Combating sodicity in the Lachlan and Macquarie Valleys of New South Wales

John McLean Bennett II

BSc (REM) Hons

The Faculty of Agriculture Food and Natural Resources
The University of Sydney
New South Wales
Australia

A thesis submitted in fulfilment of the requirements for the Degree of Doctor of Philosophy

In loving memory of my father, William “Bill” Attwood
10th of May 1940 – 02nd of January 2010

CERTIFICATE OF ORIGINALITY

The text of this thesis contains no material which has been accepted as a part of the requirements for any other degree or diploma in any university or any material previously published or written, unless due reference to the material has been made

John McLean Bennett II

Abstract

Whereas the use of gypsum for the amelioration of sodic soils under dryland and irrigated agricultural systems has been relatively well studied, experiments investigating lime as a sodicity ameliorant have shown little success. This lack of success, and the use of lime as a pH buffer, has caused it to be largely disregarded as useful for sodicity amelioration. Thus, due to the extensive evidence for gypsum use as a sodicity ameliorant and the general disregard of lime as an ameliorant, lime/gypsum combinations have only been given cursory consideration, especially under irrigation. This study is principally concerned with addressing the efficacy of lime and gypsum use for amelioration of sodic soils in the Lachlan and Macquarie Valleys of NSW. However, there is an apparent lack of knowledge encompassing the issue of sodicity and perhaps soil health in general. For this reason, it was necessary to undertake an investigation into landholders' soil health management education and the impediments associated with implementing a soil health program in the Lachlan and Macquarie Valleys.

In order to assess the efficacy of lime and gypsum use for sodicity amelioration, four field-based experimental sites were obtained, two in the Lachlan Valley (near Hillston, NSW) and two in the Macquarie Valley (one near Trangie, NSW, and the other near Warren, NSW). The soils form the Lachlan Valley were described as a Brown Vertosol and a Red Dermosol, with pH 8.0–9.0, electrolyte concentration (EC) ranging from 0.30 to 3.50 $dS.m^{-1}$ and exchangeable sodium percentage (ESP) between 10 and 38%. The soils from the Maquarie Valley were described as a Brown Vertosol and a Brown Dermosol, with pH 6.5–8.0, EC ranging from 0.20 to 0.30 $dS.m^{-1}$ and ESP between 6 and 12%. Full-field, replicated experimental-strips were treated with L0G0 (Lime 0 $t.ha^{-1}$ and Gypsum 0 $t.ha^{-1}$), L2.5G0, L0G2.5, L2.5G2.5, L2.5G5, L5G2.5 and L5G5 at each site. Due to insufficient rainfall and unsecured irrigation water, only the Lachlan Valley soils were subject to irrigation; the Macquarie Valley soils were subject to a dryland agricultural system.

The study of the dryland agricultural system shows, through pH/EC relationships, that EC is maintained at higher levels than the control where lime is applied, or where gypsum is applied alone after 2.5 years. Furthermore, the increases in EC due to lime generally result in a significant relationship between EC and aggregate stability. There is possibility of a synergistic ameliorative effect between lime and gypsum on soil sodicity levels, although this is not directly measured.

For the irrigated agricultural system, it is observed that gypsum is the primary means of amelioration through Ca^{2+} exchange after 6 months, although these effects did not persist to

2.5 years. The EC effect of gypsum is not observed after 6 months or 2.5 years post-gypsum application and approximately 12.85 $ML.ha^{-1}$ of infiltrating irrigation-water/rain. The results of this work show that the use of lime and gypsum in combination and alone is not necessarily viable for broadacre irrigated agriculture on two Lachlan Valley soils with pH >8.0.

As it is apparent that the rate of gypsum dissolution is too high under the irrigated system studied, gypsum was combined with chicken manure/wheat straw compost (CMWSC) in order to investigate the potential of creating a slow release source of calcium (Ca^{2+}). A leaching column experiment was conducted using a Brown Vertosol treated with C0G0 (CWMSC 0 $t.ha^{-1}$, gypsum 5 $t.ha^{-1}$), C0G5, C5G0, C5G5, C144G0, and C144G5. Columns were irrigated every two weeks for 14 weeks (6.5 $ML.ha^{-1}$ of irrigation water in total). The application of gypsum alone was shown to be comparable to the C5G5 treated soil, although the C5G5 treated soil retained more Ca^{2+} and leached less Ca^{2+}. Rapid decrease in soil electrolyte level was evident in all treated soils. The results of this study indicate that gypsum-enhanced CMWSC is more effective in ameliorating sodicity than the use of gypsum alone, due to a greater retention of exchangeable Ca^{2+}.

Despite mounting scientific evidence for the credibility of certain soil health management strategies such as those in this work, farmers remain hesitant to implement structured management plans and strategies. Hence, an investigation of the proportion of Lachlan and Macquarie Valley landholders who implement a structured soil health program was undertaken with focus on the impediments associated with the adoption of such programs. Non-parametric analysis of a mail-based survey supported with content analysis of landholder comments, suggests that the overall attitude towards soil health management is positive, although soil health management programs are often inconsistent, unstructured, or ad-hoc. Landholder knowledge of sodicity was found to be low, although landholders' do not believe that education is an impediment to program adoption. This research highlights that ongoing communication between landholders, agronomists, extension agencies and scientists is shown to be vital in the adoption of soil health management programs. While the initial investment in soil health management is perceived as an impediment, landholders indicate that production longevity and long-term financial gain are achievable.

Acknowledgements

First and foremost I must thank the fearless leader of ‘Team Ped’, my supervisor, Dr. Stephen “Stavros” Cattle. His tireless editing and critique of my work was invaluable, his quirky sense of humour impeccable, and his words of encouragement and understanding always well timed. Stephen provided me the opportunity to further my education in soil science, and for this I am highly appreciative.

To Associate Prof. Balwant Singh, I offer sincere gratitude for his patience in dealing with my many calcium related questions. Quite often these shot forth relentlessly for days on end. However, Balwant has always been able to offer good advice and satisfy my curiosities. It has been a pleasure to work with both Stephen and Balwant.

To the many and varied staff within the faculty that have assisted me in all things from working the photocopier to explaining ion kinetics, your time and knowledge was definitely appreciated. The names are too many to list, and I feel that this is a real testament to the inclusive atmosphere of the Faculty of Agriculture Food and Natural Resources – here’s to another 100 years.

In order for the field-based components of this thesis to come to fruition, various partnerships had to be formed. I am highly thank-full for the hard work provided by Todd Peach and Allan Jones (Agronomic Business Solutions – Hillston), as well as Dr Pat Hulme and Dave Duncan (Sustainable Soil Management – Warren). These gentlemen provided an introduction to the farmers and helped facilitate the construction of the experimental sites.

To the three landholders, Scott Laird (Mount View), Scott Mailer (Wyadra) and Gus O’Brien (Bellevue), as well as the managers of the Agriland property, Jim Bible and Mal Carpenter, I sincerely thank you for your hospitality, access to your soil, financial investment and the use of your tractors. Without them, this project could not have survived past the initial sowing of the seed. I certainly have learned a thing or two from them about the joys of irrigation and I hope they have learned a little something about sodicity.

Financial backing was principally provided by the Cotton Research and Development Corporation through the Cotton Catchment Communities CRC. Subsequent funding was provided by the Central West Catchment Management Authority and the NSW Department of Industry and Innovation (nee Department of Primary Industries) Healthy Soils for Sustainable Farms program. Database support (mail-based survey) was also provided by the Western and Lachlan Livestock Health and Pest Authorities. For this I am truly grateful.

To those who took it upon themselves to work alongside me in the laboratory and in the isolated surrounds of the field environment I extend heartfelt thanks. I would especially like to mention Tim "Schnoodle" Lewis for his efforts and general good-bloke-ness in helping in the field. The same goes for Jack Fitzgerald, who gave up many an hour to help me out in the laboratory, or help me dissipate the built up stress. Also, I extend great appreciation to Dili Mao for helping me edit my thesis.

The rest of the members, ticket holding and honorary, of 'Team Ped' also deserve a big pat on the back (and probably a beverage or two) for helping me survive these last few months and what can only be likened to removing a bandaid incredibly slowly – painful, but definitely worth it in the end! The friendship of A, Juan Holio, Toddos, Karlos and Uta has meant a great deal to me throughout my time here and I hope for a long time into the future.

Finally, I thank all of those who have not directly taken part in this endeavour, but ensured that I was able to. To my mother, Jane Attwood, my sister Rebecca Bennett and all my family I thank you for your belief and encouragement. To Phoebe Abbott, I am forever in debt; your support throughout the last few years has been amazing and unrelenting.

The University of Sydney, thanks for having me.

"My train of thought comes around every hour on the hour; the trick is not to catch the bus of procrastination, which comes by every ten minutes"
– Anon.

Table of contents

Abstract iv
Acknowledgements vi
Table of contents viii
List of tables xiii
List of figures xv

Chapter 1:

1. General introduction, aims and thesis overview 1
  1.1. Introduction 1
  1.2. Aims 6
  1.3. Thesis overview 7
    1.3.1. Chapter 1: General introduction, aims and thesis overview 7
    1.3.2. Chapter 2: The characterisation of sodic soils, ameliorative techniques and strategies for management: a review 7
    1.3.3. Chapter 3: A description of four sodic soils and the soil analytical methods employed in this work 7
    1.3.4. Chapter 4: The effects of lime ($CaCO_3$), gypsum ($CaSO_4.2H_2O$), and lime/gypsum combinations, after 2.5 years, on selected soil properties of two sodic soils under dryland cropping conditions in the Macquarie Valley, New South Wales 8
    1.3.5. Chapter 5: The efficacy of using lime ($CaCO_3$), gypsum ($CaSO_4.2H_2O$) and lime/gypsum combinations to ameliorate sodicity in two irrigated soils used for cropping in the Lachlan Valley of New South Wales 8
    1.3.6. Chapter 6: The merits of a gypsum ($CaSO_4.2H_2O$) enhanced chicken manure/wheat straw compost in ameliorating an irrigated sodic Brown Vertosol – laboratory experiment 8
    1.3.7. Chapter 7: Impediments to the adoption of soil health improvement strategies by farmers in Central West NSW 9
    1.3.8. Chapter 8: General discussion, conclusions, and future research 9
  1.4. References 9

Chapter 2:

2. The characterisation of sodic soils, ameliorative techniques and strategies for management: a review 14
  2.1. Introduction 14
  2.2. Issues associated with defining sodic soils 15
  2.3. Dispersive properties of sodic soils 16
  2.4. Differentiating sodic soils from saline soils 17
  2.5. Sources of sodium 18
  2.6. Sodic soil distribution in Australia 18
    2.6.1. Sodic soil in New South Wales 19
    2.6.2. Distribution of sodicity within the soil profile 20
  2.7. Consequences of sodic soil behaviour 20
    2.7.1. Instability to wetting: swelling, slaking and the clay mineral suite 20
    2.7.2. Hydraulic conductivity and available water content 22
    2.7.3. Soil strength, hardsetting and crusting 23
    2.7.4. Subsoil compaction 24
  2.8. Amelioration of sodic soils 24

2.8.1. Effect of electrolyte concentration 25
2.8.2. Structural amelioration through gypsum ($CaSO_4.2H_2O$) 28
2.8.3. Structural amelioration through lime 30
2.8.4. Use of alternate liming amendments 32
2.8.5. Effects of lime and gypsum combinations 33
2.8.6. The use of organic matter to ameliorate sodic soils 34
2.9. Management of sodic soils: processes and implications 39
2.9.1. Irrigation water quality 39
2.9.2. Soil disturbance and cultivation 41
2.9.3. Crop management 44
2.10. Conclusions 45
2.11. References 45

Chapter 3:

3. A description of four sodic soils and the soil analytical methods employed in this work 66
3.1. Introduction 66
3.1.1. Sampling districts 66
3.2. “Bellevue” – Warren 69
3.2.1. History and on-field operations 69
3.2.2. Soil profile characterisation 70
3.3. “Agriland” – Field 48 – Trangie 70
3.3.1. History and on-field operations 70
3.3.2. Soil profile characterisation 72
3.4. “Mount View” – Field L8 – Hillston 72
3.4.1. History and on-field operations 72
3.4.2. Soil profile characterisation 75
3.5. “Wyadra” – Field L1 – Hillston 76
3.5.1. History and on-field operations 76
3.5.2. Soil profile characterisation 78
3.6. Methods 78
3.6.1. Soil sampling 78
3.6.2. Particle size distribution 79
3.6.3. X-ray diffraction 81
3.6.4. Aggregate stability in water 82
3.6.5. Soil pH 82
3.6.6. Soil electrical conductivity 83
3.6.7. Exchangeable cations 83
3.6.8. Cation exchange capacity 85
3.6.9. Soluble ions 86
3.6.10. Total ion concentration 86
3.6.11. Nitrogen and organic carbon 86
3.6.12. Total gypsum 87
3.7. References 87
3.8. Appendix 3.A. 89

Chapter 4:

4. The effects of lime ($CaCO_3$), gypsum ($CaSO_4.2H_2O$), and lime/gypsum combinations, after 2.5 years, on selected soil properties of two sodic soils under dryland cropping conditions in the Macquarie Valley, NSW 94
  4.1. Introduction 94
  4.2. Methods 95
    4.2.1. Soil sampling and description 95
    4.2.2. Soil analyses 95
    4.2.3. Statistical analysis 96
  4.3. Results 96
    4.3.1. Changes in soil pH due to treatment application 96
    4.3.2. Changes in electrolyte concentration due to treatment application 96
    4.3.3. Changes in aggregate stability due to treatment application 98
    4.3.4. Correlation analysis 99
  4.4. Discussion 100
    4.4.1. Treatment effects on, and relationship between, pH and electrolyte concentration 101
    4.4.2. Treatment effect on aggregate stability 102
    4.4.3. The relationship between electrolyte concentration and dispersive potential 103
    4.4.4. Possibility of a synergistic effect between lime and gypsum on soil sodicity 103
  4.5. Conclusion 104
  4.6. References 104

Chapter 5:

5. The efficacy of using lime ($CaCO_3$), gypsum ($CaSO_4.2H_2O$) and lime/gypsum combinations to ameliorate sodicity in two irrigated soils used for cropping in the Lachlan Valley of New South Wales 108
  5.1. Introduction 108
  5.2. Methods 110
    5.2.1. Experimental sites 110
    5.2.2. Experimental design 111
    5.2.3. Agronomy 112
    5.2.4. Soil sampling regime, measurements and preparation 114
    5.2.5. Laboratory measurements 114
    5.2.6. Yield measurements 115
    5.2.7. Statistical analysis 116
  5.3. Results 116
    5.3.1. Changes in exchangeable cation concentrations 116
    5.3.2. Ameliorant effect on pH and EC 119
    5.3.3. Residual gypsum 120
    5.3.4. Calcium exchange efficiencies 120
    5.3.5. Changes in soluble calcium, sodium and total cation concentration . 121
    5.3.6. Aggregate stability in water after 6 months and 2.5 years 122
    5.3.7. Changes in surface total nitrogen and organic carbon after 2.5 years 124
    5.3.8. Treatment effects on crop yield and seedling height 124
  5.4. Discussion 125
    5.4.1. The short-term effects of lime and gypsum on the soil properties measured 125

5.4.2. The viability of lime and gypsum as chemical ameliorants for sodicity in the two soils 127
5.4.3. Potential synergies between lime, gypsum and plants 130
5.4.4. Aggregate stability and the longevity of observed cation exchange.. 132
5.4.5. Management implications 133
5.5. Conclusions 134
5.6. Acknowledgements 135
5.7. References 135

Chapter 6:

6. The merits of a gypsum ($CaSO_4.2H_2O$) enhanced chicken manure/wheat straw compost in ameliorating an irrigated sodic Brown Vertosol – laboratory experiment 140
6.1. Introduction 140
6.2. Methods 142
6.2.1. Collection and preparation of soil 142
6.2.2. Experimental design and treatments 143
6.2.3. Soil analyses 144
6.2.4. Leachate analyses 145
6.2.5. Compost production and analyses 146
6.2.6. Statistical analyses 146
6.3. Results 147
6.3.1. Soil chemical measurements 147
6.3.2. Leachate chemical measurements 150
6.3.3. Changes in saturated hydraulic conductivity 153
6.4. Discussion 153
6.4.1. Effects of treatment application on cation exchange 154
6.4.2. Combined effects of chicken manure/wheat straw compost and gypsumn on sodicity 155
6.4.3. Compost application rates 157
6.4.4. Longevity of electrolyte effect as affected by treatment application. 158
6.5. Conclusion 160
6.6. Acknowledgements 161
6.7. References 161

Chapter 7:

7. Impediments to the adoption of soil health improvement strategies by farmers in Central West NSW 165
7.1. Introduction 165
7.2. Methods 168
7.2.1. Sampling area 168
7.2.2. Sampling method 170
7.2.3. Statistical analysis 172
7.3. Results 173
7.3.1. Soil health factors 173
7.3.2. Attitudes towards soil health management 174
7.3.3. Planning and management 175
7.3.4. Impediments to the adoption of a soil health management plan 176
7.3.5. Incentives for the adoption of soil health management plans 187
7.4. Discussion 188

7.4.1. Landholders and soil health 188
7.4.2. The tension between soil health and maximising production 192
7.4.3. Methods of planning 193
7.4.4. Economic impediments for the adoption of soil health programs 193
7.4.5. Landholders' perception of land-use and change 194
7.4.6. The role of property size 195
7.4.7. Education as an impediment 196
7.4.8. The perception and role of agronomists and extension agencies 197
7.4.9. Effects of memberships and workshop attendance 199
7.4.10. Regional differences 200
7.4.11. Incentives for the adoption of structured soil health management plans 201
7.4.12. Recommendations 202
7.5. Conclusion 203
7.6. Acknowledgements 205
7.7. References 205

Chapter 8:

8. General discussion, conclusions and future research directions 209
8.1. General discussion 209
8.1.1. The viability of lime and gypsum use as a sodicity ameliorant in irrigated agriculture relative to dryland agriculture 209
8.1.2. Management of sodic soils containing native calcium carbonate and gypsum 211
8.1.3. The amendment-induced electrolyte effect and its longevity in irrigated agriculture 213
8.1.4. Awareness of sodicity and the importance of extension efforts 214
8.1.5. Experimental design, field variability and implications for precision agriculture 215
8.2. General Conclusions 218
8.3. Future research directions 220
8.4. References 222

List of tables

Chapter 2:

Table 2.1. Summary of the global distribution of sodic soils adapted from Murphy (2002) 19

Table 2.2 *Area of sodic and saline soils in NSW based upon figure 2.2 adapted from Mckenzie et al. (1993)* 19

Chapter 3:

Table 3.1 Mean climatic data by district based on the world standard 30 year period (1961 to 90; Bureau of Meteorology 2009). 66

Table 3.2. Crop rotation, rainfall and irrigation rate by year for the Bellevue site 70

Table 3.3 Crop rotation, rainfall and irrigation rate by year for Agriland – Field 48 Wheat produced in winter and cotton in summer. 70

Table 3.4. Particle size analysis, texture grade and soil colour for the four experimental sites C is clay (<2 µm); S is silt (2–20 µm); FS is fine sand (20–200 µm); CS is coarse sand (200–2000 µm) 73

Table 3.5. Chemical properties, dispersive index and total gypsum percentage for the four experimental sites by incremental depth. 75

Table 3.6 Crop rotation, rainfall and irrigation rate by year for Mount View The property was not landformed for irrigated cropping in winter 2001 76

Table 3.7. Crop rotation, rainfall and irrigation rate by year for Mount View 77

Chapter 5:

Table 5.1. Selected soil properties from the Mount View and Wyadra experimental sites DI represents the dispersive index as measured by aggregate stability in water (Field *et al.* 1997); C is clay (<2 µm); S is silt (2–20 µm); FS is fine sand (20–200 µm); CS is coarse sand (200–2000 µm). 111

Table 5.2. Experimental treatments with reference to amount of calcium applied and the cost per hectare Calculation of the calcium equivalent for each treatment is based on 200 kg.t^{-1} of calcium contained in gypsum (analysis shows 20% Ca^{2+} in the gypsum source) and 400 kg.t^{-1} of calcium in lime (Abbott and McKenzie 1986). The cost of each treatment is based on the actual cost for lime (AUD$110 t^{-1}) and gypsum (AUD$75 t^{-1}) used for this experiment. 112

Table 5.3. Agronomic information for the application of nutrients and chemical for both sites App. month is an abbreviation for 'application month' 113

Table 5.4 Exchangeable cation percentages, cation exchange capacity, pH and electrical conductivity in the 0–100 mm layer of the Mount View and Wyadra soils after 6 months Values within columns followed by the same letter are not significant. Values followed by an asterisk are significant at the $\alpha = 0.1$ level, while all other pairs are significant at the p-value indicated. 118

Table 5.5 Exchangeable cation percentages, cation exchange capacity, pH and electrical conductivity in the layers within 0–400 mm of the Mount View and Wyadra soils after 2.5 years Values within columns followed by the same letter are not significant. 118

Table 5.6 Residual gypsum levels and corresponding electrical conductivity on the basis of gypsum application rate, irrespective of lime, for the Mount View and Wyadra soils after 6 months and 2.5 years Numbers in parentheses are EC values (dS.m^{-1}) of a 1:5 w v^{-1} soil water extract. The values for treatments with the same gypsum application rates have been averaged as they did not differ significantly 120

Table 5.7 Changes in exchangeable cations (cmol.kg^{-1}) after 6 months following the incorporation of 5 t.ha^{-1} of lime and 5 t.ha^{-1} of gypsum in the 0–100 mm zone of Mount View and Wyadra soils Values in parentheses within the 'Change relative to L0G0' column are the difference in exchangeable cations expressed as percentage increase or decrease. 121
Table 5.8 Soluble calcium, sodium and total cation concentrations in the 0–100 mm layer of the Mount View and Wyadra soils after 6 months 121
Table 5.9 Soluble calcium, sodium and total cation concentrations in the layers within 0–400 mm of the Mount View and Wyadra soils after 2.5 years 122

Chapter 6:

Table 6.1. Initial chemical properties of the soil used in the experiment 143
Table 6.2. Experimental treatment components 144
Table 6.3 Selected chemical properties of the four compost combinations used in the experiment 147
Table 6.4 Changes in soil exchangeable cation percentages and ratios, estimated cation exchange capacity, pH and electrolyte concentration due to treatment application, after seven irrigation events and 14 weeks Values within columns followed by the same letter are not significantly different 148
Table 6.5 Ratios of major soluble cations to soluble potassium and calcium of the various compost blends Ratios calculated from Table 3 154

Chapter 7:

Table 7.1. A selection of soil health resources and their soil property focus 169
Table 7.2. Variables used in the survey and the type of response requested for each variable 171
Table 7.3. Landholder ranked importance of selected soil health management factors for the Lachland and Macquarie Valley 174
Table 7.4. Landholder attitudes to various statements concerning soil health management 175
Table 7.5. Percent of landholders with a soil health management plan of some description, the type of planning identified with and the factors that influenced the adoption of this plan 177
Table 7.6. Education, agency and extension, and land-use impediments to the adoption of a soil health management plan as ranked by landholders of the Lachlan and Macquarie Valleys 178
Table 7.7. Market, economic, and personal and social use impediments to the adoption of a soil health management plan as ranked by landholders of the Lachlan and Macquarie Valleys 179
Table 7.8. Correlations between market-based impediments and property size Relationship strength is measured using the criteria set out by Cohen (1988) 183
Table 7.9 Landholder perceived impediments that are significantly related to the researcher defined district of origin Only the two extremes of an impediment's influence are presented (i.e. 'None' and 'Large'); Imped. is abbreviation for impediment. 190
Table 7.10 Possible incentives to the adoption of a soil health management plan as ranked by landholders of the Lachlan and Macquarie Valleys 191

List of figures

Chapter 3:

Figure 3.1. The Macquarie Valley 67
Figure 3.2. The Lachlan Valley 68
Figure 3.3. Aerial view of the Bellevue experimental site. The head ditch is to the south; (–) boundaries of the field; (–) boundaries of the experimental site; ‘N’ indicates the north direction 69
Figure 3.4. Aerial view of the Agriland experimental site. The head ditch is to the southwest; (–) boundaries of the field; (–) boundaries of the experimental site; ‘N’ indicates the north direction 71
Figure 3.5. Aerial view of the Mount View experimental site. The head ditch is to the east; (–) boundaries of the field; (–) boundaries of the experimental site; ‘N’ indicates the north direction 74
Figure 3.6. Aerial view of the Wyadra experimental site. The lateral move apparatus moves to and from northeast and southeast; (–) boundaries of the field; (–) boundaries of the experimental site; ‘N’ indicates the north direction 77
Figure 3.7. Single-stroke tractor-mounted hydraulic corer used for soil core sampling after 2.5 years 79
Figure 3.8. The measuring cylinder on the right contains Mount View (600-800 mm depth) soil for particle size analysis that was observed to flocculate after approximately 2 h, as a result of naturally occurring gypsum (1.35% total gypsum, Table 3.5) 81
Figure 3.9. XRD analysis out put for the Bellevue soil at the specified depth; data series are presented in the order (from bottom to top) K, K at 100°C, K at 550°C counts, Mg, glycerol treated; (–)indicates measurement on the Co axis; (–) indicates measurement on the Cu axis) 89
Figure 3.10. XRD analysis out put for the Agriland soil at the specified depth; data series are presented in the order (from bottom to top) K, K at 100°C, K at 550°C counts, Mg, glycerol treated; (–)indicates measurement on the Co axis; (–) indicates measurement on the Cu axis) 90
Figure 3.11. XRD analysis out put for the Mount View soil at the specified depth data series are presented in the order (from bottom to top) K, K at 100°C, K at 550°C counts, Mg, glycerol treated; (–)indicates measurement on the Co axis; (–) indicates measurement on the Cu axis) 91
Figure 3.12. XRD analysis out put for the Wyadra soil at the specified depth; data series are presented in the order (from bottom to top) K, K at 100°C, K at 550°C counts, Mg, glycerol treated; (–)indicates measurement on the Co axis; (–) indicates measurement on the Cu axis) 92

Chapter 4:

Figure 4.1**.** Changes in soil pH as a result of treatment effect after 2.5 years. Graphs in column (a) pertain to Bellevue; graphs in column (b) pertain to Agriland 97
Figure 4.2. Changes in electrolyte concentration as a result of treatment application after 2.5 years. Graphs in column (a) pertain to Bellevue; graphs in column (b) pertain to Agriland 98
Figure 4.3. Changes in aggregate stability in water as a result of treatment application after 2.5 years; (a) represents Bellevue data; (b) represents Agriland data; columns within treatments represent the 0–100 mm (black), 100–200 mm (grey) and 200–400 mm (white) layers; h.s.d. intervals are ordered relative to the layer order. 99

Figure 4.4. Correlation analysis of pH and electrolyte concentration by experimental site; (a) represents Agriland; (b) represents Bellevue 100
Figure 4.5. Correlation analysis of electrolyte concentration and aggregate stability in water dispersive index by experimental site; (a) represents Agriland; (b) represents Bellevue 100

Chapter 5:

Figure 5.1. Aggregate stability in water dispersive indices after 6 months and 2 years from ameliorant application for the Mount View and Wyadra soils. For the 6 month dispersive indices, h.s.d intervals are presented at α = 0.05 significance level. For the 2.5 year dispersive indices, the h.s.d intervals are presented for each layer (α = 0.05); these represent differences between treatments/control within layers, not between layers. 123
Figure 5.2. Total nitrogen and organic carbon percentages for the Mount View and Wyadra soils after 2.5 years from ameliorant incorporation (0–100 mm). Intervals show h.s.d for Mount View data (HSD MV) and Wyadra data (HSD W) in their respective data series 124
Figure 5.3 Cotton yield, by treatment, of the first crop planted post ameliorant application for Mount View and Wyadra. Tukey h.s.d intervals are presented at α = 0.05 significance level. 124
Figure 5.4 (a) Cotton seedling height at 5 weeks post emergence for Mount View in 2007 and 2009; (b) Cotton seedling height (2007) and wheat seedling height (2009) at 5 weeks post-emergence for Wyadra. For both (a) and (b), the intervals show the h.s.d for the respective year with differences between treatments/controls occurring within years, not between years. 125
Figure 5.5. Conceptual diagram for the movement of irrigation water, solution ionic concentration, and the consequent accumulation of salts; arrows represent the movement of water; the orange colour gradient represents ionic concentration increase; the blue colour gradient of the arrows indicates ion movement with irrigation/soil water at varying concentration. 128
Figure 5.6 Conceptual cross sectional view of a soil aggregate and the relative distribution of exchangeable cations, at three different periods after amendment application 133

Chapter 6:

Figure 6.1. Differences in electrical conductivity of soil leaching columns 24 hours after an irrigation event (a) and 2 weeks after an irrigation event (b) for seven irrigation events; (**–**) C0G0 (**–**) C0G5, (**–**) C144G0, (**–**) C144G5, (**–**) C5G0, and (**–**) C5G5; intervals represent the h.s.d. for the irrigation event of the same number. 150
Figure 6.3. Differences in leachate electrical conductivity over seven irrigation events 2 weeks apart; (–) C0G0 (–) C0G5, (–) C144G0, (–) C144G5, (–) C5G0, and (–) C5G5; the interval represents the hsd at the irrigation event with the same number 153
Figure 6.4. Differences in saturated hydraulic conductivity after 14 weeks; the interval represents the h.s.d. between means. 153

Chapter 7:

Figure 7.1. The boundaries of the survey sampling region; (**–**) represents the region boundary 170

GENERAL INTRODUCTION, AIMS AND THESIS OVERVIEW

"…the development of soil structure and its maintenance over time are essential for sustained high productivity."
– Rengasamy (2000)

1. General introduction, aims and thesis overview

1.1. Introduction

A major limiting factor for productive agriculture in Australia is soil sodicity. While it should be noted that no single definition of sodicity is in current universal use, it is commonly defined as "…a non-saline soil containing sufficient exchangeable sodium to adversely affect crop production and soil structure under most conditions…" (quoted in Sumner 1993). There are two issues with this definition of sodicity; it only refers to exchangeable sodium and does not detail what a 'sufficient amount of exchangeable sodium' is. However, Northcote and Skene (1972) proposed a threshold of 6 % exchangeable sodium in a given cation exchange capacity (CEC) to define sodicity. In theory, when subject to wetting, soils with an exchangeable sodium percentage (ESP) of 6% or more will disperse into clay, silt and sand fractions and those with an ESP below this threshold will remain in a stable state (Northcote and Skene 1972). However, this is not always the case. Provided the electrolyte concentration (directly proportional to, and measured as, electrical conductivity; EC) of the soil and any percolating solution is sufficiently low, soils with an ESP below the threshold of 6% can disperse (Sumner 1993). Therefore, considering ESP alone is not entirely adequate and EC should also be considered as a governing factor of soil stability. Indeed, a soil's tendency to disperse should be represented as a matrix between ESP and EC, with threshold EC (TEC) values determining changes in stability at given ESP values (McKenzie and Murphy 2005). Hence, a dispersion-based definition rather than a definition purely centred on sodium (Na^+) may be appropriate, as was identified at the Tatura Sodicity Conference in 2001 (Surapaneni *et al.* 2002).

Dispersion occurs upon wetting of a spontaneously dispersive soil, or after wetting and mechanical disturbance, such as raindrop impact or cultivation, of a potentially dispersive soil; it is a consequence of the adverse chemical attributes of a sodic soil. Consequently, dispersion is a measure of soil stability. When a soil is saturated with Na^+ the diffuse cloud of ions adjacent to the negatively charged clay face is situated further away than when the same soil is saturated with calcium (Ca^{2+}) (Sposito 1989; Sparks 2003). This refers to a phenomenon known as the diffuse double layer (DDL) effect. A stronger attraction is the result of greater ionic valency, which means that the diffuse cloud of ions becomes closer (a thinner DDL) to the clay surface as valency increases. A thin DDL allows attractive forces, such as van der Waals forces, to hold clay particles together into flocs (Sposito 1989; Sumner 1993; Sparks 2003).

These chemical processes result in various soil physical attribute changes. Some of the associated physical ramifications of dispersion include the hard-setting of a soil horizon, pore blockage that causes decreased infiltration and water-holding capacity, decreased aeration due to water-ponding after rainfall events, increased run-off during rainfall events, increased soil strength and decreased friability/workability of the soil, and the formation of impermeable crusts on the soil surface (Rengasamy and Olsson 1991; McKenzie *et al.* 1993; So and Aylmore 1993; Greene 2002). This list is by no means exhaustive and the occurrence of dispersion does not necessarily guarantee that all of these physical changes will occur. However, this list of consequences illustrates an important point; the environment in which pastures and crops are expected to grow, under sodic circumstances, is an extremely unhealthy one indeed. It is, therefore, not surprising that the ultimate effect of sodicity is decreased productivity of agricultural soils.

The occurrence of sodicity in a soil profile is not necessarily uniform. It can occur in any horizon of a soil and also in isolated pockets, like the rhizosphere, or in different soil types within the same paddock (Murphy 2002). Generally, if topsoil is sodic, it is fair to expect the underlying subsoil to be sodic also. Sodicity is an issue that is inherent to Australian soils and is often exacerbated by land management practices. A non-sodic soil can be made sodic through human influences (e.g. use of poor quality irrigation water), although such an occurrence is far outweighed by the inherent of sodicity of Australian soil landscapes.

The occurrence of sodic soil (at least one horizon with ESP > 6%) is estimated to affect 25–30% of all Australian soils (Northcote and Skene 1972). Equating to approximately 340 million hectares (Massoud 1977; Murphy 2002), this is the greatest occurrence of sodic soil on any continent, accounting for approximately half of the sodic soil across the globe (Tanji 1990). Within NSW specifically, Northcote and Skene (1972) estimate 47% of soil to be affected by sodicity; this is notably higher than the national percentage estimate.

Solutions to sodicity and its consequences are often sought after. However, a solution may not necessarily be achievable. As detailed earlier, Australian soils are inherently sodic and this could mean that a certain level of sodicity is the natural equilibrium, and that any effort to completely eradicate sodium from the soil profile is in vain. The usual method of addressing sodicity is to displace the sodium with a cation of greater valency – commonly calcium (Shanmuganathan and Oades 1983; Sumner 1993; Qadir *et al.* 2001b). This displaced sodium cannot just disappear and must exist in somewhere in the soil profile – the result is normally movement further into the profile via leaching. Therefore, the movement and accumulation of sodium needs to be carefully managed (Rengasamy 2002). In some cases, it is possible to remove excess sodium from a given soil depth so that the sodium is no longer an influence on the plant root environment. Technically, this soil has been eradicated of sodium with reference to productive farming, but this is not so easily done, nor easily maintained. It may, therefore, be more appropriate to manage a soil at its current level of sodicity, ensuring the soil structure does not deteriorate further, rather than seeking solutions.

Calcium is the key to displacement of sodium from the clay face and the subsequent leaching of it further into the soil profile. The most common source of calcium added to the soil to ameliorate sodicity is gypsum ($CaSO_4.2H_2O$) (Bridge 1968; Loveday 1974; McKenzie 1982; Oster 1982; Ford *et al.* 1985; Abbott and McKenzie 1986; Wallace 1994; Ghafoor *et al.* 2001; Prathapar *et al.* 2005). This compound is suitable because it is relatively soluble, has moderate exchange efficiency (ratio of Na replaced to Ca dissolved) and is usually readily available at a reasonable cost. Greene and Ford (1985) calculated the solubility of gypsum in the soil solution of two red duplex soils to be between 760–828 mg.L^{-1}, with an exchange efficiency of 26–34%. Similarly, Valzano *et al.* (2001b) calculated the solubility of gypsum in the soil solution of a Brown Sodosol as 770 mg.L^{-1} with an exchange efficiency of 20–40%. Considering these field solubilities, this equates to a requirement of 120–130 mm.ha^{-1} of rainfall to completely leach 1 t.ha^{-1} of gypsum from the A horizon (Greene and Ford 1985). As the yearly average rainfall for agricultural regions of Australia is generally above 360 mm (the approximate minimum amount required to remove 3 t.ha^{-1} of gypsum from the A horizon), the question of longevity of ameliorative effect is posed. Considering the magnitude of irrigation water inputs (often above 1 m.ha^{-1} annually), it is apparent that the longevity of ameliorative effect of gypsum is likely to be substantially shortened in irrigated soils.

The use of lime ($CaCO_3$) as a sodicity ameliorant has also been explored (Gardner and Gardner 1953; Shainberg and Gal 1982; Roth and Pavan 1991; Chan and Heenan 1998; Valzano *et al.* 2001b). Lime contains approximately double the Ca^{2+} that gypsum does; 400 kg.t^{-1} as compared to 200 kg.t^{-1}, respectively (Abbott and McKenzie 1986). However, the theoretical solubility of lime in water is 15 mg.L^{-1}, which is approximately 40 times less soluble than gypsum. On face value, it would seem that this source of Ca^{2+} should provide a more prolonged ameliorative effect. However, this will only be the case in a soil with an acid to neutral pH, whereas the majority of sodic soils tend to exhibit alkaline pH (Sumner 1993; Valzano *et al.* 2001b). This is important because the traditional agronomic use of lime is to raise pH and it ceases to be soluble at a pH of approximately 8.2. Hence, only very limited success for lime as a sodicity ameliorant has been observed. However, when applied in conjunction with gypsum to dryland Sodolsols, Valzano (2001) and Bennett (2006) have shown that a synergistic effect between gypsum and lime can sometimes be observed, where the gypsum aids in the dissolution of the lime through displacement of hydrogen, along with some associated rhizospherical effects. Thus, the rate of dissolution of the lime is increased by gypsum. Dissolution of lime, augmented by gypsum, may occur in a soil with a pH up to

8.2 (the point of insolubility for lime) and possibly at bulk soil pH levels higher than 8.2 where the lime is proximal to the rhizosphere. However, the documented effects of gypsum and lime synergy within and/or external to the rhizosphere are limited to only a handful of studies (see Valzano *et al.* 2001b; Bennett 2006). Additionally, when considering the use of lime and gypsum in combination, and under irrigation, the documented observations are limited further still (see McKenzie *et al.* 1993; Chan *et al.* 1999).

Even though there has been success with gypsum and lime/gypsum combinations in ameliorating sodic horizons, this still may not result in an obvious increase in productivity. The management of sodic soils may not always be as simple as directly targeting sodium levels in the soil. Indeed, while ESP is important to soil structural stability, that value alone should only be considered as a useful guide to a soil's tendency to disperse, as other soil attributes often influence structural stability (Sumner 1993). Factors such as organic matter content, the presence or absence of other exchangeable cations, electrolyte concentration (EC), clay mineral suite, and rhizospherical conditions (such as the occurrence of exudates and polysaccharides and subsequent microbial stimulation) all affect the stability of soil aggregates to some extent (Quirk and Schofield 1955; Quirk and Aylmore 1960; Tisdall and Oades 1979; Sumner 1992; Tisdall *et al.* 1997; Sparks 2003). Hence, these factors will alter the extent to which a soil will disperse upon wetting. Organic matter content and rhizospherical effects primarily form, or instigate the formation of, physical bonds, or cementation, between soil aggregates that overcome the adverse chemical effects of a sodic soil without necessarily ameliorating the underlying problem (Nelson *et al.* 1999). On the other hand, EC augments stability through chemical interactions and is arguably the factor (from the list above) most closely associated with stabilising soil structure, as previously discussed. The clay mineral suite of a given soil will help to determine the TEC values and thus the ESP/EC point at which clay particle flocs form (Rengasamy *et al.* 1984a; Rengasamy *et al.* 1984b).

It is apparent that management for soil sodicity is complex, with further complexity being introduced by irrigation programs (Kovda *et al.* 1973; Oster and Schroer 1979; Rengasamy and Olsson 1993). In order to enhance productivity, Na^+ is required to be leached out of root-zone soil horizons by good quality irrigation water and rainfall, but this also lowers the EC. If the EC becomes too low, even soils with ESP < 6% can become unstable (Sumner 1993). On the other hand, during periods of drought there is an increased reliance on groundwater for irrigation, which is often high in EC. This reliance on groundwater can bolster the EC, meaning the soil will remain flocculated at higher ESP, but it can also cause the soil to become saline-sodic and thus decreases productivity due to salinity constraints

(Kovda *et al.* 1973; Oster and Schroer 1979). Subsequent leaching with fresh irrigation water or rainfall is therefore required. A further consideration is the end point of the leached Na^+. If a sodic B horizon exists, the Na^+ may accumulate in a 'bulge' in the subsoil, not unlike a perched water table. Additionally, if it can't leach further into the profile it becomes highly susceptible to lateral movement – termed 'transient salinity' by Rengasamy (2002). While this process is usually quite slow in a dryland farming system, it can occur quite rapidly in an irrigated system, due to the magnitude and frequency of irrigation water application. Hence, management of sodic soils must be strongly linked with management for salinity in irrigated production systems.

In order for landholders to effectively manage for sodic soils a firm understanding of the causes and ramifications of sodicity are required. However, as illustrated in a report by Watson *et al.* (2000) this is not the case. They reported that 52% of local governments did not believe sodicity to be an issue, with a further 22% unaware of sodicity. These statistics raise concern as local governments, often comprised of local landholders, are responsible for the representation of the local farming community and should be up to date with issues affecting the wellbeing and longevity of this community. At the same conference that these statistics were presented (the Tatura Sodicity Conference) it was identified that an estimated AUD$1.3 billion in annual potential production in agriculture is lost due to untreated sodic soils. Comparatively, untreated salinity caused an economic reduction in potential production of AUD$130 million (ten times less than sodicity, Watson *et al.* 2000). Interestingly, 74% of local governments believed salinity to be an issue in their area, with only 9% unsure. These are curious statistics considering that sodicity is estimated to affect 340 million ha (Murphy 2002), whereas salinity is estimated to affect 2.5 million ha of Australian soil with a forecast of 4 million ha of affected soil by 2050 (Robertson 1996). Hence, one could have logically expected a greater reported understanding of sodicity in the Watson *et al.* (2000) report as compared to salinity. The symptoms of sodic soils are often misconstrued as those of salinity, while sodicity is often heard to be defined as salinity, or the same as salinity. Therefore, management of sodicity is also hindered by a lack of understanding, or an incomplete understanding. By addressing this issue, management techniques could be improved and implemented, increasing Australia's agricultural productivity.

It is apparent that the issue of sodicity is multifaceted and the challenge of managing Australian soils for sodicity is made more difficult when coupled with irrigated agriculture. For this reason, sound management practices need to be developed. Further information is required to determine whether farmers should be trying to leach excess sodium out of a given horizon to maintain an ESP of <6, or whether farmers should seek to maintain a manageable minimum ESP with a concentrated goal of managing EC during critical windows of opportunity (such as germination and the transition to a juvenile plant) in the cropping/pasture cycle. Perhaps farmers should liken farming to mining, albeit on a small scale, where crops and pastures mine nutrients and critical chemical constituents of a healthy soil with every harvesting or stock grazing. If the soil nutrients and critical chemical constituents are considered as a finite resource within the soil, then management of these resources should be focused on the longevity of production through periodic replacement of these resources, rather than the magnitude of production for short term gain. On this basis, perhaps Ca^{2+} should be thought of and applied in the same way as fertilizers containing nitrogen and phosphorus are applied – annually and as a necessity. These aren't entirely new suggestions, and past recommendations have included:

1. the annual application of small amounts of gypsum (e.g. Valzano *et al.* 2001b);
2. the use of green manure crops to change hydrogen levels in a soil and augment the effect of gypsum (Sekhon and Bajwa 1993; Chorom and Rengasamy 1997);
3. the physical stabilisation of soil through various rhizospherical effects such as enmeshing of aggregates by plant roots or binding of aggregates due to localised root mucilage (Tisdall and Oades 1979; Tisdall *et al.* 1997; Allen 2007); and,
4. the use of various plant species to access and dissolve soilborne carbonates (phytoremediation) in order to provide an inherent source of exchangeable Ca^{2+} (Robbins 1986b; Robbins 1986a; Qadir and Oster 2002; Qadir *et al.* 2002; Mubarak and Nortcliff 2010).

However, there still remains the question of longevity of gypsum effects under irrigation and the viability of using gypsum in combination with lime to create a synergistic release of calcium in irrigation systems. Furthermore, the matter of education surrounding the origin, definition and consequences of sodicity requires attention.

1.2. Aims

The use of gypsum on both dryland and irrigated sodic soils has been relatively well studied (see Oster 1982; Ghafoor *et al.* 2001; Qadir *et al.* 2002), whereas experiments investigating lime as a sodicity ameliorant have shown little success. This lack of success, and the fact lime is used as a pH buffer, has caused it to be largely disregarded as useful for sodicity amelioration. Due to the extensive evidence for gypsum use as a sodicity ameliorant, and the general disregard of lime as an ameliorant, lime/gypsum combinations have only been given cursory consideration, especially under irrigation. Hence, this study is principally concerned with addressing lime and gypsum use for amelioration of sodic soils in the Lachlan and Macquarie Valleys of NSW. However, as has been identified, there is an ignorance encompassing the issue of sodicity and perhaps soil health in general. For this reason, a small focus of the study will be on understanding landholders' soil health management education and the impediments associated with implementing a soil health program in the Lachlan and Macquarie Valleys.

It follows that the study has these four main aims:

1. To determine if a synergistic ameliorative effect between lime and gypsum on dispersion, as observed in dryland agriculture, occurs in irrigated sodic soils.

2. To determine the viability of a single application of lime and gypsum as a means of ameliorating sodicity over a period of 2.5 years in an irrigated agricultural system.

3. To explore the use of incorporating a compost containing gypsum into an irrigated sodic soil as a means of supplying calcium, for the displacement of sodium, in a less mobile state as compared to applying gypsum alone.

4. To investigate landholders' understanding of soil health issues, specifically sodicity, by assessing their attitudes and opinions towards soil health, as well as the associated impediments of implementation of soil health management programs.

1.3. Thesis overview

1.3.1. Chapter 1: General introduction, aims and thesis overview

This chapter introduces broad issues associated with soil sodicity and gives some background concerning sodic soils. It identifies various questions about the complex nature of management for sodic soils and introduces the aims of the study in relation to these.

1.3.2. Chapter 2: The characterisation of sodic soils, ameliorative techniques and strategies for management: a review

This chapter presents the background information that pertains to current research and highlights knowledge gaps that further reinforce the justification for this study as presented in chapter one. This chapter includes: the general background of sodicity – genesis, distribution, definition and distinction – and outlines the dispersive nature of sodic soils; it presents the physical consequences of dispersion; it explains the chemical processes governing these physical consequences; and, offers an overview of methods and management techniques used to ameliorate and manage sodic soils.

1.3.3. Chapter 3: A description of four sodic soils and the soil analytical methods employed in this work

This chapter introduces the four soils used for the study, encompassing the important attributes of each soil. This includes the geographical location of each site, a history of each site, the climate, irrigation systems and availability, rainfall data, chemical composition of soil, soil texture classes, and clay mineral suite. A detailed description of the methods used in the analysis of these sodic soils is also presented.

1.3.4. Chapter 4: The effects of lime ($CaCO_3$), gypsum ($CaSO_4.2H_2O$), and lime/gypsum combinations, after 2.5 years, on selected soil properties of two sodic soils under dryland cropping conditions in the Macquarie Valley, New South Wales

This chapter investigates and discusses the effects of lime, gypsum and lime/gypsum combinations on the pH, electrolyte concentration and aggregate stability of the two properties situated in the Macquarie Valley. Due to sub-optimal rainfall, irrigation water was unable to be secured and applied to these experimental sites. Thus, the results are presented and discussed on a dryland cropping system basis. Data is presented for the long-term (2.5 years) since ameliorant application. The possibility of lime and gypsum synergy is discussed with reference to previous dryland research.

1.3.5. Chapter 5: The efficacy of using lime ($CaCO_3$), gypsum ($CaSO_4.2H_2O$) and lime/gypsum combinations to ameliorate sodicity in two irrigated soils used for cropping in the Lachlan Valley of New South Wales

This chapter investigates and discusses the effects of lime, gypsum and lime/gypsum combinations on the two irrigated Lachlan Valley properties, situated near Hillston. Data is presented for the short-term (6 months) and the long-term (2.5 years). The viability of lime and gypsum use is analysed and discussed using data collected on exchangeable cations, soluble cations, pH, electrolyte concentration, aggregate stability, nitrogen, organic carbon and crop productivity. The longevity of the electrolyte effect and aggregate stability, as compared to ionic exchange, are also discussed. This chapter has been presented in the form of a manuscript for submission to a peer-reviewed scientific journal.

1.3.6. Chapter 6: The merits of a gypsum ($CaSO_4.2H_2O$) enhanced chicken manure/wheat straw compost in ameliorating an irrigated sodic Brown Vertosol – laboratory experiment

Considering that the magnitude and frequency of irrigation water applied to agricultural soil is likely to enhance the dissolution of gypsum and movement of Ca^{2+} throughout the soil profile, this chapter investigates a potential slow release mechanism for Ca^{2+}. A comparison of gypsum, compost and gypsum-enhanced compost application in ameliorating sodicity under simulated irrigation wetting and drying cycles is undertaken. Over a 14 week period, soil leaching columns were subjected to seven irrigation events with approximately 6.5 $ML.ha^{-1}$ (in total) of good quality irrigation water. Changes in sodicity are analysed and discussed with reference to soil exchangeable cations, leachate soluble cations, compost chemical constituents (exchangeable and soluble cations), periodic electrolyte data relevant to soil conditions, and saturated hydraulic conductivity, as affected by treatment application. The possibility of synergy between gypsum and compost is discussed, as well as the occurrence and longevity of the observed electrolyte effect. The effect of highly exaggerated, commercially unviable, application rates is also presented. This chapter has been constructed in the form of a manuscript for submission to a peer-reviewed scientific journal.

1.3.7. Chapter 7: Impediments to the adoption of soil health improvement strategies by farmers in Central West NSW

It is well and good to provide strategies for the successful management of sodicity, however if landholders do not posses a knowledge of sodicity and it consequences, or are not prepared to adopt such management strategies, then these startegies become redundant. Therefore, in order to combat sodicity effectively, it is imperative to assess landholders' knowledge and preparedness to deal with such issues. On this basis, the results of a mail-based survey pertaining to the adoption of soil health management innovations by landholders of Central West New South Wales are presented in this chapter. Landholders were asked to indicate their knowledge of certain soil health issues, such as sodicity and salinity, and identify the importance of the same to the management of their properties. The implementation of a soil health management plan was indirectly analysed, and impediments to the adoption of the same were assessed through a series of categorical soil health impediment statements. The results were discussed with reference to landholders' attitudes towards soil health management, the influence of the various impediment categories, and possible means of addressing soil health management plan adoption. This was discussed considering landholder responses as both a homogenous group and as local region responses. This chapter has also been presented in the form of a manuscript for submission to a peer-reviewed scientific journal.

1.3.8. Chapter 8: General discussion, conclusions, and future research

This chapter presents a discussion of the previous chapters through a comparison of the results obtained in each chapter. Of note, a comparison of dryland and irrigated use of lime and gypsum is presented, along with reference to the viability of such applications. Limitations of the field-based experimental design are also discussed regarding the implications for future use of chemical ameliorants, and the possibility of improving soil chemical data collection via the use of proximal sensors. The general conclusions pertaining to the stated aims are presented and future research as a result of this work is detailed.

1.4. References

Abbott, TS & McKenzie, DC (1986) Improving soil structure with gypsum. Agfact AC 10, NSW Agriculture

Allen, MF (2007) Mycorrhizal fungi: highways for water and nutrients in arid soils. *Vadose Zone Journal* **6,** 291-7.

Bennett, JMcL (2006) *Interactions between chemical ameliorants and vegetation in a sodic red brown earth, Upper Bogan region, NSW*, Thesis - Australian National University, Canberra.

Bridge, BJ (1968) *soil physical properties as influenced by gypsum*, Thesis - University of Sydney, Sydney.

Chan, KY, Dexter, AR & McKenzie, DC (1999) Categories of soil structure based on mechanical behaviour and their evaluation using additions of lime and gypsum on a sodic Vertisol. *Australian Journal of Soil Research* **37,** 903-11.

Chan, KY & Heenan, DP (1998) Effect of lime (CaCO3) application on soil structural stability of a red earth. *Australian Journal of Soil Research* **36,** 73-86.

Chorom, M & Rengasamy, P (1997) Carbonate chemistry, pH, and physical properties of an alkaline sodic soil as affected by various amendments. *Australian Journal of Soil Research* **35,** 149-61.

Ford, GW, Greene, RSB & Rengasamy, P (1985) Estimation of gypsum requirement of agricultural soils. *Proceedings for the Australian Soil Science Society***,** 103-10.

Gardner, HW & Gardner, HV (1953) 'The use of lime', (Farmer & Stock-Breeder Publications Ltd: London)

Ghafoor, A, Gill, MA, Hassan, A, Murtaza, G & Qadir, M (2001) Gypsum: An economical amendment for amelioration of saline-sodic waters and soils, and for improving crop yields. *International Journal of Agriculture and Biology* **3,** 266-75.

Greene, RSB (2002) Hardsetting soils. *In* 'Encyclopedia of soil science'. (Eds. Lal, R) (Marcel Dekker: New york)

Greene, RSB & Ford, GW (1985) The effect of gypsum on cation exchange in two red duplex soils. *Australian Journal of Soil Research* **23,** 61-74.

Kovda, V, van den Berg, C & Hagan, RM (1973) 'Irrigation, drainage and salinity: An international source book', (Hutchinson and Co.: London)

Loveday, J (1974) Recognition of gypsum responsive soils. *Australian Journal of Soil Research* **25**.

Massoud, FI (1977) Basic principals for prognosis and monitoring of salinity and sodicity *In* 'Proceedings of the International Conference on Management of Saline Water for Irrigation' (Lubbock, TX: Texas Technical University)

McKenzie, DC (1982) *Evaluation of gypsum as an ameliorant for cracking-clay soils of the Moree district, N.S.W.*, Thesis - University of New England, Armidale.

McKenzie, DC, Abbott, TS, Chan, KY, Slavich, PG & Hall, DJM (1993) The nature, distribution and management of sodic soils in New South Wales. *Australian Journal of Soil Research* **31,** 839-68.

McKenzie, DC & Murphy, BW (2005) *Use this graph to interpret your soil tests and predict the dispersion and/or salinity characteristics of your soils*, Don Stanger Public Relations

Mubarak, AR & Nortcliff, S (2010) Calcium carbonate solubilization through H-proton release from legumes grown in calcaerous saline-sodic soils. *Land Degredation and Development* **21,** 24-31.

Murphy, BW (2002) Sodic soils: formation and global distribution of. *In* 'Encyclopedia of soil science'. (Eds. Lal, R) (Marcel Dekker: New York)

Nelson, PN, Baldock, JA, Clarke, P, Oades, JM & Churchman, GJ (1999) Dispersed clay and organic matter in soil: their nature and associations. *Australian Journal of Soil Research* **37,** 289-315.

Northcote, KH & Skene, JK (1972) *Australian soils with saline and sodic properties*. CSIRO Soil Publication 27, (CSIRO: Australia)

Oster, JD (1982) Gypsum use in irrigated agriculture: a review *Fertilizer Research* **3,** 73-89.

Oster, JD & Schroer, FW (1979) Infiltration as influenced by irrigation water quality. *Soil Science Society of America Journal* **43,** 444-7.

Prathapar, SA, Aslam, M, Kahlown, MA, Iqbal, Z & Qureshi, AS (2005) Gypsum slotting to ameliorate sodic soils in Pakistan. *Irrgation and Drainage* **54,** 509-17.

Qadir, M & Oster, JD (2002) Vegetative bioremediation of calcareous sodic soils: history, mechanisms, and evaluation. *Irrigation Science* **21,** 91-101.

Qadir, M, Qureshi, RH & Ahmad, N (2002) Amelioration of calcareous saline sodic soils through phytoremediation and chemical strategies. *Soil Use and Management* **18,** 381-5.

Qadir, M, Schubert, S, Ghafoor, A & Murtaza, G (2001) Amelioration strategies for sodic soils: a review. *Land Degredation and Development* **12,** 357-86.

Quirk, JP & Aylmore, LAG (1960) Swelling and shrinkage of clay-water systems. *7th International Congress of Soil Science* **11,** 378-87.

Quirk, JP & Schofield, RK (1955) The effect of electrolyte concentration on soil permeability. *Australian Journal of Soil Research* **6,** 163-78.

Rengasamy, P (2002) Transient salinity and subsoil constraints to dryland farming in Australian sodic soils: an overview. *Australian Journal of Experimental Agriculture* **42,** 351-61.

Rengasamy, P, Greene, RSB & Ford, GW (1984a) The role of clay fraction in the particle arrangement and stability of soil aggregates - a review. *Clay Research* **3,** 53-67.

Rengasamy, P, Greene, RSB, Ford, GW & Mehanni, AH (1984b) Identification of dispersive behaviour and the management of red-brown earths. *Australian Journal of Soil Research* **22,** 413-31.

Rengasamy, P & Olsson, KA (1991) Sodicity and soil structure. *Australian Journal of Soil Research* **29,** 935-52.

Rengasamy, P & Olsson, KA (1993) Irrigation and sodicity. *Australian Journal of Soil Research* **29,** 821-37.

Robbins, CW (1986a) Carbon dioxide partial pressure in lysimeter soils. *Agronomy Journal* **78,** 151-8.

Robbins, CW (1986b) Sodic calcareous soil reclamation as affected by different amendments and crops. *Agronomy Journal* **78,** 916-20.

Robertson, GA (1996) Saline land in Australia - its extent and predicted trends. *Australian Journal of Soil and Water Conservation* **9,** 4-7.

Roth, CH & Pavan, MA (1991) Effects of lime and gypsum on clay dispersion and infiltration in samples of a Brazillian Oxisol. *Geoderma* **48,** 351-61.

Sekhon, BS & Bajwa, MS (1993) Effect of organic matter and gypsum in controlling soil sodicity in rice-wheat-maize system irrigated with sodic waters. *Agricultural Water Management* **24,** 15-25.

Shainberg, I & Gal, M (1982) The effect of lime on the response of soils to sodic conditions. *Journal of Soil Science* **33,** 489-98.

Shanmuganathan, RT & Oades, JM (1983) Modification of soil physical properties by addition of calciaum compounds. *Australian Journal of Soil Research* **21,** 285-300.

So, HB & Aylmore, LAG (1993) How do sodic soils behave? The effects of sodicity on soil physical behaviour. *Australian Journal of Soil Research* **31,** 761-77.

Sparks, DL (2003) 'Environmental soil chemistry', (Academic Press: London)

Sposito, G (1989) 'The chemistry of soils', (Oxford University Press: New York)

Sumner, ME (1992) The electrical double layer and clay dispersion. *In* 'Soil crusting: chemical and physical processes'. (Eds. Sumner, ME & Stewart, BA) (Lewis Publishers: Boca Raton)

Sumner, ME (1993) Sodic soils: a new perspective. *Australian Journal of Soil Research* **31,** 683-750.

Surapaneni, A, Olsson, KA, Burrow, DP, Beecher, HG, Ham, GJ, Stevens, RM, Hulugalle, NR, McKenzie, DC & Rengasamy, P (2002) Tatura sodicity conference: knowledge gaps in sodicity research for major agricultural industries. *Australian Journal of Experimental Agriculture* **42,** 379-87.

Tanji, KK (1990) Nature and extent of agricultural salinity. *In* 'Agricultural salinity assessment and amangement'. (Eds. Tanji, KK) (American Society of Civil Engineers: New York)

Tisdall, AL, Smith, SE & Rengasamy, P (1997) Aggregation of soil by fungal hyphae. *Australian Journal of Soil Research* **35,** 55-60.

Tisdall, JM & Oades, JM (1979) Stabilization of soil aggregates by the root systems of ryegrass. *Australian Journal of Soil Research* **17,** 429-41.

Valzano, FP, Murphy, BW & Greene, RSB (2001) The long term effects of lime ($CaCO_3$), Gypsum ($CaSO_4.2H_2O$), and tillage on the physical and chemical properties of a sodic red-brown earth. *Australian Journal of Soil Research* **39,** 1307-31.

Wallace, A (1994) Use of gypsum on soil where needed can make agriculture more sustainable. *Communications in Soil Science and Plant Analysis* **25,** 109-16.

Watson, WD, Hall, NH & Hamblin, A (2000) Economic aspects of sodic, acid and saline soils in Australia. *In* 'Proceedings of the Sodicity conference: sodicity issues in agricultural industries - current research and future directions' (ISIA: Tatura, Victoria)

THE CHARACTERISATION OF SODIC SOILS, AMELIORATIVE TECHNIQUES AND STRATEGIES FOR MANAGEMENT: A REVIEW

> *"It is impossible to begin to learn that*
> *which one thinks one already knows."*
> *– Epictetus*

2. The characterisation of sodic soils, ameliorative techniques and strategies for management: a review

2.1. Introduction

Distributed throughout the world are around 950 million ha of salt-affected soils (Szabolcs 1991). Of this area, approximately 60% is considered sodic (Tanji 1990) in that they contain adverse amounts of sodium on the clay exchange sites. The annual economic impact of salt-affected soil on production value is estimated to be in excess of US$12 billion (Ghassemi *et al.* 1995), while in Australia the annual loss of potential production due solely to sodicity is approximated to be AUD$1035 million (Hajkowicz and Young 2005). Sodicity is known to have a deleterious effect on soil condition, and subsequent production, that requires careful management. Considerable research has been conducted concerning the global consequences and management of sodic soils (Rengasamy and Olsson 1991; McKenzie *et al.* 1993; So and Aylmore 1993; Sumner 1993; Jayawardane and Chan 1995; Qadir *et al.* 2001b; Dang *et al.* 2006). With sodicity occurring in up to 75 countries (Szabolcs 1994) many different soil types with various mineralogical suites and textural categories are affected. However, the consequences and concomitant implications for soil management remain similar.

A further concern for management of not just sodic soil, but all agricultural land, is the mounting pressure, from an expanding population, to increase food and fibre production (Fraiture *et al.* 2007). However, the opportunity to farm ‘new’ land is rapidly decreasing, or non-existent, in many parts of the world (Prathapar *et al.* 2005). In order address this mounting pressure without expanding the available agricultural area, farms will be required to become more productive. Hence, there will most likely be an increased reliance on irrigation to produce more on less landspace. Approximately 25% of the world’s irrigated land mass is already salt-affected (Szabolcs 1994) with the potential for this area to increase through processes such as recurrent irrigation with saline-sodic water, insufficient drainage, and inefficient farming practices. While a concerted effort is made to control salt-affected soils, such as sodic soils, these problems are still increasing (Prathapar *et al.* 2005).

To combat sodicitity and its consequences, strategies involving the use of applied gypsum, and more recently lime or lime/gypsum combinations, are usually adopted. Lime and gypsum effectively donate calcium (Ca) ions replacing sodium (Na) ions, which causes an associated increase in soil profile water supply through soil structural improvement. However, these strategies have primarily been developed for dryland farming regimes. While a reasonable quantity of information concerning the use of gypsum in irrigated sodic soils exists, there is a comparative paucity of research conducted on the effects of lime and lime/gypsum combinations on irrigated soils. Furthermore, findings of the Tatura Sodicity Conference, 2001, indicated that while gypsum is used widely by landholders to ameliorate sodicity, little is known about the long–term effects of lime/gypsum mixtures (Surapaneni *et al.* 2002). It is therefore apparent that there is a need for further research on chemical ameliorants for irrigated sodic soils, in particular.

Although chemical ameliorants have been shown to be beneficial for sodic soil remediation, they are not always available or affordable. This circumstance is especially true for broadacre farming, where sodic constraints may cause the chemical ameliorant requirement to prove uneconomical. In order to address these problems research has been conducted on the role of plant matter incorporation (Swarup 1988; Reeves 1997; Clark *et al.* 2009), manure compost application (Poona and Bhumbla 1973; Wahid *et al.* 1998; Gosh *et al.* 2010) and phytoremediation (Robbins 1986b; Robbins 1986a; Qadir *et al.* 2002; Mubarak and Nortcliff 2010) to assist with the amelioration of sodic soils. These three alternative remediation techniques have been shown to provide positive structural effects in sodic soils, generally through physical bonding (Tisdall and Oades 1979; Tisdall *et al.* 1997) and plant chemical interactions, both through the role of H-proton release and carbon dioxide partial pressure (P_{CO_2}) in solubilising pedogenic calcium carbonate (Robbins 1986a; Qadir and Oster 2002). However, as with chemical ameliorants, these processes have undergone only limited investigation in irrigated agricultural settings, especially in Australia. Furthermore, limited information exists for the use of such processes in conjunction with lime and gypsum combinations (Valzano *et al.* 2001b; Bennett 2006).

Hence, this review seeks to investigate a) the structural degradative processes of sodic soils and the associated consequences for production, b) the ameliorative and management techniques employed on such soils in the agricultural environment, and c) highlighting areas requiring further research, particularly with regard to irrigated agriculture in Australia.

2.2. Issues associated with defining sodic soils

Sodic soils have classically been decribed as"…a non-saline soil containing sufficient exchangeable Na^+ to adversely affect crop production and soil structure under most conditions…" (Anon, 1979), as quoted in Sumner (1993 pg. 686). Building on this, So and Aylmore (1993) characterise sodicity by a level of exchangeable Na sufficiently high to cause a considerable reduction in the structural stability, fertility and pasture production, in that sequence. However, there is no single sgreed definition of sodic soils, resulting in many different suggestions for an exchangeable sodium percentage (ESP) threshold level, or lower limits, to define sodicity. These include, an ESP of 5 but less than 15 for Vertosols in India

(Kadu *et al.* 2003), ESP 40 for the Indo-Gangetic Plains in India (Abrol and Fireman 1977), an ESP of 6 (Northcote and Skene 1972) or 5 (McIntyre 1979) in Australia, and an ESP of 15, as suggested by the United States Department of Agriculture (Soil Survey Staff 1999).

ESP alone is an inadequate measure of sodicity, as even soils with ESP less than 5 have been observed to disperse, provided the soil and percolating solution are sufficiently low in electrolyte. From this, it was deduced that electrical conductivity (EC), or electrolyte concentration, is also a major governing factor for such soils. In fact, McKenzie and Murphy (2005), based on the work of Rengasamy *et al.* (1984), showed that ESP and EC together produced a matrix of dispersion effects rather than acting as independent characterising factors. Hence, Sumner (1993) later suggests that a definition based on dispersion extent rather than sodium content may be appropriate, as was identified at the Tatura Sodicity Conference (Surapaneni *et al.* 2002). Subsequently, Pal *et al.* (2006) advocate the use of saturated hydraulic conductivity (K_{sat}) less than 10 mm.h^{-1}, as a weighted mean in the 0-100 cm depth of soil, as the threshold for this dispersive definition. However, a threshold based on K_{sat} is not appropriate, as it can be confounded by other processes like mechanical soil compaction and slaking.

Due to an abundance of research that uses ESP and EC to characterise sodicity, the dispersive matrix between ESP and EC will be used to define sodicity in this review.

2.3. Dispersive properties of sodic soils

From an agronomic viewpoint, the primary consequence of sodicity is soil dispersion. This term refers to the instability of soil aggregates and the subsequent separation of clay particles from the silt and sand fractions of the soil upon wetting, due to both the chemical nature of the soil and the forces that govern it. Quirk and Schofield (1995) have attributed this chemical phenomenon to the species of exchangeable cations present and the EC, measured as electrolyte concentration of the soil. Specifically, if the ratio of Na^+ compared to other exchangeable ions in the CEC is large then there is a proportional likelihood the soil will disperse, unless there is sufficient electrolyte to maintain flocculation. Even still, Sumner (1993) suggests that a soil with low ESP is capable of dispersal providing the EC of the soil is sufficiently low, or the percolating solution has total electrolyte concentration (TEC) approaching that of pure water.

Clays that are high in exchangeable Na^+ are considered chemically prone to dispersion due to the relatively large size of Na ions (Pupisky and Shainberg 1979). The large size of Na^+, and its weak positive charge, causes it to have only weak attraction to the negatively charged clay surfaces, which is further explained by diffuse double layer theory (van Olphen

1963; Charman and Murphy 1991; Sumner 1993). However, as Churchman *et al.* (1995) point out, not all soil minerals are affected in the same way or to the same extent by Na^+. For example, smectites are considered to be more prone to instability than kaolinites. Therefore, three primary behaviour determining factors for sodic soil are; the ESP of the CEC, EC of the soil solution, and the type and percentage of clay present. It is these three factors and their interaction that control dispersive potential of a given soil.

A further factor affecting dispersion in sodic soils, although to a lesser extent, is pH. This is primarily due to its implications for ion exchange, though pH also determines the solubility of soilborne mineral compounds that may aid in aggregating clay particles. The pH also affects the ability of soils to remain aggregated under wetting, as a direct result of clay exchange properties.

As the focus of this review is applied research for the amelioration of sodic soils, an in-depth discussion of the chemical processes governing the dispersive properties of sodic soils has been avoided.

2.4. Differentiating sodic soils from saline soils

The term ‘sodicity’ indicates an abundant presence of exchangeable Na on soil colloids, rather than an excess of soluble salts in solution, which ‘salinity’ implies. Therefore, sodicity should be differentiated from salinity (although sodic soils can also be saline) and management strategies for the two should be developed accordingly. Care should be taken when implementing a management strategy, as those developed for sodicity do not necessarily address salinity (and vice versa). For example, if a highly saline soil is treated with gypsum, a common strategy for sodic soils, the problem of salinity may actually be exacerbated by further increasing the EC of the soil (Valzano *et al.* 2001b). Hence, it is not only important to differentiate between saline, sodic, and saline–sodic soils, but to be able to identify these soils also.

Saline soils have traditionally received more attention than sodic soils, both in the sense of research and remediation, as symptoms of salinity occur on a readily observable level (Rengasamy and Olsson 1993). In contrast, sodicity has either latent symptoms, or when visible, as in the case of gully erosion, is misinterpreted due to lack of public education on the issue. Saline soils are defined as having “…sufficient soluble salt and/or exchangeable sodium to interfere with the growth of most crop plants…” (Loveday and Bridge 1983), as well as being chemically classified as having an EC > 0.7 $dS.m^{-1}$ in a 1:5 soil to water extract (Rengasamy 2002). From this definition, salinity is not directly linked to soil structural instability; in fact, the opposite is normally the case. Saline soils do not theoretically need to contain Na at all, as alternative soluble salts such as $CaCl_2$ may predominate; this is dependent on both the geochemical composition of the soil parent material, and in the case of irrigation, the electrolyte constituents in the percolating solution (Sumner 1993).

Saline–sodic soils simply have characteristics which place them in both the above classifications; i.e. sufficient sodium in the cation exchange complex (CEC) causing structural instability and sufficient electrolyte in solution to cause adverse growth of crops or pasture through salt toxicity. These soils generally have an EC high enough, in comparison to ESP, to maintain a flocculated soil state (Rengasamy *et al.* 1984b; Naidu and Rengasamy 1993).

2.5. Sources of sodium

Numerous studies have presented various sources for sodium in sodic soils, and these include: present atmospheric accessions – rainfall, aerosols, dust particle deposits containing salts; past atmospheric salt accession; primary and secondary rock sources (through weathering); local redistribution by drainage water; and, saline ground water (Corbett 1967; Buttler *et al.* 1973; Isbell *et al.* 1983; Birkeland 1984; Yates and Hedley 2008). However, salts are highly mobile in the soil solution and for this reason it is usually extremely difficult to determine the provenance of observed salts.

A common misconception is that sodium is an artefact of aridity. The majority of sodic soils have been mapped in semi–arid to arid environments by Northcote and Skene (1972), however the occurrence of sodicity in regions such as north-eastern Victoria and along the east coast of New South Wales (NSW) would suggest aridity is not solely responsible for sodification (Isbell *et al.* 1983). Approximately 87% of Australia's mean rainfall is transpired and evaporated, allowing for a salt prone environment (Isbell *et al.* 1983). As these processes will be prominent in semi–arid and arid environments, it is understandable how this misconception has developed.

2.6. Sodic soil distribution in Australia

It has been shown by Northcote and Skene (1972) that the area affected by sodic soils is approximately one third of the Australian continent, or 340 million ha as suggested by Murphy (2002). According to Rengasamy and Olsson (1993), this equates to the largest affected land mass in the world (Table 2.1). Furthermore, as suggested in the above section, the majority of these soils are situated in low rainfall regions (Naidu and Rengasamy 1993).

Table 2.1. Summary of the global distribution of sodic soils adapted from Murphy (2002)

Continent	*Estimated area (million ha)*
North America	9.6
South America	57.9
Africa	27.1
Europe	22.9
Northern and Central Asia	120.1
Southern Asia	1.8
Australia	340
Total	579.4

2.6.1. Sodic soil in New South Wales

As documented by McKenzie *et al.* (1993) the majority of sodicity in NSW is located west of the Great Dividing Range, but sodicity is also evident on the East Coast and Tablelands of NSW. Sodicity is observed to affect approximately 374,300 ha within NSW compared to the 35,300 ha affected solely by salinity (Table 2.2). Northcote and Skene (1972) estimate the area of soils affected by sodicity in NSW to be 47%, which slightly higher than the national average. McKenzie *et al.* (1993) and Murphy *et al.* (1998) suggest sodicity often coincides with particular geological formations and is primarily manifest in the subsoils.

Research pertaining to sodic soils within NSW appears to be concentrated in the Macquarie Valley, the central to eastern section of the Lachlan Valley, and the Gwydir Valley (Doyle *et al.* 1979; Milthorpe and Newman 1979; McKenzie and So 1989a; McKenzie and So 1989b; Harrison *et al.* 1992; Hall *et al.* 1994; Valzano *et al.* 2001b; Bennett 2006; Wong *et al.* 2008; Dang *et al.* 2010). Due to the site specific effects of sodicity and the paucity of sodicity research regarding the western regions of the Lachlan Valley, such as Hillston, there is an apparent need for further investigation in these areas.

Table 2.2 ***Area of sodic and saline soils in NSW based upon figure 2.2 adapted from Mckenzie et al. (1993)***

Salt affected soil category	*Square kilometers*	*Area (% total area of NSW)*
Saline soils - soils dominated by chlorides either in their suface soil, or subsoil, or throughout the solum	35300	4.4
Alkaline, strongly sodic and sodic soils with clay surface textures uniform texture profiles, and with intergrades to both saline and normal soils	179600	22.4
Alkaline, strongly sodic and sodic soils with sandy and loamy surface textures, and uniform and gradational texture profiles	68900	8.6
Alkaline, strongly sodic and sodic duplex soils	71300	8.9
Sodic and strongly sodic neutral (pH 6.5–7.9) duplex soils	20800	2.6
Sodic and strongly sodic acid (pH <6.5) duplex soils	33700	4.2
Total Sodic soils	374300	46.7

2.6.2. Distribution of sodicity within the soil profile

The distribution of sodicity usually varies within the soil profile; vertically as well as laterally. While a soil with a sodic surface is generally assumed to have subsoil sodicity, a sodic subsoil can arise independent of surface sodicity. Rengasamy (2002) proposes that these sodic/non-sodic relations are complex and occur through processes of transient salinity and leaching regimes. For example, given adequate leaching with good quality water and amelioration techniques, a sodic surface soil can become a non-sodic surface soil. The Na is subsequently leached into the lower horizons of the soil profile, although a cumulative reduction in subsoil permeability over time can occur that may cause the leached sodium to pool. This pooled Na cannot penetrate the subsoil, similar to a perched water table, and has a saline effect on plant roots. Furthermore, this Na can become mobile, moving laterally (through flow processes) across the impermeable subsoil, furthering the extent of sodicity and salinity in soils and promoting phenomena such as gully erosion. Gully erosion is a direct effect of subsoil sodicity (Murphy 2002) and is normally unable to be dealt with directly due to economic restraints on landholders. As a result, a focus is placed on surface sodicity remediation.

2.7. Consequences of sodic soil behaviour

Soils which disperse upon wetting detrimentally contribute to phenomena such as hardsetting, surface crusting, and increased soil strength due to blocking of pores and structural ‘slumping’. This leads to decreased hydraulic conductivity with associated decreases in infiltration and drainage, root expansion/exploration, aeration, and overall permeability (Sumner 1993; Vance *et al.* 2002).

2.7.1. Instability to wetting: swelling, slaking and the clay mineral suite

Topsoil structural instability can lead to crusting and hardsetting, causing concomitant waterlogging. This structural behaviour has been shown to translate directly to reduced crop performance (Onus 1978; So and Onus 1984). Topsoil waterlogging, and also decreased subsoil rehydration, causes roots to effectively drown during irrigation or rainfall and then be subject to water starvation after the initial irrigation/rainfall event (due to a lack of stored subsoil water). Dispersion occurs via an imbalance between repulsive electrostatic forces and attractive van der Waals forces. Two further forms of structural instability associated with sodic soils are swelling and slaking. These, as well as dispersion, are further influenced and defined via differences in clay type.

2.7.1.A. Swelling

Swelling is caused by an imbalance between repulsive and attractive forces. If swelling clays are placed in an unconfined water system they can undergo dispersion (Sumner 1993), but do not necessarily disperse in the spatially confined system of a soil profile. Swelling is ultimately dependent on imposed stresses (e.g. van der Waals forces or osmosis) as well as the required levels of ESP and EC (Emerson 1977). If ESP exceeds a threshold value, swelling will increase significantly with further increase in ESP (So & Aylmore, 1993). Furthermore, as electrolyte concentration decreases a greater difference in electric potentials between clay particles occurs, which creates greater repulsive forces in the diffuse double layer, a higher tendency to swell, and therefore a greater potential for dispersion. The process of swelling is primarily attributed to intra-crystalline swelling (within the tactiods) or osmotic swelling (swelling of the monovalent cation-dominated clay fraction), which leads to reduced hydraulic conductivity through waterlogging, increased dispersive potential, crusting and hardsetting.

2.7.1.B. Slaking

Slaking is often associated with sodic soils and, while it is a form of soil instability, it is more a matter of coincidence of occurrence rather than a direct result of sodicity. Slaking is similar to dispersion at initial observation, although aggregates actually breakdown into micro-aggregates when subject to rapid wetting (So and Aylmore 1993) rather than completely dispersing into clay particles. This would suggest that it is a physical process rather than a chemical phenomenon. However, Charman and Murphy (1991) have assigned the aggregate breakdown in slaking to the initial swelling of clays (a chemical and physical process), due to water, and the discharge of air from the pores within the soil. In addition to this, Greene (2002) suggests that slaking is usually a property of soils deficient in organic matter, whereas dispersion still occurs in soil with sufficient organic matter. Research conducted by Clark *et al.* (2009) demonstrated that addition of organic matter in the form of green manure crops and stubble caused a decrease in slaking and an increase in aggregate mean weight diameter. As sodic soils often contain low amounts of organic matter, especially if used for conventional cropping, it is apparent why there is a percieved association between sodicity and slaking.

Slaking usually has considerable impact on the surface of soils, rather than the lower profile layers, through the creation of impermeable seals (Greene 2002). The process of surface sealing consequently lowers the hydraulic conductivity of a soil (sodic or otherwise). Hence, there is a risk of deducing that a soil is sodic using the hydraulic conductivity $K_{sat} < 10\,\text{mm.h}^{-1}$ criterion of Pal *et al.* (2006) due to the incidence of slaking. Thus, such criterion should not be used in the determination of soil sodicity.

2.7.1.C. Clay mineral suite

The clay mineral suite also has a significant effect on the degree of dispersion, swelling and/or slaking. Cass and Sumner (1982a; 1982b; 1982c) have reported that soils dominated by kaolinite and iron oxides are stable to a greater degree than those containing smectite, vermiculite or illite as the dominant clay mineral. Well structured non-vertic soils were observed to behave differently to Vertisols in terms of stability, as influenced by Na (Cass and Sumner 1982b). Additionally, Emerson (1977) suggests that soils with small pores and particles, such as Ca–illite, do not suffer slaking due to crystalline swelling or rapid wetting to the same extent as kaolinites, which still slake even if initially wet. Aylmore and Sills (1982) have further shown that various clay fractions with high Mg^{2+}, in comparison to Ca^{2+}, have been characterised as structurally unstable. These numerous situations make it clear that while dispersion, swelling, and slaking occur in many soils, the magnitude of occurrence is dependent on clay mineral suite, and may be different within individual soil classes, or even individual fields.

2.7.2. Hydraulic conductivity and available water content

Where sodicity leads to aggregate instability to wetting, the soil's hydraulic conductivity (HC) is usually affected. Quirk and Schofield (1955) propose that dispersion and swelling are the major mechanisms that contribute to a reduced HC with a concomitant reduction in TEC.

HC decreases in heavy–textured soils, with ESP greater than 5, occur initially from swelling and are exacerbated by decreasing EC (Sumner 1993). While the initial swelling is a reversible process, some damage to pore networks will occur permanently through dispersion, which is a secondary instability factor. In contrast, it has been observed in various lighter–textured soils, under the same conditions, that dispersion is the primary mechanism for reduced HC via processes of pore sealing (Shainberg and Letey 1984). Pore sealing is an irreversible problem requiring external energies to reclaim HC. This implies that systems governed by dispersion, as compared to swelling dominant systems, are more severely limiting to HC; this does not discount the occurrence of both swelling and dispersion in a particular soil.

The close relationship between HC and clay dispersion in sodic soils has been presented in many studies accross various soil classes and regions (Kazman *et al.* 1983; Rengasamy *et al.* 1984b; Agassi *et al.* 1985; Ben-Hur *et al.* 1985; Miller and Scifres 1988; Shainberg *et al.* 1991; Sumner 1992; So and Cook 1993). HC is then considered an indicator of soil structural form and/or health, where high HC indicates greater distribution of macro/bio pores (So and Aylmore 1993), and low HC is typical of a compacted or hard–set environment (Greene 2002).

Available water content is determined as the water that can be extracted by crops and pastures, and is defined as the difference in moisture content between field capacity and the permanent wilting point of the soil (Gardner *et al.* 1984). Continual reduction in HC ultimately leads to the condition of water-ponding on the topsoil, as water can not penetrate the surface due to the increasing loss of porosity; the available water content is consequently unable to reach the soil's full potential. Thus, nutrient and oxygen transfer into the soil are also limited, resulting from the barrier of ponded water (Jayawardane and Chan 1995). Low oxygen levels lead to chemical transformation of nutrient ions, which render them unavailable for crops and pastures (Naidu and Rengasamy 1993).

The net effect of altered structural form in sodic soils is an environment unsuitable for effective biological production. In sodic soils the environment is one of extremes where the low water infiltration limits the potential available water content results in soil productivity loss, and a rainfall event creates a waterlogged environment, again affecting soil productivity. Hence, soils are often too wet or too dry to promote adequate growth (Rengasamy and Olsson 1993).

2.7.3. Soil strength, hardsetting and crusting

Soil strength is defined as the measure of a soil's ability to withstand external shearing forces, and if too high, can reduce the production of crops and pastures, as well as manageability. While a soil always has some degree of strength, an increase in strength has been shown to occur for a variety of reasons, including ratio/type of cations and moisture content of the soil (Shanmuganathan and Oades 1983; Jayawardane and Chan 1995; Chan *et al.* 1999). Furthermore, dispersion can cause a 'slumping' or compaction effect in soils which will contribute to soil strength as well as crusting and hardsetting.

Crusting is the formation of an impermeable barrier or 'crust' through mechanical disturbance, such as raindrop impact, of the soil surface. This phenomenon was first given importance by McIntyre (1958) who found that raindrop impact caused an observable skin or seal 0.1 mm in thickness and a lower 'washed–in' layer of thickness 2 mm, caused by mechanically–induced dispersion (raindrop impact). The crust was found to be three orders of magnitude less permeable than the bulk soil. It was further demonstrated on a South African soil that the crust formed under sprinkler and surface irrigation was a continuous function of ESP (Hutson 1971). Thus, it would appear that crusting is directly correlated to the dispersive potential of a soil. Keren and Shainberg (1981) suggest that crusting can be alleviated through the presence of a surface mulch to combat raindrop impact, or through chemical ameliorants that supply sufficient electrolyte to maintain surface structure.

Hardsetting is the formation of a massive apedal structure in the topsoil, which becomes very hard on drying. While sodic soils are known to demonstrate the characteristics of hardsetting, dispersion is not a prerequisite for this characteristic (Mullins *et al.* 1990). Hardsetting is caused by the same suite of environmental conditions that cause crusting. However, low levels of organic matter (less than 2 %) are a requirement, along with a low shrink–swell potential (Greene 2002). In order to alleviate hardset conditions a combination of initial cultivation to shatter the massive layer, increased organic matter and chemical amelioration of structure need to occur.

From the above studies it can be deduced that both crusting and hardsetting cause an increase in soil strength, which leads to the formation of structural conditions unfavourable for water infiltration. This promotes waterlogging and an environment adverse to seed germination and/or on-field vehicle or livestock traffic (So and Aylmore 1993).

2.7.4. Subsoil compaction

Compaction in the subsoil is attributed to anthropogenic influences and/or inherent conditions. In clay dominant soil systems, excessive traffic when the soil moist contributes to compaction, and will inevitably increase the bulk density of subsoils (Dang *et al.* 2006). This is due to the large water-holding capacity of clay maintaining the soil above the plastic limit for extended periods of time, which makes the soil more susceptible to physical damage than systems with lower clay contents (McGarry 1987). Dispersion, shown as inherent in many Australian subsoils (McKenzie *et al.* 1993; Dagleish and Foale 1998), will increase the subsoil bulk density further. Dang *et al.* (2006) suggest that an inherently dense subsoil results from a combination of overlaying weight of the surface horizons and the accumulation of dispersed materials in macropores and fissures.

Irrespective of anthropogenic or inherent causes, a subsoil which is compacted causes an impermeable medium within the soil that will limit root growth and subsequent yields (Irvine and Doughton 2001; Dalal *et al.* 2002), create potential for transient salinity to occur (Rengasamy 2002) and limit the plant access of soil stored moisture to above the impermeable horizon (Price 2010).

2.8. Amelioration of sodic soils

Increased run-off coupled with slaking and dispersion will increase soil loss and erosion, and is certain to cause significant reduction in crop yield for a sodic soil (So and Aylmore, 1993). Hence, the need for amelioration strategies for such soils is not so much an option but a necessity. The reclamation of sodic soils is primarily reliant on two processes, the amelioration of excessive exchangeable sodium and the maintenance of sufficient electrolyte concentration in solution. The ultimate outcome from amelioration is to ensure that the soil is well aggregated and will not undergo spontaneous dispersion on wetting. Sodic soils that do not spontaneously disperse on wetting have been identified as having a high electrolyte concentration (Quirk and Schofield 1955), a subplastic B horizon (Isbell 1996), and a Ca:Mg ratio greater than or equal to one (Rengasamy *et al.* 1986). Emerson (1983) further suggests that a sodic soil will not disperse where clay particles are bonded by organic matter.

The usual methods of amelioration of sodic soils are through the use of gypsum ($CaSO_4.2H_2O$) and, less frequently, lime ($CaCO_3$) which both give an initial electrolyte effect and displace Na from the exchange complex in the longer–term. Other amelioration methods have been tested, including composts (Courtney *et al.* 2009; Jalali and Ranjbar 2009), green manure crops (Clark *et al.* 2009) and electromelioration (Ahmad *et al.* 1997), but have failed to be more effective than gypsum in benefit–to–cost terms. In contrast, phytoremediation of saline-sodic calcareous soils, while usually not as effective as gypsum application, has proven to significantly ameliorate sodicity and provide a financial gain through the use of harvestable crops (Qadir and Oster 2002; Qadir *et al.* 2002; Mubarak and Nortcliff 2010).

2.8.1. Effect of electrolyte concentration

When the soil and/or percolating solution contain high levels of electrolyte, an increase in ESP has minimal effect on structural stabilty. However, if the TEC is reduced a concomitant decrease in structural stability of these soils is observed. Oster (1993) asserts, the maintenance of sufficient electrolyte is paramount as it also determines, along with the ESP, the rate of water intake on which reclamation depends. Thus, soils containing substantial amounts of easily weatherable minerals high in electrolyte will be more likely to be aggregated.

2.8.1.A. Contribution of mineral weathering to electrolyte concentration

As Sumner (1993) concludes, many sodic soils occurring in semi–arid environments contain large amounts of weatherable minerals such as feldspars, hornblendes, plagioclases, lime and gypsum. These minerals, when dissolved, release substantial amounts of Mg and Ca into the soil solution. Rengasamy (1983) showed that, after only 24 h of dialysis, soils containing less than 0.2% of lime had a considerable increase in electrolyte. Therefore, soils with readily weatherable minerals maintain higher EC levels than other soils and will be less prone to clay dispersion as a result. Conversely, soils which do not contain adequate levels of these minerals, or do not produce appreciable quantities of salt from short-term weathering, will be relatively sensitive to even small increases in ESP (Sumner 1993).

2.8.1.B. *Contribution of added gypsum to electrolyte concentration*

Davidson and Quirk (1961) demonstrated that crop emergence problems in sodic clay soils could be overcome through the use of mined (naturally-occurring) gypsum, dissolved in the first irrigation water and applied at the rate of 5–10 mmol(+).L^{-1} (800 kg.ML^{-1}). As a result of the small amount of gypsum used (i.e. only a small amount of Ca^{2+} added), the increases in emergence were ascribed to electrolyte interactions rather than significant structural remediation through ion exchange. McKenzie *et al.* (1993) also reported increases in crop emergence and yield due to gypsum application to a sodic Vertosol. Again, these increases were attributed mainly to the electrolyte effect of gypsum on structural stability, rather than Na exchange. Observed benefits from this effect were manifest in a slight improvement of water infiltration and, consequently, larger soil water reserves; increased A horizon porosity which reduced waterlogging; and lower shear strength. Additionally, So *et al.* (1978) observed a reduction in crusting after the application of 12.5 t gypsum ha^{-1} in conjunction with 3.8 t K_2SO_4 ha^{-1} on grey brown clays (Vertosols; ESP = 5-11, EMgP = 34-42) of central-west New South Wales. An increase in HC and a decrease in penetration resistance were also obtained and subsequently attributed to an electrolyte effect on soil stability.

Interestingly, McKenzie (1982) clearly showed that the short–term electrolyte effect was dominant on structurally unstable heavy clay soils, whereas the replacement of Na and Mg ions by Ca was dominant in the reduction of dispersion in the topsoil of lighter-textured clay soils with similar structural instability. Improvements in water infiltration and subsequent storage, through a reduction in pore blockage, on a heavy clay (Vertosol) were also shown to have occurred through electrolyte effects (McKenzie and So 1989b). These results indicate the importance of site-specific management schemes tailored to the clay mineral suite of soil.

Taylor and Olsson (1987) came to fundamentally the same conclusions as McKenzie (1982) regarding the electrolyte effect. They credited lucerne yield increases on a red–brown earth (Chromosol) to the electrolyte effect of gypsum. However, they further suggested that once the crop is established, biological stabilisation of structure takes place despite reduced EC levels in the upper part of the soil. McKenzie and So (1989a) support this, suggesting that a main impact of gypsum on sodic grey clays (Vertosols) is via an effect on vegetation cover that protects the soil surface.

The EC of the soil solution, as altered by gypsum, depends on five key factors (Qadir *et al.* 2001b):

(1) The gypsum source - phosphogypsum has been shown to have dissolution rates 10 time higher than mined gypsum (Keren and Shainberg 1981); the purity of the mined gypsum source will also effect EC levels.

(2) The particle size of gypsum - longevity of dissolution has been shown to be greater with increasing surface area of gypsum particles. Fine gypsum dissolves quickly, raising the EC, but this is followed by a sharp decrease in EC soon after. In contrast, coarser particles have been observed to provide lower initial EC levels that are maintained over a greater period of time. It has been noted that the latter is more effective on moderately sodic soils, while fine gypsum is more beneficial on highly sodic soils; mixtures of gypsum particle size are therefore proposed (Ghafoor *et al.* 1989).

(3) The velocity of the percolating solution - the time of contact between gypsum particles and water should be maximised to obtain the greatest EC benefit. Lower percolating water velocities decrease dissolution speed and allow greater soil-soil solution contact time (Keren and O'Connor 1982).

(4) The depth of gypsum incorporation into the soil - firstly, a dilution of effect results from mixing a given amount of amendment through a larger volume of soil than the same amount at a smaller volume of soil. Secondly, gypsum has been shown to have limited effect at depths greater then the incorporated depth.

(5) The initial soil characteristics – for example, the increased presence of sodium has been shown to increase the solubility of gypsum (Keren and O'Connor 1982); the pH of the soil determine the dissolution rate of gypsum; clay content of the soil will determine the speed at which leaching of soil solution occurs, and the longevity of the electrolyte effect; and, if the soil is initially high in electrolyte, the increase in electrolyte might have adverse effects in terms of soil salinity.

2.8.1.C. Contribution of added lime to electrolyte concentration

Lime has also been shown to have an electrolyte effect by releasing Ca ions, thus maintaining the EC above the required TEC (Shainberg and Gal 1982; Naidu and Rengasamy 1993). This effect of $CaCO_3$ dissolving and supplying sufficient electrolyte to maintain soil in a flocculated condition was confirmed by Shainberg and Gal (1982). They added $CaCO_3$ to non–calcareous soils in order to measure hydraulic conductivity responses to leaching with 0.001 M solutions of SAR = 10–30. Their results showed that sufficient electrolyte was provided by the $CaCO_3$ to maintain hydraulic conductivity at levels higher than were observed for untreated soils.

However, evidence for a significant electrolyte effect created by applied $CaCO_3$ is limited. The soils on which electrolyte effects have been observed are similarly limited. It follows that supplementary examination of the role of $CaCO_3$ in soil aggregation through EC influnce, across a range of soils, would be of benefit.

2.8.2. *Structural amelioration through gypsum ($CaSO_4.2H_2O$)*

Previous studies have shown that gypsum has been beneficial in structural remediation through aggregation of clay particles (So *et al.* 1978; Doyle *et al.* 1979; So and Onus 1984; Chartres *et al.* 1985; Lebron *et al.* 2002; Dang *et al.* 2010). The application of gypsum improves the condition of sodic clays (e.g. Shepherd, 1925; Loveday *et al.* 1970) by contribution of Ca^{2+} into the soil solution and replacing Na^+ on exchange sites, thereby aiding aggregation. Gypsum use was first reported by Shepherd (1925), who obtained positive pasture responses on a ‘practically impervious’ red clay (Vertosol) in the Riverina of NSW. Gypsum application, while not a new management strategy, is currently one of the most popular tactics for sodicity amelioration due to its short–term effects and availability. This short–term effect is due to the compound being highly soluble, relative to other amendments like lime (Ellington *et al.* 1997). Hence, a more rapid result can be obtained through both an initial electrolyte effect (Sahin *et al.* 2003) and further exchange complex phenomena.

One study suggested that gypsum is the key ingredient for maintaining many agricultural soils (Wallace 1994). However, this claim is primarily dependent on soil type and, to a lesser extent, regularity/quantity of gypsum applied. Further reports have shown gypsum applications to result in reductions in ESP (Doyle *et al.* 1979; Qadir *et al.* 1996; Chorom and Rengasamy 1997; Ilyas *et al.* 1997), clay dispersion (Chartres *et al.* 1985; Ellington *et al.* 1997), soil pH (Chorom and Rengasamy 1997), crust formation and hardsetting (So *et al.* 1978; Greene 2002), as well as increased hydraulic conductivity (Loveday *et al.* 1970; McKenzie and So 1989b; McKenzie and So 1989a; Verba and Devyatykh 1992; Ilyas *et al.* 1997), soil faunal activity (Verba and Devyatykh 1992), and plant function (McKenzie and So 1989a; Wallace 1994; Valzano *et al.* 2001b). However, the majority of these effects are also reported to be short–lived due to the inherent solubility of gypsum. Hence, methods to improve the longevity of effect are highly desirable for the reclamation of sodic soils.

In addition to direct effects on the chemical and physical properties of sodic soils, numerous studies have reported significant crop yield increases due to gypsum application (Bridge and Kleinig 1968; Mehanni 1974; Doyle *et al.* 1979; Kowalik *et al.* 1979; McKenzie 1982; McKenzie and So 1989a; Kamphorst 1990; Harrison *et al.* 1992; Wallace 1994; Ellington *et al.* 1997; Dang *et al.* 2010). Jones (unpublished) reported that gypsum had increased the cotton yield potential, over the three year trial period, of a red soil (Red Sodosol) with an ESP range of 5–20 % in the Macquarie valley, New South Wales. These increases were attributed to positive effects on water infiltration and stand improvement through structural amelioration. However, McKenzie *et al.* (1993) did not observe any yield increases when gypsum was combined with deep tillage treatments. They concluded that gypsum application had failed to reduce the degree of slumping of loosened soil fragments in compacted sodic subsoil after deep ripping. Loveday *et al.* (1970) obtained similar results for gypsum use on a Marrah clay loam, a member of the red, brown and grey clays group (Vertosols).

In a more recent study conducted on southern and central Queensland cropping soils, wheat grain yield was shown to significantly increase after surface application of gypsum (2.5 or 5 $t.ha^{-1}$) on soils with surface ESP 3.0, 8.9 and 12.5 (Dang *et al.* 2010). The increase in wheat yield due to gypsum application on the soil with ESP 3.0 was attributed to the fact the soil had an initial exchangeable Mg percentage of 40.1, which would have limited crop yield due to dispersion. Dispersion in a Mg-saturated system occurs because Mg has a larger hydrated radius than Ca, which causes clay particle attractive forces to be overcome by an increase in the diffuse double layer (Vance *et al.* 2002). A further soil, also determined to be sodic, did not show a significant response to gypsum application with a marginal increase in wheat yield comparable to untreated soil.

The above results highlight the following important issue: when evaluating the effectiveness of any given sodicity amelioration treatment, in this case gypsum application, consideration must be given to a myriad of factors including, but not limited to, soil type, texture, mineral suite, landscape function, climatic conditions (past and present), pH, chemical composition of both the amendment and the soil, management regimes (past and present), and application rates/methods. Depending on the management system and soil of interest, the beneficial treatment effects within the soil may not immediately translate to increased crop yield. Other underlying issues may need to be resolved in order for the treatment to have a noticeable effect on production. For example, McKenzie *et al.* (1993) used gypsum, applied via deep ripping, on an irrigated sodic grey clay subsoil; in this situation, a sodium bulge resulting from leaching could have formed above an impermeable soil layer (Rengasamy 2002), which would explain the inability for gypsum to stabilise soil fragments.

A similar scenario was encountered by Jarwal and Rengasamy (1998), who documented improvement in wheat crop yields of 75 % and 60% on a massive brown sodic soil (Dermosol; Nhill, western Victoria [VIC]) and a grey sodic soil (Vertosol; Natimuk, western VIC), respectively, due to gypsum application. However, observations of depressed yield were made when gypsum was applied to a red, calcareous sodic soil (Calcarosol) with subsoil salinity near Birchip, western VIC. Gypsum was observed to have an increasing negative effect on the yield of chickpeas and wheat in this soil likely due to a further increase in EC.

In a study of rainfed wheat grown on grey clays (Vertosols) in the Moree district of New South Wales, Doyle *et al.* (1979) observed dramatic yield responses to gypsum application. The original surface ESP values indicated their three sites were all mildly sodic. Positive yield responses were attributed mainly to reduced surface crusting with concomitant increases in wheat establishment and stored soil moisture at sowing. This raises an important consideration. The magnitude of effect that amendments will have on soil is strongly linked to the original condition of that same soil. McKenzie and So (1989a) highlighted this in their study. On the poor soils, defined by low initial crop yield and high dispersion index, yields were improved by 120, 180, and 230% with gypsum rates of 2.5, 5.0, and 7.5 t.ha^{-1} respectively. However, on better soils, characterised by higher initial crop yields and lower dispersion indices, less prominent responses were obtained; yield improvements of 60, 60, and 73% for gypsum application rates of 2.5, 5.0, and 7.5 t.ha^{-1}, respectively.

Although short–term effects of gypsum may not noticeably affect crop yields in all circumstances, the landholder may benefit indirectly through greater ease in working the soil, as well as increasing the time frame for which the soil is suitable for cultivation McKenzie and So 1989b; Valzano 2000). A consequent advantage of greater ease of tillage is reduced fuel consumption. McKenzie and So (1989b) recorded reductions in implement fuel consumption as great as 37% where gypsum had been applied to three sodic Vertosols. A more pronounced decrease in fuel consumption was observed with higher initial ESP; the three soils were classed as poor (ESP 12.2 and 6.9) and good (ESP 4.0).

It is clear from the above literature that gypsum application can be beneficial as a short–term method for improving soil properties and crop yields in sodic farming sytems. However, long–term responses are less pronounced. Hence, methods which provide longer lasting responses are desirable for landholders and environmental managers alike. For this reason, the following section evaluates lime as an alternative ameliorant with longer lasting effects.

2.8.3. Structural amelioration through lime

Lime has traditionally been used for the remediation of acidity problems (Jayawardane and Chan 1995; Wang *et al.* 1999b; Wang *et al.* 1999a) and to improve soil nutrient statis;

higher mobile amounts of nutrients such as phosphorus, sulphur, nitrogen and potassium, as well as a method to decrease the mobile aluminium and various soilborne heavy metals (Russell 1960; Holford *et al.* 1994; Aitken *et al.* 1998; Saulys and Bastiene 2006). The carbonate from the lime reacts with protons (H^+) in the soil to form HCO_3^-, thus depleting the amount of soil H^+ and causing the pH to rise (Sposito 1989; Sparks 2003). This chemical reaction is also central to the use of lime as an ameliorant for sodic soils. When HCO_3^- is formed, Ca^{2+} becomes mobile within the soil solution, effecting the displacement of Na^+ from clay exchange sites. However, it is difficult to determine the actual amount of Ca^{2+} released by lime (Ford *et al.* 1985).

Initially, lime was thought to act purely as a cementing agent and this phenomenon has been reported by various studies (Staff USSL 1954; Rimmer and Greenland 1976; Emerson 1983; Rengasamy *et al.* 1984a; McKenzie *et al.* 1993). In this process, soil particles are stabilised without noteworthy displacement of Na^+ from the exchange complex. Conversely, Shainberg and Gal (1982) suggest that this effect is attributable to increased electrolyte concentration due to lime dissolution. In their study, no evidence of cementation was found, although this doesn't necessarily discount lime as a cementing agent.

The ability for lime to dissolve is greatly reliant on soil pH (as well as particle size and purity); therefore a soil with high pH may inhibit the positive structural effects of lime. Furthermore, lime is 172 times less soluble, under standard conditions, than gypsum. While this highlights a potential for structural effects with greater longevity, an artefact of slower dissolution, it also means that lime may not have significant short–term effects on sodic soil horizons. The potential for pH to increase in a given soil is directly related to that soil's buffering capacity (Aitkin *et al.* 1998); components such as clay content, CEC, organic matter, and the initial soil pH influence the magnitude of a soil's buffering capacity. Aitken *et al.* (1998) showed that soils with a greater buffering capacity required greater additions of lime to raise the pH to the same extent as soils with lower buffering capacity. While these experiments were conducted on acidic soils, this highlights an important result for non–acidic soils also. If a sodic soil is initially well buffered, the use of lime will have little effect on raising the pH when added in relatively small quantities (Valzano 2000).

Interestingly, lime has been added in large quantities (> 50 $t.ha^{-1}$) to clay soils in Europe (Davies and Payne 1988). This management technique has been practiced over several centuries and is done to improve workability (Gardner and Gardner, 1953). Additionally, Richards (1954) reports that application of lime to Californian soil with pH in water < 7.5 is a recommended practice for the same reason. Most Australian brown, red and grey clays

(Vertosols) have topsoils that fit into this pH category (Stace *et al.* 1968), which suggests these soils may also benefit from the use of lime application.

In Australia, as early as 1925, lime was reported to have significant benefits in the Riverina on impervious red clay (Vertosol) subsoil two years after application (Shepherd 1925). From a lime and gypsum experiment, So *et al.* (1978) stated that lime had maintained a similar effect on soil structure as gypsum; an increase in fine aggregates, water stable aggregation and hydraulic conductivity were observed after approximately one year. Futhermore, Doyle *et al.* (1979) showed a significant yield increase of wheat on sodic grey clays (Vertosols) in north–west NSW, where lime had been broadcast at a rate of 5 $t.ha^{-1}$. However, in the above studies, very little, if any, mention is made of ion exchange. Alternatively, Chan and Heenan (1998) found that exchangeable Na^+ and Mg^{2+} were decreased and exchangeable Ca^{2+} and EC were increased via the use of lime. This suggests lime can be effective in ameliorating sodic soils through the mechanism of ion exchange, as well as an electrolyte effect.

Interesting results were obtained in the studies of Roth (1991) and McKenzie *et al.* (unpublished), cited in McKenzie *et al.* (1993). In the study of Roth (1991), lime was shown to have enhanced clay dispersion as pH increased due to a reduction in edge–to–face flocculation of negatively charged kaolinite faces and positively charged colloid edges. After six months, an increase in aggregation was observed that they attributed to increased Ca activity and Ca–kaolinite–organic matter bonding. Similarly, the latter study showed an initial increase in surface crusting on a Condobolin (Lachlan Valley) grey cracking clay due to lime effects. However, after five months the lime began to dissolve and replaced both Mg^{2+} and Na^+ with Ca^{2+} on the exchange sites. While lime has been shown to have an adverse effect on soil structure in the short–term, the importance of longevity of effect from lime would appear to outweigh the initial adverse effects.

2.8.4. Use of alternate liming amendments

While $CaCO_3$ is commonly referred to as lime (see above section), other liming amendments, such as shale-ash containing quick-lime (CaO) and fly-ash (FA), have been used. Recent results from a Lithuanian study on a neutral pH Cambisol (Tenosol; Isbell 1996) showed that the use of shale ash containing 16% quick-lime in trench backfill improved clay soil structure and improved permeability (Saulys and Bastiene 2006). These effects were still evident after 10 years, although the research makes no mention of soil ESP and EC. Therefore, the suitability for use on sodic soils, while not discounted, is unknown.

Fly-ash, a by product of coal power generation, has been used as a liming agent for acidic soils (Jastrow *et al.* 1981; Hodgson *et al.* 1982), an agronomic source of plant nutrient (Aitken *et al.* 1984; Kukier *et al.* 1994), to decrease phosphorus loss in specific soils (Pathan *et al.* 2002; McDowell 2005) and as an amendment for sodic soils (Kumar and Singh 2003). FA amendment of soils, measured in plant production, has proved beneficial where nutrient deficiencies in the soil were corrected, although a risk of boron and aluminium toxicity to plant and animals has also been shown (Adriano *et al.* 1980; Nass *et al.* 1993). However, these effects have been shown as inconsistent between studies (Adriano *et al.* 1980), indicating that FA itself is inconsistent in its constituents and should be analysed prior to application. Accordingly, Kumar and Singh (2003) advocate the use of FA as a feasible alternative to gypsum in the reclamation of sodic soils provided chemical analysis of the amendment is suited to the intended soil site specific conditions. They compared the use of gypsum, FA, and FA/gypsum combinations at various rates (ranging from 0% to 7.5% FA and 0% to 100% gypsum requirement [GR]) on a sodic soil (ESP > 15) containing 1% $CaCO_3$ and found that ESP was reduced by all treatments in the following general order; gypsum alone > low FA/high GR > high FA/low GR ≈ high FA. Decreases in ESP by FA were attributed to the tendency for the FA sesquioxides to hydrolyse in water and form hydroxides and ionisable acids, which subsequently aided in the dissolution of free carbonates in the soil.

2.8.5. Effects of lime and gypsum combinations

While it has been shown that lime has a slower release rate of Ca^{2+} than gypsum (i.e. less soluble) resulting in potential long–term amelioration, it has also been revealed that lime often has minimal effect on structure in the short–term, or may even cause an adverse short–term effect. To combat this, some studies have investigated using a combination of lime and gypsum (Shanmuganathan and Oades 1983; Chan *et al.* 1999; Valzano *et al.* 2001b; Bennett 2006; Dang *et al.* 2010). Valzano *et al.* (2001b) reported that a combination of these amendments (2.5 $t.ha^{-1}$ of lime and 1 $t.ha^{-1}$ gypsum) was the most effective treatment for the red-brown earth (Chromosol) studied, as the gypsum aided the release of Ca^{2+} from the lime. Increases in hydraulic conductivity and crop yield were observed alongside decreases in dispersion and ESP, as a result of the lime and gypsum blend. Even though the use of gypsum at 5 $t.ha^{-1}$ alone was shown to have comparable or better effects on soil properties, it was deduced that the use of lime and gypsum (2.5 $t.ha^{-1}$ and 1 $t.ha^{-1}$ respectively) was more effective per unit of added Ca^{2+}. According to their study, these synergistic effects were still being seen after three years. This illustrates potential for longer periods between amendment applications, while maintaining, or improving, soil productivity.

In a follow–up study conducted by Bennett (2006) at one of the experimental sites of Valzano (2001b), it was found that after eleven years the 2.5 $t.ha^{-1}$ of lime and 1 $t.ha^{-1}$

gypsum-treated soil was still significantly better in terms of structural stability, structural form and productivity compared to the untreated control soil. This study also included a laboratory experiment for various lime and gypsum treatments on a red-brown earth (Chromosol) under irrigation–like conditions. Again, a combination of lime and gypsum was observed to adequately ameliorate the structural stability; interestingly, the lime treatment at 5 $t.ha^{-1}$ was also observed to significantly decrease dispersion. The work of Chan *et al.* (1999) further supports the beneficial use of lime and gypsum in combination. They suggested that the amendments had increased both the friability and tendency of a grey Vertosol to self–mulch.

In an economic analysis, Rose *et al.* (unpublished), cited in McKenzie *et al.* (1993), showed that a mixture of gypsum (5 $t.ha^{-1}$) and lime (2.4 $t.ha^{-1}$) was the most profitable of the treatments under consideration, including the use of gypsum alone. This was deduced from three years of data pertaining to a Lachlan Valley Vertosol with surface ESP > 7. Conversely, a Queensland soil (soil type not reported) treated with a combination of lime and gypsum (rate not reported) was not observed to have an increase in wheat yield (Dang *et al.* 2010). Additionally, Hoult and Holden (unpublished) conducted a lime and gypsum trial over three years using lime (5 $t.ha^{-1}$), gypsum (12.25 $t.ha^{-1}$) and lime/gypsum (2.5 t,ha^{-1} and 7.35 $t.ha^{-1}$ respectively) on Vertosols in the Macquarie Valley (ESP 5–10 %) They reported no significant differences between treated soils, although the only characteristic analysed was crop yield. Consequently, significant responses in soil properties, not necessarily translating to yield response, may have been overlooked that.

2.8.6. The use of organic matter to ameliorate sodic soils

Organic matter (OM) differs in its origin, composition and scale of action, although the generally agreed effect on soil structure is the binding of soil particles into micro and macro aggregates (Nelson and Oades 1998). However, cases of clay dispersion have been reported as an effect of OM addition, via an increase in negative charge and complexing of Ca^{2+} (Aylmore and Sills 1982; Gupta *et al.* 1984; Sumner 1993), although this is apparently outweighed by the reporting of positive effects (Tisdall and Oades 1979; Swarup 1988; Sumner 1993; Tisdall *et al.* 1997; Wahid *et al.* 1998; Clark *et al.* 2009; Courtney *et al.* 2009; Jalali and Ranjbar 2009; Rani and Khetarpaul 2009; Gosh *et al.* 2010). It is suggested that OM induces these positive changes in structural stability through three overarching and intertwined processes: (i) direct effects resulting from the incorporation of OM into the soil; (ii) through plant roots, microbes and fungal hyphae; and, (iii) through root proton release and CO_2 production.

2.8.6.A. Direct effects of organic matter incorporation

There are numerous sources of OM that are directly applied to agricultural sodic soils, although the type of OM amendment used is usually influenced by the availability of a local OM source. Typical OM used in the management of sodic soils includes green manure and crop residue (Swarup 1988; Chorom and Rengasamy 1997; Clark *et al.* 2009; Gosh *et al.* 2010), farm yard manure (FYM) (Poonia and Bhumbla 1973; Wahid *et al.* 1998; Jalali and Ranjbar 2009; Rani and Khetarpaul 2009; Turner *et al.* 2010) and composts (Sikora and Enkiri 1999; He *et al.* 2001; Chan *et al.* 2007; Hargreaves *et al.* 2008; Courtney *et al.* 2009); other OM amendments exist, such as vermicasts, humates and fish emulsions (Quilty and Cattle accepted), but are beyond the scope of this review.

The use of green manure and crop residues have been shown to increase aggregate stability (Bronick and Lal 2005; Makoi and Ndakidemi 2007). This stability increase is mainly suggested to occur through the binding of soil aggregates (Nelson and Oades 1998) and the protection of the soil surface from raindrop impact (Rengasamy *et al.* 1984b). The incorporation of green manure and crop residues in the subsoil has also been shown to benefit the subsoil structure of various sodic irrigated pastures and subsequent crop yields (Olsson *et al.* 2002; Greenwood *et al.* 2006a; Greenwood *et al.* 2006b), as well as increase the availability of soil water when incorporated with deep ripping (Gill *et al.* 2008). In a laboratory experiment by Clark *et al.* (2009) on a Sodosol (ESP 20), it was observed that green manure (Lucerne pellets and green wheat shoots) caused a rapid decrease in slaking, while crop residue (stubble of canola and chickpea) caused a similar decrease in slaking, but over a substantially longer time frame. They attributed this to less intense activity of bacteria.

Composts and FYM have also been observed to increase aggregate stability in the short-term. While stimulation of microbial activity accounts for a large proportion of this stability, the often high soluble salt content of FYM and composts has been shown to raise the EC and consequently stabilise the soil in the short-term (Mathers and Stewart 1974; Chang *et al.* 1991; Chang *et al.* 1993; Gosh *et al.* 2010). Gosh *et al.* (2010) found that the application of cattle manure on two Gray Vertosols (at Narribri, NSW, and Dalby, QLD) with ESP > 15 gave a significant decrease in dispersion for both soils, although chicken manure was observed to similarly affect the Dalby soil only. Cattle manure was also observed to increase ESP, which suggests that stability in this case is a result of increased EC. However, the results of Turner *et al.* (2010) indicate that cattle and swine manure effected the SAR differently. Where swine effluent significantly increased the SAR, cattle manure had no significant effect. Cattle manure was also observed to have no observable effect of soil EC. This highlights that while manures can have positive effects on soil structure, the animal source and initial chemical composition of the manure will determine the overall changes.

2.8.6.B. The role of plant root exudates, microbial activity and fungal hyphae

Although different plants will affect the surface soil structure at different degrees, it is commonly accepted that root exudates and rhizosphere microbial activity contribute to a plant's ability to stabilise soil (Reid and Goss 1981; Bathke 1984; Chan and Heenan 1991). Curl and Trulove (1986) suggest that plant and microbial production of polysaccharides could be a key process in aggregation of soil mineral particles. Hence, organic material released by roots may stabilise aggregates directly, or indirectly by providing a source of energy for micro-organisms in the rhizosphere, which may in turn produce stabilising materials (Tisdall and Oades 1979). However, Sumner (1993) suggests that as OM bonds between particles decrease (e.g. as a result of cultivation) the OM remaining will mainly contribute to the negative charges on colloids, leading to a decrease in structural stability through dispersion.

Soil fungal hyphae have exhibited an ability to stabilise soil micro-aggregates into macro-aggregates by binding together mineral particles and organic materials (Tisdall 1991; Miller and Jastrow 1992). A demonstrative study by Tisdall *et al.* (1997) used a saprophytic fungi, and ectomycorrhizal and ericoid mycorrhizal fungi grown in a Vertisol (Vertosol) clay slurry for 15 or 52 days depending on the fungi. It was evident that all of the fungi aided in soil stabilisation by binding OM and clay particles to form micro-aggregates at least >2 µm, as well as enmeshing these into aggregates > 50 µm in diameter.

Allen (2007) suggests fungi are macro-organisms, as opposed to micro-organisms, that often stretch in excess of kilometres within soils. Such fungi play vital roles in soil water transport in low soil moisture environments such as semi-arid and arid soils. Allen's (2007) concept is that the fungi itself acts as a 'highway' for the transport of water throughout the soil, although the binding phenomena of fungi (Tisdall *et al.* 1997) would also aid in enhancing the soil's ability to conduct and store water.

However, the conduct of systematic cropping techniques like tillage and fertiliser application is known to dramatically reduce or completely remove certain species of fungal hyphae (Tisdall 1991; Allen 2007). Species that continue to persist in a cropped soil usually display a diminished hyphal network compared to those within perennial pastures (Allen and Boosalis 1983). It is apparent that the effect of fungal hyphae in cropped soils is limited, becasue even if cropped soils are managed with low fertiliser application and minimum tillage the increase in extended fungal hyphae networks can be expected to take several years (Weinbaum *et al.* 1996). Furthermore, it has been concluded that in many soils the existence of fungal hyphae is ephemeral, depending on the presence of easily decomposable material (Tisdall and Oades 1979). Therefore, as many sodic soils are already low in organic content and thus microbial activity, it could be expected that the initial contribution of fungi to structural stability would be low.

2.8.6.C. The role of proton and carbon dioxide release from organic matter

Although Nelson and Oades (1998) state that the general effect of OM is to bind soil particles together, Na^+ exchange resulting from OM interactions within the soil has also proved useful for the amelioration of sodic soils (Robbins 1986a; Robbins 1986b; Qadir *et al.* 1996; Qadir *et al.* 2003; Bennett 2006; Mubarak and Nortcliff 2010). These interactions involves the use of salt- and sodium-tolerant plant species to ameliorate the soil without the use of chemical ameliorants and is known as phytoremediation (Qadir *et al.* 2001b). Other terms used to describe these interactions include, bioremediation, vegetative-bioremediation, and biological reclamation (Qadir and Oster 2002). The process works where a soil contains inherent lime ($CaCO_3$) that can be dissolved through root action to supply Ca^{2+}. Pioneering studies have shown that Ca^{2+} concentrations from phytoremediation have proved sufficient to effect Na^+– Ca^{2+} exchange on the clay exchange sites and subsequently decrease sodicity (Kelley 1937; Cole 1940; Agarwal *et al.* 1979; Robbins 1986a; Robbins 1986b). The major contributing factor attributed to lime dissolution is CO_2 partial pressure (P_{CO_2}), which is documented as up to 1 kPa, or 1% of soil air by volume (Nelson and Oades 1998), and much higher under crop conditions (Robbins 1986a). The reaction describing CO_2 dissolving in water is (Equation 2.1):

$$CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons H^+ + HCO_3^- \qquad \textbf{2.1}$$

Hence, an increase in CO_2 causes a concomitant increase in H^+ and may also lower the soil pH depending on whether the soil is calcareous or not. If the soil is calcareous, then the increased H^+ is said to be neutralised through reaction with lime and a pH increase is not observed. For this reason it is not adequate to measure the effect of phytoremediation by a decrease in pH.

Work conducted by Robbins (1986a) created lysimeter based cropping conditions using calcareous sodic soil (pH 8.6, EC 2.4 $dS.m^{-1}$, ESP 33) for cotton, barley, alfalfa (*Medicago sativa* L.), tall wheat grass [*Agropyron elongatum* (Hort.) Beauv.] and sudan grass [*Sorghum bicolor* (L.) Monench x *Sorghum sudanese* (Piper) Stapf]. Under these conditions it was found that the cotton and barley crops had provided low P_{CO_2} (usually below 6 kPa) as compared to sudan grass (often above 16 kPa). Subsequent analysis showed that the greatest Na^+ removal correlated with the highest P_{CO_2} and that this effect was evident throughout the entire root zone (Robbins 1986b). A further study conducted by Chorom and Rengasamy

(1997) showed that remediation of soil structure had occurred to a similar extent where green manure was applied alone as compared to plots where gypsum was applied. They suggested that microbial activity and stubble/organic matter decomposition increased causing the observed escalation in carbon dioxide release. Subsequently, soil carbonates solubilised, leading to the observed improvement in soil stability through cation exchange.

A complementary mechanism that can ameliorate alkaline pH is the injection of protons (in the form of H^+) into the soil system, has been suggested to occur through the mineralization of organic matter and plant nutrient transformation reactions (Naidu and Rengasamy 1993). This process by which the injected H^+ dissolves calcium carbonate is displayed in Equation 2.2:

$$CaCO_3 + H^+ \rightleftharpoons Ca^{2+} + HCO_3^- \qquad \textbf{2.2}$$

The H^+ from Equation 2.1 would also assist the H^+ from plant proton release. In order to detect the effects of released protons, various research projects have been conducted (Qadir *et al.* 2002; Qadir *et al.* 2003; Mubarak and Nortcliff 2010). Mubarak and Nortcliff (2010) investigated the ability of N-fixing legumes to release H^+ using white cow pea (*Vigna unguiculata* L.), brown cow pea (*Vigna unguiculata* L.) and hyacinth bean (*Dolichos lablab* L.) on soil brought to EC 4 $dS.m^{-1}$ and SAR 30 $mmol.L^{-1}$ and repacked into leaching columns. Treatments included each legume with and without nitrogen supplementation, 100% gypsum requirement without plant, and a control. Significant quantities of Na^+ were removed in the order of gypsum = hyacinth bean relying on N fixation > hyacinth bean relying on inorganic N > white and brown cow pea > control. This equated to a 23–34% decrease in Na^+ by hyacinth bean and clearly indicates the potential for legumes to ameliorate sodic soil through H^+ release.

However, the magnitude of H^+ output from plants that do not fix N is dependent on the amount of excess cations available in the soil and the plant's ability to take up cations (Scott Russell 1977). If the plant is only able to survive into the juvenile period because of sodicity–related problems the uptake of excess cations will be fairly small and the output of protons would be similarly small. Accordingly, if a plant cannot fully develop then increases in P_{CO_2} are subsequently minimal, or nonexistent. For this reason, Bennett (2006) investigated the interaction between phytoremediation and chemical amendment application. Significant evidence was found for vegetation creating a somewhat synergistic interaction with chemical ameliorants in a laboratory experiment using a dispersive red-brown earth (ESP between 6.3 and 10.5; Red Sodosol). In all treatments where lime, gypsum and lime/gypsum combinations had been applied, in conjunction with three canola plants, improved stability was observed after three months that was greater than the control and the equivalent treatments without canola. Further evidence was obtained from a field experiment under native pasture (using the same soil) where lime at 5 t.ha^{-1} was shown to have improved soil condition over 11 years. While respiration was shown to be greater on this treatment than the control it was not possible to quantify the synergistic relationship. Furthermore, in both the laboratory and field experiment proton release was not directly measured.

Even though there is a low initial set-up cost and the added benefit of financial gain through subsequent crop harvest, the technique of phytoremediation has not been overly popular amongst farmers and scientists alike. This is mainly due to the slow rate of remediation compared to chemical ameliorants and the fact that the technique relies on natural lime occurring in soils (Qadir *et al.* 2001b; Qadir and Oster 2002). However, the research of Bennett (2006) has demonstrated the potential for phytoremediation where lime is added to the soil as an amendment, while the results of Mubarak and Nortcliff (2010) have clearly shown that proton release enhances the effects of increased P_{CO_2}. Further research involving the use of chemical amendments in conjunction with phytoremediation would be of benefit.

2.9. Management of sodic soils: processes and implications

This section explores management strategies for both dryland and irrigated farming; often the strategies employed are similar. It also approaches agricultural management as a process that requires a multifaceted consideration of the soil. McKenzie *et al.* (1993) stress that soil factors, other than sodicity alone, may also be limiting crop yield; for example, nutrient deficiencies or mechanical compaction. For this reason, management considerations such as the effects of organic matter on soil quality, irrigation water quality, soil disturbance, and crop rotation should also be considered in order to assess the actual impact of the amendment.

2.9.1. Irrigation water quality

Irrigation water quality impacts the ESP/EC matrix by altering the EC, and consequently changes the soil's dispersive potential. Soils which would not normally be considered sodic are capable of being dispersed provided the percolating solution is low enough in electrolyte. If these soils are free-draining the dispersed material can travel much deeper into the profile, however if the fabric of these soils is such that the dispersed material becomes trapped, then the hydraulic conductivity will decrease (Sumner 1993). Therefore, the quality of the irrigation water, in terms of free ions, is important not only to sodic soils, but non–sodic soils as well.

Cass and Sumner (1982a; 1982c; 1982b) reported that not only should the irrigation water quality be considered, but also properties such as ionic composition in the soil solution and on the clay exchange sites, and subsequently the EC and ESP. They found that high quality water (low EC) can often be more detrimental than water of poorer quality (containing some electrolyte) when used on soils with minimal initial electrolyte. Conversely, a soil with high EC will not benefit from poorer quality irrigation water; in fact, salinity and transient salinity may be exacerbated. Additionally, it has been shown that many irrigation water sources contain as much or even more Mg than Ca (Johnston 1975; Cass and Sumner 1982a; Cass and Sumner 1982c; Cass and Sumner 1982b; Levy *et al.* 1988), which could cause an increase in soil aggregate dispersive potential due to the larger hydrated radius of Mg.

Hulugalle *et al.* (2002) observed a major increase in air–filled porosity in the topsoil of a grey Vertosol (ESP 8.3 and $EC_{1:5}$ 0.15 $dS.m^{-1}$) to 0.15 m after irrigation with saline water. This increase was ascribed to a sharp increase in EC, however it should also be noted that exchangeable Na was also increased which may lead to long–term adverse affects. Similarly, Oster (1993) documents an improvement in soil physical condition on a non-saline, sodic soil, including decreased swelling and dispersion, after application of saline irrigation water. It was further suggested that if irrigation water available was only of good quality, application of rapidly soluble gypsum should be repeated at the soil surface. This would provide a short-term spike in EC and effect cation exchange, provided the gypsum was sufficiently soluble in the soil (van der Elshout and Kamphorst 1990; Oster 1993).

However, many Australian sodic soils are sufficiently low in electrolyte that an ESP of 5, and sometimes lower, has been observed to induce dispersion. It has been shown under humid conditions that rainfall alone can be sufficient to provide very low TEC values, which will further promote dispersion on soils considered only potentially dispersive (soils which do not disperse unless mechanically aggravated; Sumner, 1993). Interestingly, where water application involves disturbance at the soil surface, including flood and sprinkler irrigation, the average soil chemical properties in the entire profile were shown to be less important than the chemical properties of the water (Oster and Schroer 1979).

As the demand for produce increases, farmers will rely more strongly on irrigation to meet this demand. However, the current climate is one where water is scarce and it follows that the availability of high quality water for irrigation will decrease. Jayawardane *et al.* (2001) have documented several townships seeking to dispose of sewage as a treated effluent for irrigation, something that Hulugalle *et al.*(2006) suggest is seriously being considered by Australian cotton growers. In an experiment using treated sewage effluent, following gypsum application (2.5 $t.ha^{-1}$), on a grey Vertosol, it was found that deep drainage and cotton yield were not affected, while ESP increased after four years of irrigation (Hulugalle *et al.* 2006). The increase in sodicity was sustained over four years due to the high Na content in the effluent, and was unaffected by gypsum application, possibly due to a poor quality gypsum source contaminated with significant amounts of carbonate ions. Hence, sewage effluent is a feasible source of irrigation water, provided high quality gypsum is used at rates sufficient to neutralise the effects of Na in the effluent (Hulugalle *et al.* 2006).

2.9.2. Soil disturbance and cultivation

For cropping regimes, both dryland and irrigated, a degree of cultivation is usually necessary during processes of sowing, or in the case of irrigated cotton, bed preparation. As Emerson (1977; 1983) describes and Rengasamy *et al.* (1984b) identify, even minimal cultivation is capable of creating shearing forces which can break face–to–edge and interparticle bonds, resulting in structural instability. Obviously, the more intensive the soil disturbance the greater the loss of structure due to shearing forces.

Emerson (1977; 1983) and Sumner (1983) draw attention to the issues associated with continuous tillage systems. Management systems such as these are more likely to render soil stability susceptible to the effects of low levels of Na than those incorporating fallow periods and minimum-till regimes; an attendant loss of organic matter and a decrease in aggregate stability in water heightens the potential for dispersion.

With reference to Vertosols, McKenzie and So (2001b) showed that applied gypsum helped form a friable seedbed, meaning that tillage of these soils is really only needed for control of weeds, unless a shattering of compacted layers is necessary (McKenzie and So 1989b). A similar system has been suggested for a red-brown earth (Chromosol), but with the use of direct–drill in conjunction with chemical ameliorants (Valzano *et al.* 2001b). In these circumstances the recommendation is for minimum to zero tillage systems.

When initially forming irrigation fields, regardless of soil type and tillage regime intentions, it is often necessary to perform laser levelling with cut–fill techniques to develop the required flow (from head ditch to tail drain). However, laser levelling and cut–fill techniques often have undesirable consequences for soil structural stability. This is primarily due to exposing subsoil in cut areas by removing the topsoil to use as fill in the lower/uneven areas. Cay and Cattle (2003) showed that soil ESP generally doubled in the cut areas and increased slightly in the fill areas (as compared to the natural soil) for three Lachlan Valley Vertosols. Due to exposed subsoil often being less permeable, more susceptible to dispersion, and rich in exchangeable Na compared to the 'cut' topsoil, decreases in crop production occur. Jessop *et al.* (1985) reported a cotton establishment reduction of more than 50 % on cut areas as compared to areas which were fill. Similarly, Hulugalle *et al.* (2002) observed losses in profitability when sowing cotton immediately after laser levelling. From this latter study, it was suggested that laser levelled fields should be kept in fallow for 1 to 2 years. This advice is based on further observations where a field with mediocre structural stability in the upper horizons, due to laser levelling, was shown to structurally improve simply by avoidance of initial deep tillage and with time, presumably due to leaching of Na by rain. To combat the issues raised in the above studies, Blaikie *et al.* (1988) suggest that landholders need to leave some topsoil intact, or have a stockpile of topsoil which can be redistributed on cut areas after landforming operations, to promote a stable soil.

Subsoil chemical properties, particularly the tendency for greater ESP at depth, both in exposed cut areas (irrigation systems) and as limiting impermeable layers (irrigation and dryland systems), have significant consequences for structural stability. With regard to exposed subsoils in cut areas, the problem is dealt with more simply, as the subsoil is more easily accessible for ameliorative processes. However, when the subsoil depth is unchanged, management remains difficult and expensive because the overlying topsoil continues to restrict access to the subsoil. Numerous techniques have been used to modify the soil profile in sodic soils; deep ploughing, deep ripping (or subsoiling), profile inversion, hauling and sanding. Deep ploughing mixes subsoil horizons through the A horizon and is primarily undertaken on sodic soils with impermeable horizons lying above permeable horizons (Kovda *et al.* 1973), or where the soil is gypsiferous and the Ca^{2+} source is contained in the subsoil (Rasmussen *et al.* 1972). However, if the impermeable horizon, or Ca^{2+} rich horizon, is not mixed thoroughly with the A horizon then surface physical conditions have been shown to worsen or remain unchanged (Ballantyne 1983; McAndrew and Malhi 1990). The associated cost of deep ploughing is often perceived as unacceptable by landholders (Grevers and De Jong 1993) and subsequently other subsoil ameliorative methods are sought.

The most common technique used to access subsoils in Australia is that of deep ripping, where cultivation occurs to depths sometimes greater than 1 m. This techniques effectively shatters impermeable B horizons without pulling the shattered soil through the A horizon (Jayawardane *et al.* 1994), which makes it comparatively less expensive than deep ploughing (Alzubadi and Webster 1982). Nonetheless, Burgess *et al.* (1998) have shown that in even a non–sodic soil, reversion to the previous structural form commonly occurs in as little time as nine months, a serious concern for the effect–to–expense ratio.

Rengasamy *et al.* (1992) showed that deep ripping in a sodic soil was ineffective, quickly reverting to its former structural condition, without first ameliorating the sodicity. The attempt to remedy a physical problem without regard to the underlying chemical cause is a common mistake (Rengasamy 2002). In an effort to address this, gypsum slotting (deep ripping and injecting gypsum into the slots) has been examined through various studies (Stockdale 1983; Jayawardane and Blackwell 1985; Kelly 1985; Blaikie *et al.* 1988; Blackwell *et al.* 1991; Nuttall *et al.* 2005; Prathapar *et al.* 2005; McBeath *et al.* 2010), with mixed results. While this technique has been shown to increase infiltration, reduce aeration stress, and even increase yield up to 90 %, Nuttall *et al.* (2005) demonstrated in a laboratory experiment using a mildly saline-sodic Calcarosol subsoil that deep ripping with gypsum application did not significantly increase yield or ESP over a two year period. Additionally, Blackwell *et al.* (1991) has shown that the favourable structural improvements in a red-brown earth (Chromosol) from gypsum slotting are often short–lived and decline due to displaced Na^+ moving into the soil between slots, causing larger than normal lateral swelling pressure. Also, the migration of leached Na^+ from the upper horizons directly into the slots further diminishes the efficacy of this practice.

Research was conducted by Prathapar *et al.* (2005) to compare the effects of broadcast gypsum with slotted gypsum on two non-gypsiferous, saline-sodic soils (a silty clay loam and a silt loam; average EC 6 $dS.m^{-1}$ and SAR 17 $mmol.L^{-1}$) in Pakistan over five years. They found that both methods of gypsum application significantly increased hydraulic conductivity, and decreased sodicity (EC and SAR), although this was more pronounced for the slotting technique. Consequently, and as cotton yield was substantially higher on the gypsum slotted plots, it was deduced that the long-term benefits of gypsum slotting were greater than broadcast gypsum, even with the higher initial cost of gypsum slotting. While these effects were observed after 5 years, it is noted that they were observed on lighter textured soils than the majority of Australian cropping soils (predominantly clay dominant soils). In a subsequent study, McBeath *et al.* (2010) compared the effects of slotting with and without supplementary nutrients (N, P, Zn, Mn and Cu) and liquid gypsum (19% Ca at 790 [Stansbury] and 2100 $L.ha^{-1}$ [Crystal Brook]) on a Calcic, Mottled-Hypernatic, Yellow Sodosol (Isbell 1996) at Stansbury (South Australia [SA]) and an Endohypersodic, Regolithic, Hypercalcic Calcarosol (Isbell 1996) at Crystal Brook (SA) in what they termed 'a dry year' (2007). While they observed a 15-20% increase in grain harvest weight and a decrease in penetration resistance to 0.4–0.5 m at both sites, it was noted that soil water content did not improve on any treatment. An adjacent similar treatment that had been applied in 2004 exhibited minimal residual effect due to deep ripping and deep nutrient application. Their results led them to conclude that amendment needed to occur in 2-3 year intervals (possibly uneconomical) or that alternative methods of subsoil amelioration should be investigated.

Further methods such as sanding (mixing sand into soil to increase permeability), hauling (the removal and replacement of a salt-affected topsoil with good quality topsoil) and profile inversion (removal of the topsoil, deep ploughing of the subsoil and replacement of the topsoil), while technically feasible methods of subsoil remediation, have not been used on a practical level due to the logistics and expense (Qadir *et al.* 2001b).

2.9.3. Crop management

The use of monoculture crop systems for dryland wheat (Littler and Marley 1978) and irrigated cotton (Cooper 1999) has demonstrated issues concerning the carry over of diseases, nutrient depletion, water use efficiency, and soil structural decline. In the latter study, Cooper (1999) declared a system where continuous cotton is sown to be degradative with regard to soil quality and subsequent yield, while a sustainable system is exemplified by rotation in and out of cotton.

In a study conducted by Hulugalle *et al.* (2002) it was shown that continuous cotton had the highest cumulative gross profit margin over a period of five years (1994 to 1999) as compared to rotation systems combining variations of green manure faba beans (*Vicia faba* L.), dolichos (*Lablab purpureus* L.), wheat (*Triticum aestivum* L.) and long fallow periods. However, monoculture cotton is a system which is unlikely to be sustained into the long–term without a decline in soil quality. Accordingly, the study showed that the soil structure was significantly affected by cropping sequence, where continuous cropping resulted in a decline of soil structural stability and form. Furthermore, cotton in rotation with the various crops (wheat, dolichos, and faba bean) was shown to increase air–filled porosity and consequently soil aggregation.

One of the most common rotation crops for cotton in Australia is wheat. Research has shown that cotton in rotation with wheat provided an increased lint yield and quality (Hulugalle *et al.* 2001), decreased soil compaction (Hulugalle *et al.* 1999), and greater cumulative gross profit margins per hectare and per megalitre of irrigation water (Hulugalle *et al.* 1999; Hulugalle *et al.* 2001) as compared to legume crops in rotation. Even though legumes such as field pea (*Pisum sativum* L.) are shown to increase nitrogen through fixation, wheat in rotation with cotton was observed to provide a comparable soil nitrogen level after four years (Hulugalle *et al.* 1999). It should be noted that, the advantages of a wheat-cotton rotation over a legume in the study of Hulugalle *et al.* (2001) were obtained only after the application of supplementary N. While the justification for the widespread use of wheat as an effective rotation crop with cotton is apparent, the effects are soil property dependent.

Considerable research has documented the success of crop rotations in conjunction with chemical ameliorants on dryland systems (Ilyas *et al.* 1993; Ilyas *et al.* 1997; Sansom *et al.* 1998a; Sansom *et al.* 1998b). Ilyas *et al.* (1997) observed a decrease in surface and subsurface sodicity when combining the use of gypsum with a rotation of sebania–wheat–sebania. While this was the most effective treatment for reducing sodicity, it was found that even when gypsum was not used, the simple rotation of crops led to improved hydraulic conductivity. This highlights the use of crop rotation as a means for aiding structural improvement. Furthermore, gypsum alone was not observed to improve soil properties to the same extent as the rotation–gypsum treatment.

2.10. Conclusions

Sodicity is a worldwide problem that affects various industries, particularly the agricultural industry within Australia. Knowledge of the origins and consequences of sodicity, and methods of amelioration, is paramount to the longevity of irrigation and dryland farming systems alike. Australian soils are notorious for conditions which are conducive to structural instability; as a result, associated structural damage is often unavoidable following irrigation or heavy rain. Various techniques are available for the amelioration of sodic soil horizons, but the most effective combinations of these techniques are dependent on the soil clay mineral suite and texture, as well as the chemical and physical attributes of the soil in question. Furthermore, it is imperative that the underlying chemical issues be addressed before physical remediation is attempted. Hence, management practices need to be adjusted to incorporate a sodic amelioration strategy that also addresses the interactions of irrigation water quality, soil disturbance, soil organic matter and crop rotation with sodicity. The literature suggests that integrated approaches have the best results; however, the combined use of chemical ameliorants and their longevity of effect, the effects of irrigation on chemical ameliorants (and vice versa), and the amelioration of subsoil limitations imposed by sodicity would benefit from further investigation.

2.11. References

Abbott, TS, McKenzie, DC (1986) Improving soil structure with gypsum. Agfact AC 10, NSW Agriculture

Abrol, IP, Fireman, M (1977) 'Alkalai and saline soils, identification and improvement for crop production', Bulletin No. 4 (Central Soil Salinity Research Institute: Karnal, India)

Adriano, D, C,, Page, AL, Elseewi, AA, Chang, ACS, I. (1980) Utilization and disposal of fly ash and other coal residues in terrestial ecosytems: a review. *Journal of Environmental Quality* **9,** 333-4.

Agarwal, RR, Yadav, JSP, Gupta, RN (1979) 'Saline and alkaline soils of India', (Indian Council of Agricultural Research: New Delhi, India)

Agassi, M, Morin, J, Shainberg, I (1985) Effect of raindrop impact energy and water salinity on infiltration rates of sodic soils. *Soil Science Society of America Journal* **49,** 186-90.

Ahmad, E, Jones, RL, Hinesly, TD (1997) Electromelioration of a sodic horizon from an Illinois Natraqualf. *Soil Science Society of America Journal* **61,** 1761-5.

Aitken, RL, Campbell, DJ, Bell, LC (1984) Properties of Australian fly ashes relevant to their agronomic utilization. *Australian Journal of Soil Research* **22,** 443-53.

Aitken, RL, Moody, PW, Dickson, T (1998) Field amelioration of acidic soils in south-east Queensland. I. Effect of amendments on soil properties. *Australian Journal of Agricultural Research* **49,** 627-37.

Aitkin, RL, Moody, PW, Dickson, T (1998) Field amelioration of acidic soils in south-east Queensland -I- Effect of amendments on soil properties. *Australian Journal of Agricultural Research* **49,** 627-37.

Allen, MF (2007) Mycorrhizal fungi: highways for water and nutrients in arid soils. *Vadose Zone Journal* **6,** 291-7.

Allen, MF, Boosalis, MG (1983) Effects of two species of vesicular-arbuscular mycorrhizal fungi on drought tolerance of wheat. *New Phytologist* **93,** 67-76.

Alzubadi, A, Webster, GR (1982) Effects of tillage in combination with chemical amendments on reclamation of a solonetzic soil. *Canadian Journal of Soil Science* **62,** 641-9.

Anderson, MJ, Whittcomb, PJ (2000) 'DOE simplified: practical tools for effective experimentation', (Productivity Inc.: Portland, Oregon, USA)

Australian Government (2003) Native Vegetation Act 2003.

Aylmore, LAG, Sills, ID (1982) Characterisation of soil structure and stability using modulus of rupture-exchangeable sodium percentage relationships. *Australian Journal of Soil Research* **20,** 213-24.

Ballantyne, AK (1983) Five years of soil analyses and yield data on deep-plowed solonetzic soil. *Canadian Journal of Soil Science* **63,** 191-7.

Bangura, AM (1983) Farmer motivated patterns in participating in adaptive crop trials/demonstrations in Sierra Leone. *Dissertation Abstracts* **44/03A,** 864.

Barber, SA (1984) Liming materials and practices. *In* 'Soil acidity and liming'. (Eds. Adams, F) (American Society of Agronomy Inc.: Madison)

Bathke, GR (1984) Effects of soybean properties related to soil erodibility. *Journal of the Soil Science Society of America* **48,** 1398-401.

Batra, L, Kumar, A, Manna, MC, Chabra, R (1997) Microbial and chemical amelioration of alkaline soil by growing Karnal grass and gypsum application. *Experimental Agriculture* **33,** 389-97.

Ben-Hur, M, Shainberg, I, Bakker, D, Keren, R (1985) Effect of soil texture and CaCO3 content on water infiltration in crusted soil as related to water salinity. *Irrigation Science* **6,** 281-94.

Bennett, JMcL (2006) *Interactions between chemical ameliorants and vegetation in a sodic red brown earth, Upper Bogan region, NSW*, Thesis - Australian National University, Canberra.

Bennett, R (1999) *Sustainable soil management in New Zealand: farmer beliefs, attitudes and motivations*. Discussion paper in natural resource and environmental economics No. 21, (Centre for Applied Economics and Policy Studies Massey University: Palmerston North)

Birkeland, PW (1984) 'Soils and geomorphology', (Oxford University Press: New York)

Black, CA (1968) 'Soil-plant relationships', (John Wiley and Sons: New York)

Blackwell, PS, Jayawardane, NS, Green, TW, Wood, JT, Blackwell, J, Beatty, HJ (1991) Subsoil macropore space of a transitional red-brown earth after either deep tillage, gypsum or both. *Australian Journal of Soil Research* **29,** 141-54.

Blaikie, SJ, Kelly, KB, Mason, WK, Martin, FM (1988) Productivity of irrigated pastures following paraplowing and gypsum slotting of subsoil exposed by laser levelling – a short term study. *Australian Journal of Agricultural Research* **39,** 837-45.

Bridge, BJ (1968) *soil physical properties as influenced by gypsum*, Thesis - University of Sydney, Sydney.

Bridge, BJ, Kleinig, CR (1968) The effect of gypsum on the water storage in a sandy loam soil under irrigated perennial pasture. *Transactions 9th. International Congress of Soil Science* **1,** 313-23.

Bronick, CJ, Lal, R (2005) Soil structure management: a review. *Geoderma* **124,** 3-22.

Bureau of Meteorology (2006) www.bom.gov.au/cgi-bin/climate. Commonwealth of Australia, Available at [Verified

Burgess, CP, Chapman, R, Singleton, PL, Thom, ER (1998) Effects of livestock of livestock treading and mechanical loosening of soil. *Proceedings of the New Zealand Society of Soil Science***,** 99-100.

Buttler, BE, Blackburn, G, Bowler, JM, Lawrence, CR, Newell, JW, Pels, S (1973) 'Geomorphic map of the Riverine Plain of south-eastern Australian', (Australian National University Press: Canberra)

Carberry, PS, Hochman, Z, McCowan, RL, Dagleish, NP, Foale, MA, Poulton, PL, Hargreaves, JNG, Hargreaves, DMG, Cathray, S, Hillcoat, N, Robertson, MJ (2002) The FARMSCAPE approach to decision support: farmers', advisers', researchers', monitoring simulation, communication and performance evaluation. *Agricultural Systems* **74,** 141-77.

Cass, A, Sumner, ME (1982a) Soil pore structural stability and irrigation water quality: I. Empirical sodium stability model. *Soil Science Society of America Journal* **46,** 503-6.

Cass, A, Sumner, ME (1982b) Soil pore structural stability and irrigation water quality: II. Sodium stability data. *Soil Science Society of America Journal* **46,** 507-12.

Cass, A, Sumner, ME (1982c) Soil pore structural stability and irrigation water quality: III. Evaluation of soil stability and crop yield in relation to salinity and sodicity. *Soil Science Society of America Journal* **46,** 513-17.

Cay, E, Cattle, SR (2003) Unearthing problem soils in the Lachlan Valley. *Australian Cotton Grower* **24,** No. 1, 32-5.

Chamala, S (1987) Adoption processes and extension strategies for conservation farming. *In* 'Tillage: new directions in Australian agriculture'. (Eds. Cornish, PE & Pratley, JE) (Inkata Press: Melbourne)

Chamala, S, Keith, KJ, Quinn, P (1982) 'Adoption of commercial and soil conservation innovations in Queensland - information exposure, attitudes, decisions and actions', (Department of Agriculture, University of Queensland: Brisbane)

Chan, KY, Dexter, AR, McKenzie, DC (1999) Categories of soil structure based on mechanical behaviour and their evaluation using additions of lime and gypsum on a sodic Vertisol. *Australian Journal of Soil Research* **37,** 903-11.

Chan, KY, Dorahy, C, Tyler, S (2007) Determining the agronomic value of composts produced from garden organic from metropolitan areas of New South Wales, Australia. *Australian Journal of Experimental agriculture* **47,** 1377-82.

Chan, KY, Heenan, DP (1991) Differences in surface soil aggregation under six different crops. *Australian Journal of Experimental Agriculture* **31,** 683-86.

Chan, KY, Heenan, DP (1998) Effect of lime (CaCO3) application on soil structural stability of a red earth. *Australian Journal of Soil Research* **36,** 73-86.

Chang, C, Sommerfeldt, TG, Entz, T (1991) Soil chemistry after 11 annual applications of cattle feedlot manure. *Journal of Environmental Quality* **20,** 485-80.

Chang, C, Sommerfeldt, TG, Entz, T (1993) Barley performance under heavy applications of cattle feedlot manure. *Agronomy Journal* **85,** 1013-18.

Charman, P, Murphy, BW (1991) 'Soils: Their properties and management', (Sydney University Press: Sydney)

Chartres, CJ, Greene, RSB, Ford, GW, Rengasamy, P (1985) The effects of gypsum on macroporosity and crusting of two red duplex soils. *Australian Journal of Soil Research* **23,** 467-79.

Chellemi, DO, Porter, IJ (2001) The role of plant pathology in understanding soil health and its application to production agriculture. *Australian plant pathology* **30,** 103-09.

Chen, L, Tubali, K, Kost, D, Dick, W (2010) Effects of gypsum enhanced composts on yields and mineral compositions of broccoli and tall fescue. *Journal of Plant Nutrition* **33,** 1040-55.

Chi, CL, Emerson, WW, Lewis, DG (1977) Exchangeable calcium, magnesium and sodium and the dispersion of illites in water. I. characterisation of illites and exchange reactions. *Australian Journal of Soil Research* **28,** 243-53.

Chorom, M, Rengasamy, P (1997) Carbonate chemistry, pH, and physical properties of an alkaline sodic soil as affected by various amendments. *Australian Journal of Soil Research* **35,** 149-61.

Churchman, GJ, Skjemstad, J, Oades, JM (1995) Effects of clay minerals and organic matter on sodicity. *In* 'Australian sodic soils: distribution, properties and management'. (Eds. Naidu, R, Sumner, ME & Rengasamy, P) (CSIRO Publications: Melbourne)

Clark, GJ, Dodghsun, N, Sale, PWG, Tang, C (2007) Changes in chemical and biological properties of a sodic clay subsoil with addition of organic amendments. *Soil Biology and Biochemistry* **39,** 2806-17.

Clark, GJ, Sale, PWG, Tang, C (2009) Organic amendments initiate the formation and stabilisation of macroaggregates in a high clay sodic soil. *Australian Journal of Soil Research* **47,** 770-780.

Cockcroft, B, Tisdall, JM (1978) Soil management, soil structure and root activity. *In* 'Modifications fo soil structure'. (Eds. Emerson, WW, Bond, RD & Dexter, AR) (John Wiley: Chichester)

Cohen, JW (1988) 'Statistical power analysis for the behavioural sciences', (Lawrence Erlbaum Associates: Hillsdale, NJ)

Cole, E (1940) Salt affected lands reclaimed by dhub grass. *Indian Farming* **1,** 280.

Cooper, JL (1999) A grower survey of rotations used in the New South Wales cotton industry. *Australian Journal of Experimental Agriculture* **39,** 743-55.

Corbett, JR (1967) 'The living soil', (Martindale Press: Sydney)

Cordell, D, Drangert, J-A, White, S (2009) The story of phosphorus: Global food security and food for thought. *Global Environmental Change* **19,** 292-305.

Cornell, JA (2002) 'Experiments with mixtures', (John Wiley and Sons Inc.: New York)

Courtney, RG, Jordan, SN, Harrington, T (2009) Physico-chemical changes in bauxite residue following application of spent mushroom compost and gypsum. *Land Degredation and Development* **20,** 582-81.

Craze, B, Holman, G, Chapman, GA, Stone, MJ (1993) 'Soil testing procedures of the NSW Department of Conservation and Land Management', (NSW Department of Conservation and Land Management: Sydney)

Cregan, PD, Hirth, JR, Conyers, MK (1989) Amelioration of soil acidity by liming and other amendments. *In* 'Soil acidity and plant growth'. (Eds. Robson, AD) (Academic Press Australia: Sydney)

Curl, EA, Truelove, B (1986) 'The Rhizosphere', (Springer-Verlag: Berlin)

Dagleish, NP, Foale, MA (1998) 'Soil matters: monitoring soil water and nutrients in dryland farming', (Agrictural production systems research unit: Toowoomba, Qld)

Dalal, RC, Blasi, M, So, HB (2002) *High sodium levels in subsoil limits yields and water use in marginal cropping areas*. Grain Research and Development Project No. DNR 6, final report, (GRDC: Canberra)

Dang, YP, Dalal, RC, Buck, SR, Harms, B, Kelly, R, Hochman, Z, Scwenke, GD, Biggs, AJW, Furguson, NJ, Norrish, S, Routley, R, McDonald, M, Hall, C, Singh, DK, Daniells, IJ, Farquharson, R, Manning, W, Speirs, S, Grewal, HS, Cornish, PE, Bodapati, N, Orange, D (2010) Diagnosis, estent, impacts, and management of subsoil constraints in the northern grains region of Australia. *Australian Journal of Soil Research* **48,** 105-19.

Dang, YP, Dalal, RC, Routley, R, Scwenke, GD, Daniells, IJ (2006) Subsoil constraints to grain production in the cropping soils of north-eastern region of Australia: an overview. *Australian Journal of Experimental Agriculture* **46,** 19-35.

Davidson, LJ, Quirk, JP (1961) The influence of dissolved gypsum on pasture establishment of irrigated clays. *Australian Journal of Agricultural Research* **12,** 100-10.

Davies, DB, Payne, D (1988) Management of soil physical properties. *In* 'Russell's soil condition and plant growth'. (Eds. Wild, A) (Longman: London)

Department of Agriculture Fisheries and Forestry (2008) *Healthy soils for sustainable farms: Program report*. (Land & Water Australia: Canberra) http://lwa.gov.au/files/products/healthy-soils-sustainable-farms/pn20960/pn20960.pdf (accessed 25 March 2010)

Desbiez, A, Matthews, R, Tripathi, B, Ellis-Jones, J (2004) Perceptions and assessment of soil fertility by farmers in the mid-hills of Nepal. *Agricultre, Ecosystems & Environment* **103,** 191-206.

Diallo, I (1983) An assessment of farmers' attitudes and experiences under no-till corn production systems in Baltimor county, Marryland. *Dissertation Abstracts* **45/05B,** 1329.

Dillman, DA (2007) 'Mail and internet surveys: the tailored design method.' (John Wiley & Sons: New Jersey)

Dixon, G (1982) 'A course manual in agricultural and livestock extension. Rural Sociology', (Universities International Development Program: Canberra)

Doran, JW (2002) Soil health and global sustainability: translating science into practice. *Agricultre, Ecosystems & Environment* **88,** 119-27.

Doyle, AD, Taylor, DW, Yates, WJ, So, HB, McGarity, JW (1979) Amelioration of structurally unstable grey clays in the north-western wheat belt of New South Wales. *Australian Journal of Experimental Agriculture and Animal Hausbandry* **19,** 590-8.

Edmeades, DC (2002) The effect of liquid fertilisers derived from natural products on crop, pasture, and animal production: a review. *Australian Journal of Agricultural Research* **53,** 965-76.

Ellington, A, Badawy, NS, Ganning, GW (1997) Teasting gypsum requirements for dryland cropping on a red-brown earth. *Australian Journal of Soil Research* **35,** 591-607.

Emerson, WW (1977) Physical properties and structure. *In* 'Soil factors in crop production in a semi-arid environment'. (Eds. Russell, JS & Greacen, EL) (University of Queensland Press: Brisbane)

Emerson, WW (1983) Interparticle bonding. *In* 'Soils: an Australian view point'. (Eds. Division of Soils CSIRO) (CSIRO: Melbourne)

Emerson, WW, Bakker, AC (1973) The comparative effects of exchangeable calcium, magnesium, and sodium on some physical properties of red-brown earth subsoils. II. The spontaneous dispersion of aggregates in water. *Australian Journal of Soil Research* **11**.

Emerson, WW, Chi, CL (1977) Exchangeable calcium, magnesium and sodium and the dispersion of illites in water. II. Dispersion of illites in water. *Australian Journal of Soil Research* **28,** 255-62.

Fairweather, PG (1991) Statistical power and design requirements for environmental monitoring. *Australian Journal of Marine and Freshwater Research* **42,** 555-67.

Falcón, M, Corominas, E, Pérez, M, Perestelo, F (1987) Aerobic bacterial populations and environmental factors involved in the composting of agricultural and forest wastes of the Canary Islands. *Biological Wastes* **20,** 89-99.

Field, DJ (2000) *The bricks and mortar of Vertosols*, Thesis - The University of Sydney, Sydney.

Field, DJ, McKenzie, DC, Koppi, AJ (1997) Development of an improved vertisol stability test for SOILpak. *Australian Journal of Soil Research* **35,** 843-52.

Ford, GW, Greene, RSB, Rengasamy, P (1985) Estimation of gypsum requirement of agricultural soils. *Proceedings for the Australian Soil Science Society***,** 103-10.

Fraiture, Cd, Wichelns, D, Roskstrom, J, Kemp-Benedict, E (2007) Looking ahead to 2050: scenarios of alternative investment approaches. *In* 'Water for food, water for life: A comprehensive assessment of water management in agriculture'. (Eds. Molden, D) (Earthscan: Colombo)

Frank, BR (1997) Adoption of innovations in the north Queensland beef industry. III: implications for extension management. *Agricultural Systems* **55,** 347-58.

Gardner, EA, Shaw, RJ, Smith, GD, Coughlan, KJ (1984) Plant availavle water capacity: concept, measurement and prediction. *In* 'Properties and utilisation of cracking clay soils'. (Eds.: Armidale)

Gardner, HW, Gardner, HV (1953) 'The use of lime', (Farmer & Stock-Breeder Publications Ltd: London)

Gee, GW, Bauder, JW (1986) Particle-size analysis. *In* 'Methods of soil analysis'. (Eds. Klute, A) (Soil Science Society of America: Madison, Wisconsin)

Ghafoor, A, Ahmad, MM, Muhammed, S, Ahmad, N (1989) Efficiency of gypsum grades and qaulity of leaching water for reclaiming a saline-sodic soil. II.

chemical improvement of soil. *Pakistan Journal of Agricultural Sciences* **26,** 313-21.

Ghafoor, A, Gill, MA, Hassan, A, Murtaza, G, Qadir, M (2001) Gypsum: An economical amendment for amelioration of saline-sodic waters and soils, and for improving crop yields. *International Journal of Agriculture and Biology* **3,** 266-75.

Ghassemi, F, Lakeman, AJ, Nix, HA (1995) 'Salinization of land and water resources: human causes, extent, management and case studies ', (CABI Publishing: Wallignford, UK)

Ghosh, S, Lockwood, P, Hulugalle, NR, Daniel, H, Kristiansen, P, Dodd, K (2010) Changes in properties of sodic Australian Vertisols with application of organic waste products. *Soil Science Society of America Journal* **74,** 153-60.

Gill, JS, Sale, PWG, Tang, C (2008) Amelioration of dense sodic subsoil using organic amendments increases wheat yield more than using gypsum in a high rainfall zone of southern Australia. *Field Crops Research* **107,** 265-75.

Gosh, S, Lockwood, P, Hulugalle, NR, Daniel, H, Kristiansen, P, Dodd, K (2010) Changes in properties od sodic Australian Vertisols with application of organic waste products. *Soil Science Society of America Journal* **74,** 153-60.

Gravetter, FJ, Wallnau, LB (2004) 'Statistics for the behavioural sciences', (Wadsworth: Belmont, CA)

Greene, RSB (2002) Hardsetting soils. *In* 'Encyclopedia of soil science'. (Eds. Lal, R) (Marcel Dekker: New york)

Greene, RSB, Barrie, J (1982) *In* 'Proceedings of the Seminar on soil testing for gypsum requirement' (Agricultural Note Series: Shepparton, Vic)

Greene, RSB, Ford, GW (1985) The effect of gypsum on cation exchange in two red duplex soils. *Australian Journal of Soil Research* **23,** 61-74.

Greenwood, KL, Dellow, KE, Mundy, GN, Kelly, KB, Austin, SM (2006a) Improved soil and irrigation mangement for forage production. 2. Forage yield and nutritive charactersitics. *Australian Journal of Experimental Agriculture* **46,** 319-26.

Greenwood, KL, Mundy, GN, Kelly, KB, Dellow, KE, Austin, SM (2006b) Improved soil and irrigation mangement for forage production. 1. Site establishment and soil physical properties. *Australian Journal of Experimental Agriculture* **46,** 307-17.

Grevers, MCJ, De Jong, E (1993) Soil structure and crop yield over a 5-year period following subsoiling solonetzic and chernozemic soils in Saskatchewan. *Canadian Journal of Soil Science* **73,** 81-91.

Griffith City Council (2009) *Annual report*. (Griffith City Council: Griffith)

Guerin, LJ, Guerin, TF (1994) Constraints to the adoption of agricultural and environmental innovations and technologies: a review. *Australian Journal of Experimental Agriculture* **34,** 549-71.

Guerin, TF (1999) An Australian perspective on the constraints to the transfer and adoption of innovations in land management. *Environmental Conservation* **26**.

Gupta, RK, Abrol, IP (1990) Salt-affected soils: their reclamation and management for crop production. *In* 'Advances in soil science'. (Eds. Stewart, BA) (Springer-Verlag: Berlin)

Gupta, RK, Bhumbla, DK, Abrol, IP (1984) Effect of sodicity, pH, organic matter and calcium carbonate on the dispersion behaviour of soils. *Soil Science* **137,** 245-51.

Gupta, RK, Singh, RR (1988) A comparative evaluation of the reclamation efficiency of surface-concentrated versus internalyl incorporated calcium chloride and gypsum in an alkalai soil. *Soil Science* **146,** 277-83.

Hajkowicz, S, Young, M (2005) Costing yield loss from acidity, sodicity and dryland salinity to Australian agriculture. *Land Degredation and Development* **16,** 417-33.

Hajkowicz, SA, Young, MD (2002) *Values of returns to land and water and cost degradation, A consultancy report to the National Land and Water Resources Audit*. (CSIRO Land and Water: Canberra)

Hall, DJM, McKenzie, DC, MacLeod, DA, Toole, ID (1994) Amelioration of a hardsetting Alfisol through deep mouldboard ploughing, gypsum application and double cropping. III. Crop production and profitability. *Soil and Tillage Research* **28,** 287-300.

Hanay, A, Buyuksonmez, F, Kizilogu, FM, Canbolat, MY (2004) Reclamation of saline-sodic soils with gypsum and MSW compost. *Compost Science and Utilization* **12,** 175-9.

Hanay, A, Yardimci, N (1992) A research on the effects of municipal composts and barnyard manure on some physical and chemical properties of soils and soil-water relations. *Doga-Transaction Journal of Agriculture and Forestry* **16,** 91-102.

Hargreaves, JC, Adl, MS, Warman, PR (2008) A review of the use of composted municipal solid waste in agriculture. *Agriculture, Ecosystems & Environment* **123,** 1-14.

Harris, A, Fulton, M (2000a) 'The CUMA farm machinery co-operatives', (Centre for the Study of Co-operatives, University of Saskatchewan: Saskatoon, Canada)

Harris, A, Fulton, M (2000b) 'Farm machinery co-operatives in Saskatchewan and Quebec', (Centre for the Study of Co-operatives, University of Saskatchewan: Saskatoon, Canada)

Harris, A, Fulton, M (2000c) 'Farm machinery co-operatives: An idea worth sharing', (Centre for the Study of Co-operatives, University of Saskatchewan: Saskatoon, Canada)

Harrison, WJ, MacLeod, DA, McKenzie, DC (1992) The effect of clay addition and gypsum application on the physical properties of a hradsetting red-brown earth, and the response of irrigated cottons *Soil and Tillage Research* **25,** 231-44.

Hayman, PT, Alston, CL (1999) A survey of farmer practices and attitudes to nitrogen management in the northern New South Wales grains belt. *Australian Journal of Experimental Agriculture* **39,** 51-63.

He, Z, Yang, X, Khan, BA, Stoffella, PJ, Calvert, DV (2001) Plant nutrition benefits of phosphorus, potassium, calcium, magnesium, and micronutrients from compost utilization. *In* 'Compost ultilization in horticultural cropping systems'. (Eds. Stoffella, PJ & Khan, BA) (Lewis Publishers: Boca Raton, Fla.)

Hodgson, L, Dyer, D, Brown, DA (1982) Neutralization and dissolution of high calcium fly ash. *Journal of Environmental Quality* **28,** 639-47.

Holford, ICR, Schweitzer, BE, Crocker, GJ (1994) Long-term effects of lime on soil phosphorus solubility and sorption in eight acidic soils. *Australian Journal of Soil Research* **32,** 795-803.

Hoult, EH, Holden, J (unpublished) Lime & gypsum trial – Twynam Buttabone, field 10. *Twynam Cotton Research Report***,** 98-9.

Hulugalle, NR, Entwistle, PC, Cooper, JL, Scott, F, Nehl, DB, Allen, SJ, Finlay, LA (1999) Sowing wheat or field pea as rotation crops after irrigated cotton in a grey Vertosol. *Australian Journal of Soil Research* **36,** 621-40.

Hulugalle, NR, Entwistle, PC, Scott, F, Kahl, J (2001) Rotation crops for irrigated cotton in a medium-fine, self-mulching, grey Vertosol. *Australian Journal of Soil Research* **39,** 317-28.

Hulugalle, NR, Entwistle, PC, Weaver, TB, Scott, F, Finlay, LA (2002) Cotton-based rotation systems on a sodic Vertosol under irrigation: effects on soil quality and profitability. *Australian Journal of Experimental Agriculture* **42,** 341-49.

Hulugalle, NR, Weaver, TB, Ghadiri, H, Hicks, A (2006) Changes in soil properties of an eastern Australian Vertisol irrigated with sewage effluent following gypsum application. *Land Degredation and Development* **17,** 527-40.

Hutson, JL (1971) *Crust formation on some Natal soils*, Thesis - University of Natal, Pietermaritzburg.

IBM (2009) PASW Statistics 18. SPSS Inc.

Ilyas, M, Miller, RP, Qureshi, RH (1993) Hydraulic conductivity of saline-sodic soil after gypsum application and cropping. *Soil Science Society of America Journal* **57,** 1580-85.

Ilyas, M, Qureshi, RH, Qadir, M (1997) Chemical changes in a saline-sodic soil after gypsum application and cropping. *Soil Technology* **10,** 247-60.

Industry Commission (1998) *A full repairing lease - inquiry into ecologically sustainable land management*. Report no. 60, (Australian Government Publishing Service: Canberra)

Irvine, SA, Doughton, JA (2001) Salinity and sodicity, implications for farmers in Cetral Queensland. *In* 'Proceedings of the 10th annual Australian agronomy conference'. (Eds. (The Australian Society of Agronomy Inc.: Hobart)

Isbell, RF (1996) 'The Australian soil classification', (CSIRO Publishing: Melbourne)

Isbell, RF (2002) 'The Australian soil classification: revised edition', (CSIRO Publishing: Melbourne)

Isbell, RF, Reeve, RC, Hutton, JT (1983) Salt and sodicity. *In* 'Soils: an Australian viewpoint'. (Eds. Division of Soils CSIRO) (CSIRO Publications: Melbourne)

Islam, K, Singh, B, McBratney, A (2003) Simultaneous estimation of several soil properties by ultra-violet, visible, and near-infrared reflectance spectroscopy. *Australian Journal of Soil Research* **41,** 1101-14.

Jalali, M, Ranjbar, F (2009) Effects of sodic water on soil sodicity and nutrient leaching in poultry and sheep manure amended soils. *Geoderma* **153,** 194-204.

Jarwal, S, Rengasamy, P (1998) *Gypsum and stubble retention in alkaline sodic soils*. Annual Report, (Victorian Institute for Dryland Farming: Horsham)

Jastrow, JD, Zimmerman, CA, Dvorak, AJ, Hinchman, RR (1981) Plant growth and trace element uptake on acid coal refuse amended with lime or fly ash. *Journal of Environmental Quality* **10,** 154-60.

Jayawardane, NS, Biswas, TK, Blackwell, J, Cook, FJ (2001) Management of salinity and sodicity in a land FILTER systems, for treating saline waste water on a saline-sodic soil. *Australian Journal of Soil Research* **39,** 1247-58.

Jayawardane, NS, Blackwell, J (1985) The effect of gypsum enriched slots on moisture environment and aeration in an irrigated swelling clay *Australian Journal of Soil Research* **23,** 481-92.

Jayawardane, NS, Blackwell, J, Blackwell, PS (1988) Fragment size distribution within slots created in a duplex soil by a prototype rotary slotter *Soil and Tillage Research* **12,** 53-64.

Jayawardane, NS, Blackwell, J, Muirhead, WA, Kirchhof, G, Smart, R (1994) 'Slotting - a new deep tillage technique for improving crop productivity on sodic, scid and other degraded soils', (CSIRO Division of Water Resiources: Canberra)

Jayawardane, NS, Chan, KY (1995) Management of soil physical properties limiting cropping in Australian sodic soils. *In* 'Australian sodic soils: distribution, properties and management'. (Eds. Naidu, R, Sumner, ME & Rengasamy, P) (CSIRO Publications: Melbourne)

Jessop, RS, MacLeod, DA, Hulme, PJ, McKenzie, DC (1985) The effects of landforming on crop production on a red - brown earth. *Australian Journal of Agricultural Research* **23,** 85-93.

Johnston, MA (1975) The effects of different levels of exchangeable sodium on soil hydraulic conductivity *Proceedings of the South African Sugar Technologies Association* **49,** 142-7.

Jones, A (unpublished) Gypsum/lime yield response trial – "Marebone" M and P Dickson. *Macquarie Valley Trial Reports* **2001/02, 2002/03, 2003/04,** 38-9.

Kadu, PR, Vaidya, PH, Balpande, SS, Satyavathi, PLA, Pal, DK (2003) Use of hydrualic conductivity to evaluate the suitability of Vertisols for deep-rooted crops in semi-arid parts of central India. *Soil Use and Management* **19,** 208-16.

Kamphorst, A (1990) Amelioration of sodic clay soils by crack stabilisation: and experimental laboratory simulation. *Soil Science* **149,** 218-27.

Kazman, Z, Shainberg, I, Gal, M (1983) Effects of low levels of exchangeable sodium and applied phosphogypsum on the infiltration rate of various soils. *Soil Science* **135**.

Keller, DR, Brummer, EC (2002) Putting food production in context: toward a postmechanistic agricultural ethic. *BioScience* **52,** 264-71.

Kelley, WP (1937) The reclamation of alkali soils. *Californian Agricultural Experimantal Station Bulletin* **617**.

Kelly, B, Allan, C, Wilson, BP (2009) Soil indicators and their use by farmers in the Billabong Catchment, southern New South Wales. *Australian Journal of Soil Research* **47**.

Kelly, KB (1985) Effects of soil modification and treading on pasture growth and physical properties of an irrigated red - brown earth. *Australian Journal of Agricultural Research* **36,** 799-807.

Kemper, WD, Olsen, J, de Mooy, CJ (1975) Dissolution rate of gypsum in flowing water. *Proceedings of the Soil Science Society of America* **39,** 458-63.

Keren, R (1996) Reclamation of sodic-affected soils. *In* 'Soil erosion, conservation and rehabilitation'. (Eds. Agassi, M) (Marcel Dekker Inc.: New York, USA)

Keren, R, O'Connor, GA (1982) Gypsum dissolution and sodic soil reclamation as affected by water flow velocity. *Soil Science Society of America Journal* **46,** 726-32.

Keren, R, Shainberg, I (1981) Effect of dissolution rate on the efficiency of industrial and mined gypsum in improving infiltration of a sodic soil. *Soil Science Society of America Journal* **45,** 103-7.

Kloppenburg, J (1991) A social theory and de/reconstruction of agricultural science, local knowledge for an alternative agriculture. *Rural Sociology* **56,** 519-48.

Kloppenburg, J (1992) Science in agriculture: a reply to Molnar, Duffy, Cummins, and Van Saten and to Flora. *Rural Sociology* **57,** 98-107.

Kovda, V, van den Berg, C, Hagan, RM (1973) 'Irrigation, drainage and salinity: An international source book', (Hutchinson and Co.: London)

Kowalik, P, Loveday, J, McIntyre, DS, Watson, CL (1979) Deep percolation during prolonged ponding of a swelling soil, and the effect of gypsum treatments. *Agricultural Water Management* **70,** 131-47.

Kukier, U, Sumner, ME, Miller, WP (1994) Boron release from fly ash and its uptake by corn. *Journal of Environmental Quality* **23,** 596-603.

Kumar, D, Singh, B (2003) The use of coal fly ash in sodic soil reclamation. *Land Degredation and Development* **14,** 285-99.

Lebron, I, Suarez, DL, Yoshida, T (2002) Gypsum effect on the aggregate size and geometry of three sodic soils under reclamation. *Soil Science Society of America Journal* **66,** 92-8.

Lees, J, Reeve, I (1994) 'TPSKP 1994 producer survey', (Rural Development Centre: Armidale, NSW)

Leopold, A ([1949] 1987) 'A sand county almanac and sketches here and there', (Oxford University Press: New York)

Levy, GJ, van der Watt, HvH, du Plessis, HM (1988) Effect of Na/Mg and Na/Ca systems on soil hydraulic conductivity and infiltration. *Soil Science* **146,** 303-10.

Li, F, Keren, R (2008) Native $CaCO_3$ mineral dissolution and its contribution to sodic calcareous soil reclamation under laboratory conditions. *Arid Land Research and Management* **22,** 1-15.

Likert, R (1932) A technique for the measurement of attitudes. *Archievs of Psychology* **140,** 1-55.

Littler, JW, Marley, JMT (1978) 'Fallowing and winter cereal production on the Darling Downs - progress report', (Qld Department of Primary Industries: Queensland)

Lobry de Bruyn, LA, Abbey, JA (2003) Characterisation of farmers' soil sense and the implications for on-farm monitoring of soil health. *Australian Journal of Experimental Agriculture* **43,** 285-305.

Lobsey, C, Viscarra Rossel, R, McBratney, A (2010) An automated system for rapid in-field soil nutrient testing. *In* 'Proceedings of the The 19th World Conference of Soil Science' (International Union of Soil Science: Brisbane)

Loveday, J (1974) Recognition of gypsum responsive soils. *Australian Journal of Soil Research* **25**.

Loveday, J (1976) Relative significance of electrolyte and cation exchange effects when gypsum is applied to a sodic clay soil *Australian Journal of Soil Research* **14,** 361-71.

Loveday, J, Bridge, BJ (1983) Management of salt affected soils. *In* 'Soils: an Australian viewpoint'. (Eds. Division of Soils CSIRO) (CSIRO Publications: Melbourne)

Loveday, J, Pyle, JC (1973) *The Emerson dispersion test and its relation to hydraulic conductivity*. CSIRO Division of Soils Technical Paper,

Loveday, J, Saunt, JE, Flemming, PM, Muirhead, WA (1970) Soil and cotton response to tillage and ameliorant treatments in a brown clay soil 1. soil responses and water use. *Australian Journal of Experimental agriculture and Animal Hausbandry* **10,** 313-24.

Madejon, E, Lopes, R, Murillo, YM, Cabrerra, F (2001) Agricultural use of three (sugar - beet) vinasse compost: effect on crops and chemical properties of a cambisol soil in Quadalquirvirm River Valley (SW Spain). *Agricultre, Ecosystems & Environment* **84,** 55-65.

Makoi, JHJR, Ndakidemi, PA (2007) Reclamation of sodic soils in northern Tanzania, using locally available organic and inorganic resources. *African Journal of Biotechnology* **6,** 1926-31.

Mann, M, Pissarra, A, van Hoorn, JW (1982) Drainage and desalinisation of heavy clay soils in Portugal. *Agricultural Water Management* **5,** 227-40.

Massoud, FI (1977) Basic principals for prognosis and monitoring of salinity and sodicity *In* 'Proceedings of the International Conference on Management of Saline Water for Irrigation' (Lubbock, TX: Texas Technical University)

Mathers, AC, Stewart, BA (1974) Corn silage yield and soil chemical properties as affected by cattle feedlot manure. *Journal of Environmental Quality* **3,** 143-7.

May, EL (2006) *How landholders use and value their private native forests: a study of landholders with dry sclerophyll forests on the Southern Tablelands of NSW*, Thesis - Australian National University, Canberra.

McAndrew, DW, Malhi, SS (1990) Long-term effects of deep ploughing solonetzic soil on chemical characteristics and crop yield. *Canadian Journal of Soil Science* **70,** 619-23.

McBeath, TM, Grant, CD, Murray, RS, Chittleborough, DJ (2010) Effects of subsoil amendments on soil physical properties, crop response, and soil water quality in a dry year. *Australian Journal of Soil Research* **48,** 140-9.

McDowell, RW (2005) The effectiveness of coal fly-ash to decrease phosphorus loss from grassland soils. *Australian Journal of Soil Research* **43,** 853-60.

McGarry, D (1987) The effect of water content during land preparation on aspects of soil physical condition and cotton growth. *Soil and Tillage Research* **9,** 287-307.

McIntyre, DS (1958) Soil splash and the formation of surface crusts by raindrop impact. *Soil Science* **85,** 261-66.

McIntyre, DS (1979) Exchangeable sodium, subplacticity, and hydraulic conductivity of some Australian soils. *Australian Journal of Soil Research* **17,** 115-20.

McIntyre, DS, Loveday, J (1974) Particle-size analysis. *In* 'Methods for analysis of irrigated soils'. (Eds. Loveday, J) (Commonwealth Agricultural Bureaux: Rarnham Royal, Bucks.)

McKenzie, DC (1982) *Evaluation of gypsum as an ameliorant for cracking-clay soils of the Moree district, N.S.W.*, Thesis - University of New England, Armidale.

McKenzie, DC, Abbott, TS, Chan, KY, Slavich, PG, Hall, DJM (1993) The nature, distribution and management of sodic soils in New South Wales. *Australian Journal of Soil Research* **31,** 839-68.

McKenzie, DC, Murphy, BW (2005) *Use this graph to interpret your soil tests and predict the dispersion and/or salinity characteristics of your soils*, Don Stanger Public Relations

McKenzie, DC, So, HB (1989a) Effect of gypsum on vertisols of the Gwydir Valley, New South Wales 1. Soil properties and wheat growth. *Australian Journal of Experimental Agriculture* **29,** 51-62.

McKenzie, DC, So, HB (1989b) Effect of gypsum on vertisols of the Gwydir Valley, New South Wales 2. Ease of tillage. *Australian Journal of Experimental Agriculture* **29,** 63-7.

McKenzie, NJ (1992) 'Soils of the lower Macquarie Valley, New South Wales', (CSIRO Division of Soils: Canberra)

Mehanni, AH (1974) Short term effect of some methods for improving soil structure in red-brown earth soils of northern irrigation areas, Victoria. *Australian Journal of Experimental Agriculture* **14,** 689-93.

Midwood, AJ, Boutton, TW (1998) Soil carbonate decomposition by acid has little effect on $\delta^{13}C$ of organic matter. *Soil Biology and Biochemistry* **30,** 1301-7.

Miller, RM, Jastrow, JD (1992) The role of mycorrhizal fungi in soil conservation. *In* 'Mycorrhizae in sustainable agriculture'. (Eds. Bethlenfalvay, CJ & Linderman, RG) (American Society of America, Crop Science Society of America, and Soil Science Society of America: Madison, WI)

Miller, RO (1998) Nitric-perchloric acid wet digestion in an open vessel. *In* 'Handbook of Reference Methods for Plant Analysis'. (Eds. Yash, PK) (CRC Press: Boca Raton, Florida)

Miller, WP, Scifres, J (1988) effect of sodium nitrate and gypsum on infiltration and errosion of highly weathered soils. *Soil Science* **145**.

Milthorpe, PL, Newman, JC (1979) Gypsum assists reclamation of scalded sodic caly near Condobolin. *Journal of Soil Conservation New South Wales* **35**.

Moore, DM, Reynolds, RJC (1989) 'X-ray diffraction and the identification and analysis of clay minerals', (Oxford University Press: Oxford, New York)

Mowo, JG, Janssen, BH, Oenema, O, German, LA, Mrema, JP, Shemdoe, RS (2006) Soil fertility evaluation and management by smallholder farmer communities in northern Tanzania: Nutrient management in tropical agroecosystems. *Agricultre, Ecosystems & Environment* **116,** 47-59.

Mubarak, AR, Nortcliff, S (2010) Calcium carbonate solubilization through H-proton release from legumes grown in calcaerous saline-sodic soils. *Land Degredation and Development* **21,** 24-31.

Muirhead, WA, Loveday, J, Saunt, JE (1970) Soil and cotton respons to tillage and amelioration treatments in a brown clay soil: II. growth, yield and qaulity of cotton. *Journal of Experimental Agricuilture and Animal Husbandry* **10,** 324-33.

Mullins, CE, MacLeod, DA, Northcote, KH, Tisdall, JM, Young, IM (1990) Hardsetting soils: behaviour, occurrence and management. *Advances in Soil Science* **11,** 38-108.

Murphy, BW (2002) Sodic soils: formation and global distribution of. *In* 'Encyclopedia of soil science'. (Eds. Lal, R) (Marcel Dekker: New York)

Murphy, BW, Lawrie, J, King, D, Taylor, C (1998) 'Distribution of sodic soils in central western NSW. Aeolian dust: Implications for Australian mineral exploitation and environmental management': Canberra)

Mylek, M (2006) *Landholder perceptions about impediments to, and incentives for, the adoption of farm forestry in the Southern Tablelands region of NSW*, Thesis - Australian National University, Canberra.

Naidu, R, Merry, RH, Churchman, GJ, Wright, MJ, Murray, RS, Fitzpatrick, RW, Zarcinas, BA (1993) Sodicity in South Australia - a review. *Australian Journal of Soil Research* **31,** 911-29.

Naidu, R, Rengasamy, P (1993) Ion interactions and constraints to plant nutrients in Australian sodic soils. *Australian Journal of Soil Research* **31,** 801-19.

Nass, MM, Lexmond, TM, Van Beusichem, ML, Janssen Jurkovicova, M (1993) Long term supply and uptake by plants of elements from coal fly ash. *Communications in Soil Science and Plant Analysis* **24,** 899-913.

Nelson, PN, Baldock, JA, Clarke, P, Oades, JM, Churchman, GJ (1999) Dispersed clay and organic matter in soil: their nature and associations. *Australian Journal of Soil Research* **37,** 289-315.

Nelson, PN, Oades, JM (1998) Organic matter, sodicity, and soil structure. *In* 'Sodic soils: Distribution, management and envirnomental consequences'. (Eds. Sumner, ME & Naidu, R) (Oxford University Press: New York)

New South Wales Farmers Association (2008) *Constitution - NSW Farmers Association*. (NSW Farmers Asscoiation: Sydney)

Northcote, KH, Skene, JK (1972) *Australian soils with saline and sodic properties*. CSIRO Soil Publication 27, (CSIRO: Australia)

Nuttall, JG, Armstrong, RD, Connor, DJ (2005) The effect of boron tollerance, deep ripping with gypsum, and water supply on subsoil water extraction of cereals in an alkaline soil. *Australian Journal of Agricultural Research***,** 113-22.

Olsson, KA, Dellow, KE, Hirth, JR, Kelly, KB, Greenwood, KL, Blaikie, SJ (2002) Soil properties, root response and production of irrigated pasture on a red-brown earth after subsoil modification. *Australian Journal of Experimental Agriculture* **42,** 453-63.

Onus, G (1978) *A soil structural stability survey of the Gwydir valley of New South Wales*, Thesis - University of New England, Armidale.

Oster, JD (1982) Gypsum use in irrigated agriculture: a review *Fertilizer Research* **3,** 73-89.

Oster, JD (1993) Sodic soil reclamation. *In* 'Towards the rational use of high salinity tolerant plants'. (Eds. Leith, H & Al Masoom, A) (Kluwer Academic Publishers: The Netherlands)

Oster, JD, Schroer, FW (1979) Infiltration as influenced by irrigation water quality. *Soil Science Society of America Journal* **43,** 444-7.

Pal, DK, Bhattachayya, T, Ray, SK, Chandran, P, Srivastava, P, Durge, SL, Bhuse, SR (2006) Significance of soil modifiers (Ca-zeolites and gypsum) in naturally degraded Vertisols of the Peninsular India in redefining the sodic soils. *Geoderma* **136,** 210-28.

Pal, DK, Dasog, GS, Vadivelu, S, Ahuja, RL, Bhattachayya, T (2000) Secondary calcium carbonate in soils of arid and semi-arid regions of India. *In* 'Global changes and pedogenic carbonates'. (Eds. Lal, R, Kimble, JM, Eswaran, H & Stewart, BA) (Lewis Publishers: Boca Raton, Florida, USA)

Pal, DK, Srivastava, P, Bhattachayya, T (2003) Role of microtopography in the formation of sodic soils in the semi-arid part of the Indo-Gangentic Plains, India. *Catena* **51,** 3-31.

Pathan, SM, Aylmore, LAG, Colmer, TD (2002) Reduced leaching of nitrate, ammonium and phosphorus in a sandy soil by fly ash amendment. *Australian Journal of Agricultural Research* **40,** 1201-11.

Pirie, A, Singh, B, Islam, K (2005) Ultra-violet, visible, near-infrared, and mid infra-red diffuse reflectance spectroscopic techniques to predict several soil properties. *Australian Journal of Soil Research* **43,** 713-21.

Poona, SR, Bhumbla, DR (1973) Effect of farm yard manure on the availability of Ca from Ca45CO3 in a sodic soil (ESP 77.7). *Plant and Soil* **38,** 679-82.

Poonia, SR, Bhumbla, DR (1973) Effect of farm yard manure on the availability of Ca from Ca45CO3 in a sodic soil (ESP 77.7). *Plant and Soil* **38,** 679-82.

Prathapar, SA, Aslam, M, Kahlown, MA, Iqbal, Z, Qureshi, AS (2005) Gypsum slotting to ameliorate sodic soils in Pakistan. *Irrgation and Drainage* **54,** 509-17.

Price, P (2010) Combatting subsoil constraints: R&D for the Australian grains industry. *Australian Journal of Soil Research* **48,** i-iii.

Pupisky, H, Shainberg, I (1979) Salt effects on the hydraulic conductivity of a sandy soil. *Soil Science Society of America Journal* **43,** 429-33.

Qadir, M, Ghafoor, A, Murtaza, G (2001a) Use of saline-sodic waters through phytoremediation of calcareous saline-sodic soils. *Agricultural Water Management* **50,** 197-210.

Qadir, M, Oster, JD (2002) Vegetative bioremediation of calcareous sodic soils: history, mechanisms, and evaluation. *Irrigation Science* **21,** 91-101.

Qadir, M, Qureshi, RH, Ahmad, N (1996) Reclamation of a saline-sodic soil by gypsum and Leptocha fusca. *Geoderma* **74,** 207-17.

Qadir, M, Qureshi, RH, Ahmad, N (2002) Amelioration of calcareous saline sodic soils through phytoremediation and chemical strategies. *Soil Use and Management* **18,** 381-5.

Qadir, M, Schubert, S, Ghafoor, A, Murtaza, G (2001b) Amelioration strategies for sodic soils: a review. *Land Degredation and Development* **12,** 357-86.

Qadir, M, Steffens, D, Yan, F, Schubert, S (2003) Proton release by N2-fixing plant roots: a possible contribution to phytoremediation of calcareous sodic soils. *Journal of Plant Nutrition and Soil Science* **166,** 14-22.

Quilty, JR, Cattle, SR (accepted) The use and understanding of organic ammendments in Australian agriculture - a review. *Australian Journal of Soil Research.*

Quirk, JP, Aylmore, LAG (1960) Swelling and shrinkage of clay-water systems. *7th International Congress of Soil Science* **11,** 378-87.

Quirk, JP, Schofield, RK (1955) The effect of electrolyte concentration on soil permeability. *Australian Journal of Soil Research* **6,** 163-78.

Rani, V, Khetarpaul, N (2009) Nutrient composition of tomato products prepared using tomato grown under sodic condition with gypsum and farmyard manure treatment. *Journal of the Science of Food and Agriculture* **89,** 2601-7.

Rasmussen, WW, Moore, DP, Alban, AL (1972) Improvement of a solonetzic (slick spot) soil by deep ploughing, subsoiling and amendments. *Soil Science Society of America Proceedings* **36,** 137-42.

Rayment, GE, Higginson, FR (1992) 'Australian laboratory handbook of soil and water chemical methods', (Inkata Press: Sydney)

Reeves, DW (1997) The role of soil organic matter in maintaining soil quality in continuous cropping systems. *Soil and Tillage Research* **43,** 131-67.

Reid, JB, Goss, MJ (1981) Effect of living roots of different plant species on the aggregate stability of two arable soils. *Australian Journal of Soil Research* **32,** 521-41.

Rengasamy, P (1983) Clay dispersion in relation to changes in the electrolyte composition of dialysed red-brown earths *Journal of Soil Science* **34,** 723-32.

Rengasamy, P (2002) Transient salinity and subsoil constraints to dryland farming in Australian sodic soils: an overview. *Australian Journal of Experimental Agriculture* **42,** 351-61.

Rengasamy, P, Greene, RSB, Ford, GW (1984a) The role of clay fraction in the particle arrangement and stability of soil aggregates - a review. *Clay Research* **3,** 53-67.

Rengasamy, P, Greene, RSB, Ford, GW (1986) Influence of magnesium on aggregate stability in sodic Red-Brown Earths. *Australian Journal of Soil Research* **24,** 229-37.

Rengasamy, P, Greene, RSB, Ford, GW, Mehanni, AH (1984b) Identification of dispersive behaviour and the management of red-brown earths. *Australian Journal of Soil Research* **22,** 413-31.

Rengasamy, P, Olsson, KA (1991) Sodicity and soil structure. *Australian Journal of Soil Research* **29,** 935-52.

Rengasamy, P, Olsson, KA (1993) Irrigation and sodicity. *Australian Journal of Soil Research* **29,** 821-37.

Rengasamy, P, Olsson, KA, Kirby, JM (1992) Physical constraints to root growth in in the subsoil. *Proceedings of the National Workshop on Subsoil Constraints to Root Growth and High Soil Water and Nutrient use by Plants***,** 84-91.

Richards, LA (1954) Diagnosis and improvements of saline alkalai soils. *USDA Agriculture Handbook* **60**.

Rimmer, DL, Greenland, DJ (1976) Effect of $CaCO_3$ on the swelling of a soil clay. *Journal of Soil Science* **27,** 129-39.

Robbins, CW (1986a) Carbon dioxide partial pressure in lysimeter soils. *Agronomy Journal* **78,** 151-8.

Robbins, CW (1986b) Sodic calcareous soil reclamation as affected by different amendments and crops. *Agronomy Journal* **78,** 916-20.

Robertson, GA (1996) Saline land in Australia - its extent and predicted trends. *Australian Journal of Soil and Water Conservation* **9,** 4-7.

Romig, DE, M.J., G, Harris, RF, McSweeney, K (1995) How farmers assess soil health and quality. *Journal of Soil and Water Conservation* **50,** 229-36.

Roth, CH (1991) Soil crusting in South America. *In* 'Proceedings of the Proceedings of the International Symposium on Soil Crusting: Chemical and Physical Processes' (The University of Georgia: Athens, G.A.)

Roth, CH, Pavan, MA (1991) Effects of lime and gypsum on clay dispersion and infiltration in samples of a Brazillian Oxisol. *Geoderma* **48,** 351-61.

Rowell, DL (1988) Soil acidity and alkalinity. *In* 'Russell's soil conditions and plant growth'. (Eds. Wild, A) (Longman Scientific & Technical: Essex, England)

Russell, EW (1961) 'Soil conditions and plant growth', (Longmans, Green and Co. Ltd: London)

Russell, JS (1960) Soil fertility changes in the long-term experimental plots at Kybybolite, South Australia II. changes in phosphorus. *Australian Journal of Agricultural Research* **11,** 926-47.

Sahin, U, Oztas, T, Anapali, O (2003) Effects of consecutive applications of gypsum in equal, increasing, and decreasing quantities on soil hydrualic conductivity of a saline-sodic soil. *Journal of Plant Nutrition and Soil Science* **166,** 621-24.

Sansom, JJ, Chanasky, DS, Naeth, MA, Bateman, JC (1998a) In situ amelioration of sodic minespoil with chemical amendments and crop management II. soil physical properties, soil moisture and plant growth. *Canadian Journal of Soil Science* **78,** 667-74.

Sansom, JJ, Naeth, MA, Chanasky, DS, Bateman, JC (1998b) n situ amelioration of sodic minespoil with chemical amendments and crop management I. soil chemical properties. *Canadian Journal of Soil Science* **78,** 359-65.

Saulys, V, Bastiene, N (2006) The effect of lime admixture to trench backfill on the functioning of tile drainage in heavy soils. *Irrgation and Drainage* **55,** 373-82.

Scheffe, H (1958) Experiments with mixtures. *Journal of the Royal Statistical Society* **20,** 344-60.

Scott Russell, R (1977) 'Plant Root Systems - Their Function and Interactions with the Soil', (McGraw-Hill)

Sekhon, BS, Bajwa, MS (1993) Effect of organic matter and gypsum in controlling soil sodicity in rice-wheat-maize system irrigated with sodic waters. *Agricultural Water Management* **24,** 15-25.

Shainberg, I, Gal, M (1982) The effect of lime on the response of soils to sodic conditions. *Journal of Soil Science* **33,** 489-98.

Shainberg, I, Gal, M, Ferreria, AG, Goldstein, D (1991) Effect of water quality and amendments on the hydraulic properties and errosion of several Mederterranean soils *Soil Technology* **4,** 135-46.

Shainberg, I, Letey, J (1984) Response of soils to sodic and saline conditions. *Hilgardia* **52,** 1-57.

Shanmuganathan, RT, Oades, JM (1983) Modification of soil physical properties by addition of calciaum compounds. *Australian Journal of Soil Research* **21,** 285-300.

Shepherd, AN (1925) Experience on Yanco irrigation area. *Agricultural Gazette New South Wales* **36,** 261-3.

Sikora, IJ, Enkiri, NK (1999) Growth of tall fescue in compost/fetilizer blends. *Soil Science* **56,** 125-37.

Sinden, JA, King, DA (1990) Adoption of soil conservation measures in Manilla Shire, New South Wales. *Review of Marketing and Agricultural Economics* **58,** 179-92.

Smil, V (2000) Phosphorus in the environment: Natural flows and human interferences. *Annual Review of Energy and the Environment* **25,** 53-88.

So, HB, Aylmore, LAG (1993) How do sodic soils behave? The effects of sodicity on soil physical behaviour. *Australian Journal of Soil Research* **31,** 761-77.

So, HB, Cook, GD (1993) The effect of dispersion on the hydraulic conductivity of surface seals in clay soils. *Soil Technology***,** 325-330.

So, HB, Onus, G (1984) The extent of unstable grey and brown clays of the lower Gwydir Valley, New South Wales. *In* 'The properties and utilization of cracking clay soils'. (Eds. McGarity, JW, Hoult, EH & So, HB) (University of New England: Armidale)

So, HB, Taylor, DW, Yates, WJ, McGarity, JW (1978) Amelioration of structurally unstable grey and brown clays. *In* 'Modifications of soil structure'. (Eds. Emerson, WW, Bond, RD & Dexter, AR) (John wiley & sons: Chichester)

Soil Science Society of America (1997) 'Glossary of soil science terms', (Soil Science Society of America: Madison, WI)

Soil Survey Staff (1999) 'Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys', (United States Department of Agriculture, Natural Resources Conservation Service: Washington)

Sojka, RE, Upchurch, DR (1999) Reservations regarding the soil quality concept. *Soil Science Society of America Journal* **63,** 1039-54.

Sparks, DL (2003) 'Environmental soil chemistry', (Academic Press: London)

Speirs, SD (2006) *Characterising soil structural stability and form of sodic soil used for cotton production*, Thesis - The University of Sydney, Sydney.

Sposito, G (1989) 'The chemistry of soils', (Oxford University Press: New York)

Srivastava, P, Bhattachayya, T, Pal, DK (2002) Significance of the formation of calcium carbonate minerals in the pedogenisis and management of cracking clay soils (Vertisols) of India. *Clays and Clay Minerals* **50,** 111-26.

Stace, HC, Hubble, GD, Brewer, R, Northcote, KH, Sleeman, JR, Mulcahy, MJ, Hallsworth, EG (1968) 'A handbook of Australian soils', (Rellim: Adelaide)

Staff USSL (1954) 'Diagnosis and improvement of saline and alkali soils', 60, (Department of Agriculture Handbook)

Stockdale, CR (1983) Irrigated pasture productivity and its variability in the Shepparton Region of Northern Victoria. *Australian Journal of Experimental Agriculture and Animal Hausbandry* **23,** 131-9.

Sumner, ME (1992) The electrical double layer and clay dispersion. *In* 'Soil crusting: chemical and physical processes'. (Eds. Sumner, ME & Stewart, BA) (Lewis Publishers: Boca Raton)

Sumner, ME (1993) Sodic soils: a new perspective. *Australian Journal of Soil Research* **31,** 683-750.

Surapaneni, A, Olsson, KA, Burrow, DP, Beecher, HG, Ham, GJ, Stevens, RM, Hulugalle, NR, McKenzie, DC, Rengasamy, P (2002) Tatura sodicity conference: knowledge gaps in sodicity research for major agricultural industries. *Australian Journal of Experimental Agriculture* **42,** 379-87.

Swarup, A (1988) Influence of organic matter and flooding on the chenical and electrochemical properties of sodic soil and rice growth *Plant and Soil* **106,** 135-41.

Szabolcs (1991) Desertification and salinisation *In* 'Proceedings of international conference on agricultural management of salt-affected areas '. (Eds. Choukr-Allah, R) (Institut Agronomique et Veterinaire Hassan II: Agadir, Morocco)

Szabolcs (1994) Soils and salinization. *In* 'Handbook of plant and crop stress'. (Eds. Pessarakli, M) (Marcell Dekker: New York)

Tanji, KK (1990) Nature and extent of agricultural salinity. *In* 'Agricultural salinity assessment and amangement'. (Eds. Tanji, KK) (American Society of Civil Engineers: New York)

Taylor, DW, Olsson, KA (1987) Effect of gypsum and deep ripping on lucerne (Medicago sativa L.) yeilds on a red-brown earth under flood and spray irrigation. *Australian Journal of Experimental Agriculture* **27,** 841-72.

Tisdall, AL, Smith, SE, Rengasamy, P (1997) Aggregation of soil by fungal hyphae. *Australian Journal of Soil Research* **35,** 55-60.

Tisdall, JM (1991) Fungal hyphae and structural stability of soil. *Australian Journal of Soil Research* **29,** 729-43.

Tisdall, JM, Oades, JM (1979) Stabilization of soil aggregates by the root systems of ryegrass. *Australian Journal of Soil Research* **17,** 429-41.

Tucker, BM (1985) A proposed new reagent for the measurement of cation exchange properties of carbonate soils. *Australian Journal of Soil Research* **23,** 633-42.

Tucker, BM, Beatty, HJ (1974) Exchangeable cations and cation exchange capacity. *In* 'Methods for analysis of irrigated soils'. (Eds. Loveday, J) (Commonwealth Agricultural Bureaux: Farnham Royal, England)

Tucker, M, Napier, TL (1998) Perceptions of risk asscoiated with use of farm chemicals: implications for conservation initiatives. *Environmental Management* **22,** 575-87.

Turner, JC, Hattey, JA, Warren, JG, Penn, CJ (2010) Electrical conductivity and sodium adsorption ratio changes following annual applications of animal manure amendments. *Communications in Soil Science and Plant Analysis* **41,** 1043-60.

Valzano, FP (2000) *The effect of chemical ameliorants, tillage, and stubble practices on sodic soils in Australia*, Thesis - Australian National University, Canberra.

Valzano, FP, Greene, RSB, Murphy, BW, Rengasamy, P, Jarwal, SD (2001a) Effects of gypsum and stubble retention on the chemical and physical properties of a sodic grey vertosol in western Victoria. *Australian Journal of Soil Research* **39,** 1333-47.

Valzano, FP, Murphy, BW, Greene, RSB (2001b) The long term effects of lime ($CaCO_3$), Gypsum ($CaSO_4.2H_2O$), and tillage on the physical and chemical properties of a sodic red-brown earth. *Australian Journal of Soil Research* **39,** 1307-31.

van der Elshout, S, Kamphorst, A (1990) Suitability of coarse-grade gypsum for sodic soil reclamation: a laboratory experiment. *Soil Science* **149,** 228-34.

van Olphen, H (1963) 'An introduction to clay colloid chemistry', (John Wiley & Sons: New york)

Vance, WH, McKenzie, BM, Tisdall, JM (2002) The stability of soils used for cropping in northern Victoria and southern New South Wales. *Australian Journal of Soil Research* **40,** 615-24.

Verba, MP, Devyatykh, VA (1992) Changes in micromorphology of gypsiferous meadow sierozem during leaching. *Eurasian Soil Science* **24,** 12-22.

Vervoort, RW, Cattle, SR, Minasny, B (2003) The hydrology of Vertosols used for cotton production: I. Hydraulic, structural and fundamental soil properties. *Australian Journal of Soil Research* **41,** 1255-72.

Viscarra Rossel, RA, McBratney, A, Minasny, B (Eds.) (2010) *Proximal soil sensing,* (Springer: London)

Viscarra Rossel, RA, Walter, C (2004) Rapid, quantitative and spatial field measurements of soil pH using an ion sensitive field effect transistor. *Geoderma* **119,** 9-20.

Wahid, A, Akhtar, S, Ali, I, Rasul, E (1998) Amelioration of saline-sodic soils with organic matter and their use for wheat growth. *Communications in Soil Science and Plant Analysis* **29,** 2307-18.

Wallace, A (1994) Use of gypsum on soil where needed can make agriculture more sustainable. *Communications in Soil Science and Plant Analysis* **25,** 109-16.

Wang, HL, Hedley, MJ, Bolan, NS, Horne, DJ (1999a) The influence of surface incorporated lime and gypsiferous by-products on surface and subsurface soil accidity – I. Soil solution chemistry. *Australian Journal of Soil Research* **37,** 165-80.

Wang, HL, Hedley, MJ, Bolan, NS, Horne, DJ (1999b) The influence of surface incorporated lime and gypsiferous by-products on surface and subsurface soil accidity – II. Root growth and agronomic implications *Australian Journal of Soil Research* **37,** 181-90.

Watson, WD, Hall, NH, Hamblin, A (2000) Economic aspects of sodic, acid and saline soils in Australia. *In* 'Proceedings of the Sodicity conference: sodicity issues in agricultural industries - current research and future directions' (ISIA: Tatura, Victoria)

Webster, P (1999) The challenge of sustainability at the farm level: presidential address. *Journal of Agricultural Economics* **50,** 371-87.

Weinbaum, BS, Allen, MF, Allen, EB (1996) Survival of arbuscular mycorrhizal fungi following reciprocal transplanting across the Great Basin. *Ecological Applications* **6,** 1365-72.

Wilkinson, R (1996) 'Resource monitoring by Hawkes Bay farmers', (Manaaki Press: Lincoln)

Willer, H, Yuseffi-Menzler, M, Sorenson, N (2008) 'The world of organic agriculture: Statistics and emerging trends 2008', (Earthscan: London)

Wong, JWC, Ho, GE (1991) Effects of gypsum and sewage sludge amendment on physical properties of fine bauxite refining residue. *Soil Science* **152,** 326-32.

Wong, VNL, Murphy, BW, Koen, TB, Greene, RSB, Dalal, RC (2008) Soil organic carbon stocks in saline and sodic landscapes. *Australian Journal of Soil Research* **46,** 378-89.

Yates, LJ, Hedley, MJ (2008) Understanding winter sodium deposition in Taranaki, New Zealand. *Australian Journal of Soil Research* **46,** 600-09.

Zhang, X-h, Li, L-q, G-x., P (2007) Topsoil organic carbon mineralization and CO_2 evolution of three paddy soils from South China and the temperature dependance. *Journal of Environmental Sciences* **19,** 319-26.

A DESCRIPTION OF FOUR SODIC SOILS AND THE SOIL ANALYTICAL METHODS EMPLOYED IN THIS WORK

"One can not lay down hard and fast rules, but it is surely apparent that because of the poor original condition of our soils we should aim to improve them over the long term, or at least maintain them"
– Smith (1969)

3. A description of four sodic soils and the soil analytical methods employed in this work

3.1. Introduction

The theme of this thesis is combating sodicity. While both ameliorative methods and the human element of management are investigated, the majority of work relates to applied techniques for sodic soil management. This applied work is of a field and laboratory experiment nature, utilising numerous field and laboratory methods of analysis. Field-based experiments were conducted on four experimental sites, while the laboratory experiment utilised the soil from one of these sites.

3.1.1. Sampling districts

Soil was analysed from four sites, within three districts, across two valleys of NSW; from the Warren and Trangie districts of the Macquarie Valley and from the Hillston district of the Lachlan Valley. For the purpose of this study, the Macquarie and Lachlan Valleys are defined as the Macquarie-Bogan River Catchment and the Lachlan River Catchment, which are displayed in Figure 3.1 and Figure 3.2, respectively. The Macquarie Valley is described as Grassland – Hot (persistently dry) and the Lachlan Valley region is described as Grassland – Warm (persistently dry) using the Climate Classification of Australia (Bureau of Meteorology 2006). The mean climatic data for the sampling districts is displayed in Table 3.1. Irrigated field experiments were carried out on “Mount View” (Hillston) and “Wyadra” (Hillston), while dryland experiments occurred on “Bellevue” (Warren) and “Agriland” (Trangie). The original intention was to conduct irrigated experiments on “Bellevue” and “Agriland”. However, these sites do not have access to bore water and rely on rainfall and subsequent unsecured irrigation water allocation. As the rainfall during the lifetime of the experiments was intermittent, unreliable and well below the annual average, irrigation was not feasible. The soil used for the laboratory experiment was sourced from “Mount View”.

Table 3.1 Mean climatic data by district based on the world standard 30 year period (1961 to 90; Bureau of Meteorology 2009).

Valley	*District*	*Annual rainfall (mm)*	*Mean number of days with rainfall >1 mm*	*Mean annual temperature (ºC)*		
				Minimum	*Maximum*	*Mean number of days with temp >30ºC*
Lachlan	Hillston	355	46	10	24	100
Macquarie	Warren	413	49	10	25	93
	Trangie	504	50	11	25	91

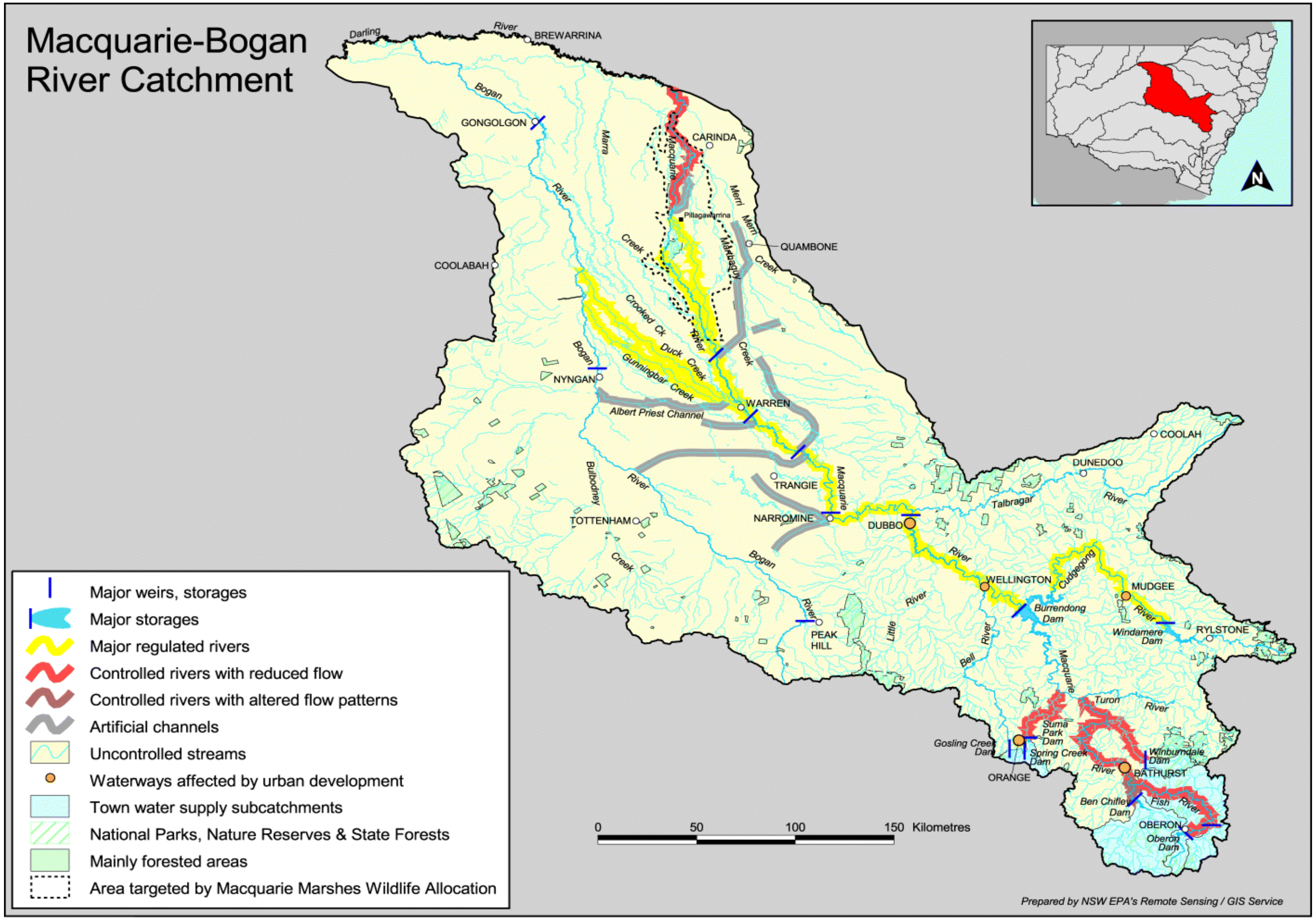


Figure 3.1. The Macquarie Valley

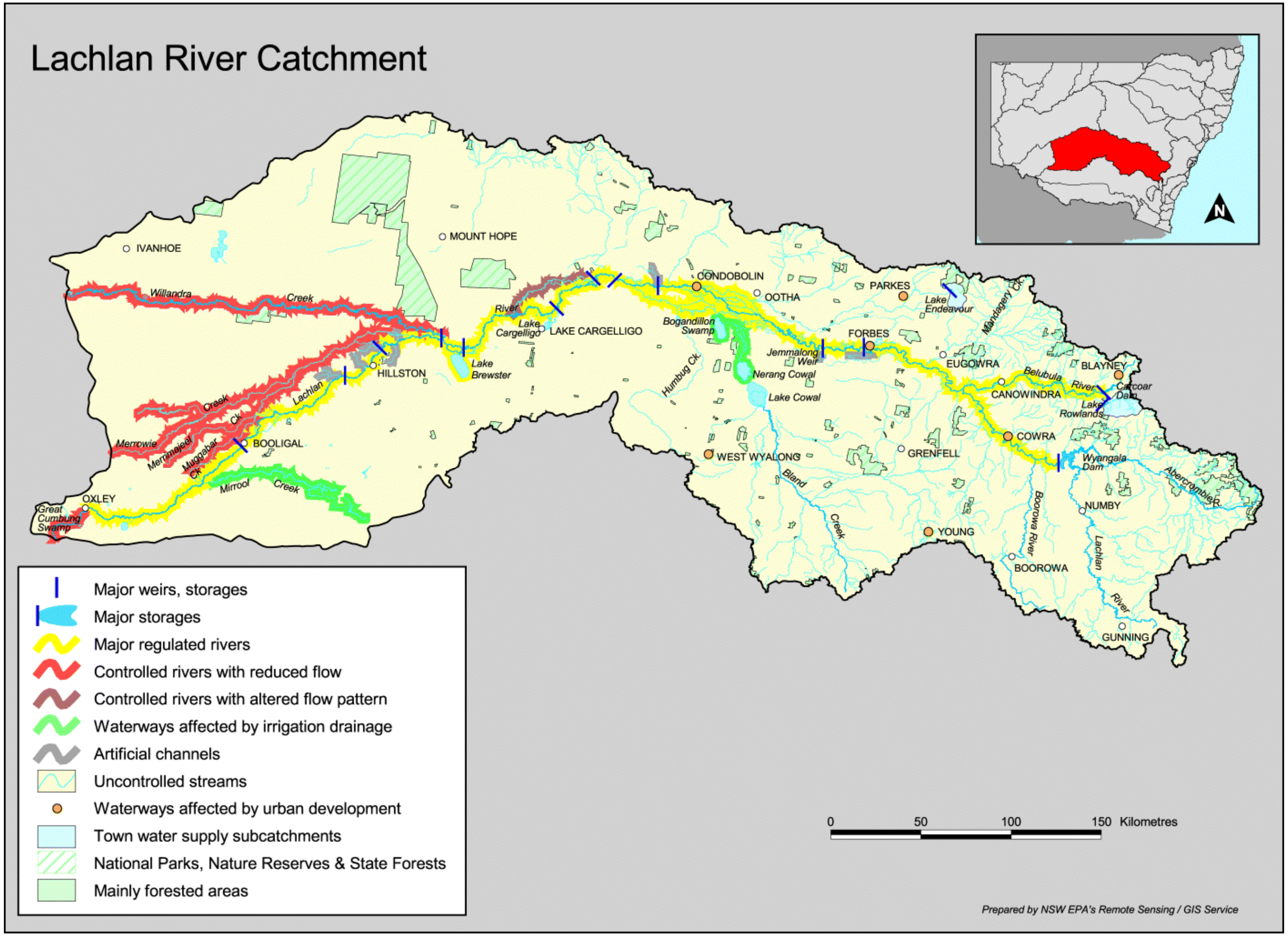


Figure 3.2. The Lachlan Valley

3.2. “Bellevue” – Warren

3.2.1. History and on-field operations

The experimental site on the “Bellevue” property is situated northeast of Warren, NSW (GR 31°32’00.70”S 147°47’46.13”E; Figure 3.3). The current landholders have owned the property since 2005 and generally do not have accurate information pertaining to landforming, cultivation practices, crop growth, or irrigation occurrence (except for 2003) prior to this point in time. The field is believed to have been landformed for irrigation in the mid 1990s, and was re-levelled in 2005 by the current owners. Prior to the original landforming, the property is known to have been used for grazing. Since 2005, the field has been used for the production of wheat, with one single irrigation event of 2 $ML.ha^{-1}$ in 2008 (Table 3.2). Irrigation for this field is conducted using flood irrigation, with one rotorbuck per two rows and a single siphon on short runs, or doubles siphons on long runs; the reason for different siphon use is to control the speed of irrigation given the irregular shape of the field (Figure 3.3). During the lifetime of the experiment, the annual rainfall has been above the mean annual average (Table 3.1).

Figure 3.3. Aerial view of the Bellevue experimental site. The head ditch is to the south; (🟥) boundaries of the field; (🟦) boundaries of the experimental site; ‘N’ indicates the north direction

The on-field operations used for wheat, whether irrigated or not, are generally consistent with conventional methods for field preparation; any stubble from previous crops is side busted, followed by a single go-devil and lilliston pass; the wheat is sown using a tine-rig and harvested at the end of the season. During the season, a single spray application may be applied depending on weeds. While conventional tillage is used, permanent 1 m beds and controlled traffic rows are used and managed via utilising GPS technology.

Table 3.2. Crop rotation, rainfall and irrigation rate by year for the Bellevue site

Year	*2001*	*2002*	*2003*	*2004*	*2005*	*2006*	*2007*	*2008*	*2009*
Rotation	–	–	cotton	fallow	fallow	wheat	fallow	wheat	wheat
Rainfall (mm)*	351	246	420	405	362	197	489	562	432
Irrigation (ML/ha)	nil	nil	10	nil	nil	nil	nil	2	nil

* Rainfall as recorded on site (i.e. not Bureau of Meteorology data)

3.2.2. Soil profile characterisation

The Bellevue soil is described as an Episodic-Endocalcareous Brown Vertosol (Isbell 2002). Clay mineralogy suggests that the soil is dominated by illite and kaolinite. Whilst smectite is present, the majority of this appeared to be interstratified with illite (XRD analysis output is presented in Appendix 3.A). The texture grade was assessed as light clay from 0–200 mm and medium clay from 200–800 mm (Table 3.4). The topsoil is quite variable in colour across the experimental site (Figure 3.3), although this did not appear to affect the mineral suite composition or texture grade; this variation was taken into account through experimental design and sampling regime. The exchangeable sodium percentage, EC and pH all increase with depth (Table 3.5). Based on Northcote and Skene (1972), the soil is described as having a low level of sodicity, which increases to moderate sodicity at depth. The soil generally only exhibits dispersion after reworking for the full range of depths analysed, although the incidence of spontaneously dispersive aggregates is greater with increasing depth. Nodules of calcium carbonate are observed between 400–800 mm, while total gypsum analysis showed that gypsum is not present in the measured depths.

3.3. "Agriland" – Field 48 – Trangie

3.3.1. History and on-field operations

The property owned by "Agriland" is situated east of Trangie, NSW (GR 31°59"20.27'E 14°807"05.06'S). Prior to 1992, Field 48 was part of a larger grazing paddock predominantly used for the grazing of sheep and cattle by a previous owner. During 1992 the paddock was split into various irrigation fields. Field 48 underwent a process of laser-bucket and mechanical-scraper levelling, deep ripping, and furrow mounding before irrigation began in the 1992/1993 cotton season. From this time until 2002, the field has been used for production of irrigated cotton and wheat in a two-year/one-year rotation, respectively. In 2003 this rotation was abandoned due to the uncertainty of drought; Table 3.3 shows the rotation format for the last nine years.

Table 3.3 Crop rotation, rainfall and irrigation rate by year for Agriland – Field 48
Wheat produced in winter and cotton in summer.

Year	*2001*	*2002*	*2003*	*2004*	*2005*	*2006*	*2007*	*2008*	*2009*
Rotation	Wheat	Cotton	Wheat	Fallow	Wheat	Cotton	Fallow	Wheat	Wheat
Rainfall (mm)*	–	–	563	373	575	177	554	602	403
Irrigation (ML/ha)	1	8	1	nil	1	8	nil	nil	nil

* Rainfall as recorded on site (i.e. not Bureau of Meteorology data); data unavailable for 2001 and 2002

Irrigation of the field is carried out using flood irrigation on one meter spaced permanent hills. Rotorbucks with a single syphon per row are used to distribute the irrigation water across the field. During irrigation of cotton, up to 8 ML.ha^{-1} are applied in a season, while wheat is not irrigated at all unless excess water is available. In these rare circumstances, wheat receives up to 1.5 ML.ha^{-1}. The field is situated close to a water reservoir and has been manipulated to take advantage of any storm run-off. However, this has been minimal in the past eight years and did not occur to an extent where irrigation was feasible during the lifetime of the experiment. Rainfall records show four years in seven (2003 through 2009) where rainfall has been slightly above the district average of 537 mm, while the other three years have been well below the average (Table 3.1). This has meant that the majority of significant rainfall events in the past eight years, while beneficial to crops in the ground, have not been substantial enough to fill reservoirs or facilitate irrigation.

Figure 3.4. Aerial view of the Agriland experimental site. The head ditch is to the southwest; (▬) boundaries of the field; (▬) boundaries of the experimental site; 'N' indicates the north direction

On field operations for cotton include: three Lilliston passes, hill rolling, planting of cotton, two separate Round-Up® spray applications, shield spraying the cotton, harvesting of the cotton, mulching and pupae busting. This equates to at least 12 traffic passes per season for cotton, although these are made on permanent traffic rows. The on-field operations for wheat are less extensive: sowing of the wheat, two separate weed sprayings, harvesting of the wheat, and mulching of the stubble if the field is to go straight into cotton. The same permanent traffic rows are used for wheat. While this is the general description of on-field operations for cotton and wheat, there is no set formula. For example, if the soil is too wet at the time of harvest, compaction occurs due to traffic. This compaction has proved detrimental to past yields. So, to mitigate this, more aggressive forms of tillage are used such as row ripping and shoulder or middle busting of rows.

3.3.2. Soil profile characterisation

The Agriland soil is described as a Calcic Sodic Brown Dermosol. The mineral suite of the Agriland soil is dominated by illite and kaolinite in the A horizon, while smectite is observed to be more prominent at depth (XRD analysis output is presented in Appendix 3.A). The Agriland soil has previously been classified as a Chromosol (Isbell 2002) in a soil survey conducted by McKenzie (1992). However, the texture grade was assessed as medium clay from 0–600 mm and heavy clay from 600–800 Table 3.4), which is not consistent with a Chromosol. It is, therefore, suggested that through intrusive deep tillage (e.g. deep ripping) occurring in the past the soil has been mixed, causing the distinct change in texture grade (Chromosol) to become lost. The topsoil colour within the experimental site is shown to be quite variable (Figure 3.4), although this did not significantly affect the mineral suite composition or texture grade; the experimental design and sampling regime accounted for this variation. Exchangeable sodium percentage, EC and pH are observed to increase with depth in the profile (Table 3.5). Based on Northcote and Skene (1972), the topsoil is described as mildly sodic increasing to moderately sodic at depth. The soil generally only exhibits dispersion after reworking for the 0–400 mm depths and spontaneously disperses at lower depths. Nodules of calcium carbonate are observed between 400–800 mm, while total gypsum analysis showed that gypsum is not present in the measured depths.

3.4. “Mount View” – Field L8 – Hillston

3.4.1. History and on-field operations

“Mount View” is a privately owned property situated northwest of Hillston, NSW (GR 33°07’58.19”S 145°18’36.92”E); the experimental site is depicted in Figure 3.5. Field L8 was previously used, as part of a larger paddock, for dryland grazing of cattle. However, in early 2000 the field was land-formed and developed for irrigation, undergoing laser-levelling and cut-and-fill procedures. Irrigation began in September 2000 and the field has since been used for the production of irrigated cotton, with one crop of irrigated wheat in 2006 (Table 3.6). Field L8 is irrigated by flood irrigation on permanent 1 m spaced rows. Irrigation water distribution is controlled using rotorbucks with double syphons pre-cotton flowering and single syphons post-cotton flowering. In the one case of wheat, rotorbucks with single syphons were used to irrigate 2 m beds. The source of irrigation water is an underground aquifer accessed by a bore, which is then pumped to the various fields using channels. The quality of this water is moderate with pH 7.5, EC 0.83 dS.m^{-1}, and SAR 5.96. For cotton, up to 10 ML.ha^{-1} of irrigation water is used per season, while wheat uses between 4–7 ML.ha^{-1}. Hillston has a mean annual rainfall of 355 mm. Over the past nine years, the rainfall has been below the district average for all years, except for 2005 (Table 3.6).

Table 3.4. Particle size analysis, texture grade and soil colour for the four experimental sites

C is clay (<2 µm); S is silt (2–20 µm); FS is fine sand (20–200 µm); CS is coarse sand (200–2000 µm)

Property	*Depth (mm)*	*C %*	*S %*	*FS %*	*CS %*	*Texture grade*	*Munsell colour*		
							Dry	*Moist*	*Moist*
Bellevue	*0–100*	36	18	26	20	Light clay	10YR 4/3	10YR 3/2	Black
	100–200	39	20	24	17	Light clay	10YR 4/3	10YR 3/2	Black
	200–400	45	16	20	20	Medium clay	10YR 5/3	10YR 3/3	Brown
	400–600	52	18	15	15	Medium clay	10YR 5/4	10YR 4/4	Brown
	600–800	51	22	18	9	Medium clay	10YR 5/4	10YR 4/4	Brown
Agriland	*0–100*	45	15	25	16	Medium clay	10YR 4/3	10YR 3/2	Black
	100–200	45	15	25	15	Medium clay	10YR 4/3	10YR 3/2	Black
	200–400	48	16	23	13	Medium clay	10YR 4/4	10YR 4/4	Brown
	400–600	52	15	21	12	Medium clay	10YR 5/4	10YR 4/4	Brown
	600–800	57	12	19	12	Heavy clay	10YR 5/4	10YR 4/4	Brown
Mount View	*0–100*	58	3	31	8	Heavy clay	10YR 5/4	10YR 5/3	Brown
	100–200	64	3	27	6	Heavy clay	10YR 5/4	10YR 5/3	Brown
	200–400	64	5	26	5	Heavy clay	10YR 5/4	10YR 5/3	Brown
	400–600	63	5	26	5	Heavy clay	10YR 5/6	10YR 5/4	Brown
	600–800	59	6	29	6	Heavy clay	10YR 5/6	10YR 5/3	Brown
Wyadra	*0–100*	67	2	23	8	Heavy clay	5YR 3/4	5YR 3/4	Red
	100–200	70	1	21	8	Heavy clay	5YR 3/4	5YR 3/4	Red
	200–400	66	2	25	7	Heavy clay	5YR 3/4	5YR 3/4	Red
	400–600	58	5	29	8	Heavy clay	7.5YR 5/6	7.5YR 5/6	Brown
	600–800	60	3	30	8	Heavy clay	7.5YR 5/6	7.5YR 5/6	Brown

Figure 3.5. Aerial view of the Mount View experimental site. The head ditch is to the east; (🟥) boundaries of the field; (🟦) boundaries of the experimental site; 'N' indicates the north direction

The on-field operations for a cotton season involve: two passes with a disc cultivator (if planting cotton post-wheat), grader boarding twice; deep ripping (250 mm), hilling and incorporation of nitrogen gas; a further cultivation, incorporation of MAP to 100 mm, Lilliston pass, rolling of rows prior to planting, sowing of cotton, various applications of spray and defoliant, harvest of cotton, mulching, root cutting and pupae busting. If the field is rotating to wheat, then nitrogen gas is incorporated after pupae busting, 2 m beds are formed, beds are rolled prior to sowing, sowing of wheat, various spraying applications, harvest of wheat, and mulching of wheat prior to disc cultivation if going into cotton. To alleviate soil structural decline due to traffic across the field, permanent GPS traffic rows are used for both cotton and wheat.

Table 3.5. Chemical properties, dispersive index and total gypsum percentage for the four experimental sites by incremental depth.

Property	*Depth (mm)*	*DI*	*pH $_{1:5}$*	*EC $_{1:5}$ (dS/m)*	*Ca*	*Mg*	*Na*	*CEC*	*ESP (%)*	*Total gypsum (%)*
					cmol(+)/kg					
Bellevue	*0–100*	5	7.1	0.20	17.4	12.3	1.9	31.9	6.1	0.00
	100–200	5	7.2	0.19	16.6	13.1	2.1	31.9	6.6	0.00
	200–400	6	7.5	0.23	16.5	14.3	2.3	33.3	6.9	0.00
	400–600	8	7.7	0.29	16.8	13.9	3.0	34.0	8.9	0.00
	600–800	9	7.9	0.34	16.9	14.2	3.3	34.6	9.5	0.00
Agriland	*0–100*	6	6.4	0.13	13.6	6.0	1.3	21.3	6.3	0.00
	100–200	6	6.6	0.12	15.7	5.0	1.6	22.5	7.1	0.00
	200–400	6	6.9	0.20	16.0	5.3	1.8	23.4	7.7	0.00
	400–600	8	7.2	0.26	11.9	7.9	2.4	22.7	10.6	0.00
	600–800	10	7.5	0.32	9.6	8.8	2.9	24.0	12.2	0.00
Mount View	*0–100*	10	8.7	0.37	9.6	8.9	2.2	20.8	10.5	0.00
	100–200	11	8.2	0.65	9.3	9.9	5.1	24.4	19.8	0.00
	200–400	13	8.9	0.88	7.2	8.6	9.9	25.8	37.5	0.08
	400–600	9	8.8	2.01	11.9	7.7	5.9	25.5	23.3	0.83
	600–800	5	8.5	3.32	16.6	5.5	1.5	23.6	6.3	1.35
Wyadra	*0–100*	10	8.6	0.31	12.1	7.9	1.7	20.8	8.2	0.00
	100–200	10	8.5	0.46	12.2	9.1	2.3	24.4	9.5	0.00
	200–400	10	8.6	0.71	14.0	12.1	4.6	27.3	16.7	0.00
	400–600	10	8.9	0.94	10.5	8.6	3.8	27.0	14.0	0.10
	600–800	6	8.9	1.28	14.9	10.1	4.5	25.8	17.4	0.38

3.4.2. Soil profile characterisation

The Mount View soil is described as an Episodic-Gypsic Brown Vertosol (Isbell 2002). The mineral suite consists mainly of smectite and kaolinite, with some illite, in the surface soil, while the subsoil contains similar attributes with an increase in illite. Interstratification of smectite and illite is evident in the subsoil (XRD analysis output is presented in Appendix 3.A). The field texture grade is heavy clay throughout the entire measured profile (Table 3.4). The soil pH and EC generally increase with depth (Table 3.5). However, ESP is observed to increase to a depth of 400 mm, after which it decreases. Of particular interest, the ESP in the 600–800 mm layer is less than that of the 0–100 mm layer, which is attributed to the presence of soluble gypsum crystals. The abundance of crystals after 6 years of irrigation (50 ML.ha^{-1}) and 1515 mm of rainfall (Table 3.6) is ascribed to an impermeable soil layer that occurs between 300–600 mm (depending on cut/fill variation) with an ESP between approximately 23 and 38% (Table 3.5). Based on the observed ESP values, the soil is described as moderately to highly sodic in the 0–600 mm layers and is only mildly sodic in the 600–800 mm layer (Northcote and Skene 1972). Nitrogen and organic carbon contents are both low for this soil (0.10 and 0.84% in the 0–100 mm layer, respectively).

Table 3.6 Crop rotation, rainfall and irrigation rate by year for Mount View
The property was not landformed for irrigated cropping in winter 2001

Year	*2001*	*2002*	*2003*	*2004*	*2005*	*2006*	*2007*	*2008*	*2009*
*Rotation - sumer season**	Cotton	Cotton	Cotton	Cotton	Cotton	Fallow	Cotton	Fallow	Cotton
Rotation - winter season	–	Fallow	Fallow	Fallow	Wheat	Fallow	Fallow	Wheat	Fallow
*Rainfall** (mm)*	252	133	313	239	364	214	272	247	212
Summer irrigation (ML/ha)	10	10	10	10	10	nil	10	nil	10
Winter irrigation (ML/ha)	nil	nil	nil	nil	7	nil	nil	6	nil

The summer season was defined as December of the respective year through to February of the following year; ** Rainfall as recorded on site (i.e. not Bureau of Meteorology data)

3.5. “Wyadra” – Field L1 – Hillston

3.5.1. History and on-field operations

The experimental site on the property “Wyadra” is situated to the west of Hillston, NSW (GR 33°33’25.09”S 145°17’35.11”E); the experimental site and field boundaries are presented in Figure 3.6. Prior to 2002 the field had been used exclusively for grazing. However, during 2002, the grazing land was split into the various fields and irrigation channels were built. As the field was to be irrigated using lateral-move apparatus, there was no requirement for the field to undergo cut-and-fill levelling operations. Since 2002, the field has predominantly been used for wheat, with the incorporation of two cotton crops and one chickpea crop (Table 3.7). Throughout the life of the experiment only one wheat and one cotton crop were grown; the field was under fallow for the rest of the time. When the field is left in fallow, a cover crop is grown, or the stubble and the trash of the previous crop are left *in situ*.

As previously mentioned, the crops are irrigated using lateral move apparatus. The irrigation water is sourced from an underground aquifer accessed by a bore, which is then pumped to the various fields using channels. The quality of this water is of moderate quality with pH 7.96, EC 0.86 dS.m^{-1} and SAR 6.07. For cotton, up to 10 ML.ha^{-1} of irrigation water is used per season, and is applied in 15 mm irrigation passes. When wheat is irrigated, between 3.5–5 ML.ha^{-1} are used in 20 mm irrigation passes. Based on Hillston having a mean annual rainfall of 390 mm, the rainfall has been below considerably average for the 2008 and 2009 seasons.

Table 3.7. Crop rotation, rainfall and irrigation rate by year for Mount View

Year	*2002*	*2003*	*2004*	*2005*	*2006*	*2007*	*2008*	*2009*
*Rotation - Sumer Season**	wheat	cotton	fallow	fallow	fallow	cotton	fallow	fallow
Rotation - Winter Season	–	fallow	wheat	chcikpeas	fallow	fallow	fallow	wheat
*Rainfall** (mm)*	171	430	277	370	219	389	290	289
Summer irrigation (ML/ha)	5	10	nil	nil	nil	10	nil	nil
Winter irrigation (ML/ha)	nil	nil	3.5	3.5	nil	nil	nil	5

* The summer season was defined as December of the respective year through to February of the following year; ** Rainfall as recorded at Hillston Airport (Bureau of Meteorology 2010) as this is the data the landholder uses

For the growth of wheat and chickpeas, disc ploughing, deep ripping (200 mm), grader-boarding and incorporation of MAP are conducted prior to sowing. After harvesting, the stubble is retained until the bed preparation for the next crop. For the growth of cotton, the soil is disc ploughed, deep ripped (200 mm) and the beds lifted up, during which MAP is incorporated. After harvest, the cotton is root-cut, pupae busted and mulched. Whilst 2 m beds are only used for cotton, these are built in a permanent position using GPS referencing. For all crops, nitrogen is applied using irrigation water applications. Traffic is controlled using permanent traffic lanes, which are also GPS referenced.

Figure 3.6. Aerial view of the Wyadra experimental site. The lateral move apparatus moves to and from northeast and southeast; (▬) boundaries of the field; (▬) boundaries of the experimental site; ‘N’ indicates the north direction

3.5.2. Soil profile characterisation

The Wyadra soil is described as a Sodic Red Dermosol with a hypocalcic subsoil layer (Isbell 2002). There is also evidence of gypsum throughout the subsoil. The mineral suite for the surface soil is dominated by kaolinite with some smectite and illite, while the subsoil contains relatively similar proportions of smectite, illite and kaolinite. Interstratified smectite and illite is detected in the subsoil (XRD analysis output displayed in Apendix 3.A). The heavy clay texture grade of the soil is consistent throughout the depths analysed (Table 3.4). The variation in topsoil colour across the experimental site (Figure 3.6) was not observed to considerably change the soil mineral suite or the texture grade; the variability was accounted for in the experimental design and sampling regime. The soil pH, EC and ESP generally increase with depth in the profile, although there is a slight decrease in ESP in the 400–600 depth consistent with the presence of gypsum. The soil is moderately sodic between the 0–200 mm depth and highly sodic between the 200–800 mm depth (Northcote and Skene 1972). Nitrogen and organic carbon contents are both low for this soil (0.10 and 0.88% in the 0–100 mm layer, respectively).

3.6. Methods

3.6.1. Soil sampling

For the field-based experiment, samples were taken on all properties after 6 months (January 2008) and 2.5 years (January 2010). In both circumstances, a 0–100 mm sample was taken using a square mouth, graduated trowel. However, after 2.5 years a 45 mm internal diameter (ID) soil core was taken from 0–900 mm depth, using a single stroke, tractor mounted, hydraulic corer (**Figure 3.7**); a minimal amount of synthetic lubricant was used for each core to aid in removal of the cores from the coring sleeve, while also minimising sample contamination. Due to cut/fill levelling of the irrigated fields, cores were split into 0–100, 100–200, 200–400, 400–600 and 600–800 mm layers rather than horizons. This was done to provide a more accurate translation of effects to the root zones of crops, which may not have been obtained using soil horizons.

Samples were taken at approximately 8 m intervals from the furrow and parallel to the rows. In 2008, fifty six samples were taken per treatment/control, while in 2010, twenty eight samples were taken per treatment/control. Given 7 treatments/control and 2 replicates, this provided 784 and 392 sample sites per property in 2008 and 2010, respectively. Due to the shear amount of samples and the cost of analysis, the 2008 samples were bulked with adjacent samples to give 14 samples per treatment, and the 2010 samples were bulked with adjacent samples to give 6 samples per treatment.

Samples from both 2008 and 2010 were allowed to air-dry before being crushed and sieved to a 2 mm threshold. A proportion of aggregates from each sample were kept aside for further analysis.

For the laboratory-based compost experiment, 200 kg of 0–200 mm soil was taken from Mount View using a square mouth, graduated shovel. Samples were taken from an untreated section of the field, 25 m in-field from the head ditch, in a known high sodicity area. After air-drying, the soil was crushed and sieved to 10 mm threshold. This was done to provide heterogeneity of aggregate sizes when cores were repacked.

Figure 3.7. Single-stroke tractor-mounted hydraulic corer used for soil core sampling after 2.5 years

3.6.2. Particle size distribution

Particle size distribution was determined using an adaptation of the pipette method described by Gee and Bauder (1986). Twenty five grams of soil (<2 mm) were measured, and the exact weight recorded, and placed into 600 ml glass bottles. If the soil was particularly sandy, up to 100 g was used. The bottle was filled with approximately 350 ml of water and 50 ml of sodium hexa-metaphosphate (HMP). Afterwards, it was capped and shaken on an end-over-end shaker for 72 h. All of the soil and liquid were transferred to a 1 L measuring cylinder and made to 1 L with water. The contents were then homogenised using a baffle rod and allowed to stand for the appropriate amount of time before measurement; clay and silt were measured at 5 min 27 sec, while clay was measured after 8 h. Measurements were taken using a 25 ml pipette from the top 10 cm of the suspension and aliquots were placed into pre-weighed 50 ml beakers. The 25 ml aliquots were then left to dry overnight in an oven set to 105°C. The dried clay was then weighed and recorded. Clay and silt percentages were then determined. This entire process was repeated without soil in order to obtain a blank sample to account for the incorporation of sodium HMP.

The clay and silt suspension was carefully poured from the 1 L measuring cylinder taking care not to lose any of the sand fraction. If the sample was to be used for X-ray diffraction, the suspension was kept, otherwise it was discarded. The sand fraction was then transferred to a 600 ml beaker and filled to a 10 cm mark with water for washing. After 5 min 27 seconds the clay and silt fraction was then discarded and the beaker filled back to the 10 cm mark with water. This washing process was repeated until the suspension was clear after 5 min 27 sec. The sand fraction was then allowed to dry overnight in an oven set to 105°C before being sorted into the fine and coarse sand fractions with a 0.2 mm sieve. The weights of the fine and coarse sand fractions were individually measured and recorded allowing determination of fine sand and coarse sand percentages.

In some circumstances, flocculation was observed in the suspension (Figure 3.8). Where this occurred, the electrolyte concentration was generally 3 $dS.m^{-1}$ and gypsum inclusions were usually visible. To overcome this flocculation, a method described by McIntyre and Loveday (1974) was used, where 25 g of soil (<2 mm) was placed into a 600 ml beaker with 25 ml of 2M HCl and filled with water to within 2.5 cm of the lip. This was then stirred on an electric stirrer for 1 h and allowed to stand until clear. The liquid was then decanted. Repeated stirring and decantation was undertaken until all gypsum was gone – the formation of small crystals after overnight standing indicates gypsum is still present. Once all of the gypsum was removed, 5 ml of M NaOH were added and the sample was processed using the original procedure described above.

Figure 3.8. The measuring cylinder on the right contains Mount View (600-800 mm depth) soil for particle size analysis that was observed to flocculate after approximately 2 h, as a result of naturally occurring gypsum (1.35% total gypsum, Table 3.5)

3.6.3. X-ray diffraction

Identification of clay minerals was conducted through X-ray diffraction of sedimented aggregate samples on ceramic tiles (Moore and Reynolds 1989). The clay suspension obtained in particle size distribution was allowed to stand for a further 16 h (totalling 24 h), before approximately 300 ml of the clay suspension was siphoned into a 400 ml beaker.

Porous ceramic tiles were placed onto a tile holder under vacuum and clay suspension was slowly applied in a 15 mm strip using a pipette. The suspension was allowed to filter through the ceramic tile until only the clay remained; this process was repeated three times or until an adequate quantity of clay was present on the tile. The clay was then treated with 2 $mol.l^{-1}$ $MgCl_2$ solution and allowed to dry before a second saturation with $MgCl_2$ solution. Once the clay was again dry, it was washed with distilled water to remove excess soluble salts. This washing process was repeated a further three times. The entire process was then repeated with a second tile, although KCl was used as the saturating solution rather than $MgCl_2$.

The KCl tile was subject to measurement at air-dry capacity, after heating in a muffle furnace for an hour at 100°C, and after heating in a muffle furnace for an hour at 550°C. The

$MgCl_2$ tile was measured at air-dry capacity and after the addition of glycerol. These various treatments allowed differentiation between kaolinite, illite and smectite peaks.

The tiles were then analysed by X-ray diffraction, to determine basal spacings of the different clay minerals, using a GBC Scientific Equipment Pty Ltd Mini Materials Analyser (GBC MMA) X-Ray Diffractometer. The parameters used to obtain diffractograms were 0.02°2θ steps at 2 sec intervals over the angle range 2–15°2θ.

3.6.4. Aggregate stability in water

A dispersive index (DI) for aggregates within the various treatments was provided using the Aggregate Stability in WATer (ASWAT) method (Field *et al.* 1997). For each sample, three 3–5 mm air-dry aggregates were carefully placed into a petri dish containing 50 ml of deionised water; care was taken not to drop the aggregates into the water in order to minimise mechanical disturbance. After 10 min and 2 h an assessment of dispersion was made, guided by a set of pictures for dispersion standards (Field 2000). A score of 0–4 was given at both 10 min and 2 h for a range of no-dispersion to complete-dispersion respectively. The 10 min and 2 h scores were then added together to give a score ranging between 0–8. All soils with an overall score between 1 and 8 had a further score of 8 added to them to give a DI range 8–16.

For aggregates scoring 0 after 2 h, a remoulding and reassessment process was undertaken. Soil (<2 mm) was worked to its plastic limit and moulded into a ball of 3–5 mm. Three of these balls per sample were then subject to the above assessment method. However, after adding the scores given at 10 min and 2 h the further score of 8 was not added to each remoulded sample. This gave a range of 0–8 DI for the remoulded samples. Therefore, an overall DI range of 0–16 was given, where a DI of 0 indicates stability, 1–8 indicates various degrees of dispersion after mechanical disturbance, and 9–16 indicates various degrees of spontaneous dispersion.

In addition to the ASWAT method, a binary assessment of slaking was made at the first 10 min interval. A score of 0 was given for no visible slaking and a score of 1 was given for visual slaking.

3.6.5. Soil pH

Soil pH was determined on a 1:5 soil:water extract. Four grams of soil were placed into a 25 ml plastic tube and 20 ml of deionised water were added. The tube was then put on an end-over-end shaker for 1 h and centrifuged at 2500 rpm for 5 min. The determination of pH was carried out using a Radiometer MeterLab™ standard pH meter (PHM210) with a manual temperature calibration. Results are reported on a 25°C basis.

3.6.6. *Soil electrical conductivity*

Soil electrical conductivity (EC) was determined using the same 1:5 soil/water extract used for the measurement of pH. EC was measured using a Radiometer MeterLab™ conductivity meter (CDM210) with automatic temperature calibration. Results are reported on a 25°C basis.

Throughout the duration of the laboratory experiment, the soil EC was directly measured in the leaching columns using a Field Scout ™ direct soil EC meter with a jab probe (2265FS). Preliminary tests showed that the estimates obtained by the 2265FS for a series of standard concentration solutions were within the stated meter accuracy of ±2% for 0–10 $dS.m^{-1}$ (95% confidence interval), but for solutions with an EC between 10 and 20 $dS.m^{-1}$ the accuracy was substantially limited (±17% on average). The ECs expected to be encountered in this experiment were between 0–10 $dS.m^{-1}$. As the probe did not adjust the conductivity reading for variation in moisture content, measurements were taken at 24 h and 2 wks after each irrigation. Treatment application will presumably affect the water holding capacity of the soil, thus consistent measurement at a given time ensures the data is comparable. The probe gives an indication of the EC relevant to the soil chemical processes at the given time, which could be expect to be somewhat similar to the saturation extract EC at a given time point. Results were reported on a time-after-irrigation basis (24 h or 2 wks).

3.6.7. *Exchangeable cations*

The major exchangeable cations (Ca^{2+}, Mg^{2+}, Na^{+}, and K^{+}) were measured using two different methods 3.6.7.A, and 3.6.7.B. This was due to both logistical challenges and necessity, as imposed by the chemical characteristics of the various soils. Cation exchange capacity (CEC) was measured as an extension of method 3.3.8B for the field-based experiment and as an extension of method 3.3.8C for the laboratory-based compost experiment.

3.6.7.A. *Choline chloride in aqueous ethanol, pre-treatment for soluble salts*

The choline chloride in aqueous ethanol method of exchangeable cation extraction (Tucker 1985) is designed to have low solubility for calcium and magnesium carbonates. It has been shown to extract less specifically absorbed cations (as compared to method 3.6.7.B) and subsequently give a more accurate measurement of cations held at the soil particles surface in the double layer. It is therefore appropriate for use on soils with free carbonate. Hence, this method was initially chosen to analyse exchangeable cations in soils where lime ($CaCO_3$) had been applied. However, it was only utilised for the first measurements of the field-based experiment.

This method employs the use of two solvents, one reagent and a flame solution (for analysis by atomic absorption spectrophotometry; AAS), consistent with Tucker (1985). The method is not widely adopted, presumably due to the cost of choline chloride, so it has been described here in full:

E solvent: 0.5 g of polyvinyl alcohol dissolved in 300 ml of deionised water and mixed with 700 ml of pure ethanol.

Y solvent: 200 ml of reagent grade glycerol (78%) mixed with 800 ml of deionised water. A crystal of thymol should be added as a preservative.

XE reagent: 280 g of choline chloride (2 mol) dissolved in 600 ml of deionised water and 1400 ml of pure ethanol.

Flame Solution (modified to allow a 1 in 10 dilution of standards): To 2 L of deionised water 45 ml of 70 % perchloric acid, 56.25 ml of 5% $La(NO_3)_36H_2O$ in deionised water, 90 ml of 1.68% CsCl in deionised water, 27 g of urea, and 112.5 ml of pure ethanol are added.

Two g of soil, ground and sieved to a 2 mm threshold, were placed in a plastic tube with 20 ml of solvent E and shaken on an end-over-end shaker for 30 min. The tubes were then placed in a centrifuge at 2500 rpm for 5 min, after which the soluble salt extract was decanted and discarded. This procedure was repeated once more with solvent E and once again with solvent Y. Exchangeable cations were extracted using the same procedure four times with 24.5 ml of reagent XE. (The original method used five treatments of reagent XE at 19.5 ml. However, it was found that no significant difference in exchangeable cation concentrations was observed when using the four extractions at 24.5 ml of reagent XE). After each extraction, the clear supernatant was filtered into 100 ml volumetric flasks. These were made to volume after the last extraction. In order to analyse by AAS, 4 ml of extract were diluted with 4 ml of deionised water and 32 ml of flame solution. Standards were prepared using the same matrix; 4 ml of standard in deionised water and 4 ml of reagent XE blank mixed with 32 ml of flame solution.

It should be noted that the alcoholic basis of the reagent used does not lend itself to analysis by inductive coupled plasma – AES (ICP-AES), as it causes the plasma torch to become unstable and switch off. Presumably this is also the case for inductive coupled plasma mass spectrophotometry (ICP-MS), but this was not tested.

Residual gypsum from treatment applications was measured as the sulfate content of the ChCl extract, as per the method of Tucker and Beatty (1974). Preliminary investigations showed that the use of the two pre-treatment solvents (E and Y) removed negligible gypsum and that the remaining gypsum was extracted through the use of ChCl in aqueous ethanol.

3.6.7.B. Alcoholic 1M ammonium acetate at pH 8.5, pre-treatment for soluble salts

This method is a modification of method 15D1 (Rayment and Higginson 1992) and those used by Tucker and Beatty (1974) and Tucker (1985). This method was used for analysis of the laboratory experiment by Varian Vista AX Simultaneous inductively coupled plasma atomic emission spectrometer (ICP-AES), as the ChCl method (3.6.7.A) caused the plasma torch to become unstable and switch off.

Extracting solution – 1M ammonium acetate (NH_4OAc) at pH 8.5: 575 ml of glacial acetic acid (CH_3COOH; 17M) were added to 7.5 L of deionised water and mixed. To this, 750 ml of ammonium hydroxide (NH_4OH; s.g. 0.91) added, mixed and cooled. This was made to 10 L and adjusted to pH 8.5.

A 2.5 g aliquot of soil (<2 mm) was pre-treated with solvents E and Y, as per the procedure for Tucker (1985), to remove soluble salts. After pre-treatment, 25 ml of 1M NH_4OAc was dispensed into each plastic tube and these were placed on a rotary shaker for 60 min. The tubes were then centrifuged for 5 min at 3000 rpm before the supernatant was filtered (Whatman N0. 42 filter paper) into 100 ml volumetric flasks. This process, post pre-treatment for soluble salts, was repeated a further three times to obtain a 100 ml extraction; N.B. the flasks were not bulked to 100 ml, as exactly 100 ml of reagent had been used, meaning that any deviation from the 100 ml mark was due to the moisture holding capacity of the sample.

Total sulphur (S) was also analysed from the same extraction solution and was used to correct for the presence of undissolved gypsum.

3.6.8. Cation exchange capacity

The cation exchange capacity was determined using a modified version of the method described by Tucker (1985). For this method, 2 g of soil (<2 mm) was treated with 25 ml of $CaCl_2$, placed on a rotary shaker for 30 min, centrifuged for 5 min at 2500 rpm and the solution decanted. This was repeated three times. After which, the $CaCl_2$ was then removed with a four washings with solvent E (3.6.7.A) using the same procedure describe for $CaCl_2$; N.B. the final washing was checked to ensure the EC was below 1 $\mu S.cm^{-1}$, if this was not so, then a further washing was required. Exchangeable calcium was then extracted as per the procedure for 3.6.7.A and analysed using AAS.

3.6.9. Soluble ions

3.6.9.A. Soil

Soluble Ca^{2+}, Na^+, K^+, Mg^+, and S (as SO_4^{2-}) contents of the soil were measured using a method developed by the New South Wales Department of Conservation and Land Management (Craze *et al.* 1993) as cited in (Valzano 2000; Valzano *et al.* 2001b). Five g of compost was placed into a 30 ml polythene vial with 25 ml of deionised water and mixed on a rotary shaker for 60 min. After centrifuging for 5 min at 3000 rpm, the clear supernatant was filtered through Whatman No. 42 filter paper into 10 ml polythene vials and analysed using a Varian Vista AX Simultaneous ICP-AES.

3.6.9.B. Leachate

Leachate from the laboratory experiment was directly measured for soluble cations, without any further treatment. Filtered subsamples of leachate were placed into 10 ml polythene vials for direct analysis of soluble Ca, Na, K, Mg, and S concentrations using a Varian Vista AX Simultaneous ICP-AES.

3.6.10. Total ion concentration

As part of the laboratory experiment, the elemental composition and moisture content of the organic amendments was conducted. The elemental analysis was undertaken by digesting 0.5 g of the organic amendment in nitric-perchloric acid as described by (Miller 1998). The composts were firstly air-dried and ground to less than 100 µm before they were digested. The resulting digest extracts were then analysed with a Varian Vista - AX Inductively Coupled Plasma Atomic Emission Spectrometer (ICP-AES) to determine the elemental composition. Gravimetric moisture content of the organic amendment was determined by oven-drying organic amendments at 105°C.

3.6.11. Nitrogen and organic carbon

Soil nitrogen and carbon content were determined by analysis with an Elementar VarioMax CNS analyser. Aliquots of soil (0.75 g) were air-dried and ground to less than 53 µm to increase the homogeneity of the soil samples and reduce the chance of anaerobic locations within soil aggregates that may harbour carbon or nitrogen (Nelson and Oades 1998). Particulate organic matter was thoroughly removed by hand prior to the grinding of the soil samples. A second aliquot of soil was pre-treated with acid (HCl 10%) and was used to destroy carbonates from the 53 µm soil (Midwood and Boutton 1998); by destroying inherent soil carbonates, the measurment of carbon can be used as a measure of organic carbon (OC) content. These samples were then analysed with the Elementar VarioMax CNS analyser (Zhang *et al.* 2007).

3.6.12. Total gypsum

The method used for total gypsum determination is consistent with method 11A1 in Rayment and Higginson (1992).

Approximately 3 ml of the 1:5 soil/water extract used for pH and EC determination was placed into a test tube. To this, 10 drops of 1M HCl and 2 ml of 1M $BaCl_2$ were added. The presence of turbidity was visually assessed; if not observed no further action was taken and gypsum was determined as not being present. When turbidity was observed, 10 g of soil (< 0.5 mm) was placed into a 250 ml plastic bottle with 100 ml of deionised water. The bottle was placed on an end-over-end shaker for 17 h and then centrifuged and filtered to provide a clear suspension. Twenty ml of the clear suspension was transferred to a 50 ml centrifuge tube containing 20 ml of acetone. The solution was mixed thoroughly by shaking, allowed to stand for 10 min and centrifuged until clear. This was then decanted ensuring no precipitate was lost. The precipitate was then redispersed using 10 ml of acetone. After centrifuging and decanting once more, the precipitate was allowed to dry out in an oven set to 47°C. Forty ml of deionised water was then added and the tube placed on an end-over-end shaker until the precipitate had dissolved. Ca^{2+} was measured using AAS and gypsum content determined.

3.7. References

Bureau of Meteorology (2006) www.bom.gov.au/cgi-bin/climate. Commonwealth of Australia, Available at [Verified]

Craze, B, Holman, G, Chapman, GA & Stone, MJ (1993) 'Soil testing procedures of the NSW Department of Conservation and Land Management', (NSW Department of Conservation and Land Management: Sydney)

Field, DJ (2000) *The bricks and mortar of Vertosols*, Thesis - The University of Sydney, Sydney.

Field, DJ, McKenzie, DC & Koppi, AJ (1997) Development of an improved vertisol stability test for SOILpak. *Australian Journal of Soil Research* **35,** 843-52.

Gee, GW & Bauder, JW (1986) Particle-size analysis. *In* 'Methods of soil analysis'. (Eds. Klute, A) (Soil Science Society of America: Madison, Wisconsin)

Isbell, RF (2002) 'The Australian soil classification: revised edition', (CSIRO Publishing: Melbourne)

McIntyre, DS & Loveday, J (1974) Particle-size analysis. *In* 'Methods for analysis of irrigated soils'. (Eds. Loveday, J) (Commonwealth Agricultural Bureaux: Rarnham Royal, Bucks.)

McKenzie, NJ (1992) 'Soils of the lower Macquarie Valley, New South Wales', (CSIRO Division of Soils: Canberra)

Midwood, AJ & Boutton, TW (1998) Soil carbonate decomposition by acid has little effect on $\delta^{13}C$ of organic matter. *Soil Biology and Biochemistry* **30,** 1301-7.

Miller, RO (1998) Nitric-perchloric acid wet digestion in an open vessel. *In* 'Handbook of Reference Methods for Plant Analysis'. (Eds. Yash, PK) (CRC Press: Boca Raton, Florida)

Moore, DM & Reynolds, RJC (1989) 'X-ray diffraction and the identification and analysis of clay minerals', (Oxford University Press: Oxford, New York)

Nelson, PN & Oades, JM (1998) Organic matter, sodicity, and soil structure. *In* 'Sodic soils: Distribution, management and envirnomental consequences'. (Eds. Sumner, ME & Naidu, R) (Oxford University Press: New York)

Northcote, KH & Skene, JK (1972) *Australian soils with saline and sodic properties*. CSIRO Soil Publication 27, (CSIRO: Australia)

Rayment, GE & Higginson, FR (1992) 'Australian laboratory handbook of soil and water chemical methods', (Inkata Press: Sydney)

Tucker, BM (1985) A proposed new reagent for the measurement of cation exchange properties of carbonate soils. *Australian Journal of Soil Research* **23,** 633-42.

Tucker, BM & Beatty, HJ (1974) Exchangeable cations and cation exchange capacity. *In* 'Methods for analysis of irrigated soils'. (Eds. Loveday, J) (Commonwealth Agricultural Bureaux: Farnham Royal, England)

Valzano, FP (2000) *The effect of chemical ameliorants, tillage, and stubble practices on sodic soils in Australia*, Thesis - Australian National University, Canberra.

Valzano, FP, Murphy, BW & Greene, RSB (2001) The long term effects of lime ($CaCO_3$), Gypsum ($CaSO_4.2H_2O$), and tillage on the physical and chemical properties of a sodic red-brown earth. *Australian Journal of Soil Research* **39,** 1307-31.

Zhang, X-h, Li, L-q & G-x., P (2007) Topsoil organic carbon mineralization and CO_2 evolution of three paddy soils from South China and the temperature dependance. *Journal of Environmental Sciences* **19,** 319-26.

3.8. Appendix 3.A.

This appendix contains the XRD analysis output for the four experimental sites.

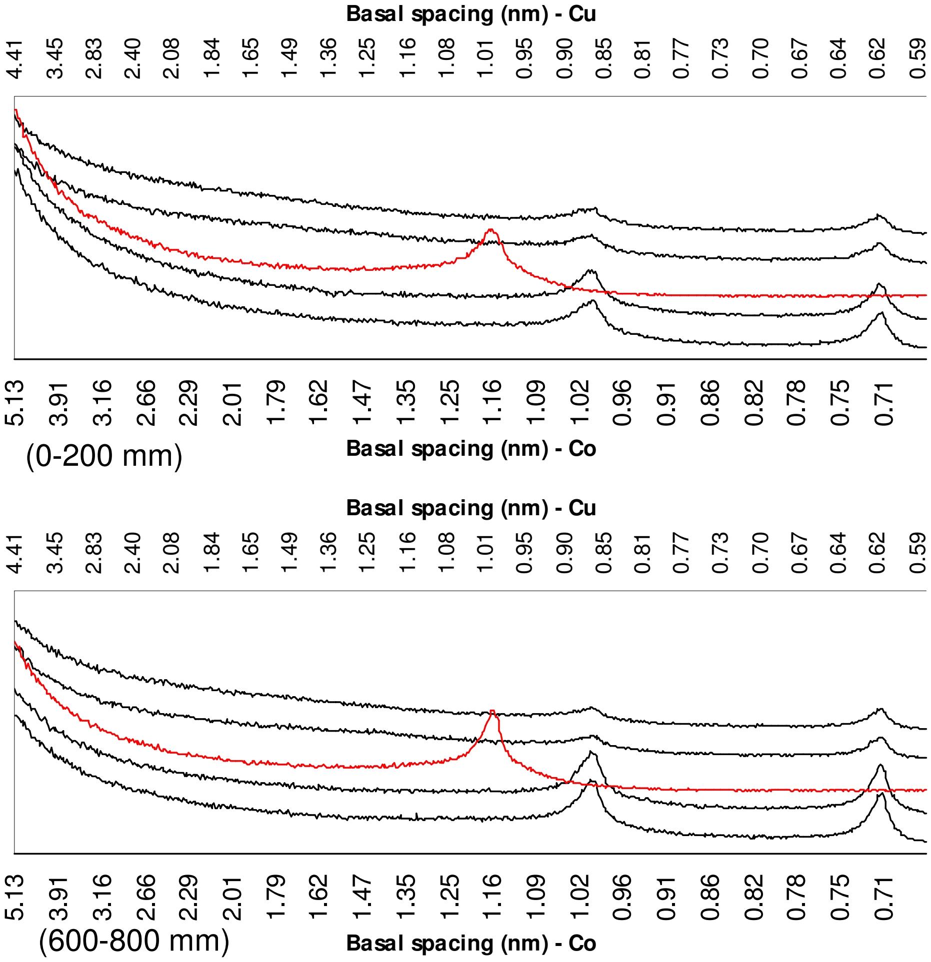


Figure 3.9. XRD analysis out put for the Bellevue soil at the specified depth; data series are presented in the order (from bottom to top) K, K at 100°C, K at 550°C counts, Mg, glycerol treated; (▬)indicates measurement on the Co axis; (▬) indicates measurement on the Cu axis)

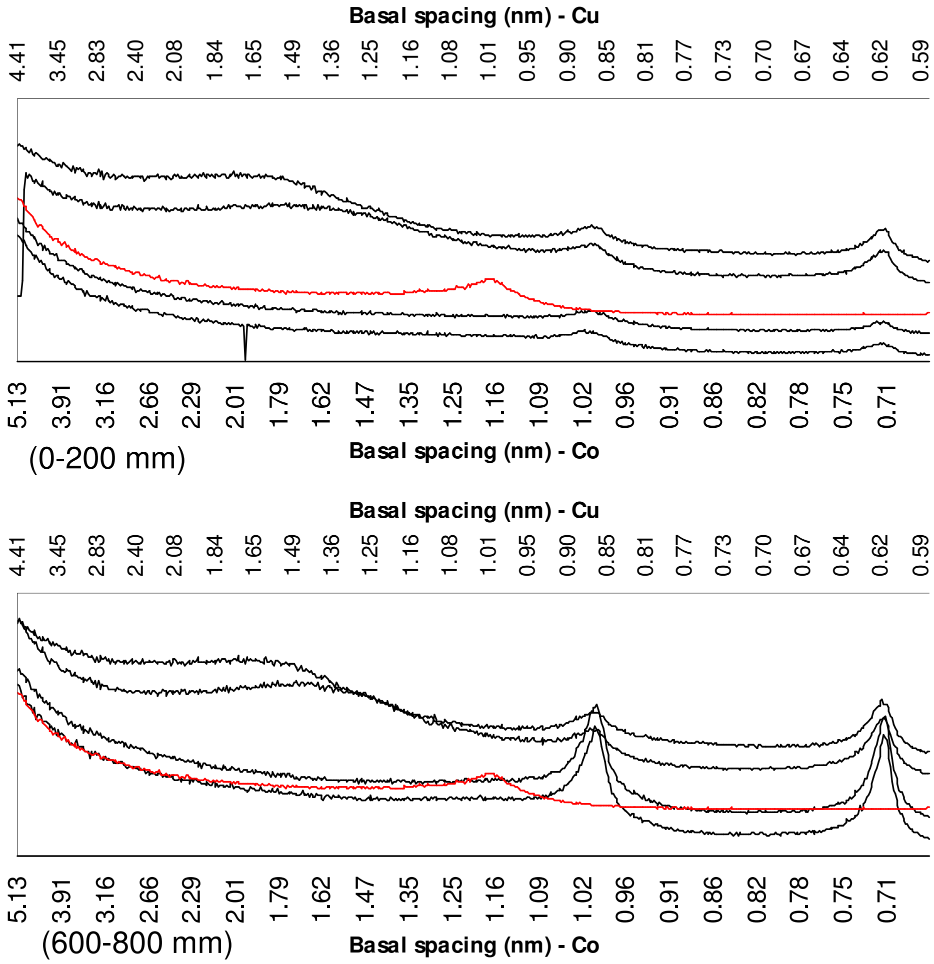
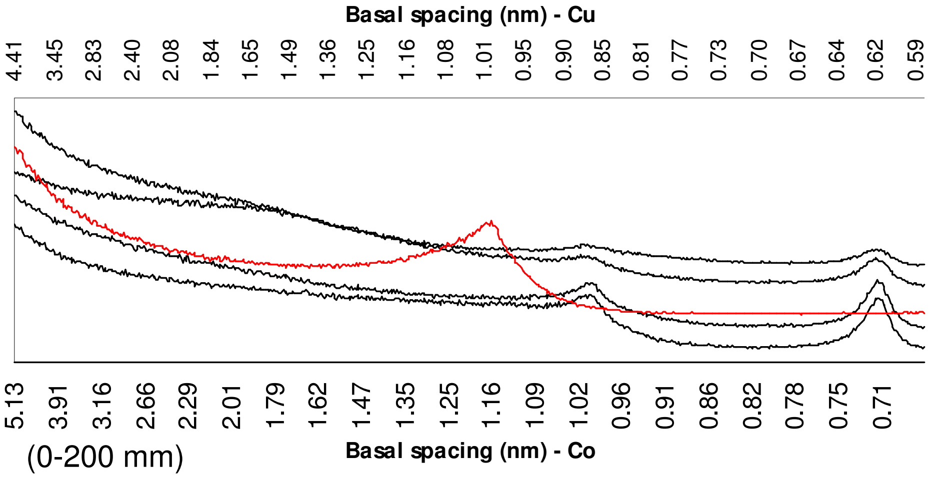


Figure 3.10. XRD analysis out put for the Agriland soil at the specified depth; data series are presented in the order (from bottom to top) K, K at 100°C, K at 550°C counts, Mg, glycerol treated; (▬)indicates measurement on the Co axis; (▬) indicates measurement on the Cu axis)



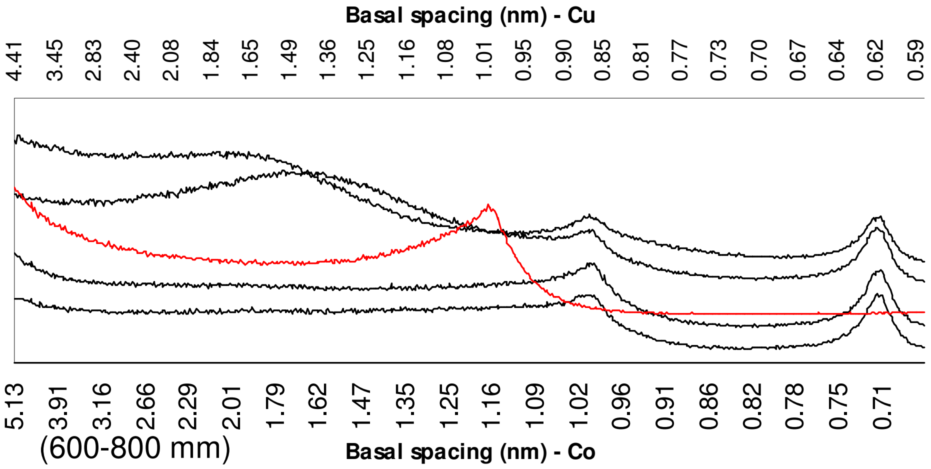
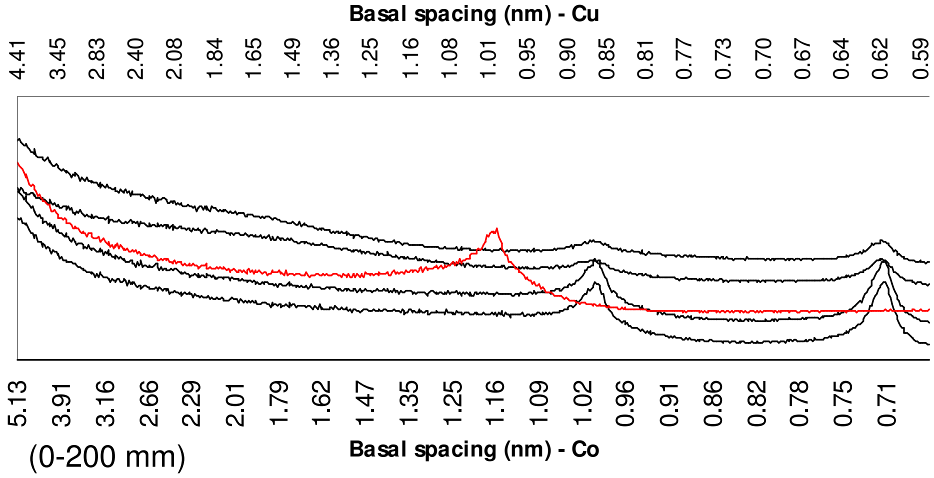


Figure 3.11. XRD analysis out put for the Mount View soil at the specified depth data series are presented in the order (from bottom to top) K, K at 100°C, K at 550°C counts, Mg, glycerol treated; (▬)indicates measurement on the Co axis; (▬) indicates measurement on the Cu axis)



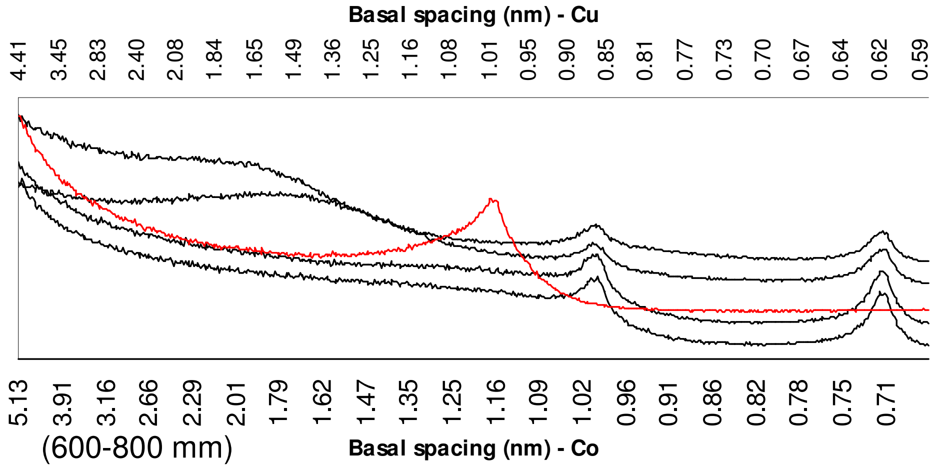


Figure 3.12. XRD analysis out put for the Wyadra soil at the specified depth; data series are presented in the order (from bottom to top) K, K at 100°C, K at 550°C counts, Mg, glycerol treated; (–)indicates measurement on the Co axis; (–) indicates measurement on the Cu axis)

THE EFFECTS OF LIME ($CaCO_3$), GYPSUM ($CaSO_4.2H_2O$), AND LIME/GYPSUM COMBINATIONS, AFTER 2.5 YEARS, ON SELECTED SOIL PROPERTIES OF TWO SODIC SOILS UNDER DRYLAND CROPPING CONDITIONS IN THE MACQUARIE VALLEY, NSW

4. The effects of lime ($CaCO_3$), gypsum ($CaSO_4.2H_2O$), and lime/gypsum combinations, after 2.5 years, on selected soil properties of two sodic soils under dryland cropping conditions in the Macquarie Valley, NSW

4.1. Introduction

The physical properties of a soil, such as permeability and soil structural stability, are sensitive to the nature of the exchangeable cations adsorbed to the negatively charged surfaces of clay minerals. The presence of excess sodium ions (Na^+) in the soils system can cause swelling and dispersion, generally at exchangeable sodium percentages (ESP) of the cation exchange capacity (CEC) greater than 6% (Northcote and Skene 1972). In contrast, calcium (Ca^{2+}) dominant systems convey a positive effect on soil physical attributes by compressing the diffuse double layer (DDL) of ions surrounding clay particles (Keren and O'Connor 1982; Sparks 2003). However, the electrolyte concentration (EC) of the soil also may nullify the effects of high ESP; high EC causes the DDL to become thinner, allowing the soil to remain stable to wetting, depending on the ESP (Sposito 1989; Sparks 2003). The practical significance of a soil containing excess Na^+ (a sodic soil) that is prone to swelling and dispersion is a propensity to for pore blockage to occur, which results in the potential loss of soil productivity (So and Aylmore 1993). Therefore, current remediation strategies tend to focus on the application of Ca^{2+} rich amendments, the most common being gypsum ($CaSO_4.2H_2O$) and more recently, lime ($CaCO_3$).

The data presented in this chapter was gathered as a part of a study into the viability of using lime, gypsum, and their combinations in ameliorating sodicity on irrigated soils. However, due to the farming operations not receiving their allocation of irrigation water for the duration of the study, the results here are reported for a dryland farming system. The use of lime and gypsum in the amelioration of sodicity under dryland conditions has been well documented (Shepherd 1925; Gardner and Gardner 1953; So *et al.* 1978; Chartres *et al.* 1985; Greene and Ford 1985; McKenzie and So 1989a; McKenzie and So 1989b; Chan and Heenan 1998; Ghafoor *et al.* 2001; Valzano *et al.* 2001a). Even still, there remains a paucity of information concerning the field-based effects of lime and gypsum combinations on sodic soils, irrigated or otherwise (Chan *et al.* 1999; Valzano *et al.* 2001b; Bennett 2006; Dang *et al.* 2010). The higher dissolution rate of gypsum causes hydrogen ions (H^+) to become displaced from the negatively charged clay faces during exchange with Ca^{2+}, which slightly lowers the pH and increases the solubility of lime (Valzano *et al.* 2001b). In the study of Valzano *et al.* (2001b), improved soil stability, due to this effect, was still observed after three years and 650 mm of significant rainfall (rainfall events totalling more than 5 mm). Additionally, a slight, but significant, increase in EC was observed after the same timeframe and rainfall in soils with lime applied at 1 t.ha^{-1} and a lime/gypsum combination applied at 2.5 t.ha^{-1}/1 t.ha^{-1}, respectively, as compared to the control soil. In a study of subsoil constraints to grain production, Dang *et al.* (2010) observed that the use of a lime/gypsum combination (rate not detailed) did not result in a crop yield increase on a sodic soil, while Valzano *et al.* (2001b) showed that lime and gypsum in combination did result in crop yield increase, through a synergistic effect on soil structure. Because the combination of lime and gypsum has been observed to provide a synergistic ameliorative effect that is apparently soil specific, it is important to present further field-based research on a broader range of soils. Therefore, this study aims to investigate the use of lime and gypsum combinations on selected soil properties relating to sodicity on two different soils in the Macquarie Valley of New South Wales (NSW) used for dryland cropping.

4.2. Methods

4.2.1. Soil sampling and description

Soils were sampled from “Bellevue”, a property near Warren (NSW; GR 31°32’00.70”S 147°47’46.13”E), and “Agriland”, near Trangie (NSW; GR 31°59’20.27”S 14°807’05.06”E), after 2.5 years using a single stroke, tractor mounted, hydraulic corer with a 45 mm internal diameter (ID) soil core. These were taken to a depth 0–900 mm. Due to cut/fill levelling of the irrigated fields, cores were split into 0–100, 100–200, 200–400, 400–600 and 600–800 mm layers rather than horizons, which provide a more accurate translation of effects to crop root zones than using soil horizons. The samples were taken at approximately 16 m intervals from the furrow and parallel to the rows. A total of twenty eight samples were taken per treatment/control, giving 392 sample sites per property. These were allowed to air-dry before being crushed and sieved to a 2 mm threshold. A proportion of aggregates from each sample were kept aside for further analysis. The soil sampled from “Bellevue” is from an Episodic-Endocalcareous Brown Vertosol. Clay mineralogy suggests that the soil is illite and kaolinite dominant. While some smectite is present, the majority of this appears to be interstratified with illite. Soil sampled from “Agriland” is from a Calcic Sodic Brown Dermosol. The mineral suite of the Agriland soil is dominated by illite and kaolinite in the A horizon, while smectite is more prominent at depth. Selected soil properties are presented in Chapter 3 for these soils in their initial condition prior to ameliorant application.

4.2.2. Soil analyses

As a result of these experimental sites undergoing dryland agricultural management throughout the duration of this study, the planned suite of soil analyses to be carried out was changed. It was determined that as the priority of investigation was amelioration viability in irrigated agriculture, the analysis of the Agriland and Bellevue soil post-lime and gypsum application, would be limited to $pH_{1:5}$, $EC_{1:5}$ and aggregate stability in water (ASWAT, Field *et al.* 1997). These methods (Chapter 3) were selected as indirect indicators of sodicity.

4.2.3. Statistical analysis

The data was observed to generally meet the criteria for normality and equality of variance to a reasonable degree. Where the assumption of normality was not met, data was log-transformed. Data were evaluated by one-way analysis of variance using MINITAB® *v.*14.11.1 at $\alpha = 0.05$ and $\alpha = 0.15$; where results are significant at $\alpha = 0.15$ they are explicitly stated. Differences between means were compared using the Tukey honestly significant difference test at $\alpha = 0.05$ and $\alpha = 0.15$, as this method reduces Type I error. Correlation analysis was also conducted between pH and EC, and EC and ASWAT. This data is presented in the form of overlayed correlation plots and the *r*-values and *p*-values reported within the text. For the analysis of ASWAT data, the Kruskal-Wallis non-parametric test was used because the DI is based on a ranking of aggregate stability, rather than a continuous scale. Thus, the use of ANOVA is not appropriate.

4.3. Results

4.3.1. Changes in soil pH due to treatment application

There appeared to be a general trend for pH to slightly increase where lime was applied on both experimental sites (Figure 4.1). However, this effect was more pronounced in the Bellevue soil at the depths measured (Figure 4.1b). For the 0–100 mm layer, the L2.5G2.5 and L2.5G5 treated soil had significantly higher pH than the L0G0 and L0G2.5 treated soils (p=0.004), while in the 100–200 mm layer, the soil treated with L2.5G5 was significantly higher in pH than the L0G2.5 treated soil (p=0.019). At the α=0.15 level, all treated soils in the 0–100 mm layer where lime had been applied became significantly higher in pH than that treated with L0G2.5, while in the 100–200 mm layer the L2.5G2.5 and L5G2.5 treated soils showed an increase in pH as compared to the L0G2.5 treated soil. The pH of the L2.5G5 treated soil was observed to be significantly higher than that treated with L0G2.5 ($0.15>p>0.05$) for the 200–400 mm layer also. Although not a significant result, where gypsum was applied alone, a slight decrease in pH was observed. The Agriland soil showed no significant difference in pH in any of the layers analysed (0–100 mm p=0.91; 100–200 mm p=0.74; 200–400 mm p=0.99; Figure 4.1a).

4.3.2. Changes in electrolyte concentration due to treatment application

Electrolyte concentration was generally observed to be greater with the application of lime and gypsum in combination after 2.5 years (Figure 4.2); again, the effect was more pronounced in the Bellevue soil (Figure 4.2a). While there were no observed significant differences at the α=0.05 level, the L2.5G5 treated soil was significantly greater in EC than the L0G2.5 treated soil (0.15>p>0.05) in the 0–100 mm layer, and those treated with L2.5G2.5 and L2.5G5 were significantly higher in EC than the L0G2.5 treated soil in the 100–200 mm layer; no observed significant difference in EC was apparent in the 200–400 mm layer, although the treated soils generally adhered to a similar mean value trend as those in the 0–100 mm layer. While there were no apparent significant EC differences in the Agriland soil for any depth, the L2.5G2.5 and L5G2.5 treated soils were consistently higher (mean value) than both the control and the L0G2.5 treated soils (Figure 4.2b).

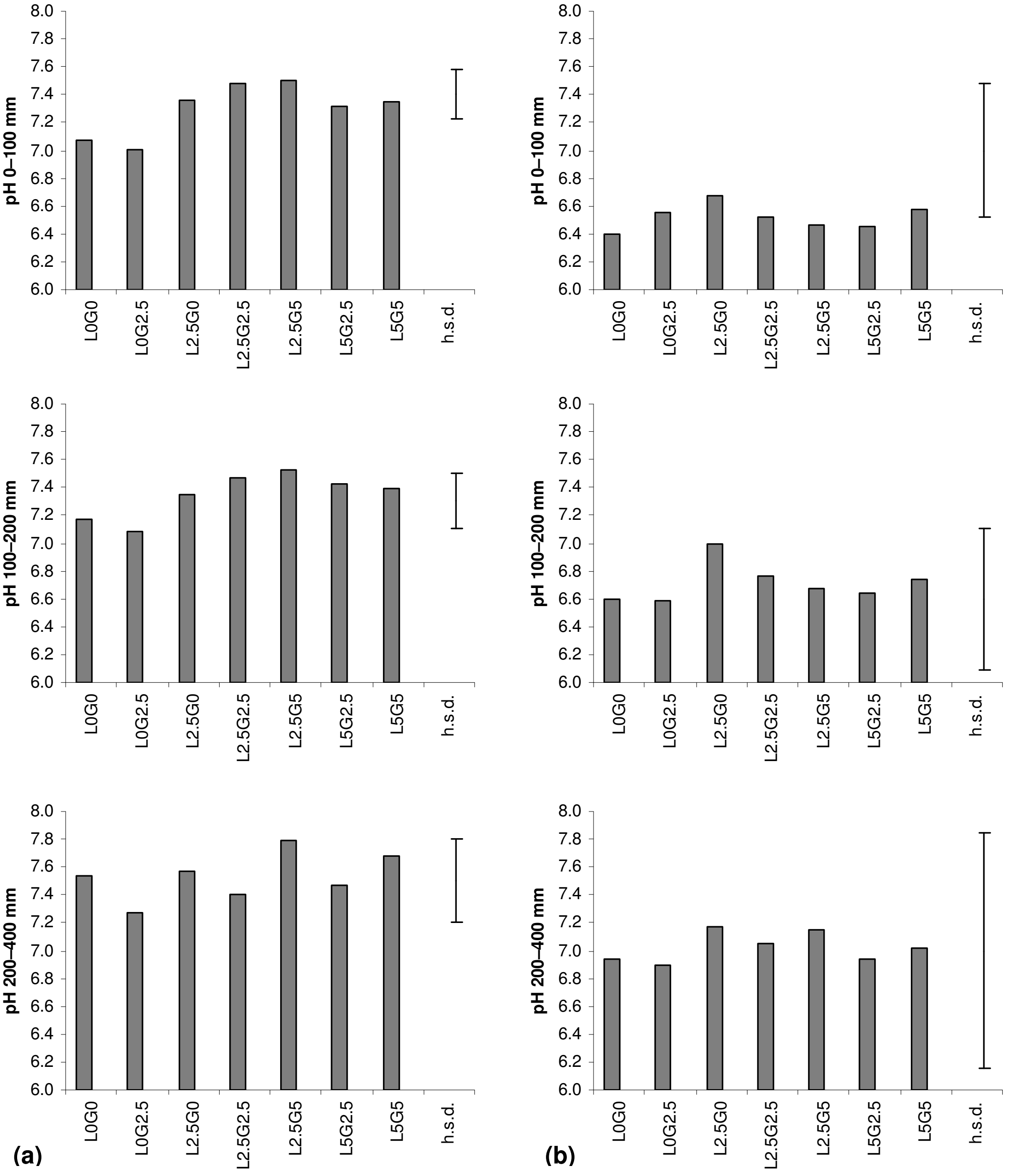


Figure 4.1. Changes in soil pH as a result of treatment effect after 2.5 years. Graphs in column (a) pertain to Bellevue; graphs in column (b) pertain to Agriland

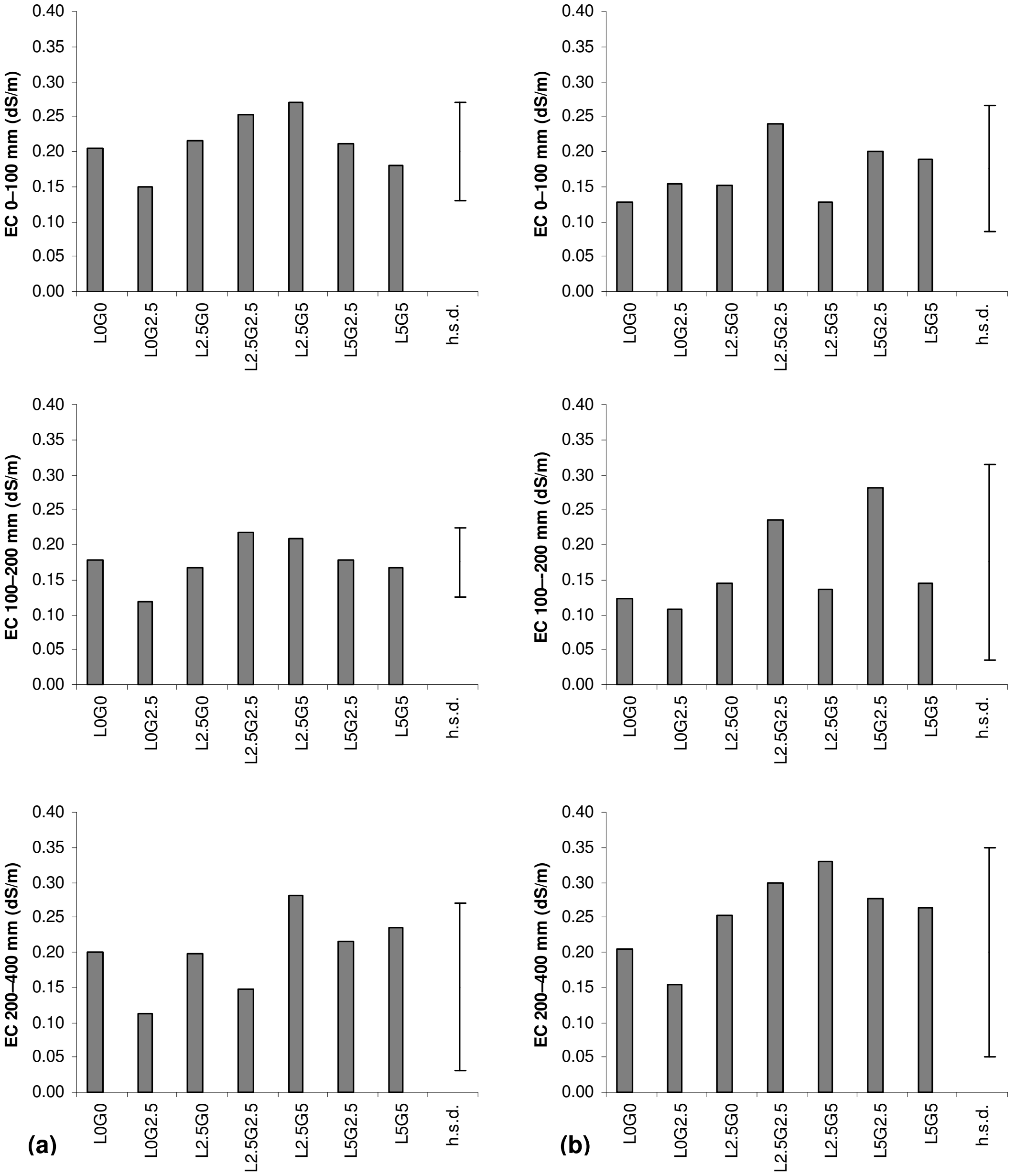


Figure 4.2. Changes in electrolyte concentration as a result of treatment application after 2.5 years. Graphs in column (a) pertain to Bellevue; graphs in column (b) pertain to Agriland

4.3.3. Changes in aggregate stability due to treatment application

For both soils, the common effect of treatments applied as a combination of lime and gypsum was to lower the dispersive potential of the soil (Figure 4.3), although not statistically significantly. The mean values for all treated and control soils were observed to be below a dispersive index of 8, which indicates that aggregates only dispersed after remoulding. Similarly, no soil scored 0, meaning that all soils remain dispersive to some extent irrespective of treatment application. In the Agriland soil, the greatest consistent decrease in DI throughout all depths was caused by application of the L2.5G2.5 and L5G2.5 treatments (Figure 4.3b).

However, in the Bellevue soil, the most consistent decrease in DI was from the L2.5G5 treatment (Figure 4.3a), although the L2.5G2.5, L5G2.5 and L5G5 treatments caused a similar decrease in DI. The effects of amendment application were generally limited to the 0–200 mm depth, with all treatment soils in the 200–400 mm layer being comparable to the untreated control soil.

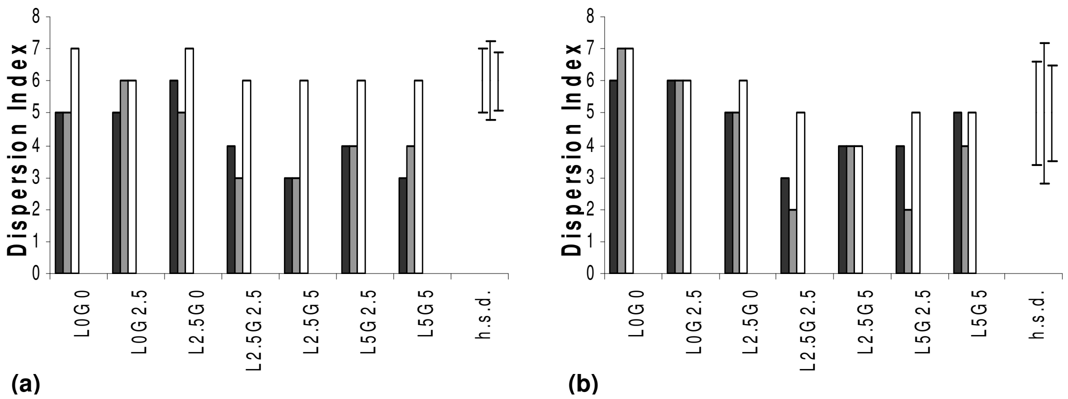


Figure 4.3. Changes in aggregate stability in water as a result of treatment application after 2.5 years; (a) represents Bellevue data; (b) represents Agriland data; columns within treatments represent the 0–100 mm (black), 100–200 mm (grey) and 200–400 mm (white) layers; h.s.d. intervals are ordered relative to the layer order.

4.3.4. Correlation analysis

Significant correlations (*p*<0.05) were obtained between pH and EC, and EC and DI, as indicated by the regression lines fitted to the correlation plots (Figure 4.4 and Figure 4.5, respectively). For the Agriland soil, only in the 200–400 mm layer does a significant correlation (*r*=0.86, *p*<0.001) between pH and EC exist (Figure 4.4a). The regression lines for the 0–100 mm and 100–200 mm layers have *r*-values of -0.12 and 0.44 at the respective *p*-values of 0.65 and 0.69. A trend for DI to decrease with increasing EC was observed for all depths at Agriland, although this was only significant for the 100–200 mm (*r*=-0.89, *p*=0.008) and 200–400 mm (*r*=-0.81, *p*=0.028) layers (Figure 4.5a). Regression for the 0–100 mm layer was observed to have an *r*-value of -0.69 at *p*-value 0.086, which suggests that the correlation between EC and DI is still representative of a treatment effect. Correlation analysis between pH and EC for Bellevue showed that pH was highly positively and significantly correlated with EC for all layers (0–100 mm: *r*=0.64, *p*=0.005; 100–200 mm: *r*=0.64, *p*=0.006; 200–400 mm: *r*=0.80, *p*<0.001; Figure 4.4b). However, for correlations between EC and DI, only the 100–200 mm layer relationship was found to be significant (*r*=-0.871, *p*=0.011) in the Bellevue soil (Figure 4.5b). The 0–100 mm and 200–400 mm layers produced highly variable relationships (*r*-0.23, *p*=0.627 and *r*=0.15, *p*=0.756, respectively).

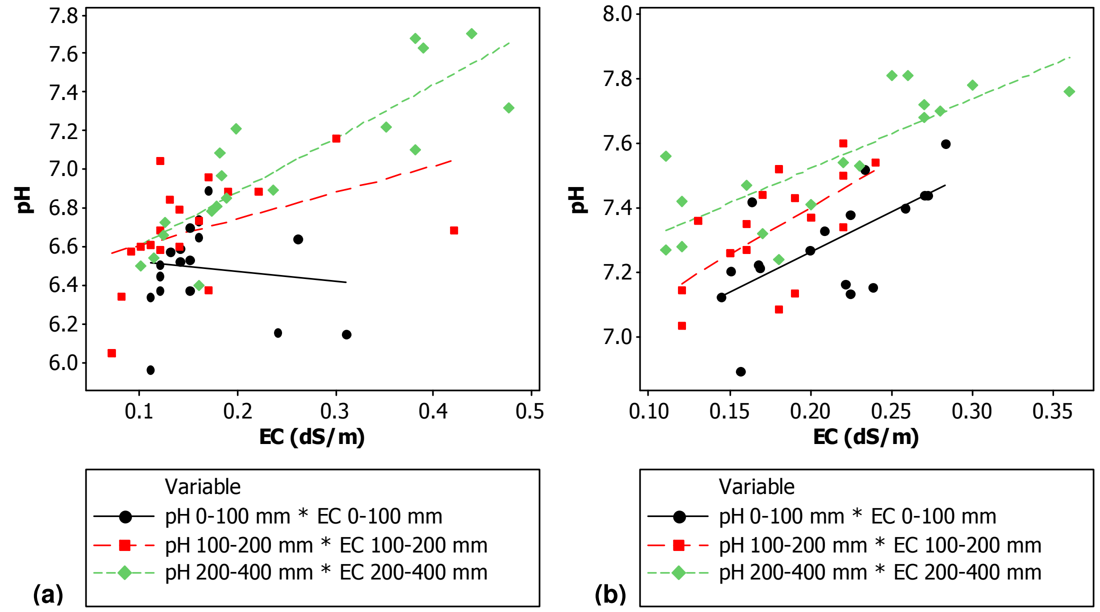


Figure 4.4. Correlation analysis of pH and electrolyte concentration by experimental site; (a) represents Agriland; (b) represents Bellevue

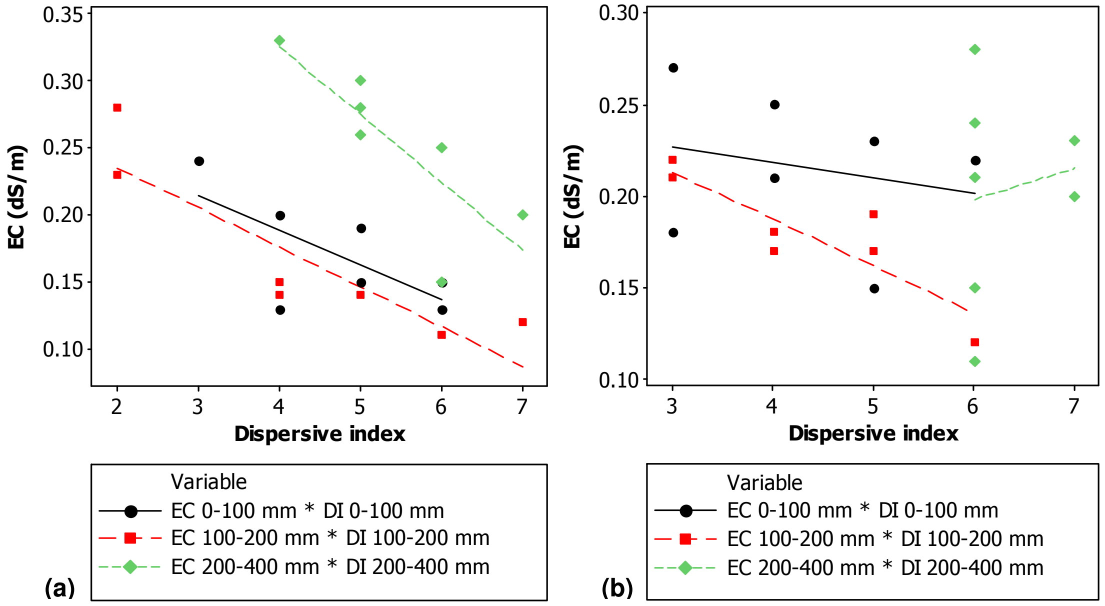


Figure 4.5. Correlation analysis of electrolyte concentration and aggregate stability in water dispersive index by experimental site; (a) represents Agriland; (b) represents Bellevue

4.4. Discussion

The soils used in this experiment were characterised by a low to moderate levels of sodicity that increases with increasing depth (approximate ESPs of 6% in 0–100 mm layers and between 9–12% in the 600–800 mm layers). Incidence of clay dispersion in the A horizon generally occurs only after mechanical interference (DI generally between 5 and 7), while the subsoil has a greater propensity to disperse spontaneously (higher incidence of DI between 9 and 16). The general effect of lime and gypsum combinations after 2.5 years was to reduce dispersion, albeit not significantly. What follows is a discussion of the potential for treatment application to lower sodicity.

4.4.1. Treatment effects on, and relationship between, pH and electrolyte concentration

Lime is known to increase the pH of soils through Ca^{2+} exchange and the formation of bicarbonate (HCO_3^-), the rate of which depends on the rate of lime dissolution (Barber 1984; Cregan *et al.* 1989), viz. the lime must dissolve in order for a change in pH to occur. The increases observed in pH for the Bellevue topsoil indicate that lime has dissolved throughout the 2.5 yr period since application and subsequently raised the pH. While the pH results for Agriland are not statistically significant, the slight rise in pH where lime has been applied could be attributed to lime dissolution. The general effect of gypsum on soil pH is a slight acidifying effect, due to displacement of H^+ (Valzano *et al.* 2001a; Valzano *et al.* 2001b). While not a significant result in this study, the consistently lower mean pH value where gypsum alone was applied is most likely due to this process. This was more pronounced in the Bellvue soil than the Agriland soil, therefore it is likely that gypsum has had a longer lasting pH effect in the Bellevue soil (control initial pH of 7.1) as compared to the Agriland soil (control initial pH of 6.4). The presence of lime where gypsum is applied has also been shown to decrease the dissolution of gypsum (Naidu *et al.* 1993). Combining the effects of pH and the presence of lime with gypsum on dissolution longevity, this would explain the propensity of the L2.5G5 treated soil to have a significantly higher pH than the soil treated with L0G2.5 at “Bellevue”.

As lime dissolves it can also augment the EC of the soil (Naidu and Rengasamy 1993). Shainberg and Gal (1982) showed that sufficient electrolyte was provided by lime to maintain hydraulic conductivity at levels higher than were observed for untreated soils (sandy soils with clay content between 4 and 13%; pH unknown). Valzano *et al.* (2001b) also observed the application of lime (1 $t.ha^{-1}$) to have increased topsoil EC after three years and 650 mm of rain in a Brown Sodosol (pH approximately 6.0–6.3 in the topsoil). Similarly, increases in soil EC for the current study were observed where lime had been applied for both Agriland and Bellevue. For the Bellevue soil, the L2.5G2.5 and L2.5G5 treatments caused a significant increase in EC as compared to the L0G2.5 treatment ($0.15>p>0.05$). Whilst gypsum is more commonly known to increase EC than lime (Davidson and Quirk 1961; McKenzie *et al.* 1993), it is likely that the EC effect due to gypsum has subsided due to leaching and the time afforded to dissolution (Sumner 1993). Interestingly, where gypsum was applied alone, the general effect was a slight decrease in EC. This can be attributed to a probable short-term improvement in soil structure, due to gypsum application, that has resulted in enhanced leaching of electrolyte over a longer period of time than lime applied alone could achieve

(Valzano *et al.* 2001a). This reinforces the short-term nature of the EC effect of gypsum and the need to reapply gypsum to maintain such an effect.

As lime is required to dissolve in order to provide a potential rise in pH, it stands that if lime is also responsible for increases in EC, pH should strongly and positively correlate with EC. This was the case for both the Agriland and Bellevue soils. Irrespective of statistical significance within each measurement (i.e. within pH or EC), a significant correlation is meaningful in that it shows the effect is a result of treatment application, and not just random ‘noise’. Of the two soils, the relationship was most consistent in the Bellevue soil, which is probably because the pH is approximately half a unit higher in this soil, meaning that the rate of dissolution would be slower. During the lifetime of the experiment 1222 and 1322 mm of rain fell on Bellvue and Agriland, respectively, that would have also affected the dissolution rate of gypsum and the subsequent effects on lime. Thus, the longevity of the EC effect is more likely to be greater for Bellevue. This is not to say that an EC effect due to lime has not occurred at Agriland. Indeed, the 200–400 mm layer shows that a highly significant relationship between pH and EC exists. The fact that the upper layers do not show such a relationship is most likely a result of improved aggregate stability and increased leaching, as well as a higher concentration of electrolyte in the leachate, due enhanced dissolution from a lower pH than the Bellevue soil.

4.4.2. Treatment effect on aggregate stability

While there were no significant effects on aggregate stability resulting from treatment application, there was an evident trend for aggregate stability to be enhanced where lime and gypsum combinations had been applied in comparison to the control soil. The variability in ASWAT data was high, which could have occurred as a result of a dilution effect, viz. a difference in ameliorant effect throughout the layer, especially as the boundary of the adjacent layer is approached. Field *et al.* (1997) state that 4 in every 6 aggregates exhibited the same ASWAT score and, for this reason, that 4 aggregates should be used as a minimum to provide a good indication of dispersive potential. In this study the minimum number of aggregates, as advised by Field *et al.* (1997), was used, but a large variability was still evident within individual samples. It is therefore suggested that the variability was most likely increased by a vertical dilution effect, as discussed above, due to the size of the individual layers. As the ASWAT test is rapid and inexpensive, greater replication in future analysis could be undertaken relative to the size of the layer. There would be benefit in investigating the aggregate stability variability as a function of sampling depth and defining critical minimum replication values as per Field *et al.* (1997).

Even though there were no observed significant differences in aggregate stability, it is appropriate to discuss the observed trends. For the Agriland soil, the L2.5G2.5 and L5G2.5 treated soils were observed to persist as the soils with the lowest DI, or equally lowest DI, throughout the layers investigated. For the Bellevue soil, the treatment providing the most consistent decrease in DI was the L2.5G5 treatment; this is possibly due to a greater amount of gypsum required to augment lime dissolution at higher pH than that of the Agriland soil. For both soils, the treatments having the greatest effect on DI throughout the investigated profile were the higher EC treatments, as compared to the remaining treatments. Hence, aggregate stability is likely augmented by lime dissolution through the addition of greater amounts of electrolyte (Shainberg and Gal 1982; McKenzie *et al.* 1993; Valzano *et al.* 2001b).

4.4.3. The relationship between electrolyte concentration and dispersive potential

The work of Quirk and Schofield (1955) shows that the flocculation of clay particles is highly dependent on the electrolyte concentration within a soil. The Agriland soil clearly shows that the EC is significantly and negatively related to the dispersive potential of the soil for all layers, while only the 100–200 mm layer for the Bellevue soil shows such a significant relationship. For the Bellevue soil, it is suggested that the recent cut-and-fill land-forming (in the year 2005, as compared to 1992 at Agriland) is responsible for the variation. It is probable that such cut/fill variability would mask the effects of treatment application, unless pronounced. Furthermore, fill areas would be more likely to benefit from a small rise in EC than would the exposed subsoil of cut areas with a higher ESP. This reinforces the fact that sodic soils, and their level of stability, are dependent on more than just one soil chemical property (Sumner 1993).

4.4.4. Possibility of a synergistic effect between lime and gypsum on soil sodicity

As soil exchangeable cations were not determined, it is only possible to speculate on the effects of lime and gypsum combinations on soil sodicity levels. However, it is feasible that synergy between lime and gypsum has occurred. Where EC levels were significantly different, application of lime and gypsum had occurred in combination. Valzano *et al.* (2001b) found a similar result for EC after three years on a Brown Sodosol where a L2.5G1 treatment had been applied. This same treatment was shown to have a higher exchangeable Ca^{2+} concentration as compared to the control, although the result was not significant, leading them to conclude that after three years the displacement of Na^+ alone was not sufficient to maintain aggregate stability. Indeed, it was a combination of the short-term ESP reduction and the long-term (3 years) maintenance of EC by the lime. Thus, the observed EC levels in the current study may be indicative of a lower ESP. Furthermore, if lime is responsible for the maintenance of EC, and greater EC where applied in conjunction with gypsum, then it is quite probable that the soil solution is Ca^{2+} enhanced where combinations are applied (Valzano *et al.* 2001b). Subsequently, it could also be expected that the exchangeable Ca^{2+} is higher than the control in this environment due to soil solution/exchange equilibrium processes (Sposito 1989; Sparks 2003). The Bellevue soil was the only soil with significant differences in EC after 2.5 years, and of the two soils, is the most likely to have benefitted from a synergistic effect, although this does not preclude the Agriland soil from such an interaction. As previously discussed, the lower pH in the Agriland soil may have caused the amendments to have completely dissolved in before soil sampling occurred after 2.5 years. The EC/pH relationship in the 200–400 mm layer for this soil suggests that lime has had an effect on soil EC, albeit possibly dwindling. Therefore, the possibility of a lime/gypsum synergy can not be ruled out after 2.5 years.

4.5. Conclusion

This study has shown, through pH/EC relationships, that EC has been maintained at higher levels than the control where lime is applied, or where gypsum is applied alone. Furthermore, the increases in EC due to lime generally result in a significant relationship between EC and aggregate stability. Trends for enhanced EC and aggregate stability were most consistent for the L2.5G2.5 treated soils at “Agriland”, and where the L2.5G5 treatment was applied at “Bellevue”. This was attributed to a lower pH in the Agriland soil. Consequently, a greater influence in lowering the pH in the Bellevue soil was likely required from gypsum to obtain the observed results. This reinforces the concerns of Valzano *et al.* (2001b) that the effects of lime and gypsum in combination are site specific and reliant on pH.

The possibility of a synergistic effect between lime and gypsum on soil sodicity levels was considered, with the greatest potential for an effect after 2.5 years being established in the Bellevue soil. However, the possibility of such a synergy having occurred in the Agriland soil was not excluded. While it is possible to speculate on the possibility of augmented effects on sodicity levels due to combined application of lime and gypsum, this work would benefit from analysis of soil exchangeable and soluble cations in the future.

4.6. References

Barber, SA (1984) Liming materials and practices. *In* 'Soil acidity and liming'. (Eds. Adams, F) (American Society of Agronomy Inc.: Madison)

Bennett, JMcL (2006) *Interactions between chemical ameliorants and vegetation in a sodic red brown earth, Upper Bogan region, NSW*, Thesis - Australian National University, Canberra.

Chan, KY, Dexter, AR & McKenzie, DC (1999) Categories of soil structure based on mechanical behaviour and their evaluation using additions of lime and gypsum on a sodic Vertisol. *Australian Journal of Soil Research* **37,** 903-11.

Chan, KY & Heenan, DP (1998) Effect of lime (CaCO3) application on soil structural stability of a red earth. *Australian Journal of Soil Research* **36,** 73-86.

Chartres, CJ, Greene, RSB, Ford, GW & Rengasamy, P (1985) The effects of gypsum on macroporosity and crusting of two red duplex soils. *Australian Journal of Soil Research* **23,** 467-79.

Cregan, PD, Hirth, JR & Conyers, MK (1989) Amelioration of soil acidity by liming and other amendments. *In* 'Soil acidity and plant growth'. (Eds. Robson, AD) (Academic Press Australia: Sydney)

Dang, YP, Dalal, RC, Buck, SR, Harms, B, Kelly, R, Hochman, Z, Scwenke, GD, Biggs, AJW, Furguson, NJ, Norrish, S, Routley, R, McDonald, M, Hall, C, Singh, DK, Daniells, IJ, Farquharson, R, Manning, W, Speirs, S, Grewal, HS, Cornish, PE, Bodapati, N & Orange, D (2010) Diagnosis, estent, impacts, and management of subsoil constraints in the northern grains region of Australia. *Australian Journal of Soil Research* **48,** 105-19.

Davidson, LJ & Quirk, JP (1961) The influence of dissolved gypsum on pasture establishment of irrigated clays. *Australian Journal of Agricultural Research* **12,** 100-10.

Field, DJ, McKenzie, DC & Koppi, AJ (1997) Development of an improved vertisol stability test for SOILpak. *Australian Journal of Soil Research* **35,** 843-52.

Gardner, HW & Gardner, HV (1953) 'The use of lime', (Farmer & Stock-Breeder Publications Ltd: London)

Ghafoor, A, Gill, MA, Hassan, A, Murtaza, G & Qadir, M (2001) Gypsum: An economical amendment for amelioration of saline-sodic waters and soils, and for improving crop yields. *International Journal of Agriculture and Biology* **3,** 266-75.

Greene, RSB & Ford, GW (1985) The effect of gypsum on cation exchange in two red duplex soils. *Australian Journal of Soil Research* **23,** 61-74.

Keren, R & O'Connor, GA (1982) Gypsum dissolution and sodic soil reclamation as affected by water flow velocity. *Soil Science Society of America Journal* **46,** 726-32.

McKenzie, DC, Abbott, TS, Chan, KY, Slavich, PG & Hall, DJM (1993) The nature, distribution and management of sodic soils in New South Wales. *Australian Journal of Soil Research* **31,** 839-68.

McKenzie, DC & So, HB (1989a) Effect of gypsum on vertisols of the Gwydir Valley, New South Wales 1. Soil properties and wheat growth. *Australian Journal of Experimental Agriculture* **29,** 51-62.

McKenzie, DC & So, HB (1989b) Effect of gypsum on vertisols of the Gwydir Valley, New South Wales 2. Ease of tillage. *Australian Journal of Experimental Agriculture* **29,** 63-7.

Naidu, R, Merry, RH, Churchman, GJ, Wright, MJ, Murray, RS, Fitzpatrick, RW & Zarcinas, BA (1993) Sodicity in South Australia - a review. *Australian Journal of Soil Research* **31,** 911-29.

Naidu, R & Rengasamy, P (1993) Ion interactions and constraints to plant nutrients in Australian sodic soils. *Australian Journal of Soil Research* **31,** 801-19.

Northcote, KH & Skene, JK (1972) *Australian soils with saline and sodic properties*. CSIRO Soil Publication 27, (CSIRO: Australia)

Quirk, JP & Schofield, RK (1955) The effect of electrolyte concentration on soil permeability. *Australian Journal of Soil Research* **6,** 163-78.

Shainberg, I & Gal, M (1982) The effect of lime on the response of soils to sodic conditions. *Journal of Soil Science* **33,** 489-98.

Shepherd, AN (1925) Experience on Yanco irrigation area. *Agricultural Gazette New South Wales* **36,** 261-3.

So, HB & Aylmore, LAG (1993) How do sodic soils behave? The effects of sodicity on soil physical behaviour. *Australian Journal of Soil Research* **31,** 761-77.

So, HB, Taylor, DW, Yates, WJ & McGarity, JW (1978) Amelioration of structurally unstable grey and brown clays. *In* 'Modifications of soil structure'. (Eds. Emerson, WW, Bond, RD & Dexter, AR) (John wiley & sons: Chichester)

Sparks, DL (2003) 'Environmental soil chemistry', (Academic Press: London)

Sposito, G (1989) 'The chemistry of soils', (Oxford University Press: New York)

Sumner, ME (1993) Sodic soils: a new perspective. *Australian Journal of Soil Research* **31,** 683-750.

Valzano, FP, Murphy, BW & Greene, RSB (2001a) Effects of gypsum and stubble retention on the chemical and physical properties of a sodic grey vertosol in western Victoria. *Australian Journal of Soil Research* **39,** 1333-47.

Valzano, FP, Murphy, BW & Greene, RSB (2001b) The long term effects of lime ($CaCO_3$), Gypsum ($CaSO_4.2H_2O$), and tillage on the physical and chemical properties of a sodic red-brown earth. *Australian Journal of Soil Research* **39,** 1307-31.

THE EFFICACY OF USING LIME ($CaCO_3$), GYPSUM ($CaSO_4.2H_2O$) AND LIME/GYPSUM COMBINATIONS TO AMELIORATE SODICITY IN TWO IRRIGATED SOILS USED FOR CROPPING IN THE LACHLAN VALLEY OF NEW SOUTH WALES

5. The efficacy of using lime ($CaCO_3$), gypsum ($CaSO_4.2H_2O$) and lime/gypsum combinations to ameliorate sodicity in two irrigated soils used for cropping in the Lachlan Valley of New South Wales

J. McL. Bennett[ABC], *S. R. Cattle*[A], *and B. Singh*[A]

[A] Faculty of Agriculture, Food and Natural Resources, The University of Sydney, NSW 2006.
[B] Cotton Catchment Communities Co-operative Research Centre
[C] Cotton Research & Development Corporation

Abstract. Information relating to the use of lime, gypsum and lime/gypsum combinations in ameliorating irrigated sodic soil is minimal compared to the same pertaining to dryland agricultural systems. Two primary factors controlling the rate of dissolution of these chemical ameliorants are the magnitude and frequency of water infiltration. Thus, it could be expected that the longevity of lime and gypsum would be reduced under the increased water application provided by irrigation systems. This paper examines the efficacy of using such chemical amendments, alone and in conjunction, in two irrigated agricultural soils (an Episodic-Gypsic Brown Vertosol and a Sodic Red Dermosol with a hypocalcic subsoil layer) under cotton (*Gossypium hirsutum* L.) and wheat (*Triticum aestivum*). Full-field, replicated experimental-strips were treated with L0G0 (Lime 0 $t.ha^{-1}$ and Gypsum 0 $t.ha^{-1}$), L2.5G0, L0G2.5, L2.5G2.5, L2.5G5, L5G2.5 and L5G5. Measurement of soil exchangeable and soluble cations, cation exchange capacity, pH, electrolyte concentration (EC), residual gypsum, aggregate stability in water (ASWAT) and crop production were measured after 6 months and 2.5 years. The exchange efficiency of calcium (Ca^{2+}) as applied as lime and gypsum was calculated after 6 months. Significant exchange of Ca^{2+} for sodium was primarily attributable to gypsum, and generally at the rate of 5 $t.ha^{-1}$ after 6 months, although these effects did not persist over 2.5 years. The EC effect of gypsum was not observed after 6 months or 2.5 years post-gypsum application and approximately 12.85 $ML.ha^{-1}$ of infiltrating irrigation-water/rain. The results of this work show that the use of lime and gypsum in combination and alone is not necessarily viable for broadacre irrigated agriculture on two Lachlan Valley soils with pH >8.0.

Additional keywords: exchangeable sodium percentage (ESP), chemical ameliorant, exchange efficiency, synergy.

5.1. Introduction

Australian sodic soils contain levels of sodium (Na^+) in excess of 6% of their cation exchange capacity (Northcote and Skene 1972) and are characterised by a tendency to disperse upon wetting either spontaneously, or after mechanical disturbance such as raindrop impact, irrigation and cultivation. Sodic soils that are likely to disperse after wetting are also prone to hardsetting, surface crusting, pore blockage and increased soil strength. The ensuing soil state is liable to have reduced infiltration, increased run-off and water-ponding, and poor aeration, which will ultimately lead to reduction in crop and pasture yields (McKenzie *et al.* 1993). Estimates for Australia's annual economic loss due to reduced productivity on sodic soil are approximately AUD$1035 million (Hajkowicz and Young 2005). Within Australia sodicity is estimated to affect 340 million ha (Murphy 2002), much of which is agricultural soil used for cropping. It stands that management of these soils is not only integral to sustaining crop and pasture productivity, but also the efficient use of rainfall and irrigation water.

Gypsum ($CaSO_2.2H_2O$) is commonly applied to cropped soils as a management strategy for the amelioration of sodicity. It has been shown to improve the structural stability of sodic soils by lowering the exchangeable sodium percentage (ESP), through displacement of Na^+ with calcium (Ca^{2+}) (So *et al.* 1978; Doyle *et al.* 1979; Rengasamy *et al.* 1984b; Greene and Ford 1985; Valzano *et al.* 2001a; Dang *et al.* 2010), as well as providing a short-term rise in electrolyte concentration (EC) throughout the dissolution period (Davidson and Quirk 1961; Taylor and Olsson 1987; McKenzie and So 1989a; McKenzie and So 1989b). Lime ($CaCO_3$), which has traditionally been used for raising pH (Jayawardane and Chan 1995; Aitken *et al.* 1998), has also been investigated for its ability to displace Na^+ via Ca^{2+}, with limited success (Roth and Pavan 1991; McKenzie *et al.* 1993; Chan and Heenan 1998). This is mainly because it is 172 times less soluble than gypsum under standard conditions. However, Valzano *et al.* (2001b) demonstrated improvement in soil structure after three years as a synergistic response from lime and gypsum applied in combination (lime 2.5 $t.ha^{-1}$, gypsum 1 $t.ha^{-1}$) in a red-brown earth (Brown Sodosol; pH 6.5–7.5 and ESP 6.0–10%) used for the production of dryland wheat. The dissolution of gypsum displaces hydrogen (H^+), causing a localised decrease in pH that subsequently increases the potential dissolution of lime. While this is a legitimate means of sodicity amelioration, it has received little attention (Shanmuganathan and Oades 1983; Chan *et al.* 1999; Valzano *et al.* 2001b; Bennett 2006), especially with relation to irrigated soils.

A further mechanism for enhanced dissolution of soil carbonates, termed as phytoremediation, is provided through the respiration and proton (H^+) output of plant roots (Robbins 1986a; Qadir *et al.* 2003; Hulugalle *et al.* 2006; Mubarak and Nortcliff 2010). Dissolution is enhanced due to an increase in localised soil acidity through the creation of carbonic acid (H_2CO_3), dependent on soil CO_2 partial pressure (P_{CO_2}), and an increase in H^+ efflux from plant roots. Robbins (1986a; 1986b) used a calcareous sodic soil (pH 8.6, ESP 33) to show that cotton (*Gossypium hirsutum* L.), barley (*Hordeum vulgare*) and sudan grass [*Sorghum bicolor* (L.) Monench x *Sorghum sudanese* (Piper) Stapf] caused a decrease in Na^+ due to an increase in P_{CO_2}, stimulating dissolution of soil carbonates. Murbarak and Nortcliff (2010) further showed that an abundance of H^+, from nitrogen-fixing legumes, was responsible for higher Ca^{2+} and lower Na^+ levels in a sodic calcareous Umbric Fluvisol. These processes have also been suggested to augment the dissolution of incorporated applications of lime and gypsum (Naidu and Rengasamy 1993; Valzano *et al.* 2001b; Bennett 2006). However, there is limited field evidence for these processes regarding external carbonate sources, particularly concerning irrigated sodic soils. Phytoremediation using pedogenic carbonates, as a sodicity amelioration technique, has increased in incidence in developing countries due to chemical ameliorant prices increasing (Qadir and Oster 2002). While the current prices of lime and gypsum used in Australian broadacre agriculture are relatively inexpensive, when combined with transport and application costs these amendments can become costly. Because lime is sparingly soluble, and therefore sparingly mobile within the profile, there would be benefit in exploring the ability for common irrigated crops to dissolve applied lime.

This paper compares the efficiency of applying lime, gypsum and lime/gypsum combinations for ameliorating sodicity in irrigated soils used for cropping. The merits of cotton and wheat (*Triticum aestivum*) for enhancing the dissolution of these chemical ameliorants are also considered.

5.2. Methods

5.2.1. Experimental sites

Two experimental sites were chosen on the basis that they were sodic, had a history of irrigation, had not undergone lime or gypsum application in the years 2002–2006 inclusive, planned on growing cotton in rotation with wheat, and had a pH in the range 7.5–9. This last criterion was chosen for two reasons; 1) landholders have shown interest in lime/gypsum combined application to soil in this pH range, and 2) as lime is insoluble at pHs exceeding 8.2, any observed dissolution of lime will occur due to localised acidity from either gypsum application or phytoremediation effects.

"Mount View"

The "Mount View" experimental site is situated in a field north-west of Hillston, NSW, (GR 33º07'58.19"S 145º18'36.92"E) which underwent land-forming for flood irrigation in early 2000. Prior to this, the land had only been used for grazing. Irrigated cotton has been the primary crop grown on this field, with one wheat crop (prior to the experiment) grown in 2006. The soil is an Episodic-Gypsic Brown Vertosol (Isbell 2002) comprised of an alkaline and sodic surface soil and an alkaline and potentially sodic subsoil. The field texture grade is heavy clay throughout the assessed depth (0–800 mm). A highly dispersive subsoil layer occurs at a depth of approximately 300–500 mm. While there is some variation in soil type across the field, the clay mineral suite is not affected by this. The predominant clay minerals in the surface soil are smectite and kaolinite, with some illite also present. In the subsoil a similar clay mineral suite occurs, but with an increase in illite. Interstratification of smectite and illite is also evident in the subsoil. Selected soil descriptive properties are presented in Table 5.1 by depth.

"Wyadra"

The "Wyadra" experimental site is situated to the west of Hillston (33°33'25.09"S 145°17'35.11"E). This field was used for grazing prior to being land-formed for lateral-move irrigation during late 2002 through to early 2003. The field has predominantly been used for the growth of wheat, with two rotations of cotton and one of chickpeas prior to the experiment. The soil is a Sodic Red Dermosol with a hypocalcic subsoil layer and evidence of gypsum throughout the subsoil. The soil is both alkaline and sodic with a uniform heavy clay texture throughout the assessed depth. Soil type is relatively uniform across the experimental site, which was confirmed by lack of significant differences in clay mineralogy. The clay mineral suite for the surface soil is dominated by kaolinite, with some smectite and illite. The subsoil contains relatively similar proportions of smectite, illite and kaolinte in the clay fraction. Interstratification of smectite and illite is also apparent in the subsoil. Table 5.1 displays selected soil descriptive properties with changes in depth.

Table 5.1. Selected soil properties from the Mount View and Wyadra experimental sites
DI represents the dispersive index as measured by aggregate stability in water (Field *et al.* 1997); C is clay (<2 µm); S is silt (2–20 µm); FS is fine sand (20–200 µm); CS is coarse sand (200–2000 µm).

Depth (mm)	*DI*	*pH $_{1:5}$ (soil:water)*	*EC $_{1:5}$ (dS/m)*	*cmol(+)/kg* *Ca*	*Mg*	*Na*	*CEC*	*ESP (%)*	*N (%)*	*C (%)*	*Total Gypsum (%)*	*Particla size analysis* *C %*	*S %*	*FS %*	*CS %*
					"Mount View"										
0–100	10	8.7	0.37	9.6	8.9	2.2	20.8	10.5	0.10	0.84	0.00	58	3	31	8
100–200	11	8.2	0.65	9.3	9.9	5.1	24.4	19.8	–	–	0.00	64	3	27	6
200–400	13	8.9	0.88	7.2	8.6	9.9	25.8	37.5	–	–	0.08	64	5	26	5
400–600	9	8.8	2.01	11.9	7.7	5.9	25.5	23.3	–	–	0.83	63	5	26	5
600–800	5	8.5	3.32	16.6	5.5	1.5	23.6	6.3	–	–	1.35	59	6	29	6
					"Wyadra"										
0–100	10	8.6	0.31	12.08	7.91	1.71	20.8	8.2	0.10	0.88	0.00	67	2	23	8
100–200	10	8.5	0.46	12.17	9.05	2.31	24.4	9.5	–	–	0.00	70	1	21	8
200–400	10	8.6	0.71	14.05	12.09	4.56	27.3	16.7	–	–	0.00	66	2	25	7
400–600	10	8.9	0.94	10.55	8.61	3.79	27.0	14.0	–	–	0.10	58	5	29	8
600–800	6	8.9	1.28	14.92	10.05	4.48	25.8	17.4	–	–	0.38	60	3	30	8

5.2.2. Experimental design

Fields were divided into experimental strips, separated by buffer-zone strips, extending the full length of the field. For the "Mount View" field, experimental strips were 16 m wide and buffer-zone strips were 4 m wide. On "Wyadra" both the experimental and buffer-zone strips were 8 m to ensure that wheel tracks from the lateral move irrigation apparatus passed through buffer-zones and not treatments. For both properties, a buffer-zone of at least 24 m was present either side of the experiment to negate edge effects, and each treatment/control had two replicates. In June and July 2007 the treatment applications of lime and/or gypsum

(Table 5.2) were applied to the experimental strips using an Agricat® self propelled, horizontal twin-spinner, spreading implement at "Mount View" and "Wyadra", respectively. No reapplication of lime or gypsum occurred during the 2.5 year period of the experiment.

Table 5.2. Experimental treatments with reference to amount of calcium applied and the cost per hectare

Calculation of the calcium equivalent for each treatment is based on 200 kg.t^{-1} of calcium contained in gypsum (analysis shows 20% Ca^{2+} in the gypsum source) and 400 kg.t^{-1} of calcium in lime (Abbott and McKenzie 1986). The cost of each treatment is based on the actual cost for lime (AUD$110 t^{-1}) and gypsum (AUD$75 t^{-1}) used for this experiment.

Treatment	*Abbreviation*	*Lime (t/ha)*	*Gypsum (t/ha)*	*Calcium Equivalent (t/ha)*	*Cost (AUD$/ha)*
Control	L0G0	0	0	0	0
1	L0G2.5	0	2.5	0.5	187.5
2	L2.5G0	2.5	0	1	275
3	L2.5G2.5	2.5	2.5	1.5	462.5
5	L2.5G5	2.5	5	2	650
4	L5G2.5	5	2.5	2.5	737.5
6	L5G5	5	5	3	925

5.2.3. Agronomy

Agronomic treatments were not used as a part of the experiment, although normal agronomic processes for the preparation and maintenance of cotton and wheat were employed uniformly across the experimental sites. These are detailed below.

Mount View

The crop rotation for "Mount View" for the period 2007-2010 was cotton – wheat – fallow – fallow – cotton (2007/2008 summer, 2008 winter, 2008/2009 summer, 2009 winter, 2009/2010 summer, respectively). Cultivation during a cotton season involved: two passes with a disc cultivator (if planting cotton post-wheat); grader boarding twice; deep ripping (250 mm), hilling and incorporation of nitrogen gas; incorporation of MAP to 100 mm; a lilliston pass; rolling of rows prior to planting; sowing of cotton; and mulching, root cutting and pupae busting. If the field was rotating to wheat, then: nitrogen gas was incorporated after pupae busting; 2 m beds were formed; beds were rolled prior to sowing; wheat was sown; and mulching of wheat prior to disc cultivation was conducted if going into cotton. Traffic across the field was controlled through permanent GPS traffic rows used for both cotton and wheat. Irrigation for cotton involved one flooding of 2 ML.ha^{-1} to fill the profile followed by nine 1 ML.ha^{-1} in-crop irrigations. For wheat 2.5 ML.ha^{-1} were applied to fill the soil profile, while 3 in-crop irrigations of 1.2 ML.ha^{-1} were applied during spring. The water used for irrigation was of moderate quality (pH 7.5, EC 0.83 dS.m^{-1}, and SAR 5.96). The various nutrients and spray applications for cotton and wheat are detailed in Table 5.3.

Wyadra

Crop rotation for “Wyadra” consisted of cotton – fallow – fallow – wheat – fallow (2007/2008 summer, 2008 winter, 2008/2009 summer, 2009 winter, 2009/2010 summer ,respectively). Cultivation for cropping seasons consisted of: disc-ploughing, ripping, graderboarding and sowing for wheat, while cotton required disc-ploughing, ripping and formation of beds prior to sowing. Mulching, root cutting and pupae busting would be undertaken post-harvest of cotton. Incorporation of nitrogen and MAP preceded sowing for all crops. When the field was left in fallow, stubble was retained and crop trash left *in situ* as surface mulch. A controlled traffic system was used through GPS and permanent traffic rows. Irrigation for cotton involved the application of 9.5 ML.ha^{-1} throughout the season; lateral-move irrigation passes averaged 15 mm.ha^{-1}. For wheat, 3.5 ML.ha^{-1} of irrigation water was applied during the season, and averaged a rate of 20 mm.ha^{-1} for each lateral-move irrigation pass. Irrigation used for the duration of the experiment was of moderate quality (pH 7.96, EC 0.86 dS.m^{-1} and SAR 6.07). Within the wheat and cotton seasons various chemical sprays and nutrients were applied; these are described in Table 5.3.

Table 5.3. Agronomic information for the application of nutrients and chemical for both sites
App. month is an abbreviation for ‘application month’

Mount View			*Wyadra*		
Input by crop	*per ha*	*App. month*	*Input by crop*	*per ha*	*App. month*
Cotton program			*Cotton program*		
Pre plant MAP	150 kg	Aug	Pre plant MAP	150 kg	Aug
Pre plant N kg as NH3	150 kg	May	Pre plant N kg as NH3	150 kg	May
Water run N kg as urea	50 kg	Nov, Dec	Water run N kg as urea	50 kg	Nov, Dec
Planting herbicide - Fluometuron 440	1 kg	Sept	Planting herbicide - Pendamethalin 440	3 L	Sept
Planting herbicide - Pendamethalin 440	3 L	Sept	Planting insecticide - Phorate 200	3 L	Sept
Planting insecticide -Phorate 200	3 kg	Sept	RR herbicide 690	1.5 kg	Oct, Nov, Dec
RR herbicide 690	1.5 kg	Oct, Nov, Dec	Insecticide - Alphacypermethrin 100	0.3 L	Jan
Insecticide - Alphacypermethrin 100	0.3 L	Jan	Growth regulant - Mepiquat Chloride38	3 L	Jan
Growth regulant - Mepiquat Chloride38	3 L	Jan	Defoliant - Thidiazuron 240 + Diuron 120	0.25 L	March
Defoliant - Thidiazuron 240 + Diuron 120	0.25 L	March	Defoliant - Ethephon 720	4 L	April
Defoliant - Ethephon 720	4 L	April			
Irrigated wheat program			*Irrigated wheat program*		
Pre-plant N kg as NH3	120 kg	April	Planting MAP	120 kg	May
Planting MAP	120 kg	May	Water run N kg as Urea	100 kg	Sept
Water run N kg as Urea	80 kg	Sept	Herbicide - Metsulfuron 600	0.005 kg	July
Herbicide - Metsulfuron 600	0.005 kg	July	Herbicide - MCPA L.V.E	0.7 L	August
Herbicide - MCPA L.V.E	0.7 L	August	Fungicide - Triadmefon 125	1 L	Sept
Fungicide - Triadmefon 125	1 L	Sept			

5.2.4. Soil sampling regime, measurements and preparation

Soil samples were taken from 0–100 mm depth after 6 months (2007/08) and after 2.5 years (2009/10) for each treatment replicate at both experimental sites. In 2007/08 a total of 56 evenly spaced samples were taken along the centre furrow, over 500 m, of each treatment replicate. Sampling sites were georeferenced using a handheld GPS. In 2009/2010 the same sampling regime was conducted for 0–100 mm depth samples, but with 28 samples being taken from every second georeferenced site. A soil core (0–900 mm) was also taken at these sites using a tractor mounted, single stroke, hydraulic corer. Cores were stored in PVC half-pipe and wrapped in plastic for transportation.

In the laboratory, the cores, while still moist, were separated into layers: 0–100 mm, 100–200 mm, 200–400 mm, 400–600 mm and 600–800 mm. Cores were separated by incremental layers, rather than horizons, because the irrigation fields had undergone cut/fill levelling. Thus, incremental layers provided a more accurate translation to rooting depth effects of treatments than horizons. Sample preparation involved air-drying followed by separating all samples into two equal proportions (along the vertical axis of the soil cores). One proportion was kept intact for aggregate stability measurements, while the other was crushed and sieved to a < 2 mm threshold for soil chemical analysis. For the measurement of total carbon (C) and nitrogen (N) a 5 g aliquot of <2 mm soil was gently crushed using mortar and pestle to pass through a 53 μm sieve.

5.2.5. Laboratory measurements

The pH and EC were measured on 1:5 soil (<2 mm):water suspensions using a Radiometer MeterLab™ standard pH meter (PHM210) and conductivity meter (CDM210). Exchangeable cations (Ca^{2+}, Mg^{2+}, Na^+, K^+) were extracted using choline chloride (ChCl) in aqueous ethanol after pretreating for soluble salts with ethanol and glycerol solutions, as described by Tucker (1985). This reagent is shown to extract less specifically-adsorbed cations than ammonium chloride, and presumably ammonium acetate, in soils containing carbonates. Cation exchange capacity (CEC) was established by flooding the cation exchange sites of samples with a calcium chloride ($CaCl_2$) reagent and subsequently extracting Ca^{2+} with $ChCl_2$ in aqueous ethanol (Tucker 1985). Concentrations of exchangeable cations in the extract were measured using a Varian Spectra 220FS atomic absorption spectrometer. ESP, exchangeable Ca^{2+} percentage (ECP), and exchangeable Mg^{2+} percentage (EMP) were calculated from the CEC.

Residual gypsum from treatment applications was measured as the sulphate content of the ChCl extract, as per the method of Tucker and Beatty (1974). Preliminary investigations showed that the use of the ethanol and glycerol pretreatments removed negligible gypsum and that the remaining gypsum was extracted through the use of ChCl in aqueous ethanol.

The data from exchangeable cation analysis and residual gypsum were used to calculate the changes in exchangeable cations relative to the control, on the basis of the Ca^{2+} applied in total (i.e. from lime and gypsum) and also assuming lime had no effect (i.e. for gypsum contribution only). This calculation was only made for the differences between the control and the L5G5 treatment due to the general lack of consistent significant changes in other treatments. The method used is consistent with Loveday (1976) and Greene and Ford (1985) with the exception that results are presented on a $cmol_c.kg^{-1}$ of Ca^{2+} basis, rather than a unit gypsum basis. As the present results come from a full field experimental site, variation in CEC is accounted for using Equation 5.1 to obtain Ca^{2+} levels for treatments of interest which are relevant to the control (Ca_r^{2+}):

$$Ca_r^{2+} = (ECP_t / 100) \times CEC_c \qquad (5.1)$$

where ECP_t is the exchangeable calcium percentage of the treatment, and CEC_c is the CEC of the control.

Soil aggregates of 3–5 mm diameter, placed in 50 ml of deionised (DI) water, were scored visually for slaking and dispersion after 10 min and 2 h. Slaking was scored dichotomously (occurred/not-occurred), while dispersion was scored from 0 to 4. Aggregates that did not disperse were remoulded and the procedure repeated. Dispersion indices were then calculated for aggregate stability in water (ASWAT) consistent with Field *et al.* (1997). This was replicated four times per sample to reduce error.

From the 53 μm soil sample aliquots, approximately 0.09 g of soil was processed in a VarioMax CNS Analyser. A paired 0.09 g of soil was treated with 6 M hydrochloric acid and left to stand overnight. These were processed for C and N as per the first 0.09 g of soil. The difference between the two measurements was used to determine residual carbonates and thus remove them from the C reading, providing a measurement of organic carbon (OC) content. Two subsamples were processed for each sample to reduce error. Measurements were taken in the 0 to 100 mm layer only, due to contamination of soil cores with lubrication oil required for removing cores from coring sleeves.

5.2.6. Yield measurements

Cotton yield was measured after 6 months by measuring the weight of cotton-modules for each individual treatment. Crop height at five weeks post-emergence was estimated for each treatment by measuring plant height on the two hills adjacent to the centre furrow

(Mount View) or on the centre bed (Wyadra - wheat). Plant height measurements were taken from within 1 m^2 quadrants at 14 GPS referenced locations from the first and last crop within the experimental time period.

5.2.7. Statistical analysis

Data generally met the criteria for normality and equality of variance to a reasonable degree. Where the assumption of normality was not met, data was log-transformed. Outliers were not able to be deleted for exchangeable cation analysis, as each data point represented multiple samples. In the case of one extreme exchangeable Na^+ value for Wyadra, the reading was cross referenced with ASWAT and EC measurements and the decision was made to exclude this data point. Data were evaluated by analysis of variance using MINITAB® *v*.14.11.1 and GenStat® *v*.10.1.0.72 software at $\alpha = 0.05$ and $\alpha = 0.10$; where results are significant at $\alpha = 0.10$ they are explicitly stated. Differences between means were compared using the Tukey honestly significant difference test at $\alpha = 0.05$ and $\alpha = 0.10$, as it is a more conservative method of comparison that reduces Type I error – accepting the alternate hypothesis where the null hypothesis should have been accepted.

For the analysis of aggregate stability in water data the Kruskal-Wallis non-parametric test was used for the determination of difference in treatment means. Because the DI is based on ranking of aggregate stability, rather than a continuous scale, the use of ANOVA is not appropriate.

5.3. Results

5.3.1. Changes in exchangeable cation concentrations

As the soils contained negligible amounts of exchangeable potassium (generally less than 1% of the CEC), and the reagent choline chloride in aqueous ethanol is known to underestimate exchangeable potassium (Tucker 1985), these results are not presented.

The exchangeable cation concentration results reported below refer to Table 5.4 for 6 month data and Table 5.5 for 2.5 year data.

Exchangeable sodium

0–100 mm Mount View and Wyadra. After six months, a decrease in ESP was generally evident where gypsum had been applied, with the exception of the L2.5G2.5-treated soil at Wyadra. Significant differences in ESP were observed between the control soil and high rate combinations of lime and gypsum; L5G5 and L2.5G5 at Mount View, and L5G5 and L5G2.5 at Wyadra. The application of lime alone was shown to maintain ESP in both fields. By 2.5 years any decrease in ESP had completely subsided in both fields for the 0–100 mm depth. While variation was large to the extent that no significant differences were observed after 2.5

years, a general increase in ESP could be seen with a propensity to be even higher in treatments with greater applications of chemical ameliorants.

100–200 mm Mount View. There were no significant differences in ESP detected after 2.5 years, although there was a general trend for ESP to be lower where chemical ameliorants had been applied. This occurred irrespective of ameliorant type.

100–200 mm Wyadra. After 2.5 years, an increase in ESP was evident where gypsum had been applied (excluding the L2.5G2.5 treated soil), although these differences were not significantly different. Lime applied alone was observed to maintain ESP, as was the L2.5G2.5 treatment.

200–400 mm Mount View. A similar trend for ESP as in the 100–200 mm layer was evident after 2.5 years. Although not significant, ESP was observed to decrease where a chemical ameliorant had been applied, irrespective of amendment type.

200–400 mm Wyadra. There was no significant difference in ESP, or obvious trend, after 2.5 years, between the control and the treated soils, or between the treated soils.

Exchangeable calcium

0–100 mm Mount View. A general increase in ECP was apparent after 6 months where gypsum had been applied, although this difference was only significant for the L5G5- and L2.5G5-treated soils; interestingly, the soil treated with L5G2.5 was significant at $\alpha=0.11$, which suggests a likely treatment effect relative to the control. Lime alone was observed to maintain ECP. After 2.5 years, any increase in ECP that had occurred after 6 months was observed to revert to a level comparable with the control.

0–100 mm Wyadra. There was no significant difference in ECP after either 6 months or 2.5 years. While a slight increase in ECP was observed for the soils treated with L5G5 and L5G2.5, and a slight decrease in ECP under the L2.5G0 treatment after 6 months, these differences were not discernible after 2.5 years.

100–200 and 200–400 mm Mount View. After 2.5 years, there were no significant differences in ECP evident, although there was a general trend for an increased ECP where chemical ameliorants had been applied, regardless of ameliorant type. This increase in ECP, while evident in the 200–400 mm layer, was greater in the 100–200 mm layer.

100–200 and 200–400 mm Wyadra. There was no noticeable difference in ECP between the control and treated soils for the 2.5 year data. For both depths, the level of ECP in treated soils was arguably the same as that in the control soil (100–200 mm, *p*=0.97, and 200–400 mm, *p*=0.95).

Table 5.4 Exchangeable cation percentages, cation exchange capacity, pH and electrical conductivity in the 0–100 mm layer of the Mount View and Wyadra soils after 6 months
Values within columns followed by the same letter are not significant. Values followed by an asterisk are significant at the α = 0.1 level, while all other pairs are significant at the p-value indicated.

Treatment	*ECP*	*EMP*	*ESP*	*CEC*	*EC (dS/m)*	*pH*	*ECP*	*EMP*	*ESP*	*CEC*	*EC (dS/m)*	*pH*
			Mount View						*Wyadra*			
Control	50.3a	38.4a	10.8a	22.3	0.35	8.2	48.4	39.6	10.0a	20.8	0.46	8.3
L0G2.5	62.9ac	27.3bc	8.9ac	22.6	0.39	8.4	46.0	42.4	8.8ac	18.5	0.35	8.2
L2.5G0	49.2a	35.2ac	10.4ac	23.3	0.37	8.7	43.9	42.8	10.2a	20.5	0.42	8.4
L2.5G2.5	58.9ac	28.7bc	8.9ac	22.6	0.43	8.5	46.5	40.4	10.5a	18.7	0.44	8.3
L2.5G5	69.9bc	25.6b	7.5bc*	22.5	0.40	8.5	48.0	40.8	8.8ac	20.1	0.32	8.3
L5G2.5	57.3ac	26.9bc	7.8ac	24.4	0.32	8.7	51.5	38.1	7.7bc	19.4	0.41	8.5
L5G5	67.3bc	25.5b	5.5bc	23.8	0.38	8.5	52.5	36.7	7.9bc	18.8	0.49	8.5
p value	0.01	0.01	0.01	0.71	0.82	0.59	0.27	0.42	0.01	0.91	0.47	0.20

* Significantly different at alpha = 0.1

Table 5.5 Exchangeable cation percentages, cation exchange capacity, pH and electrical conductivity in the layers within 0–400 mm of the Mount View and Wyadra soils after 2.5 years
Values within columns followed by the same letter are not significant.

Treatment	*ECP*	*EMP*	*ESP*	*CEC*	*EC (dS/m)*	*pH*	*ECP*	*EMP*	*ESP*	*CEC*	*EC (dS/m)*	*pH*
			Mount View						*Wyadra*			
						0–100 mm						
Control	46.2	42.6	10.5	21.5	0.37	8.7	55.2	35.9	7.8	21.8	0.28	8.8
L0G2.5	47.7	40.4	11.1	22.3	0.37	8.6	56.3	34.6	8.1	21.9	0.28	8.9
L2.5G0	46.1	41.7	11.3	24.1	0.40	8.6	57.6	34.4	6.9	23.1	0.28	8.7
L2.5G2.5	45.8	40.2	13.0	21.3	0.44	8.6	55.8	35.2	7.9	23.7	0.28	8.8
L2.5G5	46.6	40.8	11.8	22.4	0.41	8.4	54.7	34.4	9.1	23.8	0.30	8.6
L5G2.5	48.0	40.2	11.0	21.3	0.40	8.5	52.6	35.4	10.7	24.1	0.28	8.7
L5G5	44.9	40.5	13.7	22.4	0.49	8.4	52.5	37.2	9.3	22.9	0.32	8.8
p value	0.96	0.89	0.33	0.57	0.84	0.41	0.76	0.92	0.32	0.99	0.96	0.71
						100–200 mm						
Control	38.7	41.1	19.8	25.4	0.6a	8.2	51.3	38.3	9.8	24.4	0.40	8.6
L0G2.5	43.8	42.1	13.3	22.9	0.73a	7.8	51.5	35.9	12.0	23.4	0.36	8.8
L2.5G0	42.1	40.8	16.4	24.1	0.73a	8.1	53.3	36.4	9.6	23.3	0.35	8.7
L2.5G2.5	45.5	43.0	10.9	20.6	0.86a	7.1	52.3	37.3	9.8	23.6	0.26	8.8
L2.5G5	45.0	44.8	9.3	23.6	0.78a	7.1	52.0	35.8	11.4	24.7	0.43	8.5
L5G2.5	43.4	43.1	12.8	22.0	0.98ab	7.2	50.7	36.3	12.3	24.3	0.44	8.7
L5G5	41.3	43.6	14.5	21.7	1.04b	7.0	49.4	37.8	12.0	22.8	0.39	8.7
p value	0.53	0.92	0.74	0.20	0.02	0.69	0.95	0.85	0.51	0.99	0.55	0.56
						200–400 mm						
Control	28.6	33.6	37.5	26.9	1.06	8.8	46.4	39.1	14.3	26.3	0.69	8.8
L0G2.5	32.2	36.9	30.6	22.7	1.05	8.4	47.0	36.6	16.1	26.2	0.60	9.0
L2.5G0	30.8	37.1	31.8	25.0	0.76	8.9	47.2	37.1	14.7	26.5	0.65	8.8
L2.5G2.5	33.3	36.8	29.5	20.4	1.06	8.2	45.9	37.8	15.8	25.2	0.55	9.0
L2.5G5	33.8	37.9	27.9	24.8	1.19	7.9	49.5	35.0	15.0	25.7	0.74	8.9
L5G2.5	31.0	36.3	32.3	22.3	1.11	8.0	48.0	35.7	16.0	26.2	0.66	8.9
L5G5	30.5	35.7	33.2	23.6	1.25	8.1	47.2	37.7	14.8	23.7	0.68	9.0
p value	0.81	0.47	0.59	0.19	0.15	0.63	0.97	0.62	0.96	0.40	0.83	0.28

Exchangeable magnesium

0–100 mm Mount View. After 6 months, the application of gypsum, in combination or alone, significantly reduced EMP. Lime alone was observed to cause a slight decrease in EMP, although not significant. The L2.5G5 and L5G5 treatments also significantly decreased EMP as compared to the application of lime alone. After 2.5 years, this decrease in EMP had subsided in all treated soils. However, there was a propensity for EMP to be slightly lower where gypsum had been applied, albeit not a significant difference.

0–100 mm Wyadra. Significant differences in EMP between the control and treated soils were not apparent after 6 months or 2.5 years. After 6 months, it appears that a slight decrease in EMP has occurred in the soils under L5G2.5 and L5G5 treatments, and a slight increase is apparent where L2.5G0 and L0G2.5 treatments have been applied. However, these results are not statistically significant.

100–200 and 200–400 mm Mount View. After 2.5 years, the EMP levels in treated soils, for both layers, were generally higher than the control, although not significantly. The exception to this was the soils treated with L2.5G0 and L0G2.5, which were shown to have no appreciable increase of EMP in the 100–200 mm layer.

100–200 and 200–400 mm Wyadra. As with exchangeable calcium, there were no significant differences or obvious trends between the control and treated soils pertaining to EMP after 2.5 years. Again, the levels of EMP under treatments were arguably the same as that in the control soil (100–200 mm, p=0.92, and 200–400 mm, p=0.85).

5.3.2. Ameliorant effect on pH and EC

Changes in pH after 6 months and 2.5 years were not shown to be significant for any treatment (Table 5.4 and Table 5.5, respectively). This was apparent for both Mount View and Wyadra. Interestingly, in treatments where gypsum alone or lime in conjunction with gypsum had been applied, there was a notable decrease in the pH within the 100–200 and 200–400 mm layers for the Mount View soil (Table 5.5), although this was not statistically significant (p=0.69, p=0.63, respectively).

The changes in EC for 0–100 mm were shown not to be significant after either 6 months or 2.5 years for both properties (Table 5.4 and Table 5.5, respectively). Consecutive layers for the Wyadra soil also had no significant differences in EC. However, the 100–200 mm layer for the Mount View soil exhibited a significantly higher EC under the L5G5 treatment than under the control. There was an apparent trend for a higher EC in this layer where the pH was observed to be between 7.0 and 7.2. In the 200–400 mm layer of this soil, EC tended to be higher where gypsum had been applied; while this was not significant, the *p*-value suggests a treatment effect was likely to have occurred (p=0.15).

5.3.3. Residual gypsum

Analysis for residual gypsum after 6 months in the 0–100 mm zone shows that no gypsum remained *in situ* for either soil (Table 5.6). As expected, this did not change after 2.5 years for the surface layer. No residual gypsum was observed in the 100–200 mm layer in the Mount View and Wyadra soils, while the same result was obtained for the 200–400 mm layer for Wyadra (the Mount View 200–400 mm layer was not analysed due to the presence of naturally occurring sulphates).

Table 5.6 Residual gypsum levels and corresponding electrical conductivity on the basis of gypsum application rate, irrespective of lime, for the Mount View and Wyadra soils after 6 months and 2.5 years

Numbers in parentheses are EC values (dS.m^{-1}) of a 1:5 w v^{-1} soil water extract. The values for treatments with the same gypsum application rates have been averaged as they did not differ significantly.

Gypsum rate (t/ha)	*Residual gypsum (cmol/kg)*							
	Mount View				*Wyadra**			
	6 months		*2.5 years*		*6 months*		*2.5 years*	
				0–100 mm				
G0	0.0	(0.35)	0.0	(0.37)	0.0	(0.46)	0.0	(0.28)
G2.5	0.0	(0.38)	0.0	(0.40)	0.0	(0.40)	0.0	(0.28)
G5	0.0	(0.39)	0.0	(0.45)	0.0	(0.41)	0.0	(0.31)
				100–200 mm				
G0	–		0.0	(0.60)	–		0.0	(0.40)
G2.5	–		0.0	(0.85)	–		0.0	(0.35)
G5	–		0.0	(0.91)	–		0.0	(0.41)

*sulphate was also nil for all gypsum rates in the 200–400 mm layer

5.3.4. Calcium exchange efficiencies

Changes in exchangeable cations after 6 months for the Mount View and Wyadra soils expressed as a percentage of the Ca^{2+} applied are presented in Table 5.7. For Mount View, Ca^{2+} exchange efficiency was shown to be 35% considering total Ca^{2+} applied, while the exchange efficiency was 105% when considering changes as a function of gypsum only. The differences, as a percentage, relevant to the control soil for Mg^{2+} and Na^+ show that the L5G5 treatment had a greater effect on Na^+ than Mg^{2+}. However, this relationship reverses when considering the results on a unit Ca^{2+} basis (applied in total or as gypsum). The results as a function of Ca^{2+} applied as gypsum are considerably higher.

Changes in exchangeable cations due to Ca^{2+} for Wyadra are altogether different. Where considerable differences were observed as an expression of gypsum applied Ca^{2+} in the Mount View soil, the results for the Wyadra soil were approximately 4 times less for Ca^{2+} and Mg^{2+}, and half as much for Na^+. When considering these same results as a function of total applied Ca^{2+}, the exchange efficiency is shown to be low for all cations. For Wyadra, the greatest change relative to the control (L0G0) was observed in Na^+.

Table 5.7 Changes in exchangeable cations (cmol.kg^{-1}) after 6 months following the incorporation of 5 t.ha^{-1} of lime and 5 t.ha^{-1} of gypsum in the 0–100 mm zone of Mount View and Wyadra soils
Values in parentheses within the 'Change relative to L0G0' column are the difference in exchangeable cations expressed as percentage increase or decrease.

Cation	*Application rate:*		*Change relative to L0G0*	*Change as % of Ca applied^A:*	
	L0G0	*L5G5*		*Total (10.72 cmol/kg)*	*Gypsum (3.58 cmol/kg)*
			Mount View		
Ca	11.21	14.99	+3.78 (+34%)	35	105
Mg	8.5	5.7	-2.8 (-33%)	26	78
Na	2.4	1.2	-1.2 (-50%)	11	33
			Wyadra		
Ca	10.09	10.95	+0.86 (+9%)	8	24
Mg	8.3	7.7	-0.6 (-7%)	6	17
Na	2.1	1.6	-0.5 (-24%)	5	14

A (i) Ca in gypsum per hectare = 0.715 cmol/kg, while lime = 1.43 cmol/kg (when incorporated to 100 mm); (ii) all gypsum was shown as dissolved (Table 1.9), while lime dissolution was unable to be quantified; (iii) a bulk density of 1.4 was used in the calculations of efficiency .

5.3.5. Changes in soluble calcium, sodium and total cation concentration

There were no significant ($\alpha<0.05$, 0.1 or 0.15) changes in soluble cation concentrations due to treatment application after 6 months or 2.5 years in the Mount View and Wyadra soils. However, the Mount View soil exhibited some notable trends. After 6 months, there was a tendency for the soluble Ca^{2+} to be in greater concentration where gypsum had been applied and greater again where higher rates of gypsum had been applied. Soluble Na^+ and the TCC followed a similar trend. After 2.5 years, the TCC and soluble Na^+ were increased in all analysed depths with the application of lime in conjunction with gypsum at the rates L2.5G5 and L5G5. Soluble Ca^{2+} was generally higher where gypsum-alone and lime/gypsum were applied in conjunction in the 0–100 mm and 200–400 mm depths.

Table 5.8 Soluble calcium, sodium and total cation concentrations in the 0–100 mm layer of the Mount View and Wyadra soils after 6 months

Treatment	*Ca*	*Na*	*TCC*	*Ca*	*Na*	*TCC*
		(mmol$_c$.L^{-1})			*(mmol$_c$.L^{-1})*	
		Mount View			*Wyadra*	
Control	1.4	11.7	16.5	1.5	9.1	12.7
L0G2.5	1.9	16.0	19.9	2.1	11.3	15.4
L2.5G0	1.4	15.3	18.6	1.9	11.3	15.4
L2.5G2.5	1.8	17.8	21.7	1.6	12.3	15.8
L2.5G5	2.4	14.5	19.4	1.7	14.0	17.7
L5G2.5	1.9	13.9	17.8	1.6	9.5	13.3
L5G5	2.4	13.9	18.2	1.7	8.1	13.8
p value	0.16	0.22	0.28	0.56	0.42	0.48

The treated soils at Wyadra appear to have slightly higher soluble Ca^{2+} after 6 months, although this is not significantly different (p=0.56). After 2.5 years, there is no noticeable difference in soluble Ca^{2+} levels between the control and treated soils in any layer (0–400 mm). However, there is an increase in soluble Ca^{2+}, for all treated soils and the control soil in the 0–100 mm layer, from the 6 month measurements to the 2.5 years measurements. Changes in soluble Na^+ and the TCC between the control and treated soils for any layer, at both 6 months and 2.5 years, were not significant and did not appear to have any notable trends.

Table 5.9 Soluble calcium, sodium and total cation concentrations in the layers within 0–400 mm of the Mount View and Wyadra soils after 2.5 years

Treatment	*Ca*	*Na* ($mmol_c.L^{-1}$)	*TCC*	*Ca*	*Na* ($mmol_c.L^{-1}$)	*TCC*
		Mount View			*Wyadra*	
			0–100 mm			
Control	1.7	16.8	20.3	3.3	9.6	16.1
L0G2.5	2.0	19.3	23.7	3.3	10.5	16.9
L2.5G0	2.0	16.8	21.6	3.3	11.2	17.4
L2.5G2.5	2.4	16.5	22.2	2.6	10.6	15.9
L2.5G5	2.6	35.7	44.3	3.0	12.5	18.2
L5G2.5	2.2	15.9	21.1	3.1	11.1	18.5
L5G5	2.0	37.5	42.3	3.0	11.6	17.9
p value	0.32	0.16	0.16	0.79	0.76	0.87
			100–200 mm			
Control	1.4	43.4	47.0	3.4	15.4	21.5
L0G2.5	0.8	51.6	53.7	3.5	15.2	22.2
L2.5G0	1.6	40.5	44.2	2.9	14.2	20.1
L2.5G2.5	1.6	51.3	55.3	3.1	10.4	16.7
L2.5G5	0.7	53.4	55.1	3.2	16.7	24.1
L5G2.5	1.2	45.4	48.6	3.3	17.7	25.6
L5G5	1.8	56.0	60.8	2.9	19.8	26.5
p value	0.43	0.22	0.23	0.92	0.67	0.61
			200–400 mm			
Control	0.6	50.3	51.7	1.5	33.2	35.8
L0G2.5	1.9	45.4	50.2	1.9	28.7	33.0
L2.5G0	0.8	51.8	53.9	1.4	26.4	30.5
L2.5G2.5	1.5	49.6	53.6	1.7	23.8	28.7
L2.5G5	2.4	64.0	69.5	1.0	31.5	33.7
L5G2.5	1.8	42.4	46.8	1.1	33.1	35.2
L5G5	1.9	67.5	70.7	1.7	28.7	32.7
p value	0.18	0.17	0.19	0.89	0.78	0.83

5.3.6. Aggregate stability in water after 6 months and 2.5 years

Mount View. The aggregate stability results after 6 months show significantly lower DI ($p<0.01$) relative to the control in all treatments where gypsum was incorporated (Figure 5.1). The control soil DI is on the cusp of being a spontaneously dispersive soil, while gypsum application has lowered the DI to an extent where aggregates disperse only after mechanical disturbance. Where lime was applied alone, the aggregate stability was observed to be similar to that of the control soil. Additionally, all treatments containing gypsum had significantly greater aggregate stability than the soil under the L2.5G0 treatment ($p=0.04$). There were no significant differences in aggregate stability between treated soils where gypsum was applied. After 2.5 years, a trend was observed for the 0–100 and 100–200 mm layers where all treatments lowered DI and increased aggregate stability. However, this was only significant under the L5G2.5 treatment in both layers. There were no obvious trends or significant differences for aggregate stability in the 200–400 mm layer between the control and treated soils, but there was a sharp increase in DI for all soils in this layer.

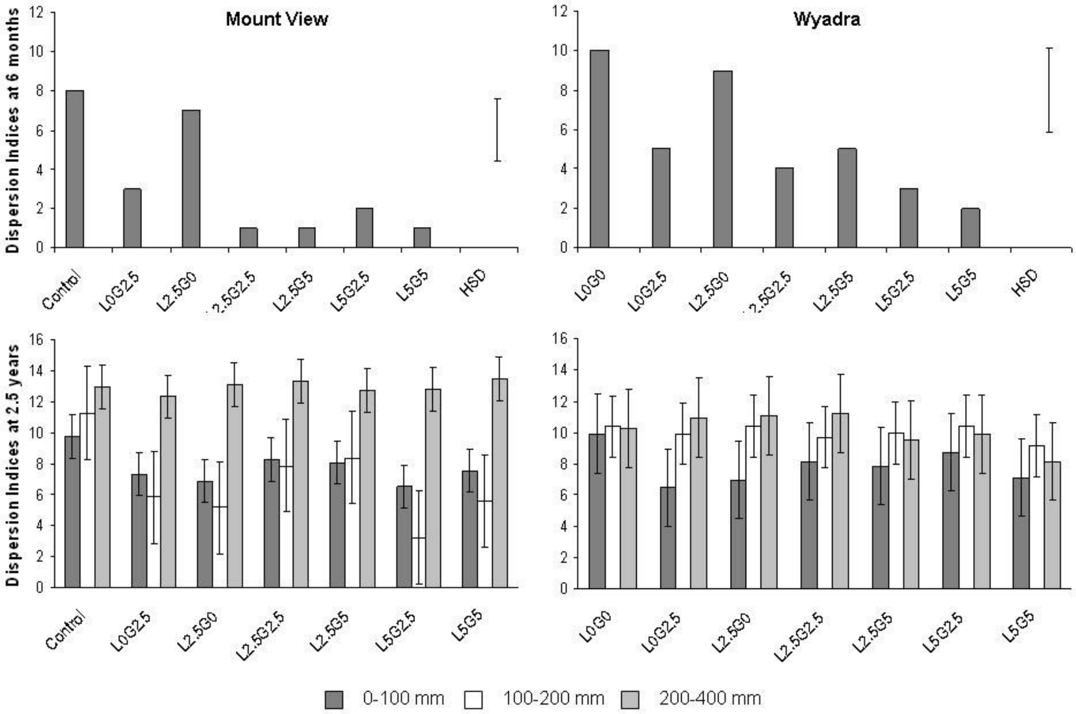


Figure 5.1. Aggregate stability in water dispersive indices after 6 months and 2 years from ameliorant application for the Mount View and Wyadra soils. For the 6 month dispersive indices, h.s.d intervals are presented at α = 0.05 significance level. For the 2.5 year dispersive indices, the h.s.d intervals are presented for each layer (α = 0.05); these represent differences between treatments/control within layers, not between layers.

Wyadra. As with the Mount View soil, wherever gypsum was applied a significant improvement in aggregate stability was observed for the 0–100 mm layer after 6 months. The control soil is observed to be a spontaneously dispersive soil, while gypsum application has lowered the DI to an extent where aggregates disperse only after mechanical disturbance. Lime alone had a DI similar to the control and was significantly different to the L2.5G2.5-, L5G2.5- and L5G5-treated soils (p=0.01), while soils treated with L0G2.5 and L2.5G5 were significantly different to that treated with L2.5G0 at p<0.10. After 2.5 years, and at the same depth, a trend was evident where treatment application resulted in lower DI, although this was not significant. For the 100–200 mm and 200–400 mm layers, no significant differences or notable trends were apparent.

5.3.7. Changes in surface total nitrogen and organic carbon after 2.5 years

After 2.5 years, the addition of lime, gypsum and lime/gypsum combinations did not result in any significant changes from control levels of total N (p=0.58 and 0.73 for Mount View and Wyadra, respectively) and OC percentages (p=0.94 and 0.92 for Mount View and Wyadra, respectively), as depicted in Figure 5.2.

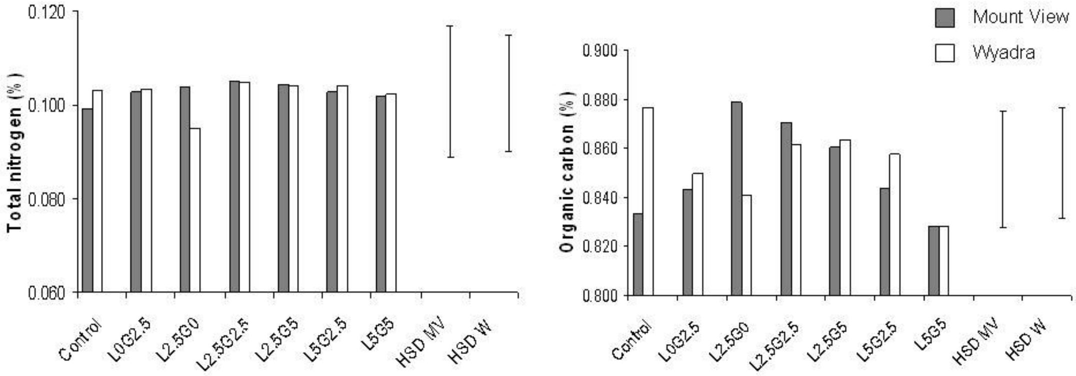


Figure 5.2. Total nitrogen and organic carbon percentages for the Mount View and Wyadra soils after 2.5 years from ameliorant incorporation (0–100 mm). Intervals show h.s.d for Mount View data (HSD MV) and Wyadra data (HSD W) in their respective data series.

5.3.8. Treatment effects on crop yield and seedling height

After approximately 6 months, cotton yield was shown not to have responded to treatment application in either the Mount View (p=0.99) or Wyadra soil (p=0.53) (Figure 5.3), even though significant positive changes in exchangeable cation concentrations and aggregate stability had been observed in the same period. Similarly, significant differences in, and trends for, seedling height 5 weeks post-emergence were not found for either soil, in 2007 (p=0.99 and 0.70 for Mount View and Wyadra, respectively) or 2009 (p=0.69 and 0.58 for Mount View and Wyadra, respectively) (Figure 5.4).

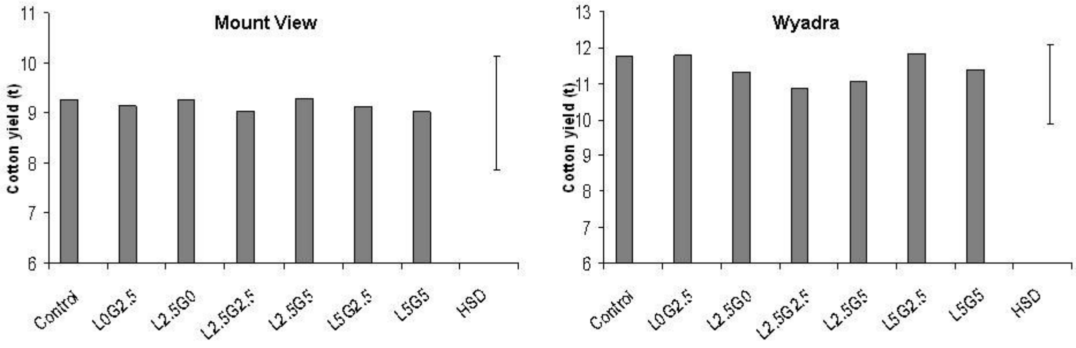


Figure 5.3 Cotton yield, by treatment, of the first crop planted post ameliorant application for Mount View and Wyadra. Tukey h.s.d intervals are presented at α = 0.05 significance level.

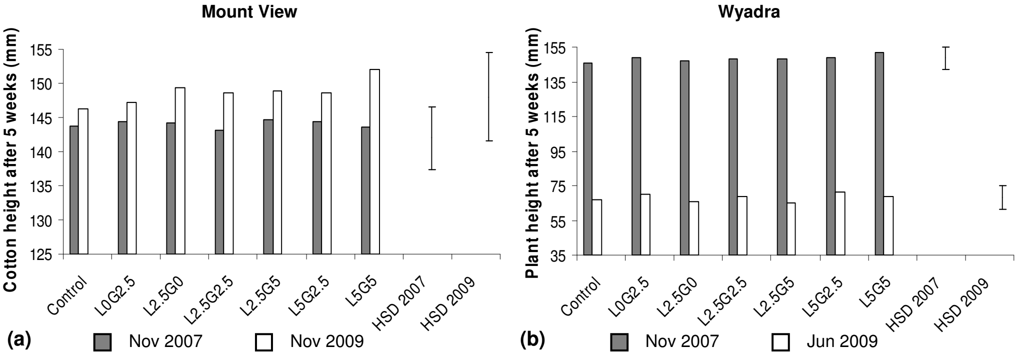


Figure 5.4 (a) Cotton seedling height at 5 weeks post emergence for Mount View in 2007 and 2009; (b) Cotton seedling height (2007) and wheat seedling height (2009) at 5 weeks post-emergence for Wyadra. For both (a) and (b), the intervals show the h.s.d for the respective year with differences between treatments/controls occurring within years, not between years.

5.4. Discussion

5.4.1. The short-term effects of lime and gypsum on the soil properties measured

Both soils used for this experiment were characterised by low to moderate levels of sodicity and insufficient electrolyte concentration to maintain the soil in a stable condition. The general effect of gypsum addition was to improve surface soil stability in the short-term, while lime addition was more likely to maintain soil in its current state, or to only improve soil stability marginally. The primary factors controlling stability are the concentration and nature of exchangeable cations and the presence of electrolyte in the soil solution (Quirk and Schofield 1955; Emerson and Bakker 1973; Sumner 1993). Gypsum is known to increase the electrolyte in soil solution (Davidson and Quirk 1961; Loveday 1976; McKenzie 1982) with the effect observed to remain significant up to five years after incorporation into the soil, depending on the initial rate of application (Greene and Ford 1985; Valzano *et al.* 2001b). After one year, Valzano *et al.* (2001b) detected a change in EC, as a response to the application of 5 t.ha^{-1} of gypsum, that was approximately 15.5 times higher than levels observed in the control of a Brown Sodosol.

The results of the current study gave no indication of an electrolyte effect after 6 months in gypsum and lime/gypsum-combination treatments, even where gypsum was applied at 5 t.ha^{-1}. This can be attributed to the magnitude of irrigation water (approximately 11 ML.ha^{-1}, or 1100 mm) and rainfall (approximately 185 mm) percolating through the soil that would subsequently dilute the soil solution and leach electrolyte further into the soil profile (Loveday 1976; Keren and Shainberg 1981). Indeed, after three years in the study of Valzano *et al.*, 650 mm of rainfall was recorded to have permeated the Brown Sodosol and subsequent EC measurement showed that the treatment effect on EC was no longer apparent. Two further factors affecting the dissolution of gypsum, and subsequently the longevity of the electrolyte effect, are soil water velocity and the contact time between gypsum and soil water (Keren and O'Connor 1982; Gupta and Singh 1988). The provision of soil water by flood irrigation would likely cause greater soil water velocity than the majority of rainfall events, resulting in a higher dissolution coefficient, but less contact time with gypsum (Keren and O'Connor 1982). Keren and O’Connor (1982) documented the net result of increased soil water velocity as decreased Ca^{2+} leaching, but this was based on the entire volume of water passing through the soil profile at a constant velocity. Therefore, while the contact time between gypsum and the soil water is most likely reduced during an irrigation event, contact time is increased between irrigation events. The drying cycle would have provided adequate time to allow gypsum dissolution and increased electrolyte in solution, which would subsequently be flushed upon the next irrigation event (Loveday 1976). Thus, it should be stressed to land managers that the longevity of electrolyte effect is more closely related to the magnitude and frequency of percolating solution rather than time alone.

After 6 months, ESP was observed to be significantly lower under the L5G5 treatment in both soils, as well as under the L2.5G5 treatment at Mount View and the L5G2.5 treatment at Wyadra. All other gypsum-treated soils were observed to have a slightly lower ESP than the control (with exception to L2.5G2.5-treated soil at Wyadra). For the Mount View soil, a reduction in ESP was accompanied by a decrease in EMP and an increase in ECP, which could be expected (Chartres *et al.* 1985; Ford *et al.* 1985; Greene and Ford 1985; Valzano *et al.* 2001a; Valzano *et al.* 2001b). However, while a slight decrease for EMP and a slight increase for ECP were observed for the associated significant decreases in ESP at Wyadra (under the L5G2.5 and L5G5 treatments), this was not so for the other gypsum-treated soils. Where the L0G2.5 and L2.5G5 treatments had been applied, a slight increase in EMP was apparently responsible for the decrease in ESP. According to previous studies concerning the effects of Mg^{2+} on the dispersive potential, an increase in Mg to the extent that the Ca/Mg ratio is similar to, or below, 1 should increase the incidence of clay dispersion (Emerson and Bakker 1973; Emerson and Chi 1977; Rengasamy *et al.* 1986). However, the aggregate stability results for the Wyadra soil, after 6 months, do not support this, and instead indicate that the application of L2.5G5 and L0G2.5 treatments significantly improved soil structural stability. We suggest that the chemical data does not completely support the physical data in the Wyadra soil for two reasons: 1) the within-field variability was large to the extent that Ca^{2+} and Mg^{2+} exchange was ‘masked’; and 2) the wetting and drying cycle of irrigation has allowed an enhanced dissolution of the gypsum and decreased the soil-soil solution contact time, meaning that diffusion of Ca^{2+} onto the clay exchange sites is likely to have occurred mainly on the exterior of aggregates (i.e. it is harder for soil solution to penetrate to the centre of aggregates). Consequently, crushing and sieving whole aggregates to a <2 mm threshold effectively dilutes the Ca^{2+} on the surface of the aggregate with cations from within the aggregate.

5.4.2. The viability of lime and gypsum as chemical ameliorants for sodicity in the two soils

The 6 month exchangeable cation results suggest that the changes in ESP, EMP and ECP are driven by gypsum, which is confirmed by the aggregate stability results (at 6 months) for both properties. However, these significant improvements did not extend into the long-term, being shown to revert to the initial condition, or worse, within 2.5 years. This further suggests that the driving source for cation exchange in the Mount View and Wyadra soil is gypsum, as all gypsum was shown to have dissolved within the initial 6 month period. In order to assess the viability of amendment application, the Na^+ exchange efficiency as a percentage of the Ca^{2+} applied (Table 5.7) was calculated for the L5G5-treated soil (Keren and O'Connor 1982; Greene and Ford 1985). The Wyadra L5G5-treated soil shows a Ca^{2+} increase of 9% for a Na^+ exchange of -24% as compared to the control soil, which equates to an 5% efficiency rate of Na^+ exchange for the total amount of Ca^{2+} applied (i.e. lime and gypsum) and a 14% efficiency rate based on the Ca^{2+} applied as gypsum. This equates to AUD\$5 effective for every AUD\$100 of applied Ca^{2+} ha^{-1} (in total) and AUD\$14 effective for every AUD\$100 of applied Ca^{2+} ha^{-1} (as gypsum). The long-term data suggests that lime has had little effect on Ca^{2+} exchange, thus the efficiency based purely on gypsum-supplied Ca^{2+} is likely to be indicative of the efficiency of gypsum in the Wyadra soil. This efficiency rate is lower than those reported for rain-fed regimes: 20–40% on a heavy clay soil treated with 10 $t.ha^{-1}.yr^{-1}$ for 4 years (Mann *et al.* 1982), 26–36% on two red-brown earths (Sodosols) treated with 15 $t.ha^{-1}$ after 5 years (Greene and Ford 1985) and 20–40% for a Brown Sodosol treated with 5 $t.ha^{-1}$ after three years (Valzano *et al.* 2001b).

The enhanced solubility, decreased exchange efficiency and decreased duration of exchange effect, as compared to previous studies (Mann *et al.* 1982; Greene and Ford 1985; Valzano *et al.* 2001b) restates an important point: the longevity of effects with regard to gypsum should be linked to the magnitude and frequency of wetting, rather than simply the duration of the effect. Interestingly though, the observed exchange efficiency rate was also lower than that for an irrigated transitional red-brown earth (Sodosol) examined by Loveday (1976). During his experiment, 12.4 $t.ha^{-1}$ of gypsum was applied to the soil and irrigated for three seasons (approximately 1.5 years) with 5–7 $ML.ha^{-1}$ per season (15–21 $ML.ha^{-1}$ in total). The observed exchange efficiency was 20–33% and 50–60% of the applied gypsum was estimated to remain in the soil in solid form. We suggest three likely reasons for this:

1) the hydraulic conductivity of a Dermosol is likely to be greater than that of a Sodosol, meaning that greater soil-soil solution contact time would exist in the Sodosol. This would promote greater diffusion of Ca^{2+} onto clay faces in exchange for Na^+;

2) the time at which the efficiency was calculated for the Wyadra soil was beyond the lifetime of the gypsum (Table 5.6), and subsequently Na^+ had been replaced with irrigation water application; and,

3) soil water velocity was shown to have less of an effect on the concentration of Ca^{2+} in the soil solution at higher rates, like in Loveday's (1976) experiment, than at rates similar to 6 $t.ha^{-1}$ (Keren and O'Connor 1982), viz. as soil structure stability increases, resulting from low rate application of gypsum, a sharp decrease of Ca^{2+} in solution occurs as there is not enough gypsum in the soil dissolving to maintain this concentration.

The results for the Mount View soil were altogether different. On the same basis for calculating exchange efficiency of Ca^{2+} for Na^+, the exchange efficiency was 11% and 33% for total Ca^{2+} and Ca^{2+} applied as gypsum, respectively. However, while the efficiency rate as calculated from gypsum is comparable to previous efficiency observations (Loveday 1976; Mann *et al.* 1982; Greene and Ford 1985; Valzano *et al.* 2001b), this equates to 105% effective exchange of Ca^{2+}. This may suggest that gypsum has had a synergistic effect with lime causing an enhanced Ca^{2+} concentration in the soil solution, although it is unlikely. Considering that the results pertain to a flood irrigated field and that more soil samples were collected closer to the tail-drain than the head-ditch, it is more likely that Ca^{2+} in solution has been flushed in the direction of the irrigation water flow (Figure 5.5). The presence of a low permeability layer at 400–600 mm depth would also have caused the Mount View soil to have maintained saturation for a period longer than that of the Wyadra soil (no obvious limiting layer) resulting in greater soil-soil solution contact time for gypsum dissolution.

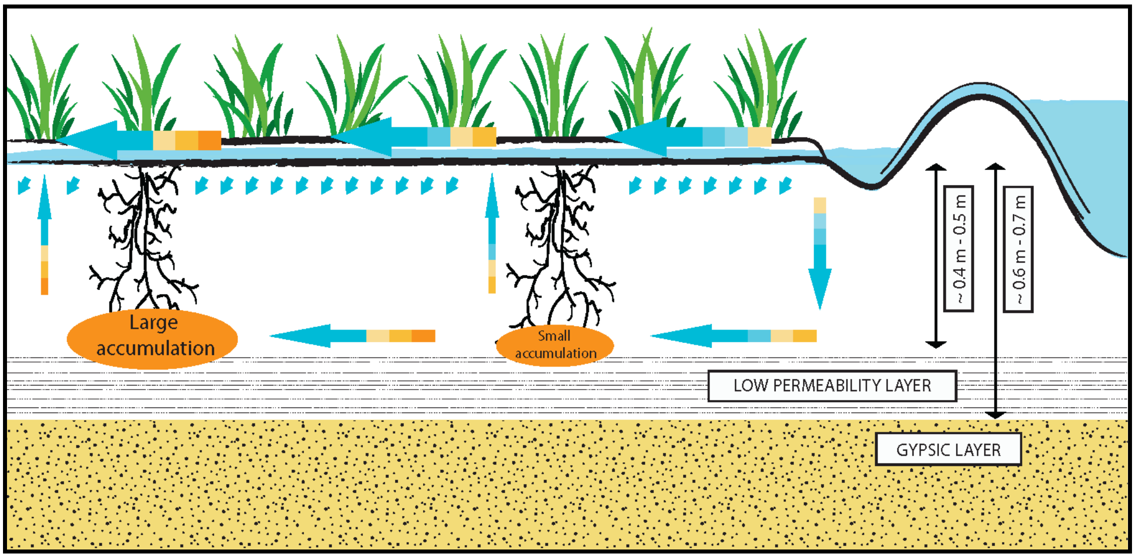


Figure 5.5. Conceptual diagram for the movement of irrigation water, solution ionic concentration, and the consequent accumulation of salts; arrows represent the movement of water; the orange colour gradient represents ionic concentration increase; the blue colour gradient of the arrows indicates ion movement with irrigation/soil water at varying concentration.

Even still, for gypsum to have been 100% effective in the 0–100 mm layer, there must have been no effect on lower layers, which is highly unlikely (Loveday 1976; Greene and Ford 1985). Using Figure 5.5, we propose the following set of parameters to account for the Ca:Na changes 2.5 years after amendment application:

1) gypsum begins to dissolve after the first irrigation and Ca^{2+} becomes more concentrated in the soil solution during the first drying cycle;

2) subsequent irrigation flushes a proportion of this soluble Ca^{2+}, and other cations/anions in solution, laterally (down the furrow) and vertically (into the profile). Assuming an initial electrolyte effect, gypsum would provide a initial increase in hydraulic conductivity (Quirk and Schofield 1955; Loveday 1974; Keren and Shainberg 1981; Keren and O'Connor 1982), which would facilitate greater vertical movement of soil solution;

3) transported cations and anions encounter the low permeability layer and begin to accumulate, as per the process of transient salinity (Rengasamy 2002);

4) evapotranspiration, plant uptake and capillary rise cause the concentration of ions directly above the impermeable layer, as well closer to the surface. Subsequent irrigation again flushes ion concentrations down the furrows resulting in greater accumulation towards the tail-drain end of the field;

5) concentration of Ca^{2+} in the flushed solution is initially sufficient to create the exaggerated efficiency effect within 6 months. However, as the applied gypsum becomes depleted, subsequent irrigation continues to flushes excess Na^{+} laterally and the net result is a soil solution higher in Ca^{2+} than before, but to a level insufficient to cope with the volume of accumulated Na^{+}.

These processes are supported by the soil solution chemistry after 2.5 years in the Mount View soil. Soluble Ca^{2+} is generally higher in all layers (0–400 mm), where gypsum has been applied, than the control soil. Furthermore, it was observed that gypsum application resulted in soluble Na^{+} accumulating in all layers to a much greater extent than in the control soil. This soluble Na^{+} accumulation was more prominent in the surface and for soil subjected to higher gypsum application, which explains the rise in ESP where the L5G5 treatment had been applied as opposed to that in the control soil.

The results obtained from these soils reiterate the concerns of previous studies that the degree to which changes occur due to amendment application are highly site specific (Valzano *et al.* 2001b; Bennett 2006). However, at both Mount View and Wyadra, the use of lime appears to have a limited effect on both the exchange complex and the electrolyte levels of the two soils. Even if a soil structural improvement effect has occurred, the changes in Na^+ and Ca^{2+} are not substantial enough to warrant the continued use of lime. Similarly, the use of gypsum may not be considered viable on either property; at Mount View Na^+ accumulated in the root zone, while at Wyadra the exchange efficiency of Ca^{2+} was low.

5.4.3. Potential synergies between lime, gypsum and plants

This experiment sought to explore two possible synergies: 1) that between lime and gypsum, as observed in Valzano *et al.* (2001b); and 2) that between plant-soil interactions and lime, as proposed by various authors (Naidu and Rengasamy 1993; Valzano *et al.* 2001b; Qadir *et al.* 2003; Mubarak and Nortcliff 2010) and investigated by Bennett (2006) for an extraneous source of lime. Because the treatment L0G5 was not included in the experiment, it is not entirely possible to separate gypsum effects from the prospect that lime has had effect in synergy with gypsum and/or plants. However, from an economic viability point of view, even if synergy between lime and gypsum has occurred the dollar cost (inputs from Table 5.2) appears to outweigh the observed benefit (increases in soil stability and the associated productivity). There were no apparent increases in crop performance throughout the duration of the experiment as a result of treatment application, and the observed soil structural improvement was shown to retreat within 2.5 years. Hence, the following discussion explores the possibility of both synergies ignoring the fact that the applied treatment combinations do not appear to be viable in the current farming systems.

Within the first 6 months the Wyadra soil was shown to respond better to the L5G2.5 and L5G5 treatments in terms of exchange of Ca^{2+} and Na^+, although these treatments were not statistically better than other treatment combinations. The effect of the gypsum-based treatments was equivalent to a 1% decrease in exchangeable sodium concentration. By 2.5 years, the soil treated with lime alone (2.5 $t.ha^{-1}$) is 1% lower in ESP than the control soil, whereas at 6 months it was almost identical in ESP. This might suggest that plant root and microbial stimulation have caused a localised lowering of pH and augmented the dissolution of the lime (Naidu and Rengasamy 1993), although it is more likely a product of variability. Interestingly, where lime/gypsum combinations have been applied, an increase in soil ESP was observed after 2.5 years as compared to the control soil. The increased structural stability observed after 6 months would have increased soil solution movement (Loveday 1976; Valzano *et al.* 2001b) and, in the absence of a limiting impermeable layer, caused Ca^{2+} to have been leached more quickly out of the upper soil layers. However, this change in ESP for soils with combined amendment application was comparable to soil ESP where gypsum was applied alone, suggesting it to be an artefact of gypsum application. This does highlight two points, though: 1) as the soil structural stability improves it becomes harder to maintain Ca^{2+}

levels using irrigation water that adds Na^+ (SAR 6.07); and 2) that any increase in solubility of lime, as a result of gypsum and/or plant-soil interactions, is quite likely masked by the addition of Na^+.

The Mount View soil is more likely to have undergone some sort of synergy pertaining to gypsum, due to the increased soil-soil solution contact time caused by the presence of a permeability limiting soil layer (400–600 mm depth). Interestingly though, after 2.5 years, anywhere gypsum has been applied, a lowering of pH was observed. This trend is evident throughout the 0–400 mm layers, but is most prominent in the 100–200 mm and 200–400 mm layers, and where gypsum was applied to the soil in combination with lime (an approximate drop in pH of 1 unit). There is no clear reason as to why this drop in pH has been observed. However, we believe the change in pH can be explained by two main mechanisms. Firstly, the initial application of gypsum has provided structural improvement that is likely to promote increased root growth/action, and subsequently the CO_2 output of plants increases. This causes an increase in ρ_{CO_2} (partial pressure of CO_2) and enhances the concentration of H^+ in the rhizosphere through the chemical reaction in Equation 5.2 (Robbins 1986a; Robbins 1986b):

$$CO_2 + H_2O \rightleftharpoons H_2CO_3 \rightleftharpoons H^+ + HCO_3^- \qquad (5.2)$$

Secondly, it is proposed that precipitation of Ca^{2+} in the topsoil and leaching of Ca^{2+} from the topsoil has caused sodium carbonate and sodium bicarbonate to control the pH system in this layer (0–100 mm). However, in the subsequent depths, Ca^{2+} is controlling the solution. Thus, as the pH was measured in water, a lower pH is recorded similar to that which might be expected from measurement in dilute $CaCl_2$ (0.01 M)(Russell 1961).

Accumulation of H^+ due to exchange by Ca^{2+} from gypsum is considered unlikely, due to the initial pH of the soil (pH 8.0–9.0) (Russell 1961; Valzano *et al.* 2001b). It might also be suggested that the breakdown of increased organic matter content in the structurally improved soil could lower pH, although our results suggest this to be highly unlikely due to there being no appreciable differences observed in organic carbon content after 2.5 years. The application of acidifying nitrogen fertilisers (NH_3 was as applied at Mount View, Table 5.3) may have also affected the pH, but these were applied across all treatment plots.

Accompanying the lowered pH in the Mount View soil was a concomitant increase in electrolyte, that was greatest in L5G5 treated soil (significant, p=0.02). While it is possible that the lowered pH has caused the dissolution of lime to have increased, thus bolstering the soil EC (Shainberg and Gal 1982; Valzano *et al.* 2001b), and there is an evident trend for the

ESP to be lower and the ECP to be higher where EC is observed to have increased, an increase in soluble Na^+ most likely explains the increase in EC. The soluble cation results also show that Ca^{2+} concentration is higher for the lime/gypsum combined soils, although comparable to both the gypsum alone treatment and higher than the lime alone treatment. However, this increase is outweighed by the presence of soluble Na^+, which accounts for the majority increase in the TCC, as compared to the control. Direct measurement of residual lime would aid in resolving the feasibility of these lime-based dissolution processes. However, residual lime was unable to be determined in either soil (Mount View or Wyadra).

While there is limited evidence for synergy occurring between lime and gypsum, and chemical ameliorants and soil-plant based interactions, this does not mean the processes have not taken place to a significant degree. Reasons for not observing significant structural improvement due to lime dissolution might also be due to a dilution effect where the main effects of lime occur in the rhizosphere, but sampling was indiscriminant regarding this zone. This would benefit from further investigation.

5.4.4. Aggregate stability and the longevity of observed cation exchange

While the chemical exchange and electrolyte effects of lime and gypsum application were generally observed to have occurred within 6 months and then reverted to control conditions or worse after 2.5 years, there was a propensity for aggregate stability to be greater where gypsum had been applied, than compared to the control soil, after 2.5 years. These differences in aggregate stability are unlikely to have been influenced by increases in OC content due to treatment application, as the results suggest that no appreciable effect on OC content was attributable to the applied treatments. It might be suggested that this effect is an artefact of the low permeability layer in the Mount View soil providing greater stability through an increased EC in the lower layers, although the trend for aggregate stability effects to outlive chemical exchange and electrolyte effects was also observed in the Wyadra soil; the soluble cation concentrations for this soil also showed that Ca^{2+} from gypsum dissolution has leached below the layers of interest in this study. In the same way that Greene and Ford (1985) explain the under-estimation of gypsum requirement due to the exchange of Ca^{2+} for Na^+ and Mg^{2+} being more complete on the outer surface of intact aggregates (i.e. it is harder for the soil solution to penetrate and instigate equilibrium change on the inside of aggregates), we suggest that once Ca^{2+} has been exchanged into the inner regions of aggregates, it is harder to diffuse back out from these exchange sites (Table 5.5). Hence, after 2.5 years, it is possible that sufficient Ca^{2+} remains within aggregates to allow stability upon wetting to remain greater than that observed in the control. As the equilibrium exchange is more complete on the outer layers of these aggregates, then subsequent chemical analysis of aggregates ground to within a 2 mm threshold are likely to yield more Na^+ in proportion to Ca^{2+}. Thus, the apparent contradicting phenomenon of aggregates remaining stable in a Na^+ dominant environment arises. Laboratory confirmation of this phenomenon is required.

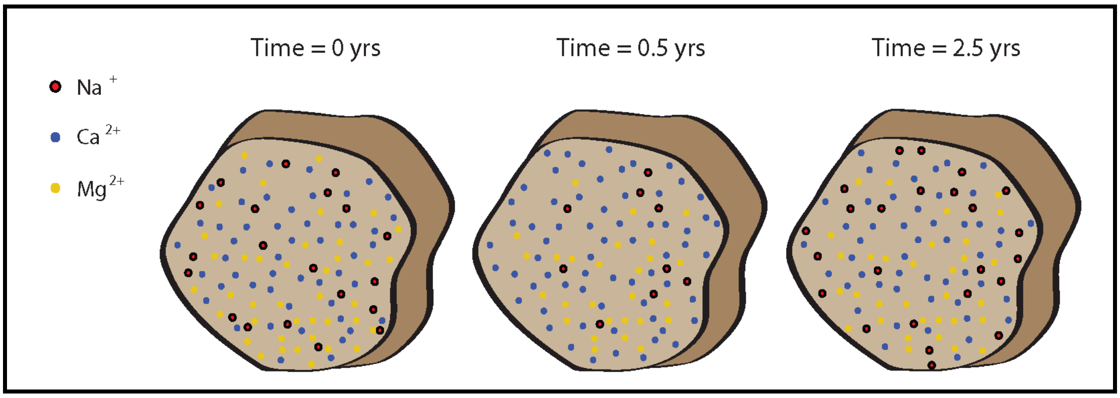


Figure 5.6 Conceptual cross sectional view of a soil aggregate and the relative distribution of exchangeable cations, at three different periods after amendment application

5.4.5. Management implications

The use of gypsum at the rate of 2.5 $t.ha^{-1}$ has been suggested as sub-optimal for the amelioration of sodicity (Hulugalle *et al.* 2006). The results presented in the current work appear to support this suggestion in that significant improvement in soil exchangeable cations was not observed to occur after 6 months at the 2.5 $t.ha^{-1}$ rate of gypsum, and significant results concerning chemical amelioration at twice that rate were not observed after 2.5 years. At the cost of AUD$325 per ha for the latter rate, and the requirement to reapply within 2.5 years to (presumably) maintain the observed effect, this application rate is not only sub-optimal, but unviable for frequent use in broadacre agriculture. However, it is important to note that this does not condemn the use of gypsum in irrigated agriculture; it merely provides guidelines for its efficient use. For example, the gypsum requirement for the Wyadra soil (assuming 100% efficient exchange of Ca^{2+}) is approximately 37.3 $t.ha^{-1}$ for 0–400 mm depth, while at the observed effective proportion of Ca^{2+} dissolved (14% effective in causing Na^+ exchange) results in a requirement of approximately 266.4 $t.ha^{-1}$ to ameliorate sodicity to a depth of 400 mm (these values are calculated as the requirement of Ca^{2+} to displace Na^+ to an ESP <6%, assuming Mg^{2+} to be of no consequence – while it is not realistic to assume Mg^{2+} to be of no consequence, it illustrates the desired point). These figures are most likely closer to ‘optimal’ rates of gypsum application, but are by no means feasible. Conversely, applying no Ca^{2+} leaves the system in deficit; i.e. plants often show a preference for Ca^{2+} to the other major exchangeable bases (Black 1968), thus uptake of Ca^{2+} is not accounted for. The irrigation water being applied to these soils also adds Na^+ with each irrigation event. Consequently, not applying a periodic source of readily available Ca^{2+} will result in sodicity levels becoming exacerbated, and ultimately a decline in productivity will ensue (So and Aylmore 1993). We suggest that Ca^{2+} application is required to be thought of in the same way as nitrogen and phosphorus fertiliser application by landholders; a source of Ca^{2+} sufficient to neutralise the effects of irrigation water quality and plant uptake that is applied with/during each cropping season.

The results of gypsum application in the Mount View and Wyadra soil were shown to differ in magnitude, most likely due to the presence of a permeability limiting layer in the Mount View soil. This reiterates the fact that ameliorant application is site specific, and that thorough investigation of the suitability of the soil for such application would be beneficial prior to use.

5.5. Conclusions

The results of this work show that the use of lime and gypsum in combination and alone is not necessarily viable for broadacre irrigated agriculture on two Lachlan Valley soils with pH >8.0. Significant exchange of Ca^{2+} for Na^{+} was primarily attributable to gypsum, and generally at the rate of 5 $t.ha^{-1}$, although the longevity of these effects was highly limited as compared to similar studies in rain-fed systems, resulting from percolating solution magnitude and frequency. The electrolyte effect of gypsum (Quirk and Schofield 1955; Loveday 1976) was also not observed after 6 months post-gypsum application and approximately 12.85 $ML.ha^{-1}$ of infiltrating irrigation-water/rain. Therefore, it is strongly suggested that the longevity of chemical ameliorant effects be described to landholders in terms of water application magnitude and frequency rather than time alone.

A synergistic effect between lime and gypsum most likely did not occur in these soils. This was attributed to both the rate of gypsum solubility and the initial pH of the soils. While difficult to determine, the possibility of wheat and cotton having provided a synergistic structural improvement through enhanced dissolution of lime, was also assessed as unlikely. If such a process had occurred, it was masked by either the variability of the data, or the application of Na^{+} with irrigation water. These processes require further investigation through the direct determination of residual lime and analysis of soil proximal to the rhisosphere.

The site specific nature of chemical ameliorant application was also highlighted, where a permeability limiting layer was observed to instigate the accumulation of salts in the Mount View soil. In such a circumstance, the use of gypsum was presumed to place the soil at risk of exacerbating sodicity under irrigation with water SAR 5.9. A Dermosol, without such a layer, was observed to result in applied gypsum dissolving and leaching faster with a Na-Ca exchange efficiency rate lower than that previously observed for an irrigated Sodosol irrigated with comparable quantities of water (Loveday 1976).

While it is apparent that the application of lime and/or gypsum is not viable at the rates explored for the reasons presented, it is stressed that this does not condemn the use of gypsum in such soils. A source of Ca^{2+} is required to neutralise the effects of Ca^{2+} uptake by plants and the possible addition of Na^{+} with irrigation water, and is recommended to be applied with each cropping season. The rates at which this occurs could be substantially less than those explored in this work and would benefit from further research.

5.6. Acknowledgements

The authors wish to thank the Cotton Research and Development Corporation, the Cotton Catchment Communities Cooperative Research Centre, the Central West Catchment Management Authority and the New South Wales Department of Industry and Innovation (nee Department of Primary Industries) Healthy Soils for Sustainable Farms program for funding this project. Sincere thanks are also extended to the landholders, Mr Scott Laird and Mr Scott Mailer, for their cooperation and hospitality throughout the project, as well as access to their soils. Statistical analysis was aided by the knowledge of Dr Tom Bishop, The University of Sydney, and Dr Joe Chapman, University of New South Wales (Australian Defence Force Academy), was greatly appreciated. Support with chemical analysis was welcome from Mr Tom Savage and Mr Jack Fitzgerald, while fieldwork support was greatly appreciated from Mr James Quilty and Mr Tim Lewis. Further thanks are extended to Miss Ichsani Wheeler for assistance with construction of diagrams.

5.7. References

Abbott, TS, McKenzie, DC (1986) Improving soil structure with gypsum. Agfact AC 10, NSW Agriculture

Aitken, RL, Moody, PW, Dickson, T (1998) Field amelioration of acidic soils in south-east Queensland. I. Effect of amendments on soil properties. *Australian Journal of Agricultural Research* **49,** 627-37.

Bennett, JMcL (2006) *Interactions between chemical ameliorants and vegetation in a sodic red brown earth, Upper Bogan region, NSW*, Thesis - Australian National University, Canberra.

Black, CA (1968) 'Soil-plant relationships', (John Wiley and Sons: New York)

Chan, KY, Dexter, AR, McKenzie, DC (1999) Categories of soil structure based on mechanical behaviour and their evaluation using additions of lime and gypsum on a sodic Vertisol. *Australian Journal of Soil Research* **37,** 903-11.

Chan, KY, Heenan, DP (1998) Effect of lime (CaCO3) application on soil structural stability of a red earth. *Australian Journal of Soil Research* **36,** 73-86.

Chartres, CJ, Greene, RSB, Ford, GW, Rengasamy, P (1985) The effects of gypsum on macroporosity and crusting of two red duplex soils. *Australian Journal of Soil Research* **23,** 467-79.

Dang, YP, Dalal, RC, Buck, SR, Harms, B, Kelly, R, Hochman, Z, Scwenke, GD, Biggs, AJW, Furguson, NJ, Norrish, S, Routley, R, McDonald, M, Hall, C, Singh, DK, Daniells, IJ, Farquharson, R, Manning, W, Speirs, S, Grewal, HS, Cornish, PE, Bodapati, N, Orange, D (2010) Diagnosis, estent, impacts, and management of subsoil constraints in the northern grains region of Australia. *Australian Journal of Soil Research* **48,** 105-19.

Davidson, LJ, Quirk, JP (1961) The influence of dissolved gypsum on pasture establishment of irrigated clays. *Australian Journal of Agricultural Research* **12,** 100-10.

Doyle, AD, Taylor, DW, Yates, WJ, So, HB, McGarity, JW (1979) Amelioration of structurally unstable grey clays in the north-western wheat belt of New South Wales. *Australian Journal of Experimental Agriculture and Animal Hausbandry* **19,** 590-8.

Emerson, WW, Bakker, AC (1973) The comparative effects of exchangeable calcium, magnesium, and sodium on some physical properties of red-brown earth subsoils. II. The spontaneous dispersion of aggregates in water. *Australian Journal of Soil Research* **11**.

Emerson, WW, Chi, CL (1977) Exchangeable calcium, magnesium and sodium and the dispersion of illites in water. II. Dispersion of illites in water. *Australian Journal of Soil Research* **28,** 255-62.

Field, DJ, McKenzie, DC, Koppi, AJ (1997) Development of an improved vertisol stability test for SOILpak. *Australian Journal of Soil Research* **35,** 843-52.

Ford, GW, Greene, RSB, Rengasamy, P (1985) Estimation of gypsum requirement of agricultural soils. *Proceedings for the Australian Soil Science Society***,** 103-10.

Greene, RSB, Ford, GW (1985) The effect of gypsum on cation exchange in two red duplex soils. *Australian Journal of Soil Research* **23,** 61-74.

Gupta, RK, Singh, RR (1988) A comparative evaluation of the reclamation efficiency of surface-concentrated versus internalyl incorporated calcium chloride and gypsum in an alkalai soil. *Soil Science* **146,** 277-83.

Hajkowicz, S, Young, M (2005) Costing yield loss from acidity, sodicity and dryland salinity to Australian agriculture. *Land Degradation and Development* **16,** 417-33.

Hulugalle, NR, Weaver, TB, Ghadiri, H, Hicks, A (2006) Changes in soil properties of an eastern Australian Vertisol irrigated with sewage effluent following gypsum application. *Land Degradation and Development* **17,** 527-40.

Isbell, RF (2002) 'The Australian soil classification: revised edition', (CSIRO Publishing: Melbourne)

Jayawardane, NS, Chan, KY (1995) Management of soil physical properties limiting cropping in Australian sodic soils. *In* 'Australian sodic soils: distribution, properties and management'. (Eds. Naidu, R, Sumner, ME & Rengasamy, P) (CSIRO Publications: Melbourne)

Keren, R, O'Connor, GA (1982) Gypsum dissolution and sodic soil reclamation as affected by water flow velocity. *Soil Science Society of America Journal* **46,** 726-32.

Keren, R, Shainberg, I (1981) Effect of dissolution rate on the efficiency of industrial and mined gypsum in improving infiltration of a sodic soil. *Soil Science Society of America Journal* **45,** 103-7.

Loveday, J (1974) Recognition of gypsum responsive soils. *Australian Journal of Soil Research* **25**.

Loveday, J (1976) Relative significance of electrolyte and cation exchange effects when gypsum is applied to a sodic clay soil *Australian Journal of Soil Research* **14,** 361-71.

Mann, M, Pissarra, A, van Hoorn, JW (1982) Drainage and desalinisation of heavy clay soils in Portugal. *Agricultural Water Management* **5,** 227-40.

McKenzie, DC (1982) *Evaluation of gypsum as an ameliorant for cracking-clay soils of the Moree district, N.S.W.*, Thesis - University of New England, Armidale.

McKenzie, DC, Abbott, TS, Chan, KY, Slavich, PG, Hall, DJM (1993) The nature, distribution and management of sodic soils in New South Wales. *Australian Journal of Soil Research* **31,** 839-68.

McKenzie, DC, So, HB (1989a) Effect of gypsum on vertisols of the Gwydir Valley, New South Wales 1. Soil properties and wheat growth. *Australian Journal of Experimental Agriculture* **29,** 51-62.

McKenzie, DC, So, HB (1989b) Effect of gypsum on vertisols of the Gwydir Valley, New South Wales 2. Ease of tillage. *Australian Journal of Experimental Agriculture* **29,** 63-7.

Mubarak, AR, Nortcliff, S (2010) Calcium carbonate solubilization through H-proton release from legumes grown in calcaerous saline-sodic soils. *Land Degredation and Development* **21,** 24-31.

Murphy, BW (2002) Sodic soils: formation and global distribution of. *In* 'Encyclopedia of soil science'. (Eds. Lal, R) (Marcel Dekker: New York)

Naidu, R, Rengasamy, P (1993) Ion interactions and constraints to plant nutrients in Australian sodic soils. *Australian Journal of Soil Research* **31,** 801-19.

Northcote, KH, Skene, JK (1972) *Australian soils with saline and sodic properties*. CSIRO Soil Publication 27, (CSIRO: Australia)

Qadir, M, Oster, JD (2002) Vegetative bioremediation of calcareous sodic soils: history, mechanisms, and evaluation. *Irrigation Science* **21,** 91-101.

Qadir, M, Steffens, D, Yan, F, Schubert, S (2003) Proton release by N2-fixing plant roots: a possible contribution to phytoremediation of calcareous sodic soils. *Journal of Plant Nutrition and Soil Science* **166,** 14-22.

Quirk, JP, Schofield, RK (1955) The effect of electrolyte concentration on soil permeability. *Australian Journal of Soil Research* **6,** 163-78.

Rengasamy, P (2002) Transient salinity and subsoil constraints to dryland farming in Australian sodic soils: an overview. *Australian Journal of Experimental Agriculture* **42,** 351-61.

Rengasamy, P, Greene, RSB, Ford, GW (1986) Influence of magnesium on aggregate stability in sodic Red-Brown Earths. *Australian Journal of Soil Research* **24,** 229-37.

Rengasamy, P, Greene, RSB, Ford, GW, Mehanni, AH (1984) Identification of dispersive behaviour and the management of red-brown earths. *Australian Journal of Soil Research* **22,** 413-31.

Robbins, CW (1986a) Carbon dioxide partial pressure in lysimeter soils. *Agronomy Journal* **78,** 151-8.

Robbins, CW (1986b) Sodic calcareous soil reclamation as affected by different amendments and crops. *Agronomy Journal* **78,** 916-20.

Roth, CH, Pavan, MA (1991) Effects of lime and gypsum on clay dispersion and infiltration in samples of a Brazillian Oxisol. *Geoderma* **48,** 351-61.

Russell, EW (1961) 'Soil conditions and plant growth', (Longmans, Green and Co. Ltd: London)

Shainberg, I, Gal, M (1982) The effect of lime on the response of soils to sodic conditions. *Journal of Soil Science* **33,** 489-98.

Shanmuganathan, RT, Oades, JM (1983) Modification of soil physical properties by addition of calciaum compounds. *Australian Journal of Soil Research* **21,** 285-300.

So, HB, Aylmore, LAG (1993) How do sodic soils behave? The effects of sodicity on soil physical behaviour. *Australian Journal of Soil Research* **31,** 761-77.

So, HB, Taylor, DW, Yates, WJ, McGarity, JW (1978) Amelioration of structurally unstable grey and brown clays. *In* 'Modifications of soil structure'. (Eds. Emerson, WW, Bond, RD & Dexter, AR) (John wiley & sons: Chichester)

Sumner, ME (1993) Sodic soils: a new perspective. *Australian Journal of Soil Research* **31,** 683-750.

Taylor, DW, Olsson, KA (1987) Effect of gypsum and deep ripping on lucerne (Medicago sativa L.) yeilds on a red-brown earth under flood and spray irrigation. *Australian Journal of Experimental Agriculture* **27,** 841-72.

Tucker, BM (1985) A proposed new reagent for the measurement of cation exchange properties of carbonate soils. *Australian Journal of Soil Research* **23,** 633-42.

Tucker, BM, Beatty, HJ (1974) Exchangeable cations and cation exchange capacity. *In* 'Methods for analysis of irrigated soils'. (Eds. Loveday, J) (Commonwealth Agricultural Bureaux: Farnham Royal, England)

Valzano, FP, Greene, RSB, Murphy, BW, Rengasamy, P, Jarwal, SD (2001a) Effects of gypsum and stubble retention on the chemical and physical properties of a sodic grey vertosol in western Victoria. *Australian Journal of Soil Research* **39,** 1333-47.

Valzano, FP, Murphy, BW, Greene, RSB (2001b) The long term effects of lime ($CaCO_3$), Gypsum ($CaSO_4.2H_2O$), and tillage on the physical and chemical properties of a sodic red-brown earth. *Australian Journal of Soil Research* **39,** 1307-31.

THE MERITS OF A GYPSUM ($CaSO_4.2H_2O$) ENHANCED CHICKEN MANURE/WHEAT STRAW COMPOST IN AMELIORATING AN IRRIGATED SODIC BROWN VERTOSOL: LABORATORY EXPERIMENT

6. The merits of a gypsum ($CaSO_4.2H_2O$) enhanced chicken manure/wheat straw compost in ameliorating an irrigated sodic Brown Vertosol – laboratory experiment

J. McL. Bennett[ABC]*, S. R. Cattle*[A]*, B. Singh*[A] *and J. R. Quilty*[AB]

[A] Faculty of Agriculture, Food and Natural Resources, John Woolley Bld A20, The University of Sydney, NSW 2006.
[B] Cotton Catchment Communities Co-operative Research Centre
[C] Cotton Research & Development Corporation

Abstract. The use of gypsum to ameliorate soil sodicity is a typical practice in Australian agriculture. However, the longevity of ameliorative effect due to gypsum application is often short-lived, due to the rate of dissolution and subsequent leaching by rainfall and/or irrigation. Gypsum was combined with chicken manure/wheat straw compost (CMWSC) in order to investigate the potential of creating a slow release source of calcium (Ca^{2+}). If adequate adsorption sites for dissolved Ca^{2+} from the incorporated gypsum exist in the CMWSC, then Ca^{2+} leaching should me minimised. A leaching column experiment was conducted using an Episodic-Gypsic Brown Vertosol treated with C0G0 (CWMSC 0 $t.ha^{-1}$, gypsum 5 $t.ha^{-1}$), C0G5, C5G0, C5G5, C144G0, and C144G5. Columns were irrigated every two weeks for 14 weeks (6.5 $ML.ha^{-1}$ of irrigation water in total). Soil EC, leachate EC, and leachate water soluble cations were determined for each irrigation event, while soil EC, pH, exchangeable cations and saturated hydraulic conductivity (K_s) were determined at the end of the experiment. The use of CMWSC alone was shown to increase potassium, and the higher rate application (C144G0) increased K_s. The C5G5 treated soil exchanged more Ca^{2+} for Na^+ and leached less Ca^{2+} compared to the application of gypsum alone. Rapid decrease in soil electrolyte level was evident in all treated soils. The results of this study indicate that gypsum-enhanced CMWSC was more effective in ameliorating sodicity than the use of gypsum alone, due to a greater retention of exchangeable Ca^{2+}.

Additional keywords: exchangeable sodium percentage, chemical amelioration**,** electrolyte concentration, leaching experiment.

6.1. Introduction

Sodicity is a major issue concerning the productivity of many cropping soils throughout the world. The incidence of sodicity in Australia is estimated to be greater than in any other country, with approximately 340 million ha of land affected (Murphy 2002). It is also estimated that sodicity causes a reduction of economic potential for on-farm income of AUD$1035 million per annum (Hajkowicz and Young 2005). Sodicity is the result of excess exchangeable sodium (Na^+) accumulation on the negatively charged clay exchange sites. By Australian definition, if the percentage of Na^+, compared to other major exchangeable bases, in the cation exchange capacity (CEC) exceeds 6% (Northcote and Skene 1972), and/or the electrolyte concentration (EC) is sufficiently low (Sumner 1993), sodic soils become prone to dispersion upon wetting. Dispersed clay particles cause a variety of physical changes in the soil such as soil slumping, decreased water infiltration and increased run-off, erosion, and hardsetting. The resulting soil environment is one not conducive to efficient production of crops and pasture.

To address dispersion, and the consequent loss of structural stability, calcium (Ca^{2+}) in the form of gypsum ($CaSO_4.2H_2O$) is often applied to the soil. There are two factors that determine the effectiveness of amelioration with gypsum; solubility and exchange efficiency of Ca^{2+}. The solubility of gypsum in the field has been estimated as approximately 765–828 $mg.L^{-1}$ (Greene and Ford 1985; Valzano *et al.* 2001b), while the exchange efficiency of Ca^{2+} has been recorded as being between 20% and 40% (Loveday 1976; Greene and Ford 1985; Valzano *et al.* 2001b). These factors are interrelated in that the rate of dissolution will determine how efficiently Ca^{2+} is exchanged. While there are numerous processes affecting dissolution and exchange efficiency, the magnitude and frequency of the percolating solution (i.e. rainfall and irrigation) will ultimately determine the length of the dissolution period and amount of Ca^{2+} leached from the soil's A horizon. Subsequently, the rate of dissolution and leaching could be expected to be higher in an irrigated system as compared to a rain-fed system. A consequence of increased Ca^{2+} mobility and a shorter gypsum dissolution period is that structural amelioration of the soil due to gypsum may not occur to the full potential, or at all.

A further strategy for the amelioration of sodic soils is to apply manure composts. Recent studies involving the use of manure composts have had mixed results (Clark *et al.* 2009; Ghosh *et al.* 2010; Turner *et al.* 2010). The use of chicken manure was shown to increase the proportion of slaking-resistant macroaggregates (>2 mm) in a Victorian Sodosol (Isbell 2002; ESP 21.4%, EC 0.32 $dS.m^{-1}$) with the effect attributed to increased fungal growth and microbial activity (Clark *et al.* 2009). Ghosh *et al.* (2010) also found increases in aggregate stability due to chicken manure application onto two Grey Vertosols (Isbell 2002) with varying ESP. They attributed this result to Ca^{2+} exchange for Na^+ and increased electrolytic concentration, although they did not discount other organic binding mechanisms. The same study also reported that cattle manure increased the Na^+ concentration and ESP of the topsoil. Conversely, Turner *et al.* (2010) found cattle manure to have no significant effect on soil EC or sodium absorption ratio (SAR) in a mesic Aridic Paleustoll (Dermosol, Isbell 2002), while swine effluent was observed to increase SAR over time. It is apparent that the use of manure compost can be beneficial to soil structure depending on the source and constituents.

While the use of compost as a soil amendment is not a typical practice in Australia, farmers are increasingly exploring more alternatives to conventional systems. This increased interest can be attributed to a variety of reasons. Friature *et al.* (2007) make the projection that food production will need to increase a further 70–90% by 2050 to satisfy global demand. Considering that history shows a reliance on fertilisers to boost production and meet demand, and that mined phosphorus (P) resources are dwindling (Smil 2000), it stands that unconventional sources of P will be sought after. Composts, including manure composts, have been shown as a possible source of P (Cordell *et al.* 2009). Australian farmers have also shown an escalating interest in organic agriculture over the last 10 years (Willer *et al.* 2008), presumably due to the value-added niche market offered by organic produce. Such enterprise requires a source of organic amendment, like compost, in order to augment soil stores of plant available nutrients. Additionally, the current climate is one where water is scarce and amendments that increase infiltration and water-holding capacity of soils are required. The addition of organic matter has been shown to achieve this in certain circumstances (Wahid *et al.* 1998). Thus, it is apparent that the increased agronomic use of compost is likely in Australia's near future.

There is potential to capitalise on the likelihood of increased agronomic compost application. By introducing gypsum into compost blends, it may be possible to dissolve the gypsum and exchange the contained Ca^{2+} onto the negatively charged organic sites for use as a sodicity ameliorant. When the compost is applied and incorporated into the soil, the organic matter containing the exchanged proportion of the Ca^{2+} is likely to remain *in situ* during rainfall and irrigation events. Thus, successive irrigation and rainfall events are less likely to leach Ca^{2+} from the A horizon, as compared to when gypsum is applied alone. Because the manure compost should inherently contain appreciable quantities of salt residues, including calcium, there is also the potential to augment the EC and increase soil aggregate stability. Therefore, the objectives of this study are to; (i) investigate the merits of a manure compost and gypsum blend in affecting cation exchange in an irrigated sodic soil, and (ii) examine the changes in EC due to compost and gypsum application throughout a simulated irrigation season wetting and drying cycle.

6.2. Methods

6.2.1. Collection and preparation of soil

The soil used for this experiment was sampled from a farm near Hillston, New South Wales (GR 33°33'25.09"S 145°17'35.11"E), used for the growth of irrigated cotton (*Gossypium hirsutum* L.) and wheat (*Triticum aestivum* L.). It is described as an Episodic-Gypsic Brown Vertosol (Isbell 2002) with 64% clay (<2 μm), 3% silt (2–20 μm) and 33% sand (20–2000 μm). Native gypsum was shown to exist below 400 mm. X-ray diffraction analysis shows that the clay mineral suite is dominated by smectite and kaolinite for the 0–200 mm depth. The initial soil chemical properties are presented in Table 6.1. Soil samples were taken (0–200 mm depth) and stored in 80 L plastic drums for transport. The soil was spread across a plastic sheet and left to air-dry in the laboratory, after which it was sieved to a 10 mm threshold to maintain a natural structure and heterogeneous distribution of aggregate size. Soil greater than 10 mm diameter was crushed and re-sieved before being mixed with the bulk; this soil constituted less than 15% (by weight) of the soil bulk.

6.2.2. Experimental design and treatments

A fully factorial laboratory experiment was conducted using two amendments (gypsum and chicken manure-wheat straw compost) and a control (unamended soil). Gypsum was applied at one rate similar to commercial rates, while the compost was applied at two rates; one similar to commercially used rates and one exaggerated rate (Table 6.2). It is suggested that organic amendments may need to be applied at a rate greater than commercially recommended to achieve the manufacturer-stated soil quality, or nutrient, effect (Edmeades 2002). With this in mind, the exaggerated application rate was designed to be at least tenfold greater than commercially recommended rates (between 5–10 $t.ha^{-1}$). Treatments were replicated six times and randomised. The experiment was conducted in a temperature controlled laboratory (18–22ºC) over 14 weeks.

Table 6.1. Initial chemical properties of the soil used in the experiment

Soil property	*Unit of measure*	*Value*
Electrical conductivity$_{1:5\ (soil:water)}$	dS/m	0.83
pH$_{1:5\ (soil:water)}$		8.6
Calcium (exchangeable)	cmol(+)/kg	14.4
Magnesium (exchangeable)	cmol(+)/kg	8.74
Sodium (exchangeable)	cmol(+)/kg	2.65
Potassium (exchangeable)	cmol(+)/kg	0.48
Cation exchange capacity	cmol(+)/kg	26.2
Exchangeable sodium percentage	%	10.1

Leaching columns were constructed as follows: Acid washed sand (1100 g) was placed on top of a single sheet of 185 mm diameter Whatman No.1 filter paper inside a 180 mm internal diameter (ID) cylindrical polythene bucket; the bucket had been pre-drilled with 8 by 3 mm ID holes for drainage of leachate. Soil (<10 mm diameter) was then was placed into the bucket to a height of 150 mm; the soil was gradually filled and tamped to achieve an approximate bulk density of 1.3 $kg.m^{-3}$ (~ 5.0 kg of soil). Where treatments were to be applied, the top 50 mm of soil was removed and placed into a strong polythene bag with the required amendment amount. This was placed into a rotary drum (similar action to a cement mixer) and mixed for 30 min before the soil/amendment mixture was replaced in the leaching column. The process was replicated for the control, but without amendment incorporation. A

300 mm length of polythene pipe (150 mm ID) was inserted 50 mm into the soil surface to act as an irrigation reservoir. The leaching column, complete with irrigation reservoir, was place onto a 80 mm high stand inside a larger polythene container (250 mm ID) designed to collect the leachate. Evaporation of leachate was stopped by securing a polythene membrane between the leaching column and the leachate reservoir.

Table 6.2. Experimental treatment components

Rate	*Rate* (t.ha^{-1})	*Compost = C* 0	5	144
Gypsum = G	0	C0G0	C5G0	C144G0
	5	C0G5	C5G5	C144G5

Forty eight hours prior to initiating the experiment, the stand was removed and 1.5 L of deionised water was added to the leachate reservoir to allow the soil to wet-up from the base with minimal disturbance to soil structure. For irrigation events, 178 mm diameter disc (attached to a wire handle) was held slightly above the soil surface to absorb the majority of kinetic energy from the irrigation water being poured in and to minimise suction on removal. Subsequent irrigation was conducted in this manner every two weeks; the purpose of this period was to simulate wetting and drying cycles in the production of irrigated crops. The first irrigation consisted of 3.2 L of deionised water (applied in two equal aliquots 6 h apart), while the subsequent six irrigations each consisted of 2.2 L of deionised water applied in single applications (equivalent to approximately 6.5 ML.ha^{-1} in total). If the soil was observed to shrink away from the irrigation reservoir walls upon drying, petroleum jelly was used to fill the void in order to limit preferential flow. Upon completion of the final irrigation event, the leaching columns were allowed to stand a further two weeks to fulfil the final drying cycle.

6.2.3. Soil analyses

Throughout the duration of the experiment, EC was directly measured in the leaching columns using a Field Scout ™ direct soil EC meter with a jab probe (2265FS). Preliminary tests showed that the estimates obtained by the 2265FS for a series of known concentration solutions were within the stated meter accuracy of ±2% for 0–10 dS.m^{-1} (95% confidence interval), but for solutions with an EC between 10 and 20 dS.m^{-1} the accuracy was substantially limited (±17% on average). The ECs expected to be encountered in this experiment were between 0–10 dS.m^{-1}. Direct EC measurements were taken at 24 h (EC_{24h}) and 2 wks (EC_{2wk}) after each irrigation to ensure that time-series comparison of the data was consistent; the meter does not include a moisture probe, thus different water contents of the soil will alter the EC reading. Therefore, the probe gives an indication of the EC relevant to the soil chemical processes at the given time. Results were reported on a time-after-irrigation basis (24 h or 2 wks).

On completion of the experiment, soil cores (50 mm ID) were taken from the 0–50 mm layer of the leaching column. These were air dried at 42ºC, crushed and sieved to a 2 mm threshold for soil analysis. Electrolyte concentration and pH were measured in 1:5 soil:water suspensions using a Radiometer MeterLab™ conductivity meter (CDM210) and standard pH meter (PHM210). Exchangeable base cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) were determined using a modification of method 15D3, Rayment and Higginson (1992), with pretreatment for soluble salts consistent with Tucker (1985). After the removal of soluble salts, 2.5 g of soil was placed into 30 ml polythene vials. Twenty five ml of ammonium acetate (NH_4OAc) buffered to pH 8.5 was added to the vials to extract the cations. Samples were then mixed on a rotary shaker for 60 min, followed by centrifuging for 5 min at 2500 rpm. The supernatant was filtered into a 100 ml volumetric flask and the extraction process was repeated three times. Exchangeable cation analysis was conducted using a Varian Vista AX Simultaneous inductively coupled plasma atomic emission spectrometer (ICP-AES). Total sulphur (S) was also analysed in the extraction solution and was used to correct for undissolved gypsum. Cation exchange capacity is presented as the sum of the exchangeable base cations (ECEC), as exploratory analysis showed that there were no significant differences between CEC and ECEC.

Saturated hydraulic conductivity (K_s) was measured using a falling head technique during the final irrigation event. The height of the head was measured at the commencement of irrigation and periodically measured (up to 12 times) throughout the duration of the irrigation event (up to 4 h 16 min). Calculations for K_s were made using Equation 6.1:

$$K_s = \frac{\sum_{i=1}^{j-1}\left[\frac{aL}{At}\ln\left(\frac{h_i}{h_{i+1}}\right)\right]}{j-1} \qquad \textbf{(6.1)}$$

where a is the area of the irrigation ring, L is the length of the soil core, A is the area of the soil core, h_i is the head height at measurement i, h_{i+1} is the height of the head one measurement after h_i, and j is the number of measurements of head height made.

6.2.4. Leachate analyses

Leachate was collected 24 h after each irrigation and stored in 30 ml polythene vials at 3°C prior to analysis. Excess leachate was discarded from the leachate reservoir post-sampling. Filtered subsamples of leachate were placed into 10 ml polythene vials for analysis of soluble Ca, Na, K, Mg, and S concentrations using a Varian Vista AX Simultaneous ICP-AES. The EC was directly measured using a Radiometer MeterLab™ conductivity meter (CDM210).

6.2.5. Compost production and analyses

The chicken manure/wheat straw compost (CMWSC) was produced using a windrow technique in which the turning of the decomposing organic material is regulated by changes in the internal temperature of the compost. Compost was produced using 27.5% chicken manure, 22.5% wheat straw, 10% pre-composted chicken litter and wheat straw, and 40% clay (EC 0.2 dS.m^{-1}, ESP 4%, ECP 58%, EMP 33%, EPP 5%); these proportions of constituents are on a per weight basis. The compost ingredients were piled in windrows, approximately 1.5 m high by 2 m at the base. These were turned vigorously, whilst being watered evenly, using an Aeromaster® PT 150 compost windrow turner. The internal temperature within the windrow was monitored on a daily basis. Turning and watering of the windrow occurred every 2 days for the first 2–3 wks to ensure that the temperature did not exceed 70°C. This temperature has been identified as a critical maximum for composting, as higher temperatures are lethal to many of the microorganisms responsible for the breakdown of organic material (Falcón *et al.* 1987). Turning continued every 3–4 days until the windrow reached maturity, which was determined as the point where the compost temperature stabilised below 40°C. The total process took approximately 8 wks. For the C144G5 treatment, gypsum was incorporated at the beginning of the composting cycle, while it was incorporated at the end of the composting cycle for the C5G5 treatment and composted a further 6 wks (due to necessity enforced by time).

The pH and EC of the composts were measured using the procedure used for soil samples (air dry, <2.0 mm). Total Ca, Na, K, Mg, P and S were extracted through a nitric-perchloric acid digest as described by Miller (1998). The resulting extracts were then analysed with a Varian Vista AX Simultaneous ICP-AES. Water soluble Ca^{2+}, Na^+, K^+, Mg^+, and S (as SO_4^{2-}) contents were measured using a method developed by the New South Wales Department of Conservation and Land Management (Craze *et al.* 1993), as cited in Valzano *et al.* (2001b). Five grams of compost was placed into a 30 ml polythene vial with 25 ml of deionised water and mixed on a rotary shaker for 60 min. After centrifuging for 5 min at 3000 rpm, the clear supernatant was filtered through Whatman No. 42 filter paper into 10 ml polythene vials and analysed using a Varian Vista AX Simultaneous ICP-AES. The chemical constituents of the four composts used in this experiment are presented in Table 6.3.

6.2.6. Statistical analyses

Results were analysed in MINITAB® *v.*14.11.1 using one-way ANOVA ($P \leq 0.05$) to determine treatment differences and two-way ANOVA to assess significant interactions between gypsum and compost. Independence was ensured by the treatment design and equal variance was apparent for all treatments using Bonferroni confidence intervals for standard deviations and Lavene's test. The assumption of normality was generally met, but where compromised a log transformation was undertaken. Where significance was detected in the one-way ANOVA, significant pairs were analysed using Tukey's pairwise comparison to limit the chance of Type I error. For graphical representation, an honest significance difference (hsd) interval is presented. Trends in the leachate data over the seven time intervals were analysed in GenStat® *v.*10.1.0.72 using nonlinear regression analysis in order to fit appropriate trend lines. Significant differences ($P \leq 0.05$) between treatments were assessed for the cumulative leachate data after irrigation event seven, as this point represented the leachate cumulative totals. Two-way ANOVA is not presented for the leachate data (with the exception of EC) because it did not present any new information.

Table 6.3 Selected chemical properties of the four compost combinations used in the experiment

	Treatment	*Ca*	*K*	*Mg*	*Na*	$S^{\dagger}$	$EC_{1:5}$ *(soil:water)*	$pH_{1:5}$ *(soil:water)*
Total ion concentration			*cmol.kg^{-1}*			*g.kg^{-1}*	*dS.m^{-1}*	
	C144G5	56.8	66.8	45.0	30.2	14.3	14.2	5.8
	C5G5	472.3	54.6	48.3	12.9	42.7	7.89	6.8
	C144G0‡	38.7	51.4	32.7	12.4	1.58	8.63	5.9
	C5G0‡	38.7	51.4	32.7	12.4	1.58	8.63	5.9
Soluble ion concentration			*mmol.L^{-1}*			*g.L^{-1}*		
	C144G5	875.0	122.9	190.9	127.0	10.9	14.2	5.8
	C5G5	766.2	54.5	124.0	62.4	9.53	7.89	6.8
	C144G0‡	100.6	116.2	111.2	70.9	1.60	8.63	5.9
	C5G0‡	100.6	116.2	111.2	70.9	1.60	8.63	5.9

† For soluble ion concentration, S is presented as SO_4^{2-}

‡ These treatments were sourced from the same compost

6.3. Results

6.3.1. Soil chemical measurements

6.3.1.A. Changes in exchangeable cation concentrations due to treatment application

There is a propensity for the compost, with and without gypsum, to significantly lower the ESP of the soil (Table 6.4). However, only treatments with gypsum lower the ESP beneath the theoretical sodicity threshold of 6%. Two-way interactions suggest that a decrease in sodicity where gypsum is applied is enhanced by the presence of compost, although this is only true for the C5G5 treatment; the C144G5 treatment has a similar effect to the control. Interestingly, where compost is applied alone, the greatest benefit is from the lower compost application (C5G0) as compared to exaggerated application (C144G0). While the C0G5, C5G5 and C144G5 treatments all significantly improve the soil ESP as compared to the C144G0 treatment, only the C5G5 treatment is significantly better than C0G5 treatment in terms of soil ESP.

Changes in the EMP are shown to be highly significant for the C0G5, C5G5 and C144G5 treated soil in comparison to the control soil (Table 6.4). Again, the two-way interactions show that the greatest decrease in EMP is achieved by application of the C5G5 treatment. The C144G5 treatment application produces results slightly better than the C0G5 treatment, although the magnitude of the decrease in EMP between the C0G0 and C144G0 treated soils is higher than that between the C0G5 and C144G5 treated soils.

Table 6.4 Changes in soil exchangeable cation percentages and ratios, estimated cation exchange capacity, pH and electrolyte concentration due to treatment application, after seven irrigation events and 14 weeks

Values within columns followed by the same letter are not significantly different

Treatment	*ECP (%)*	*EMP (%)*	*EPP (%)*	*ESP (%)*	*ECEC* # *$(cmol.kg^{-1})$*	*Ca:Mg*	*pH*	*EC $(mS.m^{-1})$*
Control	54.1bc	37.5ac	1.48e	8.79a	27.7ab	1.44a	8.99a	14.4a
C0G5	61.2a	32.3bd	1.38e	4.12c	28.9ab	1.85be	8.59c	14.8ac
C144G0	55.0b	34.8ad	3.25a	7.05b	29.1ab	1.59ae	8.79b	18.6bc
C144G5	61.5a	31.7bd	2.62b	4.21c	29.6a	1.95bd	8.55c	17.2ac
C5G0	52.2c	38.6c	2.28c	6.97b	26.7b	1.35ae	8.65b	14.6a
C5G5	65.0a	30.0b	1.96d	3.06c	28.4ab	2.18cd	8.51c	15.5ac
p-value †	<0.001	<0.001	<0.001	<0.001	0.019	<0.001	<0.001	0.008
Interaction ‡	0.019	0.001	<0.001	0.030	ns	0.006	ns	ns

Estimated CEC corrected for SO_4

† This p-value pertains to the difference between individual treatments within columns (1-way ANOVA)

‡ Shows a significant interaction between compost and gypsum at p-value displayed (2-way ANOVA); ns, not significant

The C0G5, C5G5 and C144G5 treatments are also responsible for significantly lower soil EMP than the C5G0 treatment. Additionally, there are no significant differences in EMP between the treated soils containing gypsum, although that treated with C5G5 is observed to have the lowest mean value of EMP.

The greatest increase in ECP is observed in the C5G5 treated soil, although this is statistically similar to the increases provided by the C144G5 and C0G5 treatments (Table 6.4). All of these treatments are shown to significantly increase the soil ECP as compared to the control, while the use of gypsum alone is shown to maintain a similar soil ECP to the control. The two-way interactions also show that the greatest increase in ECP occurs where the C5G5 treatment is applied, indicating that the effect of gypsum is related to the amount of compost applied. Only the C5G5 treated soil is observed to have a statistically higher ECP than both the C5G0 and C144G5 treated soils.

The soil Ca:Mg ratio is only shown to improve significantly, as compared to the control, where gypsum is applied, although the two-way interactions show that this effect is dependent on the presence of compost and is better under the C5G5 treatment (Table 6.4). While the C5G5 treatment is shown to have a similar effect as compared to the C144G5 treatment, it results in a higher mean value of Ca:Mg ratio than that of the C144G5 treated soil and a significantly higher Ca:Mg ratio than that of the C0G5 treated soil.

Wherever compost is applied a significant increase in EPP is observed, while the use of gypsum alone is shown to provide an EPP statistically similar to that of the control (Table 6.4). The use of compost alone results in a greater increase in EPP than the corresponding compost application in conjunction with gypsum. This is also supported by the two-way interactions that show the use of gypsum decreases soil EPP, and that the magnitude of this decrease is greatest where compost is applied at 144 $t.ha^{-1}$.

6.3.1.B. Changes in pH due to treatment application

The pH of the soil is shown to significantly decrease with treatment application, and this decrease is greatest where gypsum is used (Table 6.4). The pH is also significantly lower where gypsum is applied as compared to where compost is applied alone. The pH of treatments containing gypsum is shown to be statistically similar. This is also true for treatments where compost is applied alone. The lack of a two-way interaction shows that the effect of gypsum is greater on pH than the effect of compost, and that these effects are independent.

6.3.1.C. Changes in electrolyte concentration due to treatment application

The changes in EC_{24h} for the differently treated soils are presented in Figure 6.1(a). After the first irrigation, the C5G5 and C144G5 treated soils have significantly higher EC_{24h} than any other treatment or control soils, and are significantly different to each other. The EC_{24h} of the soil treated with C144G5 remains significantly different to the control soil, low application compost (C5G0) and gypsum alone treated soils throughout the seven irrigations and is generally significantly greater in electrolyte than the C144G0 treated soil. The EC_{24h} of the C5G5 treated soil, while statistically similar to the soil treated with C144G5 up to irrigation three, becomes similar to the C0G5 treated soil by irrigation four and maintains this trend until the end of the experiment. It takes three irrigations for the C0G5 treated soil to show a significantly higher EC_{24h} than the control and C5G0 treated soils, after which both the C0G5 and C5G5 treated soils are observed to generally maintain a significantly higher EC_{24h}. The EC_{24h} of the soil treated with C0G5 is significantly different to the C0G0 and C5G0 treated soils at p=0.052 and p=0.054 respectively for irrigation event seven. After irrigation five, the EC_{24h} is generally observed to plateau for all soils.

From the EC_{2wk} data, presented in Figure 6.1(b), it can be seen that there are some notable differences to the 24 h post-irrigation data [Figure 6.1(a)], but the overall trends are quite similar. The main differences occur at the start and end of the experiment. After the first irrigation event, all soils (treated or otherwise) are significantly different in EC_{2wk} except those treated with C5G5 and C144G5, which are statistically equal. By irrigation event seven, the C5G5 treated soil is no longer significantly different to that treated with C144G5, while at irrigation event three the EC_{2wk} is higher for the C5G5 treated soil. A further difference is observed in between-treatment-variation, within individual irrigation events, which is generally larger for the 24 h post-irrigation data as compared to those 2 wks post-irrigation. As for the 24 h data, the difference in EC between soils treated with C0G5 and C5G5 is significantly different until irrigation event four, after which it remains similar. Of these two treatments, only the C5G5 treated soil is significantly greater than the C5G0 treated soil in EC_{2wk}, while both soils are significantly higher in EC_{2wk} than the control soil. Using the non-linear regression models to forecast the trend-line (data not shown), it is observed that all soils are predicted to reach a plateau after two more irrigation events at 2 wks post-irrigation.

While there are numerous significant differences between treated soils and the control soil at both 24 h and 2 wks post-irrigation, only the soil treated with C144G0 is higher than the control in the $EC_{1:5}$ final data (Table 6.4). It is noted that the C144G5 treated soil is significant at p=0.056 (compared to the control) with a similar mean to the C144G0 treated soil. This is important because the two-way interaction is not significant and indicates that compost is responsible for final differences in EC (p=0.002), while gypsum has no appreciable effect (p=0.949).

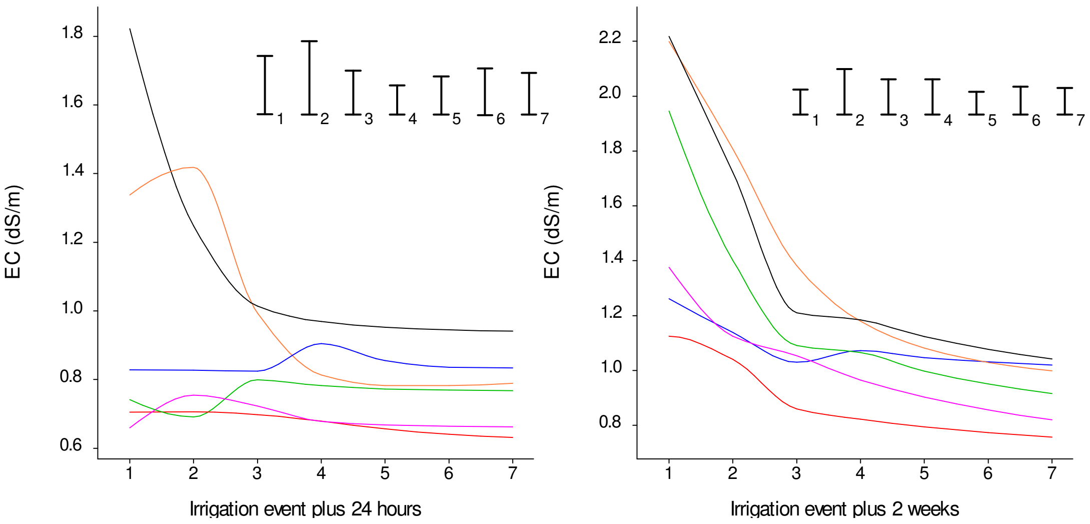


Figure 6.1. Differences in electrical conductivity of soil leaching columns 24 hours after an irrigation event (a) and 2 weeks after an irrigation event (b) for seven irrigation events; (🟥) C0G0 (🟩) C0G5, (🟦) C144G0, (⬛) C144G5, (🟪) C5G0, and (🟧) C5G5; intervals represent the h.s.d. for the irrigation event of the same number.

6.3.2. Leachate chemical measurements

6.3.2.A. Changes in leachate chemical composition as a result of treatment application

The cumulative total of leached Ca^{2+} is significantly higher where gypsum is applied, irrespective of compost application, in comparison to the control (Figure 6.2). The C5G5 treated soil is observed to leach significantly less Ca^{2+} than both the C0G5 and C144G5 treated soils, while there is no significant difference between the C5G5 and the C5G0 treated soils.

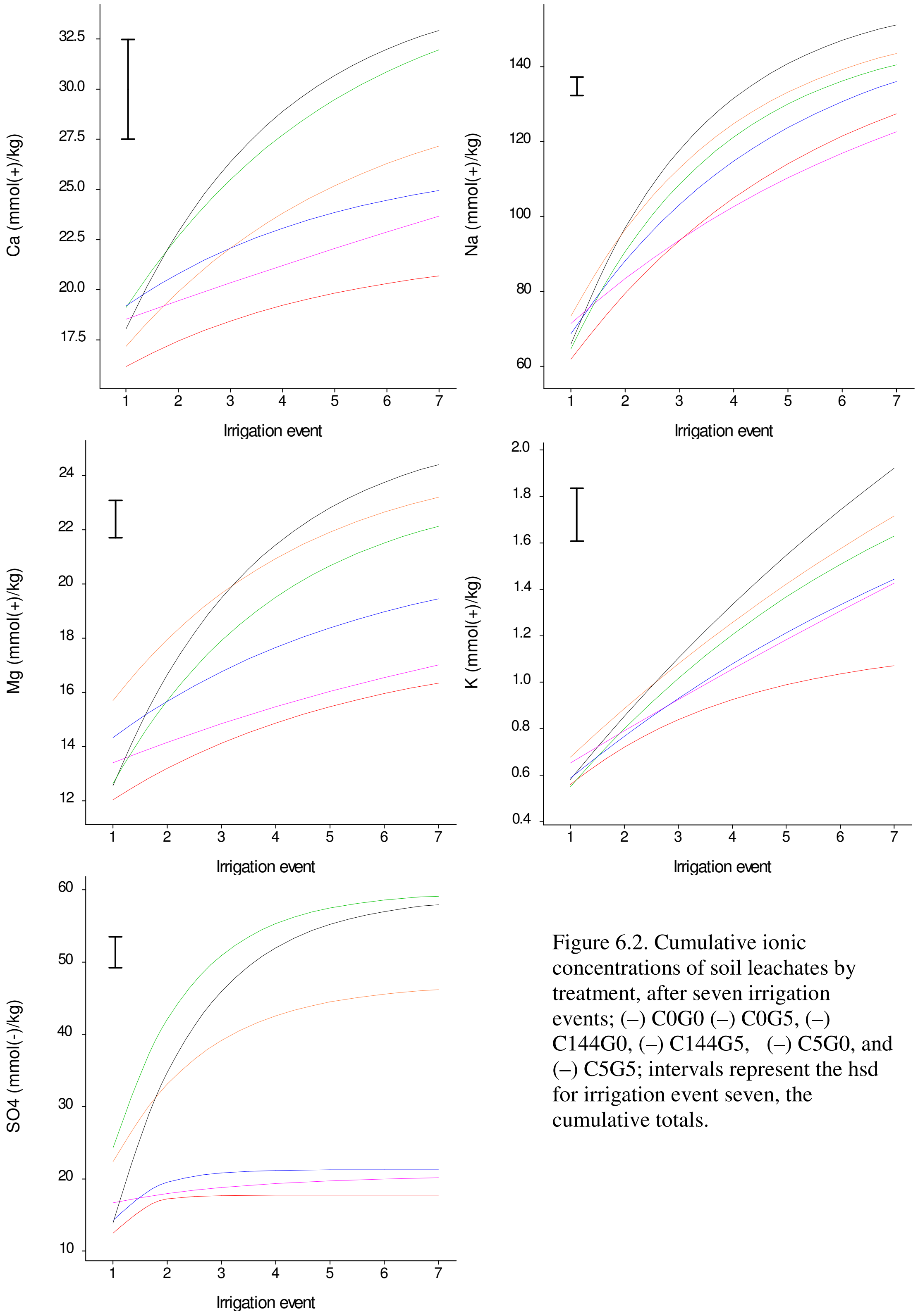


Figure 6.2. Cumulative ionic concentrations of soil leachates by treatment, after seven irrigation events; (–) C0G0 (–) C0G5, (–) C144G0, (–) C144G5, (–) C5G0, and (–) C5G5; intervals represent the hsd for irrigation event seven, the cumulative totals.

All soils (except the C5G0 treated soil) areobserved to leach more Na$^+$ than the control (Figure 6.2). The soils treated with C0G5 and C5G5 leach similar quantities of Na$^+$ and are both significantly higher in leached Na$^+$ than the C5G0 and C144G0 treated soils. The greatest amount of Na^+ leached is from the C144G5 treatment, but this could be expected considering the amount of soluble sodium applied (Table 6.3).

Where gypsum is applied, a significantly greater amount of leached Mg^{2+} is observed, although there are no significant differences between the soils treated with C0G5, C5G5 and C144G5 (Figure 6.2). Compost applied at 5 $t.ha^{-1}$ maintains a similar leaching trend to the control and is statistically similar at irrigation event seven, while the soil treated with C144G0 leachs significantly more Mg^{2+} than both the control and the C5G0 treated soils.

An increased leaching in K^+ is apparent for all treated soils in comparison to the control (Figure 6.2). However, the greatest amount of leached K^+ is generally observed where gypsum is applied, although the C0G5 treated soil is not significantly different to that treated with C144G0. The C5G5 treatment causes similar leaching to the C0G5 treatment, significantly more K^+ is leached than from both the C5G0 and C144G0 treated soils. The greatest leaching of K^+ occurs in the C144G5 treated soil, but this could be expected given the amount of K^+ applied with this treatment (Table 6.3).

The greatest leaching of SO_4^{2-} occurs where gypsum is applied, as could be expected (Figure 6.2). Where compost is applied alone, there are no significant differences in the amount of SO_4^{2-} leached as compared to the control soil. The C0G5 and C144G5 treated soils produce similar results and are both significantly higher in leached SO_4^{2-} than every other treatment, while the C5G5 treated soil is significantly greater than the control and both compost treatments.

6.3.2.B. Changes in leachate electrolyte concentration due to treatment application

The EC of the leachate is relatively similar at the start and end of the experiment under treated soils and the control soil, although some significant differences are apparent (Figure 6.3): after irrigation one the leachate EC is significantly lower in the soil treated with C5G0 as compared to all other soils, and by the end of the experiment all soils are similar to the control with the exception of that treated with C5G5, which proves to be significantly lower in EC than any other leachate. The greatest differences in leachate EC are observed between irrigation two and irrigation four, where soils treated with C0G5 and C144G5 maintain a significantly higher EC (compared to control and compost alone treatments) until irrigation five. In contrast, the C5G5 treated soil maintains a steady decline in leachate EC during this period; at irrigation two it is similar to that treated with C144G5, but by irrigation three is comparable to the control soil. By forecasting the results of the subsequent irrigations through the use of the non-linear trend line models, it is predicted that the EC of the leachate will not decrease significantly within two subsequent irrigations as trends approached a horizontal asymptote.

6.3.3. Changes in saturated hydraulic conductivity

The greatest increase in K_s occurs with the highest application of compost in conjunction with gypsum (C144G5), followed by the C144G0 treated soil (Figure 6.4). This might be expected given the magnitude of the organic matter applied to the soil, although the C144G5 treated soil also has significantly higher K_s than that treated with C144G0 (Figure 6.4). The application of gypsum generally causes an increase in K_s in all cases, with the C0G5 and G5G5 treated soils being statistically similar. However, comparing soils treated with C0G5 and C5G5, only the C5G5 treated soil has a significantly greater K_s than the control soil and that under the C5G0 treatment.

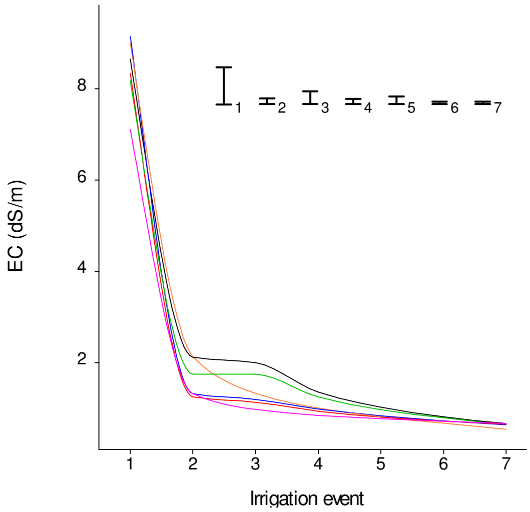


Figure 6.3. Differences in leachate electrical conductivity over seven irrigation events 2 weeks apart; (–) C0G0 (–) C0G5, (–) C144G0, (–) C144G5, (–) C5G0, and (–) C5G5; the interval represents the hsd at the irrigation event with the same number

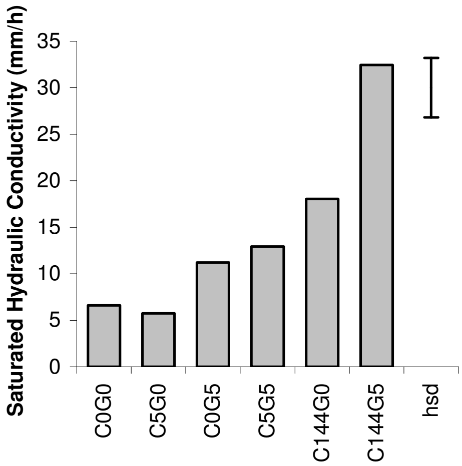


Figure 6.4. Differences in saturated hydraulic conductivity after 14 weeks; the interval represents the h.s.d. between means.

6.4. Discussion

The soil used for this experiment is moderately sodic (Northcote and Skene 1972) with a propensity for dispersion and a likelihood of sub-optimal infiltration. Generally, this soil is responsive to both chicken manure compost and gypsum in reducing the negative effects of sodicity. However, there appears to be greater reduction in sodicity under the use of compost and gypsum blends. What follows is an analysis of the major results observed.

6.4.1. *Effects of treatment application on cation exchange*

After 14 weeks, the overall effect of treatment application is to decrease the ESP of the soil. However, the cation exchange for Na^+ that occurs is different for treatments containing gypsum and those that do not. Whether gypsum is applied alone or in combination with CMWSC, Ca^{2+} concentration increases, while Na^+ concentration decreases. This Ca^{2+}–Na^+ exchange is the well-documented result of gypsum application to sodic soils (Loveday 1976; Oster 1982; Greene and Ford 1985). The same exchange was suggested as the means by which dispersion was reduced through the use of poultry manure in a sodic Vertosol (Ghosh *et al.* 2010). However, upon examination of the exchange occurring as a result of CMWSC application in this study, it is apparent that Ca^{2+} concentration does not increase where Na^+ concentration decreases. Instead, K^+ levels enhance and cause the subsequent reduction in ESP. It is possible to explain these exchanges by considering the ratio of soluble K^+ and Ca^{2+} to the other major soluble cations within the various compost blends applied (Table 6.5); the soluble cation composition of CMWS alone is dominated by K^+, while the gypsum/compost blends are dominated by Ca^{2+}.

Table 6.5 Ratios of major soluble cations to soluble potassium and calcium of the various compost blends

Ratios calculated from Table 3

Compost blend	*K:Ca*	*K:Mg*	*K:Na*	*Ca:Mg*	*Ca:Na*	*Ca:K*
C144G5	0.14	0.64	0.97	4.58	6.89	7.12
C5G5	0.07	0.44	0.87	6.18	12.28	14.05
C144G0 †	1.16	1.05	1.64	0.90	1.42	0.87
C5G0 †	1.16	1.05	1.64	0.90	1.42	0.87

† These treatments were sourced from the same compost

While K^+ is effective in lowering ESP, the magnitude of the effect is relatively small compared to that imposed by the Ca^{2+} dominant compost blends, and does not lower the ESP past the general ESP threshold of 6% (Northcote and Skene 1972), even at amendment rates ten times those commonly used. Accordingly, the application of this particular CMWSC alone is not suitable for the amelioration of sodicity through cation exchange. On the other hand, the significant exchange of Na^+ with K^+ may alleviate K nutritional imbalance previously caused by excess Na^+ (Ghosh *et al.* 2010).

Where gypsum is observed to lower ESP, a decrease in EMP is also seen. The role of Mg_{ex}^{2+} in soil dispersion relative to Na_{ex}^+ has been investigated by many researchers (Emerson and Bakker 1973; Chi *et al.* 1977; Rengasamy *et al.* 1986). Rengasamy *et al.* (1986) showed that as the Ca:Mg ratio of sodic soils (SAR>3 ≈ ESP 6%) decreased below unity, the incidence of dispersion increased. Additionally, for an irrigated red-brown duplex soil (Chromosol), a Ca:Mg ratio of 2 was presented as desirable (Cockcroft and Tisdall 1978).

None of the final Ca:Mg ratios of the soil used in this experiment have a Ca:Mg ratio below 1, suggesting that dispersion due to Mg^{2+} would be unlikely. Furthermore, where gypsum is applied the ratio is approxmiately the desirable value of 2. From Table 6.5, it is clear that the gypsum/compost blends increase the Ca:Mg ratio of the soil, meaning that dispersion due to exchangeable Mg^{2+} is highly unlikely. However, the Ca:Mg ratio for the CMWSC alone is below 1 and may present concern for dispersion due to exchangeable Mg^{2+} increases. The observed results for EMP do not reflect this, with exchangeable Mg^{2+} levels comparable to the control soil where CMWSC at 5 $t.ha^{-1}$ is applied, and slightly lower at the 144 $t.ha^{-1}$ CMWSC application rate.

6.4.2. Combined effects of chicken manure/wheat straw compost and gypsumn on sodicity

The overall effect of combining CMWSC and gypsum is an improved soil environment as compared to the application of CMWSC or gypsum alone at similar rates. The major results attesting to this are presented below:

5. The C5G5 treated soil, while statistically similar to the C0G5 and C144G5 treated soil concerning exchangeable cations, consistently displayed the better mean values for ECP, EMP and ESP (higher ECP, lower EMP and ESP). The three major exchangeable bases considered to define soil structural stability as previously discussed.

6. The only treatment to constantly and significantly ($p<0.05$) increase soil ECP and reduce soil EMP and ESP values, as compared to the C5G0 and C144G0 treatments, is the C5G5 treatment.

7. Significantly less Ca^{2+} is leached out of the C5G5 treated soil than the C0G5 soil, despite similar total Ca^{2+} amounts applied with both treatments. One ton per hectare of gypsum contains 200 $kg.ha^{-1}$ of Ca^{2+} (20% Ca^{2+} concentration recorded in product analysis), equating to 1000 $kg.ha^{-1}$ of Ca^{2+} applied in the C0G5 treatment, while the C5G5 treatment contains 94.6 $kg.t^{-1}$ of Ca^{2+} (calculated from the total Ca^{2+} concentration of the C5G5 CMWSC, in Table 6.3), equating to 946 $kg.ha^{-1}$ at the rate of 10 $t.ha^{-1}$ (required to achieve 5 $t.ha^{-1}$ CMWSC and 5 $t.ha^{-1}$ gypsum). Significantly less SO_4^{2-} is also leached from the C5G5 treated column as compared to that treated with C0G5, while the levels of Na^+ and Mg^{2+} leached from the C5G5 treated column are appreciably higher, but not statistically different.

8. The K_s of the C5G5 and C144G5 treated soils is significantly higher than the relative CMWSC-alone treated soils. Although the soil columns treated with C5G5 display a slightly greater mean value for $K_{s,}$ this result is not statistically significant ($p<0.05$). However, the C5G5 treated soil is significantly different to the control soil, where that treated with C0G5 is not.

Recent studies have shown that the use of various organic based composts, including manures, have had no, or very little, effect on exchangeable sodium concentration in soils (Madejon *et al.* 2001; Hanay *et al.* 2004; Jalali and Ranjbar 2009; Turner *et al.* 2010). Furthermore, when compared with gypsum, the effect of compost on ESP is often lower or dwarfed by that of gypsum (Hanay *et al.* 2004; Jalali and Ranjbar 2009). This trend is apparent in the results of this experiment. However, by incorporating gypsum into the composting cycle, greater decreases in ESP are observed for the C5G5 treated soil with lower Ca^{2+} inputs as compared to gypsum alone. While this could quite simply be an additive effect of compost and gypsum on ESP, this is unlikely. The addition of exchangeable K^+ is responsible for lowering the ESP in compost-alone treated soils, while Ca^{2+} is responsible in gypsum/compost-blended treated soils and K^+ is leached at higher rates from these. Furthermore, in an experiment where gypsum was applied one month prior to the application of municipal solid waste (MSW) a slight increase in ESP was observed as a result of the additive effects of gypsum and MSW (Hanay *et al.* 2004).

An experiment applying sewage sludge and gypsum in combination (although not composted in unison), and gypsum singularly, to bauxite residue showed that hydraulic conductivity was increased where a high rate combination was used, while the use of gypsum alone generally resulted in a slightly lower hydraulic conductivity (Wong and Ho 1991). Exchangeable sodium percentage and hydraulic conductivity are known to be strongly negatively correlated (Quirk and Schofield 1955), as also found by Wong and Ho (1991) with an r-value of -0.71 (p<0.001) for a red mud. Similar hydraulic conductivity changes to those of Wong and Ho (1991) were obtained for this experiment between the C5G5 and C0G5 treated soils, while the high rate application (C144G5) was not comparable, due to a much greater change compared to the C0G5 treated soil. However, the correlation between ESP and K_s (data not presented) is relatively low (r=-0.38) and not significant (p=0.12). The most likely reason for this result is that the C5G5 treatment has a greater impact on ESP than the C144G5 treatment, while for K_s the reverse is true. It is also possible that this observed enhanced infiltration is due to physical binding of soil aggregates by organic matter (Tisdall and Oades 1979; Tisdall 1991; Tisdall *et al.* 1997; Nelson *et al.* 1999). However, the combination of CMWSC and gypsum is observed to out perform CMWSC-alone.

The results obtained in this study might suggest a synergy between CMWSC and gypsum. However, the effect is not necessarily greater than the sum of the individual treatment effects. Indeed, the driving mechanism for chemical amelioration is clearly Ca^{2+} exchange due to gypsum application/incorporation. In leachates where the greatest amount of Na^+ removal occurs there is also a higher incidence of SO_4^{2-} and Ca^{2+} leaching; these are treatments with gypsum incorporated. Therefore, we suggest that the organic matter has provided adsorption sites for dissolved Ca^{2+} during composting, thus minimising Ca^{2+} leaching from the soil. This is most evident in the soluble cation leachate results for the C5G5 treated soil. The possibility of soil aggregate stability being augmented through the process of physical binding by organic matter can not be ignored as an added benefit, but was not directly measured in this circumstance.

6.4.3. Compost application rates

Much of the of research describing the use of compost on sodic soils is based on application rates much greater than those applied on a regular commercial basis (e.g. Wong and Ho 1991; Hanay *et al.* 2004; Jalali and Ranjbar 2009; Ghosh *et al.* 2010; Turner *et al.* 2010). Edmeades (2002), with reference to liquid fertilisers derived from natural products, demonstrated through a review of amendment application experiments (published and unpublished) that numerous organic amendments needed to be applied at a rate many times that recommended in order to achieve a tangible effect. For these reasons, both an exaggerated and a commercially viable rate were used in this experiment. With the exception of K_s, the results presented show that the lower treatment application rates (C5G0 and C5G5) are comparable in effect to the relatively higher rates of application (C144G0 and C144G5). The C144G5 treatment contained a greater amount of Na^+ (presumed an artefact of gypsum to compost ratio), which resulted in an increased addition of Na^+ to the soil as compared to the lower treatment application of C5G5. The C5G0 and C144G0 treatments have similar effects on the soil exchangeable cations pecentages. This can be attributed to the fact that both rates add the same ratio of exchangeable cations to the soil, and the fact that the CMWSC is inherently low in Ca^+ compared to other cations. There is evidently little advantage in applying large rates of this CMWSC for the chemical amelioration of sodic soils.

Hanay and Yardimci (1992) suggest that even small amounts of organic matter application can have significant effects on physical and biological properties such as aggregate stability, water-holding capacity and plant available nutrients. The most common process of aggregate stabilisation by organic matter is through binding and cementation, the degree to which these occur depending on the magnitude of soil and plant biological activity (Tisdall and Oades 1979; Tisdall *et al.* 1997; Clark *et al.* 2007; Clark *et al.* 2009). It could therefore be possible that the C5G0 treatment increased soil aggregate stability within the leaching columns. Soil hydraulic conductivity is strongly positively correlated to aggregate stability (So and Aylmore 1993), and thus can be used to speculate on soil structural stability. Consequently, given the hydraulic conductivity observed for the C5G0 treated soil, it is unlikely that low application fates for this CMWSC are sufficient to provide a short-term increase in aggregate stability. This may be due to low microbial activity within the soil and the compost (Clark *et al.* 2007). Conversely, CMWSC applied at 144 t.ha^{-1} resulted in a K_s approximately five times greater than that observed for the control, which is likely to have resulted from soil aggregate binding and the creation of physical bio-channels (Tisdall and Oades 1979; Tisdall 1991; Tisdall *et al.* 1997; Nelson and Oades 1998; Nelson *et al.* 1999).

As previously discussed, the final EPP of the soil is greater for CMWSC treated soils, providing a possible nutrient benefit (Ghosh *et al.* 2010), The EPP increases with an increase in application rate, but not necessarily to a large extent (Table 6.3 and Table 6.4). Other nutrients were beyond the scope of this study, but would most likely increase with application rate (Chen *et al.* 2010; Ghosh *et al.* 2010). Hence, while the application of compost materials at high hates increases hydraulic conductivity and nutrient application, it is not necessarily beneficial to the amelioration of sodicity.

6.4.4. Longevity of electrolyte effect as affected by treatment application

The role of EC in counteracting the potential for dispersion and maintaining soil stability in sodic soil is well documented (see Sumner 1993), and is dependent on the presence of soluble salts, the chemical composition of percolating solutions and the magnitude and frequency of wetting. Through the application of gypsum and/or manure composts it has been shown that increases in EC can result, and that these increases are often responsible for improved structural stability (Valzano *et al.* 2001b; Jalali and Ranjbar 2009; Ghosh *et al.* 2010). The final $EC_{1:5}$ (after 14 wks) observed for the commercial rate compost, gypsum and gypsum/compost blend are no different to that of the control, while the EC of the C144G5 and C144G0 treated soils are marginally higher than that of the control. Valzano *et al.* (2001b) concluded that the EC effect of gypsum was predominantly a short-term (one year) effect that decreased substantially in the long-term (three years) for a Brown Sodosol (Isbell 2002). These results were obtained from a dryland farming system that received 650 mm (6.5 Ml.ha^{-1}) over the three year period; approximately the same amount of irrigation water that passed through the leaching columns used in this study in only 14 wks. Furthermore, Jalali and Ranjbar (2009) showed that the final EC of leachates and the leached soil were comparable for sodic soil (Typic Calcixerolic Xerochrept) treated with gypsum, sheep manure, poultry manure, or not treated at all. These results were obtained from leaching columns with twenty pore volumes. While the final leachate EC and leached soil EC of the current study are substantially different, it is apparent from the trend line of the leachate EC that a horizontal asymptote was present and that the final treatment/control ECs were close to this. Accordingly, the lack of $EC_{1:5}$ effect after 14 wks for compost, gypsum, and compost/gypsum commercial rates can be attributed to the magnitude of leaching caused by irrigation.

Throughout the experiment significant differences in EC between treatments are apparent within EC_{24h} and EC_{2wk} data, which are likely to be governed by soil moisture variability. The effect of soil moisture can be demonstrated by considering the 24 h post-irrigation data (Figure 6.1a) and the final data for K_s (Figure 6.4). The final EC_{24h} distribution of means (post-irrigation seven) matches the differences in K_s values between the differently treated soils. It is probable that EC_{24h} values for treatments with greater K_s are higher than those with lower K_s due to faster drainage, quicker drying and a concentration of remaining salts. On the other hand, by increasing the soil volume with compost it could be expected that these leaching columns would retain more moisture (Wahid *et al.* 1998). This would explain the similar and lower EC_{2wk} obtained for the C144G0 and C144G5 treatments compared to the C5G5 treatment; the former treatments would be expected to hold substantially more soil moisture after 2 wks. Soils that were not treated with gypsum, or an exaggerated compost application, would likely take longer to drain and also have diluted EC_{2wk} as compared to soils treated with gypsum. For these reasons, the differences in final $EC_{1:5}$, EC_{24h} and EC_{2wk} are not considered to be conflicting, merely indicative of the soil in different states. Thus, two soils with similar EC, but one with a greater drainage potential, will appear to have different ECs using the direct EC measurement without moisture correction; the soil with greater potential to drain will dry quicker and the reaming salts will become concentrated, thus producing the counterintuitive result. The practical significance of this for irrigated agriculture is in the fact that treatments with a greater ability to drain between irrigation events are more likely to maintain a higher EC that could be beneficial to soil structural stability during the next wetting phase.

Within four irrigation events all treated soils have substantially smaller in EC at both 24 h and 2 wk post-irrigation. Supporting this, the EC of the leachate after four irrigation events also shows that the majority of soluble salts had been leached within this time frame or sooner. Therefore, it is apparent that the longevity of the EC effect is limited to less than 14 wks for the soil under a simulated irrigation wetting and dying cycle in laboratory conditions, due to the magnitude and frequency of application of irrigation water. However, caution must be taken in interpreting these results to the field condition. The repacked leaching columns created an environment where initial drainage would be greater than could be expected under field conditions. Nonetheless, the K_s after 14 wks (control: 6.59 $mm.h^{-1}$; C144G5: 32.46 $mm.h^{-1}$) was substantially lower than mean K_s values (41.6 and 38.9 $mm.h^{-1}$ respective to valley) estimated for six Vertosols in the Lachlan and Maquarie Valleys (Vervoort *et al.* 2003). Based on our K_s results, it is possible to suggest that the final hydraulic conductivity presented is somewhat conservative with reference to the field conditions observed by Vervoort *et al.* (2003). However, it is likely that the 24 h saturation of the soil columns prior to K_s has caused complete swelling of the clay. This is a circumstance that is unlikely to be achieved directly under a disc permeameter, as in the study of Vervoort *et al.* (2003), and is a probable explanation of the differences in values. Even still, it is fair to suggest that the EC effect in this irrigated soil under field condition would not persist up to a year as shown in dryland agriculture (Greene and Ford 1985; Valzano *et al.* 2001a; Valzano *et al.* 2001b), due to the magnitude and frequency of irrigation water application.

6.5. Conclusion

Addition of organic matter and Ca^{2+} in the form of gypsum-enhanced-CMWSC significantly reduced ESP and EMP, enhanced ECP, increased the soil K_s, and improved nutrient levels in the form of K^+. The chemical amelioration was mainly attributed to Ca^{2+} exchange interactions between the soil and gypsum. This process was observed to be greatest when compost containing 5 t.ha^{-1} gypsum and 5 t.ha^{-1} chicken manure-wheat straw was used, due to retention of Ca^{2+} on organic exchange sites. The increase in hydraulic conductivity was due to an interaction effect between gypsum and CMWSC, and was greatest where CMWSC rates were highest. The nutrient effect was entirely attributable to CMWSC presence in the soil, and again improved significantly where greater application rates were used, although not proportionally. It is therefore concluded that the only obvious advantage of high rate application is an increase in hydraulic conductivity, and that in order to ameliorate sodic soil it is more beneficial to use a lower rate of compost enhanced with gypsum. However, the use of gypsum alone at 5 t.ha^{-1} was often comparable to the C5G5 treatment, hence the question of cost to benefit is raised. It is therefore suggested that further combination rates of gypsum to CMWSC should be explored in future research. These effects were also only observed over a 14 week period. Previous research pertaining to gypsum use in field conditions has shown that a decreased ESP can be observed beyond this time frame, but this decrease is known to ebb in relation to the magnitude and condition of percolating water (Greene and Ford 1985; McKenzie *et al.* 1993; Valzano *et al.* 2001a; Valzano *et al.* 2001b). Thus, it would be advantageous to observe the ability of gypsum-enhanced-CMWSC to retain Ca^{2+} and provide chemical amelioration over periods between 1 and 3 years.

The rise in soil EC caused by the various treatments was shown to be short-lived, diminishing significantly within the 14 weeks of the experiment. The majority of electrolyte was observed to leach from the soil columns within four irrigations, or less. Only the high application rates resulted in a significantly higher soil EC upon completion of the experiment. However, the practical implications of this were minimal, with the increase being no more than 4 mS.m^{-1}. It was also found that enhanced drainage caused the soil EC, with reference to direct measurement at a given time post-irrigation, to appear more concentrated during drying cycles due to faster drainage and quicker drying. This concentration of remaining salts would be beneficial to soil stability upon subsequent irrigations.

The results of this laboratory based experiment were obtained from repacked core leaching columns. It is stressed that care should be taken when transposing these findings to field conditions. There is a paucity of information concerning the use of gypsum-enhanced-CMWSC and further information would be beneficial prior to commercial use of such a technique. Furthermore, these results are limited to composts of similar chemical composition and material constitution.

6.6. Acknowledgements

The authors wish to thank the Cotton Research and Development Corporation, the Cotton Catchment Communities Cooperative Research Centre, the Central West Catchment Management Authority and the New South Wales Department of Industry and Innovation (nee Department of Primary Industries) Healthy Soils for Sustainable Farms program for funding this project. Appreciation is extended to Mr Rick Storrier for supply and production of the compost and materials, and Mr Scott Laird for access to his soil. Technical assistance from Mr Tom Savage, the University of Sydney, was greatly appreciated, while statistical analysis advice was also sincerely appreciated from Dr Joe Chapman, the University of New South Wales (Australian Defence Force Academy).

6.7. References

Chen, L, Tubali, K, Kost, D, Dick, W (2010) Effects of gypsum enhanced composts on yields and mineral compositions of broccoli and tall fescue. *Journal of Plant Nutrition* **33,** 1040-55.

Chi, CL, Emerson, WW, Lewis, DG (1977) Exchangeable calcium, magnesium and sodium and the dispersion of illites in water. I. characterisation of illites and exchange reactions. *Australian Journal of Soil Research* **28,** 243-53.

Clark, GJ, Dodghsun, N, Sale, PWG, Tang, C (2007) Changes in chemical and biological properties of a sodic clay subsoil with addition of organic amendments. *Soil Biology and Biochemistry* **39,** 2806-17.

Clark, GJ, Sale, PWG, Tang, C (2009) Organic amendments initiate the formation and stabilisation of macroaggregates in a high clay sodic soil. *Australian Journal of Soil Research* **47,** 770-780.

Cockcroft, B, Tisdall, JM (1978) Soil management, soil structure and root activity. *In* 'Modifications fo soil structure'. (Eds. Emerson, WW, Bond, RD & Dexter, AR) (John Wiley: Chichester)

Cordell, D, Drangert, J-A, White, S (2009) The story of phosphorus: Global food security and food for thought. *Global Environmental Change* **19,** 292-305.

Craze, B, Holman, G, Chapman, GA, Stone, MJ (1993) 'Soil testing procedures of the NSW Department of Conservation and Land Management', (NSW Department of Conservation and Land Management: Sydney)

Edmeades, DC (2002) The effect of liquid fertilisers derived from natural products on crop, pasture, and animal production: a review. *Australian Journal of Agricultural Research* **53,** 965-76.

Emerson, WW, Bakker, AC (1973) The comparative effects of exchangeable calcium, magnesium, and sodium on some physical properties of red-brown earth subsoils. II. The spontaneous dispersion of aggregates in water. *Australian Journal of Soil Research* **11**.

Falcón, M, Corominas, E, Pérez, M, Perestelo, F (1987) Aerobic bacterial populations and environmental factors involved in the composting of agricultural and forest wastes of the Canary Islands. *Biological Wastes* **20,** 89-99.

Fraiture, Cd, Wichelns, D, Roskstrom, J, Kemp-Benedict, E (2007) Looking ahead to 2050: scenarios of alternative investment approaches. *In* 'Water for food, water for life: A comprehensive assessment of water management in agriculture'. (Eds. Molden, D) (Earthscan: Colombo)

Ghosh, S, Lockwood, P, Hulugalle, NR, Daniel, H, Kristiansen, P, Dodd, K (2010) Changes in properties of sodic Australian Vertisols with application of organic waste products. *Soil Science Society of America Journal* **74,** 153-60.

Greene, RSB, Ford, GW (1985) The effect of gypsum on cation exchange in two red duplex soils. *Australian Journal of Soil Research* **23,** 61-74.

Hajkowicz, S, Young, M (2005) Costing yield loss from acidity, sodicity and dryland salinity to Australian agriculture. *Land Degradation and Development* **16,** 417-33.

Hanay, A, Buyuksonmez, F, Kizilogu, FM, Canbolat, MY (2004) Reclamation of saline-sodic soils with gypsum and MSW compost. *Compost Science and Utilization* **12,** 175-9.

Hanay, A, Yardimci, N (1992) A research on the effects of municipal composts and barnyard manure on some physical and chemical properties of soils and soil-water relations. *Doga-Transaction Journal of Agriculture and Forestry* **16,** 91-102.

Isbell, RF (2002) 'The Australian soil classification: revised edition', (CSIRO Publishing: Melbourne)

Jalali, M, Ranjbar, F (2009) Effects of sodic water on soil sodicity and nutrient leaching in poultry and sheep manure amended soils. *Geoderma* **153,** 194-204.

Loveday, J (1976) Relative significance of electrolyte and cation exchange effects when gypsum is applied to a sodic clay soil *Australian Journal of Soil Research* **14,** 361-71.

Madejon, E, Lopes, R, Murillo, YM, Cabrerra, F (2001) Agricultural use of three (sugar - beet) vinasse compost: effect on crops and chemical properties of a cambisol soil in Quadalquirvirm River Valley (SW Spain). *Agricultre, Ecosystems & Environment* **84,** 55-65.

McKenzie, DC, Abbott, TS, Chan, KY, Slavich, PG, Hall, DJM (1993) The nature, distribution and management of sodic soils in New South Wales. *Australian Journal of Soil Research* **31,** 839-68.

Miller, RO (1998) Nitric-perchloric acid wet digestion in an open vessel. *In* 'Handbook of Reference Methods for Plant Analysis'. (Eds. Yash, PK) (CRC Press: Boca Raton, Florida)

Murphy, BW (2002) Sodic soils: formation and global distribution of. *In* 'Encyclopedia of soil science'. (Eds. Lal, R) (Marcel Dekker: New York)

Nelson, PN, Baldock, JA, Clarke, P, Oades, JM, Churchman, GJ (1999) Dispersed clay and organic matter in soil: their nature and associations. *Australian Journal of Soil Research* **37,** 289-315.

Nelson, PN, Oades, JM (1998) Organic matter, sodicity, and soil structure. *In* 'Sodic soils: Distribution, management and envirnomental consequences'. (Eds. Sumner, ME & Naidu, R) (Oxford University Press: New York)

Northcote, KH, Skene, JK (1972) *Australian soils with saline and sodic properties*. CSIRO Soil Publication 27, (CSIRO: Australia)

Oster, JD (1982) Gypsum use in irrigated agriculture: a review *Fertilizer Research* **3,** 73-89.

Quirk, JP, Schofield, RK (1955) The effect of electrolyte concentration on soil permeability. *Australian Journal of Soil Research* **6,** 163-78.

Rayment, GE, Higginson, FR (1992) 'Australian laboratory handbook of soil and water chemical methods', (Inkata Press: Sydney)

Rengasamy, P, Greene, RSB, Ford, GW (1986) Influence of magnesium on aggregate stability in sodic Red-Brown Earths. *Australian Journal of Soil Research* **24,** 229-37.

Smil, V (2000) Phosphorus in the environment: Natural flows and human interferences. *Annual Review of Energy and the Environment* **25,** 53-88.

So, HB, Aylmore, LAG (1993) How do sodic soils behave? The effects of sodicity on soil physical behaviour. *Australian Journal of Soil Research* **31,** 761-77.

Sumner, ME (1993) Sodic soils: a new perspective. *Australian Journal of Soil Research* **31,** 683-750.

Tisdall, AL, Smith, SE, Rengasamy, P (1997) Aggregation of soil by fungal hyphae. *Australian Journal of Soil Research* **35,** 55-60.

Tisdall, JM (1991) Fungal hyphae and structural stability of soil. *Australian Journal of Soil Research* **29,** 729-43.

Tisdall, JM, Oades, JM (1979) Stabilization of soil aggregates by the root systems of ryegrass. *Australian Journal of Soil Research* **17,** 429-41.

Tucker, BM (1985) A proposed new reagent for the measurement of cation exchange properties of carbonate soils. *Australian Journal of Soil Research* **23,** 633-42.

Turner, JC, Hattey, JA, Warren, JG, Penn, CJ (2010) Electrical conductivity and sodium adsorption ratio changes following annual applications of animal manure amendments. *Communications in Soil Science and Plant Analysis* **41,** 1043-60.

Valzano, FP, Greene, RSB, Murphy, BW, Rengasamy, P, Jarwal, SD (2001a) Effects of gypsum and stubble retention on the chemical and physical properties of a sodic grey vertosol in western Victoria. *Australian Journal of Soil Research* **39,** 1333-47.

Valzano, FP, Murphy, BW, Greene, RSB (2001b) The long term effects of lime ($CaCO_3$), Gypsum ($CaSO_4.2H_2O$), and tillage on the physical and chemical properties of a sodic red-brown earth. *Australian Journal of Soil Research* **39,** 1307-31.

Vervoort, RW, Cattle, SR, Minasny, B (2003) The hydrology of Vertosols used for cotton production: I. Hydraulic, structural and fundamental soil properties. *Australian Journal of Soil Research* **41,** 1255-72.

Wahid, A, Akhtar, S, Ali, I, Rasul, E (1998) Amelioration of saline-sodic soils with organic matter and their use for wheat growth. *Communications in Soil Science and Plant Analysis* **29,** 2307-18.

Willer, H, Yuseffi-Menzler, M, Sorenson, N (2008) 'The world of organic agriculture: Statistics and emerging trends 2008', (Earthscan: London)

Wong, JWC, Ho, GE (1991) Effects of gypsum and sewage sludge amendment on physical properties of fine bauxite refining residue. *Soil Science* **152,** 326-32.

IMPEDIMENTS TO THE ADOPTION OF SOIL HEALTH IMPROVEMENT STRATEGIES BY FARMERS IN CENTRAL WEST NSW

"I have never let my schooling
interfere with my education"
– Mark Twain

7. Impediments to the adoption of soil health improvement strategies by farmers in Central West NSW

J. McL. Bennett[ABC] *and S. R. Cattle*[A]

[A] Faculty of Agriculture, Food and Natural Resources, The University of Sydney, NSW 2006.
[B] Cotton Catchment Communities Co-operative Research Centre
[C] Cotton Research & Development Corporation

Abstract. There is inconsistency in the design, understanding, implementation and monitoring of soil health programs. Despite mounting scientific evidence for the credibility of certain soil health indicators, an increase in the reporting of program benefits, and progress in communicating these same benefits, farmers remain hesitant to implement structured management plans and strategies tailored to address soil health. The purpose of this research is to investigate the proportion of Lachlan and Macquarie Valley landholders who implement a structured soil health program and to better understand the impediments associated with the adoption of such programs. Non-parametric analysis of a mail-based survey supported with content analysis of landholder comments, suggests that the overall attitude towards soil health management is positive, although soil health management programs are often inconsistent, unstructured, or ad-hoc. This research highlights that impediments to the adoption of soil health programs are affected by region and that this is likely influenced by the availability, enthusiasm and motivation of surrounding environmental service providers. Ongoing communication between landholders, agronomists, extension agencies and scientists is shown to be vital in the adoption of soil health management programs. While the initial investment in soil health management is perceived as an impediment, landholders indicate that production longevity and long-term financial gain are achievable.

Additional keywords: attitudes, quality, extension, indicators, landholders, sodicity.

7.1. Introduction

Over the last two decades the expression ‘soil health’ has become increasingly prevalent in scientific documents, advertisements for agricultural company services, departmental extension programs, government-based discussion and policy, and farming communities. Although not a new topic, the importance placed on soil health by the Australian Government is exemplified by the recent Healthy Soils for Sustainable Farms (HSSF) program (Department of Agriculture Fisheries and Forestry 2008) where 6.51 million dollars was committed to get “more farmers moving to practices that maintain and restore our soils; which will, in turn, contribute to healthy catchments and sustainable agricultural enterprises” (Department of Agriculture Fisheries and Forestry 2008). An underlying reason for this governmental support of soil health programs is that the growing world-wide demand for food and fibre cannot be sustained with conventional high-input/high-output farming (Fraiture *et al.* 2007). Such conventional systems place enormous demands on the resilience of soils, often resulting in productivity and function decline. Governments and regulating authorities are often interested in the function of an entire catchment or ecosystem (Webster 1999), which usually relies on the correct function of the majority of individual properties within those catchments (Doran 2002). Hence, there is added motivation for governments and regulating authorities to encourage landholders to adopt programs promoting healthy soils. As there is a niche market for value-added, organically-grown produce, the incentives for managing soils without the use of chemicals have increased, also causing farmers to turn to soil health programs (Chellemi and Porter 2001).

There is inconsistency in the design, understanding, implementation and monitoring of soil health programs, primarily due to there being no one agreed definition for soil health. Research has shown that farmers tend to regard healthy soils as being those that produce healthy crops, with only a secondary consideration given to the absence of soil degradation problems such as poor soil structure and nutrient deficiency (Lobry de Bruyn and Abbey 2003). Nevertheless, the same research also reported that farmers have a tendency to choose multiple themes to explain a healthy soil, although these vary extensively (e.g. lack of erosion, organic matter content, soil feel). Hence, as farmers' understanding of soil health is inconsistent, there is an inherent bias in assessing soil health knowledge and farmers' attitudes towards implementing a soil health program. Compounding this, the term 'soil quality' is often used interchangeably with soil health, sparking debate amongst scientists. Soil quality can be defined as 'the capacity of a specific kind of soil to function within natural or managed ecosystem boundaries, to sustain biological productivity, maintain environmental quality, and promote plant and animal health' (Soil Science Society of America 1997). In comparison, the HSSF program (Department of Agriculture Fisheries and Forestry 2008) defines a healthy soil as 'one that is productive and easy to manage under the intended land-use…[with] chemical, biological and physical properties that promote the health of plants animals and humans, and contribute to profitable farming systems and growing regional economies as well as maintaining the environmental condition of our natural resources'. These definitions have obvious similarity. As proposed by Chellemi and Porter (2001), definitions for soil health and soil quality are similar in that they usually describe health or quality as a multifaceted system that is responsible for more than just maximised yield potential, or indeed any other single factor. Soil health notably provides connotations of disease or pathogens, which is something the term 'quality' is unlikely to suggest. However, the use of one term over the other is more likely due to a preference for that term, rather than there being a strong distinction between the two. Therefore, the term soil health has been used in this paper as it more explicitly recognises that a soil is a living entity, promotes the value judgement of healthy versus unhealthy, and is, most importantly, favourable with farmers

(Romig *et al.* 1995) and those responsible for developing policy (Department of Agriculture Fisheries and Forestry 2008).

The ambiguity with the definition of soil health has lead to a range of soil health systems with differing properties. Table 7.1 shows a number of soil health information resources and their foci. Some of the systems described and advice given are strongly biologically-focussed, while others are more chemically-focussed. Nonetheless, the majority of the resources in Table 7.1 implicitly or explicitly address the biological, chemical and physical components of a soil and its environment, indicating that concentration of effort on any single factor does not equate to management for a healthy soil. Furthermore, a healthy soil cannot be linked to a single quantifiable factor, such as pH or organic matter content; it has been usual for researchers and managers to identify groups of 'soil health indicators'. Over 90 different soil health indicators for plants, soil, location, techniques and animal-health/human-health have been reported (Romig et al. 1995; Hayman and Alston 1999; Carberry et al. 2002; Lobry de Bruyn and Abbey 2003; Desbiez et al. 2004; Mowo et al. 2006; Department of Agriculture Fisheries and Forestry 2008; Kelly et al. 2009). No single set of soil health indicators appears to be agreed upon by researchers or managers. However, a common concept drawn from the literature is the usefulness of soil health indicators for incorporation into a soil health program by the intended users; farmers.

The adoption of soil health programs in Australia has been slow. Despite mounting scientific evidence for the credibility of certain soil health indicators, an increase in the reporting of program benefits, and progress in communicating these same benefits, farmers remain hesitant to implement structured management plans tailored to address soil health. Kelly *et al.* (2009) proposes that farmers are losing connectivity with their land due to an over-reliance on agronomists and a decline in one-on-one advisory services from the public sector. Moreover, extension efforts and methodologies have been questioned for appropriateness by Industry Commissions (Industry Commission 1998). Lobry de Bruyn and Abbey (2003) observe that soil health programs and their indicators are often too complex to be implemented by farmers independent of external assistance and advice, while Wilkinson (1996) foresees that farmers will have to manage their soil, and prove that they have been, due to increasing national pressure for regulation. However, in order for this to occur it is first important to understand what impediments face the implementation of soil health programs. Based on previous impediment surveys of landholders (May 2006; Mylek 2006), we suggest there are six broad categories of impediments for the adoption of soil health programs: education and training impediments; agencies and extension organisation-related impediments; land-use associated impediments; market impediments; economic impediments;

and, personal and social impediments. Education and training impediments refer to the complexity of many soil health programs and their indicators. Agency and extension impediments are centred on the quality/existence of expert and technical advice regarding the implementation of innovations. Land-use impediments include previous land-use planning and the level to which these plans are currently embedded. Market impediments consider distance to amendment sources and availability of a market for providing environmental services such as carbon pooling. Economic impediments refer to capital gain and expenditure with relation to factors such as risk, staffing and production size. Personal and social impediments involve factors such as local culture, moral stance, time/commitment ratios and lifestyle. These categories allow us to understand farmers' attitudes, opinion and beliefs towards soil health at the individual and community level. Analysis of these attitudes, opinions and beliefs will aid in addressing the concerns of the Industry Commission (1998), which are that farmers have been treated as homogenous groups in past research by scientists and that there is a lack of understanding of the farmer's individuality.

The purpose of this paper is to first investigate the proportion of farmers currently implementing a structured soil health program on their property, through a survey of the Lachlan and Macquarie Valley catchments of New South Wales, and second, to understand the ongoing impediments associated with the implementation of such a program.

7.2. Methods

7.2.1. Sampling area

The data used in this study was collected from landholders in the Lachlan and Macquarie Valleys of New South Wales (Figure 7.1). The area between Hillston and Griffith, while not in the Lachlan Valley, was included as Griffith is the major city responsible for services to the western region of the Lachlan Valley; a 30 km radius was used to determine the boundary to the south of Griffith. The south eastern region of the Lachlan Valley, as depicted in Figure 1, was excluded from the study due to a limitation imposed by the participant database available. Where data was split into regions, participants were sorted by postcode into 10 pre-defined regions (Hillston/Griffith, Condobolin/Lake Cargelligo, Orange/Molong/Cowra, Bathurst, Parkes/Forbes, Dubbo/Wellington, Mudgee, Coonabarabran, Coonamble, and Nyngan/Warren). These regions were determined largely by the central/main location of environmental services available to the region. A 50 km radius around major towns (e.g. Nyngan and Warren in Nyngan/Warren region) was additionally used to aid in the allocation of participants to region, except for Parkes/Forbes, Orange/Molong/Cowra, Bathurst, the east of Wellington, and the south of Griffith, where a 30 km radius was used. Landholdings that fell into two regions or no region were excluded from regional analysis.

Table 7.1. A selection of soil health resources and their soil property focus

Resource	*Organisation*	*Year of formation or earliest publication*	*Origin*	*Focus*	*Website address**
Organic NZ	Soil & Health Association of New Zealand Inc.	1941	Auckland, New Zealand	organic farming	http://www.organicnz.org/
Victorian resources online - Soil Health	Department of Primary Industries	1996	Victoria, Australia	soil chemical, physical and biological properties and the interaction with human environments	www.dpi.vic.gov.au/dpi/vro/vrosite.nsf/pages/soilhealth_home
Soil and Health Library	Independent - Steve Solomon	1997	Tasmania, Australia	holistic agriculture	www.soilandhealth.org
Better Soils	Agriculture Bureau of South Australia	1997	South Australia, Australia	soil chemical, physical and biological properties	http://bettersoils.soilwater.com.au/about.htm
The Good Soils Project	The National Heritage Trust	1999-2001 (program finished)	New South Wales, Australia	soil chemical, physical and biological properties	http://www.tuckombillandcare.org.au/projects/good%20soil%20project.htm
Soil Health: Biological Chemical Physical	University of Western Australia	2000	New South Wales, Australia	soil biology	www.soilhealth.com
SINDI: soil quality indicators on the web	New Zealand Foundation for Research, Science and Technology	2000	New Zealand	soil chemical, physical and biological properties	http://sindi.landcare.cri.nz/
Worldewide portal to information on soil health	The Tropical Cover and Organic Resource Exchange	2001	New York, United States of America	soil chemical, physical and biological properties	http://mulch.mannlib.cornell.edu/TSHomepage.html
Healthy Soils for Sustainable Farms	Land and Water Australia	2005-2008 (program finished)	Australia	soil chemical, physical and biological properties	http://lwa.gov.au/programs/healthy-soils-sustainable-farms
Soil Health and Fertility (website section)	New South Wales Department of Primary Industries	2005	New South Wales, Australia	soil chemical, physical and biological properties	www.dpi.nsw.gov.au/agriculture/resources/soils
Cornell Soil Health	Cornell University College of Agriculture and Life Science	2007	New York, United States of America	soil chemical, physical and biological properties	http://www.hort.cornell.edu/soilhealth/
SoilQuality.org.au	Soil Quality	2007	Western Australia, Australia	soil chemical, physical and biological properties	www.soilquality.org.au
Healthy Soils and Healthy Landscape	PROfarm - developed by Industry & Investment New South Wales	2008	New South Wales, Australia	soil chemical, physical and biological properties	http://www.dpi.nsw.gov.au/agriculture/profarm/courses/healthy-soils-and-healthy-landscape
Soil Health Knowledge Bank	Department of Agriculture, Fisheries and Forestry	2009	Canberra, Australia	soil chemical, physical and biological properties	http://soilhealthknowledge.com.au/
Nutriplanner/Nulogic	Elders	Undisclosed	Australia wide	chemical properties (mainly nutrients)	http://cropping.elders.com.au/farm-supplies/agronomic-advice
Soil Quality - Natural Resources Conservation Service	United States Department of Agriculture	Undisclosed	North Carolina, America	soil chemical, physical and biological properties	http://soils.usda.gov/sqi/

*Accessed 5th June 2010

7.2.2. Sampling method

Data was collected via a mail-based survey consisting primarily of Likert-based scales (Likert 1932), categorical selection and dichotomous response questions (Table 7.2). There was opportunity provided for an open response concerning the impediments and incentives for the adoption of soil health management (SHM) strategies. Technical terms used in the construction of questions were representative of those often used by agronomists, extension agencies and landholders. The survey was based on a survey template used in the studies of May (2006) and Mylek (2006) with further reference to the tailored design method (Dillman 2007). The information to be sent to each participant included a letter of explanation, the survey, a return addressed envelope and a stamp.

Figure 7.1. The boundaries of the survey sampling region; (**–**) represents the region boundary

A participant database was obtained from various Livestock Health and Pest Authorities (LHPA) within the survey region; this database constitutes rate payers within each individual LHPA region. This was supplemented, where necessary, through the use of the White Pages$^{®}$, cross-referenced with a real-estate database for landholding size and title details. A mailing list was selected at random and stratified using demographics of council

Table 7.2. Variables used in the survey and the type of response requested for each variable

Variables	*Response form*		*Variable type*
Age	category	8 age brackets	auxiliary
Sex	dichotomy	male/female	auxiliary
Postcode	category		auxiliary
Region	category	10 regions with 'other' as an option	auxiliary
Property size	continuous		auxiliary
Main enterprise	category	8 enterprises with 'other' as an option	auxiliary
Primary occupation	dichotomy	farmer/other -provision to detail other occupation	auxiliary
Income viability	dichotomy	yes/no - provision for unsure	auxiliary
Income	category	6 income bands	auxiliary
Organisation membership*	dichotomy	yes/no - provision to detail numerous memberships	auxiliary
Workshop attendance**	dichotomy	yes/no - provision to detail numerous workshops	auxiliary
Planning related	dichotomy	yes/no	response/auxiliary
Soil health factors***	scale	5 point importance scale - not important to important	response
Management statements	scale	5 point Likert scale - strongly disagree to strongly agree	response
Impediments	scale	5 point Likert based scale - not an impediment to very large impediment	response
Incentives	scale	5 point Likert based scale - not an incentive to very large incentive	response

* For the purpose of the survey organisational memberships were defined as being environmentally or agriculturally related.

** For the purpose of the survey workshops included conferences, field days, farm walks and seminars.

*** Soil health factors are defined as soil attributes that comprise the state of a soil's health. They are not the same as soil health indicators, which we define as being designed to measure soil health factors.

regions. The surveys were initially sent to 1000 rural landholders within the boundaries of Figure 7.1. A rural landholder was defined as an individual or organisation with landholding equal to, or exceeding, 60 ha. However, responses were received with landholding less than 60 ha. These were excluded. Consequently, databases provided by the LHPA were cross-referenced with real-estate databases to exclude participants with landholdings less than 60 ha; where cross-referencing was unable to be achieved that participant was excluded. Participants were also qualified by whether or not they were the person, or part of the group, responsible for management decisions on the landholding; those who indicated they were not were excluded. The final number of eligible participants was 719.

The response rate achieved after the initial send out of the survey and one reminder card was approximately 20% $(n = 144, N = 719)$ following exclusion of ineligible participants. Non-response bias was assessed by obtaining a second sample ($n = 96, N = 100$) fromnon-responders (those who did not respond after the initial send out and reminder card) and comparing the frequency distributions for respondents and non-respondents of auxiliary variables. These variables were chosen as they described the demographic, while attitudes and opinions may not necessarily do this. As the second sample was provided via telephone, where possible, only questions that were unlikely to be affected by the method of data collection were asked; i.e. questions concerning age, sex, postcode, primary enterprise, primary occupation and property size. Income viability and income band were also requested over the telephone and while it is noted that these variables may have been subject to method bias, comparison between responders and non-responders were not significantly different. Indeed there were no significant differences observed between respondent and non-respondent frequency distributions.

7.2.3. Statistical analysis

Statistical analysis was conducted using *PASW Statistics 18* software package (IBM 2009). Frequency distributions were obtained for all variables, both response and auxiliary. For impediment and incentive data, the categories ‘large’ and ‘very large’ were combined as the landholder perceived difference between these categories was assessed as less well defined than between other categories. All other scales were reduced to three point scales for statistical analysis by collapsing the two lowest categories and two highest categories into single categories. Relationships between auxiliary variables and response variables were investigated through the use of Chi-square tests in conjunction with cross-tabulation. In these circumstances, Cramer’s V was used to test the strength of the relationship as it considers the degrees of freedom for both the row and column variable. Ordinal logistic regression (OLR) using a logit model was conducted to determine various auxiliary variables that improved the explanation of a response variable. However, OLR models were generally limited to a maximum of three auxiliary variables due to the sample size. The strength of the model association was assessed through the use of Nagelkerkes's R^2. Additionally, Spearman's Rank Order Correlation Coefficient (SROCC; ρ) was used to compare the relationship strength between a continuous auxiliary variable and ordinal response variables. In all cases where Spearman's ρ and Nagelkerke's R^2 are used, relationship strength and model effect, respectively, are defined as follows: very small $(\rho = R) < 0.1$; small $0.1 \leq (\rho = R) < 0.3$; medium $0.3 \leq (\rho = R) < 0.5$; and, large $(\rho = R) \geq 0.5$. This is consistent with Cohen's (1988) criteria for strength of effect. Where Cramer's V is used the degrees of freedom are taken into account and multiple criteria are used, determined by row numbers (*A*) minus one and column numbers (*B*) minus one, whichever is lower; i.e. by picking the lower value of $A-1$ or $B-1$, for: $(A-1, B-1) = 1$, small = 0.1, medium = 0.3, large = 0.5; $(A-1, B-1) = 2$, small = 0.07, medium = 0.21, large = 0.35; and, $(A-1, B-1) = 3$, small = 0.06, medium = 0.17, large = 0.29 (Gravetter and Wallnau 2004). For values of $A-1$ or $B-1$ larger than 3, the criteria for $(A-1, B-1) = 3$ are used. Comments made by landholders regarding impediments and incentives were analysed using content analysis process that allowed comments to be distributed into predetermined or emerging categories.

7.3. Results

7.3.1. Soil health factors

Landholders were asked to rate the importance of various SHM factors (Table 7.3) to the management of their properties irrespective of having a SHM plan or not. All of the factors listed received the vast majority or responses in the 'highly important' category, with the exception of sodicity, slaking and electrolyte. The percent of respondents who selected 'don't know' for sodicity, slaking and electrolyte was notably higher than the remaining factors (17%, 34% and 33% respectively; $N = 144$). Additionally, landholders were questioned on salinity and its definition. Given the direct relationship between salinity and electrolyte concentration, there was an interesting difference in numbers of respondents being unfamiliar with either factor. Compared to the 33% unfamiliar with electrolyte, it was found that 12% of landholders were unfamiliar with salinity and a further 1% gave an incorrect answer ($N = 135$); 87% correctly identified the definition.

Table 7.3. Landholder ranked importance of selected soil health management factors for the Lachland and Macquarie Valley

Soil health factor	*Response valid percent (%)*			*Sample Size*	*Don't know***
	Not important	***	*Highly important*	*(N)*	*(%)*
Organic carbon	10	14	77	125	9
Water infiltration	5	9	87	129	5
Sodicity	32	27	41	110	17
Nitrogen	2	15	84	135	3
Microbial diversity	5	14	81	129	6
Phosphorus	2	17	81	136	3
Slaking	40	32	28	88	34
Organic matter content	1	10	89	132	4
Electrolyte	11	34	55	85	33
Soil structure	2	9	89	131	5
Soil erosion	16	10	74	136	2

* Those selecting a category between 'not important' and 'highly important'; **Those who selected 'don't know' reported as a percent of the total response N=144

Organic matter content and soil structure were represented as the factors that the majority of landholders placed as most important to their management (86%, $N = 132$ and $N = 131$ respectively). Subsequently, 2% of respondents thought organic matter content was not important to their management, while 1% thought soil structure was not important. Despite the relationship between sodicity and soil structure, sodicity was only considered to be highly important by 41% with a further 32% suggesting sodicity to be of no importance to their property management ($N = 110$). When questioned about the definition of sodicity, 36% of landholders selected the correct definition, while the remaining 64% either did not know, thought sodicity was the same as salinity, or confused the definition of sodicity with its consequences ($N = 143$).

An analysis of the soil factor data by regions showed no significant differences for the various regions. There were also no obvious trends, suggesting that, irrespective of region, these soil health factors are regarded as important by the majority of Lachlan and Macquarie Valley landholders. Furthermore, age, sex and farming enterprise did not affect the way in which landholders responded to the importance of various soil attributes.

7.3.2. Attitudes towards soil health management

The attitude of landholders towards various SHM statements was identified (Table 7.4). A conflicting result was found where 71% ($N = 141$) of landholders agreed that their soil should be used to maximise yearly income, while 73% ($N = 138$) of landholders also agreed that if they treated and managed their soils correctly, they may not see an increase in yearly crop/pasture production, but longevity of production will be better. There was, however, no correlation between the responses for these two statements ($\rho = -0.018, p = 0.858$). The conflict was also evident in a small number of comments made by landholders regarding short-term and long-term productivity due to SHM. For example:

> *"I am convinced that fixing my soil will make my enterprise more profitable & sustainable. Healthy soil leads to less reliance on chemicals, less weeds, healthier stock – able to run more stock. Initially the cost of lime & manure is high but I hope that as I increase my stock levels my income will increase allowing more money…" (L101)*

There was a generally positive attitude towards SHM. Notably, the majority of respondents disagreed that sustainable soil health is an unachievable concept (75% $N = 139$) and agreed that their soils should be managed in such a way that what nutrient is used should be replaced (93%, $N = 143$).

These results were uninfluenced by landholders' regional location or age.

Table 7.4. Landholder attitudes to various statements concerning soil health management

	Soil health management statement	*Landholder response (%)*			
		Disagree	*Neutral*	*Agree*	*Sample size (N)*
1	My soil should be used to maximise my yearly income	15	15	71	141
2	My soil should be left the way nature intended	55	23	23	144
3	My soil should be managed in such a way that what nutrient is taken out should be put back in	3	4	93	143
4	Sustainable soil health is an unachievable concept	75	10	15	139
5	If I treat and manage my soils correctly I may not see an increase in yearly crop/pasture production, but longevity of production will be better	16	13	73	138
6	After product application, if increased crop/pasture productivity is not seen in one year I discontinue use	70	20	9	137

7.3.3. Planning and management

The positive attitude towards SHM exhibited by landholders was also reflected in the number of landholders who indicated that they have a SHM plan of some description (92%, $N = 144$) (Table 7.5). However, notably fewer landholders indicated that they have a written property plan (38%, $N = 135$) with a further 15% stating that they were currently in the process of developing a written property plan; the remainder indicated they had never had a written property plan. In contrast, 92% of landholders said they have a long-term vision for their property, displaying a moderate association with SHM plan responses ($\chi^2(1, N = 135) = 12.739$, $p < 0.001$, $V = 0.307$). A further consideration for written plans and long-term visions is whether or not landholders consider their income viable under either management regime. Through cross-tabulation it was found that having a written property plan did not significantly affect the way landholders responded to income viability ($\chi^2(2, N = 125) = 2.962$, $p = 0.227$), with similar results for having a long-term vision and income viability ($\chi^2(1, N = 125) = 0.925$, $p = 0.336$). Analysis through OLR also showed that the model for income viability was not significantly improved by including those with a written property plan or those with a vision ($p = 0.27$), although a trend was evident where those without a written plan were less likely to have a viable income or select a high income category, and those with a vision were more likely to select a low income category and not have a viable income.

Interestingly, the three most influential factors for the adoption of SHM programs were agronomists (65%, $N = 143$), neighbours and friends (61%, $N = 140$) and extension agency efforts (60%, $N = 142$) (Table 7.5). Only 2% ($N = 141$) of landholders reported that attending a soils related workshop had been influential for the adoption of a SHM plan.

Regional location and age did not significantly affect the way in which landholders responded.

7.3.4. Impediments to the adoption of a soil health management plan

The following results are derived from landholder responses to a series of statements concerning impediments for the adoption of SHM plans. These statements were separated into six broad categories: education and training impediments; agencies and extension organisation-based impediments; land-use associated impediments; market impediments; economic impediments; and, personal and social impediments. Interpretation of the scale in Table 7.6 is: not an impediment – has no effect on the implementation of SHM plans; slight impediment – some effect, but unlikely to impede implementation of a SHM plan; moderate impediment – equally likely to contribute towards stopping the implementation of a SHM plan; and, large impediment – likely to contribute towards stopping, or completely stop, the implementation of a SHM plan. This needs to be kept in mind when considering the statistical result of this section. The particular statements for each of the six categories are numbered in Table 7.6 (e.g. 29. – 'I don't own the appropriate machinery') for ease of referral throughout the text.

Where appropriate, direct quotes from participating landholders have been included using a respondent code (e.g. L121) to ensure anonymity.

Education and training impediments

Of the education and training impediments listed (Table 7.6), lack of research into broad acre SHM (3) and lack of expert advice or assistance for SHM (4), other than an agronomist, represent the greatest impediment to adoption of SHM plans; 47% (N=115) and 44% (N=125) responded with 'large impediment' respectively. Responses to the statement concerning the time taken to learn SHM skills (5) were generally spread evenly across the impediment scale, while not knowing enough (1) and not enough ongoing technical advice (2) were spread across the slight impediment to large impediment categories. It is noted that the majority of respondents to statement (2) indicated a moderate or large impediment (66%, N=127).

Table 7.5. Percent of landholders with a soil health management plan of some description, the type of planning identified with and the factors that influenced the adoption of this plan

	Yes (%)	*No (%)*	*Sample size (N)*
Factors influencing SHM plan adoption			
Community group	59	41	142
Neighbours and friends	61	39	140
Government incentives	40	60	141
Extension agency efforts	60	40	142
Agronomist	65	35	143
Soil workshop attendance	2	98	141
Planning			
SHM plan	92	8	144
Long-term vision	92	8	135
Property plan*	38	47	135

* A further 15% indicated they were currently in the process of completing a property plan

It was shown that STIPA members were less likely to view not knowing enough (1) as an impediment to adoption ($\chi^2(1, N = 130) = 4.83,\quad p = 0.028,\quad R = 0.195$), although the effect was small. Similarly, Landcare members were less likely to state that the lack of expect advice (4) was an impediment ($\chi^2(1, N = 125) = 4.693,\quad p = 0.03,\quad R = 0.195$); again the effect was small.

Results obtained from SROCC returned an expected result in that those with larger properties were more likely to agree that extra research was required into large-scale/broad-acre SHM (3)($\rho = 0.202, p = 0.03. N = 115$), but this was only a weak correlation.

Various landholders suggested that they now knew what it was they had to do in the future to manage for soil health based on their past experience, or past experience of others. For example:

> *"My wife and I have been running our farm for 9 years taking over from my parents… when it does rain we will have the hindsite (sic) we need to take advantage of every drop of rain and so improve soil quality" (L24)*
>
> *"Blindly following what dad did. Lesson learnt. I now know what I need to do" (L120)*

Table 7.6. Education, agency and extension, and land-use impediments to the adoption of a soil health management plan as ranked by landholders of the Lachlan and Macquarie Valleys

Impediments to the adoption of soil health management plans	*Frequencies (%)*				
	Not an impediment	*Slight impediment*	*Moderate impediment*	*Large impediment*	*Sample size (N)*
Education and training impediments					
1. I don't know enough about soil health management	17	26	27	30	130
2. There is not enough ongoing technical advice on soil health management	10	24	34	32	127
3. There has not been enough research into large-scale/broad-acre soil health management	7	24	23	47	115
4. It is difficult to get expert advice or assistance for management of soil health, other than an agronomist	18	18	21	44	125
5. It takes too much time to gain the knowledge and skills needed	25	30	19	25	130
Agencies and extension organisation-based impediments					
6. There is a lack of promotion of healthy soils management	12	23	29	37	130
7. Agencies and extension groups concerned with soil health fail to understand landholder objectives	14	29	25	32	126
8. There are not enough soil health success stories	19	20	30	31	125
9. There are too many agencies and extensions that at times give conflicting advice on soil health management	17	19	30	34	116
10. The cost of soil health analysis is too high to warrant using a soil analysis/health agency	8	15	28	48	120
11. There is not enough freely available support from agencies and extension groups	8	15	31	46	123
Land-use associated impediments					
12. I have managed soil health in the past and experienced no change in productivity	50	29	11	10	124
13. My current farm practices work well, so I have no reason to change	45	25	22	8	128
14. A change in my current management plan would be too hard to incorporate without losing significant income	41	26	16	17	121
15. Other factors that I can't control, such as rainfall and temperature, make soil health management a poor investment on my property	30	19	18	33	131
16. Changing my current farm plan would be too difficult	57	29	7	7	129
17. The application of extra amendments would create too much traffic on my soil, which would outweigh managing for soil health	63	23	8	6	120
18. Having a detailed soil management plan decreases my land use flexibility	55	26	13	5	121

Table 7.7. Market, economic, and personal and social use impediments to the adoption of a soil health management plan as ranked by landholders of the Lachlan and Macquarie Valleys

	Frequencies (%)				
Impediments to the adoption of soil health management plans	*Not an impediment*	*Slight impediment*	*Moderate impediment*	*Large impediment*	*Sample size (N)*
Market impediments					
19. My property is situated too far away from a gypsum source	36	15	19	30	127
20. My property is situated too far away from an appropriate organic matter supplier/source	29	15	19	37	121
21. My property is situated too far away from a source of lime	48	21	13	18	127
22. There is no market for my efforts in providing an environmental service to the community due to soil health management (e.g. carbon pooling, water quality management etc.)	32	17	17	34	119
23. My property is too far away from amendment/fertilizer (other than lime, gypsum and organic amendments) suppliers/sources	39	20	19	23	124
Economic impediments					
24. My property is too small to create profit from soil health management	72	20	7	4	130
25. Application of organic amendments has uncertain/low returns.	25	23	25	27	112
26. The initial investment is too high	11	15	32	42	118
27. Application of lime and/or gypsum has uncertain/low returns	30	28	23	20	123
28. The time period before increased productivity and income is uncertain/too long	31	25	24	20	123
29. I don't own the appropriate machinery	38	14	17	30	133
30. Contractors are too expensive	20	16	25	39	134
31. I can't justify the capital to buy the appropriate machinery	20	11	21	48	131
32. There is a lack of contractors with the correct machinery or time in my area	39	12	17	33	129
33. There is too much of an economic risk associated with investing in soil health	37	25	22	16	124
Personal and social impediments					
34. I am not in the appropriate stage of my life (e.g. I haven't decided on my long term goals, or my property may not be handed onto the next generation)	63	14	11	13	131
35. There are not enough people working on my property to implement a soil health program	50	14	11	25	133
36. There is not positive soil health social culture in my area	51	17	15	17	129
37. I do not have enough time to worry about soil health	61	18	12	9	134
38. Managing for soil health is a 'green concept' which I do not want to associate with	85	9	4	3	129

Others indicated that they didn't know what some of the soil health characteristics used in this study were, or what their impact on soil productivity was:

> *"…a lot of the issues you raised I am unfamiliar with, I am sure I have most of the other problems, we have very little help with & reduction of soil deficiencies – I have no idea in $ terms what they cost me in production." (L16)*

Some landholders proposed that further independent research into alternative soil amendments was required:

> *"I would like to have more information from accredited sources about composted manures and the advantages of composting." (L136)*
>
> *"…not enough information… [about] incorporation of biorchar in soils and the added benefits." (L17)*

While this indicates a desire for more research, it also indicates a possible disconnection with available research. A further example,

> *"There is lack of knowledge about effects of…grazing practices and clearing of large trees on soil production…" (L85)*

Agencies and extension organisation-based impediments

From the list of soil health related statements for agencies and extension organisation-based impediments (Table 7.6), the cost of soil analysis being too high to warrant using soil health agencies (10) was the major concern for respondents (48%, N=120). This was closely followed by the lack of freely available support (11) (46%, N=123). For both of these impediment statements, only 23% of respondents saw them as a not being an impediment, or only a slight impediment. The results for not enough soil health success stories (8), conflicting advice (9), failure to understand landholder objectives (7) and lack of promotion of healthy soils (6) are generally more evenly spread across the scale, although approximately a third of respondents, in all cases, see these impediments as large ones.

Also of particular interest is the comparison of responses for the 'cost of soil health analysis being too high to warrant the use of a soil health agency' (10) and 'there not being enough freely available support from agencies and extension groups' (11). The distribution of these two impediments was almost identical and skewed towards being a large impediment. Almost 60% of the variation in (10) was explained by variation in (11), which indicates a large positive correlation between these two impediments ($\rho = 0.582$, $p < 0.0001$, $N = 117$).

Members of the New South Wales Farmers Association were less likely to view lack of SHM success stories (8) or not enough freely available support (10) as a large impediment than other respondents ($\chi^2(1, N = 125) = 3.92$, $p = 0.048$, $R = 0.179$ and $\chi^2(1, N = 123) = 6.15$, $p = 0.013$, $R = 0.226$ respectively). However, the overall effect of these factors was small; indicating that while being a member of NSWFA has a significant influence on how respondents view these impediments, membership it is not the overriding factor.

By carrying out SROCC analysis it was found that property size negatively correlated with the potential impediment of receiving conflicting advice from agencies (9) ($\rho = -0.199, p = 0.032.N = 116$). Those with smaller properties were more likely to select statement (9) as a large impediment than those with large properties.

The majority of comments made by landholders with regard to agency and extension organisations pertained to local Catchment Management Authorities (CMAs) and were often negative. For example:

> *"Lack of experienced agency staff, due to cost cutting very little training being done. Few hands on extension & research staff. CMA is basically useless." (L33)*
>
> *"CMA & Govt. organisations seem interested in implementing flawed govt. policy." (L62)*
>
> *"And, get rid of CMA waste of money they are" (L70)*

Conversely, an approximately equal proportion of landholders made positive comment about CMAs providing practical support, community involvement and best management practice (BMP) plans:

> *"[With regard to implementation of an incentive system] Yes…through the CMA and their practical help." (L95)*
>
> *"Most of my neighbours have become more involved in the CMA over the last few years" (L44)*
>
> *"We have been using the CMA BMP suggestions to increase ground cover & organic matter" (L5)*

A further emergent theme is landholders' scepticism towards agronomy agencies and extension organisations. For example:

> *"The mixed messages you receive from "experts" from gov. depts. The [Department of Primary Industries] DPI is about conventional farming while the CMA is pushing sustainability pick your way through that in these conditions is a challenge." (L139)*
>
> *"There seems to be too much conflicting advice from agronomists and salesmen." (136)*

> *"Need someone with no hidden agenda to come and say lets try this because this is what it should do." (L32)*

Land-use associated impediments

Curiously, the stated land-use associated impediments were generally not considered by landholders to be large or moderate impediments towards implementing a SHM plan (Table 7.6). Lack of increased productivity due to SHM in the past (12), current farm practices already working (13), changing current practices with out losing significant income being too hard (14), changing the current farm plan being too hard (16), the benefit of extra application of soil amendments being outweighed by extra soil traffic (17), and having a detailed SHM plan decreasing flexibility (18) had, respectively, 79% ($N = 124$), 70% ($N = 128$), 67% ($N = 121$), 86% ($N = 129$), 86% ($N = 120$) and 81% ($N = 121$) of responses fall into 'not an impediment' and 'slight impediment' categories. The exception to this was uncontrollable factors such as rainfall and temperature (15). However, approximately the same proportion of respondents that considered statement (15) a large impediment, considered statement (15) to not be an impediment at all (33% versus 30% respectively, $N = 131$).

It was found that a significant relationship existed between income viability and soil health being a poor investment due to uncontrollable factors (15) ($\chi^2(1, N = 119) = 9.22$, $p = 0.002$, $R = 0.279$). Although using Choen's (1988) criteria rendered only a small relationship, those who indicated their income was viable were more likely to respond with statement (15) not being an impediment. A further significant relationship, with a medium sized effect, exists between those who have attended a DPI run workshop and the response to SHM plans decreasing land-use flexibility (18) ($\chi^2(1, N = 121) = 12.545$, $p < 0.001$, $R = 0.332$). Of those who reported attending a DPI run workshop, 100% indicated that a decrease in land-use flexibility was not an impediment to SHM.

The overwhelming majority of comments relating to land-use associated impediments were about drought and associated effects:

> *"The biggest impediments to soil health at present is lack of bloody rain. As I am writing this another dust storm is building up in the north west – 2^{nd} one in 3-4 days 25/9/09." (L105)*

> *"Impediment for improvement is still lack of rain. Can do lots but rain is still at least 50% of the equation." (L118)*

However, as was reflected in the survey responses to statement (15), a large proportion of comments indicated that while drought was a prime concern to their management and a reason behind lower production/income, SHM was still on the forefront of management planning. For example,

> *"With the ongoing drought we…improve soil health at a minimum cost which we have been trying to do with minimum till and stubble retention." (L20)*

Market impediments

Being situated too far way from a gypsum (19) or organic matter (20) source was considered a large impediment by 30% ($N = 127$) and 37% ($N = 121$) of respondents, respectively (Table 7.7). Another large impediment 34% ($N = 119$) was the lack of market for providing an environmental service to the wider community through SHM (22). However, in all three circumstances a similar proportion of respondents believed these factors to not be an impediment at all.

Those who identified as having a vision were also less likely to think that they were too far away from an organic matter source (20) ($\chi^2(1, N = 114) = 6.338,\ \ p = 0.012,$ $R = -0.236$) or that a lack of market for providing an environmental service (22) was an impediment ($\chi^2(1, N = 111) = 7.665,\ \ p = 0.006,\ \ R = -0.265$). Both of these relationships were assessed as being small.

In all circumstances, the listed market impediments were positively correlated with property size (Table 7.8). Landholders with larger properties were more likely to regard distance from any amendment sources (19, 20, 21, and 23) as a large impediment and that the lack of a market for providing an environmental service to the wider community (22) is also a large impediment.

Table 7.8. Correlations between market-based impediments and property size
Relationship strength is measured using the criteria set out by Cohen (1988)

	Market impediment	*Observed correlation with property size*			
		Spearman's ρ	*p value*	*Sample size (N)*	*Relationship strength*
19	My property is situated too far away from a gypsum source	0.193	0.029	127	small
20	My property is situated too far away from an appropriate organic matter supplier/source	0.396	<0.001	121	medium
21	My property is situated too far away from a source of lime	0.434	<0.001	127	medium
22	There is no market for my efforts in providing an environmental service to the community due to soil health management (e.g. carbon pooling, water quality management etc.)	0.24	0.009	119	small
23	My property is too far away from amendment/fertilizer (other than lime, gypsum and organic amendments) suppliers/sources	0.365	<0.001	124	medium

Economic impediments

Economic impediments were generally regarded as influential by landholders, which might be expected (Table 7.7). Of the economic impediments, the initial investment cost being too high (26) was the most strongly skewed towards being a large impediment, while not being able to justify the capital to buy machinery (31) was selected by the greatest proportion of landholders as a large impediment ($48\%, N = 131$). Further economic impediments with a noteworthy proportion of response in the large impediment category, although more evenly spread across the other response categories, were contractors being too expensive (30) and lack of contractors in the area with the appropriate machinery (32) at 39% ($N = 134$) and 33% ($N = 129$), respectively. Application of organic amendments having low/uncertain returns (25), application of lime/gypsum having low/uncertain returns (27) and not owning the appropriate machinery (29) were relatively evenly spread across all response categories. Additionally, 92% ($N = 130$) of landholders were of the opinion that their property is not too small to be profitable.

Responses to the potential impediments that the time period before increased productivity and income is uncertain/too-long (28) and there is too much of an economic risk associated with investing in soil health (33) were primarily in the lower categories (little or no impediment). The latter (33) showed that only 16% ($N = 124$) of landholders perceive risk as a large impediment.

Those who had attended a CWFS-run workshop were more likely to think that organic amendments had low or uncertain returns (25), although this was a small relationship ($\chi^2(1, N = 112) = 9.134, \quad p = 0.003, \quad R = 0.286$). Additionally, a double factor OLR model between those attending a CMA workshop, those who felt their income was viable and the impediment statement ‘the initial investment is too high’ (26) showed that attendance at said workshops and a viable income were both more likely to view the initial cost of SHM as not being too high ($\chi^2(1, N = 107) = 9.262, \quad p = 0.01, \quad R = 0.295$). A second double factor OLR model for contractors being too expensive (30) returned a significant result using income viability and total income as factors, producing a medium relationship ($\chi^2(1, N = 120) = 16.315, \quad p = 0.012, \quad R = 0.365$). Those who felt their income was viable, and those with greater income, were both less likely to view contractors as being too expensive. Furthermore, those who had attended a CMA-run workshop were less likely to suggest that there were not enough contractors in the area with appropriate machinery (32) ($\chi^2(1, N = 129) = 5.162, \quad p = 0.023, \quad R = 0.202$).

Unsurprisingly, property size was negatively correlated with the impediment statement 'my property is too small to create profit from SHM' (24) ($\rho = -0.359, p < 0.001.N = 130$). Moreover, as property size increased, respondents were more likely to suggest that lime/gypsum had low or uncertain returns ($\rho = 0.179, p = 0.047.N = 123$).

Comments related to economic impediments often linked SHM directly to productivity or the cost associated with applying amendments and their subsequent effect. For example:

> *"Soil health improvements that aren't linked directly to productivity increases have no value in broadacre agriculture. Neither banks nor grainbuys (sic) are interested in anything other than productivity…Every change must have productivity benefits." (L107)*

> *"Liming and gypsuming (sic) my paddocks are expensive to the returns possible." (L99)*

While the majority of comments were not directly related to economic impediments, an indirect relationship between the comments made and economic impediments was a common theme. One particularly frustrated landholder made the following comment with reference to the price they were given for their produce as compared to the price they paid for their inputs such as fertilisers:

> *"Farmer's are expected to feed the nation,…bear the brunt of climate change policies for the good of all the community,…and save the environment for the future. [We] are the ONLY industry who take the price they are given – pay the price that is demanded – and pay the freight both ways." (L31)*

Personal and social impediments

On the whole, none of the personal and social impediments listed were perceived as being major impediments to the adoption of SHM plans. A quarter of landholders ($N = 133$) believed there were not enough people working on their property to implement a soil health program (35) (Table 7.7), while 17% ($N = 129$) thought there was not a positive soil health culture in their area (36), although in both circumstances approximately 50% of landholders did not view these factors as impeding implementation. Not being in the appropriate stage of life (34) and not having enough time to worry about SHM (37) were considered by 77% ($N = 131$) and 79% ($N = 134$) of respondents, respectively, to either not be an impediment, or only a slight impediment. Notably, 94% ($N = 129$) of landholders do not have the opinion that SHM is a 'green concept' that they don't want to associate with (38). In direct contrast, one landholder stated:

> *"Alot (sic) view this [SHM] as a 'Greenie' driven campaign to get them off their land." (L27)*

Those who indicated that they had a viable income were less likely to believe that there were not enough people working on their farm to implement a SHM plan (35) ($\chi^2(1, N=121)=6.276,\ \ p=0.012,\ \ R=0.232$), that there was not a positive soil health culture in their area (36) ($\chi^2(1, N=117)=8.664,\ \ p=0.003,\ \ R=0.276$), and that they did not have enough time to worry about SHM (37) ($\chi^2(1, N=122)=5.798,\ \ p=0.012,$ $R=0.228$). In all cases, having a viable income only had a small effect on the overall relationship.

Further impediments were evident in landholders' opinion of government legislation and the effect it could have on specified local areas. These concerns were focus on the perception that farming regions are/would be treated as homogenous areas by current/future legislation. For example:

> *"We don't want our land & farms controlled by state & federal government people who only have textbook knowledge of what is right for the different areas of the state…We need to have local community groups set up to run with this information on soil health…so that the decisions are made by local people who know the areas history and can have a plan in its future." (L63)*

Additionally, the Native Vegetation Act 2003 (Australian Government 2003) was mentioned in numerous comments made by farmers about Invasive Native Species and the associated impediments to SHM; i.e. through "time wasting rigmarole" and, again, blanket legislation.

Analysis by region and enterprise

The above results were obtained by analysis of landholders' responses as a whole. For this reason, further analysis of the six defined categories and their associated impediments was conducted by researcher-defined regions and the major enterprise that individual landholders identified with.

Through Chi-square analysis, a distinct trend was found for the Orange/Molong/Cowra region landholders across all of the significant results (Table 7.9). This region consistently produced the highest, and in two cases, second highest proportion of the total data in the 'not an impediment' category for any significant impediment statement in Table 7.6 or Table 7.7. A similar, but less obvious, trend was evident for Coonabarabran, Mudgee and Dubbo/Wellington regions. However, the Dubbo/Wellington region landholders' responses were more inclined to be evenly spread across the two extremes ('not an impediment' and ‘large impediment’). For example, the application of lime/gypsum having low or uncertain returns (27), and other factors I can’t make SHM a poor investment (15) both have a similar response percentages in the two extremes (no impediment and large impediment).

In general, the significant results obtained were because of differences in the percentage of respondents selecting ‘not an impediment’ by region. However, respondents from both the Hillston/Griffith and Nyngan/Warren regions were more inclined to select ‘large impediment’ for factors such as rainfall and temperature (15). Additionally, respondents in the Hillston/Griffith and Condobolin/Lake Cargelligo regions were more likely to feel that their properties were too far from a lime source (21). Respondents from the Hillston/Griffith region were more likely to report, as a large impediment to SHM, their distance from other amendment sources (23) and there being a lack of contractors in the area with appropriate machinery or time (32).

While cross analysis by region provided further insight into the way various impediments were assessed by landholders, the results obtained for cross-tabulation of the impediment statement data with primary enterprise did not. One significant result was observed between the impediment of there not being enough ongoing technical advice and those landholders who identified with their main enterprise as being cattle production ($\chi^2(8, N = 125) = 15.851$, $p = 0.45$, $V = 0.252$). Of note, 18% of respondents identified as having only one main enterprise, while 38% had two, 32% had three, 8% had four, and 3% identified as having more than four farming enterprises ($N = 141$); the majority of landholders were conducting mixed-farming operations.

Age and sex

It was noted that the age and sex of respondents had no statistical effect on how landholders responded to the ranking of impediment statements.

7.3.5. Incentives for the adoption of soil health management plans

Incentives for the adoption of SHM plans were presented in a series of statements. The results were obtained by asking landholders to rank their responses. From the ten incentive statements listed (Table 7.10) the majority of responses were for the large incentive category. However, promotion of soil health in the local community (3) and the creation of grower-based healthy soils committees with environmental organisation support (9) displayed only a slight majority of responses as an incentive. Of note, these were the only incentives to exhibit less than a 50% majority in the ‘large incentive’ category and greater than 10% in the ‘not an incentive’ category.

Further incentives, and comments about incentives, were suggested by 32% ($N = 144$) of responding landholders. Two main themes were evident, the first of which was a desire for more research into soil health through conduct of field experiments across different areas and enterprises within the Lachlan and Macquarie Valleys. For example:

> *"…we need more research so we can evaluate what is best for our land. We are doing our own farm trials…" (L139)*
>
> *"…farmers need to see [what] they do will work in their specific area. This would require demo farms in specific soil types and rainfall zones to show that it does work in their situation." (L103)*
>
> *"The understanding of how certain farming practices impact on soil health…in a given local area would still be useful. On property testing & especially soil pits are a fantastic guide to how farming techniques are effecting (sic) the different zones of the soil. Showing farmers what is healthy & what is not is a message that never grows old…How long it takes to change the soil is what scares people the most." (L124)*

The second theme encompassed economic incentives. While many of the landholders' comments restated economic incentives already listed, there was repeated suggestion of tax incentives, or a reward system for work done, rather than money paid up-front for future work. For example:

> *"…tax relief/rebates to help cover costs. If we were to…at least cover costs in the current time, a lot more farmers would be willing to embrace change…" (L27)*
>
> *"Tax incentives rather than up front dollars would be a good form of incentive as it supports operations that are profitable & avoids farms that are tax sinks. A reward system for successfully implemented soil programs rather than funding for a proposed project may be a far better way to influence results." (L5)*

One landholder, who listed government assistance as a large incentive for the adoption of a SHM plan, stated the following opinion with regard to the governments input to farming regulations:

> *"Govts. Tell you one thing than (sic) 20 yrs later change their minds e.g. land clearing, increasing irrigating. If Govt. limits our individual rights for common good Govt. should pay us for common good." (L82)*

Interestingly, none of the independent variables, including age, sex and region, affected the way in which landholders ranked the listed incentives or featured in identified themes of landholder comments.

7.4. Discussion

7.4.1. Landholders and soil health

While landholders were not directly questioned as to their opinion of what SHM entailed, they were asked to rank in importance a variety of soil health factors. It was apparent, irrespective of whether or not a landholder indicated they had a SHM program, that management of these factors was, in majority, highly important. However, this research suggests that where landholders are unsure of what a soil health factor is, they are more likely to select it as not being important. Even though Lobry de Bruyn and Abbey (2003) state that the slow adoption of soil health indicators suggests that these indicators are not locally relevant to farmers, the perceived irrelevance of soil health indicators may actually be caused by a farmer's unwillingness to suggest they don't understand something; i.e. 'I don't know what it is, therefore it probably isn't important.' This study also finds that the region in which landholders reside has no significant effect on how they rank the importance of soil health factors. Hence, while an indicator may potentially be regional, the soil attributes they are designed to measure are considered as locally relevant by the majority of Lachlan and Macquarie Valley landholders.

The type of farming enterprise can change how soil health indicators and properties are ranked in importance by landholders (Romig *et al.* 1995; Lobry de Bruyn and Abbey 2003; Kelly *et al.* 2009). The findings of this current study, which include responses from landholders with a variety of single- and mixed-enterprise operations, suggest that the identified primary enterprise did not affect the way soil factors were ranked. Presumably, this is due to the majority of landholders having mixed farming enterprises that encompass elements of grazing and cropping. Soil organic matter content was presented as one of the two most important soil health factors by landholders, which is consistent with previous research (Romig *et al.* 1995; Lobry de Bruyn and Abbey 2003; Kelly *et al.* 2009).

The overall acceptance of the presented soil factors, with the exceptions of sodicity, slaking and electrolyte, as highly important to landholders' individual property management is encouraging for SHM. Factors such as organic matter content, soil structure, water infiltration, microbial diversity and nutrients were all ranked highly. This shows, regardless of intention to manage for soil health or not, that farmers realise their property management needs to cover aspects of soil chemical, physical, and biological properties. This realisation is also reflected by the majority of soil health based information resources presented in Table 7.1. Therefore, it could be assumed that farmers are likely to understand the concept of soil health, although it is not possible to directly determine that from the current research.

.

Table 7.9 Landholder perceived impediments that are significantly related to the researcher defined district of origin

Only the two extremes of an impediment's influence are presented (i.e. 'None' and 'Large'); Imped. is abbreviation for impediment.

	Region percentages given by their contribution to the total sample percentage (%)													
Imped. Influence	*Hillston/ Griffith*	*Condobolin/ East of Lake Cargelligo*	*Orange/ Molong/ Cowra*	*Bathurst*	*Parkes/ Forbes*	*Dubbo/ Wellington*	*Mudgee*	*Coonab - arrabran*	*Coon - amble*	*Nyngan/ Warren*	*Total percent (%)*	*p value*	*Sample Size (N)*	*Cramer's V*
15. Other factors I can't control, such as rainfall and temperature make SHM a poor investment														
None	2	1	6	2	2	4	4	5	4	2	31	0.023	124	0.333
Large	8	2	1	2	2	3	5	2	1	6	31			
16. Changing my current farm plan would be too difficult														
None	4	2	12	7	4	7	7	7	4	3	57	0.014	122	0.343
Large	1	0	0	0	0	2	2	0	0	3	7			
21. My property is situated too far away from a lime source														
None	1	2	13	7	5	5	6	7	2	3	49	0.001	119	0.378
Large	5	4	0	0	0	3	1	0	2	2	16			
23. my property is situated too far away from amendment/fertiliser (other than lime/gypsum/organic)														
None	3	2	11	3	3	3	6	4	2	2	39	0.002	116	0.373
Large	7	3	0	0	1	4	2	0	1	2	20			
27. Application of lime/gypsum has uncertain/low returns														
None	0	1	7	3	2	6	2	5	3	2	30	0.049	119	0.317
Large	3	0	0	2	1	6	5	2	1	1	20			
28. The time period before increased productivity and income is uncertain/too long														
None	2	2	5	3	1	6	3	5	3	2	30	0.049	119	0.317
Large	2	3	0	3	2	4	3	2	1	2	10			
32. There is a lack of contractors with the correct machinery or time in my area														
None	1	0	9	5	2	7	6	7	1	3	39	<0.001	122	0.391
Large	9	3	2	2	2	4	1	2	1	4	32			
33. There is too much of an economic risk associated with investing in soil health														
None	1	1	10	2	2	7	5	6	4	1	39	0.005	117	0.363
Large	3	1	1	3	1	3	1	3	1	0	16			
34. I am not in the appropriate stage of my life														
None	5	2	13	6	2	8	10	10	4	4	62	0.04	125	0.323
Large	2	0	1	2	1	2	2	0	1	2	12			
36. There is not a positive soil health culture in my area														
None	2	1	8	3	4	7	9	9	4	4	52	0.025	121	0.335
Large	2	2	3	3	0	2	1	0	2	2	15			
37. I do not have enough time to worry about soil health														
None	2	2	11	6	3	10	11	9	5	4	63	0.032	126	0.325
Large	1	1	0	1	0	2	1	0	1	1	6			

Table 7.10 Possible incentives to the adoption of a soil health management plan as ranked by landholders of the Lachlan and Macquarie Valleys

Possible incentives for the adoption of a soil health plan	*Frequencies (%)*				
	Not an incentive	*Slight incentive*	*Moderate incentive*	*Large incentive*	*Sample size (N)*
1. Increased property value through improvements in soil health	7	18	25	52	136
2. Access to freely and readily available information on soil health	5	10	29	56	132
3. Promotion of soil health in your community	13	19	32	35	134
4. Providing an asset for future generations through soil health management	3	9	25	63	134
5. Successful soil health stories from growers	5	19	38	38	132
6. The creation of a market for landholder efforts in providing an environmental service to the community through soil health management (e.g. carbon pooling, water quality management etc.)	8	12	28	52	125
7. Compensation by government organisations for proper soil health management	5	10	18	67	134
8. Subsidised amendments for the remedy of officially recognised soil health issues, where these issues are determined by both the grower and a government organisation representative	3	8	29	60	133
9. The creation of a grower-based healthy soils committee, or sub-branch of an existing committee, with support from environmental organisations	17	20	26	38	131
10. Easy access to soil health advice/recommendations at a subsidised cost	5	12	22	61	134

7.4.2. The tension between soil health and maximising production

Landholders held the general opinion that their soils should be used to maximise their income. This is not unexpected, as past research has shown that profitability is a impetus for management decisions (Bennett 1999; Guerin 1999), most likely due to the industrialisation of agriculture (Keller and Brummer 2002). What is interesting is that there appears to be conflict between landholders' attitudes towards short-term productivity and long-term productivity. Approximately the same number of landholders, believing their soil should be used to maximise yearly income, also believed that if their soils were managed correctly a yearly increase in productivity may not be seen, but longevity of productivity would be greater. This, and the comments made by some landholders, implies that there is tension relating to the concept of sustainability versus profitability.

Attitudes focusing on productivity can be explained through the agricultural production paradigm (see Keller and Brummer 2002), which has resulted in production-based economic farming models (A) that influence landholders to focus solely on increasing production. An alternative model is the ecological model (B), which focus on land as a biota, including soil, plants, animals (Leopold [1949] 1987), as well as the water and energy flowing through it (Keller and Brummer 2002). It is noted that the definition of an ecological model is similar to the definition of soil health given by HSSF (Department of Agriculture Fisheries and Forestry 2008) with the exception that the HSSF definition includes a production element. While there is classically an alleged rift between the two production paradigm models, termed as the "A-B cleavage" by Leopold ([1949] 1987), the HSSF's definition of soil health is a realistic compromise. As the results of the current research suggest, productivity is essential to landholders; "neither banks nor grain buyers are interested in anything other than productivity" (L107). However, the results also show that landholders place importance on soil health factors from chemical, physical and biological contexts, and do not simply stop applying SHM amendments if an instant increase in productivity is not observed, which suggests that the 'cleavage' is diminishing. The tension concerning profitability versus sustainability could then be explained by the focus on productivity being an artefact of the productivity paradigm, while the contrasting attitude concerning sustainability is a relatively new one that has only recently become prevalent through current circumstance and extension efforts such as the HSSF; i.e. given time and consistent effort, this tension should be resolved in favour of production longevity.

The overall attitude towards SHM is positive with the vast majority of landholders believing that sustainable soil health is achievable, while the idea that managing for soil health is a 'green concept' they don't want to associate with has also been debunked. Additionally, although the majority of farmers disagreed that their soils should be "left the way nature intended," an overwhelming number believed their soils should be managed in such a way that the nutrients taken out should be replaced. This shows that landholders in the Lachlan and Macquarie Valleys are apparently not impeded by a negative attitude towards SHM. Consequently, their positive attitude should translate to openness for change, which is one of the main reasons for adoption of an innovation (Chamala 1987).

7.4.3. Methods of planning

A blanket approach to encouraging and promoting SHM is not desirable or effective (Frank 1997; Industry Commission 1998; Tucker and Napier 1998; Guerin 1999; Lobry de Bruyn and Abbey 2003). There is a need to understand the 'multiple ways of knowing' (Kloppenburg 1991; 1992) and multiple lifestyles (Frank 1997) in order to communicate SHM information in an effective fashion. This is also evident in the current research findings, where the overwhelming majority of landholders signify having a SHM program of some description, while less than half of the landholders professed to having a written property plan. Moreover, the same numbers of landholders identifying with managing for healthy soils also indicated that they have a long term vision, with a moderate relationship between the two groups. This highlights the need for agronomists and extension officers to disseminate information through various means and to be prepared to work with multiple methods of management. It should also be acknowledged that, while not a significant result, there is a trend for those who have a written property plan to also have higher income and consider their income viable. Whilst Tucker and Napier (1998) suggest that simply changing the way farmers record and manage their farming enterprises is not an efficient approach, the above trend suggests a potential advantage in promoting the recording and planning of farming inputs and outputs.

This study purposely did not supply a single definition of soil health; it instead relied on the farmers' current knowledge of soil health, conscious or otherwise. Even though the result for those with a SHM plan was not based on a single definition of what a SHM plan entails, it does suggest that landholders are considering SHM and, in their opinion, managing for it to some extent. The extent and method of this SHM is unknown, although with approximately half of farmers indicating they do not have a written property plan, it is assumed that many of the SHM programs are inconsistent, unstructured or ad-hoc. Therefore, agronomists and extension efforts should focus on bringing consistency to SHM programs, albeit in conjunction with the landholders themselves.

7.4.4. Economic impediments for the adoption of soil health programs

The impact of economic factors on the adoption of farming system innovations, including SHM programs, has been discussed by numerous sources (Chamala 1987; Guerin

1999; Chellemi and Porter 2001; Keller and Brummer 2002) with the common theme that profitability is key. This has been displayed in the current results to a large extent. Guerin (1999) specifically makes the point that the initial capital and ongoing management costs are paramount to the adoption of an innovation, and that farmers need to be able to see the financial benefits of adopting, as well as the long-term benefits of productivity maintenance. This was generally echoed in the current research, with the initial investment being too high strongly identified as an impediment to SHM adoption. However, considerably less landholders believe that the time period before increased productivity and income is too long and that investment in soil health is too large an economic risk. This suggests that the latter half of Guerin's (1999) point has been addressed to some extent; that is, landholders are currently more inclined to see the prospect for financial gain and productivity longevity through SHM, but simply can't afford the initial cost.

A second economic factor influencing SHM adoption is evident in impediment statements concerning machinery, either directly or indirectly. Indeed, the economic impediment with the greatest response in the 'large impediment' category is not being able to justify buying the appropriate machinery. The obvious solution to this would be to utilise contractors, although large numbers of landholders believe contractors to either be too expensive or too sparse in their area for their particular needs. Additionally, approximately a third of landholders see not owning the correct machinery as a large issue, although a greater proportion see this as not an issue at all. Presumably this is due to the latter group owning the machinery or their ability to hire contractors. When considering landholders' perception of their income viability, and into which income band they fall, it is apparent that the cost of contractors is of significantly less concern if a viable income and/or high income existed. This would have further affected the tendency of landholders to select not owning the correct machinery as not being an impediment.

7.4.5. Landholders' perception of land-use and change

With the exception of uncontrollable environmental factors, land-use impediments are considered as only a slight impediment, if at all. Of particular interest is that past experience with no increased productivity through SHM does not register as a significant impediment to landholders. This is contrary to previous suggestions (Guerin and Guerin 1994; Guerin 1999) that negative experiences cause farmers to reject innovations and develop the attitude that their adoption behaviour does not affect their productivity. It could be argued that the large response for past experience not being an impediment is because there has been no past experience. However, 92% of landholders suggest that they are doing something about soil health, which implies some experience must have been gained. So, we suggest that there has been no, or insignificant, *negative* past experience and that landholders are satisfied with the outcomes of their SHM efforts.

There also appears to be satisfaction with the concept of soil health being positive for Australian landholders and their management systems. Guerin and Guerin (1994) put forward that farmers will consider a new idea by the advantages it possesses over the process it is designed to replace. Complementing this, Diallo (1983) suggests that farmers must have an understanding and belief of the new idea in order to adopt it. In essence, farmers must have an open mind and willingness to implement change if adoption of SHM is to occur. The current results, with regard to land-use impediments, exhibit a clear willingness to change. The majority of landholders indicate that that their plans are not too difficult to change, with or without, economic loss, and that even if current practices are working well considering change is not ruled out. Dixon (1982) adds that if one is to go outside the social norm, one would risk being perceived as a deviant and outcast from social circles. So, even though the individual landholder might be in favour of change, this does not necessarily mean adoption of SHM will occur if the local social environment does not favour change. In the case of the current research the vast majority of farmers favour change, with more than half of them also indicating that a positive soil health culture in their area was not an issue. It appears that the concept of the ‘recalcitrant farmer’ is not rife amongst the Lachlan and Macquarie Valley landholders. In fact the opposite is evident.

7.4.6. The role of property size

Property size varies considerably within the Lachlan and Macquarie Valleys, with holdings typically increasing in size with distance from the coastal mountain ranges. This trend is strongly negatively correlated with annual average rainfall, suggesting that property size will, directly or indirectly, influence the way in which landholders implement change in management practices on their properties. Indeed, Chamala (1987) and Chamala *et al.* (1982) state that property size and location affect the way in which farmers set their goals and, subsequently, their attitudes concerning management practices.

In the current research, it was found that market-based impediments were associated with property size. When not considering the effects of property size, large proportions of farmers are observed to select a market impediment as being large, while a similar, or larger, proportion of farmers indicated the same impediment to not exist. However, when landholding was taken into account, it is shown that those with smaller properties are more likely to select ‘not an impediment’ and those with larger properties are more likely to select ‘large impediment’. This can be explained by geographical isolation; i.e. as property size increases the distance between properties and services increases. Additionally, some services, such as gypsum mines, only occur in specific locations making them more sensitive to increases in distance and, hence, property size.

It has also been established that property size affected the way landholders judged the effects of lime and gypsum. Those with larger properties are more inclined to view the resulting soil changes due to lime and gypsum as producing uncertain or low returns. Risk as an impediment to adoption of innovations has been identified by many authors (Chamala 1987; Guerin 1999; Chellemi and Porter 2001; Lobry de Bruyn and Abbey 2003) who generally agree that as the level of risk associated with an innovation heightens, the probability of adoption declines. There is an associated risk with the application of amendments such as lime and gypsum regarding effects (Valzano *et al.* 2001b), and the subsequent returns, which can be shown to increase with property size. As income is not a sole function of property size, it stands that there is a smaller amount of risk associated with applying amendments to a smaller area; i.e. a smaller property does not necessarily make a small profit, thus is more likely to be able to absorb the risk of lime and gypsum not working per hectare than a property of ten times the magnitude with a similar profit margin. This would also explain why those with larger properties are more inclined to agree that not having a market for environmental services rendered through SHM was an impediment. If such a market existed then these landholders would have the ability to offset the cost and risk associated with SHM. Furthermore, bulk producers, including those with SHM plans, often require extended lines of credit (e.g. through pre-selling produce) in order to finance future operations and are less likely to make a decision that will offset an immediate profit for a tangible gain (Chellemi and Porter 2001).

7.4.7. Education as an impediment

Education as an impediment to SHM was shown to have a moderate influence. With the exception of broadacre research and expert advice, responses were relatively evenly spread over the impediment categories. While at a least a quarter of landholders indicated education as a large impediment, the general consensus is that education does not have an overriding influence on the implementation of SHM programs. Comments made by landholders suggest that past experience provides adequate knowledge to continue with SHM. However, there appears to be conflict between the influence of education as an impediment and landholders knowledge; i.e. there may be a propensity for landholders to think they understand adequately, irrespective of whether or not they do. This is highlighted in the current research through: (i) landholders' tendency to select 'not important' for soil health factors, such as slaking, that also had the highest proportion of landholders select 'don't know'; (ii) the number of landholders who actually know what sodicity is, compared to those who said it was important to their management; and, (iii) direct comments made by farmers with reference to their knowledge of soil health factors. Therefore, it is quite possibly the case that soil health education is still a major hurdle to consistent SHM.

Although landholders may have overrated their understanding of soil health issues, this does not necessarily make education an impediment to adoption. In the same way that Kelly *et al.* (2009) suggests that there is an over-reliance on agronomists and extension agencies, it is quite likely for those with a lesser SHM education to feel comfortable in implementing such a program through relying on the supervision and advice of their agronomist or local extension officer.

The extent to which education is perceived as an impediment to SHM adoption is also influenced by those who design and communicate the innovation. A proactive attitude toward higher education has been exhibited by farmers, with up to a quarter of them in the North West cropping region of New South Wales having attained some sort of tertiary qualification (Lobry de Bruyn and Abbey 2003). Landholders generally want and seek to understand processes and information that will aid them in their farming enterprises, although reason provides that simple innovations are likely to be adopted over those that are complex (Guerin and Guerin 1994). The current results indirectly show that the complexity of SHM is still a major concern for landholders. Almost half of the farmers indicate that there is a requirement for more ongoing expert advice or assistance for SHM, while approximately a third believe more ongoing technical advice is required. This shows a reliance on experts and technicians in order for landholders to be able to sustain a structured and consistent SHM program. Subsequently, it can be deduced that SHM is complex. While it is not necessarily possible to make the soil physical, chemical and biological systems and interactions less complex, it should be kept in mind by those promoting structured SHM programs that adoption longevity is reliant on ongoing external advice. While we agree with Kelly *et al.* (2009) that farmers are at risk of losing connectivity with their land, the only apparent way around a reliance on external advice is through further and higher education, which is not necessarily an option. Therefore, this requirement for external advice must continue, but landholders should be encouraged to remain involved on all levels, from on-the-ground decision-making through to the conduct of research, contrary to the beliefs of Sojka and Upchurch (1999).

7.4.8. The perception and role of agronomists and extension agencies

In contrast to previous research (Lees and Reeve 1994), which found adoption of farming methods to be influenced, in order, by ‘seeing the method working on a local property’ (78%), ‘talking to a local producer using the method’ (63.5%) and ‘having the method explained at a local field day’ (60.7%), our survey results indicate that agronomists and extension agencies feature in the three most influential factors. Interestingly, soil based workshop attendance, or ‘field day’ attendance, has almost no effect on the probability of landholders adopting a SHM plan. This is seemingly contradictory in that many of these workshops are run by extension agencies, although it could be explained by a desire for one-on-one consultation with extension officers and agronomists. Financial and educational incentives might also help to explain this contradiction; i.e. a perceived educational or financial benefit may be offered to attend a workshop, however, this benefit is implicitly provided by the extension agency rather than the workshop itself. Irrespective of this contradiction, agronomists and extension agencies are shown to have great influence on landholder adoption of SHM. Whilst this adds weight to a perception of over-reliance on agronomists and extension agencies, we believe it shows a decrease in the apparent distrust (Guerin 1999) of agronomists by landholders.

However, based on the comments of landholders, scepticism is certainly still an issue concerning agronomists and extension staff. Of particular interest, CMAs are just as likely to be considered negatively as they are to be portrayed positively. While past experience and success of funding proposals to CMAs would certainly influence response, the most likely reason for this rift concerns government priority and policy. Lobry de Bruyn and Abbey (2003) found a similar association between bureaucratic ‘red-tape’ (regulation) and organisations that are perceived to represent this, such as the CMA (in their case the Department of Land and Water Conservation), where landholders were reluctant to deal with such organisations. Furthermore, government priority of funding and staffing has lead to a decrease in expertise and numbers of staff within the CMA and similar organisations. Therefore, extension staff do not have the capacity or resources available to allow all landholders to receive the attention they require.

National programs such as the HSSF (Department of Agriculture Fisheries and Forestry 2008) are a strong catalyst for the adoption of SHM, but cannot provide ongoing advice to sustain such management. For this reason, landholders, agronomists, extension staff and researchers need to remain connected and communicative. While this is not a recent recommendation (Chamala *et al.* 1982; Chamala 1987), it is one that is echoed in the current findings. Many landholders express a desire for further work in various research areas; in some cases this appears justified, given the priority status afforded to some topics (e.g. carbon sequestration), but other comments display a clear detachment from bodies of information that already exist. For example, communication on certain identified issues, such as salinity, has been prolific and is reflected in the knowledge landholders displayed in the current research. However, other issues of equal or greater SHM and economic importance, such as sodicity (Watson *et al.* 2000), do not reflect this importance in the same results. These issues have also not been communicated to the same prolific extent. It is evident that communication is a vital element in SHM adoption and that a central information hub accessible by all SHM stakeholders could be advantageous. This was also an outcome and current extension, in the form of a developing website (Table 7.1), of the HSSF report (Department of Agriculture Fisheries and Forestry 2008).

7.4.9. Effects of memberships and workshop attendance

Complementary to, and often intertwined with, extension efforts are memberships with environmental and agricultural groups, and workshops or field days. Lees and Reeve (1994) have shown that field days are important influences on landholders, while our survey results suggest that the direct influence of workshops is minimal. However, further indirect influences due to workshops are evident. All of those who had attended a DPI-run workshop disagreed that SHM decreased flexibility of management. Attendees at CWFS workshops are more likely to believe that organic amendments have low/uncertain returns, presumably due to an increased awareness of the lack of unbiased scientific knowledge (Quilty and Cattle, accepted). Those who attended a CMA workshop are less likely to think the initial cost of SHM is too high and less likely to agree that there is a lack of contractors in the area. As the initial cost of SHM is identified as a major impediment to adoption, it appears that CMA workshops have an important influence in breaking this perception down. Furthermore, the CMA workshop attendees also exhibit a greater networking with agricultural services, such as contractors, within their local areas.

Benefits of agricultural and environmental group membership are also revealed. STIPA members feel that educational knowledge of SHM is less likely to be an impediment. Members of the NSWFA are less likely to think that a lack of SHM success stories and freely available support are a large impediment, which is not unexpected considering the inclusion of these elements in the NSWFA objectives (New South Wales Farmers Association 2008). Additionally, Landcare members are less likely to view finding expect advice and assistance for SHM as an impediment. Landcare have previously been identified as providing examples of the long-term productivity benefit of SHM (Guerin 1999), so it follows that such an organisation should have an established network of ‘experts’ known to its members. Importantly, having difficulty finding expert advice and assistance was identified as one of the major impediments to SHM adoption. As this perceived impediment is diminished where a landholder is a Landcare member it is clear that in communicating and promoting SHM, environmental and agronomic group membership and attendance at relevant workshops are effective mechanisms by which to alter or reinforce landholder perception and networking.

7.4.10. Regional differences

The previous discussion is based on survey responses from farmers across both the Lachlan and Macquarie Valleys. Others have cautioned against treating large groups of farmers as a homogenous cohort when considering the implementation of innovations such a SHM programs and conveyance of information (Industry Commission 1998; Guerin 1999; Lobry de Bruyn and Abbey 2003). When the sample population is distributed by researcher-defined regions, the survey results provide some important trends. Farmers of the Orange/Molong/Cowra region consistently display a positive attitude towards the implementation of SHM, while those of the Mudgee, Coonabarabran and Dubbo/Wellington regions display a similar positive attitude, albeit to a lesser extent. In contrast, farmers of the Hillston/Griffith region display a generally positive attitude to SHM, but claim to be impeded by issues such as distances to amendment sources, lack of contractors in the area, and drought. These differences can be partially explained by the effects of rainfall, isolation, and inherent land quality (i.e. semi-arid vs. temperate environments). However, we suggest that there is an overriding human element responsible for the consistency of response given in areas such as the Orange/Molong/Cowra region. Such a consistent positive and unimpeded response, even while surrounding regions view the same impediments as moderate to large, seems very unlikely without a specific social context.

The most probable social factor for these regional responses is the motivation and enthusiasm of landholder communities. For example, groups of landholders who are enthused and motivated with the concept of SHM may not feel impeded by issues such as having to source amendment products over long distances, not having enough time, or not being in the appropriate stage of their lives. Bangura (1983) and Sinden and King (1990) both show that motivation is influential in farmers' adoption of innovations, with motivation driven by socioeconomic status and awareness of income/capital gains. Our results show that perception of production longevity and financial gain is relatively similar for all regions with no significant differences detected; a similar result was found for income viability and income band when assessed by region. Therefore, according to previous research, motivations should also be similar across regions. However, motivation, in all probability, is driven by the diversity of environmental/agricultural services available, the enthusiasm of extension staff and agronomists, and the ability to converse with other landholders on a regular basis. The Orange/Molong/Cowra region is well represented by environmental/agricultural services and research stations, and the distance between properties/towns is relatively small. In comparison, the Hillston/Griffith region's environmental services are concentrated in Griffith, in the south of the region, and the distance between properties and towns is considerably larger. Furthermore, the city of Griffith has a primary agricultural focus on horticulture and viticulture, with the major exports being citrus fruit and grapes (Griffith City Council 2009). In these two circumstances, the regional motivation towards, and enthusiasm for, SHM could be expected to be very different. However, motivation and enthusiasm were not quantitatively measured in this current research, and would benefit from further investigation.

7.4.11. Incentives for the adoption of structured soil health management plans

Survey responses indicate that landholders have a tendency to consider any of the incentives listed as being influential to the implementation of SHM programs, irrespective of region, property size and farming enterprise. As is the case with impediments, economic incentives outweigh social incentives. However, whereas social impediments are considered a large impediment by less than one fifth of landholders, a least one third of landholders see further promotion of SHM and the forming of grower-based groups as a large incentive. This highlights an important point about the relationship between impediments and incentives; just because a factor is not seen to impede the implementation of SHM programs does not necessarily mean that factor should not remain a focus, or element, of future endeavours for SHM adoption efforts.

The greatest incentive, of those presented, is compensation by governments for proper soil management. This sentiment is echoed in survey responses by a large number of landholders, either directly or indirectly. A common concern of landholders is how government compensation for land management is administered and how government financial incentives are presented. Numerous comments make reference to farmers with poor farming practices receiving funding, or properties being used as tax sinks, wasting government budget. A suggestion made by various landholders is to have an incentive program that issues funding on a remuneration-based system, where farmers have to prove they have been consistently managing soil health, presumably by a set of structured regional guidelines. Interestingly, Based on the opinions of landholders, and the apparent weight given to financial incentives, it can be deduced that relevant financial incentives outweigh the burden of sensible regulation. One comment concerning government legislation, and changes in the same, suggests that a further incentive to SHM plan adoption would be consistent SHM policy that, if proved to be misinformation or incorrect practice, has a contingency clause for compensation of affected landholders.

Incentives relating to property improvement and stewardship were also well received by landholders. This shows that farmers realise they are responsible for the future of agriculture and are not just simply interested in short term gain at the expense of longevity of production. Sinden and King (1990) also found that stewardship was an important factor for the impetus of landholders to adopt a resource management system. It follows that if handing on a resource in a productive state is a priority for landholders, then information and assistance for managing that resource is also going to be of priority; a result that is evident in the response to information-based incentives. Landholders showed preference for easy access to soil health advice and recommendations at a subsidised cost over access to freely and readily available information, which suggests that complexity is an issue. It may also suggest that landholders aren't confident in their ability to synthesise and implement information.

Interestingly, successful soil health stories, while still a large incentive to the majority of landholders, is considered the least important information-based incentive. This is most likely a consequence of landholders having already acknowledged that soil health is important and that SHM works. This result is also somewhat contradictory to the many comments made by landholders regarding a desire for more farm-based demonstration sites. Perhaps this is due to a desire for physical evidence rather than just 'stories'. An important point drawn from the landholder comments on demonstration sites is that they be area-specific.

7.4.12. Recommendations

This research suggests that there are three main areas for consideration in improving the adoption of structured SHM programs: ongoing communication and support; the initial cost of program implementation; and the availability and expense of appropriate machinery. Accordingly, targeting incentives and future efforts towards these three considerations would presumably increase the adoption and permanence of structured SHM plans. A focus on providing ongoing technical and expert advice through future extension efforts should occur, while a central information portal, not unlike the Soil Health Knowledge Bank (Table 7.1), would also be advantageous. The creation of a research register where scientists can upload information on current and completed research would allow other rural stakeholders the opportunity to remain in connection with current research. Such an initiative could include the ability for all stakeholders to upload information and share ideas, which would help in addressing the ability for landholders to remain in contact with the research element of agriculture.

In order to address the perceived high initial investment in SHM, we suggest there are two approaches that should be used in conjunction. Firstly, financial incentives provided on a remuneration basis for appropriate SHM would encourage adoption of SHM plans. In doing this, a set of criteria would need to be developed that encompass correct management. It is important that these criteria are able to be understood by those intended to meet/implement them. Secondly, our results show that CMA workshops were successful in decreasing the perception of a high initial investment. The use of further workshops that detail initiation strategies for SHM and are tailored towards management strategy transition from conventional farming to SHM is recommended.

The establishment of organised buying groups for machinery, or farm machinery cooperatives would aid in addressing the cost of new farm machinery and the lack of and/or cost of contractors. Harris and Fulton (2000a; 2000b; 2000c) have documented the success and benefits of farm machinery cooperatives, which include a reduction in equipment and machinery costs up to 70%. They suggest that such a cooperative needs to include the following critical factors: compatibility of members; clear economic benefits; appropriate and defined levels of investment; ongoing communication and planning; accurate records; and written agreements. A residual effect of such a scheme is the requirement for farmers to manage their properties in conjunction with other farmers. This could further aid in improving communication about farming practices and strategies between farmers. It is therefore recommended that investigation into the merits of such an initiative be undertaken in the Lachlan and Macquarie Valleys.

7.5. Conclusion

The majority of landholders in the Lachlan and Macquarie Valleys indicate that they manage their properties for healthy soils with the general understanding that their approach must be multifaceted, including soil chemical, physical and biological aspects. Although Lobry de Brun and Abbey (2003) show that soil health indicators are influenced by region, in this study landholders believe that soil health factors (which indicators are designed to measure) are not influenced by region in soil health management planning However, there remains a propensity for SHM plans to be inconsistent, unstructured, or ad-hoc. There is also an apparent tension between short-term profitability and production longevity where the same proportion of farmers who believe their soils should be used to maximise their annual income, also believe that correct management of their properties will provide sustained production, while not necessarily increasing production. In order to deal with this tension and the propensity for unstructured SHM plans, agronomists and extension agencies will need to remain flexible in their approach when dealing with multiple management methods and disseminating information through multiple methods. A structured approach to SHM should be encouraged, although not forced, with a focus on involving the landholder at all stages of planning.

An overall positive attitude towards SHM is exhibited by landholders from areas with ready access to environmental and agronomic services. There is a general satisfaction with past soil health management experiences that leads to a clear willingness to change farming practices in order to manage for soil health. Accordingly, there is minimal belief that a negative culture exists in farming communities that discredits the notion of the ‘recalcitrant’ farmer in relation to SHM. However, while there is a positive attitude towards SHM and a willingness to implement such management plans, landholders indicate that they simply can not afford the initial investment of implementing a SHM plan, even though they concede that long-term financial gain and productivity longevity can result from SHM. In addressing this cost, a remuneration based subsidy for appropriate SHM is favourable with landholders. Additionally, the ongoing cost of sustaining a SHM plan does not appear to be an impediment to SHM, although it was shown that landholders can not justify buying the specialised machinery and that contractors are too expensive, unavailable or do not have the required equipment. The creation of a grower-formed machinery co-operative responsible for purchasing and ongoing maintenance of machinery may be advantageous in addressing this impediment and in encouraging greater communication between local farmers.

Education is largely viewed as not being an impediment for SHM by landholders of the Lachlan and Macquarie Valleys. However, this is contradictory to the knowledge displayed by landholders for issues, such as sodicity, electrolyte concentration and slaking. This indicates that while education may be lacking for particular soil health factors, education can be removed as an impediment for SHM through a reliance on agronomists and extension agencies. Furthermore, it shows that landholders find SHM to be complex, something that was echoed in a desire for an increase in the provision of technical and expert advice. As it is not possible to make the soil chemical, physical and biological systems and their interactions simpler, or possible to educate all farmers to an adequate level to sustain SHM without external assistance, a reliance on agronomists and extension agencies must continue. However, landholders need to be involved at all levels of management, including on-the-ground decisions through to research, in order not to lose substantial connectivity with their properties.

Accordingly, it is indicated that there exists an increased value, trust and reliance on agronomists and extension agencies, compared to the past. Yet communication between researchers, agronomists and extension agencies, and landholders will need to increase. Various comments made by landholders requesting further research into areas with adequate information already in existence is testament to this. Furthermore, there is an evident scepticism of government-based agencies relating to their role in policy creation and implementation. This also extends to a view that such agencies do not posses the ability to adequately service the requirements of local landholders. Conversely, these same agencies have been shown to be an effective means (through workshops) by which to alter landholder perception of impediments, such as initial investment in SHM, and networking amongst stakeholders in the agricultural sector. The continual provision of workshops will provide a greater awareness of government agency abilities and help to decrease scepticism. This aside, the role of agronomists and extension agencies is vital in sustaining SHM in the Lachlan and Macquarie Valleys; an incentive for the adoption of SHM is easy access to expert advice and assistance at a subsidised cost, which is viewed more favourably than free access to information.

7.6. Acknowledgements

We would like to extend our appreciation to the landholders who participated in this research and the funding bodies: CRDC, CRC CCC, NSW DPI, and Central West CMA. Also, gratitude is given to the various LHPAs that assisted in the provision of participant databases, and to Prof. Virginia Lesser (Oregon State University), Dr Jacki Schirmer (Australian National University), Dr Stephen Sutton (James Cook University) and Dr Aldo Steffe (NSW Department of Industry and Investment) for assistance with statistical analysis.

7.7. References

Australian Government (2003) Native Vegetation Act 2003.

Bangura, AM (1983) Farmer motivated patterns in participating in adaptive crop trials/demonstrations in Sierra Leone. *Dissertation Abstracts* **44/03A,** 864.

Bennett, R (1999) *Sustainable soil management in New Zealand: farmer beliefs, attitudes and motivations*. Discussion paper in natural resource and environmental economics No. 21, (Centre for Applied Economics and Policy Studies Massey University: Palmerston North)

Carberry, PS, Hochman, Z, McCowan, RL, Dagleish, NP, Foale, MA, Poulton, PL, Hargreaves, JNG, Hargreaves, DMG, Cathray, S, Hillcoat, N & Robertson, MJ (2002) The FARMSCAPE approach to decision support: farmers', advisers', researchers', monitoring simulation, communication and performance evaluation. *Agricultural Systems* **74,** 141-77.

Chamala, S (1987) Adoption processes and extension strategies for conservation farming. *In* 'Tillage: new directions in Australian agriculture'. (Eds. Cornish, PE & Pratley, JE) (Inkata Press: Melbourne)

Chamala, S, Keith, KJ & Quinn, P (1982) 'Adoption of commercial and soil conservation innovations in Queensland - information exposure, attitudes, decisions and actions', (Department of Agriculture, University of Queensland: Brisbane)

Chellemi, DO & Porter, IJ (2001) The role of plant pathology in understanding soil health and its application to production agriculture. *Australian plant pathology* **30,** 103-09.

Cohen, JW (1988) 'Statistical power analysis for the behavioural sciences', (Lawrence Erlbaum Associates: Hillsdale, NJ)

Department of Agriculture Fisheries and Forestry (2008) *Healthy soils for sustainable farms: Program report*. (Land & Water Australia: Canberra) http://lwa.gov.au/files/products/healthy-soils-sustainable-farms/pn20960/pn20960.pdf (accessed 25 March 2010)

Desbiez, A, Matthews, R, Tripathi, B & Ellis-Jones, J (2004) Perceptions and assessment of soil fertility by farmers in the mid-hills of Nepal. *Agricultre, Ecosystems & Environment* **103,** 191-206.

Diallo, I (1983) An assessment of farmers' attitudes and experiences under no-till corn production systems in Baltimor county, Marryland. *Dissertation Abstracts* **45/05B,** 1329.

Dillman, DA (2007) 'Mail and internet surveys: the tailored design method.' (John Wiley & Sons: New Jersey)

Dixon, G (1982) 'A course manual in agricultural and livestock extension. Rural Sociology', (Universities International Development Program: Canberra)

Doran, JW (2002) Soil health and global sustainability: translating science into practice. *Agricultre, Ecosystems & Environment* **88,** 119-27.

Fraiture, Cd, Wichelns, D, Roskstrom, J & Kemp-Benedict, E (2007) Looking ahead to 2050: scenarios of alternative investment approaches. *In* 'Water for food, water for life: A comprehensive assessment of water management in agriculture'. (Eds. Molden, D) (Earthscan: Colombo)

Frank, BR (1997) Adoption of innovations in the north Queensland beef industry. III: implications for extension management. *Agricultural Systems* **55,** 347-58.

Gravetter, FJ & Wallnau, LB (2004) 'Statistics for the behavioural sciences', (Wadsworth: Belmont, CA)

Griffith City Council (2009) *Annual report*. (Griffith City Council: Griffith)

Guerin, LJ & Guerin, TF (1994) Constraints to the adoption of agricultural and environmental innovations and technologies: a review. *Australian Journal of Experimental Agriculture* **34,** 549-71.

Guerin, TF (1999) An Australian perspective on the constraints to the transfer and adoption of innovations in land management. *Environmental Conservation* **26**.

Harris, A & Fulton, M (2000a) 'The CUMA farm machinery co-operatives', (Centre for the Study of Co-operatives, University of Saskatchewan: Saskatoon, Canada)

Harris, A & Fulton, M (2000b) 'Farm machinery co-operatives in Saskatchewan and Quebec', (Centre for the Study of Co-operatives, University of Saskatchewan: Saskatoon, Canada)

Harris, A & Fulton, M (2000c) 'Farm machinery co-operatives: An idea worth sharing', (Centre for the Study of Co-operatives, University of Saskatchewan: Saskatoon, Canada)

Hayman, PT & Alston, CL (1999) A survey of farmer practices and attitudes to nitrogen management in the northern New South Wales grains belt. *Australian Journal of Experimental Agriculture* **39,** 51-63.

IBM (2009) PASW Statistics 18. SPSS Inc.

Industry Commission (1998) *A full repairing lease - inquiry into ecologically sustainable land management*. Report no. 60, (Australian Government Publishing Service: Canberra)

Keller, DR & Brummer, EC (2002) Putting food production in context: toward a postmechanistic agricultural ethic. *BioScience* **52,** 264-71.

Kelly, B, Allan, C & Wilson, BP (2009) Soil indicators and their use by farmers in the Billabong Catchment, southern New South Wales. *Australian Journal of Soil Research* **47**.

Kloppenburg, J (1991) A social theory and de/reconstruction of agricultural science, local knowledge for an alternative agriculture. *Rural Sociology* **56,** 519-48.

Kloppenburg, J (1992) Science in agriculture: a reply to Molnar, Duffy, Cummins, and Van Saten and to Flora. *Rural Sociology* **57,** 98-107.

Lees, J & Reeve, I (1994) 'TPSKP 1994 producer survey', (Rural Development Centre: Armidale, NSW)

Leopold, A ([1949] 1987) 'A sand county almanac and sketches here and there', (Oxford University Press: New York)

Likert, R (1932) A technique for the measurement of attitudes. *Archievs of Psychology* **140,** 1-55.

Lobry de Bruyn, LA & Abbey, JA (2003) Characterisation of farmers' soil sense and the implications for on-farm monitoring of soil health. *Australian Journal of Experimental Agriculture* **43,** 285-305.

May, EL (2006) *How landholders use and value their private native forests: a study of landholders with dry sclerophyll forests on the Southern Tablelands of NSW*, Thesis - Australian National University, Canberra.

Mowo, JG, Janssen, BH, Oenema, O, German, LA, Mrema, JP & Shemdoe, RS (2006) Soil fertility evaluation and management by smallholder farmer communities in northern Tanzania: Nutrient management in tropical agroecosystems. *Agricultre, Ecosystems & Environment* **116,** 47-59.

Mylek, M (2006) *Landholder perceptions about impediments to, and incentives for, the adoption of farm forestry in the Southern Tablelands region of NSW*, Thesis - Australian National University, Canberra.

New South Wales Farmers Association (2008) *Constitution - NSW Farmers Association.* (NSW Farmers Asscoiation: Sydney)

Quilty, JR & Cattle, SR (accepted) The use and understanding of organic ammendments in Australian agriculture - a review. *Australian Journal of Soil Research.*

Romig, DE, M.J., G, Harris, RF & McSweeney, K (1995) How farmers assess soil health and quality. *Journal of Soil and Water Conservation* **50,** 229-36.

Sinden, JA & King, DA (1990) Adoption of soil conservation measures in Manilla Shire, New South Wales. *Review of Marketing and Agricultural Economics* **58,** 179-92.

Soil Science Society of America (1997) 'Glossary of soil science terms', (Soil Science Society of America: Madison, WI)

Sojka, RE & Upchurch, DR (1999) Reservations regarding the soil quality concept. *Soil Science Society of America Journal* **63,** 1039-54.

Tucker, M & Napier, TL (1998) Perceptions of risk asscoiated with use of farm chemicals: implications for conservation initiatives. *Environmental Management* **22,** 575-87.

Valzano, FP, Murphy, BW & Greene, RSB (2001) The long term effects of lime ($CaCO_3$), Gypsum ($CaSO_4.2H_2O$), and tillage on the physical and chemical properties of a sodic red-brown earth. *Australian Journal of Soil Research* **39,** 1307-31.

Watson, WD, Hall, NH & Hamblin, A (2000) Economic aspects of sodic, acid and saline soils in Australia. *In* 'Proceedings of the Sodicity conference: sodicity issues in agricultural industries - current research and future directions' (ISIA: Tatura, Victoria)

Webster, P (1999) The challenge of sustainability at the farm level: presidential address. *Journal of Agricultural Economics* **50,** 371-87.

Wilkinson, R (1996) 'Resource monitoring by Hawkes Bay farmers', (Manaaki Press: Lincoln)

GENERAL DISCUSSION, CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

“A scientist's aim in a discussion
with his colleagues is not to
persuade, but to clarify.”
– Leo Szilard

8. General discussion, conclusions and future research directions

8.1. General discussion

Semi-arid and arid soils are often characterised by high proportions of exchangeable Na^+, which leads to soil instability upon wetting and a concomitant loss of productivity (Northcote and Skene 1972; So and Aylmore 1993; Pal *et al.* 2003). The application of an extraneous source of Ca^{2+} is required in order to displace Na^+ and improve structural stability (see Sumner 1993; Ghafoor *et al.* 2001; Qadir *et al.* 2001b). However, calcium salt dissolution rate, and subsequent movement, present challenges through cation exchange and electrolyte concentration for the successful amelioration of sodicity. Compounding this is the current education pertaining to sodicity, the occurrence of native lime and gypsum in sodic soils, and the cost of methods for monitoring/analysing soil sodicity.

8.1.1. The viability of lime and gypsum use as a sodicity ameliorant in irrigated agriculture relative to dryland agriculture

While the use of lime and gypsum combinations in the dryland experiment was observed to have had a positive, and possibly synergistic, effect on pH, EC and aggregate stability after 2.5 years, such an effect was not evident under irrigated conditions at the same application rates. However, it is not just a matter of stating that the use of lime and gypsum combinations is not feasible for irrigated agriculture. There is certainly evidence that suggests that the solubility and subsequent leaching of gypsum is too high in an irrigated system to affect the cation exchange significantly in the long-term, or to aid in the dissolution of lime. Other factors such as pH and irrigation water quality will affect the way in which ameliorant combinations work, as well as the extent of the effect. The pH of the Lachlan Valley soils was generally 8.0 or higher; i.e. it was approaching, or higher than, the pH where lime is no longer soluble and Ca^{2+} precipitation in $CaCO_3$ is likely to occur (Russell 1961; Srivastava *et al.* 2002; Pal *et al.* 2003). On the other hand, the pH in the Macquarie Valley soils, where lime was observed to have dissolved over the 2.5 years period, was usually between 6.0 and 7.5. This pH is similar to that of the Brown Sodosol used in the study of Valzano *et al.* (2001b) where lime and gypsum was observed to have had a synergistic effect on cation exchange under a dryland cropping regime. Hence, the pHs of the Lachlan Valley soils suggest that it is unlikely that lime had a detectable effect on soil sodicity, irrespective of the solubility of gypsum.

The original design of this experiment would have allowed a comparison of the effects of different pH soils, under field condition, on the viability of lime and gypsum combinations in ameliorating sodicity. However, lack of irrigation water allocation caused the Macquarie Valley soils to be treated as dryland cropping systems. It would, therefore, be advantageous to investigate the merits of lime and gypsum combinations, under irrigation, in soils of pH below 7.5.

The results of the gypsum alone application (2.5 t.ha^{-1}) show that the positive structural effects do not persist up to 2.5 years, for both irrigated and dryland cropping regimes. This reiterates the suggestion that gypsum is required to be applied regularly, if not yearly (Shanmuganathan and Oades 1983; Valzano *et al.* 2001b). Analysis for residual gypsum in the irrigated soils showed that even gypsum applied at 5 t.ha^{-1} had dissolved after 6 months, which could be expected given the estimate of 120–130 mm of rainfall, or irrigation water equivalent, to completely dissolve and remove 1 t.ha^{-1} of gypsum from the A horizon (Greene and Ford 1985). Likewise, the gypsum alone treated soils (2.5 t.ha^{-1}) in the Macquarie Valley exhibited similar, or lower, ECs and no appreciable difference in aggregate stability compared to the control soils after 2.5 years. These results support the notion that such application rates are sub-optimal for the amelioration of sodicity (Hulugalle *et al.* 2006), especially if this effect is expected to last up to three years. However, an important distinction should be made here, if the desired effect of amelioration is expected to last less than 6 months, then such rates of application may well be optimal.

Based on the criteria for desirable ESP (≤6 %) and EMP (≤25%) (Greene and Barrie 1982), the total gypsum requirement was calculated for two moderately sodic dryland cropping soils (average ESP 10% and 8%, and EMP 34% and 40% for 0–250 mm depth, respectively) as 13.5 t.ha^{-1} and 18.3 t.ha^{-1} respectively (Greene and Ford 1985). However, the observed effects of 15 t.ha^{-1} applied to both soils only represented that of 28% of the applied gypsum and 36% of the dissolved gypsum, which suggest that much higher rates would have been required to reach the desired criteria of Greene and Barrie (1982). Under irrigation, the exchange efficiency (Ca:Na exchange) of gypsum was 14% (Wyadra, Lachlan Valley), with total dissolution after 6 months (the exchange efficiency of gypsum was confounded in the Mount View soil as discussed in Chapter 5). Using this exchange efficiency value, it was calculated that approximately 267 t.ha^{-1} of gypsum would be required in total to ameliorate the soil (0–400 mm depth) to an ESP <6 (this was also calculated ignoring the effects of Mg^{2+}). Hence, the amount of gypsum required to ameliorate even moderately sodic soils, irrigated or dryland, is not feasible to sustainable agricultural practices, especially on broadacre landholdings. Because the apparent viability of gypsum use in irrigated agriculture is low, it is therefore suggested that management techniques for sodicity be adapted to replace the Ca^{2+} uptake of plants and neutralise the Na^{+} input of irrigation water; not unlike the application of fertiliser, on a requirement and necessity basis.

It is seemingly not practicable to ameliorate sodicity using gypsum alone in irrigated agriculture at the current commercial application rate of 2.5 t.ha^{-1}, or even at 5 t.ha^{-1} in conjunction with lime. However, there appears to be merit in the use of gypsum-enhanced chicken manure/wheat straw compost as an ameliorant. Combined application of 5 t.ha^{-1} of gypsum composted with 5 t.ha^{-1} of chicken manure/wheat straw compost was shown to cause less leaching of Ca^{2+}, while causing more exchange of Ca^{2+}, from the soil than the equivalent rate of gypsum-alone or greater applications of compost. Thus, it may be possible to increase the viability of gypsum use in irrigated agriculture by combining it with compost to create a less mobile source of Ca^{2+}; a slow release mechanism. Given these results were obtained from a soil under a simulated irrigation season, it is possible that such a method could be more effective in a dryland environment. Consideration also needs to be given to the mixture rate of gypsum with the compost. The use of 5 t.ha^{-1} of gypsum and 5 t.ha^{-1} of compost may not necessarily be economical, as the observed differences between this rate and the application of gypsum alone (5 t.ha^{-1}) may not necessarily be large enough to justify the cost of the compost and composting process. Thus, other mixtures need to be explored, as well as field validated. The use of mixture experimental design would be advisable (see Anderson and Whittcomb 2000; Cornell 2002)

8.1.2. Management of sodic soils containing native calcium carbonate and gypsum

Native calcium carbonate generally occurs in semi-arid and arid soils (Li and Keren 2008) Both soils in the Macquarie Valley and the Wyadra soil from the Lachlan Valley contained native calcium carbonate in the subsoil. In all three soils the presence of calcium carbonate nodules (possibly nonpedogenic calcium carbonate, NPC; Srivastava *et al.* 2002) and calcium carbonate inclusions with diffuse boundaries (presumably pedogenic calcium carbonate, PC; Srivastava *et al.* 2002) was observed. According to Srivastava *et al.* (2002), the dissolution of NPC and subsequent recrystallization of Ca^{2+} (from dissolution) is responsible for the formation of PC. However, PCs also form in soils containing Ca^{2+} when the pH rises above 8.4, due to the increasing presence of carbonate and bicarbonate, again through the process of precipitation (Rowell 1988). The low dissolution of PC is usually a limiting factor in their contribution to sodicity amelioration (Keren 1996). Furthermore, at pH > 8.0 the displacement of Na^{+} by Ca^{2+} from such carbonate is not viable (Pal *et al.* 2000). It has been suggested that an external source of Ca^{2+} (e.g. gypsum) applied to a calcareous soil can indirectly increase the dissolution of PC by improving aggregation and, in turn, the ρ_{CO_2} of the soil (Gupta and Abrol 1990; Pal *et al.* 2000). However, as was shown throughout this work, the use of gypsum to ameliorate sodicity in irrigated soil was did not lead to long-term soil structural improvements due to the magnitude and frequency of wetting.

A further technique for augmenting/initiating the dissolution of PC is phytoremediation. This technique primarily involves increasing the ρ_{CO_2} through the processes of plant root respiration and decomposition of organic matter, causing an increase in carbonic acid and associated dissolution of PC (Robbins 1986b; Robbins 1986a; Qadir and Oster 2002; Qadir *et al.* 2002). A secondary phytorememdiation mechanism involved with PC dissolution is the use of plants with high proton output that cause a concomitant decrease in pH. Subsequently, PC in the vicinity of the lower pH is dissolved at a higher rate. This effect has been observed to be most successful with nitrogen-fixing crops (Qadir *et al.* 2003; Mubarak and Nortcliff 2010). To date, the majority of this research has been conducted in the Middle East (Qadir *et al.* 1996; Batra *et al.* 1997; Ghafoor *et al.* 2001; Qadir *et al.* 2001a; Qadir and Oster 2002; Qadir *et al.* 2002; Qadir *et al.* 2003; Mubarak and Nortcliff 2010). These techniques for accessing PC and ameliorating sodicity need to be investigated in Australian irrigated soils given that a large proportion of irrigated agriculture occurs in semi-arid sregions (Northcote and Skene 1972) likely to contain calcareous layers (Pal *et al.* 2006).

Gypsic inclusions were observed for both the Mount View and Wyadra soils, although there was approximately 3.5 times greater abundance at Mount View. Pedogenic processes aside, the presence of a low permeability layer at Mount View is likely responsible for the greater abundance of gypsum than observed in the Wyadra soil at similar depths. Deep ploughing (the mixing of the B horizon with the A horizon) is one option available to access the gypsum in these soils (Qadir *et al.* 2001a). This process would require ploughing to a depth below the permeability limiting layer and sufficiently deep into the gypsic layer to allow sufficient mixing. If sufficient mixing does not occur the topsoil can actually become worse (the impermeable layer has ESP ≈ 38% at Mount View) (McAndrew and Malhi 1990). The results may also only be short lived (Ballantyne 1983), which questions the economic practicality of such a management strategy (Grevers and De Jong 1993). Given the total gypsum percentage at Mount View (approximately 0.83 % at 400–600 mm and 1.35% at 600–800 mm depth) compared to that at Wyadra (approximately 0.10 % at 400–600 mm and 0.38% at 600–800 mm depth) this technique would likely only be suited to the Mount View soil, if either.

Deep ripping, or subsoiling, has been presented as an alternative to deep ploughing (Muirhead *et al.* 1970; Grevers and De Jong 1993). This technique involves the ripping of channels/trenches through the A horizon and into the B horizon without mixing the soil profile. However, as this method does not mix the soil, the gypsum contained in the subsoil does not necessarily benefit the topsoil. While the ripped channels are conducive to increased root growth and water infiltration, these positive effects can be short-lived (Loveday *et al.*

1970). The application and incorporation of gypsum with deep ripping may maintain structural form for a longer period of time, although the success of gypsum application in the Mount View and Wyadra soils was limited and shown to revert to control conditions within 2.5 years (a function of wetting magnitude and frequency). Thus, such procedures may not be suitable for these soils, and will most likely not take advantage of the native gypsum. Jaywardane *et al.* (1988) proposed 'slotting', which involves the use of a rotary slotter to dig straight edge trenches, or 'slots'. This method does mix the soil, although it appears to be limited to a depth that would not completely mix the gypsic layer through the topsoil (Jayawardane and Blackwell 1985; Blackwell *et al.* 1991; Jayawardane *et al.* 1994). This amount of mixing would, therefore, most likely result in the exacerbation of sodic conditions in the topsoil from lower layers with high ESP inr the Mount View and Wyadra soils (Ballantyne 1983; McAndrew and Malhi 1990).

8.1.3. The amendment-induced electrolyte effect and its longevity in irrigated agriculture

The importance of enhancing the soil EC to improve soil structural stability is well documented, and gypsum is generally recognised as the most common method for achieving this (Quirk and Schofield 1955; Davidson and Quirk 1961; Loveday 1976; Rengasamy 1983; Shanmuganathan and Oades 1983; Rengasamy *et al.* 1984b; Sumner 1993; McKenzie and Murphy 2005). Lime has also been shown to have a limited effect on EC (Shainberg and Gal 1982; Naidu and Rengasamy 1993; Valzano *et al.* 2001b). In the dryland circumstance, gypsum was observed to have no significant effect on soil EC after 2.5 years, while there was a general trend for an increase in EC where lime had been applied. This effect was greatest in the Bellevue soil where the L2.5G2.5 and L2.5G5 treatments had been applied (significant at $p<0.15$, compared to the L0G2.5 treatment), which suggests that gypsum has augmented the dissolution of lime at the given pH (Valzano *et al.* 2001b).

However, such results as those observed under dryland agriculture were not evident in irrigated soils after 6 months or 2.5 years for lime or lime/gypsum treatments. The most likely reason for lime not having had an EC effect is again due to the pH of the Lachlan Valley soils being high. Gypsum was also observed to have had no appreciable effect on soil EC after the same time periods, which can be attributed to dissolution and leaching of gypsum, given the magnitude of irrigation water applied was sufficient to dissolve and leach much more than 5 $t.ha^{-1}$ of gypsum (Greene and Ford 1985; Valzano *et al.* 2001b). This would also have resulted in an insubstantial effect of gypsum on lime dissolution and any subsequent EC effect of lime.

Where the effect of increased electrolyte has been shown to last between 1 and 3 years in a dryland situation (Greene and Ford 1985; Valzano 2000; Valzano *et al.* 2001a; Valzano *et al.* 2001b), the application of gypsum was observed to last less than 6 months under irrigation in the Lachlan Valley. This shorter period of effect was further supported by the laboratory experiment results that showed the electrolyte effect (due to 5 $t.ha^{-1}$ of gypsum) lasted less than 14 weeks under simulated irrigated wetting and drying cycles (using the Mount View soil, Lachlan Valley). Indeed, the EC measurements of the leachate from this experiment showed that the majority of the electrolyte was leached within two irrigation events, that any prolonged effect was severely diminished after four irrigation events, and that the EC of gypsum-treated soil was comparable and approaching the EC of the control soil between 5 and 7 irrigation events. While these results may not be completely indicative of the field environment (i.e. drainage may be substantially higher in the laboratory), the field based observations appear to support them. Accordingly, Loveday (1976) showed that the maximum effect of EC on hydraulic conductivity was immediately upon irrigation. These results are in keeping with finer gypsum particles becoming soluble upon the first irrigation, increasing the electrolyte in solution significantly, and subsequently leaching rapidly with further irrigation events (Kemper *et al.* 1975). Therefore, the period of electrolyte effect in irrigated soils is severely diminished compared to the same in dryland soils, and management practices would need to be adjusted in light of this.

8.1.4. Awareness of sodicity and the importance of extension efforts

While sodicity has been estimated to affect 47% of New South Wales (McKenzie *et al.* 1993) and 340 million ha Australia wide (Murphy 2002), which constitutes approximately one third of the continent (Northcote and Skene 1972), it was reported in 2000 that 52% of local governments did not believe sodicity to be an issue, with a further 22% unaware of sodicity (Watson *et al.* 2000). This is concerning as local governments, often comprised of local landholders, are responsible for the representation of the local farming community and should be cognisant with issues affecting the wellbeing and longevity of this community. However, Hajkowicz and Young (2005) argue that, through various programs (unlisted in their paper) operating throughout 1995-2005, the awareness and understanding of sodicity, acidity and salinity could be assumed to be high, although they concede that sodicity is the least well known of these issues. They also suggest that farmers have an intimate knowledge of the response that could be expected from treatment, suggesting that the choice not to apply amendments is informed and indicative of marketplace definition of the optimum proportion of soil treatment – 4% of affected land (Hajkowicz and Young 2002). Contradictory to this are the results observed in the survey of Lachlan and Macquarie Valley landholders that show only 36% of landholders knew what sodicity was, while the remaining 64% either did not know, thought sodicity was the same as salinity, or confused the definition of sodicity with its consequences. Hence, the awareness of sodicity is low and the assumption of optimal treatment of sodic soils cannot be made.

In order for landholders to effectively manage for sodic soils a firm understanding of the causes and ramifications of sodicity are required. Therefore, methods for sodicity amelioration, such as those investigated in this thesis, become redundant without this underlying knowledge. Communication between those responsible for land management innovations (usually research scientists) and those intended to use them (usually farmers) is vital to their adoption and continued use (Guerin and Guerin 1994; Guerin 1999). Thus, the link of communication between scientists and farmers, most commonly achieved through research extension organisations and agronomists, is vital in combating sodicity. Survey results showed that there is increased trust in agronomists and extension, which results in a large reliance on these organisations to assist in farm planning (Kelly *et al.* 2009). However, it must be assumed that communication has, until now, failed on the issue of sodicity.

The results obtained in the dryland and irrigated experiments of this thesis highlight the management and site-specific effects of gypsum and lime use on sodicity. This will present challenges for extension officers and agronomists alike. It means that a flexible approach will need to be taken towards encouraging landholders to address sodicity, as well as acknowledgement of the multiple methods of learning (Kloppenburg 1991; Kloppenburg 1992) and a requirement for ongoing advice and assistance in monitoring of effects. Importantly, the variable nature of lime and gypsum effects will require extension officers and agronomists to have a well grounded understanding of the mechanisms that govern the effects of such amendments in different soil environments. This emphasises the need for more field-based research on such effects and provides justification for the same. Given the apparent decrease of expertise and funding for government environmental organisations, there would be merit in ascertaining the level of knowledge of extension staff and agronomists regarding issues such as sodicity.

8.1.5. Experimental design, field variability and implications for precision agriculture

The field experiments in this work were originally designed to allow for the incorporation of field-based electro-magnetic (EM) and cut/fill maps in order to reduce the ‘noise’ of the data taken at field scale. However, this was not feasible due to logistical complications that resulted in cation analyses having to be outsourced and the associated cost of this. The cost of analysis required that bulking of similar samples occur, in order to lower the amount of analysis. This eliminated the possibility of creating full field maps to illustrate cation concentration variability and decrease random error, through incorporating the EM and cut/fill maps into statistical analysis. Subsequently, analysis of experimental sites was generally limited to one-way analysis of variance with two replicates per treatment, which hampered statistical power greatly (Fairweather 1991). It is therefore possible that Type II error has occurred throughout the field-based research; Type II error occurs when the alternate hypothesis is not accepted (i.e. the null hypothesis of no difference is accepted) when it should have been. As landholders could not feasibly be expected to sample to the point where statistical power is high, this highlights an issue with rejecting treatment applications on possibly incorrect grounds.

The current cost of cation concentration analysis, using conventional methods, does not allow for the creation of maps for ECP and ESP at the broad-acre agriculture level (Viscarra Rossel and Walter 2004). Such maps would facilitate the precision application of lime and/or gypsum. A possible solution would be to create a predictive model for application of lime and gypsum amendments. However, the work in this thesis reiterates the management and site-specific effects of such amendment on sodicity. Given that there is a paucity of information pertaining to combined lime and gypsum use and the subsequent effects on sodicity in agriculture (dryland or otherwise), it stands that there would also be insufficient data on which to base a useful predictive model. Hence, further field-based investigation and collection of data from existing sites using amendments is required to reach this point.

It could be argued that the use of other rapid measurements for stability and its governing chemical attributes, such as ASWAT (Field *et al.* 1997) and electrolyte concentration, might offer indirect measurement of sodicity levels, thus allowing mapping. Relationships between EC and ESP have been shown to define critical thresholds for aggregate stability (Loveday and Pyle 1973; Rengasamy *et al.* 1984b; McKenzie and Murphy 2005). However, the use of EC and ASWAT to determine ESP is not possible, as the ASWAT procedure does not allow for a quantitative measure of the properties defining it, and does not allow for the inclusion of other properties affecting soil stability such as the clay mineral suite, or bonding effects of organic matter (Tisdall and Oades 1979; Tisdall *et al.* 1997; Speirs 2006). Knowing the EC and dispersive index of a soil from ASWAT may allow estimation of a maximum ESP, but the above mentioned issues will still affect the accuracy of this value and the associated error would presumably be too high to aid in the determination of amendment effects. Research in the field of proximal soil sensing has shown that soil properties such as pH, clay mineral suite, soil colour, OC content, air-dry gravimetric water content, CEC, exchangeable Ca^{2+} and Mg^{2+}, and nitrogen content can successfully be determined through the use of ultra-violet, visible, near-infrared and mid-infrared reflectance spectroscopy (see Viscarra Rossel *et al.* 2010). However, this technology has had limited success for the prediction exchangeable Na^{+} and K^{+} (Islam *et al.* 2003; Pirie *et al.* 2005). Without a measure of at least Na^{+}, it is still not possible to provide accurate precision agricultural maps for sodicity management. In spite of this, developing technology includes a multi-ion measurement system that will allow direct and rapid in-field measurement of sodium using ion exchange kinetics (Lobsey *et al.* 2010). Such a system should prove useful in mapping sodium on a field-basis, allowing assessment of lime and gypsum effects on sodium at the field-scale and possibly decreasing the chance of Type II error.

8.2. General Conclusions

From the topics and themes investigated in this thesis, the following general conclusions are drawn. With regard to the viability of lime and gypsum use as a sodicity ameliorant, some conclusions are:

- Soil pH would only have allowed minimal dissolution of lime in the Lachlan Valley soils as compared to the soils of the Macquarie Valley. Subsequently, 2.5 years may not be a sufficient period in which to observe the 'long-term' effect of lime. On this basis, the use lime alone is likely to be of no value within 2.5 years, but may become viable after longer periods. That said, soil improvements due to lime are more likely to occur in the Macquarie Valley soils.

- The solubility of gypsum, and subsequent leaching, is too high under irrigation in the Lachlan Valley soils to allow for significant changes in soil attributes after 2.5 years. Thus, the use of low rate gypsum application is both sub-optimal and unviable. However, there appears to merit in the application of gypsum to these soils in the very short-term (less than 6 months).

- The use of lime and gypsum combinations in the irrigated Lachlan Valley soils does not appear to be practicable as the gypsum is unable to affect the dissolution rate of the lime and the pH is too high for adequate dissolution in the absence of gypsum. Subsequently, synergy was not observed between the amendments in the irrigated soils.

- There is possible merit in the use of gypsum-enhanced chicken manure/wheat straw compost in ameliorating sodic soils under irrigation. This amendment was shown to increase calcium exchange, while reducing calcium leaching, but requires field validation.

- The extent of the structural/chemical effect of lime and gypsum was shown to be strongly linked to the frequency and magnitude of wetting. The effects of chemical ameliorants should therefore be conveyed to the desired end-users (farmers) in these terms, rather than only providing an expected timeframe of effect.

With regard to the amendment-induced electrolyte effect and its longevity in irrigated agriculture, some conclusions are:

- Neither lime nor gypsum provided an appreciable electrolyte effect after 6 months or 2.5 years in irrigated soil, while an effect was observed from lime/gypsum combinations after 2.5 years under dryland conditions.

- Laboratory simulation of an irrigated season wetting and drying cycle showed that the majority of electrolyte was leached from the soil (where 5 $t.ha^{-1}$ of gypsum was applied) within two irrigations events and there were no apparent differences in control and treated soil electrolyte levels after 7 irrigations.

- The electrolyte effect is significantly curbed in irrigated soil as compared to the same in dryland conditions, due to the magnitude and frequency of wetting.

With regard to the awareness of sodicity and the importance of extension efforts, some conclusions are:

- The current awareness of sodicity is low, and sufficient sodicity amelioration efforts, as defined by the market, cannot be assumed to have occurred even though Hajkowicz and Young (2005) suggest they have.

- Communication of existing research concerning sodicity has apparently failed to reach the desired users (farmers). Subsequently, methods of amelioration for sodicity become redundant.

- Extension officers and agronomists will need to remain flexible in their approach towards encouraging the management of sodicity. A significant hurdle to this is the site and management-specific nature of effect when using lime and gypsum.

With regard to experimental design, field variability and implications for precision agriculture, some conclusions are:

- The statistical power of the field-based experiments was limited and the possibility of Type II error (accepting the null hypothesis when it should have been rejected) occurring exists.

- The current field-based experimental design does not allow for field-scale mapping of sodicity. Thus, subsequent monitoring will be expensive and probably beyond the means of landholders. The use of emerging sensor technology may aid in reducing this cost.

8.3. Future research directions

As a result of the work conducted in this thesis, various directions for future research have been identified throughout the numerous chapters. These are outlined below.

Due to a lack of irrigation water allocation, the field experiments in the Macquarie Valley were required to be analysed as soils under a dryland cropping system. The results obtained from pH, EC and aggregate stability measurements suggest that a synergistic effect between lime and gypsum could have occurred after 2.5 years. While there was no obvious effect due to lime and gypsum in the irrigated Lachlan Valley soils after 2.5 years, and results after 6 months appeared to be restricted to gypsum alone treatments, the pH was likely too high to provide sufficient dissolution of lime in the absence of gypsum. On the other hand, the pH in the Macquarie Valley was similar to those providing for synergy to occur in a dryland environment (Valzano *et al.* 2001b). Thus, there is still a requirement to assess the viability of lime and gypsum combinations in irrigated soils with pH less than 8.0.

On a per dollar basis, the application of lime and gypsum to the Lachlan Valley soils was generally shown to be unviable given the effects reported. Due to the amount of irrigation water applied to these soils, and the quality of that water, it was theorised that acceptance of the inherent levels of sodicity may indeed be the optimal management technique for these irrigated sodic soils. In accepting the inherent levels of sodicity, the focus should be on not exacerbating these levels, and maintaining a steady level of sodicity. In order to do this, an amount of calcium to be applied with each crop (or throughout the season) would need to be determined in order to balance the calcium lost via harvesting of crops, and the sodium applied with the irrigation water. Therefore, there is a need to determine the various calcium requirements of crops with reference to depletion of soil stocks, as well as determine the best method in which to replace these (e.g. as calcium-enhanced irrigation water, as an annual amendment application, as a regular amendment application throughout the cropping season). The development of an annual calcium budget system would be highly advantageous in aiding landholders to manage sodicity levels.

The use of plants to enhance the effects of lime and gypsum in sodic soils was explored by Bennett (2006) under dryland conditions and suggested to be advantageous to the dissolution of lime over a period of 11 years. Furthermore, it has been shown that plants, including cotton, can increase soil carbon dioxide partial pressure, and sometimes result in the improvement of ESP levels in calcareous sodic soils (Robbins 1986a; Robbins 1986b; Qadir *et al.* 2001a; Qadir *et al.* 2001b). The possibility of wheat and cotton in augmenting the dissolution of lime in irrigated soils of the Lachlan Valley was considered in this work. However, the results suggested that such a process did not occur, or was unable to be detected using the analytical methods employed. The likelihood is that these effects would be most prominent in the rhizosphere. Hence, further research concerning the ability of commonly used crops in augmenting the dissolution of sodicity amendments, and the proximity of the effect to the rhizospere, would be advantageous. Furthermore, there is an apparent requirement to investigate and report the process of phytoremediation through the use of nitrogen-fixing plants (e.g. legumes) in Australian agriculture, both dryland and irrigated. The effect of these plants on applied calcium carbonates should also be considered.

An enhanced aggregate stability in water was observed to persist after 2.5 years and irrigation/rainfall in excess of 2500 mm, even though the associated chemical results showed the soil to have undesirable properties for soil stability. We propose that, while it is harder for exchangeable calcium to access cation exchange sites in the interior of intact soil aggregates (Greene and Ford 1985), once calcium has infiltrated aggregates it is harder to leach than calcium exchanged onto the outer surface of aggregates. By grinding aggregates to less than 2 mm, excess sodium exchanged to the outer layers of the aggregates dilutes the presumably small amount of calcium central to the aggregate and, thus, it appears upon chemical analysis that aggregate stability is prolonged even though unfavourable chemical conditions exist. However, this is purely conceptual and would benefit from further investigation. There would be merit in sampling the outer surfaces of peds and comparing these to inner ped proportions through standard procedures of analysis for soil exchangeable cations.

The laboratory experiment showed that the use of gypsum-enhanced chicken manure/wheat straw compost was beneficial in ameliorating moderate levels of sodicity, to an extent that was generally greater than gypsum alone at comparable rates. It is theorised that the gypsum/compost combination acts as a medium for dissolved calcium to exchange onto, thus causing the calcium to be harder to remove upon subsequent irrigation. The fact that more calcium was exchanged into the soil and less calcium was leached than by the use of gypsum alone would support this, but further investigation into how this beneficial effect occurs would be advantageous. Furthermore, the mixture that was required to observe these effects may not necessarily be optimal. Indeed, 5 t.ha^{-1} of gypsum combined with 5 t.ha^{-1} of compost, while not outside commercial application recommendation, may be excessive for broad-acre agriculture. Thus, through the use of mixture design with gypsum, compost and possibly soil depth as levels (Scheffe 1958; Cornell 2002), it may be possible to determine the optimal combination of gypsum and compost over the desired depth of application. These processes also need to be field-validated using numerous soils.

The mail-based survey of Lachlan and Macquarie Valley landholders illustrated that there is a general positive culture towards the implementation of soil health management plans, although these were often unstructured. Furthermore, it was revealed that an apparent low level of understanding existed for the issue of sodicity. Given the positive culture, but the low level of education concerning certain soil health issues, it would be beneficial to examine the current extension methods and their effectiveness. In association with this, landholders expressed a desire for more ongoing advice and technical assistance. Such issues were found to be highly linked to the region in which landholders resided. Thus, a point at which to start measuring the effectiveness of extension agencies and agronomy services, and potentially creating a model of desirable/working methods of landholder involvement, would be the regions in which these issues were not indicated as being limiting to soil health management. Future investigation of these themes could be done through a series of surveys (mail/internet based) and face-to-face interviews, in order to obtain a 'rich' data set (Lobry de Bruyn and Abbey 2003; Kelly *et al.* 2009).

A further impediment observed in the survey data was the availability of contractors, or a lack of contractors with appropriate machinery, and the expense of acquiring the required specialist machinery for certain aspects of soil health management. Farming machinery cooperatives have proven as a workable solution to similar circumstances in Canada (Harris and Fulton 2000c; Harris and Fulton 2000a; Harris and Fulton 2000b). Information pertaining to comparable initiatives in Australia is apparently non-existent. It is proposed that such a scheme may be a practical solution to the current landholder concerns, which would not only address machinery associated issues, but also encourage farmers to work together and communicate their ideas. Therefore, an investigation should be conducted into the workability of such a program for Australian farmers.

8.4. References

Abbott, TS, McKenzie, DC (1986) Improving soil structure with gypsum. Agfact AC 10, NSW Agriculture

Abrol, IP, Fireman, M (1977) 'Alkalai and saline soils, identification and improvement for crop production', Bulletin No. 4 (Central Soil Salinity Research Institute: Karnal, India)

Adriano, D, C,, Page, AL, Elseewi, AA, Chang, ACS, I. (1980) Utilization and disposal of fly ash and other coal residues in terrestial ecosytems: a review. *Journal of Environmental Quality* **9,** 333-4.

Agarwal, RR, Yadav, JSP, Gupta, RN (1979) 'Saline and alkaline soils of India', (Indian Council of Agricultural Research: New Delhi, India)

Agassi, M, Morin, J, Shainberg, I (1985) Effect of raindrop impact energy and water salinity on infiltration rates of sodic soils. *Soil Science Society of America Journal* **49,** 186-90.

Ahmad, E, Jones, RL, Hinesly, TD (1997) Electromelioration of a sodic horizon from an Illinois Natraqualf. *Soil Science Society of America Journal* **61,** 1761-5.

Aitken, RL, Campbell, DJ, Bell, LC (1984) Properties of Australian fly ashes relevant to their agronomic utilization. *Australian Journal of Soil Research* **22,** 443-53.

Aitken, RL, Moody, PW, Dickson, T (1998) Field amelioration of acidic soils in south-east Queensland. I. Effect of amendments on soil properties. *Australian Journal of Agricultural Research* **49,** 627-37.

Aitkin, RL, Moody, PW, Dickson, T (1998) Field amelioration of acidic soils in south-east Queensland -I- Effect of amendments on soil properties. *Australian Journal of Agricultural Research* **49,** 627-37.

Allen, MF (2007) Mycorrhizal fungi: highways for water and nutrients in arid soils. *Vadose Zone Journal* **6,** 291-7.

Allen, MF, Boosalis, MG (1983) Effects of two species of vesicular-arbuscular mycorrhizal fungi on drought tolerance of wheat. *New Phytologist* **93,** 67-76.

Alzubadi, A, Webster, GR (1982) Effects of tillage in combination with chemical amendments on reclamation of a solonetzic soil. *Canadian Journal of Soil Science* **62,** 641-9.

Anderson, MJ, Whittcomb, PJ (2000) 'DOE simplified: practical tools for effective experimentation', (Productivity Inc.: Portland, Oregon, USA)

Australian Government (2003) Native Vegetation Act 2003.

Aylmore, LAG, Sills, ID (1982) Characterisation of soil structure and stability using modulus of rupture-exchangeable sodium percentage relationships. *Australian Journal of Soil Research* **20,** 213-24.

Ballantyne, AK (1983) Five years of soil analyses and yield data on deep-plowed solonetzic soil. *Canadian Journal of Soil Science* **63,** 191-7.

Bangura, AM (1983) Farmer motivated patterns in participating in adaptive crop trials/demonstrations in Sierra Leone. *Dissertation Abstracts* **44/03A,** 864.

Barber, SA (1984) Liming materials and practices. *In* 'Soil acidity and liming'. (Eds. Adams, F) (American Society of Agronomy Inc.: Madison)

Bathke, GR (1984) Effects of soybean properties related to soil erodibility. *Journal of the Soil Science Society of America* **48,** 1398-401.

Batra, L, Kumar, A, Manna, MC, Chabra, R (1997) Microbial and chemical amelioration of alkaline soil by growing Karnal grass and gypsum application. *Experimental Agriculture* **33,** 389-97.

Ben-Hur, M, Shainberg, I, Bakker, D, Keren, R (1985) Effect of soil texture and CaCO3 content on water infiltration in crusted soil as related to water salinity. *Irrigation Science* **6,** 281-94.

Bennett, JMcL (2006) *Interactions between chemical ameliorants and vegetation in a sodic red brown earth, Upper Bogan region, NSW*, Thesis - Australian National University, Canberra.

Bennett, R (1999) *Sustainable soil management in New Zealand: farmer beliefs, attitudes and motivations*. Discussion paper in natural resource and environmental economics No. 21, (Centre for Applied Economics and Policy Studies Massey University: Palmerston North)

Birkeland, PW (1984) 'Soils and geomorphology', (Oxford University Press: New York)

Black, CA (1968) 'Soil-plant relationships', (John Wiley and Sons: New York)

Blackwell, PS, Jayawardane, NS, Green, TW, Wood, JT, Blackwell, J, Beatty, HJ (1991) Subsoil macropore space of a transitional red-brown earth after either deep tillage, gypsum or both. *Australian Journal of Soil Research* **29,** 141-54.

Blaikie, SJ, Kelly, KB, Mason, WK, Martin, FM (1988) Productivity of irrigated pastures following paraplowing and gypsum slotting of subsoil exposed by laser levelling – a short term study. *Australian Journal of Agricultural Research* **39,** 837-45.

Bridge, BJ (1968) *soil physical properties as influenced by gypsum*, Thesis - University of Sydney, Sydney.

Bridge, BJ, Kleinig, CR (1968) The effect of gypsum on the water storage in a sandy loam soil under irrigated perennial pasture. *Transactions 9th. International Congress of Soil Science* **1,** 313-23.

Bronick, CJ, Lal, R (2005) Soil structure management: a review. *Geoderma* **124,** 3-22.

Bureau of Meteorology (2006) www.bom.gov.au/cgi-bin/climate. Commonwealth of Australia, Available at [Verified

Burgess, CP, Chapman, R, Singleton, PL, Thom, ER (1998) Effects of livestock of livestock treading and mechanical loosening of soil. *Proceedings of the New Zealand Society of Soil Science***,** 99-100.

Buttler, BE, Blackburn, G, Bowler, JM, Lawrence, CR, Newell, JW, Pels, S (1973) 'Geomorphic map of the Riverine Plain of south-eastern Australian', (Australian National University Press: Canberra)

Carberry, PS, Hochman, Z, McCowan, RL, Dagleish, NP, Foale, MA, Poulton, PL, Hargreaves, JNG, Hargreaves, DMG, Cathray, S, Hillcoat, N, Robertson, MJ (2002) The FARMSCAPE approach to decision support: farmers', advisers', researchers', monitoring simulation, communication and performance evaluation. *Agricultural Systems* **74,** 141-77.

Cass, A, Sumner, ME (1982a) Soil pore structural stability and irrigation water quality: I. Empirical sodium stability model. *Soil Science Society of America Journal* **46,** 503-6.

Cass, A, Sumner, ME (1982b) Soil pore structural stability and irrigation water quality: II. Sodium stability data. *Soil Science Society of America Journal* **46,** 507-12.

Cass, A, Sumner, ME (1982c) Soil pore structural stability and irrigation water quality: III. Evaluation of soil stability and crop yield in relation to salinity and sodicity. *Soil Science Society of America Journal* **46,** 513-17.

Cay, E, Cattle, SR (2003) Unearthing problem soils in the Lachlan Valley. *Australian Cotton Grower* **24,** No. 1, 32-5.

Chamala, S (1987) Adoption processes and extension strategies for conservation farming. *In* 'Tillage: new directions in Australian agriculture'. (Eds. Cornish, PE & Pratley, JE) (Inkata Press: Melbourne)

Chamala, S, Keith, KJ, Quinn, P (1982) 'Adoption of commercial and soil conservation innovations in Queensland - information exposure, attitudes, decisions and actions', (Department of Agriculture, University of Queensland: Brisbane)

Chan, KY, Dexter, AR, McKenzie, DC (1999) Categories of soil structure based on mechanical behaviour and their evaluation using additions of lime and gypsum on a sodic Vertisol. *Australian Journal of Soil Research* **37,** 903-11.

Chan, KY, Dorahy, C, Tyler, S (2007) Determining the agronomic value of composts produced from garden organic from metropolitan areas of New South Wales, Australia. *Australian Journal of Experimental agriculture* **47,** 1377-82.

Chan, KY, Heenan, DP (1991) Differences in surface soil aggregation under six different crops. *Australian Journal of Experimental Agriculture* **31,** 683-86.

Chan, KY, Heenan, DP (1998) Effect of lime (CaCO3) application on soil structural stability of a red earth. *Australian Journal of Soil Research* **36,** 73-86.

Chang, C, Sommerfeldt, TG, Entz, T (1991) Soil chemistry after 11 annual applications of cattle feedlot manure. *Journal of Environmental Quality* **20,** 485-80.

Chang, C, Sommerfeldt, TG, Entz, T (1993) Barley performance under heavy applications of cattle feedlot manure. *Agronomy Journal* **85,** 1013-18.

Charman, P, Murphy, BW (1991) 'Soils: Their properties and management', (Sydney University Press: Sydney)

Chartres, CJ, Greene, RSB, Ford, GW, Rengasamy, P (1985) The effects of gypsum on macroporosity and crusting of two red duplex soils. *Australian Journal of Soil Research* **23,** 467-79.

Chellemi, DO, Porter, IJ (2001) The role of plant pathology in understanding soil health and its application to production agriculture. *Australian plant pathology* **30,** 103-09.

Chen, L, Tubali, K, Kost, D, Dick, W (2010) Effects of gypsum enhanced composts on yields and mineral compositions of broccoli and tall fescue. *Journal of Plant Nutrition* **33,** 1040-55.

Chi, CL, Emerson, WW, Lewis, DG (1977) Exchangeable calcium, magnesium and sodium and the dispersion of illites in water. I. characterisation of illites and exchange reactions. *Australian Journal of Soil Research* **28,** 243-53.

Chorom, M, Rengasamy, P (1997) Carbonate chemistry, pH, and physical properties of an alkaline sodic soil as affected by various amendments. *Australian Journal of Soil Research* **35,** 149-61.

Churchman, GJ, Skjemstad, J, Oades, JM (1995) Effects of clay minerals and organic matter on sodicity. *In* 'Australian sodic soils: distribution, properties and management'. (Eds. Naidu, R, Sumner, ME & Rengasamy, P) (CSIRO Publications: Melbourne)

Clark, GJ, Dodghsun, N, Sale, PWG, Tang, C (2007) Changes in chemical and biological properties of a sodic clay subsoil with addition of organic amendments. *Soil Biology and Biochemistry* **39,** 2806-17.

Clark, GJ, Sale, PWG, Tang, C (2009) Organic amendments initiate the formation and stabilisation of macroaggregates in a high clay sodic soil. *Australian Journal of Soil Research* **47,** 770-780.

Cockcroft, B, Tisdall, JM (1978) Soil management, soil structure and root activity. *In* 'Modifications fo soil structure'. (Eds. Emerson, WW, Bond, RD & Dexter, AR) (John Wiley: Chichester)

Cohen, JW (1988) 'Statistical power analysis for the behavioural sciences', (Lawrence Erlbaum Associates: Hillsdale, NJ)

Cole, E (1940) Salt affected lands reclaimed by dhub grass. *Indian Farming* **1,** 280.

Cooper, JL (1999) A grower survey of rotations used in the New South Wales cotton industry. *Australian Journal of Experimental Agriculture* **39,** 743-55.

Corbett, JR (1967) 'The living soil', (Martindale Press: Sydney)

Cordell, D, Drangert, J-A, White, S (2009) The story of phosphorus: Global food security and food for thought. *Global Environmental Change* **19,** 292-305.

Cornell, JA (2002) 'Experiments with mixtures', (John Wiley and Sons Inc.: New York)

Courtney, RG, Jordan, SN, Harrington, T (2009) Physico-chemical changes in bauxite residue following application of spent mushroom compost and gypsum. *Land Degredation and Development* **20,** 582-81.

Craze, B, Holman, G, Chapman, GA, Stone, MJ (1993) 'Soil testing procedures of the NSW Department of Conservation and Land Management', (NSW Department of Conservation and Land Management: Sydney)

Cregan, PD, Hirth, JR, Conyers, MK (1989) Amelioration of soil acidity by liming and other amendments. *In* 'Soil acidity and plant growth'. (Eds. Robson, AD) (Academic Press Australia: Sydney)

Curl, EA, Truelove, B (1986) 'The Rhizosphere', (Springer-Verlag: Berlin)

Dagleish, NP, Foale, MA (1998) 'Soil matters: monitoring soil water and nutrients in dryland farming', (Agrictural production systems research unit: Toowoomba, Qld)

Dalal, RC, Blasi, M, So, HB (2002) *High sodium levels in subsoil limits yields and water use in marginal cropping areas*. Grain Research and Development Project No. DNR 6, final report, (GRDC: Canberra)

Dang, YP, Dalal, RC, Buck, SR, Harms, B, Kelly, R, Hochman, Z, Scwenke, GD, Biggs, AJW, Furguson, NJ, Norrish, S, Routley, R, McDonald, M, Hall, C, Singh, DK, Daniells, IJ, Farquharson, R, Manning, W, Speirs, S, Grewal, HS, Cornish, PE, Bodapati, N, Orange, D (2010) Diagnosis, estent, impacts, and management of subsoil constraints in the northern grains region of Australia. *Australian Journal of Soil Research* **48,** 105-19.

Dang, YP, Dalal, RC, Routley, R, Scwenke, GD, Daniells, IJ (2006) Subsoil constraints to grain production in the cropping soils of north-eastern region of Australia: an overview. *Australian Journal of Experimental Agriculture* **46,** 19-35.

Davidson, LJ, Quirk, JP (1961) The influence of dissolved gypsum on pasture establishment of irrigated clays. *Australian Journal of Agricultural Research* **12,** 100-10.

Davies, DB, Payne, D (1988) Management of soil physical properties. *In* 'Russell's soil condition and plant growth'. (Eds. Wild, A) (Longman: London)

Department of Agriculture Fisheries and Forestry (2008) *Healthy soils for sustainable farms: Program report*. (Land & Water Australia: Canberra) http://lwa.gov.au/files/products/healthy-soils-sustainable-farms/pn20960/pn20960.pdf (accessed 25 March 2010)

Desbiez, A, Matthews, R, Tripathi, B, Ellis-Jones, J (2004) Perceptions and assessment of soil fertility by farmers in the mid-hills of Nepal. *Agricultre, Ecosystems & Environment* **103,** 191-206.

Diallo, I (1983) An assessment of farmers' attitudes and experiences under no-till corn production systems in Baltimor county, Marryland. *Dissertation Abstracts* **45/05B,** 1329.

Dillman, DA (2007) 'Mail and internet surveys: the tailored design method.' (John Wiley & Sons: New Jersey)

Dixon, G (1982) 'A course manual in agricultural and livestock extension. Rural Sociology', (Universities International Development Program: Canberra)

Doran, JW (2002) Soil health and global sustainability: translating science into practice. *Agricultre, Ecosystems & Environment* **88,** 119-27.

Doyle, AD, Taylor, DW, Yates, WJ, So, HB, McGarity, JW (1979) Amelioration of structurally unstable grey clays in the north-western wheat belt of New South Wales. *Australian Journal of Experimental Agriculture and Animal Hausbandry* **19,** 590-8.

Edmeades, DC (2002) The effect of liquid fertilisers derived from natural products on crop, pasture, and animal production: a review. *Australian Journal of Agricultural Research* **53,** 965-76.

Ellington, A, Badawy, NS, Ganning, GW (1997) Teasting gypsum requirements for dryland cropping on a red-brown earth. *Australian Journal of Soil Research* **35,** 591-607.

Emerson, WW (1977) Physical properties and structure. *In* 'Soil factors in crop production in a semi-arid environment'. (Eds. Russell, JS & Greacen, EL) (University of Queensland Press: Brisbane)

Emerson, WW (1983) Interparticle bonding. *In* 'Soils: an Australian view point'. (Eds. Division of Soils CSIRO) (CSIRO: Melbourne)

Emerson, WW, Bakker, AC (1973) The comparative effects of exchangeable calcium, magnesium, and sodium on some physical properties of red-brown earth subsoils. II. The spontaneous dispersion of aggregates in water. *Australian Journal of Soil Research* **11**.

Emerson, WW, Chi, CL (1977) Exchangeable calcium, magnesium and sodium and the dispersion of illites in water. II. Dispersion of illites in water. *Australian Journal of Soil Research* **28,** 255-62.

Fairweather, PG (1991) Statistical power and design requirements for environmental monitoring. *Australian Journal of Marine and Freshwater Research* **42,** 555-67.

Falcón, M, Corominas, E, Pérez, M, Perestelo, F (1987) Aerobic bacterial populations and environmental factors involved in the composting of agricultural and forest wastes of the Canary Islands. *Biological Wastes* **20,** 89-99.

Field, DJ (2000) *The bricks and mortar of Vertosols*, Thesis - The University of Sydney, Sydney.

Field, DJ, McKenzie, DC, Koppi, AJ (1997) Development of an improved vertisol stability test for SOILpak. *Australian Journal of Soil Research* **35,** 843-52.

Ford, GW, Greene, RSB, Rengasamy, P (1985) Estimation of gypsum requirement of agricultural soils. *Proceedings for the Australian Soil Science Society***,** 103-10.

Fraiture, Cd, Wichelns, D, Roskstrom, J, Kemp-Benedict, E (2007) Looking ahead to 2050: scenarios of alternative investment approaches. *In* 'Water for food, water for life: A comprehensive assessment of water management in agriculture'. (Eds. Molden, D) (Earthscan: Colombo)

Frank, BR (1997) Adoption of innovations in the north Queensland beef industry. III: implications for extension management. *Agricultural Systems* **55,** 347-58.

Gardner, EA, Shaw, RJ, Smith, GD, Coughlan, KJ (1984) Plant availavle water capacity: concept, measurement and prediction. *In* 'Properties and utilisation of cracking clay soils'. (Eds.: Armidale)

Gardner, HW, Gardner, HV (1953) 'The use of lime', (Farmer & Stock-Breeder Publications Ltd: London)

Gee, GW, Bauder, JW (1986) Particle-size analysis. *In* 'Methods of soil analysis'. (Eds. Klute, A) (Soil Science Society of America: Madison, Wisconsin)

Ghafoor, A, Ahmad, MM, Muhammed, S, Ahmad, N (1989) Efficiency of gypsum grades and qaulity of leaching water for reclaiming a saline-sodic soil. II. chemical improvement of soil. *Pakistan Journal of Agricultural Sciences* **26,** 313-21.

Ghafoor, A, Gill, MA, Hassan, A, Murtaza, G, Qadir, M (2001) Gypsum: An economical amendment for amelioration of saline-sodic waters and soils, and for improving crop yields. *International Journal of Agriculture and Biology* **3,** 266-75.

Ghassemi, F, Lakeman, AJ, Nix, HA (1995) 'Salinization of land and water resources: human causes, extent, management and case studies ', (CABI Publishing: Wallignford, UK)

Ghosh, S, Lockwood, P, Hulugalle, NR, Daniel, H, Kristiansen, P, Dodd, K (2010) Changes in properties of sodic Australian Vertisols with application of organic waste products. *Soil Science Society of America Journal* **74,** 153-60.

Gill, JS, Sale, PWG, Tang, C (2008) Amelioration of dense sodic subsoil using organic amendments increases wheat yield more than using gypsum in a high rainfall zone of southern Australia. *Field Crops Research* **107,** 265-75.

Gosh, S, Lockwood, P, Hulugalle, NR, Daniel, H, Kristiansen, P, Dodd, K (2010) Changes in properties od sodic Australian Vertisols with application of organic waste products. *Soil Science Society of America Journal* **74,** 153-60.

Gravetter, FJ, Wallnau, LB (2004) 'Statistics for the behavioural sciences', (Wadsworth: Belmont, CA)

Greene, RSB (2002) Hardsetting soils. *In* 'Encyclopedia of soil science'. (Eds. Lal, R) (Marcel Dekker: New york)

Greene, RSB, Barrie, J (1982) *In* 'Proceedings of the Seminar on soil testing for gypsum requirement' (Agricultural Note Series: Shepparton, Vic)

Greene, RSB, Ford, GW (1985) The effect of gypsum on cation exchange in two red duplex soils. *Australian Journal of Soil Research* **23,** 61-74.

Greenwood, KL, Dellow, KE, Mundy, GN, Kelly, KB, Austin, SM (2006a) Improved soil and irrigation mangement for forage production. 2. Forage yield and nutritive charactersitics. *Australian Journal of Experimental Agriculture* **46,** 319-26.

Greenwood, KL, Mundy, GN, Kelly, KB, Dellow, KE, Austin, SM (2006b) Improved soil and irrigation mangement for forage production. 1. Site establishment and soil physical properties. *Australian Journal of Experimental Agriculture* **46,** 307-17.

Grevers, MCJ, De Jong, E (1993) Soil structure and crop yield over a 5-year period following subsoiling solonetzic and chernozemic soils in Saskatchewan. *Canadian Journal of Soil Science* **73,** 81-91.

Griffith City Council (2009) *Annual report*. (Griffith City Council: Griffith)

Guerin, LJ, Guerin, TF (1994) Constraints to the adoption of agricultural and environmental innovations and technologies: a review. *Australian Journal of Experimental Agriculture* **34,** 549-71.

Guerin, TF (1999) An Australian perspective on the constraints to the transfer and adoption of innovations in land management. *Environmental Conservation* **26**.

Gupta, RK, Abrol, IP (1990) Salt-affected soils: their reclamation and management for crop production. *In* 'Advances in soil science'. (Eds. Stewart, BA) (Springer-Verlag: Berlin)

Gupta, RK, Bhumbla, DK, Abrol, IP (1984) Effect of sodicity, pH, organic matter and calcium carbonate on the dispersion behaviour of soils. *Soil Science* **137,** 245-51.

Gupta, RK, Singh, RR (1988) A comparative evaluation of the reclamation efficiency of surface-concentrated versus internalyl incorporated calcium chloride and gypsum in an alkalai soil. *Soil Science* **146,** 277-83.

Hajkowicz, S, Young, M (2005) Costing yield loss from acidity, sodicity and dryland salinity to Australian agriculture. *Land Degredation and Development* **16,** 417-33.

Hajkowicz, SA, Young, MD (2002) *Values of returns to land and water and cost degradation, A consultancy report to the National Land and Water Resources Audit.* (CSIRO Land and Water: Canberra)

Hall, DJM, McKenzie, DC, MacLeod, DA, Toole, ID (1994) Amelioration of a hardsetting Alfisol through deep mouldboard ploughing, gypsum application and double cropping. III. Crop production and profitability. *Soil and Tillage Research* **28,** 287-300.

Hanay, A, Buyuksonmez, F, Kizilogu, FM, Canbolat, MY (2004) Reclamation of saline-sodic soils with gypsum and MSW compost. *Compost Science and Utilization* **12,** 175-9.

Hanay, A, Yardimci, N (1992) A research on the effects of municipal composts and barnyard manure on some physical and chemical properties of soils and soil-water relations. *Doga-Transaction Journal of Agriculture and Forestry* **16,** 91-102.

Hargreaves, JC, Adl, MS, Warman, PR (2008) A review of the use of composted municipal solid waste in agriculture. *Agriculture, Ecosystems & Environment* **123,** 1-14.

Harris, A, Fulton, M (2000a) 'The CUMA farm machinery co-operatives', (Centre for the Study of Co-operatives, University of Saskatchewan: Saskatoon, Canada)

Harris, A, Fulton, M (2000b) 'Farm machinery co-operatives in Saskatchewan and Quebec', (Centre for the Study of Co-operatives, University of Saskatchewan: Saskatoon, Canada)

Harris, A, Fulton, M (2000c) 'Farm machinery co-operatives: An idea worth sharing', (Centre for the Study of Co-operatives, University of Saskatchewan: Saskatoon, Canada)

Harrison, WJ, MacLeod, DA, McKenzie, DC (1992) The effect of clay addition and gypsum application on the physical properties of a hradsetting red-brown earth, and the response of irrigated cottons *Soil and Tillage Research* **25,** 231-44.

Hayman, PT, Alston, CL (1999) A survey of farmer practices and attitudes to nitrogen management in the northern New South Wales grains belt. *Australian Journal of Experimental Agriculture* **39,** 51-63.

He, Z, Yang, X, Khan, BA, Stoffella, PJ, Calvert, DV (2001) Plant nutrition benefits of phosphorus, potassium, calcium, magnesium, and micronutrients from compost utilization. *In* 'Compost ultilization in horticultural cropping systems'. (Eds. Stoffella, PJ & Khan, BA) (Lewis Publishers: Boca Raton, Fla.)

Hodgson, L, Dyer, D, Brown, DA (1982) Neutralization and dissolution of high calcium fly ash. *Journal of Environmental Quality* **28,** 639-47.

Holford, ICR, Schweitzer, BE, Crocker, GJ (1994) Long-term effects of lime on soil phosphorus solubility and sorption in eight acidic soils. *Australian Journal of Soil Research* **32,** 795-803.

Hoult, EH, Holden, J (unpublished) Lime & gypsum trial – Twynam Buttabone, field 10. *Twynam Cotton Research Report***,** 98-9.

Hulugalle, NR, Entwistle, PC, Cooper, JL, Scott, F, Nehl, DB, Allen, SJ, Finlay, LA (1999) Sowing wheat or field pea as rotation crops after irrigated cotton in a grey Vertosol. *Australian Journal of Soil Research* **36,** 621-40.

Hulugalle, NR, Entwistle, PC, Scott, F, Kahl, J (2001) Rotation crops for irrigated cotton in a medium-fine, self-mulching, grey Vertosol. *Australian Journal of Soil Research* **39,** 317-28.

Hulugalle, NR, Entwistle, PC, Weaver, TB, Scott, F, Finlay, LA (2002) Cotton-based rotation systems on a sodic Vertosol under irrigation: effects on soil quality and profitability. *Australian Journal of Experimental Agriculture* **42,** 341-49.

Hulugalle, NR, Weaver, TB, Ghadiri, H, Hicks, A (2006) Changes in soil properties of an eastern Australian Vertisol irrigated with sewage effluent following gypsum application. *Land Degredation and Development* **17,** 527-40.

Hutson, JL (1971) *Crust formation on some Natal soils*, Thesis - University of Natal, Pietermaritzburg.

IBM (2009) PASW Statistics 18. SPSS Inc.

Ilyas, M, Miller, RP, Qureshi, RH (1993) Hydraulic conductivity of saline-sodic soil after gypsum application and cropping. *Soil Science Society of America Journal* **57,** 1580-85.

Ilyas, M, Qureshi, RH, Qadir, M (1997) Chemical changes in a saline-sodic soil after gypsum application and cropping. *Soil Technology* **10,** 247-60.

Industry Commission (1998) *A full repairing lease - inquiry into ecologically sustainable land management*. Report no. 60, (Australian Government Publishing Service: Canberra)

Irvine, SA, Doughton, JA (2001) Salinity and sodicity, implications for farmers in Cetral Queensland. *In* 'Proceedings of the 10th annual Australian agronomy conference'. (Eds. (The Australian Society of Agronomy Inc.: Hobart)

Isbell, RF (1996) 'The Australian soil classification', (CSIRO Publishing: Melbourne)

Isbell, RF (2002) 'The Australian soil classification: revised edition', (CSIRO Publishing: Melbourne)

Isbell, RF, Reeve, RC, Hutton, JT (1983) Salt and sodicity. *In* 'Soils: an Australian viewpoint'. (Eds. Division of Soils CSIRO) (CSIRO Publications: Melbourne)

Islam, K, Singh, B, McBratney, A (2003) Simultaneous estimation of several soil properties by ultra-violet, visible, and near-infrared reflectance spectroscopy. *Australian Journal of Soil Research* **41,** 1101-14.

Jalali, M, Ranjbar, F (2009) Effects of sodic water on soil sodicity and nutrient leaching in poultry and sheep manure amended soils. *Geoderma* **153,** 194-204.

Jarwal, S, Rengasamy, P (1998) *Gypsum and stubble retention in alkaline sodic soils*. Annual Report, (Victorian Institute for Dryland Farming: Horsham)

Jastrow, JD, Zimmerman, CA, Dvorak, AJ, Hinchman, RR (1981) Plant growth and trace element uptake on acid coal refuse amended with lime or fly ash. *Journal of Environmental Quality* **10,** 154-60.

Jayawardane, NS, Biswas, TK, Blackwell, J, Cook, FJ (2001) Management of salinity and sodicity in a land FILTER systems, for treating saline waste water on a saline-sodic soil. *Australian Journal of Soil Research* **39,** 1247-58.

Jayawardane, NS, Blackwell, J (1985) The effect of gypsum enriched slots on moisture environment and aeration in an irrigated swelling clay *Australian Journal of Soil Research* **23,** 481-92.

Jayawardane, NS, Blackwell, J, Blackwell, PS (1988) Fragment size distribution within slots created in a duplex soil by a prototype rotary slotter *Soil and Tillage Research* **12,** 53-64.

Jayawardane, NS, Blackwell, J, Muirhead, WA, Kirchhof, G, Smart, R (1994) 'Slotting - a new deep tillage technique for improving crop productivity on sodic, scid and other degraded soils', (CSIRO Division of Water Resiources: Canberra)

Jayawardane, NS, Chan, KY (1995) Management of soil physical properties limiting cropping in Australian sodic soils. *In* 'Australian sodic soils: distribution, properties and management'. (Eds. Naidu, R, Sumner, ME & Rengasamy, P) (CSIRO Publications: Melbourne)

Jessop, RS, MacLeod, DA, Hulme, PJ, McKenzie, DC (1985) The effects of landforming on crop production on a red - brown earth. *Australian Journal of Agricultural Research* **23,** 85-93.

Johnston, MA (1975) The effects of different levels of exchangeable sodium on soil hydraulic conductivity *Proceedings of the South African Sugar Technologies Association* **49,** 142-7.

Jones, A (unpublished) Gypsum/lime yield response trial – “Marebone” M and P Dickson. *Macquarie Valley Trial Reports* **2001/02, 2002/03, 2003/04,** 38-9.

Kadu, PR, Vaidya, PH, Balpande, SS, Satyavathi, PLA, Pal, DK (2003) Use of hydrualic conductivity to evaluate the suitability of Vertisols for deep-rooted crops in semi-arid parts of central India. *Soil Use and Management* **19,** 208-16.

Kamphorst, A (1990) Amelioration of sodic clay soils by crack stabilisation: and experimental laboratory simulation. *Soil Science* **149,** 218-27.

Kazman, Z, Shainberg, I, Gal, M (1983) Effects of low levels of exchangeable sodium and applied phosphogypsum on the infiltration rate of various soils. *Soil Science* **135**.

Keller, DR, Brummer, EC (2002) Putting food production in context: toward a postmechanistic agricultural ethic. *BioScience* **52,** 264-71.

Kelley, WP (1937) The reclamation of alkali soils. *Californian Agricultural Experimantal Station Bulletin* **617**.

Kelly, B, Allan, C, Wilson, BP (2009) Soil indicators and their use by farmers in the Billabong Catchment, southern New South Wales. *Australian Journal of Soil Research* **47**.

Kelly, KB (1985) Effects of soil modification and treading on pasture growth and physical properties of an irrigated red - brown earth. *Australian Journal of Agricultural Research* **36,** 799-807.

Kemper, WD, Olsen, J, de Mooy, CJ (1975) Dissolution rate of gypsum in flowing water. *Proceedings of the Soil Science Society of America* **39,** 458-63.

Keren, R (1996) Reclamation of sodic-affected soils. *In* 'Soil erosion, conservation and rehabilitation'. (Eds. Agassi, M) (Marcel Dekker Inc.: New York, USA)

Keren, R, O'Connor, GA (1982) Gypsum dissolution and sodic soil reclamation as affected by water flow velocity. *Soil Science Society of America Journal* **46,** 726-32.

Keren, R, Shainberg, I (1981) Effect of dissolution rate on the efficiency of industrial and mined gypsum in improving infiltration of a sodic soil. *Soil Science Society of America Journal* **45,** 103-7.

Kloppenburg, J (1991) A social theory and de/reconstruction of agricultural science, local knowledge for an alternative agriculture. *Rural Sociology* **56,** 519-48.

Kloppenburg, J (1992) Science in agriculture: a reply to Molnar, Duffy, Cummins, and Van Saten and to Flora. *Rural Sociology* **57,** 98-107.

Kovda, V, van den Berg, C, Hagan, RM (1973) 'Irrigation, drainage and salinity: An international source book', (Hutchinson and Co.: London)

Kowalik, P, Loveday, J, McIntyre, DS, Watson, CL (1979) Deep percolation during prolonged ponding of a swelling soil, and the effect of gypsum treatments. *Agricultural Water Management* **70,** 131-47.

Kukier, U, Sumner, ME, Miller, WP (1994) Boron release from fly ash and its uptake by corn. *Journal of Environmental Quality* **23,** 596-603.

Kumar, D, Singh, B (2003) The use of coal fly ash in sodic soil reclamation. *Land Degredation and Development* **14,** 285-99.

Lebron, I, Suarez, DL, Yoshida, T (2002) Gypsum effect on the aggregate size and geometry of three sodic soils under reclamation. *Soil Science Society of America Journal* **66,** 92-8.

Lees, J, Reeve, I (1994) 'TPSKP 1994 producer survey', (Rural Development Centre: Armidale, NSW)

Leopold, A ([1949] 1987) 'A sand county almanac and sketches here and there', (Oxford University Press: New York)

Levy, GJ, van der Watt, HvH, du Plessis, HM (1988) Effect of Na/Mg and Na/Ca systems on soil hydraulic conductivity and infiltration. *Soil Science* **146,** 303-10.

Li, F, Keren, R (2008) Native $CaCO_3$ mineral dissolution and its contribution to sodic calcareous soil reclamation under laboratory conditions. *Arid Land Research and Management* **22,** 1-15.

Likert, R (1932) A technique for the measurement of attitudes. *Archievs of Psychology* **140,** 1-55.

Littler, JW, Marley, JMT (1978) 'Fallowing and winter cereal production on the Darling Downs - progress report', (Qld Department of Primary Industries: Queensland)

Lobry de Bruyn, LA, Abbey, JA (2003) Characterisation of farmers' soil sense and the implications for on-farm monitoring of soil health. *Australian Journal of Experimental Agriculture* **43,** 285-305.

Lobsey, C, Viscarra Rossel, R, McBratney, A (2010) An automated system for rapid in-field soil nutrient testing. *In* 'Proceedings of the The 19th World Conference of Soil Science' (International Union of Soil Science: Brisbane)

Loveday, J (1974) Recognition of gypsum responsive soils. *Australian Journal of Soil Research* **25**.

Loveday, J (1976) Relative significance of electrolyte and cation exchange effects when gypsum is applied to a sodic clay soil *Australian Journal of Soil Research* **14,** 361-71.

Loveday, J, Bridge, BJ (1983) Management of salt affected soils. *In* 'Soils: an Australian viewpoint'. (Eds. Division of Soils CSIRO) (CSIRO Publications: Melbourne)

Loveday, J, Pyle, JC (1973) *The Emerson dispersion test and its relation to hydraulic conductivity*. CSIRO Division of Soils Technical Paper,

Loveday, J, Saunt, JE, Flemming, PM, Muirhead, WA (1970) Soil and cotton response to tillage and ameliorant treatments in a brown clay soil 1. soil responses and water use. *Australian Journal of Experimental agriculture and Animal Hausbandry* **10,** 313-24.

Madejon, E, Lopes, R, Murillo, YM, Cabrerra, F (2001) Agricultural use of three (sugar - beet) vinasse compost: effect on crops and chemical properties of a cambisol soil in Quadalquirvirm River Valley (SW Spain). *Agricultre, Ecosystems & Environment* **84,** 55-65.

Makoi, JHJR, Ndakidemi, PA (2007) Reclamation of sodic soils in northern Tanzania, using locally available organic and inorganic resources. *African Journal of Biotechnology* **6,** 1926-31.

Mann, M, Pissarra, A, van Hoorn, JW (1982) Drainage and desalinisation of heavy clay soils in Portugal. *Agricultural Water Management* **5,** 227-40.

Massoud, FI (1977) Basic principals for prognosis and monitoring of salinity and sodicity *In* 'Proceedings of the International Conference on Management of Saline Water for Irrigation' (Lubbock, TX: Texas Technical University)

Mathers, AC, Stewart, BA (1974) Corn silage yield and soil chemical properties as affected by cattle feedlot manure. *Journal of Environmental Quality* **3,** 143-7.

May, EL (2006) *How landholders use and value their private native forests: a study of landholders with dry sclerophyll forests on the Southern Tablelands of NSW*, Thesis - Australian National University, Canberra.

McAndrew, DW, Malhi, SS (1990) Long-term effects of deep ploughing solonetzic soil on chemical characteristics and crop yield. *Canadian Journal of Soil Science* **70,** 619-23.

McBeath, TM, Grant, CD, Murray, RS, Chittleborough, DJ (2010) Effects of subsoil amendments on soil physical properties, crop response, and soil water quality in a dry year. *Australian Journal of Soil Research* **48,** 140-9.

McDowell, RW (2005) The effectiveness of coal fly-ash to decrease phosphorus loss from grassland soils. *Australian Journal of Soil Research* **43,** 853-60.

McGarry, D (1987) The effect of water content during land preparation on aspects of soil physical condition and cotton growth. *Soil and Tillage Research* **9,** 287-307.

McIntyre, DS (1958) Soil splash and the formation of surface crusts by raindrop impact. *Soil Science* **85,** 261-66.

McIntyre, DS (1979) Exchangeable sodium, subplacticity, and hydraulic conductivity of some Australian soils. *Australian Journal of Soil Research* **17,** 115-20.

McIntyre, DS, Loveday, J (1974) Particle-size analysis. *In* 'Methods for analysis of irrigated soils'. (Eds. Loveday, J) (Commonwealth Agricultural Bureaux: Rarnham Royal, Bucks.)

McKenzie, DC (1982) *Evaluation of gypsum as an ameliorant for cracking-clay soils of the Moree district, N.S.W.*, Thesis - University of New England, Armidale.

McKenzie, DC, Abbott, TS, Chan, KY, Slavich, PG, Hall, DJM (1993) The nature, distribution and management of sodic soils in New South Wales. *Australian Journal of Soil Research* **31,** 839-68.

McKenzie, DC, Murphy, BW (2005) *Use this graph to interpret your soil tests and predict the dispersion and/or salinity characteristics of your soils*, Don Stanger Public Relations

McKenzie, DC, So, HB (1989a) Effect of gypsum on vertisols of the Gwydir Valley, New South Wales 1. Soil properties and wheat growth. *Australian Journal of Experimental Agriculture* **29,** 51-62.

McKenzie, DC, So, HB (1989b) Effect of gypsum on vertisols of the Gwydir Valley, New South Wales 2. Ease of tillage. *Australian Journal of Experimental Agriculture* **29,** 63-7.

McKenzie, NJ (1992) 'Soils of the lower Macquarie Valley, New South Wales', (CSIRO Division of Soils: Canberra)

Mehanni, AH (1974) Short term effect of some methods for improving soil structure in red-brown earth soils of northern irrigation areas, Victoria. *Australian Journal of Experimental Agriculture* **14,** 689-93.

Midwood, AJ, Boutton, TW (1998) Soil carbonate decomposition by acid has little effect on δ^{13}C of organic matter. *Soil Biology and Biochemistry* **30,** 1301-7.

Miller, RM, Jastrow, JD (1992) The role of mycorrhizal fungi in soil conservation. *In* 'Mycorrhizae in sustainable agriculture'. (Eds. Bethlenfalvay, CJ & Linderman, RG) (American Society of America, Crop Science Society of America, and Soil Science Society of America: Madison, WI)

Miller, RO (1998) Nitric-perchloric acid wet digestion in an open vessel. *In* 'Handbook of Reference Methods for Plant Analysis'. (Eds. Yash, PK) (CRC Press: Boca Raton, Florida)

Miller, WP, Scifres, J (1988) effect of sodium nitrate and gypsum on infiltration and errosion of highly weathered soils. *Soil Science* **145**.

Milthorpe, PL, Newman, JC (1979) Gypsum assists reclamation of scalded sodic caly near Condobolin. *Journal of Soil Conservation New South Wales* **35**.

Moore, DM, Reynolds, RJC (1989) 'X-ray diffraction and the identification and analysis of clay minerals', (Oxford University Press: Oxford, New York)

Mowo, JG, Janssen, BH, Oenema, O, German, LA, Mrema, JP, Shemdoe, RS (2006) Soil fertility evaluation and management by smallholder farmer communities in northern Tanzania: Nutrient management in tropical agroecosystems. *Agricultre, Ecosystems & Environment* **116,** 47-59.

Mubarak, AR, Nortcliff, S (2010) Calcium carbonate solubilization through H-proton release from legumes grown in calcaerous saline-sodic soils. *Land Degredation and Development* **21,** 24-31.

Muirhead, WA, Loveday, J, Saunt, JE (1970) Soil and cotton respons to tillage and amelioration treatments in a brown clay soil: II. growth, yield and qaulity of cotton. *Journal of Experimental Agricuilture and Animal Husbandry* **10,** 324-33.

Mullins, CE, MacLeod, DA, Northcote, KH, Tisdall, JM, Young, IM (1990) Hardsetting soils: behaviour, occurrence and management. *Advances in Soil Science* **11,** 38-108.

Murphy, BW (2002) Sodic soils: formation and global distribution of. *In* 'Encyclopedia of soil science'. (Eds. Lal, R) (Marcel Dekker: New York)

Murphy, BW, Lawrie, J, King, D, Taylor, C (1998) 'Distribution of sodic soils in central western NSW. Aeolian dust: Implications for Australian mineral exploitation and environmental management': Canberra)

Mylek, M (2006) *Landholder perceptions about impediments to, and incentives for, the adoption of farm forestry in the Southern Tablelands region of NSW*, Thesis - Australian National University, Canberra.

Naidu, R, Merry, RH, Churchman, GJ, Wright, MJ, Murray, RS, Fitzpatrick, RW, Zarcinas, BA (1993) Sodicity in South Australia - a review. *Australian Journal of Soil Research* **31,** 911-29.

Naidu, R, Rengasamy, P (1993) Ion interactions and constraints to plant nutrients in Australian sodic soils. *Australian Journal of Soil Research* **31,** 801-19.

Nass, MM, Lexmond, TM, Van Beusichem, ML, Janssen Jurkovicova, M (1993) Long term supply and uptake by plants of elements from coal fly ash. *Communications in Soil Science and Plant Analysis* **24,** 899-913.

Nelson, PN, Baldock, JA, Clarke, P, Oades, JM, Churchman, GJ (1999) Dispersed clay and organic matter in soil: their nature and associations. *Australian Journal of Soil Research* **37,** 289-315.

Nelson, PN, Oades, JM (1998) Organic matter, sodicity, and soil structure. *In* 'Sodic soils: Distribution, management and envirnomental consequences'. (Eds. Sumner, ME & Naidu, R) (Oxford University Press: New York)

New South Wales Farmers Association (2008) *Constitution - NSW Farmers Association.* (NSW Farmers Asscoiation: Sydney)

Northcote, KH, Skene, JK (1972) *Australian soils with saline and sodic properties.* CSIRO Soil Publication 27, (CSIRO: Australia)

Nuttall, JG, Armstrong, RD, Connor, DJ (2005) The effect of boron tollerance, deep ripping with gypsum, and water supply on subsoil water extraction of cereals in an alkaline soil. *Australian Journal of Agricultural Research***,** 113-22.

Olsson, KA, Dellow, KE, Hirth, JR, Kelly, KB, Greenwood, KL, Blaikie, SJ (2002) Soil properties, root response and production of irrigated pasture on a red-brown earth after subsoil modification. *Australian Journal of Experimental Agriculture* **42,** 453-63.

Onus, G (1978) *A soil structural stability survey of the Gwydir valley of New South Wales*, Thesis - University of New England, Armidale.

Oster, JD (1982) Gypsum use in irrigated agriculture: a review *Fertilizer Research* **3,** 73-89.

Oster, JD (1993) Sodic soil reclamation. *In* 'Towards the rational use of high salinity tolerant plants'. (Eds. Leith, H & Al Masoom, A) (Kluwer Academic Publishers: The Netherlands)

Oster, JD, Schroer, FW (1979) Infiltration as influenced by irrigation water quality. *Soil Science Society of America Journal* **43,** 444-7.

Pal, DK, Bhattachayya, T, Ray, SK, Chandran, P, Srivastava, P, Durge, SL, Bhuse, SR (2006) Significance of soil modifiers (Ca-zeolites and gypsum) in naturally degraded Vertisols of the Peninsular India in redefining the sodic soils. *Geoderma* **136,** 210-28.

Pal, DK, Dasog, GS, Vadivelu, S, Ahuja, RL, Bhattachayya, T (2000) Secondary calcium carbonate in soils of arid and semi-arid regions of India. *In* 'Global changes and pedogenic carbonates'. (Eds. Lal, R, Kimble, JM, Eswaran, H & Stewart, BA) (Lewis Publishers: Boca Raton, Florida, USA)

Pal, DK, Srivastava, P, Bhattachayya, T (2003) Role of microtopography in the formation of sodic soils in the semi-arid part of the Indo-Gangentic Plains, India. *Catena* **51,** 3-31.

Pathan, SM, Aylmore, LAG, Colmer, TD (2002) Reduced leaching of nitrate, ammonium and phosphorus in a sandy soil by fly ash amendment. *Australian Journal of Agricultural Research* **40,** 1201-11.

Pirie, A, Singh, B, Islam, K (2005) Ultra-violet, visible, near-infrared, and mid infra-red diffuse reflectance spectroscopic techniques to predict several soil properties. *Australian Journal of Soil Research* **43,** 713-21.

Poona, SR, Bhumbla, DR (1973) Effect of farm yard manure on the availability of Ca from Ca45CO3 in a sodic soil (ESP 77.7). *Plant and Soil* **38,** 679-82.

Poonia, SR, Bhumbla, DR (1973) Effect of farm yard manure on the availability of Ca from Ca45CO3 in a sodic soil (ESP 77.7). *Plant and Soil* **38,** 679-82.

Prathapar, SA, Aslam, M, Kahlown, MA, Iqbal, Z, Qureshi, AS (2005) Gypsum slotting to ameliorate sodic soils in Pakistan. *Irrgation and Drainage* **54,** 509-17.

Price, P (2010) Combatting subsoil constraints: R&D for the Australian grains industry. *Australian Journal of Soil Research* **48,** i-iii.

Pupisky, H, Shainberg, I (1979) Salt effects on the hydraulic conductivity of a sandy soil. *Soil Science Society of America Journal* **43,** 429-33.

Qadir, M, Ghafoor, A, Murtaza, G (2001a) Use of saline-sodic waters through phytoremediation of calcareous saline-sodic soils. *Agricultural Water Management* **50,** 197-210.

Qadir, M, Oster, JD (2002) Vegetative bioremediation of calcareous sodic soils: history, mechanisms, and evaluation. *Irrigation Science* **21,** 91-101.

Qadir, M, Qureshi, RH, Ahmad, N (1996) Reclamation of a saline-sodic soil by gypsum and Leptocha fusca. *Geoderma* **74,** 207-17.

Qadir, M, Qureshi, RH, Ahmad, N (2002) Amelioration of calcareous saline sodic soils through phytoremediation and chemical strategies. *Soil Use and Management* **18,** 381-5.

Qadir, M, Schubert, S, Ghafoor, A, Murtaza, G (2001b) Amelioration strategies for sodic soils: a review. *Land Degredation and Development* **12,** 357-86.

Qadir, M, Steffens, D, Yan, F, Schubert, S (2003) Proton release by N2-fixing plant roots: a possible contribution to phytoremediation of calcareous sodic soils. *Journal of Plant Nutrition and Soil Science* **166,** 14-22.

Quilty, JR, Cattle, SR (accepted) The use and understanding of organic ammendments in Australian agriculture - a review. *Australian Journal of Soil Research.*

Quirk, JP, Aylmore, LAG (1960) Swelling and shrinkage of clay-water systems. *7th International Congress of Soil Science* **11,** 378-87.

Quirk, JP, Schofield, RK (1955) The effect of electrolyte concentration on soil permeability. *Australian Journal of Soil Research* **6,** 163-78.

Rani, V, Khetarpaul, N (2009) Nutrient composition of tomato products prepared using tomato grown under sodic condition with gypsum and farmyard manure treatment. *Journal of the Science of Food and Agriculture* **89,** 2601-7.

Rasmussen, WW, Moore, DP, Alban, AL (1972) Improvement of a solonetzic (slick spot) soil by deep ploughing, subsoiling and amendments. *Soil Science Society of America Proceedings* **36,** 137-42.

Rayment, GE, Higginson, FR (1992) 'Australian laboratory handbook of soil and water chemical methods', (Inkata Press: Sydney)

Reeves, DW (1997) The role of soil organic matter in maintaining soil quality in continuous cropping systems. *Soil and Tillage Research* **43,** 131-67.

Reid, JB, Goss, MJ (1981) Effect of living roots of different plant species on the aggregate stability of two arable soils. *Australian Journal of Soil Research* **32,** 521-41.

Rengasamy, P (1983) Clay dispersion in relation to changes in the electrolyte composition of dialysed red-brown earths *Journal of Soil Science* **34,** 723-32.

Rengasamy, P (2002) Transient salinity and subsoil constraints to dryland farming in Australian sodic soils: an overview. *Australian Journal of Experimental Agriculture* **42,** 351-61.

Rengasamy, P, Greene, RSB, Ford, GW (1984a) The role of clay fraction in the particle arrangement and stability of soil aggregates - a review. *Clay Research* **3,** 53-67.

Rengasamy, P, Greene, RSB, Ford, GW (1986) Influence of magnesium on aggregate stability in sodic Red-Brown Earths. *Australian Journal of Soil Research* **24,** 229-37.

Rengasamy, P, Greene, RSB, Ford, GW, Mehanni, AH (1984b) Identification of dispersive behaviour and the management of red-brown earths. *Australian Journal of Soil Research* **22,** 413-31.

Rengasamy, P, Olsson, KA (1991) Sodicity and soil structure. *Australian Journal of Soil Research* **29,** 935-52.

Rengasamy, P, Olsson, KA (1993) Irrigation and sodicity. *Australian Journal of Soil Research* **29,** 821-37.

Rengasamy, P, Olsson, KA, Kirby, JM (1992) Physical constraints to root growth in in the subsoil. *Proceedings of the National Workshop on Subsoil Constraints to Root Growth and High Soil Water and Nutrient use by Plants***,** 84-91.

Richards, LA (1954) Diagnosis and improvements of saline alkalai soils. *USDA Agriculture Handbook* **60**.

Rimmer, DL, Greenland, DJ (1976) Effect of $CaCO_3$ on the swelling of a soil clay. *Journal of Soil Science* **27,** 129-39.

Robbins, CW (1986a) Carbon dioxide partial pressure in lysimeter soils. *Agronomy Journal* **78,** 151-8.

Robbins, CW (1986b) Sodic calcareous soil reclamation as affected by different amendments and crops. *Agronomy Journal* **78,** 916-20.

Robertson, GA (1996) Saline land in Australia - its extent and predicted trends. *Australian Journal of Soil and Water Conservation* **9,** 4-7.

Romig, DE, M.J., G, Harris, RF, McSweeney, K (1995) How farmers assess soil health and quality. *Journal of Soil and Water Conservation* **50,** 229-36.

Roth, CH (1991) Soil crusting in South America. *In* 'Proceedings of the Proceedings of the International Symposium on Soil Crusting: Chemical and Physical Processes' (The University of Georgia: Athens, G.A.)

Roth, CH, Pavan, MA (1991) Effects of lime and gypsum on clay dispersion and infiltration in samples of a Brazillian Oxisol. *Geoderma* **48,** 351-61.

Rowell, DL (1988) Soil acidity and alkalinity. *In* 'Russell's soil conditions and plant growth'. (Eds. Wild, A) (Longman Scientific & Technical: Essex, England)

Russell, EW (1961) 'Soil conditions and plant growth', (Longmans, Green and Co. Ltd: London)

Russell, JS (1960) Soil fertility changes in the long-term experimental plots at Kybybolite, South Australia II. changes in phosphorus. *Australian Journal of Agricultural Research* **11,** 926-47.

Sahin, U, Oztas, T, Anapali, O (2003) Effects of consecutive applications of gypsum in equal, increasing, and decreasing quantities on soil hydrualic conductivity of a saline-sodic soil. *Journal of Plant Nutrition and Soil Science* **166,** 621-24.

Sansom, JJ, Chanasky, DS, Naeth, MA, Bateman, JC (1998a) In situ amelioration of sodic minespoil with chemical amendments and crop management II. soil physical properties, soil moisture and plant growth. *Canadian Journal of Soil Science* **78,** 667-74.

Sansom, JJ, Naeth, MA, Chanasky, DS, Bateman, JC (1998b) n situ amelioration of sodic minespoil with chemical amendments and crop management I. soil chemical properties. *Canadian Journal of Soil Science* **78,** 359-65.

Saulys, V, Bastiene, N (2006) The effect of lime admixture to trench backfill on the functioning of tile drainage in heavy soils. *Irrgation and Drainage* **55,** 373-82.

Scheffe, H (1958) Experiments with mixtures. *Journal of the Royal Statistical Society* **20,** 344-60.

Scott Russell, R (1977) 'Plant Root Systems - Their Function and Interactions with the Soil', (McGraw-Hill)

Sekhon, BS, Bajwa, MS (1993) Effect of organic matter and gypsum in controlling soil sodicity in rice-wheat-maize system irrigated with sodic waters. *Agricultural Water Management* **24,** 15-25.

Shainberg, I, Gal, M (1982) The effect of lime on the response of soils to sodic conditions. *Journal of Soil Science* **33,** 489-98.

Shainberg, I, Gal, M, Ferreria, AG, Goldstein, D (1991) Effect of water quality and amendments on the hydraulic properties and errosion of several Mederterranean soils *Soil Technology* **4,** 135-46.

Shainberg, I, Letey, J (1984) Response of soils to sodic and saline conditions. *Hilgardia* **52,** 1-57.

Shanmuganathan, RT, Oades, JM (1983) Modification of soil physical properties by addition of calciaum compounds. *Australian Journal of Soil Research* **21,** 285-300.

Shepherd, AN (1925) Experience on Yanco irrigation area. *Agricultural Gazette New South Wales* **36,** 261-3.

Sikora, IJ, Enkiri, NK (1999) Growth of tall fescue in compost/fetilizer blends. *Soil Science* **56,** 125-37.

Sinden, JA, King, DA (1990) Adoption of soil conservation measures in Manilla Shire, New South Wales. *Review of Marketing and Agricultural Economics* **58,** 179-92.

Smil, V (2000) Phosphorus in the environment: Natural flows and human interferences. *Annual Review of Energy and the Environment* **25,** 53-88.

So, HB, Aylmore, LAG (1993) How do sodic soils behave? The effects of sodicity on soil physical behaviour. *Australian Journal of Soil Research* **31,** 761-77.

So, HB, Cook, GD (1993) The effect of dispersion on the hydraulic conductivity of surface seals in clay soils. *Soil Technology***,** 325-330.

So, HB, Onus, G (1984) The extent of unstable grey and brown clays of the lower Gwydir Valley, New South Wales. *In* 'The properties and utilization of cracking clay soils'. (Eds. McGarity, JW, Hoult, EH & So, HB) (University of New England: Armidale)

So, HB, Taylor, DW, Yates, WJ, McGarity, JW (1978) Amelioration of structurally unstable grey and brown clays. *In* 'Modifications of soil structure'. (Eds. Emerson, WW, Bond, RD & Dexter, AR) (John wiley & sons: Chichester)

Soil Science Society of America (1997) 'Glossary of soil science terms', (Soil Science Society of America: Madison, WI)

Soil Survey Staff (1999) 'Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys', (United States Department of Agriculture, Natural Resources Conservation Service: Washington)

Sojka, RE, Upchurch, DR (1999) Reservations regarding the soil quality concept. *Soil Science Society of America Journal* **63,** 1039-54.

Sparks, DL (2003) 'Environmental soil chemistry', (Academic Press: London)

Speirs, SD (2006) *Characterising soil structural stability and form of sodic soil used for cotton production*, Thesis - The University of Sydney, Sydney.

Sposito, G (1989) 'The chemistry of soils', (Oxford University Press: New York)

Srivastava, P, Bhattachayya, T, Pal, DK (2002) Significance of the formation of calcium carbonate minerals in the pedogenisis and management of cracking clay soils (Vertisols) of India. *Clays and Clay Minerals* **50,** 111-26.

Stace, HC, Hubble, GD, Brewer, R, Northcote, KH, Sleeman, JR, Mulcahy, MJ, Hallsworth, EG (1968) 'A handbook of Australian soils', (Rellim: Adelaide)

Staff USSL (1954) 'Diagnosis and improvement of saline and alkali soils', 60, (Department of Agriculture Handbook)

Stockdale, CR (1983) Irrigated pasture productivity and its variability in the Shepparton Region of Northern Victoria. *Australian Journal of Experimental Agriculture and Animal Hausbandry* **23,** 131-9.

Sumner, ME (1992) The electrical double layer and clay dispersion. *In* 'Soil crusting: chemical and physical processes'. (Eds. Sumner, ME & Stewart, BA) (Lewis Publishers: Boca Raton)

Sumner, ME (1993) Sodic soils: a new perspective. *Australian Journal of Soil Research* **31,** 683-750.

Surapaneni, A, Olsson, KA, Burrow, DP, Beecher, HG, Ham, GJ, Stevens, RM, Hulugalle, NR, McKenzie, DC, Rengasamy, P (2002) Tatura sodicity conference: knowledge gaps in sodicity research for major agricultural industries. *Australian Journal of Experimental Agriculture* **42,** 379-87.

Swarup, A (1988) Influence of organic matter and flooding on the chenical and electrochemical properties of sodic soil and rice growth *Plant and Soil* **106,** 135-41.

Szabolcs (1991) Desertification and salinisation *In* 'Proceedings of international conference on agricultural management of salt-affected areas '. (Eds. Choukr-Allah, R) (Institut Agronomique et Veterinaire Hassan II: Agadir, Morocco)

Szabolcs (1994) Soils and salinization. *In* 'Handbook of plant and crop stress'. (Eds. Pessarakli, M) (Marcell Dekker: New York)

Tanji, KK (1990) Nature and extent of agricultural salinity. *In* 'Agricultural salinity assessment and amangement'. (Eds. Tanji, KK) (American Society of Civil Engineers: New York)

Taylor, DW, Olsson, KA (1987) Effect of gypsum and deep ripping on lucerne (Medicago sativa L.) yeilds on a red-brown earth under flood and spray irrigation. *Australian Journal of Experimental Agriculture* **27,** 841-72.

Tisdall, AL, Smith, SE, Rengasamy, P (1997) Aggregation of soil by fungal hyphae. *Australian Journal of Soil Research* **35,** 55-60.

Tisdall, JM (1991) Fungal hyphae and structural stability of soil. *Australian Journal of Soil Research* **29,** 729-43.

Tisdall, JM, Oades, JM (1979) Stabilization of soil aggregates by the root systems of ryegrass. *Australian Journal of Soil Research* **17,** 429-41.

Tucker, BM (1985) A proposed new reagent for the measurement of cation exchange properties of carbonate soils. *Australian Journal of Soil Research* **23,** 633-42.

Tucker, BM, Beatty, HJ (1974) Exchangeable cations and cation exchange capacity. *In* 'Methods for analysis of irrigated soils'. (Eds. Loveday, J) (Commonwealth Agricultural Bureaux: Farnham Royal, England)

Tucker, M, Napier, TL (1998) Perceptions of risk asscoiated with use of farm chemicals: implications for conservation initiatives. *Environmental Management* **22,** 575-87.

Turner, JC, Hattey, JA, Warren, JG, Penn, CJ (2010) Electrical conductivity and sodium adsorption ratio changes following annual applications of animal manure amendments. *Communications in Soil Science and Plant Analysis* **41,** 1043-60.

Valzano, FP (2000) *The effect of chemical ameliorants, tillage, and stubble practices on sodic soils in Australia*, Thesis - Australian National University, Canberra.

Valzano, FP, Greene, RSB, Murphy, BW, Rengasamy, P, Jarwal, SD (2001a) Effects of gypsum and stubble retention on the chemical and physical properties of a sodic grey vertosol in western Victoria. *Australian Journal of Soil Research* **39,** 1333-47.

Valzano, FP, Murphy, BW, Greene, RSB (2001b) The long term effects of lime ($CaCO_3$), Gypsum ($CaSO_4.2H_2O$), and tillage on the physical and chemical properties of a sodic red-brown earth. *Australian Journal of Soil Research* **39,** 1307-31.

van der Elshout, S, Kamphorst, A (1990) Suitability of coarse-grade gypsum for sodic soil reclamation: a laboratory experiment. *Soil Science* **149,** 228-34.

van Olphen, H (1963) 'An introduction to clay colloid chemistry', (John Wiley & Sons: New york)

Vance, WH, McKenzie, BM, Tisdall, JM (2002) The stability of soils used for cropping in northern Victoria and southern New South Wales. *Australian Journal of Soil Research* **40,** 615-24.

Verba, MP, Devyatykh, VA (1992) Changes in micromorphology of gypsiferous meadow sierozem during leaching. *Eurasian Soil Science* **24,** 12-22.

Vervoort, RW, Cattle, SR, Minasny, B (2003) The hydrology of Vertosols used for cotton production: I. Hydraulic, structural and fundamental soil properties. *Australian Journal of Soil Research* **41,** 1255-72.

Viscarra Rossel, RA, McBratney, A, Minasny, B (Eds.) (2010) *Proximal soil sensing,* (Springer: London)

Viscarra Rossel, RA, Walter, C (2004) Rapid, quantitative and spatial field measurements of soil pH using an ion sensitive field effect transistor. *Geoderma* **119,** 9-20.

Wahid, A, Akhtar, S, Ali, I, Rasul, E (1998) Amelioration of saline-sodic soils with organic matter and their use for wheat growth. *Communications in Soil Science and Plant Analysis* **29,** 2307-18.

Wallace, A (1994) Use of gypsum on soil where needed can make agriculture more sustainable. *Communications in Soil Science and Plant Analysis* **25,** 109-16.

Wang, HL, Hedley, MJ, Bolan, NS, Horne, DJ (1999a) The influence of surface incorporated lime and gypsiferous by-products on surface and subsurface soil accidity – I. Soil solution chemistry. *Australian Journal of Soil Research* **37,** 165-80.

Wang, HL, Hedley, MJ, Bolan, NS, Horne, DJ (1999b) The influence of surface incorporated lime and gypsiferous by-products on surface and subsurface soil accidity – II. Root growth and agronomic implications *Australian Journal of Soil Research* **37,** 181-90.

Watson, WD, Hall, NH, Hamblin, A (2000) Economic aspects of sodic, acid and saline soils in Australia. *In* 'Proceedings of the Sodicity conference: sodicity issues in agricultural industries - current research and future directions' (ISIA: Tatura, Victoria)

Webster, P (1999) The challenge of sustainability at the farm level: presidential address. *Journal of Agricultural Economics* **50,** 371-87.

Weinbaum, BS, Allen, MF, Allen, EB (1996) Survival of arbuscular mycorrhizal fungi following reciprocal transplanting across the Great Basin. *Ecological Applications* **6,** 1365-72.

Wilkinson, R (1996) 'Resource monitoring by Hawkes Bay farmers', (Manaaki Press: Lincoln)

Willer, H, Yuseffi-Menzler, M, Sorenson, N (2008) 'The world of organic agriculture: Statistics and emerging trends 2008', (Earthscan: London)

Wong, JWC, Ho, GE (1991) Effects of gypsum and sewage sludge amendment on physical properties of fine bauxite refining residue. *Soil Science* **152,** 326-32.

Wong, VNL, Murphy, BW, Koen, TB, Greene, RSB, Dalal, RC (2008) Soil organic carbon stocks in saline and sodic landscapes. *Australian Journal of Soil Research* **46,** 378-89.

Yates, LJ, Hedley, MJ (2008) Understanding winter sodium deposition in Taranaki, New Zealand. *Australian Journal of Soil Research* **46,** 600-09.

Zhang, X-h, Li, L-q, G-x., P (2007) Topsoil organic carbon mineralization and CO_2 evolution of three paddy soils from South China and the temperature dependance. *Journal of Environmental Sciences* **19,** 319-26.