and Bartlett 1985; Bailey *et al.* 1989 a & b), and in a study with a moderate amount of OM level (1.9%) from north-eastern Victoria (Slattery and Coventry 1993), the LR (using Hochman model) was underestimated by 60% to achieve the final pH. In the study reported here however OM was not used to predict LR rate (Zvi. Hochman pers. com. 1998). Hochman *et al.* (1995) has suggested that OM under the range of 1-2% has insufficient effect on the buffering capacity of the soil and its liming requirement. The high correlation coefficient gained between pH observed versus pH predicted values in this study confirms the decision of not using OM in the Hochman's model for LR calculation. This study suggests that extractable Al measured by the methods used in this study may not be sufficient, as they do not distinguish between the real Al values, such as between toxic monomeric and non-toxic complexed forms. Differentiation may be especially important in soils of high buffering capacity and high OC content, where Al complexes with organic acid ligands may alleviate the toxic effects of Al (Hargrove 1986; Suthipradit *et al.* 1990). This aspect will be investigated further in chapter 7, using the long-term Tarlee data.

Using lime treatments calculated by the Hochman model generally increased yield to levels that were 30 to 60% higher than the control at all sites. Lime at the lower rates (1 t/ha) did not provide the same yield advantage compared to L2 and L3 (the only exception was the wheat crop at the GR site for 2000 season). Improving yield with increasing lime occurred up to the 'predicted' lime rate (L2) and then there appeared to be a yield reduction. This decrease in yield appeared to affect yield earlier at the GR site for wheat. In contrast, increasing lime rates improved the yield continuously at the DS site. Data provided in this study (Table 4.8) indicate that pH alone could explain the differences observed in grain yield, but in the following sections other factors such as Ca, Al and Mn are considered in the yield equation in an attempt to improve the observed changes in grain yield.

#### 4.4.2 Relationship between yield and soil properties

The regression of Al saturation percentage of ECEC (Al%) and yield (t/ha) shows that the yield decreases as the S treatment increased the availability of Al on exchangeable cation sites, and yield increases as the Al saturation percentage of ECEC decreases. The S treatment was found to have an Al saturation percentage of ECEC generally around 4%, but not greater than 8% and for other treatments there was an Al saturation percentage of ECEC lower than 0.5%. At the GR and MR sites the Al saturation percentage of the ECEC on the unlimed treatment was 0.5 and 0.26% respectively, and with this value only very sensitive cultivars would be likely to be affected by Al toxicity (Fenton *et al.* 1996). Even soils with Al saturation percentage values of the ECEC between 15% and 30%, there have been reports of no restriction to plant growth through Al toxicity (Kamprath 1970; Evans and Kamprath 1970; Reeves and Sumner 1970; Oates and Kamprath 1983; Geeves *et al.* 1992; Slattery *et al.* 1995). Thus, in this study, possibly the Al only caused reduction in yield wherever Al% of ECEC was higher than 4%, especially where the S treatment was used. It would appear that liming to achieve a pH<sub>Ca</sub> of 5.2 has removed Al toxicity and further liming to achieve pH<sub>Ca</sub> 5.5-6.0 may have improved other soil properties (possibly Ca or N availability) to realise further yield gains.

The amount of lime required to reduce Al<sub>Ca</sub> to lower than 1 mg/kg for the 3 sites was about 1 t/ha for the GR and DS sites and 0.75 t/ha for the MR site. These lime rates correspond to raising the soil pH<sub>Ca</sub> to a value of 5.2 for all sites. At this pH<sub>Ca</sub> most of the crop species in this study were at about 55-75% of their potential yield. At pH<sub>Ca</sub> 5.2 the extractable Mn<sub>Ca</sub> levels were about 20-30 mg/kg and increasing pH to higher levels further decreased Mn levels to 8-10 mg/kg (at pH<sub>Ca</sub> 5.5-6.0). At this latter pH<sub>Ca</sub> most plant species reached 80-90% of their potential yield.

In this study liming increased the ECEC at all sites with increasing pH (Figure 4.10). The exchange sites vacated by H<sup>+</sup>, Al and Mn were almost all taken up by Ca (Table 4.10 and 4.12). The increase (P>0.05) in ECEC at all sites with lime application and subsequent increase in Ca and Ca percentage of ECEC as observed for all treatments at all sites (Table 4.12) is evidence for this direct effect. Similar results were reported for studies undertaken for many different acid soils in northern NSW (Hochman *et al.* 1995) and New Zealand (Edmeades 1982). The relationship found in this study for soil pH<sub>Ca</sub> (X) and

Ca saturation percentage of the ECEC (Y) followed a very similar trend to that described for a Victorian soil by Slattery *et al.* (1995) as:  $(Y = 85.6X - 6.1X^2 - 213.7$  with  $R^2 = 0.90)$ . At low levels of soil Ca (2-3 cmol(+)/kg) present for the DS site and higher Al saturation percentage (7.6%), the uptake of Ca may be inhibited by the presence of toxic amounts of Al (Kamprath 1984). Inadequate supplies of Ca for plant growth have been shown for highly weathered acidic soils with low CEC levels (Barber 1984), which apparently affect plant growth due to the lack of protective action of Ca against Al toxicity (Alva *et al.* 1986). So soil types with different Al levels may not show responses to inactivation of Al (Bromfield *et al.* 1983; Hoyt and Nyborg 1987; Conyers *et al.* 1991), but may improve with additional Ca. Figure 4.10 shows that the Al saturation percentage of ECEC is reduced to insignificant levels at  $pH_{Ca}$  5.0-5.2, similarly to many other Australian soils (Bromfield *et al.* 1983; Conyers 1983; Hochman *et al.* 1989). Thus it is concluded here that measuring the Al saturation percentage of ECEC alone could not adequately predict the yield responses for all sites and species in this study, especially when the Al saturation percentage of the ECEC was very low.

The observations on relationship between yield and lime treatments suggest that an acidity related restriction on yield (on GR and MR sites only) was first relieved (possibly Al and Mn toxicity) for wheat and durum and, where the pH increased higher than the value predicted by the model, then some other possible constraints may have been limiting the grain yield. This event could be related to Mg and K deficiency caused by high values for the Ca:Mg and Ca:K ratios after further lime application (MAAF 1986), or displacement of both Mg and K, resulting in nutrient losses by leaching (Edmeades 1982). It has been suggested that when the ratio between Ca and Mg and Ca and K exceeds 4.0 to 5.0, or when the ratio between Mg and K falls below 2.0 to 2.5, then Mg and K deficiencies may occur (MAAF 1986). The data shown in Table 4.10 indicate that the Ca:Mg ratios for GR and MR soils were not improved below 5.0 and 9.0 with increasing lime rates from L1 toward L3 respectively. In contrast on the DS site where the yield kept improving with the higher lime rates (L3) this ratio (Ca:Mg) start to increase above 10.6. It is noteworthy to mention that the Ca:Al ratios were improved with increasing lime rates (Table 4.10) at all sites from as low as 290 at DS site to high as 6800 in GR site. This ratio decreased to a low average of 20 for S treatments at all sites.

No plant tissue analyses were conducted in this study, which may have given an indication on possible induced nutrient deficiencies (such as Mn or Zn). But Zn deficiency has been shown previously in both acidic and calcareous sands in South Australia (Donald and Prescott 1975). Because Zn availability declines at higher pH values ( $\text{pH}_{\text{Ca}}$  range 5.5-7.0), or by overliming (Kamprath and Foy 1971; Bolland *et al.* 2000), then Zn availability may be restricted in the present study at the higher pH values, even knowing that Zn was supplemented with fertiliser application. Also, Reuter (1989 and 1992) has shown that Zn deficiency occurs in plants growing on a range of virgin soils in South Australia (for example on acidic sands, acid to neutral red brown earths). Many of these soil types are also characterised by low Zn availability (Reuter, 1989 and 1992).

The overall information provided in this chapter suggests that to improve lime prediction, an agreement between plant response and lime required to reach maximum yield for each species may also be needed. So the importance of calculating the amount of lime required to achieve 90% of maximum yield/species could help to decide cost to benefit ratios of tonnes of lime to the percent of achieved yield. With this approach, the level of tolerance of each species to the toxic effects of elements such as Al and Mn will be considered in the lime requirement model, which cannot be achieved with other methods. For example, better responses are gained when both Al and Mn were removed from soil solution at low pH to gain better responses to lime application (Bromfield *et al.* 1983; Hoyt and Nyborg 1987; Conyers *et al.* 1991). Similarly in this study, the inclusions of Al and Mn in the calculation show better responses with pH and yield data compare with other soil properties (Table 4.13). Therefore in the next section pH, Al and Mn data will be used in an evaluation of their performances in the prediction of yield and lime requirements.

#### **4.4.3 Prediction of yield and field lime requirement**

From the regression analyses of grain yield on pH (Table 4.8 and Figure 4.1), expected grain yields could be calculated for any soil pH. In most cases, these relationships accounted for 80-90% of the variation in yield as determined by soil pH. However, the relationship between Al and pH shows a significant variation in extractable  $\text{Al}_{\text{Ca}}$  over the  $\text{pH}_{\text{Ca}}$  range 4 to 5. This observation is important, as the greatest variability in Al would

correspond to those soils that would be considered strongly acid. If it was required to use the relationship between Al or Mn as an index of the amount of lime required to raise soil pH, then interpretation of the data may prove difficult. So it would be better to show the Al and Mn relationship with yield, and then use these data with pH data for each site to establish a more accurate prediction of yield for each crop (Table 4.14).

However the results from Table 4.13 suggest that  $\text{pH}_{\text{Ca}}$  is a more sensitive indicator of soil chemical changes than  $\text{Al}_{\text{Ca}}$  or  $\text{Mn}_{\text{Ca}}$ , and pH may still be the better soil measurement for obtaining accurate lime predictions over a range of soil types. So pH, Al, and Mn values for all sites in this study have been used (Table 4.14) to identify which values could have a limiting effect on yield. From these data the expected yield can be calculated by regression for a given value of soil pH, Al, or Mn, similar to the approach used by Slattery and Coventry (1993), where they discriminated these responses to lime on the basis of soil type and crop species. In order to determine which of the soil properties could most accurately predict yield, yield was modeled using backward elimination analysis (Trevor Hancock pers. comm. 2001) against soil pH, Al, and Mn. Backward elimination was continued until the greatest regression coefficient was found for each relationship. The relationship and the significance of the addition of each soil property to each model is shown in Table 4.14.

In this analysis, pH alone accounted for 44-77% of the variation in the GR and MR site for wheat, and 63-90% for barley, durum and faba at 3 sites. The addition of Al and Mn into the model in 3 sites improved the relationship. At the GR site the inclusion of Al and Mn together improved the relationship from 44 to 77% for wheat, and from 63 to 74% for barley for Al alone and from 44 to 77% for faba for Al and Mn together. For the MR site these improvement were 77 to 85% for wheat, 79 to 97% for barley for Al and Mn inclusion and nothing for durum. With the DS data the fitness of the model increased from 90 to 98 % for barley and 87 to 97% for faba beans by inclusion of Al or Mn as individual or Al and Mn together. Similarly, Conyers *et al.* (2001) reported that where 0.01 M  $\text{CaCl}_2$  extractable Al was used there was a significant improvements to the response model by the inclusion of  $\text{Mn}_{\text{Ca}}$ , but where 1M KCl exchangeable Al was used as the independent variable the regression model did not benefit from the inclusion of Mn (Conyers *et al.* 2000). So as the Al and Mn together could improve the regression model,

it appears that they could be used for these sites and crop species as an important factor in the lime requirement model.

The major difficulty in obtaining the 'best' LR with all methods is the lack of calibration against observed crop responses in the field. This would suggest that the only true standard against which rapid methods for the estimation of LR can be calibrated is the LR based on the results of field experimentation on the crops and soils of interest. When such calibrations are carried out, meaningful estimates of LR can be obtained from laboratory methods (Sumner 1997). Thus to calculate the rate of lime required to give maximum yield for a given crop species, response curves were constructed using the regression equations from Table 4.7 to predict lime requirement based on pH, Al and Mn over a range of relative yields. For these response curves, pH values were chosen to correspond to known lime additions at each site, and the % relative yield over the 2 seasons for each species were plotted against pH for each soil at each site (Figure 4.10). These lime requirement curves can be used to predict the lime rate that achieves 80-90% maximum yield for different species on the 3 sites on common red earth soil type in the mid-north South Australia. The relative accuracies of lime predictions vary from  $\pm 0.1$  t/ha at site DS to  $\pm 0.4$  t/ha at site GR (Table 4.14).

Response curves for wheat and durum show that its largest yield gains occurred at  $\text{pH}_{\text{Ca}}$  5.2-5.5, which requires a lower amount of lime (about 1 t/ha) for wheat at GR site and medium amount of lime (about 1.5 t/ha) at MR site for wheat and durum. With these soil types, wheat and durum reaches 80-90% of maximum yield at about pH 5.5, and it is unlikely to be economic to attempt to obtain 100% yield by applying additional lime (about 3 t/ha). For barley these 90% responses were obtained at  $\text{pH}_{\text{Ca}}$  of 5.3 to 5.5 with the addition of 2 (GR), 1.5 (MR) and 4 t/ha (DS). For faba beans in GR and DS sites yield response curve peaked at L1 and L2 treatments respectively, and start to decrease with increase of lime and pH in GR but continued its upward trend for MR site until it reached a plateau after  $\text{pH}_{\text{Ca}}$  5.8. The cost of raising soil pH to a higher level of pH for more yield probably is a decision that could be related to the cost of lime in the area. According to Ridley (1995), increasing the pH with higher lime rate may be useful, but at the same time achieving higher pH may also speed up the risk of soil acidification in the future.

**Table 4.14** Equations derived from backward elimination of field determined lime requirement to reach 90% of relative grain yield using pH alone, pH and Al, pH and Mn and pH, Al and Mn for all species at 3 sites.  $R^2$  is the coefficient of the variation, and P is probability. \*\*\* significant at  $P=0.001$ , \*\* significant at  $P=0.01$ , \* significant at  $P=0.05$ , and ns= not significant.

Regression equation	$R^2$	P
<b>Wheat GR site</b>		
yield = -1.39 + 0.68 pH	0.44	***
yield = 1.92 + 0.09 pH - 0.16 Al	0.56	ns
yield = 4.63 - 0.34 pH - 0.04 Mn	0.65	ns
yield = 8.57 - 0.88 pH + 0.57 Al - 0.16 Mn	0.77	***
<b>Barley GR site</b>		
yield = -1.62 + 0.74 pH	0.63	***
yield = 0.16 + 0.42 pH - 0.1 Al	0.74	**
yield = 1.14 + 0.27 pH - 0.02 Mn	0.72	ns
yield = -0.28 + 0.5 pH - 0.13 Al + 0.01 Mn	0.74	ns
<b>Faba GR site</b>		
yield = -1.39 + 0.68 pH	0.44	***
yield = 1.92 + 0.09 pH - 0.16 Al	0.56	ns
yield = 4.63 - 0.34 pH - 0.04 Mn	0.65	ns
yield = 8.57 - 0.88 pH + 0.57 Al - 0.16 Mn	0.77	***
<b>Wheat MR site</b>		
yield = -2.32 + 0.77 pH	0.77	***
yield = -4.11 + 1.29 pH + 0.1 Al	0.79	ns
yield = -3.96 + 1.25 pH + 0.02 Mn	0.78	ns
yield = 0.86 + 0.53 pH + 1.04 Al - 0.22 Mn	0.85	**
<b>Barley MR site</b>		
yield = -3.75 + 1.29 pH	0.79	***
yield = -0.74 + 0.78 pH - 0.32 Al	0.82	*
yield = 0.71 + 0.55 pH - 0.06 Mn	0.85	*
yield = 0.79 + 0.6 pH + 2.73 Al - 0.42 Mn	0.97	***
<b>Durum MR site</b>		
yield = -1.15 + 0.71 pH	0.66	***
yield = 2.27 + 0.12 pH - 0.23 Al	0.81	ns
yield = 3.20 - 0.02 pH - 0.05 Mn	0.76	ns
yield = -0.16 + 0.52 pH - 0.49 Al + 0.07 Mn	0.83	ns
<b>Barley DS site</b>		
yield = -0.57 + 0.69 pH	0.9	***
yield = 1.74 + 0.31 pH - 0.07 Al	0.97	***
yield = 1.56 + 0.36 pH - 0.02 Mn	0.98	***
yield = 1.49 + 0.38 pH - 0.01 Al - 0.02 Mn	0.98	*
<b>Faba DS site</b>		
yield = -2.74 + 0.79 pH	0.87	***
yield = -0.31 + 0.37 pH - 0.06 Al	0.96	***
yield = -0.12 + 0.38 pH - 0.02 Mn	0.97	***
yield = -0.10 + 0.37 pH - 0.01 Al - 0.02 Mn	0.97	*

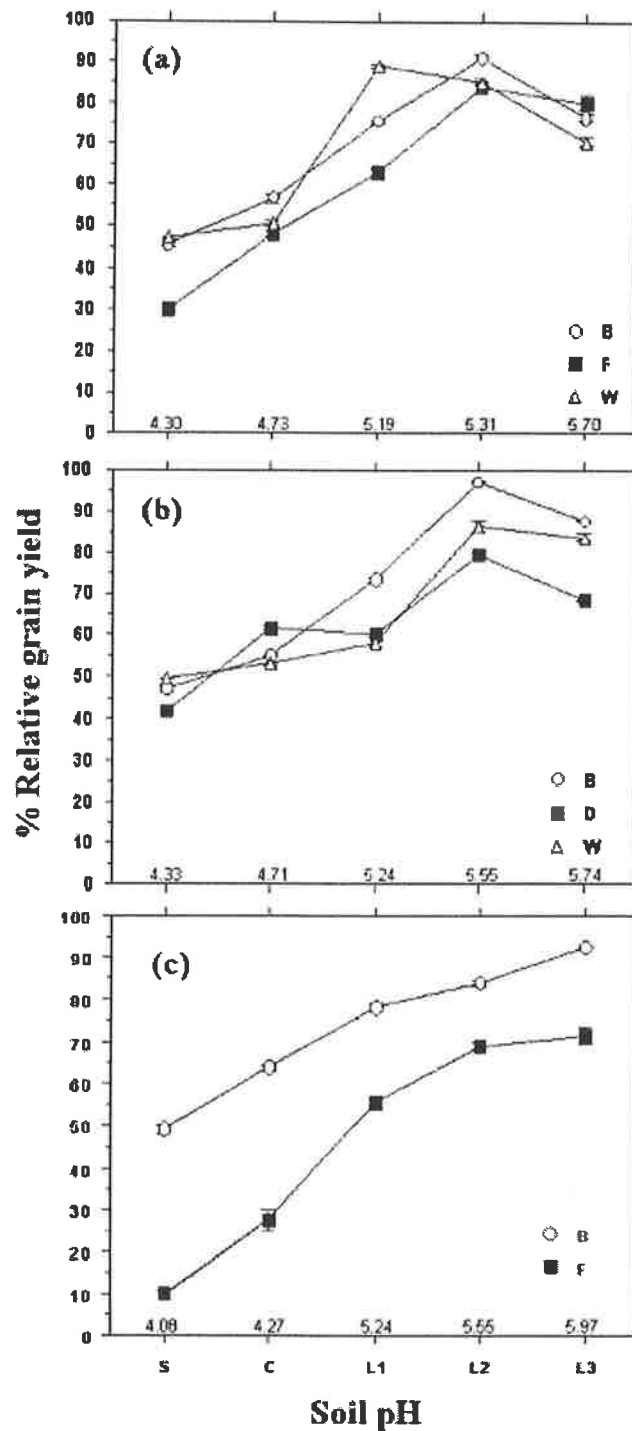


Figure 4.10 Lime requirement curves for % relative yield for all crops on GR (a), MR (b) and DS (c) at various target treatments. Lime rates indicated represent the amount required to increase the pH of the soil. The original soil pH for each site indicated as control (c).

Also, the precise rate of lime required to achieve the target pH may not be an issue in places where lime application is cheap (such as South Australia), but can be important for places where lime is expensive. For example if 2 t/ha can achieve 85% of maximum yield at the MR site for wheat for \$40 per hectare limed, applying extra 2 tones (overall \$80/ha lime) could only achieve an extra 3% yield, so it not be economical to apply the 4 t/ha lime. Similarly with the DS site, L3 (3 t/ha) improved yield by 90% and the lower L2 rate (2 t/ha) shows 80% of yield could be achieved and it may be worthwhile to apply more lime to get the higher yield.

#### **4.5 Conclusions**

The data presented in this study demonstrate that the approach used for predicting lime responsiveness of a soil has worked for all sites. The lime requirement calculated using the model of Hochman *et al.* (1989) provided very good estimates of the final pH. The parameters that affect pH buffering and that have been used here to predict the effects of lime rates are soil TEC, Al and pH of unlimed soil. The lime requirement calculated by titration methods may ameliorate toxicity due to the effect of Al and Mn, but they may not be enough to achieve 90% of potential yield, as shown in this study. Here in the mid-north of South Australia, with red brown earth soils, the levels of Al are very low compared with other acid-soil types and comparable studies in Australia. The data given in this study suggest the best option could be increasing pH, and subsequently Ca and ECEC of the soil to reach higher yield, rather than targeting to remove Al toxicity alone. Using the lime treatments calculated by the Hochman model generally increased yield by 30-60% higher than the control at all sites. It would appear that liming to achieve a  $\text{pH}_{\text{Ca}}$  of 5.2 has removed Al toxicity, and further liming to achieve  $\text{pH}_{\text{Ca}}$  5.5-6.0 may have improved other soil properties (possibly Ca or N availability) to realise further yield gains. The amount of lime required to reduce  $\text{Al}_{\text{Ca}}$  to lower than 1 mg/kg for the 3 sites was about 1 t/ha for the GR and DS sites and 0.75 t/ha for the MR site. These lime rates correspond to raising the soil  $\text{pH}_{\text{Ca}}$  to a value of 5.2 for all sites. At this  $\text{pH}_{\text{Ca}}$ , most of the crop species in this study were at about 55-75% of their potential yield. At  $\text{pH}_{\text{Ca}}$  of 5.5-6.0, most plant species reached to 80-90% of their potential yield. At these higher pH values the exchange sites vacated by  $\text{H}^+$ , Al and Mn were almost all taken up by Ca. Thus

it is concluded here that measuring the Al saturation % of ECEC alone could not adequately predict the yield responses for all sites and species, especially when the Al saturation % of the ECEC was very low. Possibly the extractable Al measured by the methods used in this study may not be sufficient, as they do not distinguish between toxic monomeric and non-toxic complexed Al forms. Differentiation may be especially important in soils of high buffering capacity and high OC content, where Al complexes with organic acid ligands may alleviate the toxic effects of Al. This aspect of Al chemistry is reported in more detail in chapter 7 using the long-term Tarlee data.

To improve lime prediction it is important to have an agreement between plant response and lime required to reach maximum yield for each species. From the regression analyses of grain yield on pH, the expected grain yields could be calculated for any soil pH. In most cases, these relationships accounted for 80-90% of the variation in yield as determined by soil pH. However, the relationship between Al and pH shows a significant variation in extractable  $Al_{Ca}$  over the  $pH_{Ca}$  range 4 to 5. This observation is important, as the greatest variability in Al would correspond to those soils that would be considered strongly acid ( $pH < 4.8$ ). So it would be better to show the Al and Mn relationship with yield, and then use these data with pH data for each site to establish a more accurate prediction of yield for each crop. At the GR site the inclusion of Al and Mn together improved the relationship from 44 to 77% for wheat, and from 63 to 74% for barley for Al alone and from 44 to 77% for faba for Al and Mn together. For the MR site these improvements were 77 to 85% for wheat, 79 to 97% for barley for Al and Mn inclusion and no response for durum. With the DS data the fitness of the model increased from 90 to 98 % for barley and 87 to 97% for faba beans by inclusion of Al or Mn as individual or Al and Mn together. To calculate the rate of lime required to give maximum yield for a given crop species, response curves were constructed using the regression equations. These lime requirement curves can be used to predict the lime rate that achieves 80-90% maximum yield for different species on the 3 sites on common red earth soil type in the mid-north South Australia. Response curves, for wheat and durum show that its largest yield gains occurred at  $pH_{Ca}$  5.2-5.5, which requires a lower amount of lime (1 t/ha) for wheat at GR site and medium amount of lime (about 1.5 t/ha) at MR site for wheat and durum. With these soil types, wheat and durum reaches 80-90% of maximum yield at about pH 5.5, and it is unlikely to be economic to attempt to obtain 100% yield by

applying additional lime (about 3 t/ha). For barley these 90% responses were reached at  $\text{pH}_{\text{Ca}}$  of 5.3 to 5.5 with the addition of 2 (GR), 1.5 (MR) and 4 t/ha (DS). For faba beans in GR and DS site yield response curve reached a maximum peak at L1 and L2 respectively and start to decrease with increase of lime and pH in GR but continued its trend for MR site reached a plateau after  $\text{pH}_{\text{Ca}}$  5.8. Whilst these data strongly suggest that Al and Mn related factors may be implicated in the yield response, it is also important that other factors (eg. Ca and N availability) are considered with respect to these lime responses. This is considered in more detail in the next chapter.

## Chapter 5

### 5. Aspects of management for high-input intensive cropping systems that may be involved in the acidity complex on red brown earth soils

#### 5.1 Introduction

Liming has been shown to increase the grain yield of some crop species (Chapter 4), indicating that soil acidity may be implicated on the red-brown earth soils in the mid-north of South Australia. But it is well appreciated that the expression of acid soil infertility is complex (Foy 1984), and the result of liming on acid soil cannot be simply described by any single factor. As soil pH increases due to lime addition, or more acidic due to sulphur addition, then soil factors associated with high and low pH (especially Al), and various nutrient factors can cause plant yields to be affected. Elsewhere yield responses due to liming have been shown to be closely related to exchangeable Al, Al saturation% of ECEC and  $Al_{Ca}$  (Bromfield *et al.* 1983; Hoyt and Nyborg 1987; Webber *et al.* 1976; Conyers *et al.* 1991). Also, below pH 4.7 the pH buffering is known to be primarily due to  $Al_K$  (Kamprath 1970; Reeve and Sumner 1970; Farina *et al.* 1980). Liming studies on acidic soils have also shown an important role for Ca after liming, with the ECEC of soil increasing with lime application associated with the increase in exchangeable Ca (Edmeades 1982; Hochman *et al.* 1992; Slattery and Coventry 1993).

In South Australia a high proportion of the cropping soils are sodic, and a small proportion of these (1.9% out of 32.9%) are sodic-acid soils (Naidu *et al.* 1993). Sodicity can influence soil structure and nutrient availability in a way that eventually can affect plant growth and plant productivity (Gupta and Abrol 1990; Naidu and Rengasamy 1993). The standard practice in managing a soil sodicity problem is the use of an amendment such as gypsum. This has been widely practiced in South Australia and together with reduced tillage and stubble retention has enabled a more intensive approach to crop production. Where sodic-acid situations exist, simultaneous application of gypsum and lime to soil has been practiced by some farmers in South Australia. But there is little known from field studies on what mutual or additive benefits accrue from using these two soil amendments together and the associated change in the soil chemistry.

As soil management has improved associated with a combination of gypsum use, stubble management and reduced tillage, farmers have adopted a more high input approach to cropping, with soils able to sustain more crops grown in sequence. Given such management, and with the soil allowing more efficiency with water use, then N-fertiliser use has also become a regular feature of cropping practices. The long-term rotation trial that was initiated in 1977 at Tarlee was exceptional in that many of the standard practices of the 1990's were anticipated and included in the experiment (Schultz 1995). This trial has also given an indication that soil pH is decreasing, especially with the use of N-fertiliser and legumes in the sequence (Schultz 1995; Xu *et al.* 2002).

In this chapter the data from the experimental sites (GR, MR and DS sites) that were used for evaluation of lime responsiveness (Chapter 4) are again reported, but here providing information from gypsum (G), and lime and gypsum (L+G) treatments. The purpose of these gypsum treatments was to establish whether gypsum alone or as a lime+gypsum application have the potential to improve crop performance in addition to any benefits obtained from ameliorating acidity per se. Further, in this chapter the effects of soil amendments on N content of grain are given as these data can provide an insight into the nature of the responsiveness of the treatments, and also relate to aspects of higher input farming in this region.

## **5.2 Materials and methods**

### **5.2.1 Site selection, soil description and experimental design**

Soil descriptions for the 3 sites are shown in Table 4.1, and soil chemical characterization is shown in Table 3.1. Lime and S rates were estimated from models developed by Hochman *et al.* (1989). The amount of gypsum required for treatments G and L+G were calculated by the method of Gupta and Abrol (1990) and this method is described in chapter 3. The rate for gypsum was 4 t/ha and for lime + gypsum treatment was 2.5+2.5 t/ha. The gypsum was 80% pure containing 21.15% Ca, 16.18% S, 0.02% soluble chloride and 2% free moisture. Crop management, crop measurement, soil sampling and soil chemical analyses used here are similar to those used in chapter 4.

### **5.2.2 Protein and N content measurement**

Protein was measured by the method of O<sub>2</sub>/O<sub>3</sub> Dumas Combustion total nitrogen determination (Rayment and Higginson 1992). Then the total nitrogen of the grain was determined and multiplied by a constant value to find the grain protein levels for each crop species. For example this constant for wheat is 6.25. Also the N content for the wheat crop was calculated by multiplying grain yield with protein % for 1999 and 2000 seasons (Table 5.5).

### **5.2.3 Exchangeable sodium percentage (ESP) measurement**

The ESP which describes the level of adsorbed Na in the soil was calculated using the following formula:  $ESP=100(\text{Exchangeable Na}/\text{CEC})$ . Exchangeable Na and ECEC are measured by the same method described in chapter 4.

### **5.2.4 Statistical analysis**

Analysis of variance was applied to the relative yields of the crops for the two growing seasons to determine significant differences within these sites. Also ANOVA was used to determine the least significant differences between treatments for the soil extraction analyses, and between yields for the G and L+G treatments at the three sites.

## **5.3 Results**

### **5.3.1. Yield and soil treatments**

The yield responses for the 1999 and 2000 seasons for C, G and L+G treatments are shown in Table 5.1. The grain yields for G and L+G plots were not improved for any crop species when compared to C treatment in the 1999 season, at all 3 sites. In the 2000 season, L+G has increased yield ( $P<0.05$ ) for wheat (DM production), barley and faba bean at DS site when compared with G and C treatments. At this site, the G treatment only improved yield for barley compared to the C treatment. At the GR site, the L+G treatment increased yield ( $P<0.05$ ) for barley, faba bean and wheat compared with both G and C treatments. Similarly with the MR site, grain yield for barley and wheat were increased ( $P<0.05$ ) for the L+G compared to C treatment. However neither the G nor L+G treatments resulted in a grain yield improvement for durum. In contrast to the DS site, the grain yield for barley was not increased at either the MR or GR sites with the G treatment.

### 5.3.2 Soil solid phase chemical parameters

#### 5.3.2.1 Soil pH

The soil  $pH_w$  and  $pH_{Ca}$  results for G and L+G treatments in GR, MR and DS sites for the 1999 and 2000 season are shown in Table 5.2. In the 1999 or 2000 season  $pH_w$  was not significantly increased by G or L+G treatment compared to C treatment at any site. In 1999,  $pH_{Ca}$  data are significantly increased ( $P < 0.05$ ) with the L+G treatment compared to the C treatment at GR and DS sites but were not significantly changed at the MR site. In the 2000 season, soil  $pH_{Ca}$  for the L+G treatment was higher at all sites compared to the C and G treatments ( $P < 0.05$ ) (Figure 5.1). The order of the effects of different treatments on soil  $pH_{Ca}$  in MR, GR and DS sites was similar and only was significant for L+G treatment ( $P < 0.05$ ). In most cases, except at MR site in 1999 season, the pH measured in water was lower where G applied compared to control treatment due to the salt effect (Ahern *et al.* 1995).

#### 5.3.2.2 Soil solid phase properties

Soil cation properties are shown in Table 5.2 for G and L+G treatments in 1999 and 2000 season at all sites. Soil exchangeable Al and Mn in 1999 were decreased ( $P < 0.05$ ) with L+G treatment only at the DS site, compared to the C treatment. Similarly, soil extractable (0.01 M  $CaCl_2$ ) Al and Mn in the 1999 season were decreased significantly ( $P < 0.05$ ) with L+G treatment at the DS site. None of the  $Al_K$  or  $Mn_K$  values were changed with G or L+G treatment at any other sites when compared to C treatment in the 1999 season. In the 2000 season, all extractable and exchangeable Al and Mn values were significantly ( $P < 0.05$ ) decreased with L+G treatment compared to C treatment. Also the G treatment at the DS site decreased the extractable and exchangeable Al and Mn in the 2000 season compared to the C treatment, but these values were still significantly higher than those obtained with the L+G treatment ( $P < 0.05$ ).

Both G and L+G increased ( $P < 0.05$ ) the concentration of exchangeable Ca for all sites compared to C treatment in both 1999 and 2000 seasons. The order of this increase for both years and at all sites followed a similar trend as  $L+G > G > C$ . The Mg level did not change significantly ( $P = 0.05$ ) with any treatment in the 1999 season, but in 2000 it did

decrease with the G and L+G treatments at all sites. Also the Ca/Al ratios were higher for L+G treatment compared to G and C treatments in both seasons. The Ca/Mg ratios are higher for both G and L+G treatment compared to C treatment at all sites and seasons. There was no difference between the Ca or Al properties between different plots where the different crop species were grown with the exception here of the significant decrease ( $P < 0.05$ ) for extractable Al and Mn with G treatment for the barley plots at the DS site (Table 5.3).

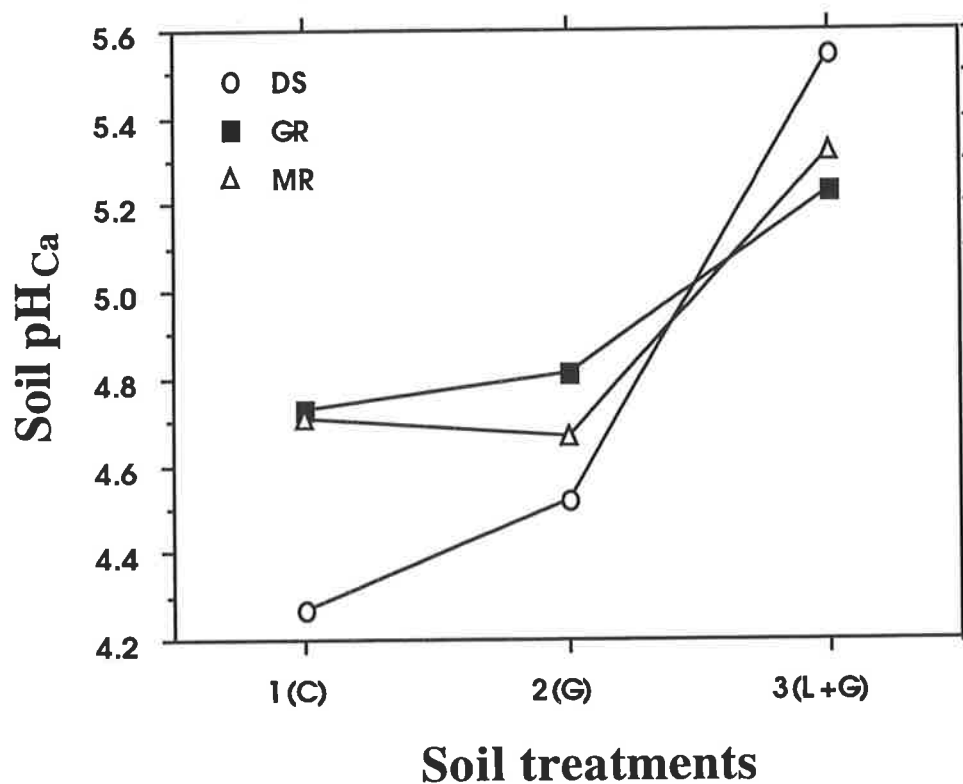


Figure 5.1 The relationship between soil  $pH_{Ca}$  and soil treatments for different sites in 2000 season.

**Table 5.1 Mean yield data for G and L+G treatments for 2 growing seasons at 3 experimental sites (DS, GR, and MR).**

Site	Trt.	Crop (99)	Crop (2000)	Mean yield 1999 (t/ha)	Mean yield 2000 (t/ha)
DS	C	Barley	Barley	2.46	2.56
DS	G	Barley	Barley	2.38	2.79
DS	L+G	Barley	Barley	2.23	3.68
<b>lsd5%</b>				<b>0.12</b>	<b>0.12</b>
DS	C	Canola	Faba	1.94	0.75
DS	G	Canola	Faba	1.97	0.62
DS	L+G	Canola	Faba	2.18	1.48
<b>lsd5%</b>				<b>0.13</b>	<b>0.18</b>
DS	C	Wheat	Wheat	2.29	0.67 (9.86) <sup>1</sup>
DS	G	Wheat	Wheat	2.37	0.45 (10.44)
DS	L+G	Wheat	Wheat	2.46	0.52 (10.80)
<b>lsd5%</b>				<b>0.20</b>	<b>0.19 (0.88)</b>
GR	C	Barley	Barley	2.13	1.70
GR	G	Barley	Barley	2.14	2.10
GR	L+G	Barley	Barley	1.95	2.41
<b>lsd5%</b>				<b>0.09</b>	<b>0.12</b>
GR	C	Durum	Faba	2.51	1.20
GR	G	Durum	Faba	2.33	1.34
GR	L+G	Durum	Faba	2.54	1.70
<b>lsd5%</b>				<b>0.12</b>	<b>0.19</b>
GR	C	Wheat	Wheat	1.75	1.52
GR	G	Wheat	Wheat	1.52	1.55
GR	L+G	Wheat	Wheat	1.69	2.07
<b>lsd5%</b>				<b>0.11</b>	<b>0.50</b>
MR	C	Canola	Barley	2.00	2.20
MR	G	Canola	Barley	1.93	2.70
MR	L+G	Canola	Barley	2.30	3.28
<b>lsd5%</b>				<b>0.05</b>	<b>0.56</b>
MR	C	Durum	Durum	2.39	2.47
MR	G	Durum	Durum	2.43	1.94
MR	L+G	Durum	Durum	2.64	2.39
<b>lsd5%</b>				<b>0.31</b>	<b>0.19</b>
MR	C	Wheat	Wheat	2.72	2.12
MR	G	Wheat	Wheat	2.55	2.65
MR	L+G	Wheat	Wheat	2.85	3.45
<b>lsd5%</b>				<b>0.21</b>	<b>0.56</b>

<sup>1</sup>Data in parenthesis is dry matter production (grain yield being lost by frost damage)

**Table 5.2 The mean data for the effect of G and L+G treatments on soil properties for 1999 and 2000 seasons at 3 sites.**

Site	Year	Trt.	pH <sub>w</sub>	pH <sub>Ca</sub>	Ca (cmol+/kg)	Mg (cmol+/kg)	Al <sub>0a</sub> (mg/kg)	Mn <sub>Ca</sub> (mg/kg)	Al <sub>K</sub> (cmol+/kg)	Mn <sub>K</sub> (cmol+/kg)	ECEC	%Al of ECEC	Ca:Al ratio	Ca:Mg ratio
GR	1999	C	5.73	4.74	4.70	1.70	1.70	24.75	0.06	0.08	7.84	0.81	78	2.76
GR	1999	G	5.14	4.74	7.30	1.50	1.90	30.00	0.06	0.07	10.15	0.63	122	4.87
GR	1999	L+G	5.48	5.20	10.90	1.60	1.03	22.50	0.02	0.07	13.76	0.14	545	6.81
<b>lsd 5%</b>	<b>1999</b>		<b>0.41</b>	<b>0.44</b>	<b>2.11</b>	<b>0.30</b>	<b>1.62</b>	<b>13.42</b>	<b>0.06</b>	<b>0.05</b>	<b>2.07</b>	<b>0.73</b>	<b>243</b>	<b>1.73</b>
DS	1999	C	5.31	4.31	2.20	0.50	7.20	38.75	0.17	0.10	4.13	4.10	13	4.40
DS	1999	G	4.77	4.46	4.50	0.50	6.70	38.00	0.14	0.10	6.20	2.19	32	9.00
DS	1999	L+G	5.43	5.38	7.30	0.50	1.35	21.00	0.02	0.06	8.86	0.21	365	14.60
<b>lsd 5%</b>	<b>1999</b>		<b>0.60</b>	<b>0.69</b>	<b>1.72</b>	<b>0.10</b>	<b>3.35</b>	<b>9.44</b>	<b>0.09</b>	<b>0.03</b>	<b>1.60</b>	<b>2.26</b>	<b>187</b>	<b>4.36</b>
MR	1999	C	5.47	5.08	3.80	0.70	2.22	12.33	0.03	0.05	5.22	0.58	127	5.43
MR	1999	G	5.77	5.10	5.29	0.60	1.68	14.50	0.03	0.04	6.93	0.43	176	8.67
MR	1999	L+G	5.70	5.09	9.30	0.60	1.00	7.90	0.01	0.02	10.50	0.12	930	15.50
<b>lsd 5%</b>	<b>1999</b>		<b>0.44</b>	<b>0.44</b>	<b>1.49</b>	<b>0.23</b>	<b>4.84</b>	<b>8.98</b>	<b>0.02</b>	<b>0.03</b>	<b>1.70</b>	<b>0.43</b>	<b>243</b>	<b>4.38</b>
GR	2000	C	6.06	4.73	4.80	1.15	1.93	24.00	0.04	0.07	7.35	0.50	120	4.17
GR	2000	G	5.76	4.81	6.35	0.82	2.23	22.67	0.03	0.06	8.46	0.41	212	7.71
GR	2000	L+G	5.81	5.23	8.45	0.63	0.87	11.93	0.01	0.03	10.28	0.05	845	13.51
<b>lsd 5%</b>	<b>2000</b>		<b>0.47</b>	<b>0.47</b>	<b>1.32</b>	<b>0.20</b>	<b>1.05</b>	<b>4.68</b>	<b>0.02</b>	<b>0.02</b>	<b>1.09</b>	<b>0.38</b>	<b>666</b>	<b>4.02</b>
DS	2000	C	5.53	4.27	2.45	0.36	7.97	30.67	0.17	0.07	4.21	4.01	14	6.77
DS	2000	G	5.22	4.52	4.95	0.29	4.47	21.33	0.07	0.05	6.32	1.37	71	17.18
DS	2000	L+G	5.59	5.55	5.40	0.24	1.63	14.00	0.01	0.03	6.62	0.17	540	22.62
<b>lsd 5%</b>	<b>2000</b>		<b>0.58</b>	<b>0.80</b>	<b>1.13</b>	<b>0.06</b>	<b>1.92</b>	<b>5.86</b>	<b>0.04</b>	<b>0.02</b>	<b>0.95</b>	<b>2.75</b>	<b>220</b>	<b>6.87</b>
MR	2000	C	5.93	4.71	4.20	0.59	1.63	14.00	0.01	0.03	5.48	0.26	420	7.09
MR	2000	G	5.64	4.67	5.10	0.40	1.50	12.00	0.02	0.03	5.90	0.05	255	11.90
MR	2000	L+G	5.95	5.32	6.30	0.30	0.67	5.50	0.001	0.01	7.17	0.02	567	21.36
<b>lsd 5%</b>	<b>2000</b>		<b>0.47</b>	<b>0.53</b>	<b>0.85</b>	<b>0.12</b>	<b>0.66</b>	<b>3.38</b>	<b>0.02</b>	<b>0.02</b>	<b>0.79</b>	<b>0.24</b>	<b>2677</b>	<b>6.15</b>

**Table 5.3 The effect of soil treatments on CaCl<sub>2</sub> extractable Al and Mn (mg/kg) within the crop species plots, in 2000 season at 3 experimental sites. Durum (D) or faba bean (B) were used from 2000 growing season.**

Crop	Treatment	MR site		GR site		DS site	
		Al <sub>Ca</sub>	Mn <sub>Ca</sub>	Al <sub>Ca</sub>	Mn <sub>Ca</sub>	Al <sub>Ca</sub>	Mn <sub>Ca</sub>
Barley	C	1.5	13.0	1.2	19.0	8.6	27
	G	1.4	11.0	1.7	18.0	1.2	11
	L+G	0.7	5.5	0.5	8.8	1.2	10
(D) or (B)	C	1.5(D)	14.0(D)	2.8(B)	30.0(B)	7.6(B)	33(B)
	G	1.6(D)	13.0(D)	3.1(B)	30.0(B)	6.0(B)	29(B)
	L+G	0.5(D)	5.4(D)	1.2(B)	17.0(B)	2.1(B)	18(B)
Wheat	C	1.9	15.0	1.8	23.0	7.7(B)	32
	G	1.5	12.0	1.9	20.0	6.2	24
	L+G	0.8	5.6	0.7	10.0	1.6	14
<b>lsd 5%</b>		<b>0.52</b>	<b>4.09</b>	<b>0.69</b>	<b>6.40</b>	<b>3.64</b>	<b>8.14</b>

The % of ECEC for each individual cation for all treatments in 3 sites is shown in Table 5.4 for the 2000 season. ECEC of the soil for GR, MR and DS sites were significantly ( $P < 0.05$ ) increased after the addition of G and L+G, compared to C treatment at all sites. However, the ECEC levels were significantly higher ( $P < 0.05$ ) with L+G treatment compared to G treatment at all sites and generally followed a similar trend improving in the order of L+G > G > C. Also, Al saturation percentage of the ECEC showed a decrease ( $P < 0.05$ ) with L+G treatment compared to G and C treatments in both 1999 and 2000 seasons (Table 5.2). The decrease in soil Al% of ECEC with L+G treatment in 1999 season only happened at DS and MR sites, but with the 2000 season data there was a decline at all 3 sites. The only exception here was the significant decrease ( $P < 0.05$ ) of Al% of ECEC with the G treatment, and only at the DS site. Similarly Mn% of ECEC is decreased with L+G treatment compared to C and G treatments. Calcium saturation percentage of the ECEC showed an increase with G and L+G treatments at all sites, with almost 80% of ECEC was occupied with Ca. Mg% of ECEC was decreased with both G and L+G treatments at all 3 sites but Na% of ECEC was decreased only for DS site.

**Table 5.4 Effective CEC and percentage of the ECEC for each individual cation for treatments in three sites, in the 2000 season.**

Site	Treatment	ECEC	Al%	Mn%	Ca%	Mg%	Na%	K%
MR	C	5.48	0.26	0.59	76.65	10.82	4.02	7.67
	G	5.90	0.28	0.46	84.40	6.84	4.07	6.95
	L+G	7.17	0.02	0.14	87.88	4.13	2.79	5.02
GR	C	7.35	0.50	0.94	65.32	15.68	5.04	12.52
	G	8.46	0.41	0.69	75.10	9.73	3.55	10.53
	L+G	10.28	0.05	0.32	82.16	6.08	3.11	8.27
DS	C	4.21	4.01	1.64	58.19	8.60	6.65	20.90
	G	6.32	1.06	0.75	78.30	4.56	3.48	15.86
	L+G	6.62	0.17	0.49	81.05	3.58	3.15	15.56
<b>Lsd 5%</b>		<b>1.62</b>	<b>1.74</b>	<b>0.45</b>	<b>7.71</b>	<b>3.00</b>	<b>2.10</b>	<b>5.54</b>

### 5.3.3 Protein

The N content (grain yield  $\times$  protein%) and protein % for the wheat grain harvest in the 1999 and 2000 seasons are shown in Table 5.5. Grain protein % ranged from 11.4 to 12.5 in 1999 and 8.2 to 9.4 in the 2000 season, depending on soil treatments and site. But within the 1999 and 2000 seasons there were no differences ( $P=0.05$ ) between protein levels. The protein levels obtained were generally lower in the 2000 season. The N content ( $\text{kg ha}^{-1} \text{ year}^{-1}$ ) ranged from 182 to 353 in 1999 and 119 to 313 in the 2000 season. The N content in the 1999 season did not change significantly within treatments. In the 2000 season this property has been increased significantly ( $P<0.05$ ) with L+G and lime treatments at the GR and MR sites (Table 5.5). S and G treatments did not affect the protein and N content at any site. Protein data for the wheat grain at the DS site are not shown due to the frost damage.

**Table 5.5 Grain protein % and N content for wheat crop on GR, MR and DS sites in 1999 and 2000 growing seasons.**

Site	Treatment	Wheat Protein 1999(%)	Wheat Protein 2000(%)	N content 1999 (kg/ha/year)	N content 2000 (kg/ha/year)
GR	C	11.40	8.72	199	133
GR	G	12.00	8.21	182	127
GR	L+G	12.10	8.61	204	179
	Lime				
GR	treatment <sup>1</sup>	12.50	8.75	237	224
GR	S	12.00	8.44	205	119
<b>lsd5%</b>		<b>ns<sup>2</sup></b>	<b>ns</b>	<b>47</b>	<b>44</b>
MR	C	12.50	9.35	340	199
MR	G	11.90	8.95	303	252
MR	L+G	12.40	8.72	353	299
MR	Lime treatment	11.80	9.06	325	313
MR	S	12.00	8.44	307	168
<b>lsd5%</b>		<b>ns</b>	<b>ns</b>	<b>63</b>	<b>54</b>

<sup>1</sup>lime treatment is L2 from chapter 4; <sup>2</sup>ns is stands for not significant

#### 5.3.4 ESP of the soil

The ESP for all treatments from the 3 sites (GR, MR and DS) is presented in Table 5.6. The mean value for 3 sites indicates that L+G treatment significantly decreased ESP more than G, and G more than the C treatment ( $P < 0.05$ ). Overall the ESP values for the lime or S treatments did not differ ( $P = 0.05$ ) from the control value. However data for the individual sites indicate that G, L+G and lime decreased the value of ESP at the DS and GR sites significantly compared to C treatments, but at the MR site the ESP decreased only with L+G treatment. This may have been influenced by the lower values of ESP to begin with at the MR site (Table 5.6). The S treatment did not decrease soil ESP at any site compared to C treatment. The data in Table 5.6 indicate that the ESP level at the DS site and the C treatment was higher compared to other 2 sites, and was in order of

DS>GR>MR. This value also was higher at the beginning of the experiment in 1998 at the DS site compared to other two sites. In summary, the DS site is the only site that could be described as showing a sodicity problem in the surface soil (Table 4.1).

**Table 5.6 ESP values with treatments at GR, MR and DS sites for 2000 season.**

Treatment	ESP			
	DS	GR	MR	Mean for 3 sites
C	6.65	5.04	4.02	5.24
G	3.48	3.55	4.07	3.70
L+G	3.15	3.11	2.79	3.02
Lime <sup>1</sup>	5.25	3.57	3.51	4.03
S	5.65	4.90	4.50	5.02
lsd5%	1.24	0.72	0.53	1.32

<sup>1</sup>the mean value for all lime treatments

#### 5.4 Discussion

The data given in chapter 4 showed that liming the soil at the 3 sites generally improved yield, and here again the L+G treatment also improved the yield. This latter improvement in yield was most likely favoured by the lime proportion of the L+G treatment, related to improving soil pH, although possibly the gypsum proportion, through improving soil condition (i.e. ECEC and ESP), may have been beneficial. But there was no an additive effect on yield of the L+G compared with lime treatment. The increase in soil pH in the L+G treatment occurred because of lime proportion in the L+G treatment, as the G alone did not change pH (Smith *et al.* 1994).

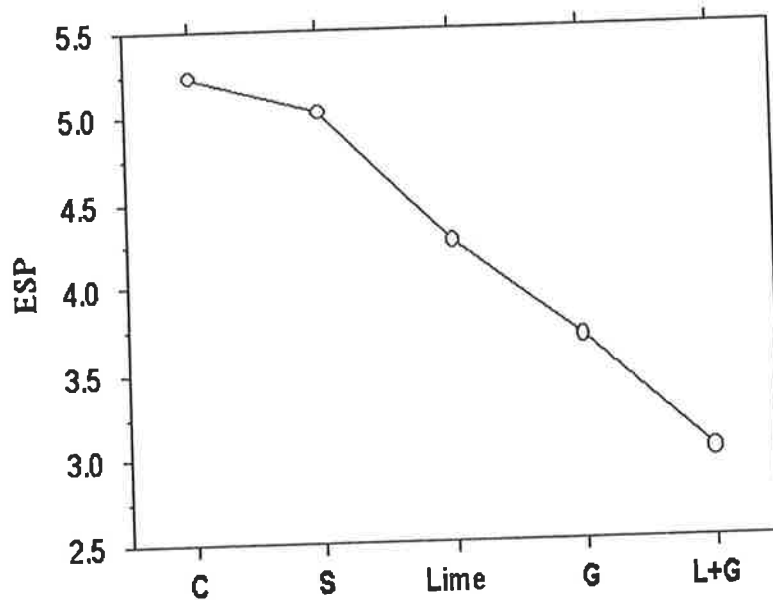
It is difficult to discriminate what aspect (or aspects) of the soil acidity complex, or soil environment, is changed by the G or L+G treatments in contributing to any yield improvements. But whatever the aspects are, from the overall data in this study it is not possible to assume or generalise that G treatment can increase yield for a similar soil type. Data in this study suggest that Al decreased with the G treatment at the DS site. Also

there was a higher sodicity level in the surface soil of the DS site (compared to other sites) and decreasing ESP in this site by G treatment may produce a favoured condition for a sensitive crop such as barley, and hence increase its grain yield.

The improvement of yield in the barley crop with the G treatment at the DS site may also be related to improving soil condition and chemical properties due to release of Ca in the soil solution (Shainberg and Gal 1982; Shanmuganathan and Oades 1983; Rengasamy *et al.* 1984; Muneer and Oades 1989 a & b). This increase in Ca has been reflected in higher ECEC of the soil for G and L+G treatments. Also the lower ESP value obtained with the G treatment (Figure 5.2) may be enhanced due to the greater solubility of gypsum, which maintained the concentration of  $\text{Ca}^{2+}$  cations at higher value in the soil solution (Muneer and Oades 1989 a & b). The other possibility is the improvement in ionic strength of the soil solution, which could indirectly lower the activity of  $\text{Al}^{3+}$  (Adams 1978). Also sulfate from gypsum may reduce the amount of  $\text{Al}^{3+}$  present in the soil solution through combining Al with sulfate to form  $\text{AlSO}_4^+$  which is much less toxic to plants than  $\text{Al}^{3+}$  (Pavan *et al.* 1982; Kinraide and Parker 1987). But notwithstanding the above possible impacts with these data there is no real evidence to conclude that sodicity is affecting yield.

Other studies have suggested that yield improvement with gypsum treatment is possible and may occur while there is a higher ratio of Ca% of ECEC, through improved Ca availability to plants (Adams 1978). Here the data for the grain yield and the Al% and Ca% of ECEC for GR, MR and DS show that an increase in grain yield in the 2000 season was likely not associated with an increase in the Ca% of ECEC, but rather the decrease in Al% of ECEC (eg. higher yield for barley at DS site). In the 1999 season the Ca% of ECEC was improved for G and L+G but yield was not improved, but the Al% of ECEC was unchanged. However in the 2000 season, by decreasing Al% of ECEC, the yield for L+G treatment was improved, but the Al% of ECEC for G treatment was still high (toxic) and so, did not improve the yield. So any improvement in yield for the barley crop with the G treatment at the DS site is not because of the G treatment it is because of the lower level of Al % of ECEC in the first place in the soil environment at this site. At the same time, lowering the ESP of the soil with the G and L+G treatments may partially be influencing the increased yield for barley at the DS site. For a given soil and plant, a

critical ESP could be a limiting factor on growth, with influences through structural factors important in seedling emergence and root penetration (Shainberg and Letey 1984; Goldberg *et al.* 1988). The overall ESP values at the 3 sites indicate that ESP was lower with G and L+G treatments (Figure 5.2) compared with lime application.



**Figure 5.2** The overall relationship between ESP and the effect of treatment averaged for 3 sites (GR, MR and DS) for 2000 seasons

However, lime not only can increase soil pH and reduce the Al level of the soil but also can increase the availability of N and thus improve crop growth (Edmeades *et al.* 1995). So it is important to check the grain N content with the different soil treatments.

The grain yields for wheat were generally lower in the 2000 season despite the significant increase with lime treatments compared to other treatments. This was matched with a general decline in grain protein % and N content (Table 5.4) in 2000 compared to 1999. This would be due to the decision to not apply additional N at the tillering stage in 2000, compared with an application of N at tillering in the 1999 season. Given that there were few responses to lime in 1999, compared with 2000, then it is quite possible the lime responses may just reflect increased N availability due to lime increasing N mineralization (Helyar and Porter 1989; Bolan *et al.* 1991). The N content values were less in 2000 compared with 1999 with the C, G and S treatments, but did not differ within

the 2 years with L+G and lime treatments. This, as mentioned above, may be due to improved N availability, but also could be due to improved root growth and uptake of N.

Notwithstanding the uncertainty about this component of the crop response, the cropping systems in this region of South Australia are using in many instances much higher rates of N-fertiliser than were used in this study. It has been shown at a nearby long-term site (Tarlee, Figure 3.1) that N-fertiliser does considerably increase crop production (Schultz 1995). Indeed, the amount of N-fertiliser used in crop systems throughout Australia has increased substantially in recent years, particularly in medium-high rainfall cropping areas, and this agricultural practice will accelerate soil acidification on low buffer capacity soils. The effect of N-fertiliser use at the Tarlee site has been shown to increase soil acidification (Xu *et al.* 2002). This site is typical of this region of South Australia in that farming has required gypsum use and reduced tillage and stubble retention systems to offset soil degradation by wind erosion and compaction and allow more intensive cropping without yield reduction. N-fertiliser use is important, but any long-term impact of this practice on grain yields due to acidification is still unknown.

### 5.5 Conclusions

The data given in chapter 4 showed that liming the soil generally improved yield, and here again (chapter 5) the L+G treatment has improved the yield. This latter improvement in yield was most likely favoured by the lime proportion of the L+G treatment, related to improving soil pH, increasing N mineralization, reducing Al toxicity or due to improved root growth and uptake of N and allowing more efficiency with water use. The simultaneous application of gypsum and lime could be beneficial where there is high Al toxicity levels and sodic soils, but from the data given here it is not possible to assume or generalise that the G treatment will increase yield for a similar soil type.

If N was not supplied in the form of N-fertiliser to crops in intensive rotations then there is likely to be a lower possibility of yield improvement in the presence of lime treatment. The application of N-fertiliser certainly can be highly beneficial under a high-input approach to cropping, with soils able to sustain more crops grown in sequence (Schultz 1995). Notwithstanding the uncertainty about this component of the crop response of the

3 sites studied, it has been shown at Tarlee, that N-fertiliser use does considerably increase crop production, but also that this practice is likely to accelerate soil acidification (Xu *et al.* 2002). Given that the Tarlee site is typical of this cropping region of South Australia, the data from this site will be evaluated in the next chapter to define the effect of high input management practices on soil acidity factors and crop production.

## Chapter 6

### 6. Effects of crop rotations, stubble management and application of nitrogenous fertiliser on soil pH and other soil properties at Tarlee, South Australia.

#### 6.1 Introduction

High input cropping systems contribute to soil acidification in the higher rainfall areas (>500mm) of Australia (Helyar *et al.* 1997). In the medium rainfall areas (400-500 mm average annual rainfall) soil acidification can also occur (Dolling 1995; Helyar *et al.* 1990). The two most important sources of soil acidification out of many causes in cropping systems are acid production from the C and N cycles (Helyar and Porter 1989). The understanding of these N and C cycle processes is important as they provide background for the development of non-acidifying management strategies or developing techniques to minimise the need for lime (Cregan *et al.* 1989). The amount of N-fertiliser used in crop systems throughout Australia has increased with time in recent years and, in the high rainfall cropping areas, this agricultural practice is likely to accelerate soil acidification. Similarly, using legumes in cropping systems can contribute to soil acidification. Soil acidification is important, not only because of its current impacts on the growth of plants, but because the areas affected and the intensity of the problem can rapidly increase with time.

Some survey studies have shown that surface soil pH is declining in the cropping regions of South Australia (Merry *et al.* 1996; Jeffrey and Hughes 1995). In a recent study (Xu *et al.* 2002) have shown that the overall soil acidification was increased by some intensive cropping systems (1978-1992). Some of the soils in this study now are strongly acidic ( $\text{pH}_{\text{Ca}}$  4.2-4.4) in the top 10cm, and may be beginning to show a strong presence of Al (Xu *et al.* 2002), and there now is concern that this acidity is affecting field crop production. Prior to this study by Xu *et al.* (2002) there has been no attempt to quantify the nutrient processes (C and N cycles) associated with acidification and subsequently balance acidification for South Australia. Elsewhere studies have shown that below  $\text{pH}_{\text{Ca}}$  4.7 the pH buffering is primarily due to  $\text{Al}_\text{K}$  (Kamprath 1970; Reeve and Sumner 1970;

Farina *et al.* 1980), and it is likely that given the pH drop in South Australia is showing a similar pH range (Xu *et al.* 2002), then Al or Mn buffering reactions may be of considerable importance.

In the study here, soil samples are used from a long-term rotation trial at Tarlee (1978-1996), South Australia, to estimate the soil acidification rates under different management practices in a 450–500 mm rainfall area. Also, the influence of N and C fractions on soil properties and ability to impact on soil acidification is reported here. Further the effect of these practices on soil pH, soil Al and Mn chemistry and soil exchangeable base cations is examined. Also, the effect of these management practices on grain yield will be assessed. The information on soil acidification, Al and other soil properties may help to understand the pH buffering in naturally acidified soil. Also, the knowledge gained on the rate of soil acidification can be used in estimating lime required to raise or maintain soil pH (Helyar and Porter, 1989) and subsequently avoid yield loss.

## **6.2 Materials and methods**

### **6.2.1 Site selection and soil description**

The field experiment was established in 1977 at Tarlee (34°27' S., 138°77' E.), South Australia, and is described in detail by Schultz (1995). This experiment is selected to represent medium-high rainfall regions of South Australia. Only selected treatments from the original experiment were used in this study. These were the 4 two-year rotations (wheat-wheat, wheat-bean, wheat-lupin and wheat-fallow) that had been continuously used up to 1996; two stubble treatments (removed and retained); and 2 rates of nitrogen (0, 80 kg N/ha as ammonium nitrate) applied to the wheat phase. The stubble removal treatment initially involved burning, but from 1988 the practice of burning was discontinued and the stubble was cut and removed from the experimental plots. There were 2 phases to allow each crop to be grown each year, and 2 replicates. The mean annual rainfall from 1978 to 1996 was 479 mm and the rainfall for each year is shown in Table 3.4. The soil at the site is classified as a hard-setting red-brown earth with a sandy loam texture (Northcote 1979). Some soil properties at the start of the trial in 1978 are given in Table 3.3. The soil description for the Tarlee site (done by R.H. Merry, CSIRO Land and Water on 11<sup>th</sup> October 1990) is given in Table 6.1. Also, plate 6.1 shows the

Tarlee soil profile, which below 35 cm depth changes to silty clay and coarser structure with weathered rock and carbonate nodules.

### **6.2.2 Soil sampling**

Tarlee site soil samples collected in 1978, 1984, 1986, 1992 and 1996 were used in this study. These soils had all been air dried, ground to pass a 2-mm sieve and stored in plastic bags at room temperature. The choice of years was restricted by the availability of soils remaining in storage, and also the expensive operating cost for the analyses required. Some soil and plant data were also obtained from J. Schultz and D. Melinda (both from SARDI).

### **6.2.3 Soil solid phase chemical analysis**

The methods for analysing soil  $\text{pH}_{\text{Ca}}$ ,  $\text{pH}_{\text{w}}$ , EC, Al, Mn, Ca, Mg, Na, K and ECEC is described in section 4.2.5.2 of chapter 4. Soil organic properties were obtained from J. Schultz (from SARDI). Organic carbon percentage (OC%) was measured similar to the method of Walkley and Black (Rayment and Higginson 1992). Nitrate nitrogen ( $\text{NO}_3\text{-N}$ ) was measured using 2 M KCl extractant and then determined by automated colorimetric procedures (Rayment and Higginson 1992). Total-N was measured using the Leco combustion method using Leco CN-2000 (Rayment and Higginson 1992), which requires no digestion.

### **6.2.4 Field pH buffer capacity**

Measuring pHBC involved the reaction of  $\text{Ca}(\text{OH})_2$  buffer solution with soils from different experimental treatments. The method for analysing pHBC is described in section 4.2.5.1 of chapter 4.

### **6.2.5 Soil acidification rates**

Soil acidification rate (AR,  $\text{kmol H}^+ \text{ ha}^{-1} \text{ year}^{-1}$ ) was calculated from the difference between initial and final soil pH according to the method of Helyar and Porter (1989), using Equation 15:

$$\text{AR} = (\text{pH}_{1978} - \text{pH}_{1996})(\text{pHBC} \times \text{BD} \times \text{V}) / \text{T} \quad (15)$$

Where the pH in 1978 and 1996 was measured in 0.01 M CaCl<sub>2</sub>; pHBC is soil pH buffer capacity (cmol H<sup>+</sup> kg<sup>-1</sup> pH<sup>-1</sup> unit); BD is bulk density (k gm<sup>-3</sup>); V is volume of soil sample (m<sup>3</sup> ha<sup>-1</sup>); and T is time (years). In this study, the value of BD for soil in 1978 was used; the BD value is 1.4 kg/m<sup>3</sup> (J Schultz, unpublished data).

The component of the mean acidification rate that can be attributed to the loss of OM from the surface 0-10 cm of soil was determined by the method of Helyar and Porter (1989) using the following formulae:

$$\text{OM CEC}_{1978} = [\text{OC}\% \text{ 1978} \times \text{BD} \times a (\text{pH}1978 - 1.5)] \quad \text{cmol (H}^+) \text{ kg}^{-1} \text{ OC}^{-1} \text{ pH}^{-1} \text{ unit}$$

$$\text{OM CEC}_{1992} = [\text{OC}\% \text{ 1992} \times \text{BD} \times a (\text{pH}1992 - 1.5)] \quad \text{cmol (H}^+) \text{ kg}^{-1} \text{ OC}^{-1} \text{ pH}^{-1} \text{ unit}$$

$$\text{OM CEC}_{1996} = [\text{OC}\% \text{ 1996} \times \text{BD} \times a (\text{pH}1996 - 1.5)] \quad \text{cmol (H}^+) \text{ kg}^{-1} \text{ OC}^{-1} \text{ pH}^{-1} \text{ unit}$$

$$\text{Acc (1978-1992)} = [\text{OM CEC}_{1992} - \text{OM CEC}_{1978}] \times [\text{Soil layer thickness (cm)}] \times b/c (\text{kmol H}^+ \text{ ha}^{-1} \text{ yr}^{-1})$$

$$\text{Acc (1978-1996)} = [\text{OM CEC}_{1996} - \text{OM CEC}_{1978}] \times [\text{Soil layer thickness (cm)}] \times b/c (\text{kmol H}^+ \text{ ha}^{-1} \text{ yr}^{-1})$$

Where OM CEC is organic matter cation exchange capacity; OC% is organic carbon content (g/100g) in each year; BD is the bulk density (kg m<sup>-3</sup>) in 1978, 1992 and 1996; a is the slope coefficient for the titration of organic acid groups in soil organic matter; pH is measured in 0.01 M CaCl<sub>2</sub> for each year; Acc is C-cycle acidification from soil OM; b is a conversion factor to account for the thickness of the soil layer (cm) and to convert the units to kmol (H<sup>+</sup>) ha<sup>-1</sup>; and c is the number of years over which the change in OC occurred (in this case are 14 and 18 years). A value for 'a' (58.48 cmol (+) kg OC<sup>-1</sup> pH<sup>-1</sup> unit), was used according to Curtin *et al.* (1996), which is based on the assumption that the contribution of OM to buffer capacity was approximately 34 cmol (+) kg OC<sup>-1</sup> pH<sup>-1</sup> unit (Helyar and Porter 1989; Curtin *et al.* 1996) multiplied by 1.72. This 1.72 factor accords with an OM:C ratio of 1.72:1.0 (J. Baldock pers. comm. 2001).

**Table 6.1 Soil descriptions for the Tarlee site, South Australia**

Attribute	Unit
Location:	Tarlee, South Australia
Landform:	Crest, low rounded hill
Microtopography:	Slight surface roughness due to cultivation
Slope:	0°
Elevation:	200m (from topographic map)
Rainfall (annual average):	471 mm
Drainage:	Possible restriction at plough pan; Iron staining in root channels of B2k horizon.
Australian Soil Classification:	Lithocalcic Red Chromosol
Great Soil Group:	Red-brown earth
Northcote (1974) classification:	Dr2.13
US Soil Taxonomy:	Fine, mixed, thermic Calcic Palexeralf

Surface to

- 9 cm Ap Dark reddish brown 5YR 3/3 (moist and dry), fine sandy loam; massive or very weak fine granular structure; many fine roots that tend to concentrate in cultivation planes; few small (< 1 mm) pores; sharp, even boundary (cultivation pan) to
- 12 cm A1 Dark reddish brown 5YR 3/3 (moist and dry), fine sandy loam; weak fine granular angular blocky (10 – 20 mm) structure; increased number of fine (< 1 mm) pores; sharp, even boundary to
- 29 cm B2t Dark reddish brown 5YR 3/3 (moist and dry), silty medium clay; weak, coarse prismatic parting to strong, angular blocky or polyhedral (5 – 10 mm) pedes; common fine roots; few fine (< 1 mm) pores; friable (moist); sharp, even boundary to
- 40 cm B2k Reddish brown 5YR 4/3 (m), 5YR 6/3 (d); silty light clay; coarse (20-30 mm) polyhedral structure; friable (m), firm (d); calcium carbonate (> 2 mm) 55%; orange (iron) discoloration in root channels; sharp, wavy boundary to
- 50 cm B2k Brown 7.5YR 5/4 (m), 5YR 7/3 (d), as above (70% > 2mm), harder, nodular calcium carbonate (5 – 10 mm); abrupt, wavy boundary to
- 53 cm C Weathered rock (85% > 2 mm) dipping to N or NE at about 15°; with reddish yellow (7.5YR 6/6, d), weak red (2.5 YR 5/2, d), grey (5YR 5/1) and white layers 1-2 mm thick; clear, wavy boundary to
- 63 cm C Weathered rock (77% > 2 mm); white (10YR 8/1, d) sandy material in a finer matrix (5YR 7/3, d); massive; carbonate nodules.
- 63 + cm R Hard, weathered rock.



**Plate 6.1** Photograph of the Tarlee soil profile showing shallow red-brown earth soil, after 35 cm depth reaches silty clay and coarser structure with weathered rock and carbonate nodules.

#### 4.2.6 Statistical analysis

The coefficient of variation ( $R^2$ ) was calculated for each relationship from the analyses. Analysis of variance (ANOVA) was applied to the relative yields of the crops over selected growing seasons to determine significant differences between these practices. Also ANOVA was used to determine the least significant differences between treatments for soil extraction analysis and between yields for all management practices. Because there were no significant changes in soil properties between management practices prior to 1992, the interaction between management practices is only shown in Figure 6.5 and 6.6.

### 6.3 Results

#### 6.3.1 Grain yield

The grain yield data from the Tarlee site for all years and management practices is shown in Table 6.2. The overall data for the interaction of year with management practices show that from 1978 to 1986 grain yield was significantly ( $P < 0.05$ ) higher for W-F, W-L and W-B compared to W-W rotations, and this increase was influenced by N application but not stubble practice. Overall, there was an increase in grain yield with time with all rotations, stubble management and N-fertiliser treatments from 1986 toward 1992 (Figure 6.1), but the 1996 yields were significantly lower ( $P < 0.05$ ) with W-W, W-F and W-B compared to W-L than in previous years but not significantly lower than 1978 yield values. The lowest grain yield in 1996 was obtained with the combination of wheat-wheat, stubble removed and no N-fertiliser application. The overall order of the effects of different rotations on grain yield for all years was  $W-B \cong W-L > W-F > W-W$  ( $P < 0.05$ ). There was a significant interaction ( $P < 0.05$ ) between the N-fertiliser treatments and rotations, where the addition of fertiliser increased yield relative to the nil fertiliser treatment in the absence of legume crop in the rotation (Table 6.2). Figure 6.1 and Table 6.2 show that for each individual year the highest yield always was with the higher N-fertiliser application compared to nil-fertiliser.

## 6.3.2 Soil solid phase chemical parameters

### 6.3.2.1 Soil pH

The pH data from the Tarlee site for all years (1978 to 1996) and management practices are shown in Table 6.3, 6.4, 6.5, 6.6 and 6.7. There was a decrease in soil  $\text{pH}_{\text{Ca}}$  and  $\text{pH}_{\text{W}}$  with time with all rotation, stubble management and N-fertiliser treatments (Figure 6.2 and 6.3). Overall, the data show the effect of legume rotations and higher N-fertiliser rates on soil pH are significantly higher than the stubble management effects (Figure 6.2 and 6.3). There was a significant interaction ( $P < 0.05$ ) between the N fertiliser treatments with rotations, where the addition of N-fertiliser decreased pH relative to the nil-N treatment in the absence of the legume crop in the rotation (Figure 6.2 and 6.3 section c). The order of the effect of rotations in declining pH is  $\text{W-B} \cong \text{W-L} < \text{W-W} < \text{W-F}$ . Also, where no N-fertiliser is used, W-L and W-B (or legumes) have caused the greatest pH decline.

For each individual year between 1978-1986 the only significant differences for pH values from initial pH values are obtained where there were applications of 80 kg/ha N-fertiliser and only with W-W rotations. The data for 1986 to 1996 indicate that the stubble-retained practice has contributed to the decline in soil  $\text{pH}_{\text{Ca}}$  but the biggest effect has been with the use of 80 kg/ha N fertiliser relative to the nil-fertiliser treatment. Therefore, after 19 years, in 1996, with the effects of combination of treatment inputs, the pH change for the treatment of  $\text{W-L} \cong \text{W-F} \cong \text{W-W}$  and N-fertiliser application is greatest amongst all treatments, with a  $\text{pH}_{\text{Ca}}$  and  $\text{pH}_{\text{W}}$  values of 4.4 and 5.2 compared to the starting value 6.2 and 7.0 respectively. The pH data for these management practices and all years at Tarlee is shown with different depths (Figure 6.4). It can be seen that there was only a significant decrease in soil  $\text{pH}_{\text{Ca}}$  for the management treatments in the 0-10 cm soil depth.

**Table 6.2 The effect of rotation, stubble management and N-fertiliser rates on grain yield (t/ha) between 1978-1996 at Tarlee site.**

Rotation	Stubble	N	Yield 78 (t/ha)	Yield 84 (t/ha)	Yield 86 (t/ha)	Yield 92 (t/ha)	Yield 96 (t/ha)
W-Wheat	Remove	0	1.01	1.10	0.98	0.94	0.69
		80	1.75	2.10	2.00	2.51	2.48
	Retain	0	0.67	1.32	1.11	1.09	1.05
		80	2.39	2.20	2.19	2.69	2.49
<b>Isd5%</b>			<b>0.08</b>	<b>0.04</b>	<b>0.06</b>	<b>0.06</b>	<b>0.16</b>
W-Beans	Remove	0	1.95	2.69	2.36	2.26	1.87
		80	2.14	3.01	2.60	2.94	1.90
	Retain	0	1.82	3.03	2.73	2.52	2.17
		80	2.21	3.10	2.94	2.87	2.17
<b>Isd5%</b>			<b>0.12</b>	<b>0.18</b>	<b>0.08</b>	<b>0.12</b>	<b>0.14</b>
W-Lupins	Remove	0	1.43	2.47	2.20	2.45	2.06
		80	2.80	2.44	2.32	2.93	2.53
	Retain	0	1.44	2.72	3.09	2.70	2.08
		80	2.22	2.59	2.91	2.96	2.99
<b>Isd 5%</b>			<b>0.16</b>	<b>0.14</b>	<b>0.18</b>	<b>0.22</b>	<b>0.18</b>
W-Fallow	Remove	0	2.26	1.95	2.21	2.16	1.08
		80	2.86	2.97	2.80	3.05	2.01
	Retain	0	1.51	1.62	2.19	2.05	1.64
		80	2.41	2.50	2.81	2.92	2.57
<b>Isd 5%</b>			<b>0.12</b>	<b>0.20</b>	<b>0.12</b>	<b>0.14</b>	<b>0.22</b>
R			***	***	***	***	***
S			***	ns	***	ns	***
N			***	***	***	***	***
R*S			***	***	***	***	***
R*N			***	***	***	***	***
S*N			***	**	**	**	ns
R*S*N			***	ns	**	ns	***

\*\*\* = P<0.001, \*\* = P<0.01 and \* = P<0.05, and ns is not significant. R, S and N illustrate rotation, stubble and nitrogen treatments respectively.

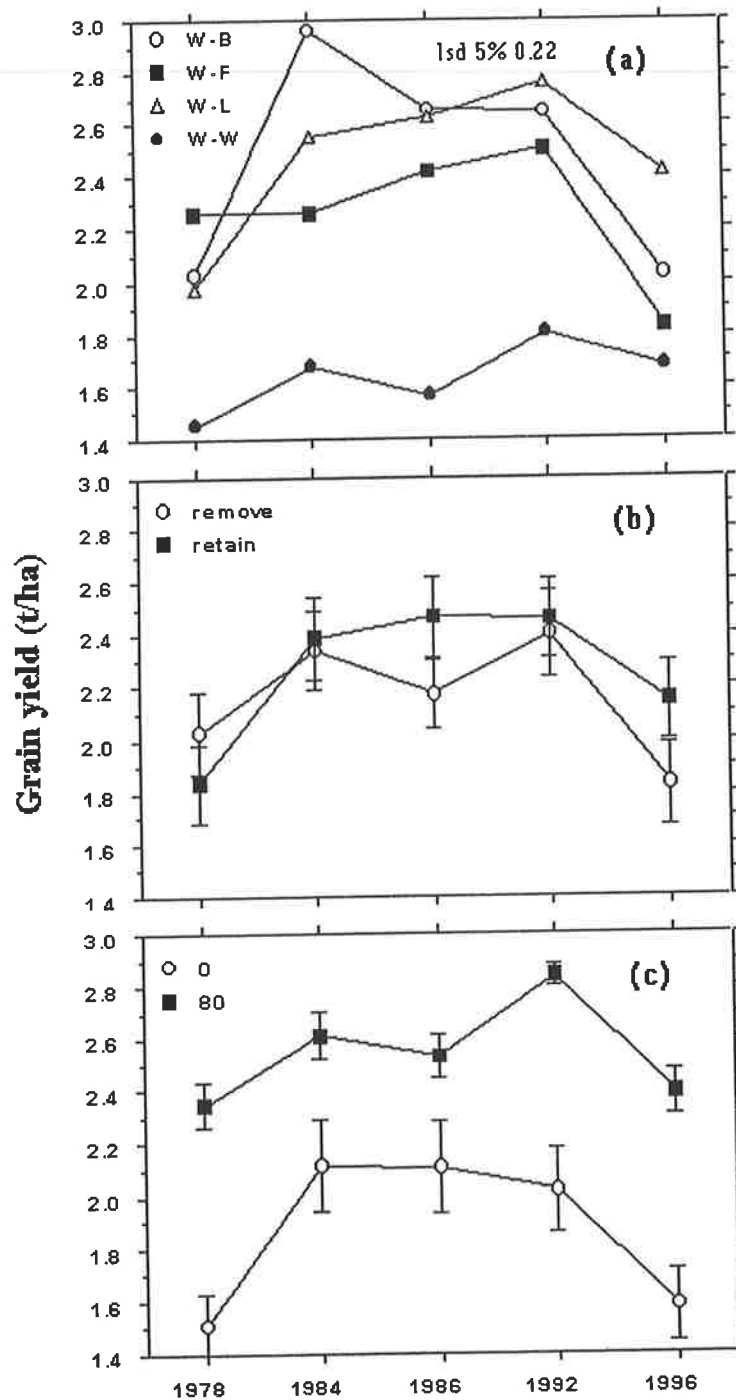


Figure 6.1 The effect of year with the main effects of rotation (a), stubble management (b) and N-fertiliser rates (c) on grain yield (t/ha) between 1978-1996 at Tarlee site (main effects). Error bars indicate standard errors of deviation.

**Table 6.3 The effect of rotation, stubble management and N-fertiliser rates on solid phase chemical characteristics in 1978 at Tarlee site.**

Rotation	Stubble	N	pH <sub>Ca</sub>	Ca <sup>2+</sup>	Al <sub>K</sub> (cmol +/kg)	Mn <sub>K</sub> (cmol +/kg)	Al <sub>Ca</sub> (mg/kg)	Mn <sub>Ca</sub> (mg/kg)	ECEC (cmol+ /kg)	Al % ECEC	Mn % ECEC
W-Wheat	Remove	0	6.48	6.62	0.003	0.07	0.07	18.47	10.40	0.03	0.67
		80	6.00	6.62	0.003	0.07	0.07	18.47	10.40	0.03	0.67
	Retain	0	6.34	6.62	0.003	0.07	0.06	18.47	10.40	0.03	0.67
		80	6.65	6.62	0.003	0.07	0.06	25.54	10.40	0.03	0.67
W-Beans	Remove	0	5.48	6.79	0.003	0.09	0.16	25.54	10.62	0.03	0.85
		80	5.64	6.79	0.003	0.09	0.16	25.54	10.62	0.03	0.85
	Retain	0	6.03	6.79	0.003	0.09	0.09	25.54	10.62	0.03	0.85
		80	5.98	6.79	0.003	0.09	0.09	na*	10.62	0.03	0.85
W-Lupins	Remove	0	6.36	6.65	0.003	0.08	0.07	na	10.58	0.03	0.76
		80	6.09	6.65	0.003	0.08	0.07	na	10.58	0.03	0.76
	Retain	0	6.28	6.65	0.003	0.08	0.07	na	10.58	0.03	0.76
		80	6.05	6.65	0.003	0.08	0.07	na	10.58	0.03	0.76
W-Fallow	Remove	0	6.20	6.60	0.003	0.06	0.09	na	10.47	0.03	0.57
		80	6.28	6.60	0.003	0.06	0.09	na	10.47	0.03	0.57
	Retain	0	6.10	6.60	0.003	0.06	0.09	na	10.47	0.03	0.57
		80	6.05	6.60	0.003	0.06	0.09	na	10.47	0.03	0.57

\*na (not available)

**Table 6.4 The effect of rotation, stubble management and N-fertiliser rates on solid phase chemical characteristics in 1984 at Tarlee site.**

Rotation	Stubble	N	pH <sub>Ca</sub>	Ca <sup>2+</sup>	Al <sub>K</sub> (cmol +/kg)	Mn <sub>K</sub> (cmol +/kg)	Al <sub>Ca</sub> (mg/kg)	Mn <sub>Ca</sub> (mg/kg)	ECEC (cmol+ /kg)	Al % ECEC	Mn % ECEC
W-Wheat	Remove	0	6.31	6.12	0.003	0.04	0.08	9.68	9.18	0.03	0.44
		80	5.50	5.98	0.002	0.16	0.08	35.13	9.36	0.02	1.71
	Retain	0	6.12	6.12	0.002	0.09	0.07	19.64	9.23	0.02	0.98
		80	5.63	5.98	0.002	0.11	0.11	28.65	9.31	0.02	1.18
W-Beans	Remove	0	5.52	4.33	0.004	0.12	0.17	25.28	7.43	0.05	1.62
		80	5.95	4.00	0.002	0.13	0.12	20.81	6.88	0.03	1.89
	Retain	0	5.11	4.33	0.004	0.17	0.32	37.01	7.49	0.05	2.27
		80	4.77	4.00	0.004	0.18	0.70	42.01	6.93	0.06	2.60
W-Lupins	Remove	0	5.19	4.28	0.003	0.15	0.16	33.90	7.35	0.04	2.04
		80	5.40	4.10	0.003	0.13	0.12	29.03	6.91	0.04	1.88
	Retain	0	5.23	4.28	0.006	0.16	0.18	32.29	7.36	0.08	2.17
		80	6.00	4.10	0.005	0.12	0.11	23.22	6.90	0.07	1.74
W-Fallow	Remove	0	5.90	4.00	0.002	0.15	0.09	20.95	6.80	0.03	2.21
		80	5.85	4.00	0.002	0.11	0.09	20.00	6.76	0.03	1.63
	Retain	0	5.91	4.00	0.003	0.08	0.11	19.21	6.73	0.05	1.19
		80	5.42	4.00	0.004	0.15	0.21	32.60	6.80	0.06	2.21

**Table 6.5 The effect of rotation, stubble management and N-fertiliser rates on solid phase chemical characteristics in 1986 at Tarlee site.**

Rotation	Stubble	N	pH <sub>Ca</sub>	Ca <sup>2+</sup>	Al <sub>K</sub> (cmol +/kg)	Mn <sub>K</sub> (cmol +/kg)	Al <sub>Ca</sub> (mg/kg)	Mn <sub>Ca</sub> (mg/kg)	ECEC (cmol+ /kg)	Al % ECEC	Mn % ECEC
W-Wheat	Remove	0	5.79	5.43	0.003	0.04	0.06	9.39	8.28	0.04	0.48
		80	4.90	5.27	0.002	0.14	0.04	33.75	8.49	0.02	1.65
	Retain	0	5.39	5.33	0.003	0.10	0.11	18.20	8.45	0.04	1.18
		80	4.91	5.17	0.018	0.14	0.46	38.82	8.59	0.21	1.63
W-Beans	Remove	0	5.14	4.25	0.009	0.12	0.30	24.48	7.69	0.12	1.56
		80	5.27	4.10	0.012	0.13	0.30	22.43	7.00	0.17	1.86
	Retain	0	5.11	4.20	0.009	0.18	0.46	29.63	7.65	0.12	2.35
		80	4.97	4.12	0.021	0.16	0.50	25.80	6.90	0.30	2.32
W-Lupins	Remove	0	6.18	4.19	0.003	0.14	0.03	30.07	7.15	0.04	1.96
		80	4.86	3.95	0.015	0.13	0.54	27.74	6.92	0.22	1.88
	Retain	0	5.48	4.14	0.006	0.16	0.17	30.63	7.30	0.08	2.19
		80	4.57	3.51	0.026	0.15	0.79	25.76	6.90	0.38	2.17
W-Fallow	Remove	0	6.40	4.14	0.002	0.11	0.04	19.56	6.51	0.03	1.69
		80	5.26	4.20	0.004	0.12	0.12	20.03	6.60	0.06	1.82
	Retain	0	6.11	4.60	0.002	0.16	0.06	19.31	6.56	0.03	2.44
		80	5.25	4.25	0.010	0.10	0.39	32.03	6.62	0.15	1.51

**Table 6.6 The effect of rotation, stubble management and N-fertiliser rates on solid phase chemical characteristics in 1992 at Tarlce site.**

Rotation	Stubble	N	pH <sub>Ca</sub>	Ca <sup>2+</sup>	Al <sub>K</sub> (cmol +/kg)	Mn <sub>K</sub> (cmol +/kg)	Al <sub>Ca</sub> (mg/kg)	Mn <sub>Ca</sub> (mg/kg)	ECEC (cmol+ /kg)	Al % ECEC	Mn % ECEC
W-Wheat	Remove	0	5.53	4.70	0.01	0.06	0.35	9.17	7.82	0.128	0.767
		80	4.82	4.56	0.07	0.14	1.55	27.97	7.63	0.917	1.835
	Retain	0	5.27	4.70	0.01	0.12	0.41	24.10	7.88	0.127	1.523
		80	4.80	4.56	0.07	0.21	0.79	42.44	7.70	0.909	2.727
<b>Isd 5%</b>			<b>0.24</b>	<b>0.21</b>	<b>0.02</b>	<b>0.02</b>	<b>0.1</b>	<b>3.1</b>	<b>0.02</b>	<b>0.26</b>	<b>0.36</b>
W-Beans	Remove	0	5.25	4.11	0.06	0.13	0.45	21.10	7.07	0.849	1.839
		80	4.26	3.71	0.09	0.11	0.26	20.01	6.84	1.316	1.608
	Retain	0	4.90	4.11	0.06	0.13	1.08	28.60	7.07	0.849	1.839
		80	4.57	3.71	0.09	0.21	1.92	36.22	6.94	1.297	3.026
<b>Isd 5%</b>			<b>0.32</b>	<b>0.21</b>	<b>0.02</b>	<b>0.02</b>	<b>0.04</b>	<b>4.1</b>	<b>0.02</b>	<b>0.26</b>	<b>0.36</b>
W-Lupins	Remove	0	5.18	4.08	0.07	0.12	0.36	24.73	6.92	1.011	0.173
		80	4.77	3.65	0.08	0.16	0.64	34.36	6.76	1.183	2.367
	Retain	0	4.78	4.08	0.07	0.17	0.85	39.54	7.08	0.989	2.401
		80	4.42	3.65	0.08	0.18	2.17	39.53	6.76	1.183	2.663
<b>Isd 5%</b>			<b>0.14</b>	<b>0.21</b>	<b>0.02</b>	<b>0.02</b>	<b>0.08</b>	<b>2.96</b>	<b>0.02</b>	<b>0.26</b>	<b>0.36</b>
W-Fallow	Remove	0	5.53	4.70	0.01	0.10	0.20	17.46	7.85	0.127	1.274
		80	5.48	4.70	0.05	0.12	0.27	25.92	7.88	0.635	1.523
	Retain	0	5.45	4.70	0.01	0.12	0.23	21.95	7.87	0.127	1.525
		80	4.88	4.30	0.05	0.15	0.62	34.17	7.27	0.688	2.063
<b>Isd 5%</b>			<b>0.26</b>	<b>0.21</b>	<b>0.02</b>	<b>0.02</b>	<b>0.06</b>	<b>6.98</b>	<b>0.02</b>	<b>0.26</b>	<b>0.36</b>
R			***	***	***	***	***	***	***	***	***
S			***	ns	***	***	***	***	***	***	***
N			***	***	***	***	***	***	***	***	***
R*S			ns	ns	***	***	***	***	ns	ns	Ns
R*N			*	***	***	***	***	***	ns	***	***
S*N			ns	ns	***	***	***	ns	***	***	***
R*S*N			*	ns	***	***	***	***	***	ns	ns

\*\*\* = P<0.001, \*\* = P<0.01 and \* = P<0.05, and ns is not significant. R, S and N illustrate rotation, stubble and nitrogen treatments respectively.

**Table 6.7 The effect of rotation, stubble management and N-fertiliser rates on solid phase chemical characteristics in 1996 at Tarlee site.**

Rotation	Stubble	N	pH <sub>Ca</sub>	Ca <sup>2+</sup>	Al <sub>K</sub> (cmol +/kg)	Mn <sub>K</sub> (cmol +/kg)	Al <sub>Ca</sub> (mg/kg)	Mn <sub>Ca</sub> (mg/kg)	ECEC (cmol+ /kg)	Al % ECEC	Mn % ECEC
W-Wheat	Remove	0	5.12	4.28	0.01	0.11	0.13	18.64	7.32	0.15	1.46
		80	4.28	2.94	0.13	0.21	2.12	31.82	5.56	2.38	3.71
	Retain	0	5.20	3.79	0.005	0.11	0.15	16.99	6.27	0.09	1.70
		80	4.18	2.66	0.23	0.19	2.71	28.10	4.97	4.43	3.72
<b>Isd 5%</b>			<b>0.3</b>	<b>0.1</b>	<b>0.01</b>	<b>0.04</b>	<b>0.04</b>	<b>15.1</b>	<b>0.08</b>	<b>0.04</b>	<b>0.78</b>
W-Beans	Remove	0	4.83	2.98	0.03	0.14	0.62	23.42	5.63	0.62	2.43
		80	4.30	2.68	0.04	0.17	1.26	28.83	5.26	0.78	3.28
	Retain	0	4.89	3.16	0.04	0.13	1.11	20.82	5.44	0.75	2.37
		80	4.31	2.39	0.14	0.14	2.19	24.85	4.69	2.95	3.95
<b>Isd 5%</b>			<b>0.12</b>	<b>0.02</b>	<b>0.01</b>	<b>0.02</b>	<b>0.04</b>	<b>6.76</b>	<b>0.04</b>	<b>0.08</b>	<b>0.36</b>
W-Lupins	Remove	0	4.93	4.19	0.01	0.14	0.32	21.67	7.15	0.18	1.97
		80	4.33	2.95	0.12	0.18	1.67	31.57	5.42	2.20	3.41
	Retain	0	4.82	3.14	0.04	0.14	1.03	22.67	5.52	0.75	2.61
		80	4.30	2.41	0.15	0.13	2.31	24.30	4.50	3.35	3.95
<b>Isd 5%</b>			<b>0.18</b>	<b>0.1</b>	<b>0.01</b>	<b>0.02</b>	<b>0.08</b>	<b>5.68</b>	<b>0.1</b>	<b>0.1</b>	<b>0.26</b>
W-Fallow	Remove	0	5.22	3.14	0.004	0.09	0.08	16.06	6.01	0.07	1.56
		80	4.70	3.20	0.01	0.15	0.20	29.17	5.94	0.20	2.51
	Retain	0	5.27	3.60	0.003	0.11	0.09	16.76	6.56	0.05	1.70
		80	4.50	2.85	0.03	0.17	0.66	32.03	5.52	0.56	3.05
<b>Isd 5%</b>			<b>0.4</b>	<b>0.06</b>	<b>0.01</b>	<b>0.04</b>	<b>0.04</b>	<b>10.06</b>	<b>0.06</b>	<b>0.02</b>	<b>0.84</b>
R			***	***	***	ns	***	ns	***	***	***
S			ns	***	***	ns	***	ns	***	***	ns
N			***	***	***	***	***	***	***	***	***
R*S			ns	***	***	ns	***	ns	***	***	ns
R*N			***	***	***	***	***	ns	***	***	***
S*N			ns	***	***	ns	***	ns	*	***	ns
R*S*N			ns	***	***	ns	***	ns	***	***	ns

\*\*\* = P<0.001, \*\* = P<0.01 and \* = P<0.05, and ns is not significant. R, S and N illustrate rotation, stubble and nitrogen treatments respectively.

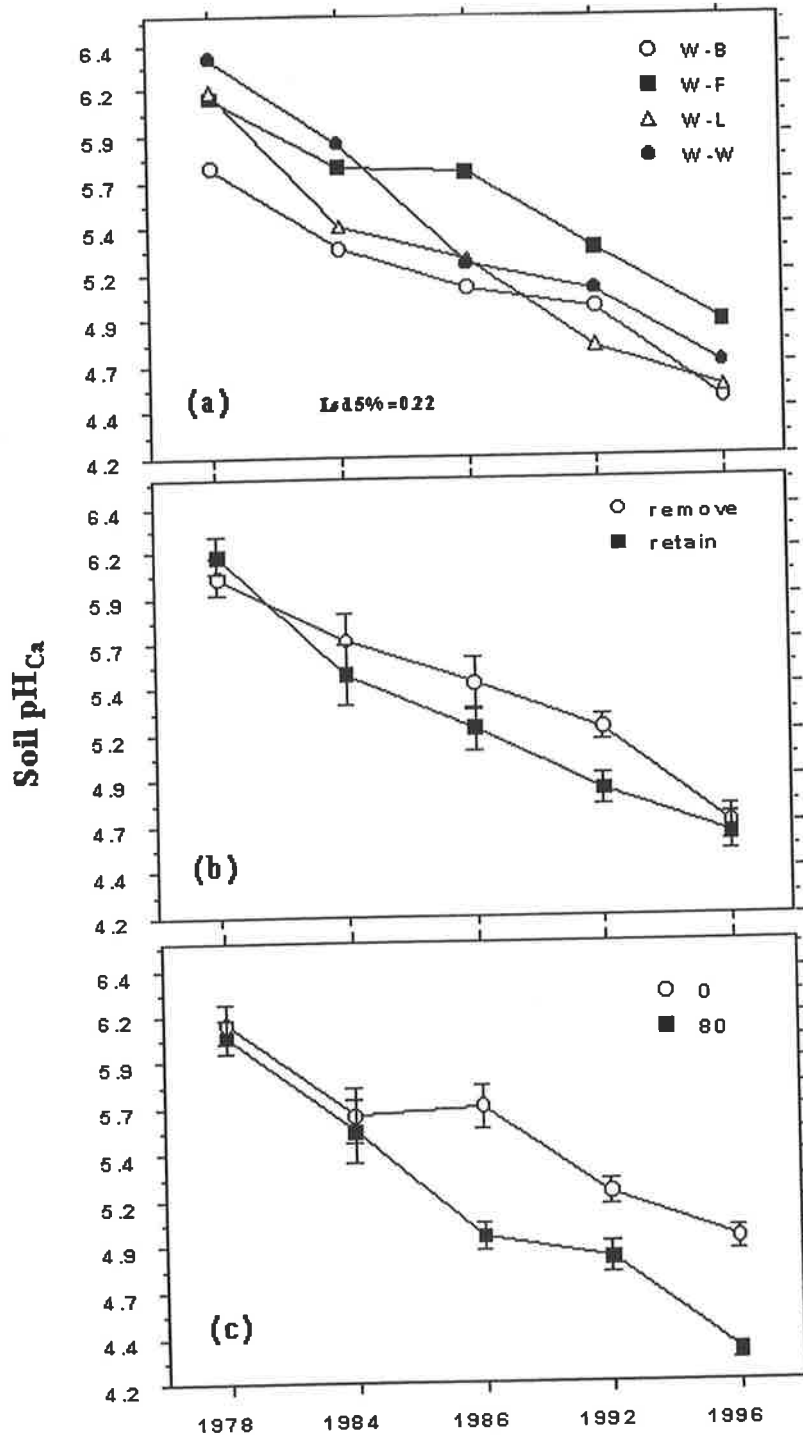


Figure 6.2 The effect of year with the main effects of rotations (a), stubble managements (b) and N-fertiliser rates (c) on soil pH<sub>Ca</sub> between 1978-1996 at Tarlee site. Error bars indicate standard errors of deviation.

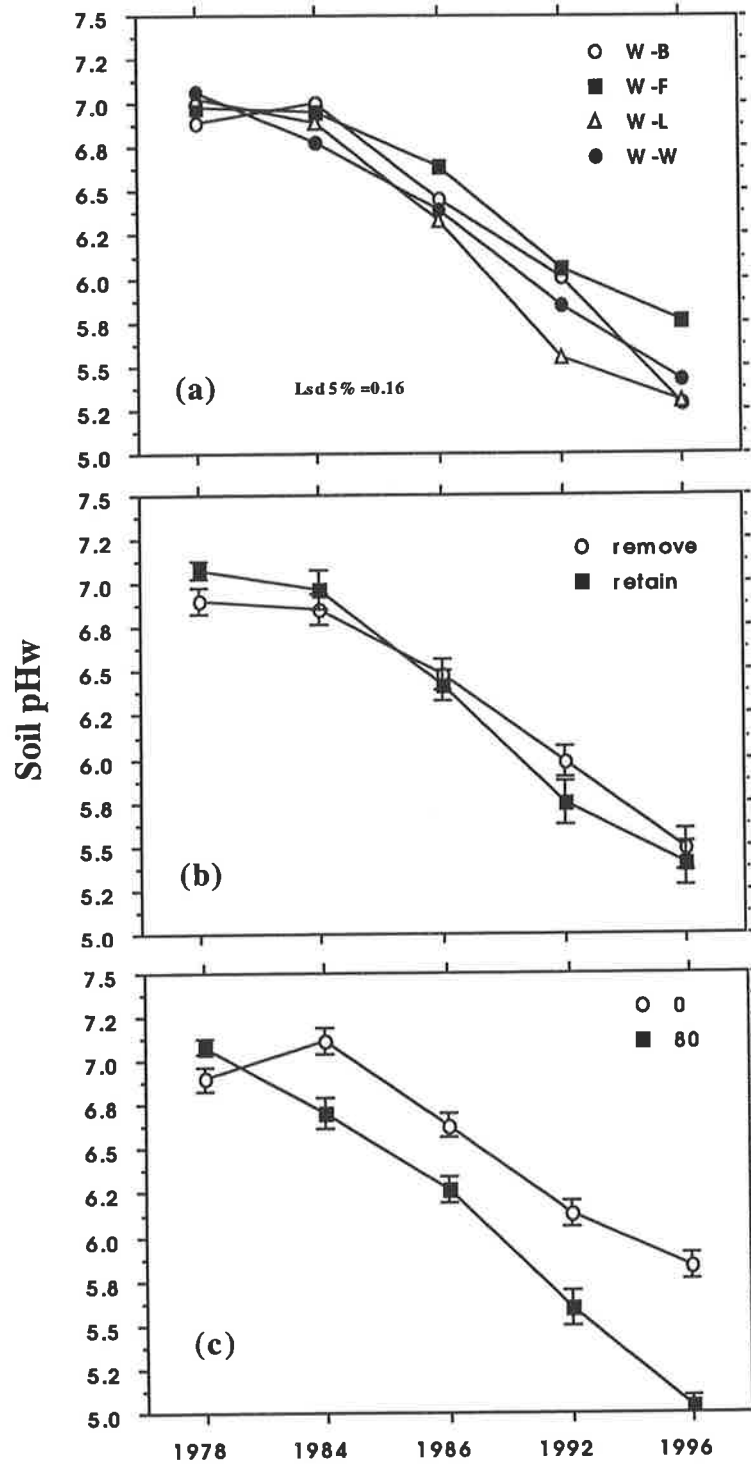


Figure 6.3 The effect of year with the main effects of rotations (a), stubble managements (b) and N-fertiliser rates (c) on soil pH<sub>w</sub> between 1978-1996 at Tarlee site. Error bars indicate standard errors of deviation.

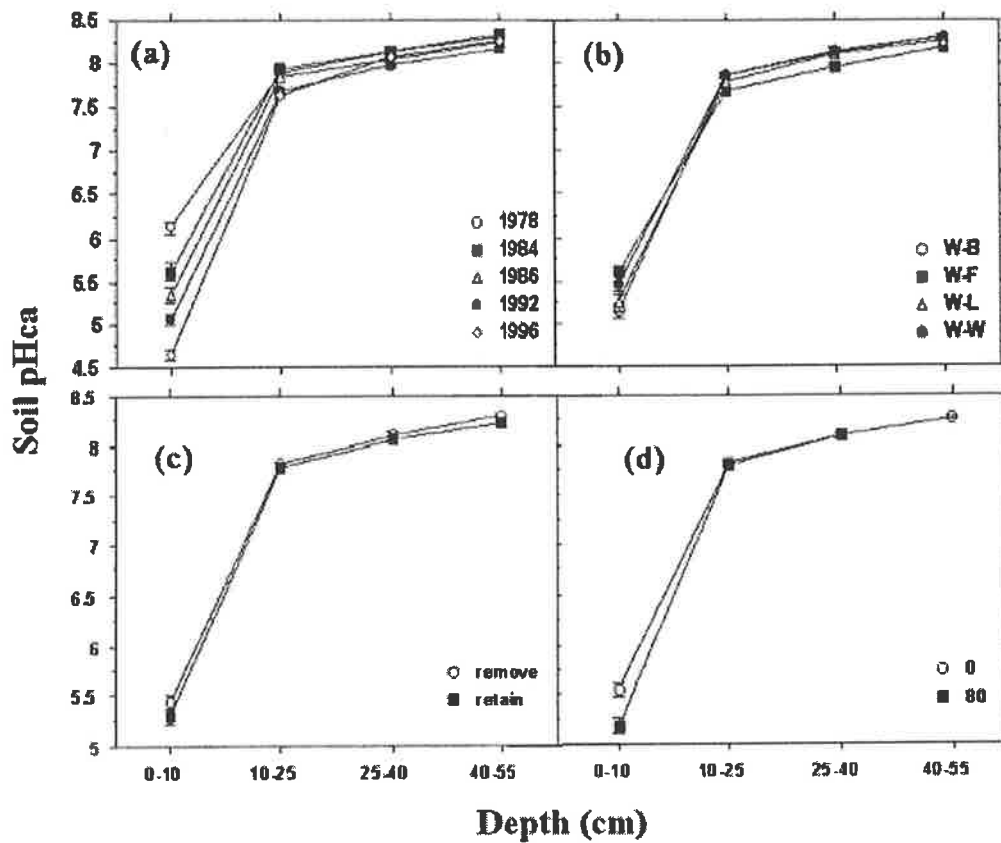


Figure 6.4 Relationship between soil pH<sub>Ca</sub> and soil depth for year (a), rotations (b), stubble managements (c) and Nitrogen rates (d) at Tarlee site.

### 6.3.2.2 Soil Al, Mn and other solid phase properties

Soil exchangeable (1M KCl as  $Al_K$ ) and extractable (0.01 M  $CaCl_2$  as  $Al_{Ca}$ ) Al and Mn data are shown in Table 6.3 to 6.7 for all management practices between 1978-1996. There was a significant interaction with N-fertiliser and stubble treatment and with rotation. The overall data for the interaction of years with management practices indicate that  $Al_{Ca}$  and  $Al_K$  both are increased significantly ( $P>0.05$ ) with higher N-fertiliser rates and stubble retention for all rotations, but not for W-F (Figure 6.5 and 6.6). Levels of both Al values were increased mostly with 80 kg/ha and stubble retention but this change is more apparent from 1986 toward 1996. The W-F rotation has significantly ( $P>0.05$ ) lower levels of the Al measures compared to the other rotations. There was a significant increase in Al concentration, particularly with the 1992 and 1996 samples. But for both years, the relative levels remained in the same order of  $WB \cong WL \cong WW > WF$ . The overall data indicate that the use of N-fertiliser in the rotation has had a much greater effect on increasing Al than either legume in the rotation or stubble removal. Similarly both  $Mn_{Ca}$  and  $Mn_K$  are increased with years, and also are significantly influenced by stubble retention ( $P<0.05$ ) compared to other factors, but remained unchanged or insignificant after 1986 toward 1996. Both exchangeable and extractable Al and Mn were negatively correlated with soil  $pH_{Ca}$  (Figure 6.7 and 6.8). The overall relationships between exchangeable and extractable Al and Mn for all management practices are increased as the pH declined (Figure 6.7 and 6.8). The overall data for all management practices show that  $pH_{Ca}$  of 5.0 is the 'break of curve' value for Al data where there is a significant increase in Al values (Figure 6.7). Figure 6.7 indicated that exchangeable and extractable Al both increased as high as 20 and 3 mg/kg respectively where the soil  $pH_{Ca}$  decreased lower than 5.0. Similarly, Figure 6.8 shows that exchangeable and extractable Mn both increased for these soil management practices to maximum values of 60 and 45 mg/kg at  $pH_{Ca}$  of 4.5.

The Al saturation percentage of ECEC also showed generally an increase with the N-fertiliser application and stubble retention (Table 6.3 to 6.7). The overall data for all years indicate that the Al% of ECEC is significantly different in order of  $W-W > W-L \cong W-B > W-F$  (Figure 6.9). But for the 1996 data only, the Al% of ECEC is higher with 80 kg/ha N compared to nil N treatment and is not affected with stubble practices. Similarly 1996 data indicated that Mn% of ECEC is significantly higher for N-fertiliser application.

The regression data for soil  $\text{pH}_{\text{Ca}}$  and  $\text{Al}\%$  of ECEC and  $\text{Mn}\%$  of ECEC indicate that both values did increase with the decrease in soil  $\text{pH}_{\text{Ca}}$  (Figure 6.10). There was a negative relationship between the  $\text{Al}$  or  $\text{Mn}$  saturation % of ECEC and  $\text{pH}_{\text{Ca}}$  for all management practices (Figure 6.10). Where  $\text{pH}_{\text{Ca}}$  was decreased to a lower level than 4.5, then both  $\text{Al}\%$  and  $\text{Mn}\%$  of ECEC were observed to increase to more than 4.5 and 5.0  $\text{cmol (+)/kg}$  respectively. The arrow in Figure 6.10 indicates the 'break of curve' for  $\text{Al}\%$  and  $\text{Mn}\%$  of ECEC values. The sum of exchangeable cations (ECEC) has decreased with W-W, W-L and W-B rotations from 1978 toward 1996, but is not affected with W-F rotation (Figure 6.11). W-L rotation with stubble retained and 80 kg/ha N caused the highest decline and is holding the lowest ECEC value of 4.5  $\text{cmol (+)/kg}$ .

The change in the total ECEC through the duration of this experiment for all management practices is also shown in Figure 6.11. The overall data for ECEC showed decreases ( $P < 0.05$ ) with increasing rates of N fertiliser, stubble retained practices and inclusion of legumes into the rotation. The value of ECEC did not change with stubble-retained practices with W-F rotation and only changed significantly ( $P < 0.05$ ) wherever there was N-fertiliser treatment. The W-L and W-B rotations both caused the greatest decline in ECEC and the W-W rotation was less than these two rotations. In the 1996 season the application of N-fertiliser resulted in a greater decrease in ECEC. Also, exchangeable Ca decreased over the time (1978-1996) at the Tarlee site for all management practices. This effect is not influenced by stubble practices, but 80 kg/ha N significantly decreased this value compared to nil N fertiliser ( $P < 0.05$ ). The highest value was observed for Ca in W-W and W-L rotation with nil N, and the lowest Ca value was gained with W-B and W-L together with 80 kg/ha N. Overall, the Ca saturation percentage of the ECEC showed a decline especially for W-W and W-legumes with stubble retained and 80 kg/ha N fertiliser. The Mg value also changed with the different rotations and management practices. The Mg level followed a similar trend as with the Ca data but here the stubble retained and 80 kg/ha N rate both resulted in lower values compared to the other treatments (data are not shown here).

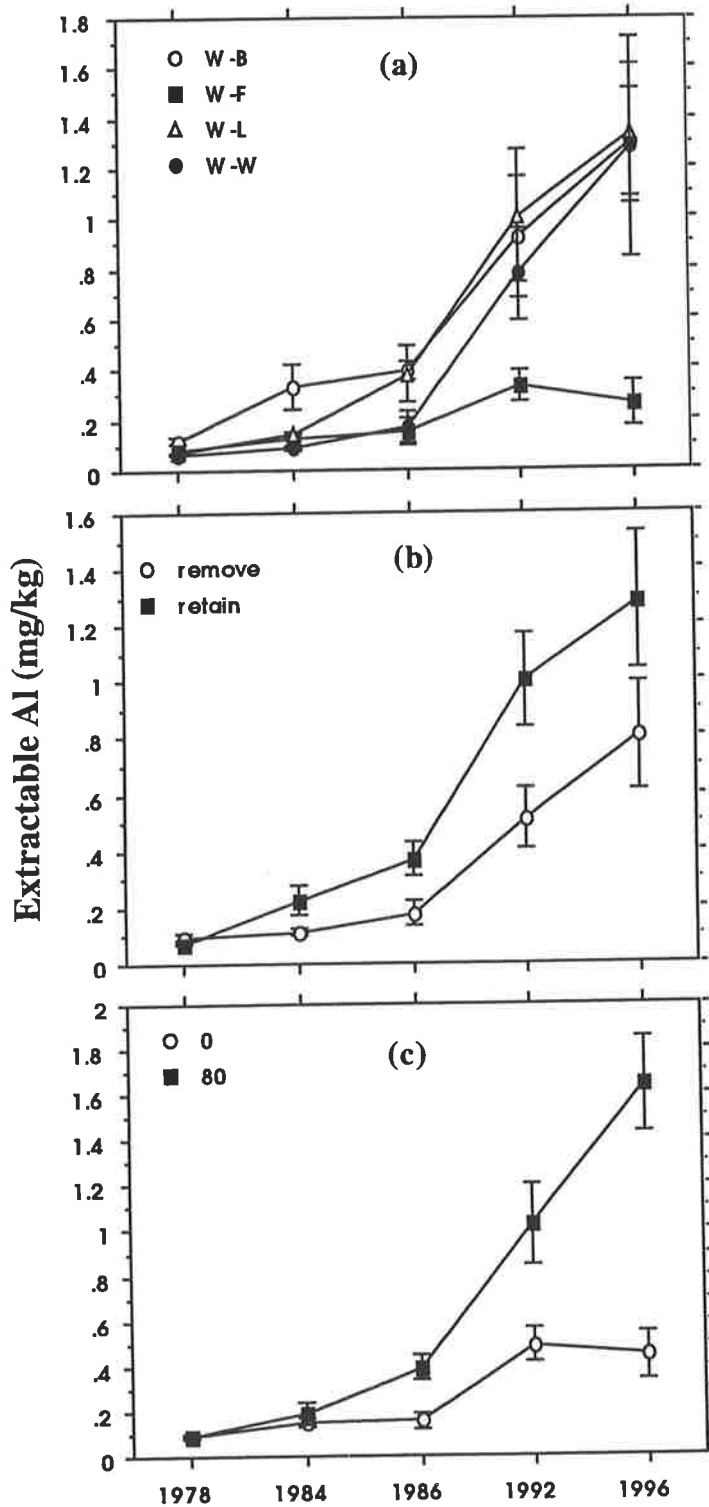


Figure 6.5 The interaction effect of year with rotations (a), stubble managements (b) and N-fertiliser rates (c) on soil extractable Al ( $Al_{Ca}$ ) between 1978-1996 at Tarlee site. Error bars indicate standard errors of deviation.

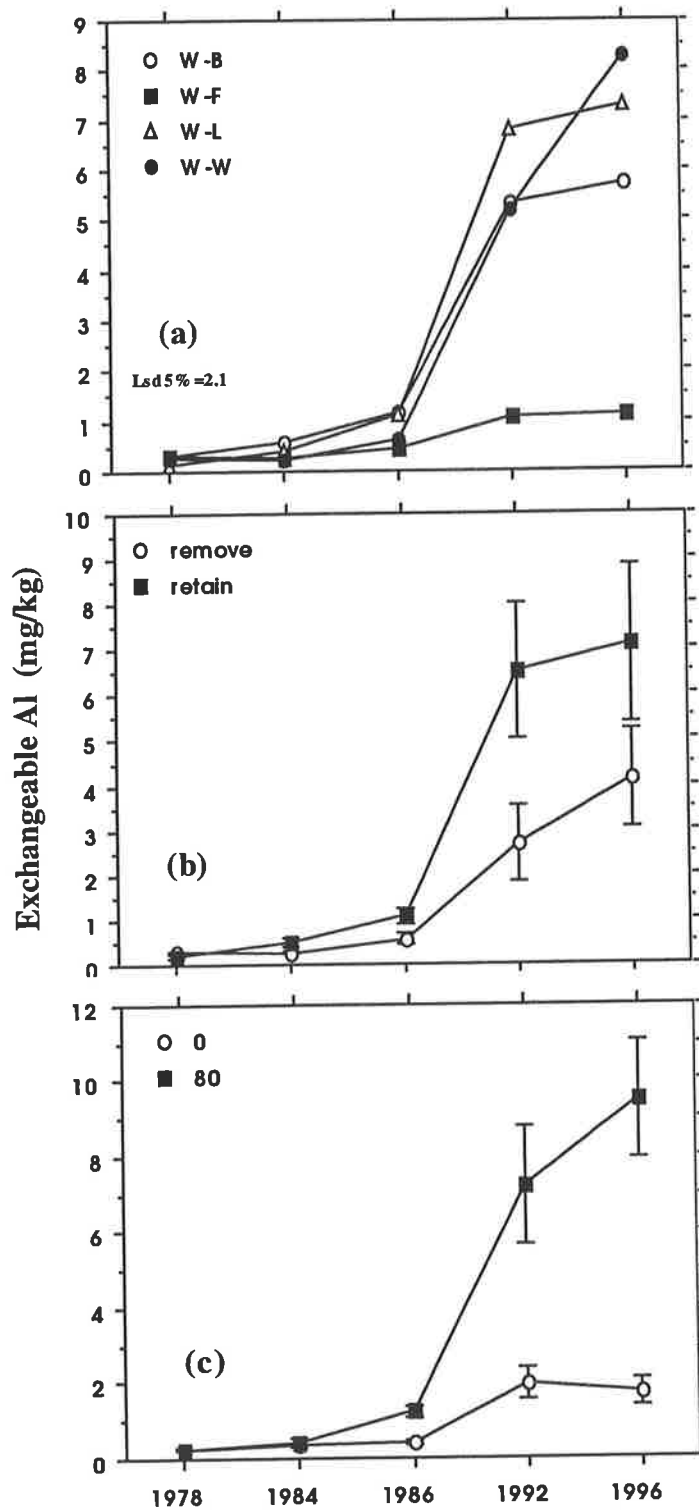


Figure 6.6 The interaction effect of year with rotations (a), stubble managements (b) and N-fertiliser rates (c) on soil exchangeable Al ( $Al_K$ ) between 1978-1996 at Tarlee site. Error bars indicate standard errors of deviation.

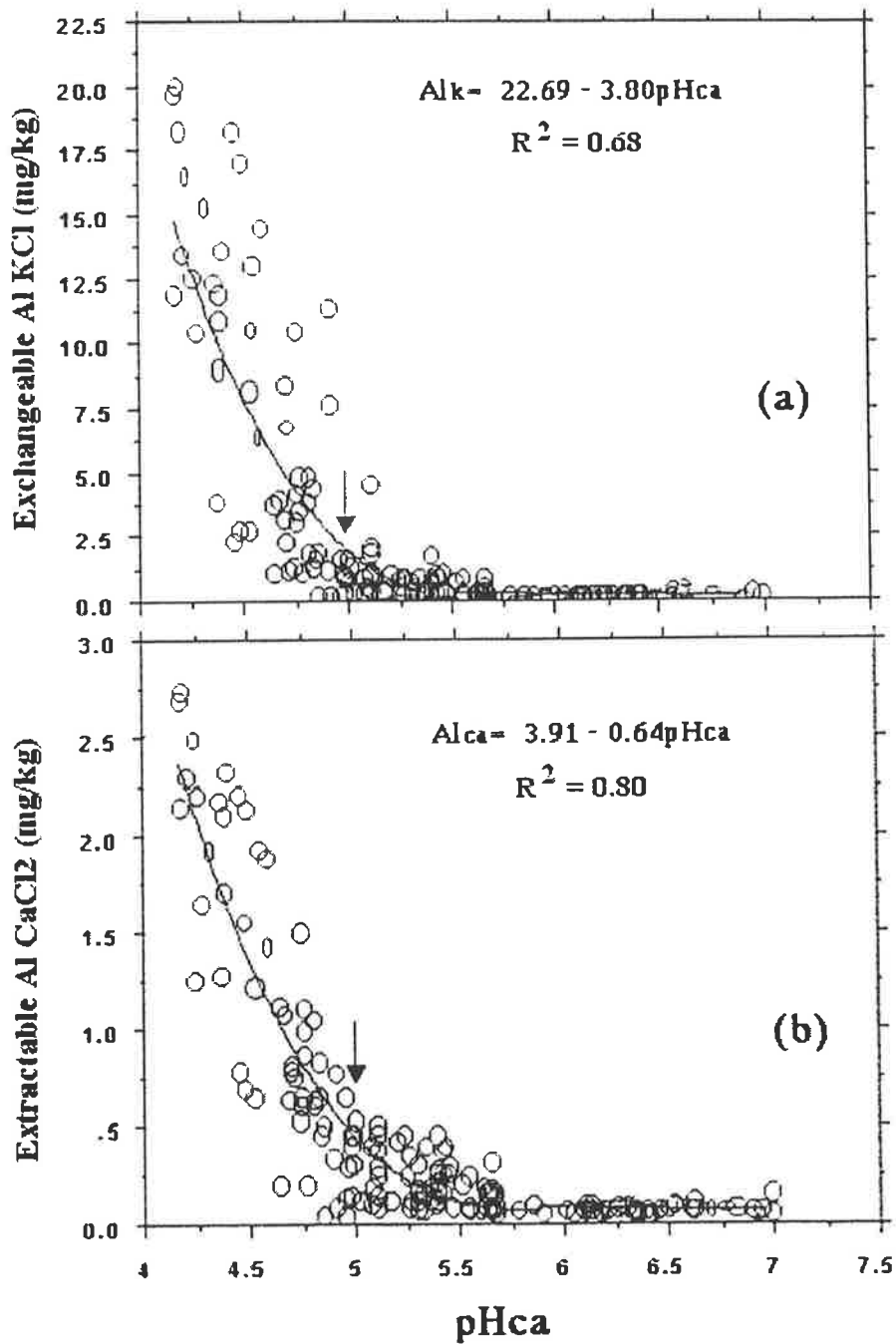


Figure 6.7 The overall relationships between exchangeable ( $\text{Al}_K$ ) and extractable Al ( $\text{Al}_{\text{Ca}}$ ), both in mg/kg, and  $\text{pH}_{\text{Ca}}$  for all management practices at Tarlee site between 1978-1996. The arrow shows the 'break of curve' value.

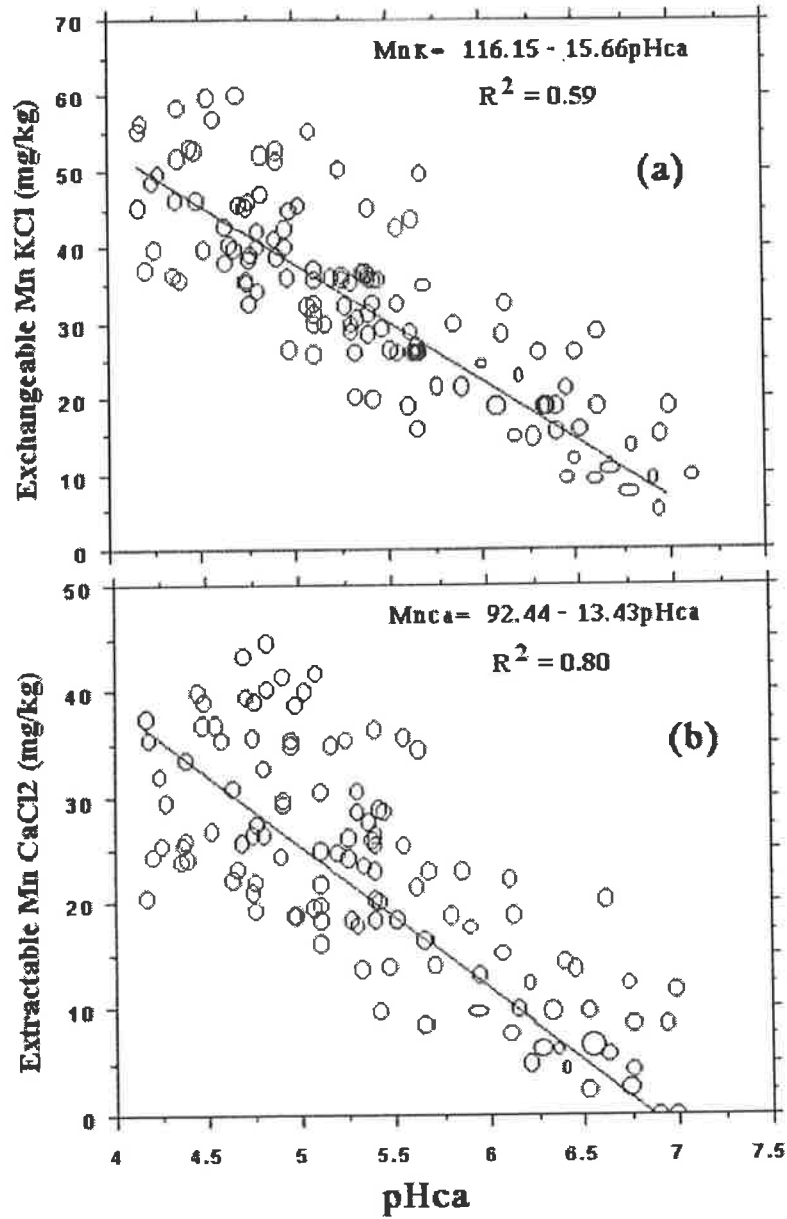


Figure 6.8 The overall relationships between exchangeable ( $Mn_K$ ) and extractable Mn ( $Mn_{Ca}$ ), both in mg/kg, and  $pH_{Ca}$  for all management practices at Tarlee site between 1978-1996.

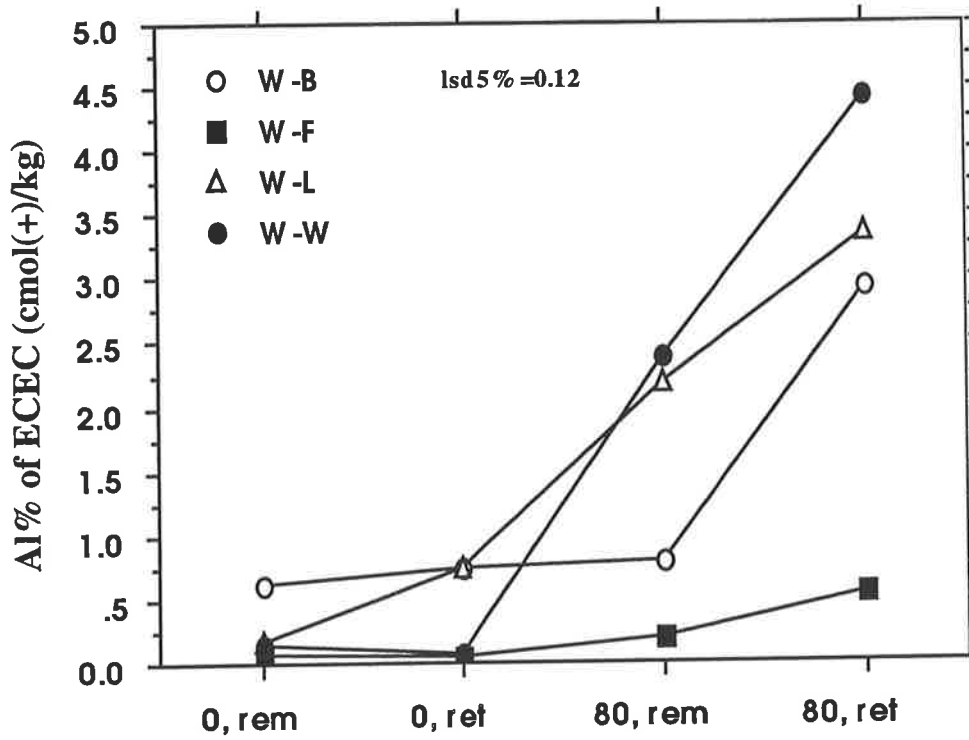


Figure 6.9 The effect of rotations, stubble managements and N-fertiliser rates on Al% of ECEC (cmol+/kg) for 1996 season at Tarlee site.

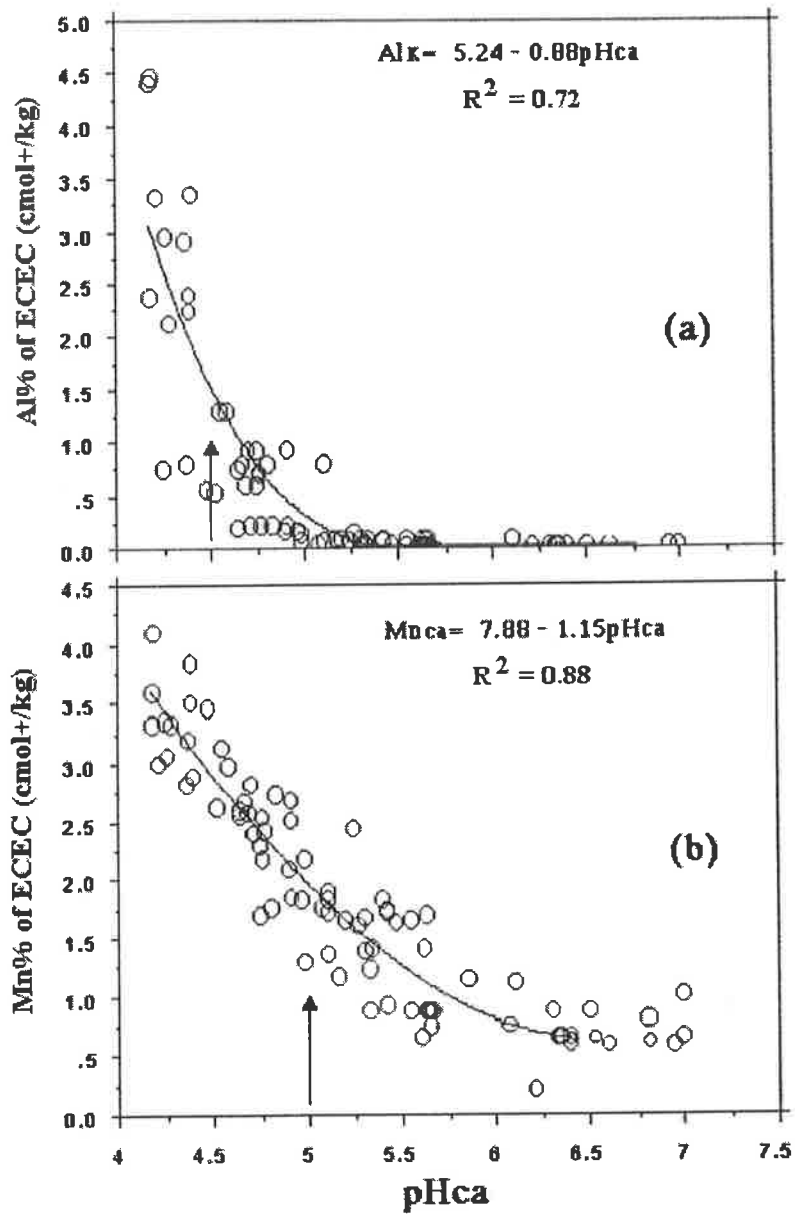


Figure 6.10 The overall relationships between Al% of ECEC (a) and Mn% of ECEC (b) both in cmol (+)/kg, and  $pH_{Ca}$  for all management practices at Tarlee site between 1978-1996. The arrow shows the 'break of curve' value.

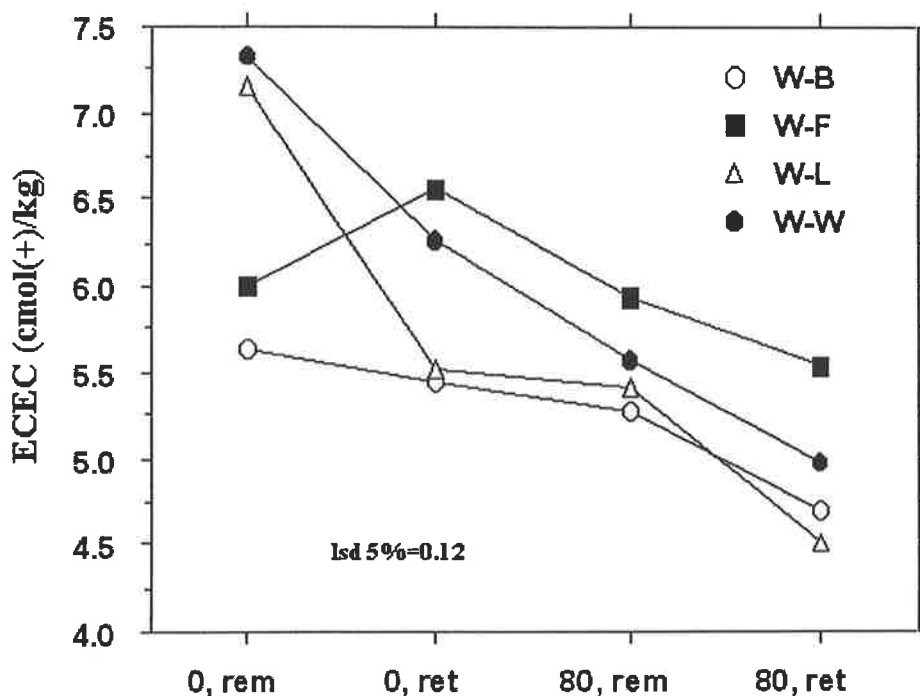


Figure 6.11 The effect of rotations, stubble managements and N-fertiliser rates on soil ECEC (cmol (+)/kg) for 1996 season at Tarlee site.

### 6.3.3 Acidification rates

#### 6.3.3.1 Total acidification rates

The mean acidification rates (AR) from 1978 to 1992 and 1978 to 1996,  $\Delta\text{pH}_{\text{Ca}}$  and  $\text{pH}_{\text{BC}}$  are given in Table 6.8. The acidification rates for the different management practices varied from 0.79 to 3.15 and 1.23 to 6.33  $\text{kmol H}^+/\text{ha}^{-1}\cdot\text{year}$  for 1992 and 1996 respectively. In 1992, consistent with the decline in soil  $\text{pH}_{\text{Ca}}$ , retained stubble and 80 kg/ha N fertiliser and W-L and W-B followed by W-W had the highest acidification rates. Similarly in 1996, soil  $\text{pH}_{\text{Ca}}$  retained stubble and 80 kg/ha N fertiliser and W-W followed closely by W-L and W-B are the highest acidification rates. The mean AR observed under the W-F rotation provided the lowest rate amongst all rotations. Within the same rotation, N-fertiliser application and stubble retained practices increased the soil acidification.

**Table 6.8 Soil acidification rates in 0-10 cm soil layer at Tarlee trial (1978-1996) for 4 rotations, 2-stubble management and 2 N rates.**

Rotation	Stubble	N <sup>1</sup>	pH <sub>Ca</sub> 1978	ΔpH 1992	ΔpH 1996	pHBC <sup>1</sup> 1978	pHBC 1996	AR <sup>1</sup> 1992	AR 1996
W-Wheat	Remove	0	6.48	0.95	1.36	15.60	15.80	1.64	1.85
		80	6.00	1.18	1.72	15.60	17.53	2.04	2.60
	Retain	0	6.34	1.07	1.14	15.40	27.63	1.82	2.71
		80	6.65	1.85	2.47	15.40	29.77	3.15	6.33
W-Beans	Remove	0	5.48	0.53	0.76	14.30	18.77	0.84	1.23
		80	5.64	1.07	1.34	14.30	27.11	1.69	3.13
	Retain	0	6.03	0.50	1.34	14.30	14.85	0.79	1.71
		80	6.20	0.72	1.89	14.30	16.63	1.14	2.71
W-Lupins	Remove	0	6.36	1.18	1.43	14.50	16.86	1.89	2.08
		80	6.09	1.32	1.76	14.50	18.95	2.12	2.87
	Retain	0	6.28	1.50	1.57	13.70	25.25	2.28	3.41
		80	6.05	1.58	1.75	13.70	30.77	2.40	4.64
W-Fallow	Remove	0	6.20	0.67	0.98	15.00	25.19	1.11	2.13
		80	6.28	0.80	1.58	15.00	33.54	1.33	4.56
	Retain	0	6.10	0.65	0.83	14.50	19.74	1.04	1.41
		80	6.05	1.17	1.55	14.50	23.36	1.88	3.12

<sup>1</sup>Unit for N-fertiliser rate is kg/ha, pHBC is cmol H<sup>+</sup> kg<sup>-1</sup> pH<sup>-1</sup> and AR is kmol H<sup>+</sup> ha<sup>-1</sup>·year

### 6.3.3.2 Carbon cycle acidification rates

The C-cycle component of acidification ( $A_{CC}$ ) due to the loss in OC in soil from different management practices is shown in Table 6.9. The OC% was significantly ( $P < 0.05$ ) higher for the 1996 data compared to previous years. However the OC% was significantly ( $P < 0.05$ ) higher for both W-B and W-L rotations compared to W-W rotation in the 1992 season. Similar results were obtained where OM-CEC for the 1992 season was calculated. By using the Helyar and Porter (1989) model for C cycle acid additions, the OM losses during the 1978-1992 period accounted for a consumption of acid at a rate of 4.88 for W-W, 1.66 for W-B and 3.36 kmol ( $H^+$ )/ha.year for W-L rotations (Table 6.9). These values for the 1996 season are in the order of 1.83, 1.57 and 2.19 kmol ( $H^+$ ) ha<sup>-1</sup>.year for W-W, W-B and W-L rotations respectively.

A summary of the components of the soil acidification is given in Table 6.10, where it can be seen in the columns designated as 'unaccounted' that the largest contribution to acidification was estimated to come from nitrate leaching. Nitrate leaching, as a component of acidification was higher in the stubble retained and 80 kg/ha N fertiliser practices. The C-cycle component of acidification was lower in stubble removed and nil-N rate fertiliser practices, but was the opposite in the W-B rotation. Rates of acidification due to product removal and retained (grain and stubble) and N-fertiliser are not calculated here because of the inter-relation effect of these parameters with other soil properties such as soil water dynamics. This role will be investigated in chapter 8 of this thesis using APSIM program as 'OC biomass'.

**Table 6.9 Components of acidification ( $A_{CC}$ ) attributed to the change in OM in the surface 0-10 cm soil layer for all management practices from 1978-1992 and 1978 to 1996.**

Rot	Stu	N	OC% (78)	OC% (92)	OC% (96)	pH <sub>Ca</sub> (78)	pH <sub>Ca</sub> (92)	pH <sub>Ca</sub> (96)	OM- CEC <sup>1</sup> (78)	OM- CEC (1992)	OM- CEC (1996)	$A_{CC1}$ (1992)	$A_{CC}$ (1996)
W-W	Rem	0	0.94	0.80	0.91	6.48	5.53	5.12	383.3	263.9	269.7	-0.85	-0.62
		80	0.94	0.85	1.09	6.00	4.82	4.28	346.3	231.0	248.1	-0.82	-0.54
	Ret	0	0.87	0.75	0.99	6.34	5.27	5.20	344.7	231.5	299.9	-0.80	-0.25
		80	0.87	0.10	1.32	6.65	4.80	4.18	366.8	270.2	289.6	-2.41	-0.42
<b>Total</b>			<b>3.62</b>	<b>2.5</b>	<b>4.31</b>				<b>1441</b>	<b>753.4</b>	<b>1107</b>	<b>-4.88</b>	<b>-1.83</b>
W-B	Rem	0	0.86	0.80	0.99	5.48	4.95	4.72	280.2	225.9	260.9	-0.39	-0.11
		80	0.86	0.90	1.09	5.64	4.57	4.30	291.5	226.2	249.9	-0.46	-0.23
	Ret	0	1.04	1.00	1.06	6.03	5.53	4.69	385.7	329.9	276.8	-0.40	-0.60
		80	1.04	1.05	1.24	6.20	5.48	4.31	400.2	342.1	285.3	-0.41	-0.63
<b>Total</b>			<b>3.8</b>	<b>3.75</b>	<b>4.38</b>				<b>1358</b>	<b>1124</b>	<b>1073</b>	<b>-1.66</b>	<b>-1.57</b>
W-L	Rem	0	0.99	0.80	1.03	6.36	5.18	4.93	393.9	241.0	289.2	-1.09	-0.58
		80	0.99	0.95	1.02	6.09	4.77	4.33	372.0	254.3	236.3	-0.84	-0.75
	Ret	0	0.90	0.90	1.01	6.28	4.78	4.71	352.2	241.7	265.4	-0.78	-0.48
		80	0.90	1.00	1.16	6.05	4.47	4.30	335.3	243.2	265.9	-0.65	-0.38
<b>Total</b>			<b>3.78</b>	<b>3.65</b>	<b>4.22</b>				<b>1453</b>	<b>980.2</b>	<b>1057</b>	<b>-3.36</b>	<b>-2.19</b>

<sup>1</sup>Unit for OM CEC is  $\text{cmol}(+) \text{kg}^{-1} \text{OM}^{-1} \text{pH}^{-1}$  unit and for ACC is  $\text{kmol H}^+ \text{ha}^{-1} \text{year}$

**Table 6.10 Summary of acidification for C-cycle components and total acidification in kmol (H<sup>+</sup>) ha<sup>-1</sup> year<sup>-1</sup> for all management practices from 1978 to 1992 and 1978 to 1996.**

Rotation	Stubble	N	AR 1992	AR 1996	ACC 1992	ACC 1996	Unaccounted acidification for 1992	Unaccounted acidification for 1996
W-Wheat	Remove	0	1.64	1.85	-0.85	-0.62	0.79	1.23
		80	2.04	2.60	-0.82	-0.54	1.22	2.06
	Retain	0	1.82	2.71	-0.80	-0.25	1.02	2.46
		80	3.15	6.33	-2.41	-0.42	0.74	5.91
W-Beans	Remove	0	0.84	1.23	-0.39	-0.11	0.45	1.12
		80	1.69	3.13	-0.46	-0.23	1.23	2.90
	Retain	0	0.79	1.71	-0.40	-0.60	0.39	1.11
		80	1.14	2.71	-0.41	-0.63	0.73	2.08
W-Lupins	Remove	0	1.89	2.08	-1.09	-0.58	0.80	1.50
		80	2.12	2.87	-0.84	-0.75	1.28	2.12
	Retain	0	2.28	3.41	-0.78	-0.48	1.50	2.93
		80	2.40	4.64	-0.65	-0.38	1.75	4.26

#### 6.3.4 Soil organic matter properties

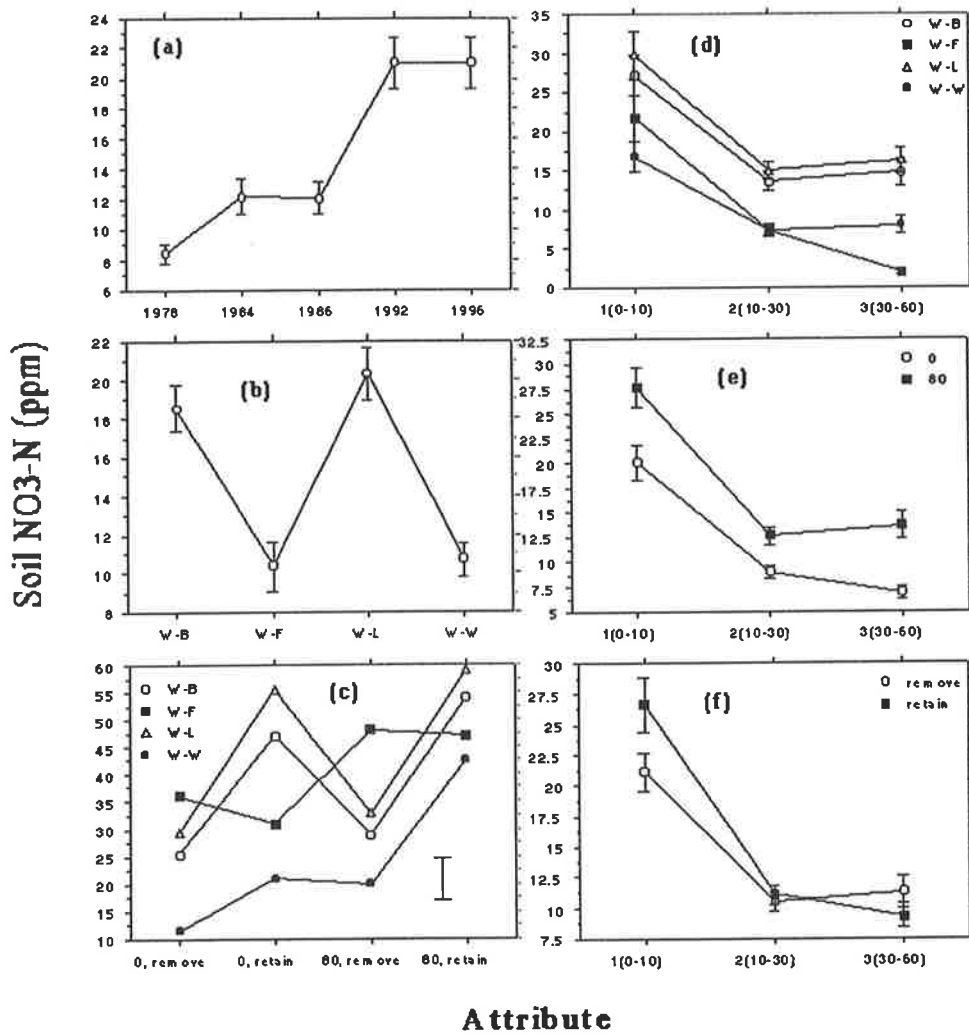
The data for soil OM properties over the period of the study (1978-1996), with different management practices, are shown in Table 6.11. The relationships between years, soil depths, and management practices for NO<sub>3</sub>-N, organic C and total N in different depths respectively are shown in Figures 6.12, 6.13, and 6.14 respectively. These data indicate that management practices have influenced the soil OM values with continuous wheat and W-F rotations being generally low and wheat sown with lupin being the highest in most instances. Table 6.11 shows that wheat sown with legumes has a large positive effect on the organic properties of the soil when residue is retained and when 80 kg/ha N was applied. Trends in the soil NO<sub>3</sub>-N from 1978 to 1996 for W-L and W-B rotations show that this property increased significantly during this period compared to W-F and W-W (Figure 6.12). Nitrate-N is higher in wheat-legumes and combination with 80 kg/ha N-fertiliser. The stubble-retained practices also have a small effect on increasing NO<sub>3</sub>-N

value during this period. Soil organic C and total-N are both following the same trend, and all three rotations are following the same trend in order of W-W=W-L=W-B>W-F. Trends in the soil organic C and total N both show increases from 1978 to 1996. Organic-C is higher in legume with combination with higher 80 kg/ha N rates and legume in the rotation (W-W, W-B and W-L). The stubble retained or removed practices did not affect this trend significantly. Total N is higher with combinations of 80 kg/ha N and inclusion of the legumes in rotation, and W-B is significantly higher than other rotations. All soil organic properties in the W-F rotation in 0-10 cm soil layer are lower compared to other rotations. Also all these properties were significantly higher for the stubble retained and 80 kg/ha N practices than for the stubble removed and 0 kg/ha N rate in 0-10 cm depth. Soil organic C and total N levels decreased with increasing soil depth for all management practices, and only were significantly different for the 0-10 cm soil layer. But soil NO<sub>3</sub>-N was increased with depth by the effect of different rotations and N rates down to the subsoil. Figure 6.12 (d, e and f) all are showing that NO<sub>3</sub>-N is leached into the subsoil (30-60 cm depth), but the effect of legumes and 80 kg/ha N fertiliser is more obvious.

**Table 6.11 Soil organic C (%), NO<sub>3</sub>-N (ppm) and total N (%) in the 0-10 cm soil layer for all soil management practices at Tarlee between 1978-1996.**

Rot	Stu	N	N-N ppm 78	N-N ppm 84	N-N ppm 86	N-N ppm 92	N-N ppm 96	TN (%) 78	TN (%) 84	TN (%) 86	TN (%) 92	TN (%) 96	OC (%) 78	OC (%) 84	OC (%) 86	OC (%) 92	OC (%) 96
W-W	Rem	0	7.3	10.6	8.70	11.5	11.5	0.09	0.08	0.09	0.09	0.09	0.94	0.87	0.77	0.80	0.91
		80	7.30	20.5	25.3	20.0	20.0	0.09	0.09	0.09	0.09	0.11	0.94	0.93	0.93	0.85	1.09
	Ret	0	5.5	6.4	5.20	21.0	21.0	0.10	0.08	0.08	0.08	0.09	0.87	0.75	0.84	0.75	0.99
		80	5.5	20.2	23.6	42.5	42.5	0.10	0.09	0.10	0.10	0.11	0.87	1.04	0.88	0.10	1.32
<b>lsd 5%</b>			<b>ns</b>	<b>12</b>	<b>12.5</b>	<b>8</b>	<b>12.5</b>	<b>ns</b>	<b>ns</b>	<b>0.01</b>	<b>0.02</b>	<b>0.02</b>	<b>0.16</b>	<b>ns</b>	<b>0.12</b>	<b>0.2</b>	<b>0.12</b>
W-B	Rem	0	11.2	31.9	12.8	25.5	25.5	0.09	0.09	0.09	0.09	0.09	0.86	0.88	0.90	0.80	0.99
		80	11.2	29.1	26.5	29.0	29.0	0.09	0.09	0.09	0.10	0.12	0.86	1.00	0.98	0.90	1.09
	Ret	0	8.6	26.5	11.7	47.0	47.0	0.09	0.10	0.09	0.10	0.11	1.04	1.11	1.18	1.00	1.06
		80	8.6	28.0	27.6	54.0	54.0	0.09	0.09	0.10	0.10	0.14	1.04	1.08	1.09	1.05	1.24
<b>lsd 5%</b>			<b>ns</b>	<b>19.1</b>	<b>13.9</b>	<b>18</b>	<b>14</b>	<b>0.04</b>	<b>ns</b>	<b>0.01</b>	<b>0.02</b>	<b>0.02</b>	<b>0.10</b>	<b>ns</b>	<b>0.08</b>	<b>0.2</b>	<b>0.08</b>
W-L	Rem	0	7.6	40.1	9.5	29.5	29.5	0.09	0.09	0.09	0.09	0.08	0.99	0.79	1.10	0.80	1.03
		80	7.6	37.1	24.5	33.0	33.0	0.09	0.09	0.10	0.11	0.01	0.99	0.85	0.86	0.95	1.02
	Ret	0	7.4	36.3	5.9	55.5	55.5	0.10	0.10	0.09	0.10	0.10	0.90	1.01	0.97	0.90	1.01
		80	7.4	29.4	27.4	59.0	59.0	0.10	0.10	0.09	0.11	0.11	0.90	1.04	0.77	1.00	1.16
<b>lsd 5%</b>			<b>ns</b>	<b>16.2</b>	<b>16.3</b>	<b>21</b>	<b>16.3</b>	<b>ns</b>	<b>ns</b>	<b>0.01</b>	<b>0.02</b>	<b>0.02</b>	<b>0.06</b>	<b>ns</b>	<b>0.08</b>	<b>0.2</b>	<b>0.08</b>
W-F	Rem	0	0.01	9.1	6.8	36.0	36.0	0.00	0.08	0.08	0.09	0.09	0.00	0.88	0.80	0.85	0.99
		80	0.01	12.2	22.5	48.0	48.0	0.00	0.08	0.09	0.09	0.11	0.00	0.88	0.92	0.90	1.12
	Ret	0	0.01	9.80	11.0	31.0	31.0	0.00	0.08	0.09	0.09	0.11	0.00	0.81	0.82	0.95	0.92
		80	0.01	14.6	23.8	47.0	47.0	0.00	0.09	0.09	0.09	0.11	0.00	0.96	0.90	1.00	0.98
<b>lsd 5%</b>			<b>ns</b>	<b>5.4</b>	<b>14.2</b>	<b>22</b>	<b>14.8</b>	<b>ns</b>	<b>ns</b>	<b>0.01</b>	<b>0.02</b>	<b>0.02</b>	<b>ns</b>	<b>ns</b>	<b>0.28</b>	<b>0.2</b>	<b>0.28</b>
<b>R</b>			<b>ns</b>	<b>***</b>	<b>*</b>	<b>***</b>	<b>*</b>	<b>***</b>	<b>ns</b>	<b>***</b>	<b>***</b>	<b>***</b>	<b>***</b>	<b>ns</b>	<b>***</b>	<b>ns</b>	<b>***</b>
<b>S</b>			<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>***</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>**</b>	<b>ns</b>
<b>N</b>			<b>ns</b>	<b>ns</b>	<b>*</b>	<b>*</b>	<b>*</b>	<b>ns</b>	<b>ns</b>	<b>*</b>	<b>*</b>	<b>*</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>**</b>	<b>*</b>
<b>R*S</b>			<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>*</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>
<b>R*N</b>			<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>
<b>S*N</b>			<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>
<b>R*S*N</b>			<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>	<b>ns</b>

\*\*\* = P<0.001, \*\* = P<0.01 and \* = P<0.05, and ns is not significant. R, S and N illustrate rotation, stubble and nitrogen treatments respectively. N-N is NO<sub>3</sub>-N, TN is total nitrogen and OC is organic carbon.



**Figure 6.12** Soil NO<sub>3</sub>-N (ppm) in different years (a), rotations (b), N and stubble practices with rotations (c), different depths (d, e and f) for Tarlee experiment site. Error bars indicate standard errors of deviation.

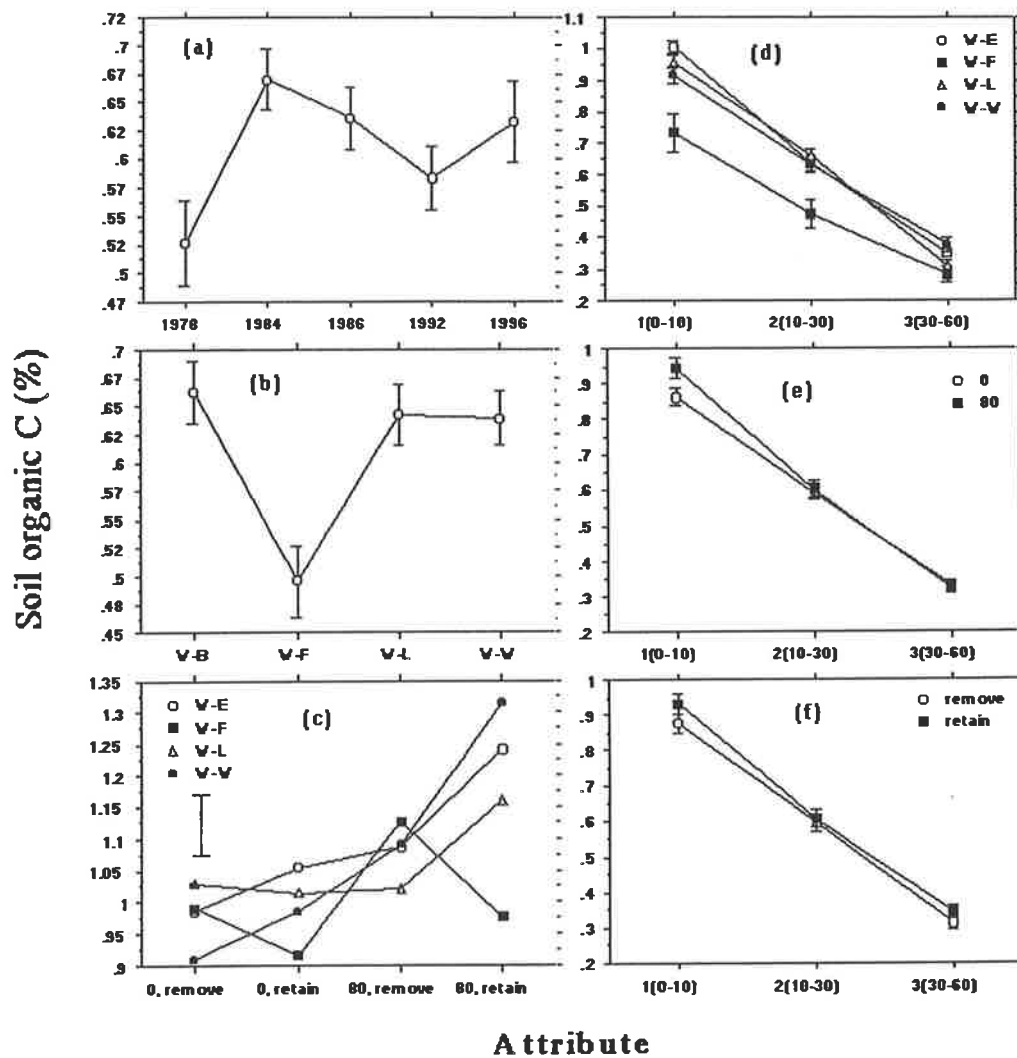


Figure 6.13 Soil organic C (%) in different years (a), rotations (b), N and stubble practices with rotations (c), different depths (d, e and f) for Tarlee experiment site. Error bars indicate standard errors of deviation.

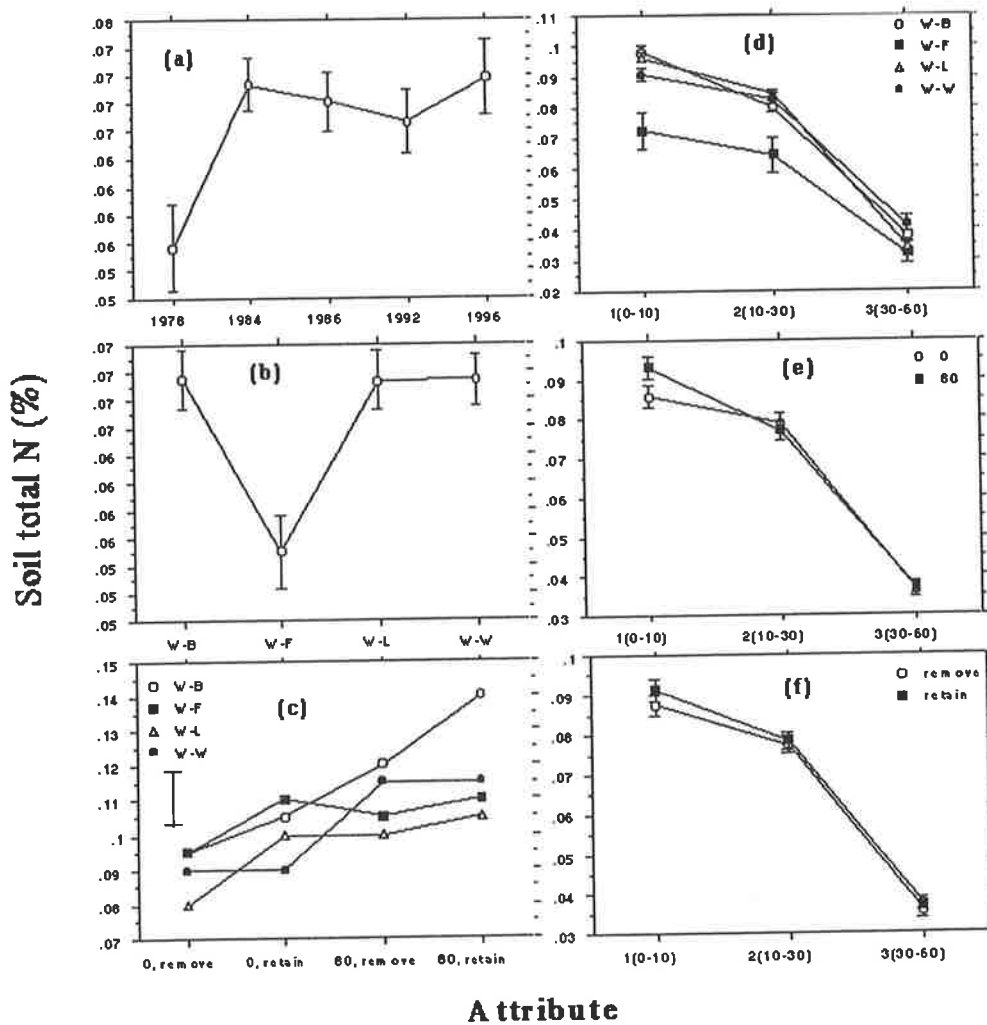


Figure 6.14 Soil total N (%) in different years (a), rotations (b), N and stubble practices with rotations (c), different depths (d, e and f) for Tarlee experiment site. Error bars indicate standard errors of deviation.

## 6.4 Discussion

### 6.4.1 Soil acidification

Soil and plant processes associated with C and N cycles are recognised as the main causes of soil acidification in agricultural soils in Australia (Helyar and Porter 1989). In the Tarlee study it is clear that agricultural management practices that are considered the basis of current 'best farm practices' have caused soil acidification to different extents. If management is to be considered with appropriate respect regarding soil acidification, it is necessary to understand the association and impacts of these different management practices on plant production and soil processes. For example, product removal, as part of the C cycle, is likely to be major contributing process to soil acidification. In this study stubble retained and 80 kg/ha ammonium nitrate fertiliser significantly affected acidification rates. The nil-N and stubble removed practices, provided an overall value for all rotations of  $7.29 \text{ kmol H}^+ \text{ ha}^{-1} \cdot \text{year}$ , which is much lower than the overall acidification rates at 80 kg/ha N and stubble retained ( $16.8 \text{ kmol H}^+ \text{ ha}^{-1} \cdot \text{year}$ ). The addition of N-fertiliser at the same time improved the overall yield (Figure 6.1), but the acidity produced from this system may eventually be inhibiting further yield improvement (eg. 1996 season). However it is not possible to rule out other possibilities, which may cause lower yield results, such as was apparent in the 1996 season. For example weed management, late sowing and dry finish (as occurred in 1996); also in situations where there is high N content of soil the crop may be disadvantaged due to the increased proportion of water transpired during the vegetative phase (Angus and van Herwaarden 2001). Thus the yield data for 1996 do not allow any conclusion about relative influence of these factors on trends in grain yield. Indeed given the similar rates of decline (Figure 6.1 part c) in 1996 for the nil and N-fertiliser treatments and the difference between treatments in measured acidity factors (main effects), then it is most probable that the smaller yields were due to other factors than soil acidity.

The C cycle component of acidification that has been attributed to the accumulation of OM and removal of alkali in exported produce in Australian cropping systems is recorded as varying between 15-100% of the total acidification. For example, this component can be 16-21% for cereals (Coventry and Slattery 1991), 15-48% when lupins were used with cereals in rotations (Coventry and Slattery 1991; Dolling 1995). In the Tarlee study, the

measured changes in soil OM with changing soil pH were used to determine rates of soil acidification. These measured values may be underestimated because the approach used here, to calculate rates of acidification based on soil C, assumes that the slope of the titration curve for OM has an average CEC of 34 cmol(+)/kg. But this value could vary from as low as 7 to as high as 83 depending upon the amount of humic acid present in the total C fractions (Helyar and Porter 1989). So the amount of acidification attributed to the C-cycle for the combination of N and stubble management, for each rotation, decreased in the order of 23.4%, 19.5% and 18.1% for W-W, W-L and W-B respectively of the total acidification for each management. The negative value for C-cycle acidification (Table 6.10) in this study shows that OM will consume those protons produced by either proton excretion by roots or hydrolysis reactions in the soil solution (Slattery *et al.* 1998). Thus the negative impacts of soil acidification would be higher for those soils with low OM content, than soil with higher OM. Also the higher pHBC in higher OM content soils may provide some protection against Al toxicity (complexation), despite the lower pH and higher AR. The higher contribution of continuous wheat than legumes to C-cycle (Table 2.3) has been shown before (Dolling *et al.* 1994 a & b and Helyar *et al.* 1997), and where the proportion of wheat in the rotation decreases, the contribution of C-cycle also decreases. The lower value in rotations with legumes is probably due to the higher buffering capacity of the OM with these practices (Table 6.9). Also the lower C-cycle value (Table 6.10) in W-legumes rotations can possibly be explained given these materials are contributing more from nitrate proportions to the total acidification rate compared to cereals. This clearly can be seen in Table 6.10 where the unaccounted C-cycle for these management practices is significantly higher than when compared with the W-W rotation.

Another important reason for N-fertiliser to cause soil acidification is nitrification, followed by  $\text{NO}_3^-$  leaching. The use of ammonia-based fertilisers in crop farming systems has increased substantially in southern Australia in recent years. This practice could cause soil acidification by nitrification, followed by  $\text{NO}_3^-$  leaching. The amount of N-fertiliser recovery by arable crops is generally in the range of 40-60% (Kumar and Goh 2000). Some of the fertiliser remains in the soil for potential use by subsequent crops, and some is lost through leaching. However the likelihood of the rainfall causing leaching at the Tarlee site with 483 mm annual rainfall has been suggested to be low (Cox and Ashley

2000). Notwithstanding a low potential for drainage and leaching, the opportunity still exists for some leaching of  $\text{NO}_3^-$  down into the soil profile, out of the reach of plant roots, and therefore the  $\text{H}^+$  produced during the ammonification-nitrification process remains in the surface soil. Leaching this  $\text{NO}_3^-$  from one soil layer to the next (cascading effect) is enough to cause soil acidification, even though part of the leached  $\text{NO}_3^-$  is taken up by plant roots (C. Verburg pers. comm. 2001). However the results from this study (1978-1996) suggest that N-fertiliser application has accelerated soil acidification of the surface soil in the mid-north of South Australia, even though this environment is classified as a medium rainfall area with low-leaching potential in soil profile. The effect of rainfall on  $\text{NO}_3^-$  leaching for the Tarlee environment will be examined further in chapter 8.

Also the presence of legumes in agricultural systems directly influences soil acidity through the N and C cycles (Helyar and Porter 1989). Legumes increase soil organic N through  $\text{N}_2$ -fixation, and the subsequent oxidation of organic N, followed by  $\text{NO}_3^-$  leaching is a main acidifying process (Helyar 1976). The excretion of  $\text{H}^+$  from legume roots, due to the uptake of more cations than anions (Haynes 1983), is another reason for accelerated soil acidification associated with legume growth. In Australia, using legumes in cropping systems has been shown to have substantial effects on soil acidification, especially where lupins are grown in the rotation (Coventry and Slattery 1991; Loss *et al.* 1993; Dolling 1996). Acidification rates for agricultural soils have been shown to vary where cereal/legume have been used depending upon the frequency of legume use in the rotation (Helyar *et al.* 1990; Coventry and Slattery 1991; Loss *et al.* 1993; Poss *et al.* 1995; Xu *et al.* 2002). Thus legumes with associated higher fertiliser rates in the system can produce high crop yields, but also have the capacity to rapidly promote soil acidification (Williams 1980; Coventry 1992).

Similarly to the above studies, this experiment found that the wheat-lupin rotation gave the highest acidification rate. For example the W-L (2.08-4.56  $\text{kmol (+) ha}^{-1}\cdot\text{year}$ ) rotations in this study are showing values similar to those calculated in Victorian cropping systems (4.11  $\text{kmol (+) ha}^{-1}\cdot\text{year}$ ) (Coventry and Slattery 1991). But the Tarlee values were higher compared to the study with W-L by Dolling *et al.* (1994 a & b) and Dolling (1996) in Western Australia (WA) at 2.4-3.4  $\text{kmol (+) ha}^{-1}\cdot\text{year}$ . The Tarlee values were also higher when compared to studies by Heenan *et al.* (1998) (NSW) and

Loss *et al.* (1993) (WA) at 0.7 and 0.4 kmol (+) ha<sup>-1</sup>·year respectively. In the present study, the wheat-lupin rotation not only resulted in the highest soil acidification, but also the biggest loss of exchangeable base cations. It is likely that most of the exchangeable base cation loss occurred with product removal, although there could be some cation loss by leaching.

At the same time, the retention of stubble at the Tarlee site caused more acidification than where there was regular stubble removal. Stubble retention returns organic anions and residue-N to soils. The addition of plant materials to soil can cause soil pH to increase, decrease or remain unchanged. The direction and extent of soil pH change depends on the concentrations of excess cations/organic anions and N in plant materials, and initial soil pH (Tang and Yu 1999). Decarboxylation of organic anions and ammonification of plant residue-N are major causes for soil pH to increase, while nitrification of mineralised residue N causes soil pH to decrease (Pocknee and Sumner 1997; Tang and Yu 1999). The results from such incubation experiments indicate that the addition of plant material to soil increased soil pH to some extent in acidic soil (Pocknee and Sumner 1997; Tang and Yu 1999), while in moderate acidic soils, and alkaline soils, the addition of plant material resulted in a decrease of soil pH (Nelson and Oades 1998; Tang and Yu 1999). It is likely at the Tarlee site that the pH decrease associated with stubble retention was due to nitrification of mineralised organic N, and subsequent nitrate leaching.

By the retention of stubble it can be assumed that soil organic C as an organic amendment and related CEC effects altogether could increase the soils buffering capacity (Brams 1971). It is reasonable to expect that the continuous removal of OM from intensively cropped soils would have caused a decrease in the soils buffering capacity resulting in accelerated rates of acidification. Higher pHBC for stubble-retained practices, according to the present study, could be related to the higher concentration of OC influenced by stubble retention and the subsequent formation of organo-metallic complexes. The addition of organic material should be improving the CEC of the soil (Starr *et al.* 1996) through increasing the negative charge capacity of the soil, and therefore would provide better control of the pH buffering capacity of the soil against pH changes. Thus in an intensified cropping system, the deposition of large amounts of OM to the system whilst contributing to soil acidification, could also be providing buffering to control the activity

of Al. It has been calculated that for every 1% loss of OC there is an associated loss of 2.97 cmol (+)/kg soil of negative charge (Chan *et al.* 1992), and an increase in the critical Al level by 0.3 cmol (+)/kg (Kapland and Estes 1985). OM also plays an important role in controlling the level of toxic Al in the soil solution by forming organo-metallic complexes (Bloom *et al.* 1979; Hargrove 1986). This subject will be explored in the next chapter.

The calculation of acidification values for each management practice does enable, with some accuracy, the total amount of the lime required to maintain production at optimal soil conditions. The equivalent amount of lime required to neutralize this acidification at the Tarlee site over the 18-year period of the experiment has been summarised in Table 6.12. It was observed that the amount of lime required every year, ranged between 0.7 to 3.2 t ha<sup>-1</sup>·year for the lowest to highest acidification rates with various management practices. For example the amount of CaCO<sub>3</sub> required to neutralise the acidification after 1 year of W-W in the worst scenario (retained stubble and 80 kg/ha) would be 0.32 t ha<sup>-1</sup>·year; this amount would be 3.2 t/ha of CaCO<sub>3</sub> per 10 year.

Also information from this study on the C-cycle component of acidification, due to loss in OC (Table 6.10), as 'unaccounted form' is showing that the largest contribution to acidification was estimated to come from nitrate leaching. Nitrate leaching, as a component of acidification was higher in the stubble retained and 80 kg/ha N fertiliser practices, and was lower in stubble removed and nil N rate fertiliser practices, but was opposite in the W-B rotation. Measuring the value for each component of acidification (accounted or unaccounted form) could help to choose better strategies in future for managing cropping systems.

**Table 6.12 Lime (CaCO<sub>3</sub>) required to neutralise the effects of soil acidification (using Helyar and Porter 1989) for the different management practices at the Tarlee site.**

Rotation	Stubble	N	AR 1996 (kmol H <sup>+</sup> ha <sup>-1</sup> yr <sup>-1</sup> )	CaCO <sub>3</sub> (t ha <sup>-1</sup> yr <sup>-1</sup> )	CaCO <sub>3</sub> (t ha <sup>-1</sup> 10 yr <sup>-1</sup> )
W-Wheat	Remove	0	1.85	0.09	0.9
		80	2.60	0.13	1.3
	Retain	0	2.71	0.14	1.4
		80	6.33	0.32	3.2
W-Beans	Remove	0	1.23	0.06	0.6
		80	3.13	0.16	1.6
	Retain	0	1.71	0.09	0.9
		80	2.71	0.14	1.4
W-Lupins	Remove	0	2.08	0.10	1.0
		80	2.87	0.14	1.4
	Retain	0	3.41	0.17	1.7
		80	4.64	0.23	2.3
W-Fallow	Remove	0	2.13	0.11	1.1
		80	4.56	0.23	2.3
	Retain	0	1.41	0.07	0.7
		80	3.12	0.16	1.6

To date most studies (Bolan et al. 1991; Helyar and Porter 1989; Williams 1980), and this study here, have come to a similar conclusion that the main cause for accelerated acidification is associated with N inputs into cropping systems in excess of the needs of the crop. With knowledge on the processes leading to net acid accumulation, and careful management systems it is possible to develop some strategies that minimize acid addition. The theoretical framework of Helyar and Porter (1989) has been used to measure the overall soil acidification (Table 6.8) that was influenced by the N and C processes in the

field. As has been shown in the literature review (Chapter 2) where, given the complex environmental conditions, there are many things that can influence the estimation of acidification rates (Ridley 1995; Verburg *et al.* 1998). Only a few studies (eg. Poss *et al.* 1995) have attempted to find the rate of acidification by measuring direct values for separate depths and processes behind the causes of acidification. However in most studies, rates of acidification have been compiled for the entire root-zone without provision for differential rate of acidification within the profile. In a few cases a proton budget has been measured separately for each depth (Poss *et al.* 1995), but in most cases the bulk assessment had masked the tendency for the surface soil to become acid and subsoil become more alkaline.

Earlier studies have not included information on either when N is mineralised, or when or where in the soil it becomes available to a following crop. The development of an approach for measuring net mineralisation, together with measurements of the profile of mineral N, allows a more detailed examination of this process to be made. A technique is needed to replace slow and laborious techniques of obtaining data on mineral N in the soil profile with something more suitable for routine use. Helyar (1991) suggested that achieving a model related to mineralisation, leaching and uptake by crops might provide useful information for making best use of subsoil mineral N, and may assist in minimizing the acidification associated with nitrate leaching. Thus to achieve these goals, the data given in this chapter will be used against the APSIM model to monitor the N-fluxes both at the surface and at the depth, and to compare the outcomes with real data obtained from the field studies. Information obtained can then be used in terms of decision-making for its remediation, adopting non-acidifying practices and attempts to understand and explain the processes and effects on soil properties for the next 10-20 years of management practices.

#### **6.4.2 Soil properties**

This study has shown that with the W-F rotation with no N-fertiliser application, soil Al and Mn have not been changed dramatically (Table 6.6 & 6.7). But with the application of N-fertiliser there was a significant increase in soil acidification, especially for W-W and W-legumes with stubble retention and 80 kg/ha N-fertiliser, and consequently a

significant increase in Al and Mn solubilities.  $Al_{Ca}$  is usually accepted as a good indicator of crop toxicity (Ritchie 1989), and it is recognised that there is a significant variation between  $Al_{Ca}$  over the  $pH_{Ca}$  range 4.0 to 5.0. For example at a  $pH_{Ca}$  4.3,  $Al_{Ca}$  can vary from as low as 0.6 mg/kg to as high as 9.6 mg/kg. Similarly to the results given by Aitken (1992), the  $Al_{Ca}$  increased with the decrease in soil pH at Tarlee site. The  $Al_{Ca}$  (extracted by 0.01 M  $CaCl_2$ ) is often seen as a good predictor for plant toxicity (Coventry 1992), and Fenton *et al.* (1996) have indicated critical concentrations of  $Al_{Ca}$  for a range of highly sensitive plants (0.5 to 2.0 mg/kg) and sensitive plants (2.0 to 4.0 mg/kg). In the Tarlee study, when N-fertiliser was used, the  $Al_{Ca}$  measured in the 1992 soils was 1.58 and 2.45 mg/kg (0-10 cm depth) for the wheat-bean and wheat-lupins rotations respectively. With the soil progressively acidifying, more Al is being released into soil solution in 1996, as 2.19 and 2.31 mg/kg were the measures from the wheat-bean and wheat-lupins rotations respectively. Most of this Al could exchange with soil exchangeable Ca, Mg, K and Na, and occupy the soil exchangeable sites on soil surfaces and may be toxic to plant growth.

The non-exchangeable forms of reactive Al may also become significant sources of phytotoxic Al with time (Juo and Kamprath 1979), and normally these forms may not be detectable by routine laboratory methods (such as 1 M KCl or 0.01 M  $CaCl_2$ ). In the Tarlee study, as the soil pH decreased from 1992 toward 1996, the increase in Al may be associated with an increase in the amount of Al bound with organic matter, which is not detectable. The presence of specific organic acid ligands (Kwong and Huang 1979; Harper 1994; Smith *et al.* 1995; Slattery *et al.* 1998) in soil solution has been shown to be effective in reducing Al toxicity by complexation, in favour of crop growth and yield. At  $pH_{Ca} < 4.8$ , Al becomes the dominant cation, so Al-monomers could be used to explain related changes. Many studies (Kerven *et al.* 1995; Blamey *et al.* 1983; Renkou and Guoliang 1997) have shown that the concentration of the monomeric species ( $Al^{3+} + Al(OH)^{2+} + Al(OH)^+_2 + Al(OH)_3$ ) will be controlled mostly by either complexation with organic acids and increases as the pH reduced. So the complexation of Al with OM may be another reason that Al may not be associated at this stage with any yield reduction.

There is considerable evidence showing that plant growth is better correlated with solution Al activities than Al concentration (Blamey *et al.* 1983; Bruce *et al.* 1988; Alva *et al.* 1986). Parker *et al.* (1992) showed that in solutions at low ionic strength to which

40  $\mu\text{M}$  Al was added, the activity of the Al monomers was reduced from 22  $\mu\text{M}$  at pH 4.0 to <5.0  $\mu\text{M}$  at pH 4.5. At high ionic strength even the introduction of high Al concentrations to nutrient solutions may not expose plant growth to Al toxicity (Wheeler *et al.* 1992; Bell *et al.* 1989; Blamey *et al.* 1991). These studies suggest that variability may occur when comparing the relative tolerance to plants to Al toxicity in solution culture with high ionic strength, and in soils, assuming that the soil has been correctly identified as Al toxic (Foy 1976; Scott and Fisher 1989). So addition of soil solution data on Al into a yield equation may improve the understanding on factors affecting yield. The complexation effect of Al with organic acids with Al species in soil solution is investigated in the next chapter.

It is possible therefore that where the percentage of Al in ECEC was low in 1992, then with the further development of soil acidification in 1996, the Al availability was increased. The increase in Al in the soil environment with further soil acidification was blocking the exchange site from being occupied by Ca and thus did decrease the ECEC of the soil in 1996 compared to 1992 data (Table 6.6 & 6.7). This has been shown earlier that at low levels of soil Ca and higher Al saturation%, the uptake of Ca may be inhibited by the presence of toxic amounts of Al (Kamprath 1984) and having a negative effect on ECEC (Thomas and Hargrove 1984). The Al saturation % in this study against  $\text{pH}_{\text{Ca}}$  (Figure 6.10) is showing a marked increase in Al saturation% (up to 7.6%) below  $\text{pH}_{\text{Ca}}$  4.7. At the Tarlee site, this increase in Al% of ECEC is higher especially for those management practices which induced soil acidification.

Like  $\text{Al}_{\text{Ca}}$ ,  $\text{Mn}_{\text{Ca}}$  is a good indicator for Mn toxicity for plants (Ritchie 1989) and the  $\text{Mn}_{\text{Ca}}$  also increased with the increased acidity at Tarlee. Bromfield *et al.* (1983) observed the critical  $\text{Mn}_{\text{Ca}}$  concentration toxicity with *Brassica napus*, a Mn-sensitive species, is 20mg/kg. Based on this result, it is possible that Mn toxicity can occur at this site for sensitive plants at the lower pH (pH<5.5). But because available Mn in soil can vary up to five-fold throughout a year, the potential for Mn toxicity in acid soils may only exist at certain times of the year (Fenton *et al.* 1996). Also the results from Table 6.7 indicate that the difference between treatment means are not significant for Mn and this may not be enough to use Mn here as a factor for yield toxicity response. In the next chapter the use

of soil solution data for Al and Mn may reflect these differences. Such calculations of the activity of cations in soil solution may be useful in that they determine the actual concentrations that plant roots may be exposed to in the soil.

### 6.5 Conclusions

The data given in this chapter indicate that the continuous cropping system practiced in the lower and mid-north regions of South Australia, with stubble retention and high N-fertiliser inputs, is rapidly acidifying the soil. These practices at the same time improved the overall yield, but the acidity produced from this system, as using solid-phase chemistry measures, does not allow any conclusion about relative influence of these factors on yield reduction. The soil pH values were decreased for all management practices particularly with the effect of legume-rotations and higher N-fertiliser rates. Where no N-fertiliser is used, W-legume rotations have caused the greatest pH decline. Therefore, after 19 years, in 1996, a  $pH_{Ca}$  and  $pH_w$  values of 4.4 and 5.2 were attained compared to the starting value 6.2 and 7.0 respectively. Acidification rates calculated in the present study can be used in estimating lime required to raise or maintain soil pH and subsequently avoiding yield loss. Generally the equivalent amount of lime required to neutralize this acidification at the Tarlee site over the 19-year period has ranged between 0.6 to 3.2 t ha<sup>-1</sup> for every 10-year for the lowest to highest acidification rates with various management practices. But to maintain production at an optimal level, these lime rates are required to be field validated similar to the approach used in chapter 4 of this thesis.

With the higher soil acidification and associated decrease in soil pH, both the Al and Mn are increased. The use of N-fertiliser in the rotation has had a much greater effect on increasing Al or Mn than either legume or stubble management. There is a significant variation of Al over the  $pH_{Ca}$  range 5.0 to 4.0, and the negative value for C-cycle acidification (Table 6.10) in this study is showing that OM will consume those protons produced in the soil system at lower pH values. So  $pH_{BC}$  would be lower for those soils with low OM content, than soil with higher OM. The higher observed soil-OM properties where residue is retained from legumes with 80 kg/ha N with higher  $pH_{BC}$  recorded for these management practices clearly indicate this fact. The higher contribution of continuous wheat than legumes to the C-cycle is probably due to the lower buffering

capacity of the OM with W-W practices. This clearly shows the influence of the type of crop-residue remaining in the field as stubble, which contributing less to the C-cycle value and more to the total acidification rate by W-legumes to nitrate proportions compared to cereals. Also the higher pHBC in higher OM content soils may provide some protection against Al toxicity (complexation), despite the lower pH and higher AR. So the presence of specific organic acid ligands in soil solution and the complexation of Al with OM may be important in this system, and are investigated in the next chapter. As reported here, only estimates of the contribution of each of the main nutrient processes can be provided at this stage, but more comprehensive data will be given in chapter 8 with directly measured values. Given the importance of OM oxidation to the proton budget, the measurement of the change in soil organic anions is critical if annual budgets are to be estimated accurately. Also the overall rate of acidification has been calculated for each management practice but the contribution of each process has not been correctly identified including the contribution from N-nitrification,  $\text{NO}_3^-$  leaching, and ammonification process (from N-fertiliser or from legumes).

Whatever the explanation, the study carried out here in medium rainfall area, permits the generalisation that the leaching potential for  $\text{NO}_3^-$  was evident on a red-brown soil in South Australia. The observed acidification of this soil, also suggests that the root development or absorption, with excess N accumulation in the soil, are not sufficient to take up  $\text{NO}_3^-$  leached to depth in the soil profile.

## Chapter 7

### 7. Effects of different management practices on soil solution, soil organic acids and complexation of toxic Al forms in soil solution

#### 7.1 Introduction

Acid soil infertility is linked with toxicities of soil Al, Mn or H ions to plants, and deficiencies of P, Mo, Ca and Mg in soils, with the possible reduction in plant yields (Cregan and Scott 1998; Ritchie 1989). As shown in the last chapter, high input cropping systems associated with N-fertiliser application and the use of legumes in the cropping phase can cause soil acidification. In the study described in this chapter, the Al% of ECEC was shown to be high, but at this stage was probably not severely affecting wheat yields. However it is recognised that it is difficult to directly attribute measures such as extractable and exchangeable Al (or Mn) to reductions in grain yield. Indeed, some studies suggest that using soil solution measures (such as  $\text{pH}_{\text{SS}}$ ) are a more appropriate direct measure on the influence of acidity factors on the plant growth (Bruce *et al.* 1988; Bessho and Bell 1992; Slattery *et al.* 1995). The monomeric forms of Al in soil solution are also known to be toxic to plant growth (Coleman and Thomas 1984; Kwong and Huang 1979; Hue *et al.* 1986; Suthipradit *et al.* 1990). With the  $\text{pH}_{\text{Ca}}$  drop at the Tarlee site (described in the last chapter) to a value of about 4.2, then it is possible that the soil there may be dominated by monomeric forms of Al, which may be toxic to plant growth (Coleman and Thomas 1984).

In cropping systems, the type of rotation and thus the vegetative residues present under different crop rotations may be important in influencing the concentration and type of organic acids in the soil solution (Huang and Violante 1986). This is especially important under strongly acidic soils where the presence of specific organic acids in solution can detoxify monomeric Al (Kwong and Huang 1979; Hue *et al.* 1986). So the reduction in the toxicity of Al through complexation with organic acids may occur in cropping systems with a process for retaining residues, and this process may also be an important factor in sustaining crop yields. For example the addition of fulvic acid to soil solutions containing up to 50  $\mu\text{M}$  Al has been shown to completely alleviate the toxic effects of Al

on root growth (Suthipradit *et al.* 1990). Thus the binding of monomeric Al by low molecular weight organic acids can be important in soil as part of an amelioration process (Hargrove and Thomas 1981; Hue *et al.* 1986). This knowledge of the long-term management effects on soil OM, and the types of organic acids present, together with information on Al complexation, can be useful for the understanding of amelioration of acidified soils.

In this chapter soils from the Tarlee experiment are again used, this time to investigate the influence of the different rotations, N-fertiliser rates and stubble practices on various soil OM fractions. In particular, the focus will be on the ability of these fractions with the various management treatments to influence soil solution pH, soil solution cation activities and Al species. Further, the partitioning of soil solution Al into both monomeric and complex Al is a useful means of obtaining more a significant relationship between Al toxicity and crop growth (Hue *et al.* 1986; Wright and Wright 1987); thus the effect of organic acid complexation with Al species on reduction of toxicity and overall grain yield will be examined here.

## **7.2 Materials and methods**

### **7.2.1 Site specification**

This experiment was established in 1977 at Tarlee, South Australia, and is described in detail by Schultz (1995). Selected treatments were used in the studies in this chapter; viz, 4 two-year rotations (wheat-wheat, wheat-bean, wheat-lupin and wheat-fallow) applied continuously up to 1996; two stubble treatments (removed and retained); and 2 rates of nitrogen (0, 80 kg /ha N as ammonium nitrate) applied to the wheat phase. The materials and methods are similar to the previous chapter unless indicated here. Some soil and plant data are obtained from J. Schultz (from SARDI), and are appropriately acknowledged, otherwise the soil analyses were undertaken as described below.

### **7.2.2 Soil solution phase chemical parameters**

For the soil solution measurements made here, the procedure was followed exactly as provided by Dr. Bill Slattery. This method is paraphrased below as part of the provided methodology. Soil solutions were prepared from 300g of air-dried soil samples, wet to

10-kPa matric suction potential and incubated for 24 h (Menzies and Bell 1988). The soil solution was centrifuged at 2000g for 45 min according to the method of Gillman (1976). Immediately following centrifugation, soil solutions were filtered through a 0.22  $\mu\text{m}$  membrane filter (Millipore GSWP) and analysed for pH and EC. An 8 mL subsample of the filtrate was further filtered through a 0.025  $\mu\text{m}$  filter (Millipore VSWP) for monomeric Al ( $\text{Al}_{\text{mono}}$ ) determinations, as this pore size has been shown to be necessary to avoid contamination from Al-containing micro-particulates (Menzies *et al.* 1991). Also, a 10mL aliquot of the 0.22  $\mu\text{m}$  subsample was rotary evaporated to dryness immediately after centrifugation for the determination of LMWOA (low molecular weight organic acid) by HPLC. The remaining filtrate was stored in plastic centrifuge tubes at 4°C for later analysis of cations (Ca, Mg, K, and Na) by Atomic Absorption Spectrometry (AAS).

Soil solution monomeric Al in the presence of organic acids was determined using the short-term colorimetric procedure developed by Kerven *et al.* (1989). Total soluble Al ( $\text{Al}_{\text{tot}}$ ) was determined by the pyrocatechol violet method (Menzies *et al.* 1992), which discriminates against microparticulates and organic ligands. Complexed Al ( $\text{Al}_{\text{comp}}$ ) was calculated as the difference between  $\text{Al}_{\text{tot}}$  and  $\text{Al}_{\text{mono}}$ . The GEOCHEM (Parker 1992, version 2) computer program was used to calculate activities of Ca ( $a_{\text{Ca}^{2+}}$ ), Al ( $a_{\text{Al}^{3+}}$ ) and the sum of activities of Al monomers (Al-monomers) in the soil solution (Sposito and Mattigod 1980). Calculations were performed using a fixed ionic strength calculated from the EC of the soil solution. It was assumed that all of the solid material was removed from the solution by filtration, and no solid surface/solution interactions were considered in these calculations.

The organic acids were determined by HPLC after rotary evaporating a 10mL aliquot of the 0.22  $\mu\text{m}$  filtered soil solution to dryness and then resuspending the residue in 500  $\mu\text{L}$  of 0.01M  $\text{H}_2\text{SO}_4$ . The final sample clean-up before injection onto the HPLC was performed by filtering the concentrated sample through a 3 mL C-18 seppak cartridge. HPLC was performed using the following Waters<sup>TM</sup> components: model 501 solvent delivery system, model 484 UV-Vis detector and a GBC<sup>TM</sup> model LL1610 auto-sampler. Then the retention time for individual chromatogram peaks were compared with the

retention time (i.e. time it takes to detect a peak after injection onto the column) of known standards (Bill Slattery pers. comm. 2001). Calibration curves for each LMWOA were measured using the peak response (height), from which the concentration of the LMWOA in the unknown samples could be determined (Bill Slattery pers. comm. 2001). The soil solution analysis used for soil samples are from replicated soil samples from the Tarlee experiment in the 1996 season. The soils were from the same management treatments as described in chapter 6. Statistical analysis methodology is the same as described in chapter 6.

## **7.3 Results**

### **7.3.1 Soil Solution chemistry**

#### **7.3.1.1 Soil solution pH**

The data for the effect of different management practices on soil solution chemical characteristics are shown in Table 7.1. An examination of the soil  $\text{pH}_{\text{SS}}$  for 1996 showed that there were substantial differences ( $P < 0.05$ ) in soil  $\text{pH}_{\text{SS}}$  with rotations, stubble management and N-fertiliser treatments (Figure 7.1). The overall order of the effects of different rotations on soil  $\text{pH}_{\text{SS}}$  was: wheat-bean  $\cong$  wheat-lupin  $\cong$  wheat-wheat  $>$  wheat-fallow. The application of N-fertiliser, relative to the nil-fertiliser treatment, decreased soil  $\text{pH}_{\text{SS}}$  for all management practices. The data indicate that stubble retention only had a small influence on soil  $\text{pH}_{\text{SS}}$ , with a decrease with the wheat-legume rotations (Table 7.1). However, with the combination of treatment effects, the  $\text{pH}_{\text{SS}}$  for the treatment of W-W, stubble retention and N-fertiliser application (80kg/ha) is lowest ( $P < 0.05$ ) amongst all treatments, with a  $\text{pH}_{\text{SS}}$  value of 4.6, compared to the starting value 6.5 in 1978. The stubble-retained practice with 80 kg/ha N resulted a drop in  $\text{pH}_{\text{SS}}$  in the surface soil, while below  $\text{pH}_{\text{SS}}$  of 5.5 there was an increase in  $I_{\text{S}}$  with decreasing  $\text{pH}_{\text{SS}}$  and above a  $\text{pH}_{\text{SS}}$  of 5.5 there was a decrease in ionic strength ( $I_{\text{S}}$ ) with increasing  $\text{pH}_{\text{SS}}$ . Therefore this change in pH may influence the increase in  $I_{\text{S}}$  in the 1996 season between different rotations (Table 7.1).

#### **7.3.1.2 Soil solution cations**

Soil solution cations and soil solution Al ( $\text{Al}_{\text{mono}}$ ,  $\text{Al}_{\text{comp}}$  and  $\text{Al}_{\text{tot}}$ ) concentrations for the 1996 soil samples are given in Table 7.1. The soil solution Al parameters were generally

increased ( $P > 0.05$ ) in the order of  $W-W > W-B \cong W-L > W-F$ . The stubble-retained practice has only a small effect on increasing this Al property in W-B and W-L rotations but showed a significant increase ( $P < 0.05$ ) with stubble-removed practices. In contrast, the use of 80 kg/ha N-fertiliser in the cropping practice significantly contributed to increasing the Al level of the soil solution when compared to nil N use, in the order of  $W-W \cong W-B \cong W-L > W-F$ . The increase in Al data is consistent with the observed decreases in soil pH<sub>SS</sub>. The relationships between Al<sub>SS</sub>, Mn<sub>SS</sub>, with different management practices are shown in Figure 7.2. The Al<sub>SS</sub> decreased and Mn<sub>SS</sub> increased with higher fertiliser rate and stubble retained practices. However the W-F rotation was always the lowest value amongst all treatments.

The Al<sub>mono</sub> concentration showed a similar trend to that of Al<sub>tot</sub> and Al<sub>comp</sub> for different management practices (Figure 7.3) and showing the highest Al levels for stubble retained with 80 kg/ha N-fertiliser. The complexation of Al has increased with increasing the acidifying effect of management practices (Figure 7.3 section c). A comparison of the plant available indices of soil Al for the Tarlee data indicate that using legumes in the rotation, and stubble retained and 80 kg N/ha, creates an environment with higher toxic Al than the other practices. The activity of Al<sup>3+</sup> for nil N and removed stubble was lower ( $< 0.01 \mu\text{M}$ ) than either stubble retained ( $2.45 \mu\text{M}$ ) or combined with 80 kg/ha N ( $9.08 \mu\text{M}$ ). However the amount of percentage complexed Al in this study shows that almost half of the Al has been complexed by organic acids wherever the stubble was retained (Table 7.1). However small proportion of this complexed Al may include some inorganic polymeric Al (Martin Fey pers. comm. 2002).

Soil solution derived cations and Al<sup>3+</sup> activities generated from GEOCHEM data are given in Table 7.2. The activity of Al has been increased with the addition of N-fertiliser and the stubble retained practice ( $P < 0.05$ ). The order of increase in activity for different rotations are  $W-L > W-B = W-W > W-F$  ( $P < 0.05$ ). The activity of the soil solution Ca and Mg generally increased with stubble-retained practices, and activities increased with N-fertiliser compared to nil N fertiliser. The highest activity for Ca and Mg was with W-B rotation, stubble retention and 80 kg N/ha. The activity of soil solution Mn did not change

with stubble practices but 80 kg N/ha significantly ( $P>0.05$ ) increased Mn activity in order of W-B>W-L=W-W>W-F.

**Table 7.1 The effect of rotations, stubble managements and N-fertiliser rates on soil solution chemical characteristics in 1996 at Tarlee site.**

Rot.	Stu.	N	pH <sub>ss</sub>	EC (dS/m)	Is (mM)	Ca (mM)	Al (mM)	Mn (mM)	Al <sub>tot</sub> (µM)	Al <sub>mono</sub> (µM)	Al <sub>comp</sub> (µM)	% Al <sub>comp</sub>
W-W	Rem	0	6.50	0.88	0.011	51	0.24	2.36	1.73	1.00	0.73	42
		80	4.92	0.66	0.009	33	0.12	4.62	16.39	8.97	7.42	45
	Ret	0	6.47	0.72	0.009	48	0.53	2.43	1.91	1.00	0.91	48
		80	4.62	0.92	0.012	71	0.19	6.77	34.3	16.94	17.37	51
<b>Isd 5%</b>			<b>0.1</b>	<b>0.04</b>	<b>0.004</b>	<b>0.7</b>	<b>0.02</b>	<b>0.06</b>	<b>0.04</b>	<b>0.08</b>	<b>0.12</b>	<b>1</b>
W-B	Rem	0	5.93	0.74	0.010	22	1.11	2.09	3.92	1.37	2.55	65
		80	4.88	0.56	0.007	41	0.16	4.82	11.71	6.57	5.14	44
	Ret	0	5.49	0.63	0.008	44	0.41	3.51	7.42	3.83	3.59	48
		80	4.80	0.95	0.012	58	0.19	6.31	25.21	12.71	12.49	50
<b>Isd 5%</b>			<b>0.06</b>	<b>0.28</b>	<b>0.004</b>	<b>0.7</b>	<b>0.02</b>	<b>0.06</b>	<b>0.12</b>	<b>0.12</b>	<b>0.16</b>	<b>0.5</b>
W-L	Rem	0	6.29	0.46	0.006	29	0.51	1.88	2.7	2.59	0.10	4
		80	4.93	0.78	0.010	42	0.13	4.75	15.92	8.83	7.09	45
	Ret	0	5.35	1.08	0.014	64	0.23	4.93	7.68	3.63	4.05	53
		80	4.80	1.03	0.013	73	0.17	7.31	24.12	12.43	11.69	48
<b>Isd 5%</b>			<b>0.08</b>	<b>0.06</b>	<b>0.004</b>	<b>0.3</b>	<b>0.02</b>	<b>0.14</b>	<b>0.06</b>	<b>0.06</b>	<b>0.08</b>	<b>0.9</b>
W-F	Rem	0	6.54	0.38	0.005	33	0.97	1.86	1.27	0.93	0.34	27
		80	5.40	0.54	0.007	42	0.31	3.88	3.83	2.13	1.70	44
	Ret	0	6.81	0.45	0.006	16	0.75	1.03	1.76	1.68	0.08	5
		80	5.39	0.64	0.008	29	0.72	3.61	8.78	3.31	5.47	62
<b>Isd 5%</b>			<b>0.01</b>	<b>0.02</b>	<b>0.004</b>	<b>0.7</b>	<b>0.02</b>	<b>0.16</b>	<b>0.12</b>	<b>0.12</b>	<b>0.16</b>	<b>1.2</b>
R			***	***	***	***	***	***	***	***	***	***
S			***	***	***	***	***	***	***	***	***	***
N			***	***	***	***	***	***	***	***	***	***
R*S			***	***	***	***	***	***	***	***	***	***
R*N			***	*	*	***	***	***	***	***	***	***
S*N			***	**	***	***	***	***	***	***	***	***
R*S*N			***	***	***	***	***	***	***	***	***	***

\*\*\* =  $P<0.001$ , \*\* =  $P<0.01$  and \* =  $P<0.05$  and ns is not significant or  $P>0.05$ . Also R, S and N are rotation, stubble and nitrogen treatments respectively.

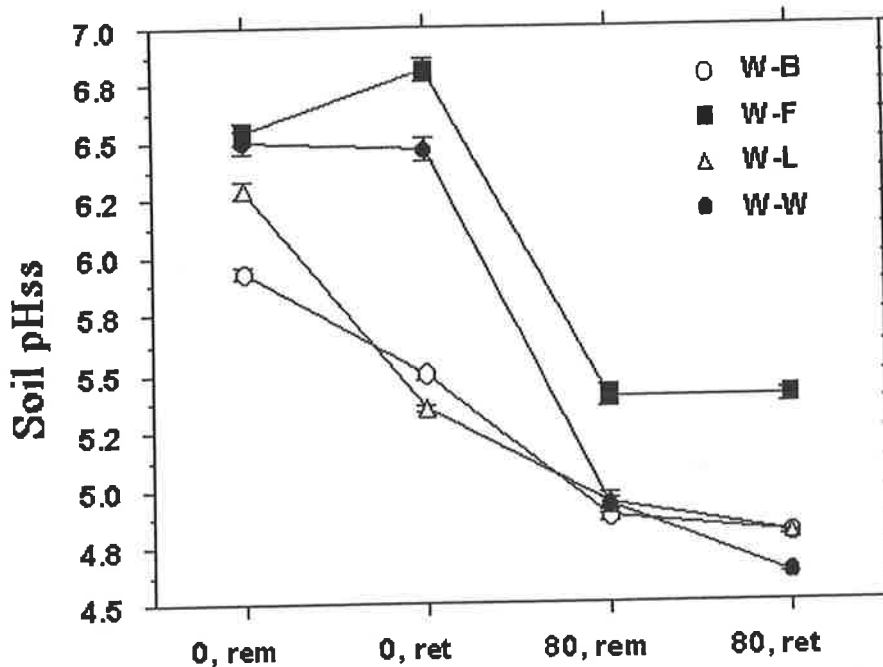


Figure 7.1 The comparative effect of rotations, stubble management and N-fertiliser rates on soil pH<sub>SS</sub> measured in 1996 at the Tarlee site.

### 7.3.1.3 Sum of the activities of monomeric species of Al

The derived monomeric Al<sup>3+</sup> activities generated from GEOCHEM data (Parker *et al.* 1992) are given in Table 7.3. The summed activities of the monomeric Al species (Al<sup>3+</sup> + Al(OH)<sup>2+</sup> + Al(OH)<sup>+2</sup> + Al(OH)<sub>3</sub>) which is called  $\Sigma$ Al-monomers, for each of the management practices showed similar trends to those obtained for the Al<sub>mono</sub> concentrations (Figure 7.4). The  $\Sigma$ Al-monomers were increased as the pH of the soil solution decreased. The highest summed activities of monomeric Al species were in the W-L rotation. The order of activities for all rotations are W-L > W-B = W-W > W-F. The highest activity for the  $\Sigma$ Al-monomers was generally found to be in the stubble retained with 80 kg/ha N-fertiliser (Figure 7.4). The equally dominant Al were both Al<sup>3+</sup> and Al(OH)<sup>2+</sup> for W-F rotation with stubble removed and nil N fertiliser (Table 7.3), although the Al<sup>3+</sup> species was more dominant in the lowest pH<sub>SS</sub> plots influenced by stubble retention and 80 kg/ha N fertiliser. The Al<sup>3+</sup> and Al(OH)<sup>2+</sup> both increased exponentially as pH<sub>SS</sub> decreased, but Al(OH)<sub>3</sub> decreased as the pH reduced and Al(OH)<sup>+2</sup> was unchanged (Figure 7.5).

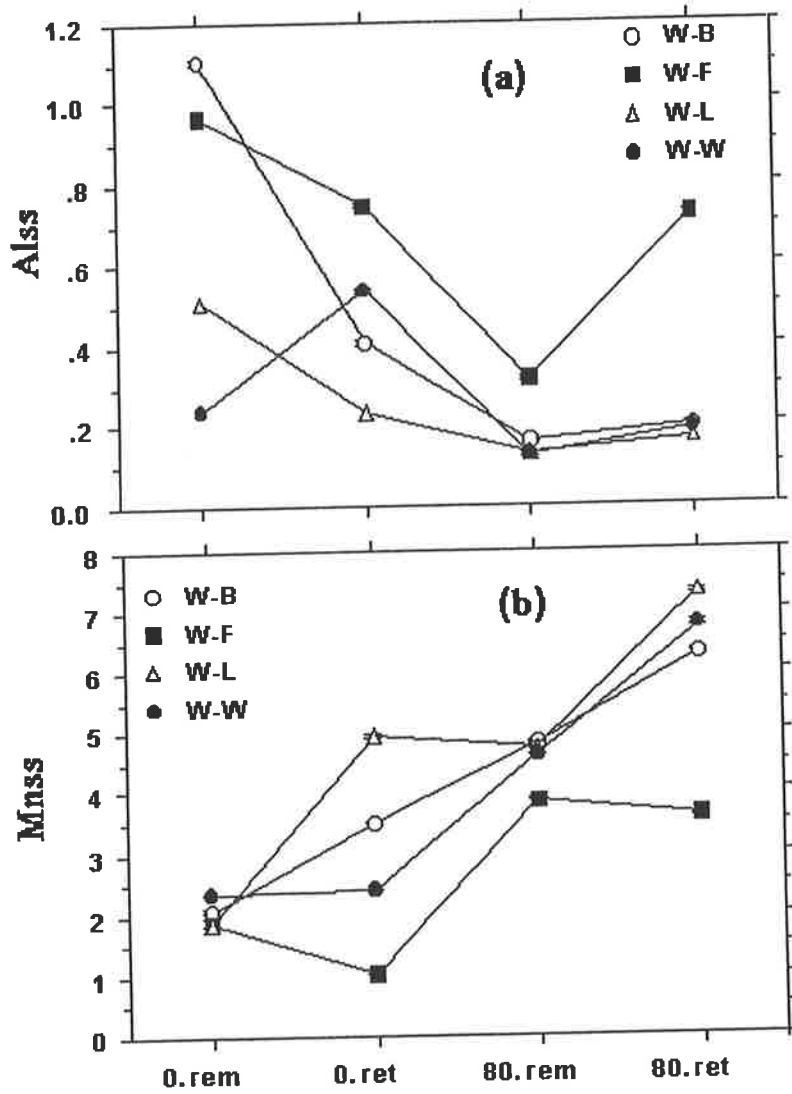


Figure 7.2 The comparative effect of rotations, stubble management and N-fertiliser rates on soil Al<sub>SS</sub> (a) and Mn<sub>SS</sub> (b) in 1996 at Tarlee site.

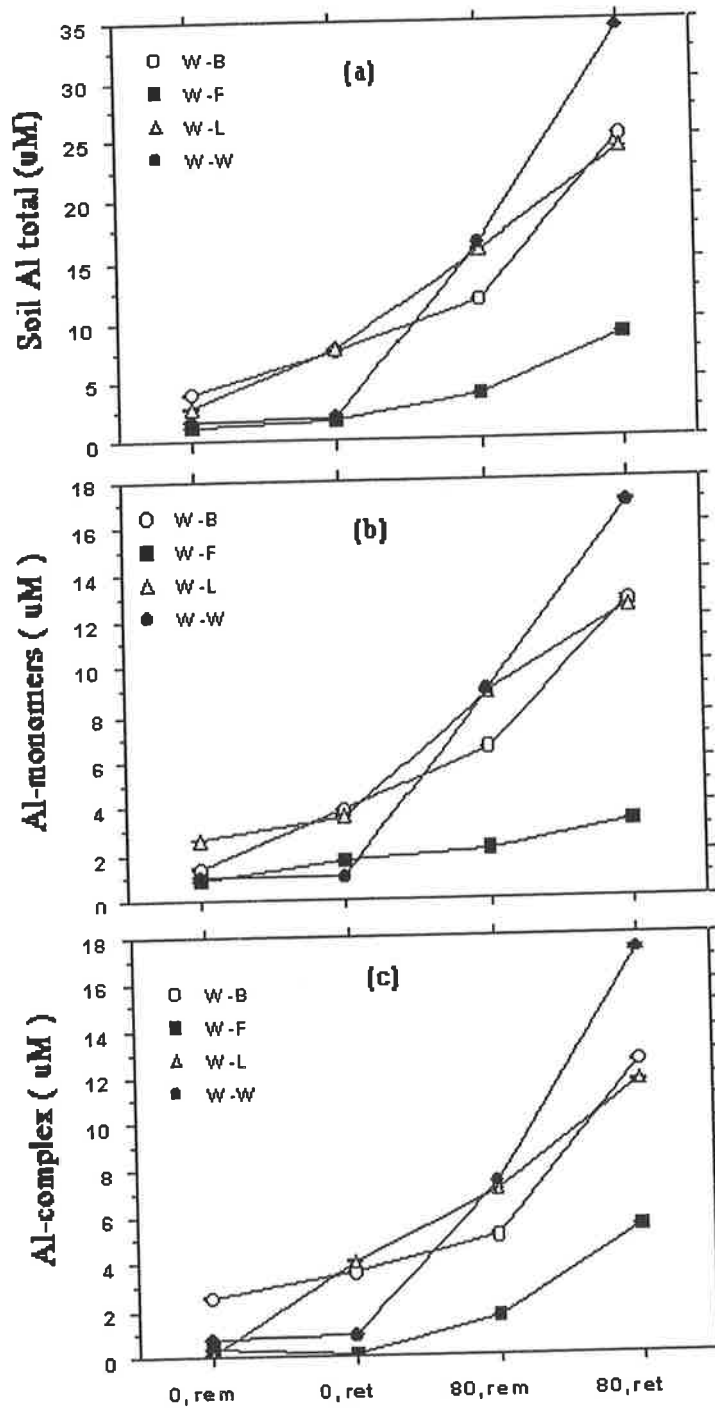


Figure 7.3 The effect of rotations, stubble management and N-fertiliser rates on soil  $Al_{tot}$  (a),  $Al_{mono}$  (b) and  $Al_{comp}$  (c) in 1996 at Tarlee site.

**Table 7.2 Activities of cations in soil solutions for 4 rotations, 2-stubble management and 2 N-fertiliser rates in 1996 as determined by GEOCHEM-PC program (Parker *et al.* 1992).**

Rotation	Stubble	N	Cation activity					
			Ca (mM)	Mg (mM)	Na (mM)	K (mM)	Mn (mM)	Al (µM)
W-Wheat	Remove	0	14.69	3.49	62.09	19.01	1.39	0.002
		80	27.80	6.58	63.90	28.74	3.23	2.990
	Retain	0	30.16	9.20	50.76	25.38	2.36	0.043
		80	40.09	12.61	91.94	26.98	4.22	5.132
<b>Isd 5%</b>			<b>0.52</b>	<b>0.44</b>	<b>1.14</b>	<b>0.6</b>	<b>0.04</b>	<b>1.020</b>
W-Beans	Remove	0	20.30	10.15	46.88	14.77	2.08	0.0002
		80	29.79	9.46	46.94	19.10	3.32	2.145
	Retain	0	50.35	16.69	67.14	28.51	3.45	0.118
		80	52.60	15.17	49.15	37.80	5.12	5.251
<b>Isd 5%</b>			<b>8.44</b>	<b>0.34</b>	<b>0.12</b>	<b>0.26</b>	<b>1.42</b>	<b>1.160</b>
W-Lupins	Remove	0	32.89	9.19	26.09	21.68	1.47	0.0001
		80	21.38	10.32	52.06	20.30	2.89	2.2246
	Retain	0	30.37	12.32	30.55	32.36	1.51	0.0001
		80	45.19	10.84	62.09	27.77	4.22	16.721
<b>Isd 5%</b>			<b>0.48</b>	<b>0.28</b>	<b>0.34</b>	<b>0.2</b>	<b>0.02</b>	<b>1.160</b>
W-Fallow	Remove	0	23.88	7.56	74.56	27.61	1.33	0.0001
		80	30.97	10.80	57.08	31.44	2.78	0.085
	Retain	0	11.86	4.66	40.09	18.64	0.74	0.0001
		80	21.16	9.72	45.87	29.58	2.59	0.087
<b>Isd 5%</b>			<b>0.54</b>	<b>1.32</b>	<b>0.40</b>	<b>0.22</b>	<b>0.12</b>	<b>0.120</b>
R			***	***	***	***	***	***
S			***	***	***	***	***	***
N			***	***	***	***	***	***
R*S			***	***	***	***	***	***
R*N			***	***	***	***	ns	***
S*N			***	ns	***	ns	ns	***
R*S*N			***	***	***	***	ns	***

\*\*\* = P<0.001, \*\* = P<0.01 and \* = P<0.05 and ns is not significant or P>0.05.

Also R, S and N are rotation, stubble and nitrogen treatments respectively.

**Table 7.3 Ionic strength (mM) and activities of monomeric Al species ( $\mu\text{M}$ ) for 4 rotations, 2-stubble management and 2 N rates in 1996 as calculated by GEOCHEM-PC program (Parker *et al.* 1992).**

Rotation	Stubble	N	Is (mM)	Al species Activity				$\Sigma\text{Al}$ -monomers
				$\text{Al}^{3+}$ ( $\mu\text{M}$ )	$\text{Al}(\text{OH})^{2+}$ ( $\mu\text{M}$ )	$\text{Al}(\text{OH})^+_{2}$ ( $\mu\text{M}$ )	$\text{Al}(\text{OH})_3$ ( $\mu\text{M}$ )	
W-Wheat	Remove	0	0.012	0.018	0.119	0.019	0.021	0.18
		80	0.009	2.243	1.336	0.019	0.002	3.60
	Retain	0	0.095	0.132	0.324	0.019	0.008	0.48
		80	0.012	3.222	1.603	0.019	0.002	4.85
			<b>0.003</b>	<b>0.520</b>	<b>0.160</b>	<b>0.018</b>	<b>0.002</b>	<b>0.66</b>
W-Beans	Remove	0	0.010	0.004	0.052	0.020	0.050	0.13
		80	0.008	1.800	1.180	0.020	0.002	3.01
	Retain	0	0.008	0.262	0.452	0.020	0.006	0.74
		80	0.012	3.297	1.603	0.020	0.002	4.92
			<b>0.003</b>	<b>0.660</b>	<b>0.220</b>	<b>0.018</b>	<b>0.092</b>	<b>0.88</b>
W-Lupins	Remove	0	0.006	0.001	0.032	0.011	0.081	0.13
		80	0.010	1.849	1.205	0.020	0.002	3.08
	Retain	0	0.014	0.002	0.034	0.020	0.074	0.13
		80	0.013	7.130	2.372	0.020	0.001	9.52
			<b>0.003</b>	<b>0.500</b>	<b>0.160</b>	<b>0.018</b>	<b>0.018</b>	<b>0.68</b>
W-Fallow	Remove	0	0.005	0.001	0.029	0.020	0.088	0.14
		80	0.007	0.207	0.401	0.020	0.006	0.64
	Retain	0	0.006	0.001	0.016	0.020	0.165	0.21
		80	0.010		0.408	0.020	0.006	0.65
			<b>0.003</b>		<b>0.10</b>	<b>0.018</b>	<b>0.038</b>	<b>0.18</b>
R			***	***	***	ns	***	***
S			***	***	***	ns	ns	***
N			***	***	***	ns	***	***
R*S			***	***	***	ns	***	***
R*N			*	***	***	ns	***	***
S*N			*	***	***	ns	ns	***
R*S*N			***	***	***	ns	***	***

\*\*\* =  $P < 0.001$ , \*\* =  $P < 0.01$  and \* =  $P < 0.05$  and ns is not significant or  $P > 0.05$ .

Also R, S and N are rotation, stubble and nitrogen treatments respectively.

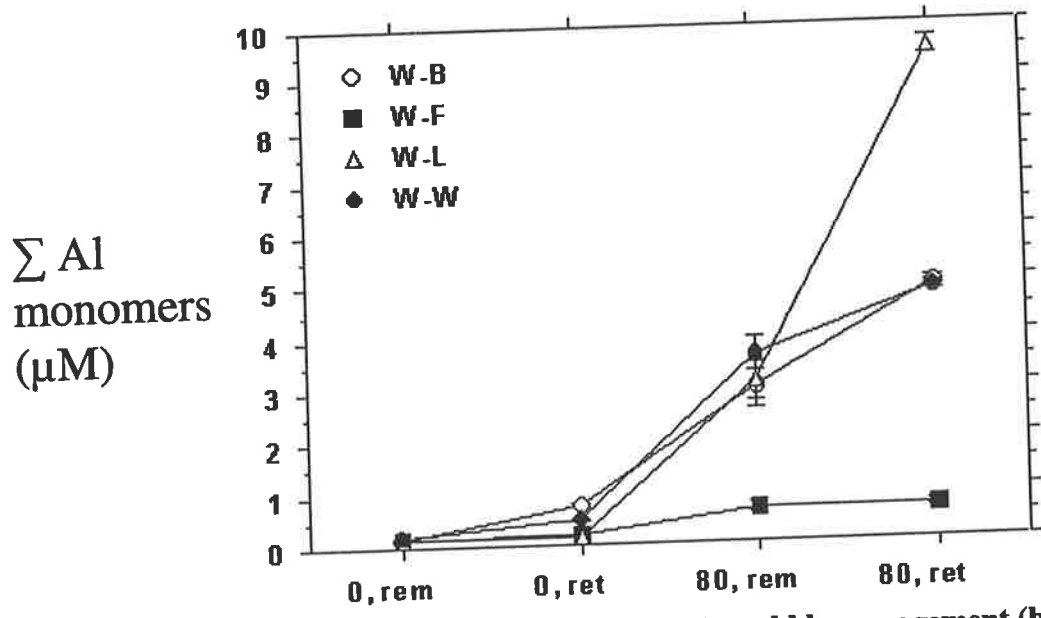


Figure 7.4 Relationship between different rotations (a), stubble management (b) and N rates on  $\Sigma$ Al-monomers ( $\mu$ M) in 1996 season at Tarlee site.

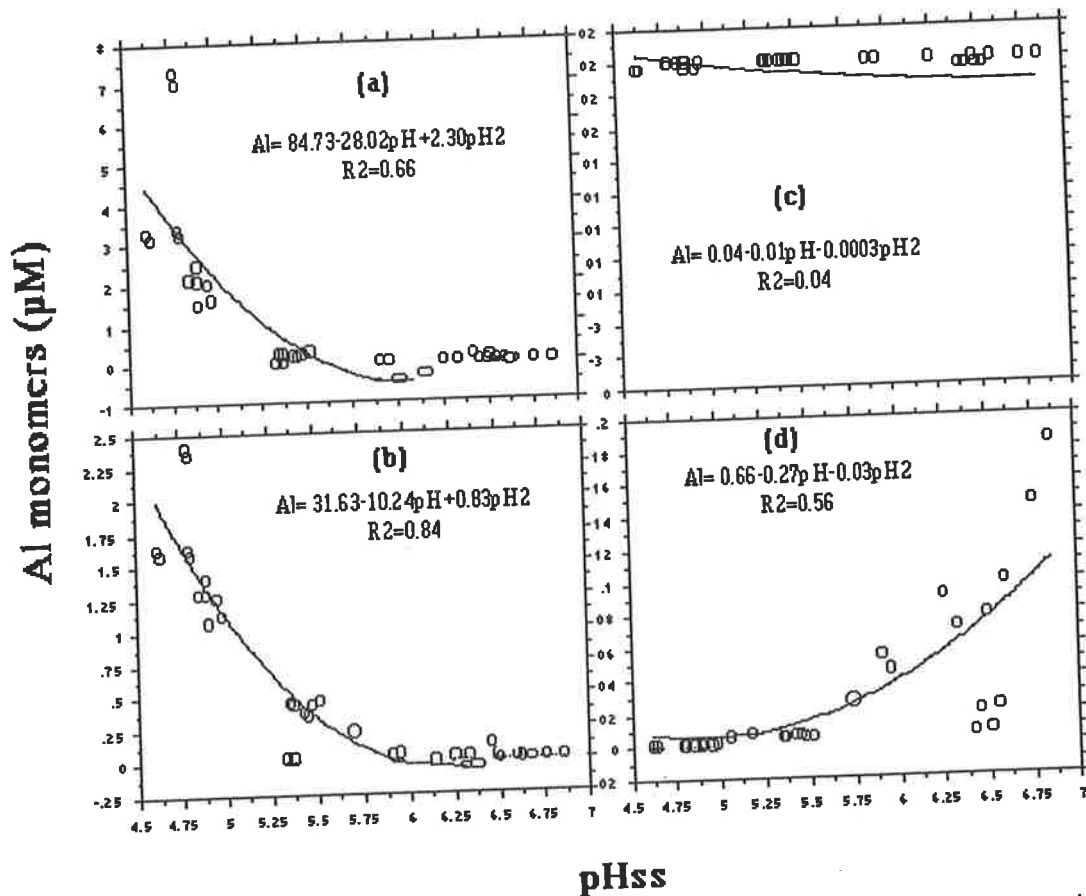


Figure 7.5 Relationship between Al monomers ( $\text{Al}^{3+}$  (a),  $\text{Al}(\text{OH})^{2+}$  (b),  $\text{Al}(\text{OH})^+$  (c) and  $\text{Al}(\text{OH})_3$  (d)) of soil solution as calculated by GEOCHEM (Parker *et al.* 1992) and  $\text{pH}_{\text{SS}}$  for all soil management practices in 1996 at Tarlee site.

### 7.3.3 Low molecular weight organic acids

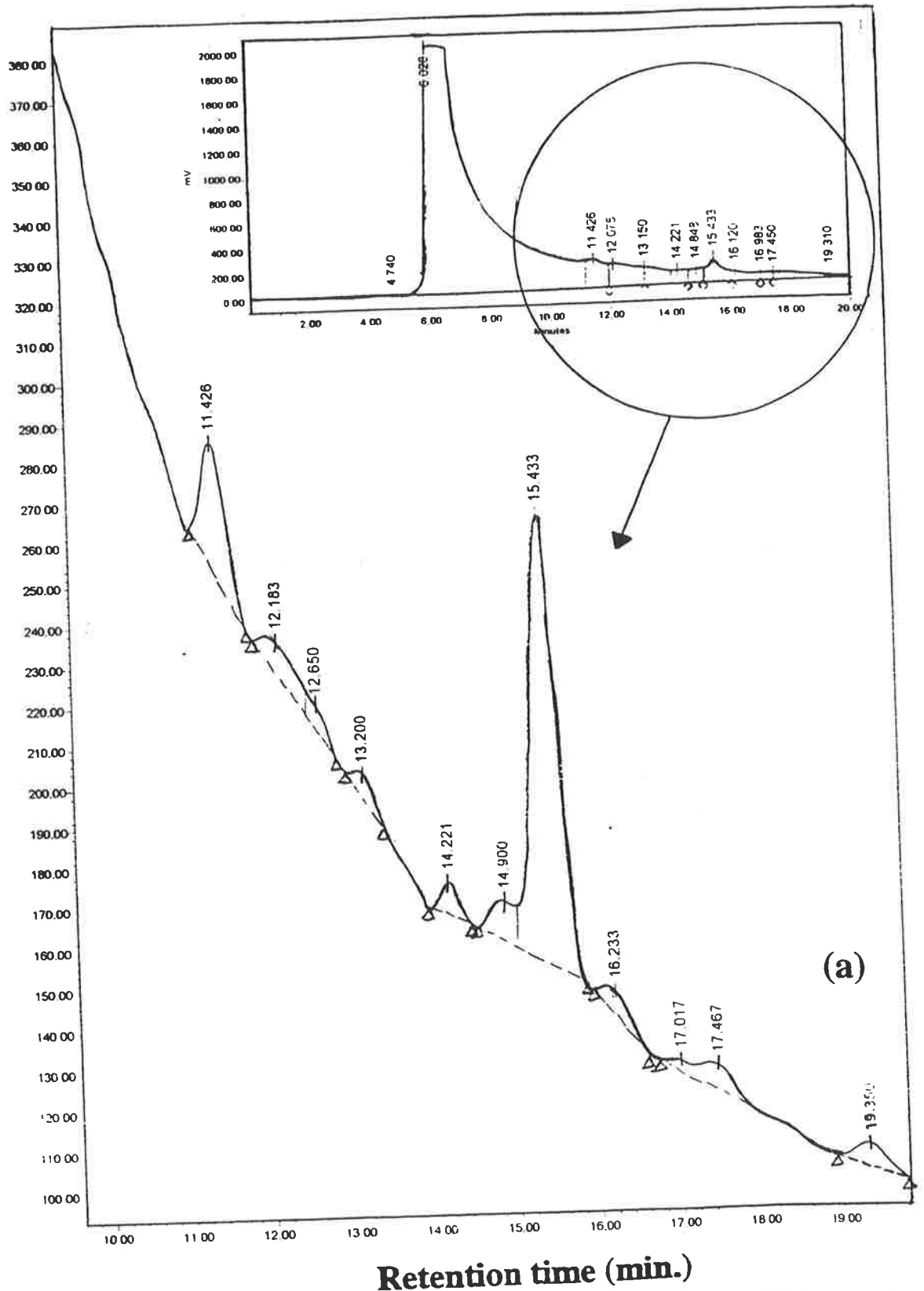
The effects of the different management practices on the low molecular weight organic acids (LMWOA) in the soil solution are shown in Table 7.4. Also, Figure 7.6 shows the peak responses for individual LMWOA separated according to their different retention times by HPLC. The position of each peak has been compared with the position of standard organic acid solutions. The results (Table 7.4 and Figure 7.6) indicate wherever stubble was retained, the presence of malic, succinic and fumaric were characterised as part of total concentration of LMWOA, compared to stubble removed practices. The presence of some or all of these properties is more obvious in retained practices, especially in W-B, W-L and W-F rotations. The presence of LMWOA in the W-L rotation followed the same pattern, but the only difference is that malic acid was absent. In the W-

W rotation, the most abundant organic acid seems to be t-aconitic (much higher concentration) and fumaric for stubble-retained practices compared to stubble removed. However the overall results for all rotations indicate that the fumaric acid was observed for all rotations with stubble-retained compared to stubble-removed practices. Also the most abundant LMWOA in all practices were t-aconitic and formic acids.

**Table 7.4 Effects of different management practices from 1996 soil samples at Tarlee on soil solution low molecular weight organic acids (LMWOA) and resulted peak heights (PH) in mV and retention time (RT) in minutes.**

Rotation	Organic acid	W-W Rem 0	W-W Rem 80	W-W Ret 0	W-W Ret 80	W-B Rem 0	W-B Rem 80	W-B Ret 0	W-B Ret 80	W-L Rem 0	W-L Rem 80	W-L Ret 0	W-L Ret 80	W-F Rem 0	W-F Rem 80	W-F Ret 0	W-F Ret 80
RT	oxalic																
PH	oxalic																
RT	citric																
PH	citric																
RT	tartaric																
PH	tartaric																
RT	malic							9.7	9.8								
PH	malic							20.4	6.5								
RT	t-aconitic	11.4	11.4	31.5	32.4	11.4	11.4	11.3	11.4	11.4	11.4	41.4	31.4	11.3	11.3	11.4	11.4
PH	t-aconitic	12.9	11.2	27.1	31.6	33.1	35.3	51.7	42.1	9.3	10.9	63.9	30.1	35.8	23.6	28.6	68.1
RT	Succinic	12.7	12.6	12.7	12.6	12.6	12.6	12.4	12.6			12.7	12.6			12.7	12.6
PH	Succinic	7.2	6.9	10.5	5.5	24.7	9.6	6.2	3.2			3.7	3.0			4.4	6.1
RT	formic	14.7	14.7	14.8	14.9	14.8	14.6	14.7	14.6	14.6	14.6	14.7	14.7	14.6	14.6	14.1	14.7
PH	formic	6.3	5.3	8.7	8.2	16.3	2.3	15.7	6.8	5.9	4.2	11.9	11.6	4.4	6.3	28.1	29.2
RT	fumaric			16.3	16.2			16.4	16.1			16.3	16.1			16.3	16.2
PH	fumaric			4.1	6.2			5.5	4.3			5.5	5.7			3.5	5.5

Peak response (MV)



(a)

Figure 7.6 Peak responses at 254 nm, shown for individual LMWOA separated according to their different retention times on 5- $\mu$ m spherisorb octyl C-8 (250 by 4.6 mm, Biorad™ Aminex HPX87H) by HPLC for W-W rotation and 80 kg/ha N-fertiliser with retained (a) or removed (b) stubble practices. The position of each peak is compared with the position of standard organic acid solutions.

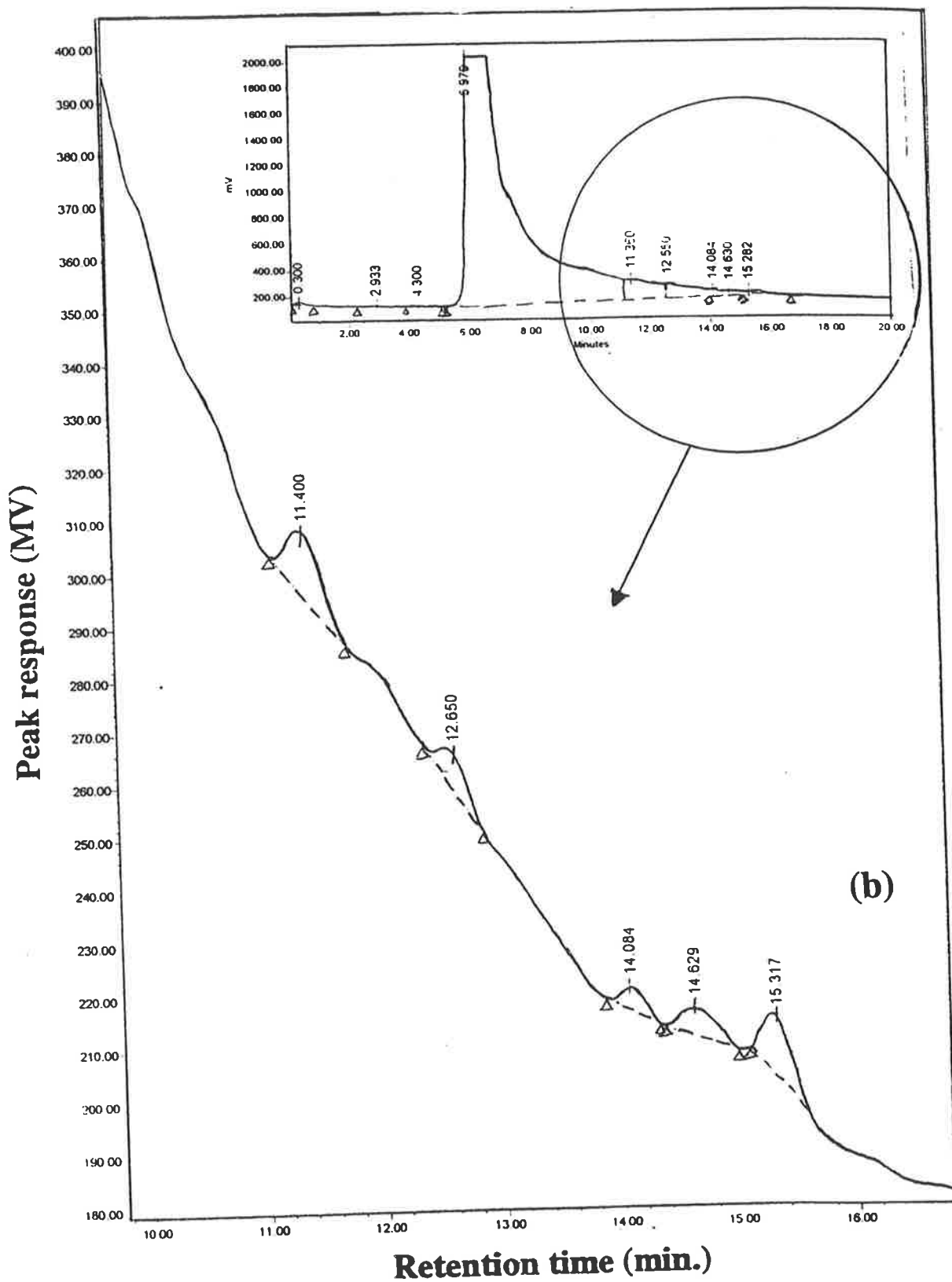


Figure 7.6 continued

## 7.4 Discussion

### 7.4.1 Soil solution properties

In the previous chapter it was shown that where plant residues were retained in the topsoil then generally there were higher levels of soil OM than with the treatments where the residue is removed. Also higher OC concentrations were obtained in response to N-fertiliser; this outcome of some improvement in organic matter levels with stubble input is in agreement with other studies (Dalal *et al.* 1991; Ladd *et al.* 1994). A beneficial outcome of an increase in soil OM is the removal of the hydroxyl form of Al from soil solution thus providing both the opportunity for cations to occupy exchange sites, and an increase in the CEC of the soil (Starr *et al.* 1996). Therefore with an increase in the CEC of the soil (Starr *et al.* 1996), the likelihood of better control of the pH buffering capacity of the soil against pH changes is achievable in the soil environment (Bloom *et al.* 1979; Hargrove and Thomas 1981). This all depends on the effects of OM and the associated changes in the soil pH. Generally, decarboxylation of organic anions and ammonification of plant residue-N are major causes for soil pH to increase, while nitrification of mineralised residue N causes soil pH to decrease (Pocknee and Sumner 1997; Tang and Yu 1999). In the Tarlee study, the adding of OM to a high initial pH soil (eg.  $pH_w = 6.2$  in 1977) may have caused some dissociation of  $H^+$  from the OM, which can lower the soil pH and result in the dissolution or release of Al. But eventually in some of the management practices shown in the present study, an increased soil buffering could be related to a higher concentration of organic C and the subsequent formation of organo-metallic complexes, which could account for the higher complexation with monomeric Al (Bloom *et al.* 1979; Hargrove 1986). The OM addition to soil in the form of stubble retention can decrease soluble Al because the extent of Al binding by the OM is more than those effects that help to increase Al dissolution caused by pH reduction (Bloom *et al.* 1979; Hargrove and Thomas 1981). Thus the presence of OM in the form of LMWOA in soil solutions may form complexes with Al and prevent subsequent hydrolysis (Kwong and Huang 1979; Violante and Violante 1980; Huang and Violante 1986; Hue *et al.* 1986; Inoue and Huang 1986), and improve buffer capacity thereby preventing further decline in soil pH.

The presence of specific organic acid ligands (Kwong and Huang 1979; Harper 1994; Smith *et al.* 1995; Slattery *et al.* 1998; Ma 2000; Ryan *et al.* 2001) in soil solution has

been shown to be effective in reducing Al toxicity. The type of released organic acid depends on plant species, which for wheat is malate (Delhaize *et al.* 1993). The release of these organic acids also depends upon the presence of toxic  $Al^{3+}$  in the external solution (Delhaize *et al.* 1993; Zheng *et al.* 1998). So the type of organic acids released from organic materials, which are returned to soil surfaces, could play an important role in Al detoxification (i.e. the organic acid is involved in complexation and reduces Al level) (Huang and Violante 1986). Organic acid anions will be excreted into the soil environment from root exudates and during the decay of plant material (especially leaves), and through microbial synthesis in the rhizosphere (Rovira 1994). Hue *et al.* (1986) classified the LMWOAs into three groups based on their ability to complex Al and the strength of the bonds subsequently formed (Table 7.5). The relative contribution of each type of organic C or calibration curve for each LMWOA can be estimated by identifying the peak from the already known samples-peak as a proportion of the total integrated area of the entire spectrum (as explained in the materials and methods section).

Organically complexed forms of Al produce less toxicity compared to  $Al^{3+}$  and monomeric Al-hydroxy species (Hue *et al.* 1986; Ritchie 1989). Figure 7.7 indicates that complexation of OM with Al has been increased by increasing the OM property of the soil. Also the higher percentage Al complexation values obtained in this study (Table 7.4), for those rotations which have low pH values shows the contribution of the organic material as an ameliorative input on Al toxicity. Soil conditions in this study associated with stubble-retained practices favoured the release of more LMWOA such as malic, succinic and fumaric from decomposing plant material (Table 7.4). For example, higher concentrations of these LMWOA are more obvious in the stubble-retained practices with W-B rotation, rather than with the removed practice and the same rotation. However the key organic acids (as observed in this study) responsible for complexation with Al would seem to be succinic, malic and fumaric for the faba beans and succinic and fumaric for wheat and lupin type of stubble. In other studies, tartaric acid, succinic acid and dicarboxylic acid from stubbles of cereal plants were responsible for complexation with Al. Thus the evidence given here would suggest that stubble retention seems to provide an opportunity for complexation of Al.

**Table 7.5 Complexing strength of LMWOA with Al (from Hue *et al.* 1986)**

<b>Strength of Al-organic acid complex</b>	<b>Organic ligand</b>
(I) Strong	citrate, oxalate, tartrate, tannate, dl-tartrate, dl-malate.
(II) Moderate	malate, malonate, salicylate, dl-aspartate.
(III) Weak	succinate, lactate, formate, acetate, phthalate, p-OH benzoate.

Tan (1986) suggested that the presence of LMWOA in soil solution is important in the dissolution of primary and secondary minerals. For example citric and succinic acid affect mineral decomposition by reducing the soil pH until the clay minerals begin to dissolve, releasing polyvalent cations such as  $Al^{3+}$ . However Sposito (1996) showed that the dissolution reaction that consumes protons may partially be reversed by hydrolysis of the  $Al^{3+}$  released at higher pH values. The occurrence of malic and succinic acids under W-B and not under W-W and W-L rotations, and also fumaric under all retained, and not under any removed practices, is consistent with the understanding that these organic acids are exuded by roots of beans or cereal plants respectively as part of a control mechanism against the effects of high soil solution Al (Delhaize *et al.* 1993). These organic acids may be derived from either plant or microbial intermediates of the citric acid cycle. These LMWOA are the most transient components of the organic carbon pool in the soil (Slattery *et al.* 1995). Thus if these Al-organic complexes in the surface soil start to move through the soil profile for any reason, then this may result in a decrease in soil pH in the subsoil. Because at higher pH, particularly in South Australia with more alkaline subsoil, there is possibility of hydrolysis of these complexes and releasing of Al to the soil solution environment. This effect needs to be investigated further by another study on the presence of LMWOA in all depths, and under all management practices.

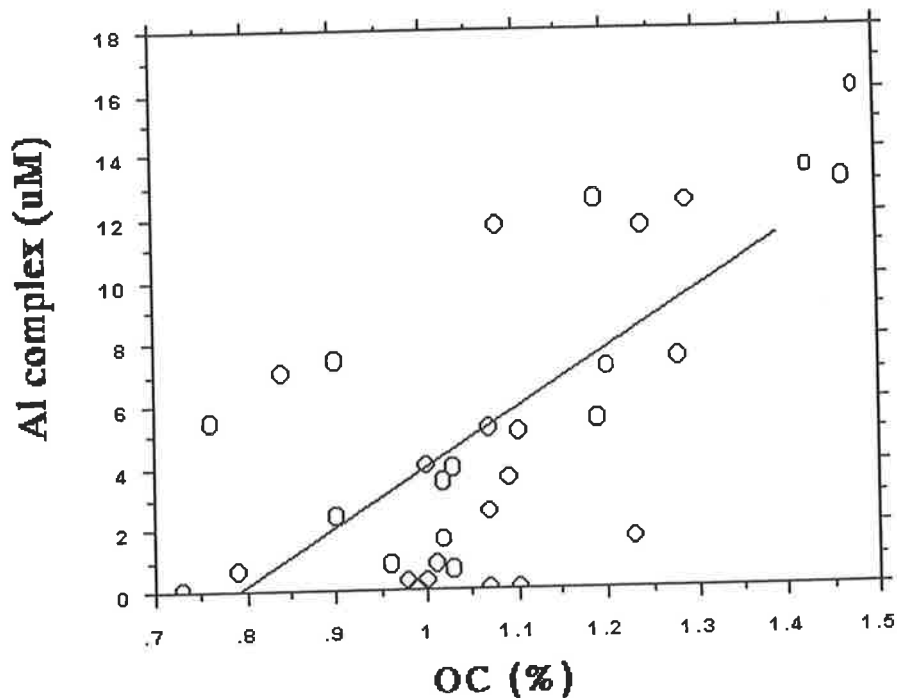


Figure 7.7 The relationship between OC% and  $Al_{comp}$  for overall management practices in 1996 at Tarlee experiment ( $R^2=0.35$ ).

Also the activity of  $Al^{3+}$  in soil solution is controlled by the dissociation and precipitation of Al minerals (Menzies *et al.* 1994). The  $Al^{3+}$  species were dominant in the lowest  $pH_{SS}$  plots influenced by stubble retention and 80 kg/ha N fertiliser (Table 7.3). The relationship between the sum of the activities of the monomeric species of  $Al^{3+}$ , as calculated using GEOCHEM (Parker *et al.* 1992), and  $pH_{SS}$ , showed that by decreasing pH as influenced by acidifying practices the overall Al increases (Figure 7.8). The relationship between soil solution pH and  $\log(Al^{3+})$  for all management practices as determined from GEOCHEM (Parker *et al.* 1992) shows reasonable agreement with that for the theoretical gibbsite line shown by Menzies *et al.* (1994), and described by Lindsay and Walthall (1989) (Figure 6.10). Aluminium activity is controlled by dissolution reactions and the precipitation of Al minerals (Al oxides and Al hydroxide) (Menzies *et al.* 1994) and is only dependent on soil pH. This relationship shows that the  $Al^{3+}$  activity decreases with increased  $pH_{SS}$ . The increase in soil OC in the surface soil for stubble-retained practices (Table 6.11), would contribute to soil buffering and may account for a deviation from the gibbsite line, which can be seen in the lower part of the Figure 7.8 (at

pH<sub>ss</sub> >5.5) with more scatter of the data. Thus the deposition of large amounts of OM to the system may contribute to soil buffering to control the activity of Al<sup>3+</sup>.

Another important factor with control of toxic levels of Al in soil solution is the provision of a higher ionic strength, such is favoured in the Tarlee study by some of the management practices (Table 7.3). Parker *et al.* (1992) showed that in solutions at low ionic strength to which 40 µM Al was added, the activity of the Al monomers was reduced from 22 µM at pH 4.0 to <5.0 µM at pH 4.5. At high ionic strength even the applying of high Al concentrations to nutrient solutions may not expose the plant to Al toxicity (Wheeler *et al.* 1992; Bell *et al.* 1989; Blamey *et al.* 1991). These studies suggest that using high ionic strength in soil solution studies, in comparing relative tolerance of crops to Al toxicity, may not reveal the true response of crops to Al toxicity, because the solution has not been correctly prepared as Al toxic, unless the ionic strength is also corrected (Foy 1976; Scott and Fisher 1989). Evidence from soil solution experimentation suggest that at low ionic strength, even <5µM of Al can inhibit plant growth (Blamey *et al.* 1983; Alva *et al.* 1986; Bruce *et al.* 1988; Edmeades *et al.* 1983). Increasing the ionic strength decreases the activity of Al<sup>3+</sup> because of large decreases in the activity co-efficient of trivalent ions with increased ionic strength (Sposito 1981). In addition, Al activity is affected not only by solution ionic strength but also by pH. In this Tarlee study, the higher ionic strength observed on the stubble retained with 80 kg/ha N-fertiliser treatment may have provided a favoured condition that prevents toxic effects of Al on plant growth. Also higher activity of Ca as shown in Table 7.2 in more acidified treatments.

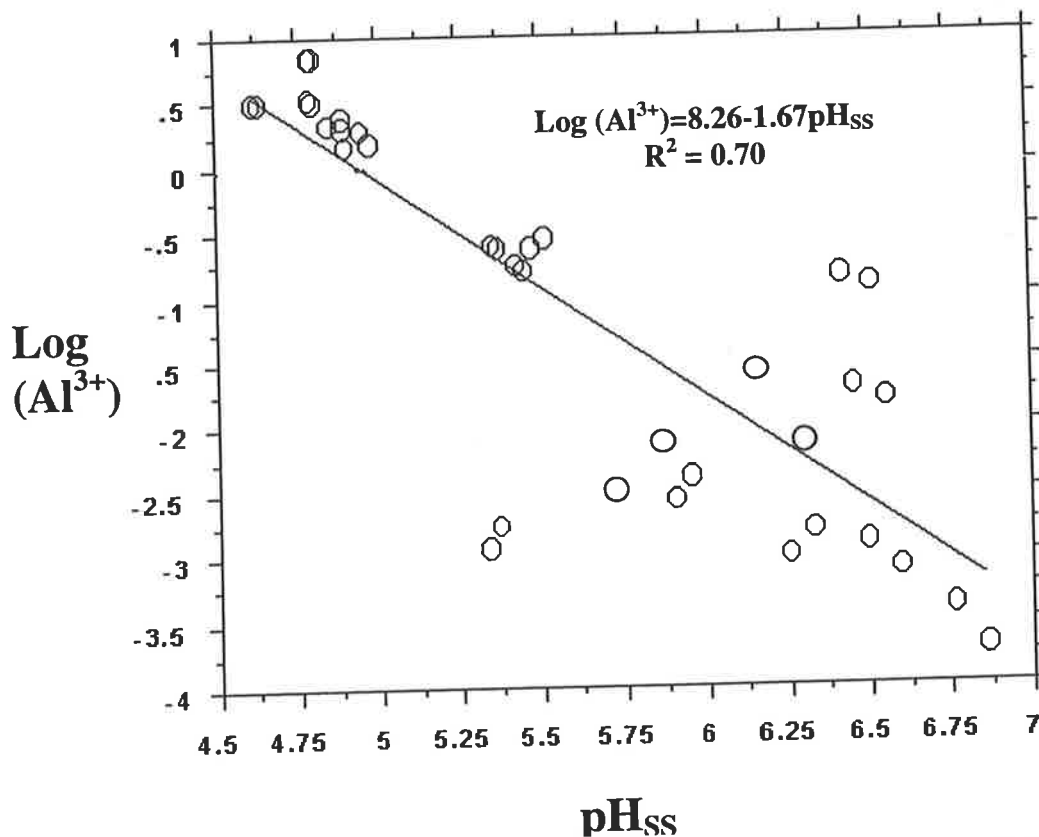


Figure 7.8 Relationships between  $\text{log Al}^{3+}$  activity as determined by GEOCHEM and  $\text{pH}_{\text{ss}}$  for soil solution for all management practices, Tarlee site and 1996 data.

#### 7.4.2 Soil properties and grain yield

As the monomeric forms of Al dominate in strongly acid soils ( $\text{pH}_{\text{Ca}} < 4.5$ ), it is this form that is likely to be toxic to plant growth (Coleman and Thomas 1984). The sum of the activity of monomeric Al ( $\text{Al}^{3+}$  and the hydroxy-Al species) in soil solution is considered by some authors as the best Al measure to describing relationships between plant growth and phytotoxicity of Al (Pavan *et al.* 1982; Bruce *et al.* 1988; Alva *et al.* 1987). But others suggest using the relationship between  $\text{pH}_{\text{ss}}$  with Al, as this more closely resembles the point of increase in Al level under a specific pH (Bessho and Bell 1992; Menzies *et al.* 1994; Moody *et al.* 1995).

Data from various soil solution studies suggest that critical  $\text{Al}_{\text{tot}}$  was  $10 \mu\text{M}$  for barley with a critical  $\text{pH}_{\text{Ca}}$  of 5.1-5.2 at low phosphorus (P) levels,  $50 \mu\text{M}$  with a critical  $\text{pH}_{\text{Ca}}$  of

4.7-4.8 at high levels of P (Bache and Crooke 1981) and critical  $Al_{Tot}$  of  $\leq 5 \mu M$  at  $pH_{Ca}$  4.8 (Slattery *et al.* 1995) at high P levels. Also critical levels for  $Al_{tot}$  are  $5 \mu M$  for acid tolerant cultivars such as wheat (Matong) and triticale (Currency) and as low as  $2 \mu M$  for acid sensitive cultivars such as canola (Marnoo) and barley (Schooner) (Slattery *et al.* 1995). However the relationship between different Al properties and  $pH_{SS}$  in this chapter, for all management practices is best described by the relationship between  $Al_{tot}$  and  $pH_{SS}$  ( $R^2=0.93$ ). Also the relationship between yield and different Al properties (Figures are not shown here) show that in this study the relationship between  $Al_{tot}$  ( $\mu M$ ) and  $pH_{SS}$  for all management practices is the best described relation ( $R^2=0.68$ ), compared to other Al values. The yield reaches to a stable condition after the  $Al_{tot}$  starts to reach higher than  $10 \mu M$ .

As a caution to the above, Blamey *et al.* (1992) have suggested that using such cation activities may not provide a good index of plant toxicity as a yield-limiting factor under all conditions, because there might be ionic strength changes with variation in pH under different management practices. Therefore it could be better to use different ratios of activities of cations in soil solution, and taking the valency of each ion into consideration may present a better approach for these comparisons (Blamey *et al.* 1992). For example Ca activity was an important factor in plant root protection against Al toxicity and subsequent yield improvement where the ratio of activity of  $Ca^{2+}/\sum Al$  monomers was the best-described equation (eg.  $R^2=0.70$ ) for the prediction of grain yield (Slattery *et al.* 1995). This approach may need to be investigated for the Tarlee data in another study for the effects of all management practices.

## 7.5 Conclusions

The data given in this chapter indicate that the continuous cropping system with stubble retention and high N-fertiliser inputs increased the concentration of soil solution total and monomeric Al. The  $pH_{SS}$  for the treatment of W-W, stubble retention and N-fertiliser application (80kg/ha) is lowest amongst all treatments, with a  $pH_{SS}$  value of 4.6, compared to the starting value 6.5 in 1978. The increase in Al level of the soil solution is consistent with the observed decreases in soil  $pH_{SS}$  with higher fertiliser rate and stubble retained practices. The soil solution Al parameters ( $Al_{mono}$ ,  $Al_{comp}$  and  $Al_{tot}$ ) were

generally increased ( $P > 0.05$ ) in the order of  $W-W > W-B \cong W-L > W-F$ . The  $\Sigma Al$ -monomers, for each of the management practices showed similar trends to those obtained for the  $Al_{mono}$  concentrations and were increased as the pH of the soil solution decreased and especially showed highest activities in the W-L rotation with the stubble retained with 80 kg/ha N-fertiliser. The dominant Al species with this treatment with the low pH was the  $Al^{3+}$  species, but  $Al(OH)_3$  declined and  $Al(OH)_2^+$  were unchanged as the pH decreased.

Wherever there was higher organic C the complexation of OM with Al was increased in the soil. A higher concentration of LMWOAs was more obvious in the stubble-retained practices with the W-B rotation, rather than with the stubble removed practices. The key organic acid (as observed in this study) responsible for complexation with Al would seem to be succinic, malic and fumaric for the faba beans and succinic and fumaric for wheat and lupin types of stubble. The occurrence of malic and succinic acids under W-B and not under W-W and W-L rotations, and also fumaric under all retained and not under any removed practices, is consistent with the understanding that these organic acids are exuded by roots of beans or cereal plants respectively as part of a control mechanism against the effects of high soil solution Al. However the presence of LMWOAs that are capable of forming strong bonds with  $Al^{3+}$  did not reduce the activity of  $Al^{3+}$  in soil solution, but their complexation did reduce the total Al (mM) for stubble retained with N-fertiliser treatments as the highest acidified practices. This study suggests that in such situations grain yield responses to liming may not always be reliably explained by the Al toxicity or pH values. Such responses could also be attributed to the complexing of monomeric Al, and thus the combination of the Al monomers together with the OC content may provide a better description of the yield responsiveness.

Clearly stubble retained practices must be further investigated with other management practices described in this chapter, in order to understand the biological ecosystem that provides the supply of organic acids that may help control the buffering capacity of the soil and potential control of chemical toxicities through Al complexation. In the next chapter the use of such simulation studies to help to explain or differentiate the influence

of the components agricultural system on OM production, especially C and N dynamics, is described.

## Chapter 8

### **8. Testing APSIM against the long-term (1977-1996) Tarlee data as part of understanding the behaviour of soil water, nitrogen and carbon dynamics under different management practices**

#### **8.1 Introduction**

There is evidence that high input cropping systems contribute to soil acidification in the higher rainfall cropping areas (>500 mm) of Australia (Helyar *et al.* 1997). Here it has been shown that soil acidification is occurring in the medium-rainfall cropping region (400-500mm) of South Australia (chapter 6 and Xu *et al.* 2002). The processes involved in soil acidification and an approach for measuring acidification have been described by Helyar and Porter (1989), and this has been the basis of many acidification studies in Australia. Similarly, this theoretical approach to measure the overall soil acidification and to explain the processes behind soil acidification has been used here with the long-term Tarlee data. As described in the literature review, given the complex conditions of a soil-plant-environment, there are many things that can influence the estimation of acidification rates (Ridley 1995; Verburg *et al.* 1998). Only a few studies (eg. Poss *et al.* 1995) have attempted to determine rates of acidification by measuring direct values for separate depths, and thereby understand processes behind the causes of acidification.

The data presented in chapter 6 show the long-term influences of various management practices on soil properties. For Tarlee, there were no large differences between management practices until 1992, but after that, stubble retention with 80 kg/ha N fertiliser has caused a higher acidification than removed practices with nil N-fertiliser. However, although the overall acidification rate for each management practice was measured, the so-called “unaccounted forms” for the soil acidification (see Table 6.10) and processes behind acidifying practices remained unexplained. These unaccounted-forms could be related to nitrate leaching and unaccounted C-cycle acids. To date, there has been no attempt to explain or simulate the nutrient processes behind soil acidification for a South Australian environment.

Most studies in Australia (eg. Bolan *et al.* 1991; Helyar and Porter 1989; Williams 1980) conclude that the main cause for accelerated acidification is associated with N inputs into cropping systems in excess of the needs of the crop. Water and nitrogen are frequently the major limitations to crop production, and these variable inputs can be subject to management practices (Probert *et al.* 1998b). The performance of APSIM (introduced in sections 2.3.5 and 3.8 of this thesis) in describing crop production comes from its ability to predict changes in soil water and nitrogen with sufficient accuracy, since these are the two factors to which the crop readily responds (Probert *et al.* 1998a). Because APSIM was planned as a model that could be applied to complex farming systems, studies that compare model predictions with farming system performance over long-term cropping sequences are particularly important (e.g. Turpin *et al.* 1996; Probert *et al.* 1995, Jones *et al.* 1996, Probert *et al.* 1998a, Paydar *et al.* 1999, Probert and McCown 2000). Indeed the most useful model evaluation reports are those that have examined “predicted” and “observed” values of a range of plant and soil variables over an extended period (Dalal *et al.* 1995; Probert and McCown 2000).

This chapter reports the modelling of the experimental observations from the Tarlee long-term trial (1978-1996). To discriminate between soil-horizons and to determine some processes behind soil acidification, the Tarlee data will be used against the APSIM model to monitor fluxes both at the surface and by depth, and compare these outcomes (predicted) with real data (observed) from the field studies (eg. chapter 6). In this study, three modules to determine the dynamics of water, carbon and nitrogen in the soil system (SOILWAT, SOILN and RESIDUE) have been used. By testing APSIM against the Tarlee data, it may be possible to determine the accuracy of these simulated data in explaining the processes behind soil acidification and, importantly, it may be possible to predict future changes in soil pH with various farming systems.

## **8.2 Materials and methods**

### **8.2.1 The experiment**

The background for the Tarlee experiment has been described in chapter 6; the treatments used in the modelling study described here are 2 two-year rotations (wheat-wheat and wheat-bean); two stubble treatments (removed and retained); and 2 rates of nitrogen (0 or 80 kg /ha N as ammonium nitrate). The data have been used to test the performance of the APSIM model in predicting changes in soil water, C and N properties. Some soil properties at the start of the trial are given in Table 3.3. The observed data are from replicated experiments and are used for comparison with simulated values for the same treatments by APSIM.

### **8.2.2 The models**

For the simulations, APSIM was configured with the soil SOILWAT (Probert *et al.* 1998b), a wheat crop module (Meinke *et al.* 1998; Keating *et al.* 2001), a surface residue module (Probert *et al.* 1998b), and a soil nitrogen module (Probert *et al.* 1998b). This combination was parameterised with data obtained from the Tarlee site and treatments as given above.

In this thesis the soil and water information including pH, volumetric water content at Crop Lower Limit (LL15 or CLL), volumetric water content at Drained Upper Limit (DUL), OM and bulk density were used from the Tarlee site to characterize the soil profile (Table 8.1) for running the APSIM program (Stuart Brown pers comm. 2001). The long-term weather data (1950-2000) from the Tarlee weather station (5 km from experimental site) has been used to specify this information into APSIM. The specific agronomic information regarding varieties, seeding rates, sowing time, sowing depth, tillage system, fertiliser rates, stubble practices, water and residue has been up-dated into each specified module. Simulation of the experiment was carried out by running the model from 1978 to the end of the 1996 season. Comparing the observed and predicted water and N data for each set of management practices tested the performance of the model. Here the coefficient of determination ( $R^2$ ) was chosen as a measure of the association between observed and predicted values. However a diagram for observed

versus predicted values will be presented with specific management practices in some cases.

In Table 8.1, soil bulk density (BD) is dry soil weight (g) divided by the total volume of soil (cc). The DUL is gravimetric water percentage multiplied by BD (g/cc). Gravimetric water percentage is equal to ((wet weight of soil sample – dry weight of soil sample)/ dry weight of soil sample – container tare) × 100. Crop lower limit (LL15) is gravimetric water percentage (when crop is mature and stressed) × BD (g/cc). Saturation (SAT) can be estimated as SAT (% volumetric) = (PO – e) × 100. Where e = 0.03 for heavy soils and up to 0.07 for sandy soils. PO (total porosity) = (1-BD/2.65) × 100, where BD/2.65 is the fraction of the soil volume occupied by solid (sand, silt and clay) particles, based on an assumed density of 2.65 g/cc for the solid matter in the soil. A density figure of 2.65 g/cc holds for a wide range of soils, the exceptions being the organic soils (lower) and oxisols (higher); PO in this case is a decimal fraction, not %. SWcon is the drainable fraction of soil water (SW), when SW is between DUL and saturation condition, but if SW>SAT then a cascade of water to the next layer will automatically happen.

**Table 8.1 Hydraulic parameters used in this experiment in soil water module.**

Depth (cm)	Depth layer (mm)	LL15 (mm/mm)	DUL (mm/mm)	SAT (mm/mm)	BD (g/cc)	SWcon
0-10	100	0.129	0.220	0.370	1.600	0.300
10-25	150	0.460	0.460	0.460	1.340	0.300
25-40	150	0.380	0.380	0.460	1.350	0.300
40-55	150	0.380	0.380	0.425	1.440	0.300

### **8.2.3 Modeling the experiment**

There are some aspects of the data-set that may cause problems for modelling with APSIM. During the experiment, several varieties of wheat and faba beans have been grown. However one variety for each species has been grown in each year. This may create difficulties with planting date  $\times$  phenology responses for different varieties. Other factors, notably weeds and crop diseases even though carefully controlled, may have influenced crop growth and yield in some seasons, but such effects are not included in the models. Four soil profiles down to 55 cm depth are used for this study, these were separated into the 0-10, 10-15, 15-30 and 30-55 cm depths. The lack of data down to 150 cm depth, and because there were few roots below 55 cm, and also the water content below this depth remained almost unchanged with time (Jeff Schultz pers. comm. 1999), is the basis for not accounting for root extraction below 55 cm in the water balance. Thus in running APSIM the depth down to 55 cm only has been simulated. The effect of this assumption will be discussed later.

An important advantage of the Tarlee-trial data compared to other long-term studies, is the presence of information for soil organic C and total N at the commencement of the experiment; these values are normally estimated in other such studies. These are vital data for evaluating model predictions of changing soil fertility through time. So the APSIM program was specified to simulate the various management practices as continuous runs (1978-1996), with soil conditions (soil-water, organic C, nitrate-N, hydraulic parameters) initialised only at the start of the experiment before the 1978 crop. The actual planting dates were used, but the model harvested the crop the day after it was deemed to be mature. There was no attempt to tune the model with the real day of harvest. Data used for initialization or observed data for comparison with simulations are treatment means. Generally there was no difficulty in specifying APSIM to mimic the actual management practices.

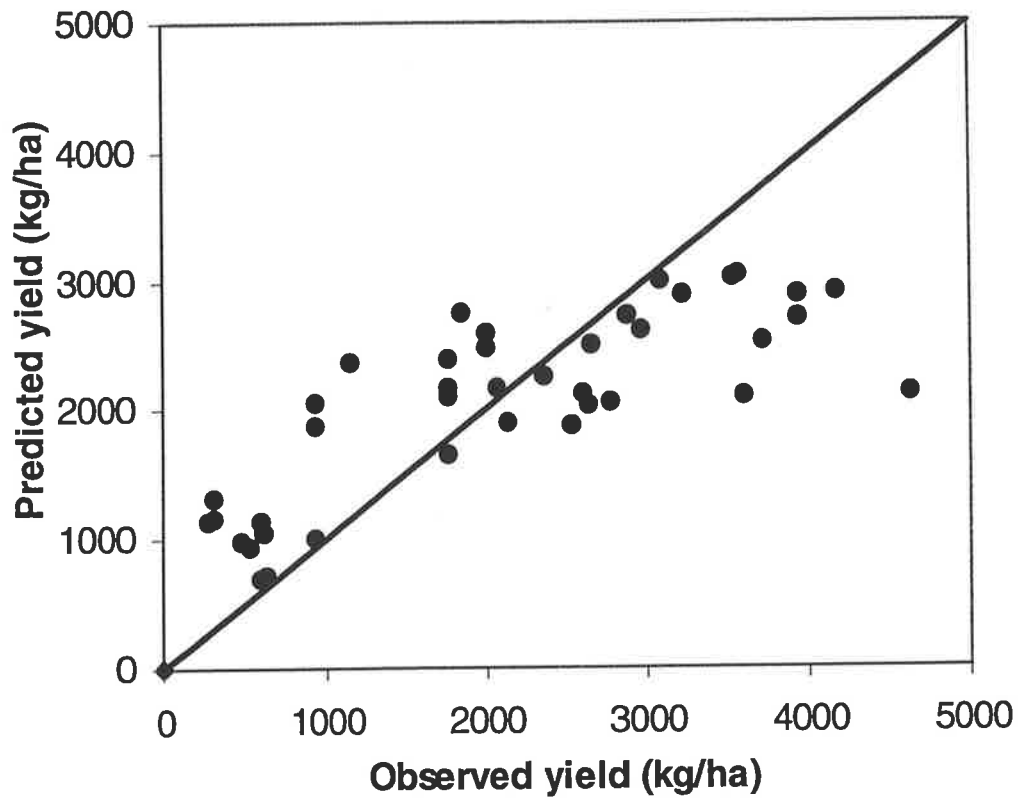
## **8.3 Results**

### **8.3.1 Grain yield**

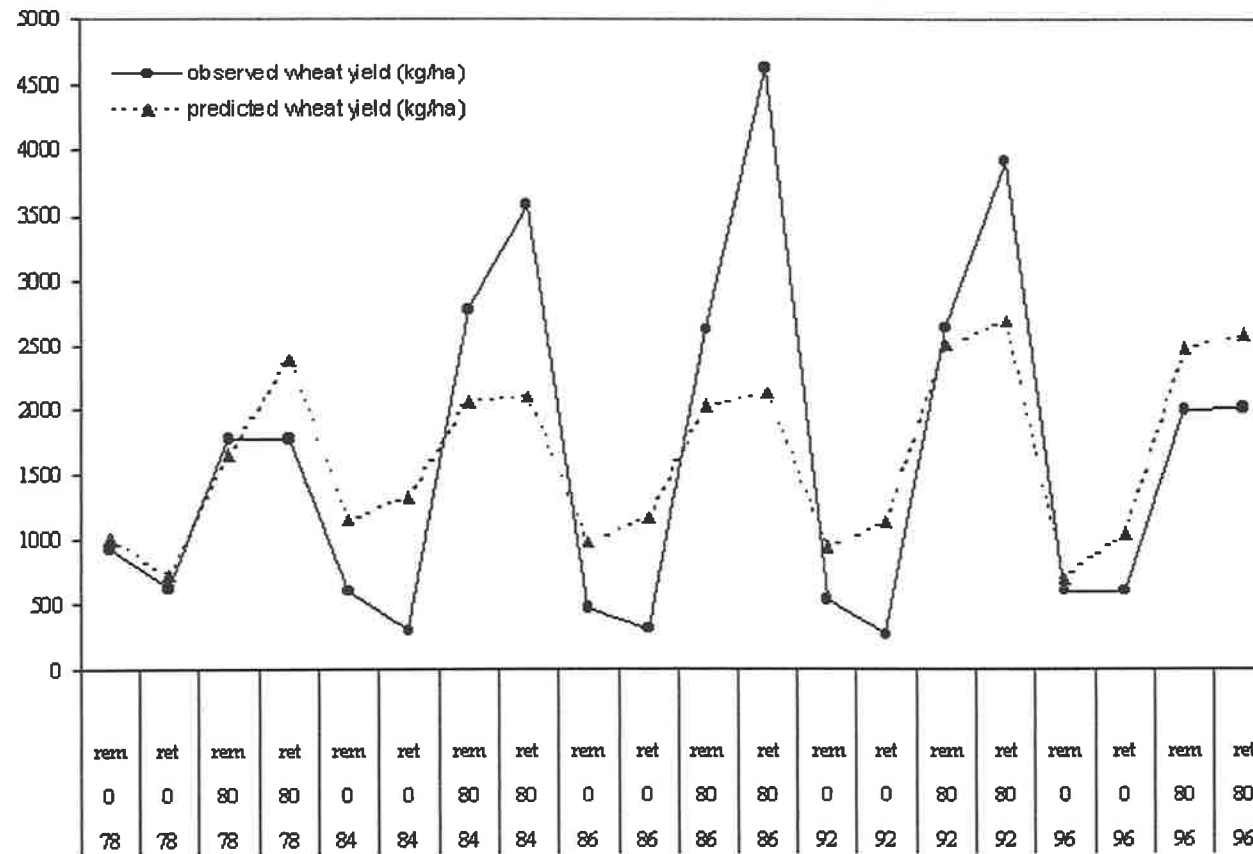
Effects of different management practices on grain yield as observed and predicted by the model between 1978-1996 at Tarlee are given in Table 8.2. A comparison of the predicted and observed grain yields across all management practices is shown in Figure 8.1. Figure 8.1 shows that the model has predicted grain yields values well ( $R^2=0.63$ ). However, this figure suggests that APSIM shows signs of insensitivity, in that it tends to under-predict high yields. Therefore the effect of all management practices for predicted and observed data has been compared separately for W-B rotation (Figure 8.2) and W-W rotation (Figure 8.3) to explain these situations. The goodness of fit between observed and predicted yields was similar for both rotations, but for the overall management practices, the range seems to be smaller in case of predicted values compared to observed yield data from the field experiment. This shortcoming especially is more noticeable where there were retained practices with 80 kg/ha N-fertiliser. There is no obvious reason why the APSIM model should not be able to mimic these changes, yet yields in 1986 for the W-B rotation diverged greatly from the experimental observations. So looking into other effects of these management practices on the soil and water balance may reveal some background to this behaviour.

**Table 8.2 Wheat grain yield (kg/ha) from observed field values and predicted by APSIM between 1978-1996, Tarlee site, for all management practices.**

Date	Rotation	N rate	Stubble	Observed wheat yield (kg/ha)	Predicted wheat yield (kg/ha)
1978	W-B	0	Remove	929	2050
1978	W-B	0	Retain	929	1868
1978	W-B	80	Remove	1775	2091
1978	W-B	80	Retain	1775	2157
1978	W-W	0	Remove	929	1009
1978	W-W	0	Retain	632	724
1978	W-W	80	Remove	1775	1650
1978	W-W	80	Retain	1775	2388
1984	W-B	0	Remove	1853	2743
1984	W-B	0	Retain	3085	2985
1984	W-B	80	Remove	3514	3010
1984	W-B	80	Retain	3561	3046
1984	W-W	0	Remove	598	1148
1984	W-W	0	Retain	298	1325
1984	W-W	80	Remove	3586	2095
1984	W-W	80	Retain	2777	2054
1986	W-B	0	Remove	1155	2374
1986	W-B	0	Retain	2878	2727
1986	W-B	80	Remove	2952	2604
1986	W-B	80	Retain	4166	2895
1986	W-W	0	Remove	477	984
1986	W-W	0	Retain	311	1156
1986	W-W	80	Remove	4634	2124
1986	W-W	80	Retain	2632	2034
1992	W-B	0	Remove	2357	2260
1992	W-B	0	Retain	3713	2515
1992	W-B	80	Remove	3216	2890
1992	W-B	80	Retain	3926	2870
1992	W-W	0	Remove	530	940
1992	W-W	0	Retain	272	1135
1992	W-W	80	Remove	3929	2690
1992	W-W	80	Retain	2647	2510
1996	W-B	0	Remove	2533	1870
1996	W-B	0	Retain	2600	2125
1996	W-B	80	Remove	2139	1905
1996	W-B	80	Retain	2076	2170
1996	W-W	0	Remove	604	690
1996	W-W	0	Retain	604	1055
1996	W-W	80	Remove	2010	2585
1996	W-W	80	Retain	2006	2480



**Figure 8.1 Plot of observed value from field experiment versus simulated grain yields using APSIM for overall management practices at the Tarlee site.**



**Figure 8.2 Grain yields (kg/ha) for the effect of W-B rotation, two stubble managements, and two N-fertiliser rates between 1978-1996 simulated with APSIM, compared with observed data from experiment.**

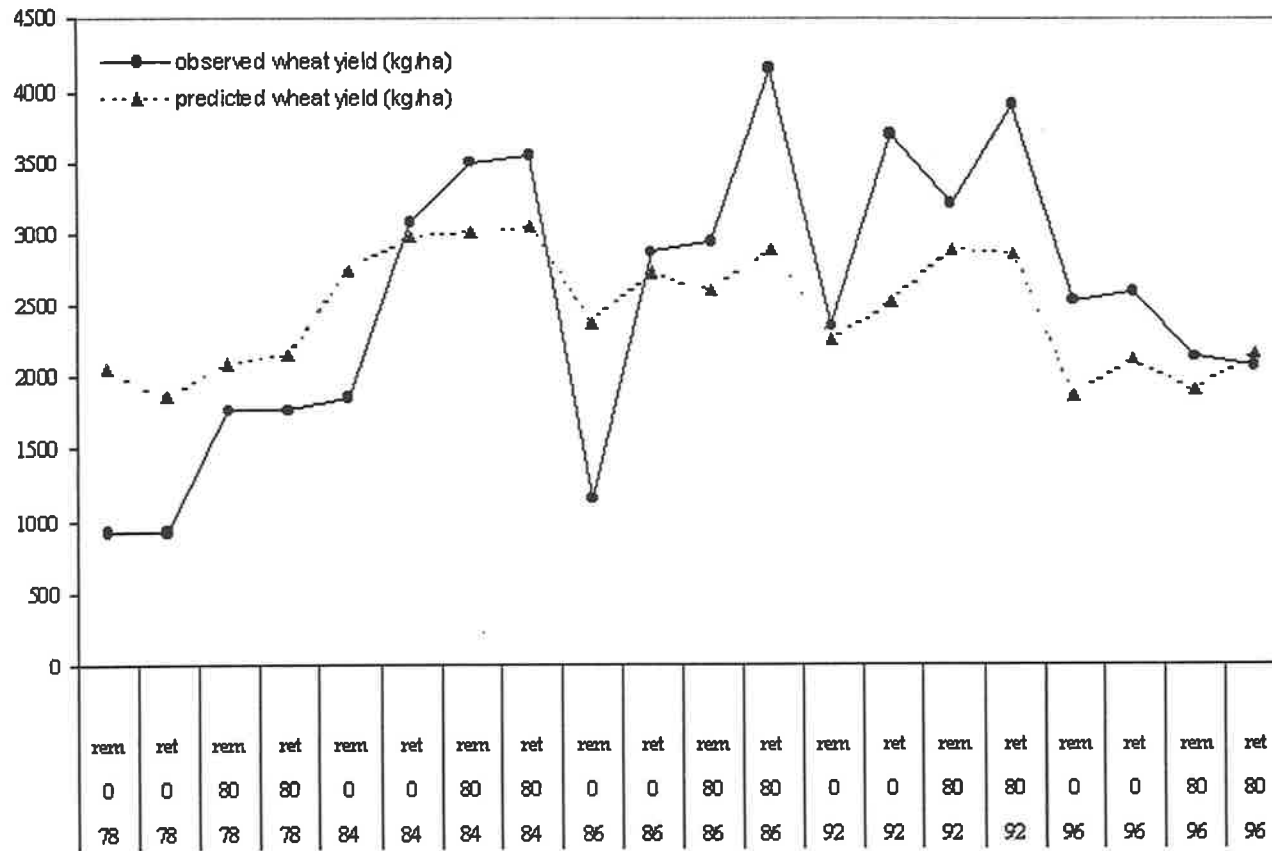


Figure 8.3 Grain yields (kg/ha) for the effect of W-W rotation, two stubble managements, and two N-fertiliser rates between 1978-1996 simulated with APSIM, compared with observed data from experiment.

### **8.3.2 Soil water**

The effects of different management practices on soil water (SW) as observed, and predicted by the model for 1992 at Tarlee is shown in Table 8.3. A comparison of the predicted and observed grain yields across all management practices for the total soil water (mm) stored in the soil profile is shown in Figure 8.4 (W-B) and Figure 8.5 (W-W). The APSIM predictions were in reasonable agreement with observed data ( $R^2=0.83$ ). These Figures are indicating that the SW was over-predicted by the model, but the predicted and observed are almost following the same trend as influenced by management practices.

The quantity of extractable soil water (esw) in the soil profile for 1992 is presented in Figure 8.6. There were generally differences in the amount of water between N-fertiliser treatments, stubble practices and rotations under different management practices in this season. At this time there was more water available under retained stubble management practices than removed practices in both predicted and observed values. It was anticipated that larger soil water storage would occur under stubble retained, because of lower evaporation from the surface soil layers and surface run off. Also the data show that the soil profile under nil N-fertiliser treatments had higher esw than with 80 kg/ha N-fertiliser; this condition may have been influenced by higher crop growth and water utilization under the N-fertiliser treatment.

### **8.3.3 Rainfall and drainage**

Both monthly and growing season (April-October) rainfall and drainage (1978-1996) are presented in Table 8.4. The long-term average annual rainfall (50 years) at the Tarlee site is 477 mm. The overall rainfall and drainage were higher in the 1992 and 1996 growing seasons compared to long-term average values. A calculated amount of monthly drainage (by the model) for all management practices is shown in Figure 8.7. The APSIM prediction suggests that drainage in this environment is variable between different years and months, but is constantly higher with higher rainfall. Over 100 mm drainage occurred only in September 1992. Soil water drainage in the 0-55 cm layer was greater in 1992, especially with the high amount of rainfall (above 100 mm) in August and September. The overall drainage was 237 for 1992 season with the above average rainfall of 796 mm

in 1992; this may suggest that this could result in  $\text{NO}_3^-$  leaching in some treatments in this season.

**Table 8.3 Soil water (SW) from observed field values and predicted by APSIM for all management practices, 1992 season at Tarlee site.**

Rotation	N rate	Stubble	Depth (cm)	SW predicted (mm)	SW observed (mm)
W-B	0	Rem	0-10	33.45	15.01
W-B	0	Rem	10-25	53.73	40.30
W-B	0	Rem	25-40	54.21	49.02
W-B	0	Rem	40-55	54.64	51.75
W-B	0	Ret	0-10	33.95	10.65
W-B	0	Ret	10-25	54.46	46.50
W-B	0	Ret	25-40	54.89	46.68
W-B	0	Ret	40-55	55.33	45.47
W-B	80	Rem	0-10	27.77	4.42
W-B	80	Rem	10-25	49.76	26.67
W-B	80	Rem	25-40	50.01	29.86
W-B	80	Rem	40-55	50.32	27.68
W-B	80	Ret	0-10	33.36	9.85
W-B	80	Ret	10-25	53.56	43.24
W-B	80	Ret	25-40	54.00	41.73
W-B	80	Ret	40-55	54.45	38.87
W-W	0	Rem	0-10	35.83	6.83
W-W	0	Rem	10-25	55.66	27.07
W-W	0	Rem	25-40	56.15	36.80
W-W	0	Rem	40-55	56.59	47.97
W-W	0	Ret	0-10	36.10	7.17
W-W	0	Ret	10-25	56.36	43.74
W-W	0	Ret	25-40	56.82	44.13
W-W	0	Ret	40-55	57.26	55.33
W-W	80	Rem	0-10	27.15	5.17
W-W	80	Rem	10-25	49.42	30.68
W-W	80	Rem	25-40	48.35	24.38
W-W	80	Rem	40-55	48.19	17.30
W-W	80	Ret	0-10	32.67	6.46
W-W	80	Ret	10-25	52.62	42.61
W-W	80	Ret	25-40	53.20	41.21
W-W	80	Ret	40-55	53.63	28.32

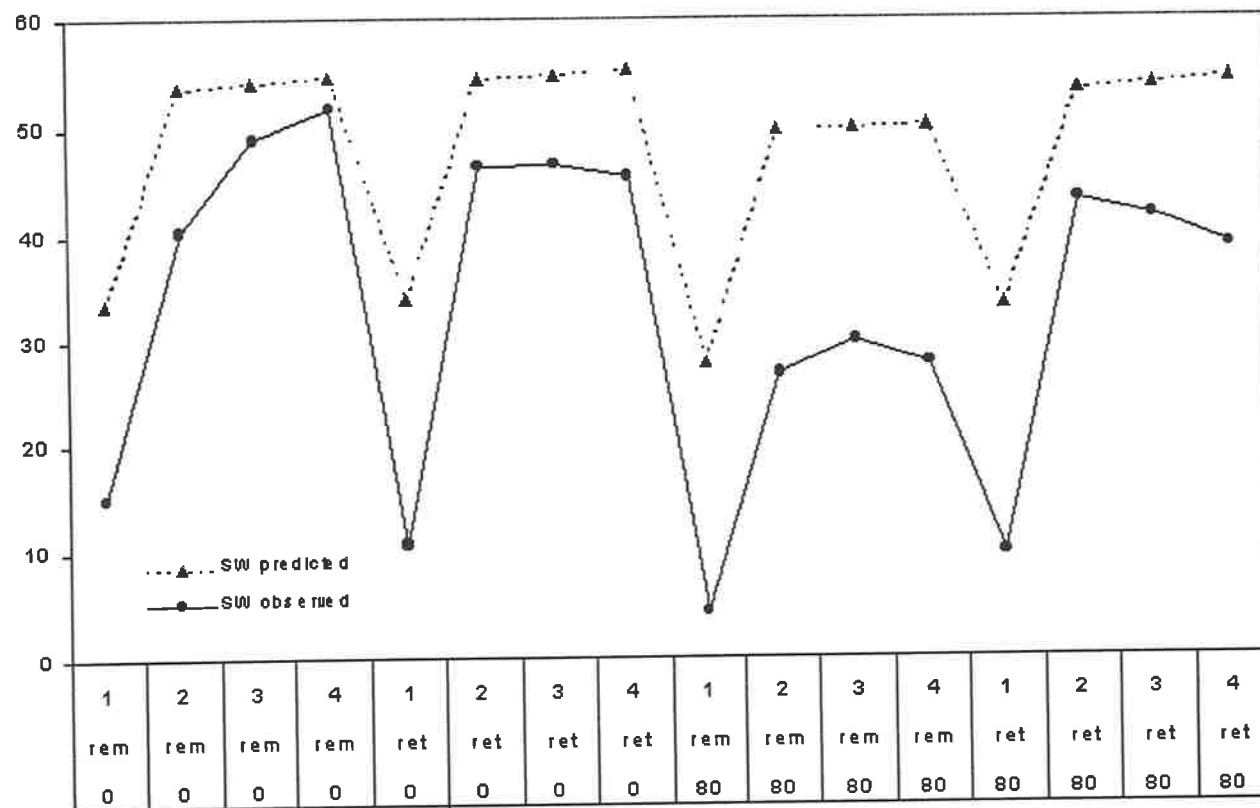
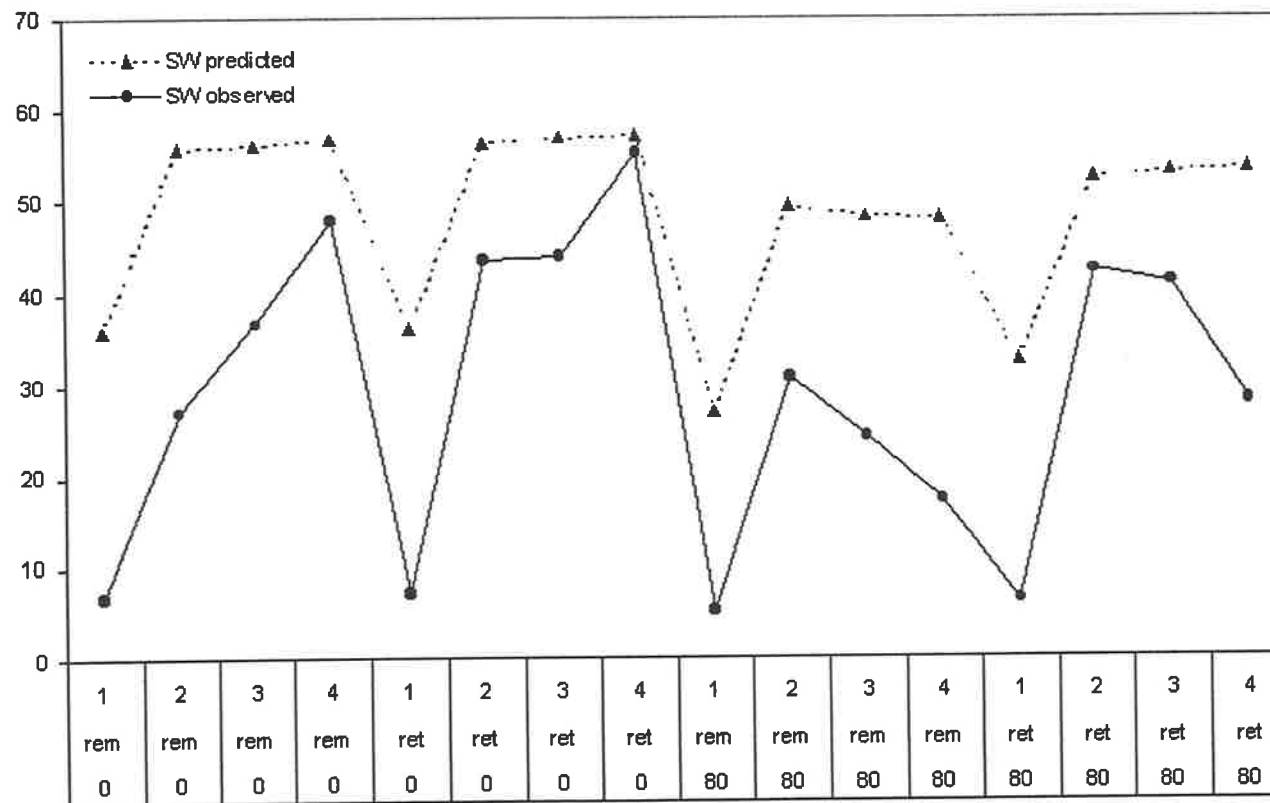
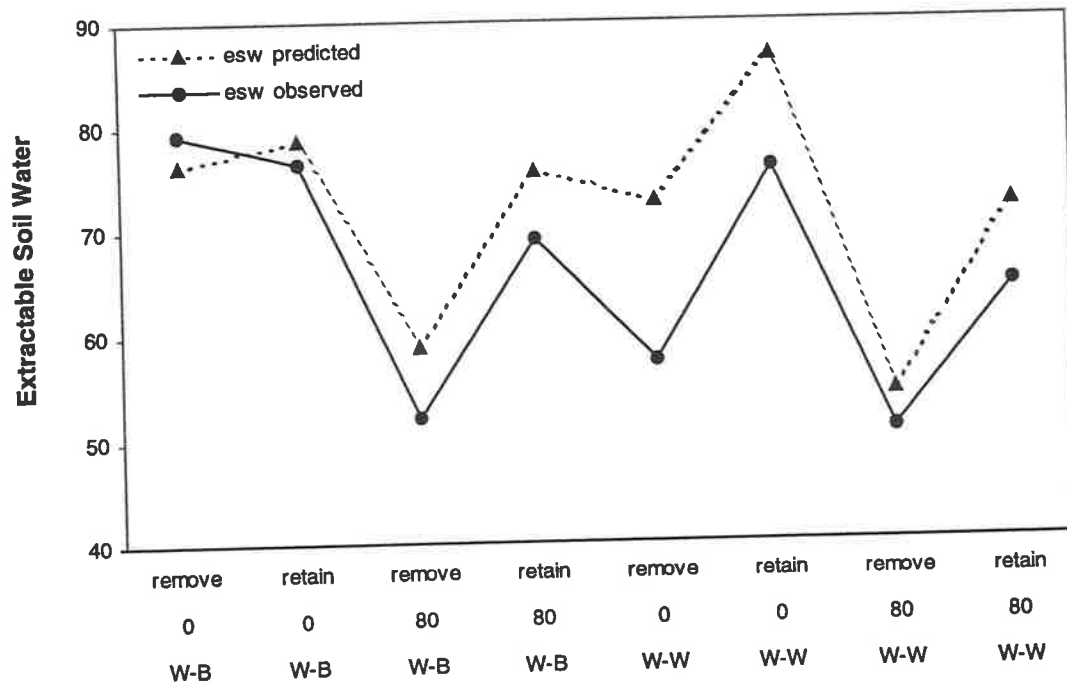


Figure 8.4 Soil water (mm) for the effect of W-B rotation, two stubble managements, and two N-fertiliser rates in 1992 season simulated with APSIM, compared with observed experiment data.

1,2,3 and 4 are the 0-10, 10-25, 25-40 and 40-55 cm depths respectively.



**Figure 8.5 Soil water (mm) for the effect of W-W rotation, two stubble managements, and two N-fertiliser rates in 1992 season simulated with APSIM, compared with observed experiment data. 1,2,3 and 4 are the 0-10, 10-25, 25-40 and 40-55 cm depths respectively.**



**Figure 8.6** Extractable soil water (mm) for the overall effect of rotations, stubble managements, and N-fertiliser rates in 1992 season simulated with APSIM, compared with observed experiment data.

#### 8.3.4 Soil organic related components

Predicted and observed data for  $\text{NO}_3^-$ -N in different soil profile are shown in Table 8.5. Figure 8.8 and 8.9 show the effect of management practices on total  $\text{NO}_3^-$  reserve. Overall, the 'goodness' of data-fit for APSIM predicted and observed nitrate-N data was very good ( $R^2=0.54$ ). APSIM generally predicted the nitrate accurately in all treatments but over-predicted and under-predicted nitrate at W-W and W-B, especially where stubble was retained with 80kg/ha N-fertiliser treatments. Figure 8.8 and 8.10 indicate that the total  $\text{NO}_3^-$  for the W-W rotation has increased to 75 kg/ha compared to 130 kg/ha shown in predicted values in APSIM in retained stubble with 80 kg/ha treatments during March to August. This value is lower for the same management practices in the W-B rotation but both values (observed and predicted) are very close to each other (Figure 8.9 and 8.11). Also the monthly total values of  $\text{NO}_3^-$  for W-W for removed and retained practices are very low (0-20 kg/ha) (Figure 8.10). These mostly were increased to maximum values during March and April after the addition of the N-fertiliser, and thereafter decrease toward the end of the season. These values increase to the highest observed values of 160 kg/ha of  $\text{NO}_3^-$  in 1986 with 80 kg/ha N-fertiliser, compared to 230 kg/ha with N-fertiliser and stubble retained practices in 1992 season (Figure 8.10).

However for the W-B rotation, these values increased to maxima of 160 and 190 kg/ha  $\text{NO}_3^-$  at stubble-retained and removed practices both in 1986 season (Figure 8.11). In contrast to W-W, in the W-B rotation the total  $\text{NO}_3^-$  value increased to a maximum of 60 kg/ha  $\text{NO}_3^-$  only with inclusion of legumes in the cropping system without N-fertiliser (Figure 8.11). This has been confirmed where the absence of this influence (inclusion of legumes) is apparent in Figure 8.12 compared to Figure 8.13. However the influence of 80 kg/ha N-fertiliser with legume caused more leaching than where no fertiliser was used (plus the legume). This was evident where more  $\text{NO}_3^-$  is being leached to lower depths with N-fertiliser (Figure 8.12 and 8.13). The amount of  $\text{NO}_3^-$  leached to the subsoil (to lower than 30 cm depth) was increased to a maximum value of 40 and 55 kg/ha  $\text{NO}_3^-$  for retained and removed practices respectively for W-W rotation with 80 kg/ha N-fertiliser. The amount of leached  $\text{NO}_3^-$  to the deeper soil profile (lower than 30 cm depth) was

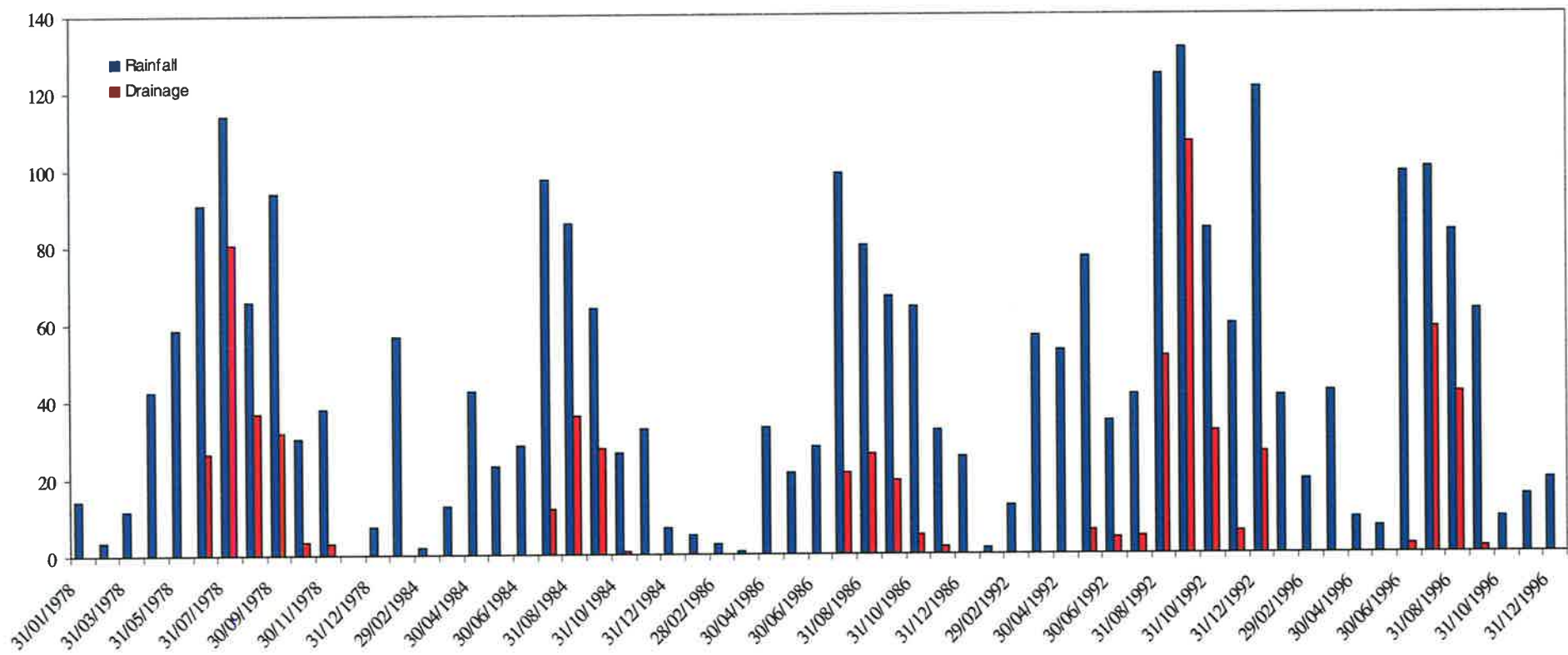
increased to maxima of 50 and 30 kg/ha for removed and retained practices respectively in W-B rotations and 80 kg/ha N-fertiliser.

Features of each prediction by APSIM for nitrate are the decline in pre-planting nitrate through time, especially for stubble-removed practices with nil N-fertiliser rates, which is consistent with the observed data (Figure 8.10 and 8.11). For nil N-fertiliser rates each year the crop removed most of the nitrate from the soil. Both the predicted and observed decrease in nitrate in the profile during the 1992 season is consistent with leaching, that is accelerated, and most likely caused higher acidification rate in this season. However to understand each specific effect of management practices on nitrate in the soil profile the depth profile data are given (Figure 8.12 and 8.13). Both figures show that nitrate is being leached to lower depth.

The presence of  $\text{NO}_3^-$  in soil depth was similar at the start of the experiment for different depths but towards 1992 and 1996 the values for  $\text{NO}_3^-$  at depth show that  $\text{NO}_3^-$  has accumulated, and this value remain high at the end of season especially for stubble retained and 80 kg/ha N-fertiliser practices, with values around 30 and 60 kg/ha  $\text{NO}_3^-$  for W-B and W-W rotations respectively (Figure 8.12 and 8.13). The increase in  $\text{NO}_3^-$  values in the 25-55 cm layer was accompanied by a decrease of  $\text{NO}_3^-$  in the surface 0-25 cm and this decrease from surface and increase in depth values may be contributing to the increase in the leaching of  $\text{NO}_3^-$  from the surface to depth in August and September. This is consistent with these treatments having the highest drainage, especially for the 1992 season. Some of the  $\text{NO}_3^-$  leached into the lower depth may have been assimilated by crop roots, but with the accelerated leaching processes of the unused  $\text{NO}_3^-$  (July-September) this will result in  $\text{NO}_3^-$  leaching to lower depths. The low concentration of  $\text{NO}_3^-$  in the soil depth after September indicates that some  $\text{NO}_3^-$  may be consumed by the crop or some leached to lower soil profile (deeper than 55cm).

**Table 8.4 Monthly rainfall and drainage at the Tarlee site between 1978-1996.**

1978													
Date	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Rainfall (mm)	14	3.6	11.3	42	58.4	90.8	114.2	65.8	93.8	30	37.8	7.4	569
Drainage (mm/mm)	0	0	0	0	0	26.4	80.6	36.8	31.8	3.4	3.1	0	182
1984													
Date	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Rainfall (mm)	57	2	12.6	42	23	28.4	97.3	86	63.8	26.4	32.4	7	478
Drainage (mm/mm)	0	0	0	0	0	0	11.6	35.9	27.4	0.6	0	0	76
1986													
Date	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Rainfall (mm)	4.8	2.6	0.9	33	20.8	28	98.7	80	66.6	64.2	32.2	25	457
Drainage (mm/mm)	0	0	0	0	0	0	20.8	25.8	19.1	4.9	2.0	0	73
1992													
Date	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Rainfall (mm)	1.6	12	56.4	53	77.2	34.4	41.2	124.2	131.2	84.2	59.4	121	796
Drainage (mm/mm)	0	0	0	0	6.0	4.4	4.6	51.2	106.9	31.6	5.6	26.4	237
1996													
Date	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Rainfall (mm)	41	19	41.8	9	7	98.8	99.8	83.6	63	9.2	15	19	506
Drainage (mm/mm)	0	0	0	0	0	2.4	58.5	41.5	1.5	0	0	0	104



**Figure 8.7 Monthly rainfall and drainage (both in mm) for 1978, 1984, 1986, 1992 and 1996 seasons at Tarlee site.**

In the 0-55 cm soil layer, mineralization of organic matter in surface soil would increase the soil  $\text{NO}_3^-$  in the autumn before sowing. The soil  $\text{NO}_3^-$  content decreased during the first part of the cropping season, and reached its lowest value at stem elongation, thus may presumably relate to crop uptake or possibly due to immobilisation or denitrification reactions. It is evident from Figure 8.14 that denitrification is higher for both stubble-retained practices with 80-kg/ha N fertiliser compared to other practices for both W-W and W-B rotations. Nitrogen mineralisation however was more influenced by 80 kg/ha N-fertiliser in the W-W rotation and less to the stubble practices but for W-B rotation influenced with both 80 kg/ha and retained stubble practices (Figure 8.15). Mineralisation of OM increased soil  $\text{NO}_3^-$  to 250 and 450 kg/ha for W-B and W-W respectively (Figure 8.15). Figure 8.16 shows that  $\text{NH}_4$  values were higher only for the plots that received 80 kg/ha N-fertiliser compared to nil N-fertiliser and stubble retention practices. These values are all increasing toward the 1996 season, and start from maxima of 100 kg/ha  $\text{NH}_4$ -total for W-B and W-W rotations in 1978 to as high as 450 kg/ha at 1996. W-B rotations without N-fertiliser are showing significantly higher values (150 kg/ha  $\text{NH}_4$ ) compared to W-W rotations (50 kg/ha  $\text{NH}_4$ ) without N-fertiliser application, and this was not influenced with stubble practices. Overall ammonium values remained low at all layers toward the end of season in each year and only remained high for treatments that received N-fertiliser application (8.16).

The amount of total biomass C in unfertilised plots in W-W rotation indicate that the biomass C was approximately 500 and 1000 kg/ha for removed and retained stubble practices respectively (Figure 8.17). For fertilised plots these values reached to a maximum of 2500 and 5000 kg/ha for removed and retained stubble practices respectively in 1990. This suggests that in the W-W rotation, only fertilised plots showed higher biomass C production. In contrast in W-B rotations, the amounts of biomass C were higher in retained practices even without N-fertiliser application. So the highest biomass in W-B rotation was achieved in stubble retention with 80 kg/ha N-fertiliser (maximum of 4200 kg/ha) and followed closely by retained practices with nil-fertiliser (maximum of 3500 kg/ha). However in both rotations (W-W and W-B), the biomass C starts to decrease toward the 1996 season. Thus the result may suggest that the export of the stubble, as part C-cycle (stubble and grain removal) under W-B rotation, has more potential to produce acidification in plots that removed their stubbles.

**Table 8.5 The soil NO<sub>3</sub>-N (ppm) for each depth and year measured as total observed field values and predicted by APSIM between 1978-1992 in Tarlee site for all management practices.**

Date	Rot	N	Stubble	Predicted				Observed			
				NO <sub>3</sub> -N (0-10)	NO <sub>3</sub> -N (10-30)	NO <sub>3</sub> -N (30-60)	Total predicted	NO <sub>3</sub> -N (0-10)	NO <sub>3</sub> -N (10-30)	NO <sub>3</sub> -N (30-60)	Total observed
1978	W-B	0	Ret	7.27	2.61	3.33	13.20	8.60	16.80	7.25	32.65
1978	W-B	0	Rem	11.25	12.03	0.31	23.59	11.20	14.35	5.90	31.45
1978	W-B	80	Ret	62.44	18.81	1.72	82.97	8.60	16.80	7.25	32.65
1978	W-B	80	Rem	18.04	32.48	6.84	57.37	11.20	14.35	5.90	31.45
1984	W-B	0	Ret	21.85	22.39	1.74	45.99	26.55	6.85	3.10	36.50
1984	W-B	0	Rem	14.04	17.62	0.74	32.40	31.90	7.40	4.00	43.30
1984	W-B	80	Ret	28.01	28.85	3.92	60.79	28.00	5.00	3.25	36.25
1984	W-B	80	Rem	18.55	20.91	0.78	40.24	29.05	11.50	9.55	50.10
1986	W-B	0	Ret	19.63	18.69	0.39	38.71	11.70	6.95	10.05	28.70
1986	W-B	0	Rem	16.53	11.91	0.11	28.55	12.80	5.35	9.40	27.55
1986	W-B	80	Ret	39.80	32.47	0.55	72.83	27.60	15.25	18.95	61.80
1986	W-B	80	Rem	24.86	14.86	0.12	39.84	26.50	6.40	9.65	42.55
1992	W-B	0	Ret	22.26	29.57	3.49	55.32	47.00	11.00	11.50	69.50
1992	W-B	0	Rem	10.83	14.30	0.87	26.01	25.50	14.50	10.50	50.50
1992	W-B	80	Ret	40.01	45.51	2.04	87.56	54.00	19.00	21.00	94.00
1992	W-B	80	Rem	62.24	51.24	4.33	117.81	29.00	27.50	40.50	97.00
1978	W-W	0	Ret	7.27	2.61	3.33	13.20	7.30	11.60	4.10	23.00
1978	W-W	0	Rem	6.40	2.95	1.54	10.89	5.50	8.10	2.80	16.40
1978	W-W	80	Ret	7.46	13.58	13.32	34.36	7.30	11.60	4.10	23.00
1978	W-W	80	Rem	7.27	2.61	3.33	13.20	5.50	8.10	2.80	16.40
1984	W-W	0	Ret	1.72	2.52	0.24	4.48	10.60	4.60	1.80	17.00
1984	W-W	0	Rem	1.42	1.47	0.14	3.03	6.45	2.90	0.80	10.15
1984	W-W	80	Ret	16.41	20.62	13.15	50.18	20.55	8.90	15.30	44.75
1984	W-W	80	Rem	16.01	18.66	14.55	49.22	20.20	8.60	13.40	42.20
1986	W-W	0	Ret	1.72	2.21	0.08	4.02	8.70	2.20	3.10	14.00
1986	W-W	0	Rem	1.89	2.32	0.11	4.33	5.20	1.75	3.85	10.80
1986	W-W	80	Ret	20.64	8.49	14.06	43.19	25.30	7.95	11.25	44.50
1986	W-W	80	Rem	24.03	20.90	19.05	63.97	23.35	3.90	9.45	36.70
1992	W-W	0	Ret	1.38	2.07	0.22	3.68	11.50	4.50	1.00	17.00
1992	W-W	0	Rem	1.05	2.15	0.26	3.46	5.50	1.50	4.20	11.20
1992	W-W	80	Ret	20.90	34.98	5.67	61.55	20.00	15.50	19.50	55.00
1992	W-W	80	Rem	64.99	40.96	25.20	131.14	21.00	2.50	1.00	24.50

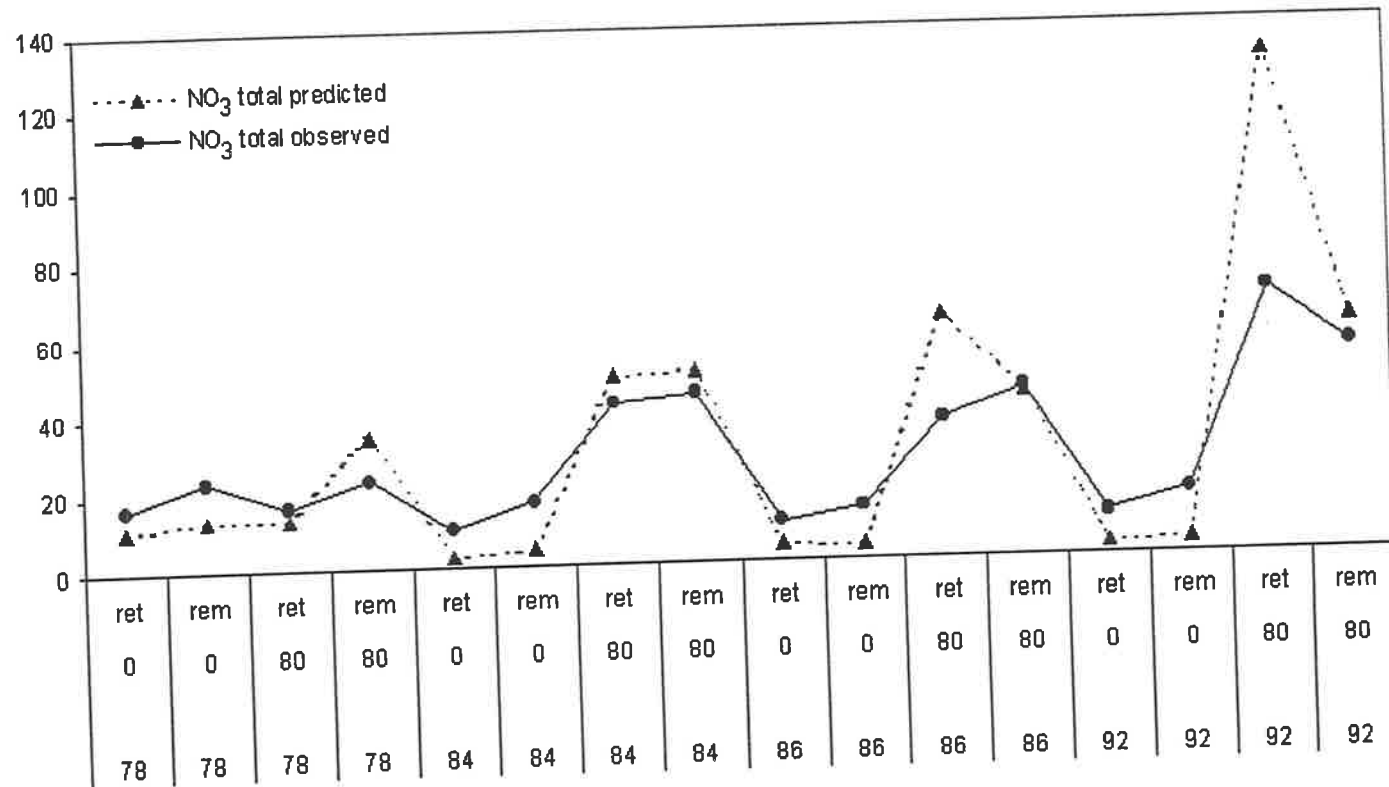


Figure 8.8 Total NO<sub>3</sub>-N (kg/ha) for all depths for the effect of W-W rotation, two stubble managements, and N-fertiliser rates in between 1978-1992 season simulated with APSIM, compared with observed data from experiment.

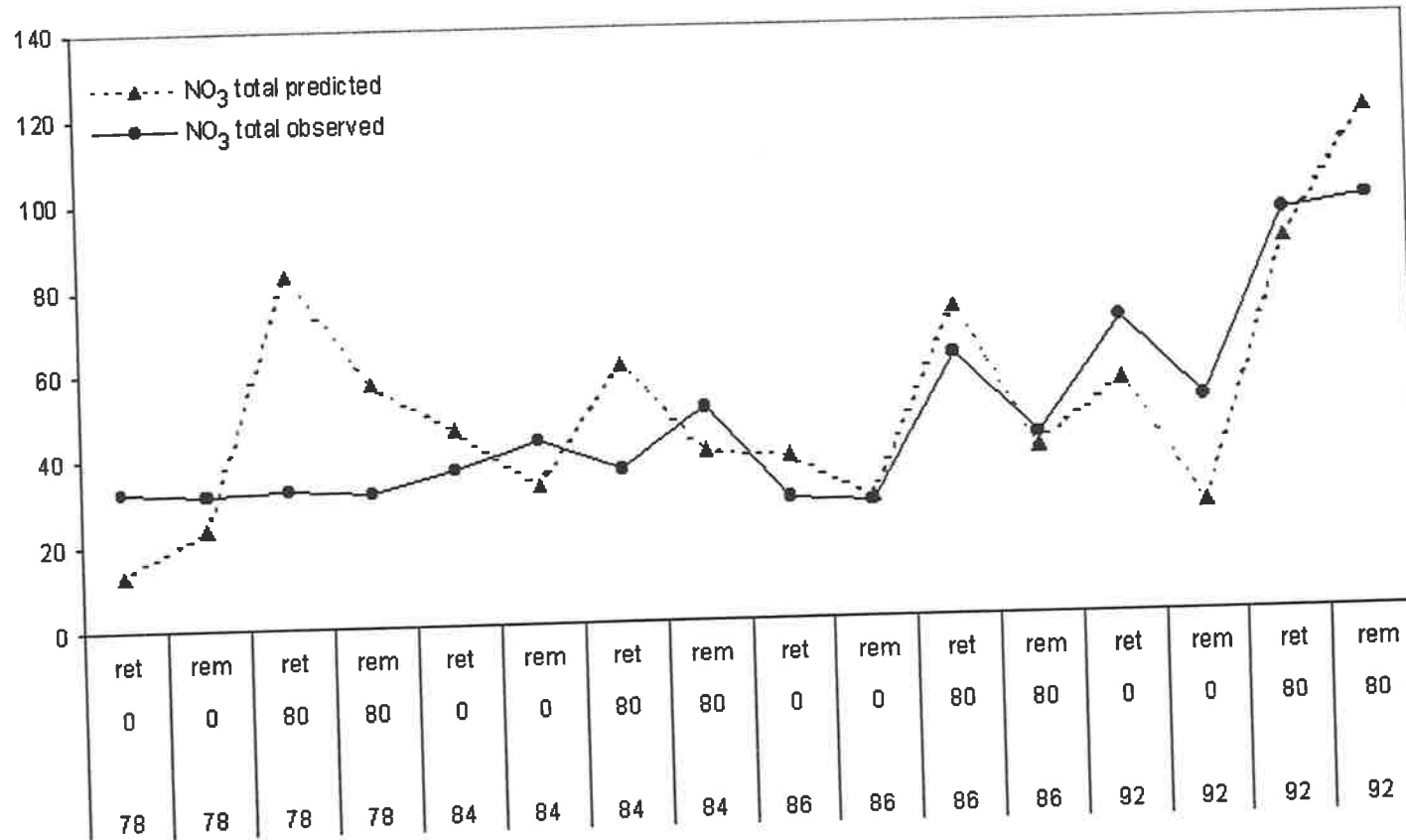


Figure 8.9 Total NO<sub>3</sub>-N (kg/ha) for all depths for the effect of W-B rotation, two stubble managements, and N-fertiliser rates in between 1978-1992 season simulated with APSIM, compared with observed data from experiment.

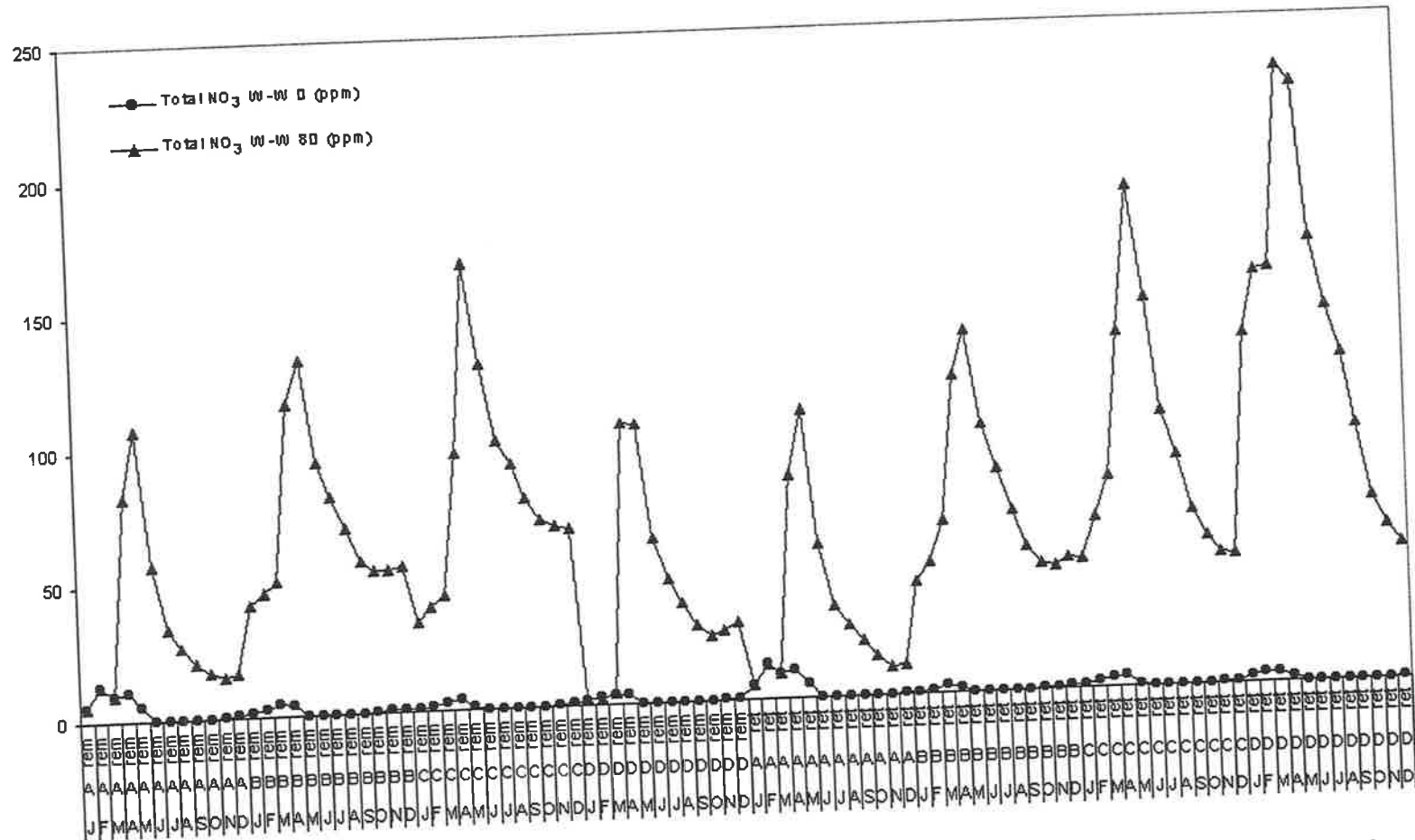


Figure 8.10 The monthly total NO<sub>3</sub>-N (kg/ha) for total soil layers and all management practices between 1978-1992 at Tarlee site predicted by APSIM. A, B, C and D are indicating year 1978, 1984, 1986 and 1992 respectively.

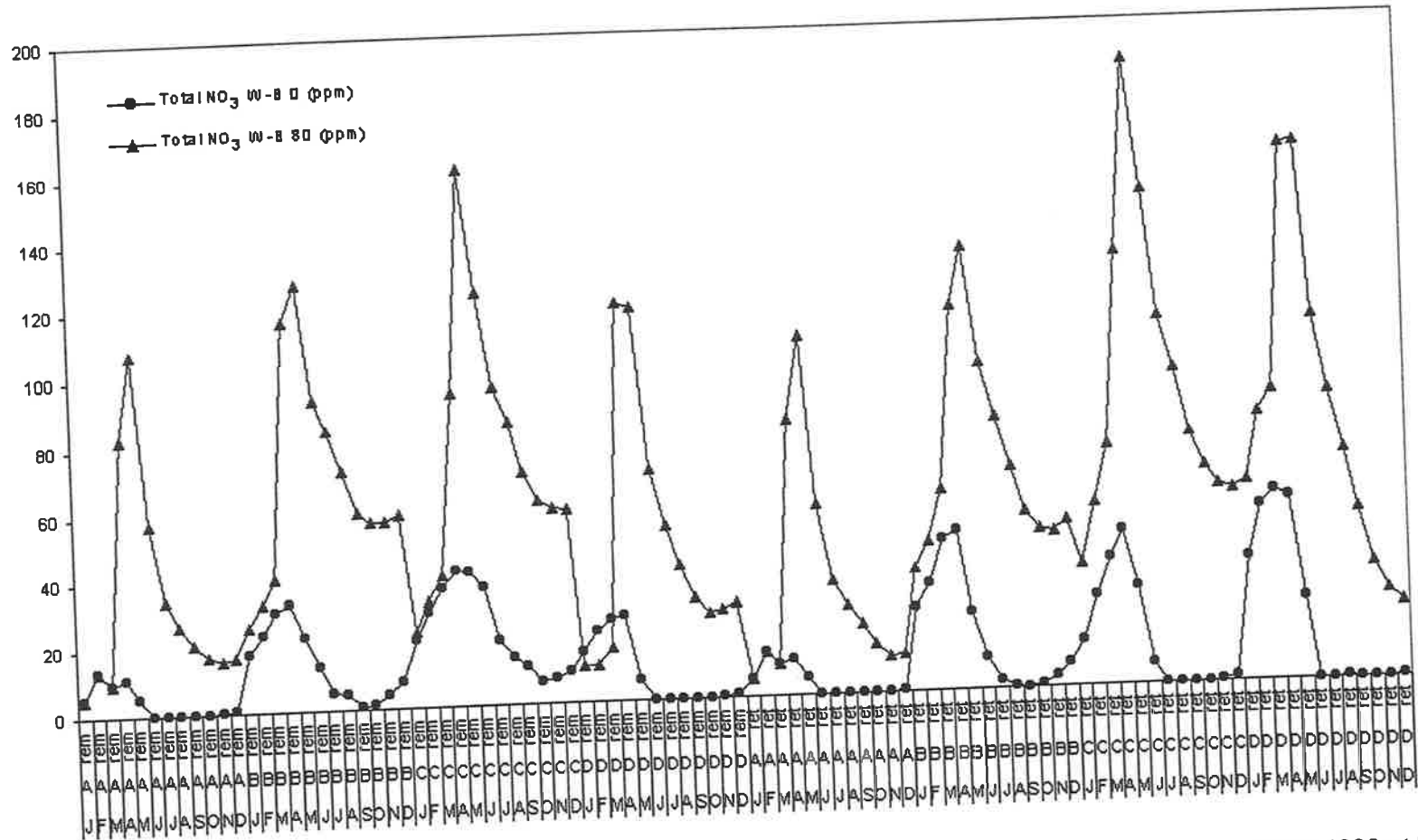


Figure 8.11 The monthly total  $\text{NO}_3\text{-N}$  (kg/ha) for total soil layers and all management practices between 1978-1992 at Tarlee site predicted by APSIM. A, B, C and D are indicating year 1978, 1984, 1986 and 1992 respectively.

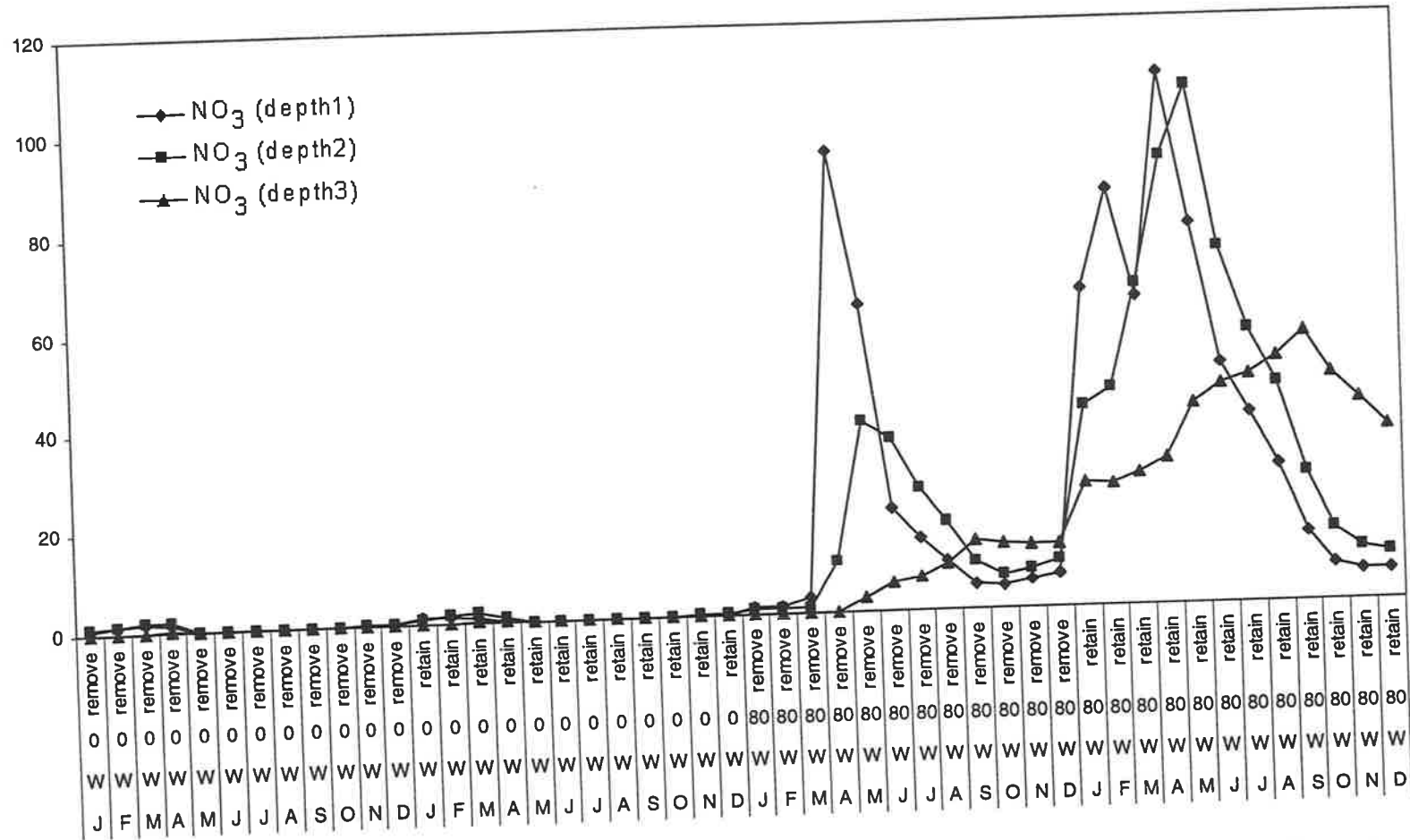


Figure 8.12 NO<sub>3</sub> (kg/ha) for 3 depths for the effect of W-W rotation with two stubble managements and two N-fertiliser rates for 1992 season simulated with APSIM.

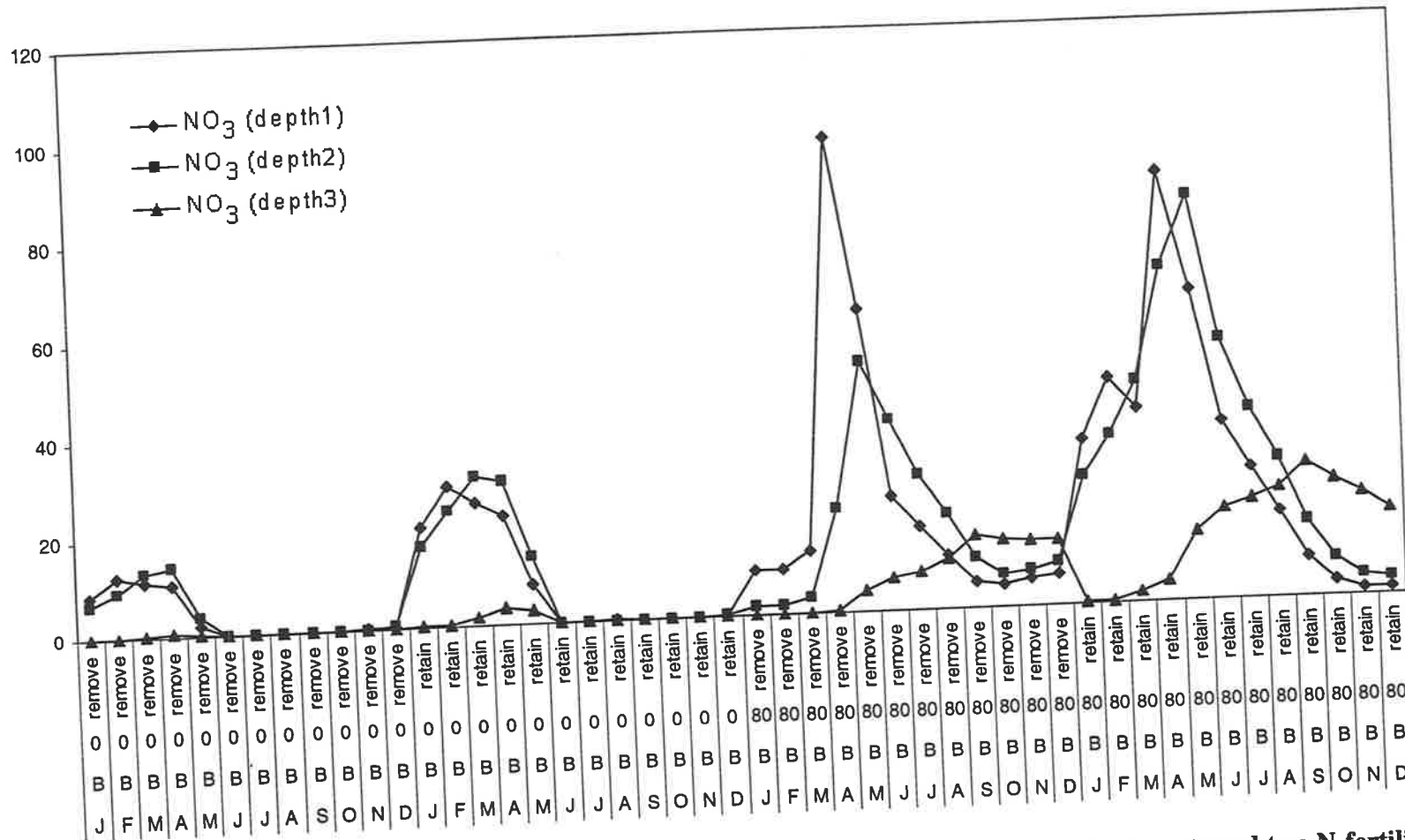
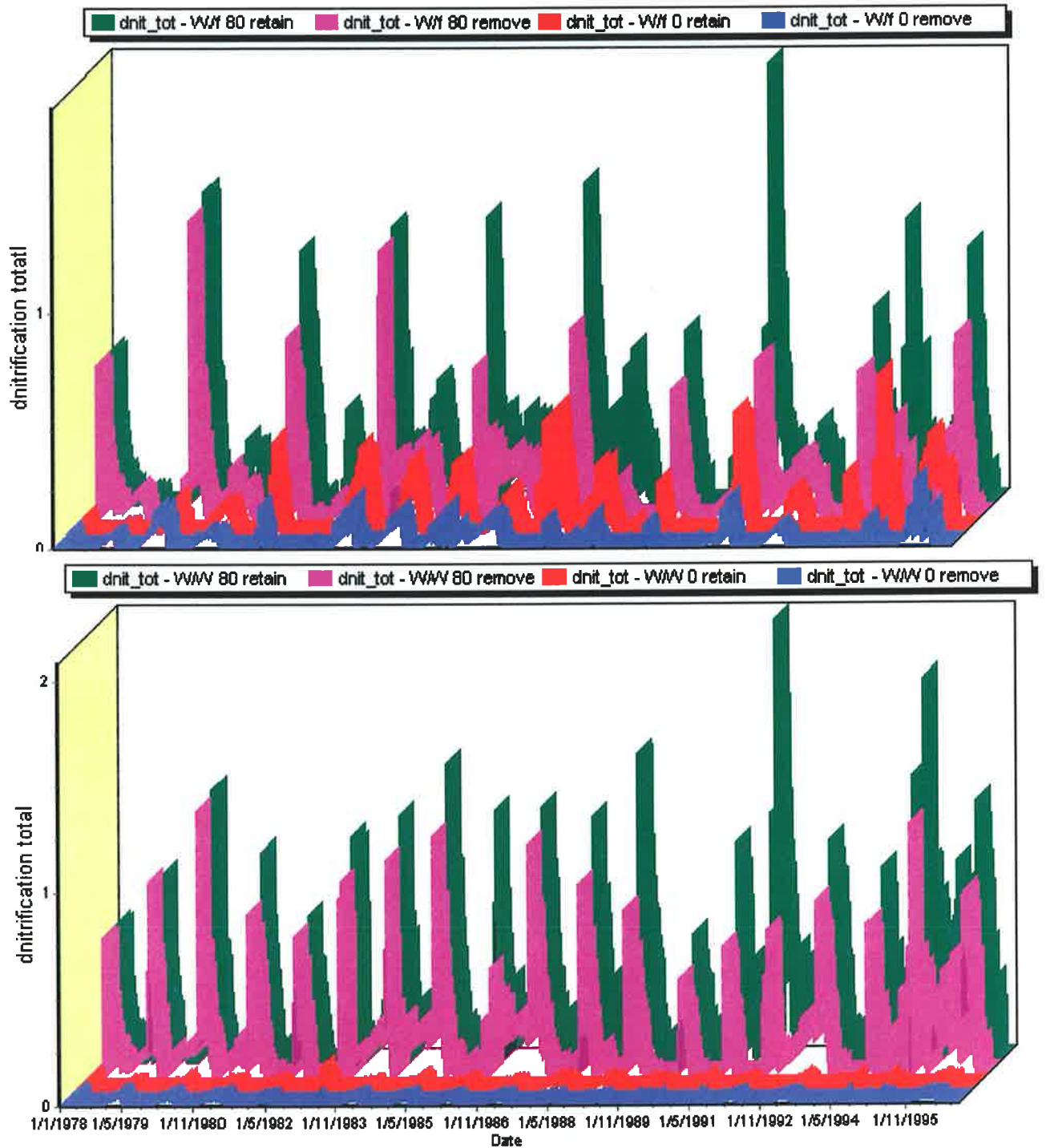
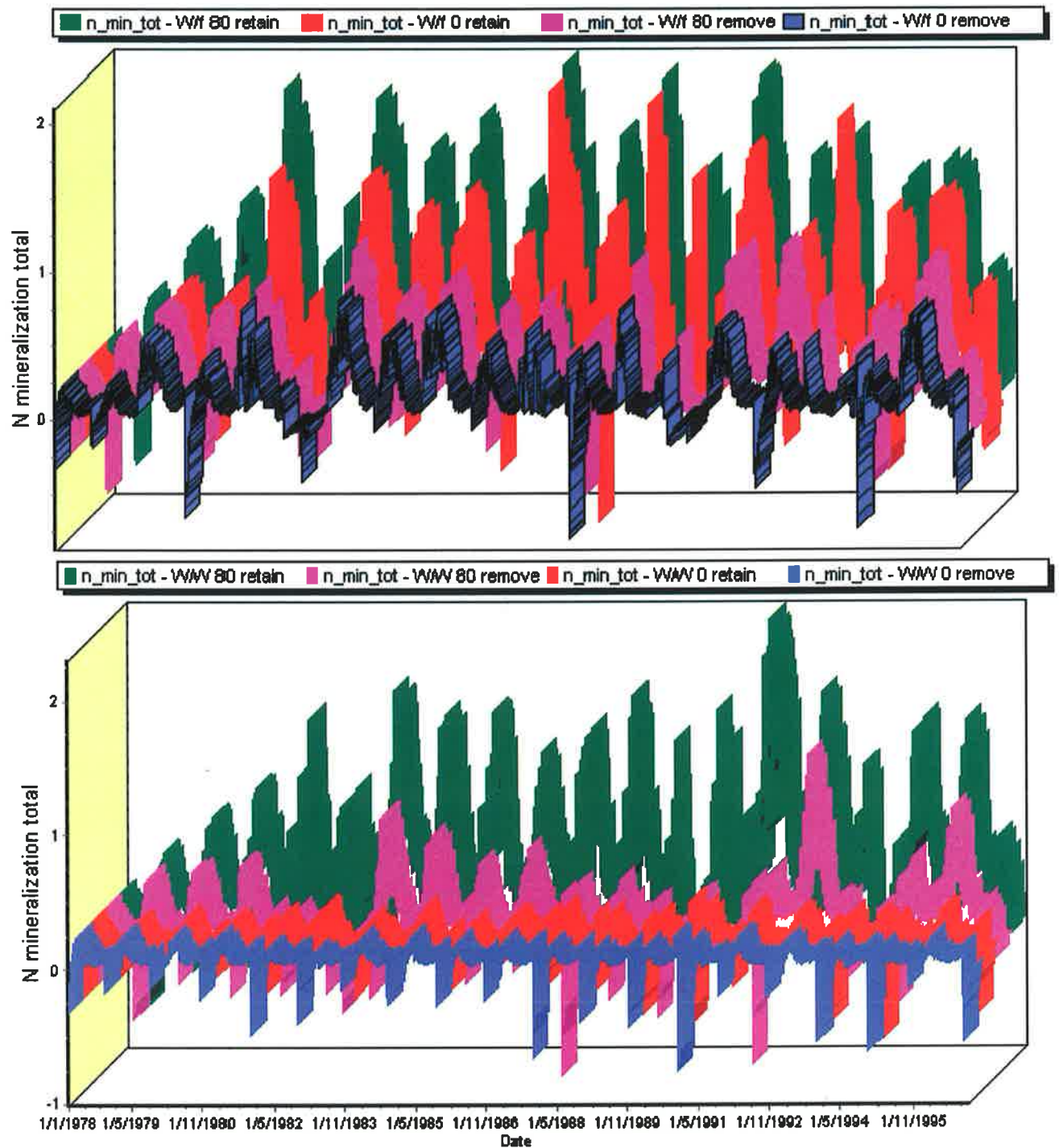


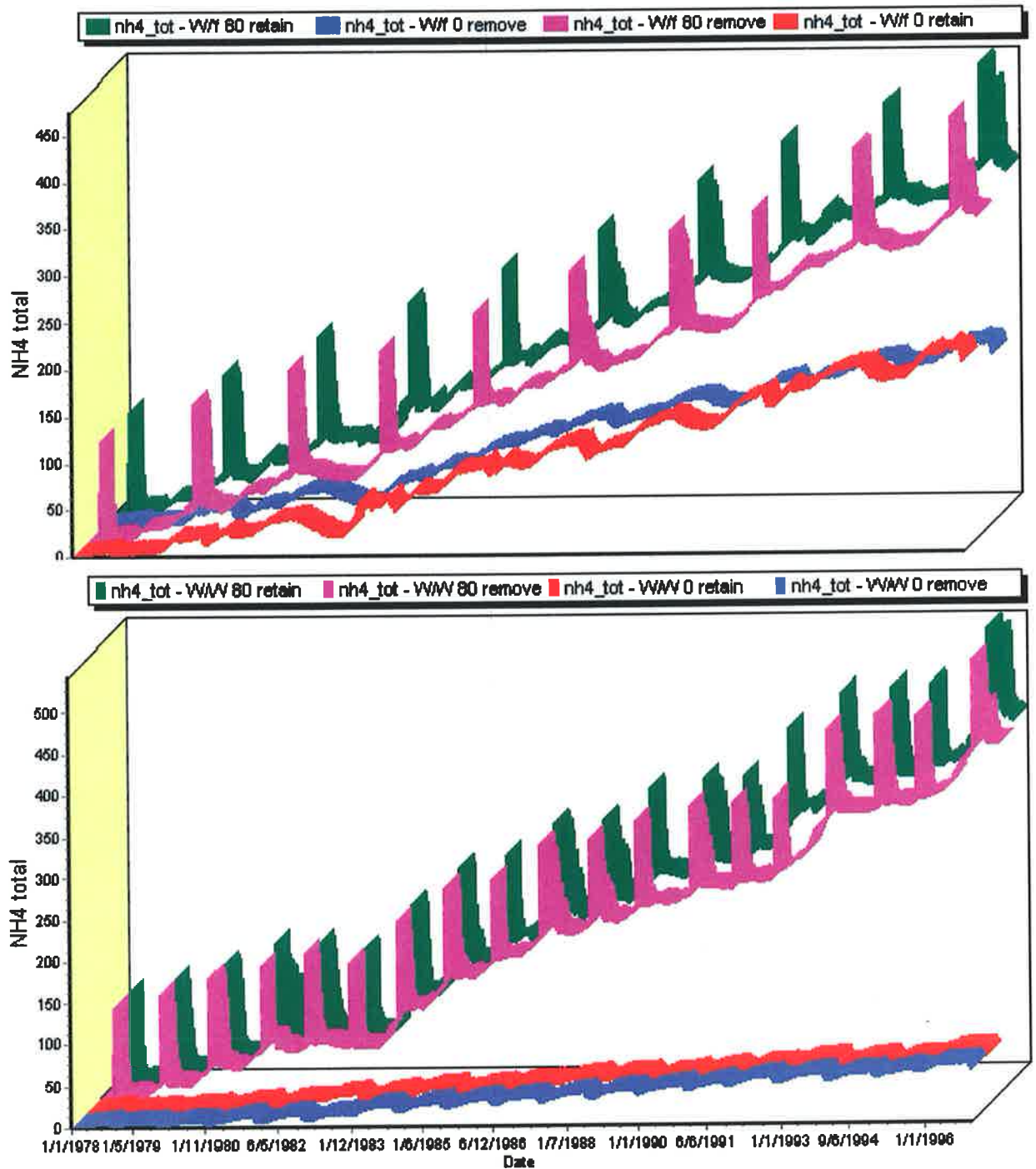
Figure 8.13 NO<sub>3</sub> (kg/ha) for 3 depths for the effect of W-B rotation with two stubble managements and two N-fertiliser rates for 1992 season simulated with APSIM.



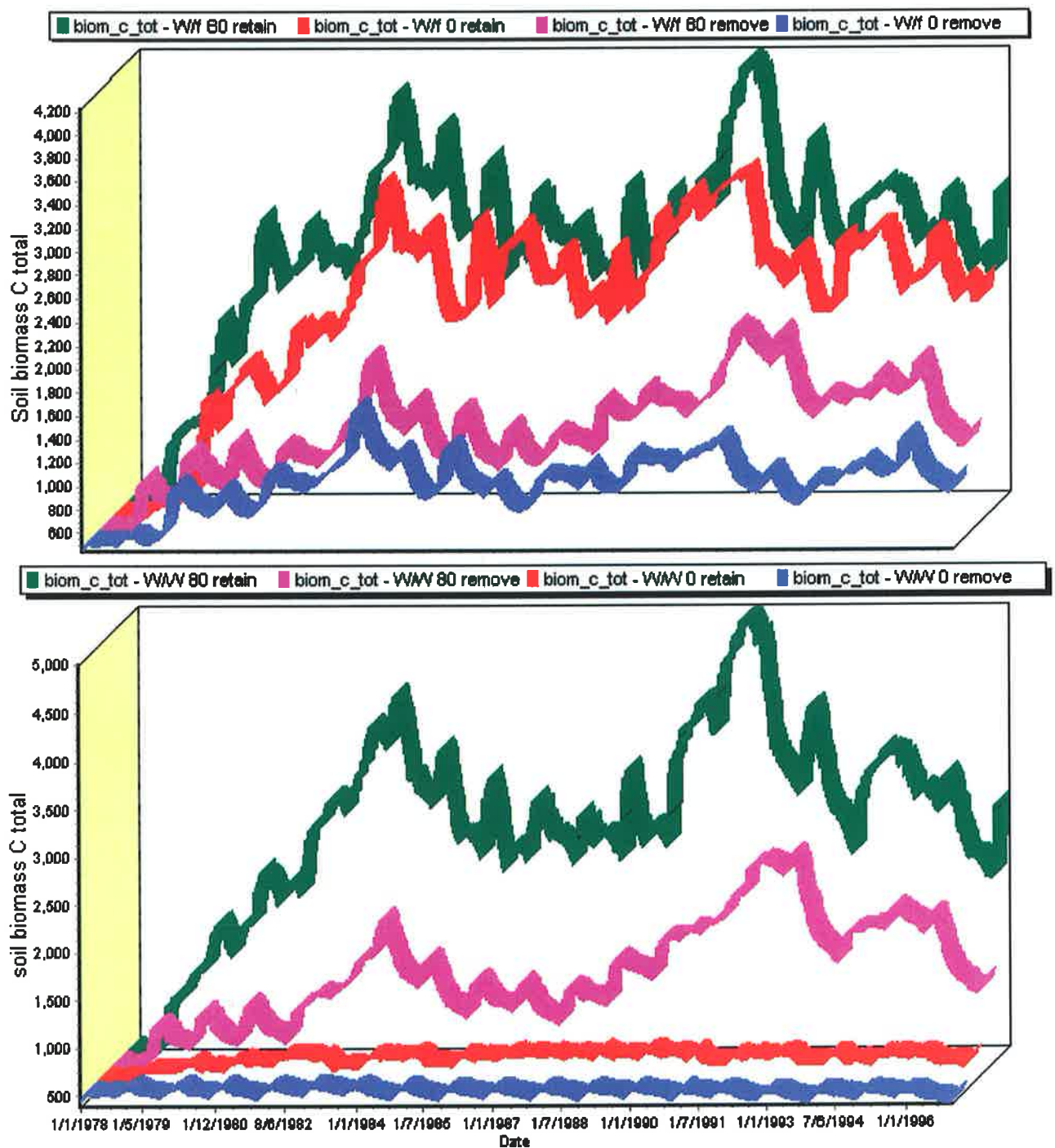
**Figure 8.14 Total denitrification (kg/ha) for the effect of W-B (above) and W-W (below) rotation with two stubble managements and two N-fertiliser rates between 1978-1996 season simulated with APSIM.**



**Figure 8.15 Total N mineralisation (kg/ha) for the effect of W-B (above) and W-W (below) rotation with two stubble managements and two N-fertiliser rates between 1978-1996 season simulated with APSIM.**



**Figure 8.16 Total ammonium (kg/ha) for the effect of W-B (above) and W-W (below) rotation with two stubble managements and two N-fertiliser rates between 1978-1996 season simulated with APSIM.**



**Figure 8.17 The total soil biomass (kg/ha) for the effect of W-B (above) and W-W (below) rotation with two stubble managements and two N-fertiliser rates between 1978-1996 season simulated with APSIM.**

## 8.4 Discussion

### 8.4.1 Soil changes

The main processes contributing to acidification within an ecosystem have generally been categorized in terms of the  $H^+$  production or consumption associated with soil nutrient cycles (Helyar 1976; Kennedy 1986; Reuss and Johnson 1986; Binkley and Richter 1987; Helyar and Porter 1989; Bolan *et al.* 1991). The N and C cycles contribute most to the acid and alkaline reactions in agricultural systems, and understanding these processes is important as they provide background for development of non-acidifying management strategies (Helyar 1976; Helyar and Porter 1989; Bolan *et al.* 1991; Kennedy 1992; Helyar *et al.* 1997).

Product removal, as part of the C cycle, is likely to be a major contributing process to acidification. The results from this experiment have shown that with the application of N-fertiliser in W-W and W-B rotations, there were overall increases in wheat yields (Figure 8.2 & 8.3) and soil biomass C (Figure 8.17). This will have accelerated acidification partly through the removal of more alkaline plant materials from the field. However the effects of management practices on yield and biomass C have varied from season to season. In years of low rainfall, water is the main limitation and stubble retention may improve the efficiency for conservation of water, which is reflected in improved water values especially for W-B rotations with stubble-retained practices. But the N-fertiliser responses with stubble retention become greater in years of good rainfall. The stubble retention was more responsive to applied N for W-W and W-B rotations with stubble retention and good rainfall in 1992.

Another important reason for soil acidification is nitrification, followed by  $NO_3^-$  leaching. The main form of nitrogen for plant uptake is  $NO_3^-$ -N, formed from nitrification of ammonia either during the mineralisation of organic matter (Figure 8.15) or from fertiliser addition (Figure 8.16). If uptake of  $NO_3^-$  does not occur by any source (plant or microbial), then the  $NO_3^-$  is leached from the rooting zone (Figure 8.7), resulting in a net  $H^+$  production for each  $NO_3^-$  leached (Helyar 1976; Binkley and Richter 1987; Bolan *et al.* 1991). In this study the highest proportion of acidity in W-W and W-B rotations possibly comes from N-fertiliser addition. However for the W-B rotation, it may be the type of stubble from the faba bean in the retained practices that has caused the higher leaching of  $NO_3^-$  to lower depth in the profile, even in the absence of N-fertiliser (Figure 8.16). It has been shown earlier (in

chapter 6) that stubble retained from legumes even without N-fertiliser can produce higher acidity compared to stubble from other crops. The largest input of N to Australian agricultural systems generally occurs through  $N_2$ -fixation by legumes, and the resulting acidification is often related to a limited  $NO_3^-$  and  $NH_4^+$  uptake by plant and lower nitrification (Helyar and Porter 1989). Legumes increase soil organic N through  $N_2$ -fixation, and the subsequent oxidation of organic N, followed by  $NO_3^-$  leaching is a main acidifying process (Helyar 1976). The excretion of  $H^+$  from legume roots, due to the uptake of more cations than anions (Haynes 1983), is another reason for accelerated soil acidification associated with legume growth.

The return of crop residues and the mineralisation of organic anions may generate enough alkalinity to balance the acidity generated as a consequence of  $NO_3^-$  production and leaching (Poss *et al.* 1995). In this study the rate of mineralisation of the OM in soil layers can be increased from the increase in  $NO_3^-$  in soil layers at the beginning of autumn and decreased later in the season. The highest rate of acidification is due to the total  $NO_3^-$  leaching, which was high with the combination of stubble retention and 80 kg/ha N-fertiliser in the W-B rotation and the higher N-fertiliser rate with W-W rotations.

But the retention of stubble at the Tarlee site caused more leaching than where there was regular stubble removal. Stubble retention returns organic anions and residue-N to soils (Figure 8.12 & 8.13). It is likely that at the Tarlee site, the pH decrease associated with stubble retention was due to nitrification of mineralised organic N, and subsequent nitrate leaching. In the fertilised plots acid addition occurred, especially in September, due to plant accumulation of  $NO_3^-$  formed in the same layer, without excretion of the equivalent amount of bicarbonate. Acidity produced in an earlier period of the year (May or June) by the mineralisation of the organic nitrogen was neutralised later when the  $NO_3^-$  content of the soil decreased either by denitrification or immobilisation reactions. So net acid addition due to leaching of  $NO_3^-$  to subsoil was important compared to other factors. The higher crop biomass C production in fertilised and retained stubble practices for both rotations would provide more acidity to the surface soil due to increased crop N uptake. Also the formation of  $NO_3^-$  by mineralisation and leaching the excess  $NO_3^-$ , especially higher for stubble retained and 80kg/ha treatments, is likely to be responsible for higher acidification rates for these practices.

The higher rainfall and drainage in 1992 caused  $\text{NO}_3^-$  to be moved from the surface soil to sub-horizons. When  $\text{NO}_3^-$  has moved to subsoil, the  $\text{H}^+$  produced through nitrification remains in the surface soil. This process causes soil acidification in the surface soil, even though part of the leached  $\text{NO}_3^-$  can be taken up from the subsoil by plant roots, which was the case in this study as partially  $\text{NO}_3^-$  had declined toward the end of season (Figure 8.12 & 8.13). Some of the ammonium remains in the soil for potential use by subsequent crops, and some is lost through leaching or volatilisation (Figure 8.16). However, the results from this study show that nitrification and subsequent downward movement of  $\text{NO}_3^-$  to the subsoil did occur and caused permanent acidification in surface soil.

#### **8.4.2 The accuracy of the model**

In presenting the outputs from simulations in the previous section, the ability (or failure) of the model to capture the main features of the experimental findings can be highlighted. The study suggests that the deviation between predicted and observed values were low and the long-term simulation of soil fertility represents a powerful tool for providing insights into the behaviour of such long-term cropping systems. The simulation described here has given some confidence that such models are capable of providing a reasonably predictive description of certain aspects of the water C, N and solute balances. The current evaluation was, however, limited to specific assumptions used for this study and caused some over-prediction or under-prediction of data, but did not show any inherent weakness of the model.

Whilst both predicted and observed values appear to deal with the same soil processes, and have broad similarities, they show some dissimilarities caused by model descriptions and how crop growth is modelled within a limited soil depth. To accommodate the required outputs to the first 60 cm soil, a 4-layer model using the depths 0-10, 10-25, 25-40, 40-55 was used. Nevertheless soil data for running APSIM normally is required up to 1.5 meters depth, which is something that future model evaluations will need to take into account. So the low depth profile considered in this study in APSIM simulation meant that the water balance dealt only with the 55 cm soil profile. Therefore the overall LL15 and DUL as the two important factors in water balance could be misrepresented in simulation data by APSIM. This resulted in variable consumption of water and  $\text{NO}_3^-$  for crop production and consequently

caused lower or higher prediction of yield compared with observed values. However the overall predictions of the water dynamics were good, but may significantly improve if accurately re-initialised with at least 1.5 m soil depth information. Running the program with this new information may completely correct those over- and under-predicted data (Zvi Hochman pers. comm. 2002).

The other suggested cause of over- or under-prediction of data may relate to when a long run simulation is attempted on a sequence of crops, as in the present study. This approach may be sensitive to carry-over effects from one crop to the next (especially in soil-water balance) and contribute to lack of fit between observed and predicted data (Probert *et al.* 1995). Such errors can add up to poor performance of APSIM on N responsiveness, and finally grain yields may show poor predicted values, because in APSIM yield predictions from the wheat module are very sensitive to interactions of water and N supply (Probert *et al.* 1995). Nonetheless, the APSIM predictions of yield here were closer to the observed data than many other similar studies or a regression approach.

The further development of such data input from the Tarlee field experiments into APSIM modules can be expected to improve its capability to simulate the dynamics of soil-water, soil C and N and crop growth. In future it may be possible to run these data against the soil pH module, similar to that of Hochman *et al.* (1998), in which the SOILpH module was tested against observed values for a typical moderately acid soil at Goondiwindi, Queensland. The SOILpH module gives APSIM extra potential for investigating the effects of management options such as cropping rotations and fertiliser use on long-term acidification rates and productivity, and the evaluation of the susceptibility of different environments (soil climate combinations) to acidification by alternative cropping systems.

However, an ability to simulate soil pH does not of itself provide a means of simulating long-term effects of soil acidification in the whole system. The link that is missing is the feedback between the soil pH and plant growth. Plants do not respond directly to pH. Rather, effects of soil acidity are noticeable through toxicities of Al or Mn, or deficiency of Ca. Besides influencing plant production, soil pH also affects the turnover of soil organic matter. Soil processes such as mineralisation, nitrification and urea hydrolysis are pH dependent. Whilst the SOILN module does include

routines to represent the effects of pH on the dynamics of soil C and N, its ability to capture the consequences of soil acidification on N mineralisation or C balance has not been tested here in these simulations. At the moment the effect of soil acidification on crop performance is not included, but it is hoped that this response will be incorporated into the various crop modules of APSIM in the near future for the Tarlee data-set.

### 8.5 Conclusion

In this chapter, measuring direct values for C, N and water dynamics for each depth, as influenced with specific management practices, helped to understand and discriminate between some of the important processes behind the soil acidification. A comparison of the predicted and observed data at Tarlee, across all management practices, showed that the model has predicted values well ( $R^2 = 0.58-0.83$ ). The quantity of extractable soil water (esw) in the soil profile for all management practices showed that generally there was more water available under retained stubble management practices than removed practices. The efficiency for conservation of water, which is reflected in improved water values especially for W-B rotations with stubble-retained practices, is especially important in years with poor rainfall. In contrast with above average rainfall (796 mm) and drainage (237mm), as happened in the 1992 season,  $\text{NO}_3^-$  leaching is an outcome especially in this system with excess nutrients.

The high concentration of the  $\text{NO}_3^-$  and  $\text{NH}_4^+$  exported by leaching (as shown in lower soil profiles) is a likely reason for soil acidification in this study. The presence of  $\text{NO}_3^-$  in soil depth was similar early in the experiment for different depths but towards 1992 and 1996 the values for  $\text{NO}_3^-$  at depth show that  $\text{NO}_3^-$  has accumulated, especially for stubble retained and 80 kg/ha N-fertiliser practices. The total  $\text{NO}_3^-$  for the W-W rotation in retained with 80 kg/ha treatments was higher compared to the same management practices in the W-B rotation. However the influence of 80 kg/ha N-fertiliser with legume caused more leaching of  $\text{NO}_3^-$  to lower profiles than where no fertiliser was used (Figure 8.12 and 8.13). Mineralization of OM would increase the soil  $\text{NO}_3^-$  but some may be utilized by the crop, immobilised or denitrified. For example N mineralisation was more influenced by 80 kg/ha N-fertiliser in the W-W rotation but influenced more with both 80 kg/ha and retained stubble practices in W-B rotation. Denitrification was higher for both stubble-retained practices with 80-

kg/ha N fertiliser compared to other practices for both W-W and W-B rotations.  $\text{NH}_4$  values were higher only for the plots that received 80 kg/ha N-fertiliser compared to nil N-fertiliser and stubble retention practices. However the W-B rotations without N-fertiliser showed significantly higher values compared to W-W rotations without N-fertiliser application, and this was not influenced with stubble practices. This study suggests that the amount of total biomass C in W-W rotation, with only fertilised plots had higher biomass C production. In contrast in W-B rotations, the amounts of biomass C was higher in retained practices even without N-fertiliser application. So the highest biomass in W-B rotation was achieved in stubble retention with 80 kg/ha N-fertiliser and followed closely by retained practices with nil-fertiliser. This may suggest that the export of the stubble as part of the C-cycle (stubble and grain removal) under W-B rotation has more potential to produce acidification in plots where the stubble was removed.

In the W-W rotation with retained and removed practices, with 80 kg/ha N-fertiliser, the losses of  $\text{NO}_3^-$  were 40 and 15 kg/ha. This would equate to acid addition of 2.86 and 1.07 kmol ( $\text{H}^+$ )/ha respectively. Losses under W-B and retained with and without N-fertiliser and removed practices, with 80 kg/ha N-fertiliser, are 25, 5 and 15 which equates to 1.78, 0.36 and 1.07 k mol ( $\text{H}^+$ )/ha acid deposition into the soil. The rates of soil acidification here would require all the above acidification rates in the order of 1400, 500, 900, 200 and 500 kg lime/ha/year to balance this acidification under these management practices. These values are rather similar to those predicted in chapter 6 for the same management practices.

Overall, the information obtained here gives some confidence about the accuracy of adopting simulation models. While the performance of the modelling can be improved for the scenarios used in this study, the predictions by the model are very close to values from field studies. The current evaluation was limited to the specific assumptions used for this study and caused some over-prediction or under-prediction of data, but did not show any inherent weakness of the model. So there is confidence that these models can provide a very powerful tool to explain the processes for the next 10-20 years of management practices on soil properties.

## Chapter 9

### 9 General discussion

This study has embraced both field-based investigations, chemical studies and modeling based on high input cropping systems in the lower to mid-north region of South Australia. The hypothesis of this thesis was that the high-input cropping systems practiced in the 450-500 mm rainfall region are contributing to permanent acidification of the soil.

The experiments outlined showed that soil acidification is occurring in the medium rainfall areas of South Australia (450-500 mm), with extensive evidence of accelerated acidification after 19 years at a site at Tarlee. Although the surface soil pH has declined in these regions of South Australia, there is no strong evidence to suggest from these data that the yield at Tarlee is affected by increased acidity. However the acidity was most likely affecting crop production in the field experiments, particularly where the sulfur treatment was used to produce a lower pH. Under these induced lower pH conditions, Al and Mn were increased and ECEC (especially Ca) was reduced to very low values. The higher (or different) OM properties at the Tarlee site, compared to the other 3 field sites, may be working as a buffer against negative effects associated with pH change. Lime application is a key approach in managing soil acidity in most acidified areas. Using the lime treatments calculated by the Hochman model generally increased yield by 30-60% relative to the control at all sites.

The data demonstrate that the approach used for predicting lime responsiveness of a soil has worked for the 3 field sites. Target pH was achieved after 12 months where the model of Hochman *et al.* (1989) was used to test and predict liming requirement of acidic soils. The good correlation between observed and predicted pH values from the liming model used in this study would indicate that the values that are affecting pH buffering here are soil TEC, Al and pH. The other important factor is the soil OM, which could act as a source for hydrolysis of  $Al^{3+}$  ions on OM exchange sites and exchange by  $H^+$  on the strongly acidic carboxyl groups (Magdoff and Bartlett 1985), and could play an important role in pH buffering (Bloom *et al.* 1979). This factor can increase the pHBC of the soil and thus resist pH change caused by soil acidifying processes. Thus where OM content of soil is reasonably high, then it may

be better that the OM content is considered in calculating the liming requirement of the soil, similar to the method proposed by Hochman *et al.* (1995). However the OM of the 3 field sites studies was moderately low (almost 1%).

In the Tarlee study it is clear that the agricultural management practices that are considered the basis of current 'best farm practices' have caused soil acidification to different extents. Also soil OM properties where these stubble residues were retained from legumes (and with 80 kg/ha N applied) were improved. With these management treatments the OM content was about 1.5%. The soil pH values were decreased for all management practices particularly with the effect of legume-rotations and higher N-fertilizer rates. With the higher soil acidification and greater decrease in soil pH, the Al and Mn both are increased. However in this soil environment where the OM was improved, even with the higher Al toxicity level, there was no obvious restriction on plant growth (Kamprath 1970; Evans and Kamprath 1970; Reeves and Sumner 1970; Oates and Kamprath 1983; Geeves *et al.* 1992; Slattery *et al.* 1995). It is possible here that the OM content of this soil may have provided some protection against Al toxicity (complexation).

The presence of specific organic acid ligands found with the Tarlee study shows that in the soil solution, the LMWOA may play an important role in Al detoxification (i.e. the organic acid is involved in complexation and reduces Al level) (Kwong and Huang 1979; Huang and Violante 1986; Harper 1994; Smith *et al.* 1995; Slattery *et al.* 1998; Ma 2000; Ryan *et al.* 2001). The key organic acid (as observed in this study) responsible for complexation with Al would seem to be succinic, malic and fumaric for the faba beans and succinic and fumaric for wheat and lupin type of stubble. This suggests that it may be possible to use stubble retained practices further in order to optimise the biological ecosystem that provides the supply of LMWOA, and that this may help control the buffering capacity of the soil and potential chemical toxicities through Al complexation. The methods used in this thesis for the detection of LMWOAs were based on whole soil and will not specifically differentiate between those organic anions exuded by roots or those produced by microbial decomposition of OM. Therefore further study may be necessary to identify the origin of LMWOAs and what anions are responsible for complexation of Al<sup>3+</sup>. The key finding here is that stubble retained practices create a soil environment that had a high capacity to form strong complexes with toxic Al as well as buffering

against pH changes. This further supports the approach recommended to farmers to use management practices that retain stubble in some form.

The soil system simulation described here has given some confidence that such models are capable of providing a reasonably predictive description of certain aspects of the water C, N and solute balances. The current evaluation was however limited to specific assumptions used for this study and may cause some over-prediction or under-prediction of data, but did not show any inherent weakness of the model. With further use of this model, long-term data may provide a very powerful tool for the prediction of management practices on acidification and soil properties for the next 10-20 years.

### **9.1 Conclusion**

In this study it is shown that acidification is occurring in the medium-rainfall cropping regions (450-500mm) of South Australia. Further it is shown that there are potential benefits of lime use, and that there is great opportunity for continuing high input cropping but in a strategic way. Data from the long-term Tarlee site can be used further to provide an understanding of the causes and rates of development of soil acidification in this type of environment, and thus assist with acidification control or amelioration. The combination of such data from the Tarlee site with available liming data, and an applied modeling approach, could be significant in terms of improving decision making to keep grain production in a stable and sustainable state. It is anticipated that the research given here can have immediate impact on the cropping industries in the designated areas. This type of study can be expanded for more soil types in this region, allowing the expression of rotational cropping as a function of soil, nutrient and water characteristics specific to soil types and crop requirements. So the overall outcome will greatly benefit the grains industry in South Australia and elsewhere in Australia where acidification is an emerging environmental problem.

## Chapter 10

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