Development of a Proximal Soil Sensing System for the Continuous Management of Acid Soil

Raphael A. Viscarra Rossel

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Australian Centre for Precision Agriculture
Department of Agricultural Chemistry and Soil Science
The University of Sydney
New South Wales
Australia

MMI
Certificate of originality

I hereby certify that the text of this thesis contains no material that has been accepted as part of the requirements for any degree or diploma in any university nor any material previously published or written unless the reference to this material is made.

Raphael A. Viscarra Rossel
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The notion that agriculturally productive land may be treated as a relatively homogeneous resource at the within-field scale is not sound. This assumption and the subsequent uniform application of planting material, chemicals and/or tillage effort may result in zones within a field being under- or over-treated. Arising from these are problems associated with the inefficient use of input resources, economically significant yield losses, excessive energy costs, gaseous or percolatory release of chemicals into the environment, unacceptable long-term retention of chemicals and a less-than-optimal growing environment. The environmental impact of crop production systems is substantial. In this millennium, three important issues for scientists and agrarian communities to address are the need to efficiently manage agricultural land for sustainable production, the maintenance of soil and water resources and the environmental quality of agricultural land.

Precision agriculture (PA) aims to identify soil and crop attribute variability, and manage it in an accurate and timely manner for near-optimal crop production. Unlike conventional agricultural management where an averaged whole-field analytical result is employed for decision-making, management in PA is based on site-specific soil and crop information. That is, resource application and agronomic practices are matched with variation in soil attributes and crop requirements across a field or management unit. Conceptually PA makes economic and environmental sense, optimising gross margins and minimising the environmental impact of crop production systems. Although the economic justification for PA can be readily calculated, concepts such as environmental containment and the safety of agrochemicals in soil are more difficult to estimate. However, it may be argued that if PA lessens the overall agrochemical load in agricultural and non-agricultural environments, then its value as a management system for agriculture increases substantially.

Management using PA requires detailed information of the spatial and temporal variation in crop yield components, weeds, soil-borne pests and attributes of physical, chemical and biological soil fertility. However, detailed descriptions of fine scale variation in soil properties have always been difficult and costly to perform. Sensing and scanning technologies need to be developed to more efficiently and economically obtain accurate information on the extent and variability of soil attributes that affect crop growth and yield. The primary aim of this work is to conduct research towards the development of an ‘on-the-go’ proximal soil pH and lime requirement sensing system for real-time continuous management of acid soil. It is divided into four sections.

Section one consists of two chapters; the first describes global and historical events that converged into the development of precision agriculture, while chapter two provides reviews of statistical and geostatistical techniques that are used for the quantification of soil spatial variability and of topics that are integral to the concept of precision agriculture. The review then focuses on technologies that are used for the complete enumeration of soil, namely remote and proximal sensing.

Section two comprises three chapters that deal with sampling and mapping methods. Chapter three provides a general description of the environment in the experimental field. It provides descriptions of the field site, topography, soil condition at the time of sampling, and the spatial variability of surface soil chemical properties. It also described the methods of sampling and laboratory analyses. Chapter four discusses some of
the implications of soil sampling on analytical results and presents a review that quantifies the accuracy, precision and cost of current laboratory techniques. The chapter also presents analytical results that show the loss of information in kriged maps of lime requirement resulting from decreases in sample size. The message of chapter four is that the evolution of precision agriculture calls for the development of ‘on-the-go’ proximal soil sensing systems to characterise soil spatial variability rapidly, economically, accurately and in a timely manner. Chapter five suggests that for sparsely sampled data the choice of spatial modelling and mapping techniques is important for reliable results and accurate representations of field soil variability. It assesses a number of geostatistical methodologies that may be used to model and map non-stationary soil data, in this instance soil pH and organic carbon. Intrinsic random functions of order k produced the most accurate and parsimonious predictions of all of the methods tested.

Section three consists of two chapters whose theme pertains to sustainable and efficient management of acid agricultural soil. Chapter six discusses soil acidity, its causes, consequences and current management practices. It also reports the global extent of soil acidity and that which occurs in Australia. The chapter closes by proposing a real-time continuous management system for the management of acid soil. Chapter seven reports results from experiments conducted towards the development of an ‘on-the-go’ proximal soil pH and lime requirement sensing system that may be used for the real-time continuous management of acid soil. Assessment of four potentiometric sensors showed that the pH Ion Sensitive Field Effect Transistor (ISFET) was most suitable for inclusion in the proposed sensing system. It is accurate and precise, drift and hysteresis are low, and most importantly it’s response time is small. A design for the analytical system was presented based on flow injection analysis (FIA) and sequential injection analysis (SIA) concepts. Two different modes of operation were described. Kinetic experiments were conducted to characterise soil:0.01M CaCl₂ pH (pH\textsubscript{CaCl₂}) and soil:lime requirement buffer (pH\textsubscript{buffer}) reactions. Modelling of the pH\textsubscript{buffer} reactions described their sequential, biphasic nature. A statistical methodology was devised to predict pH\textsubscript{buffer} measurements using only initial reaction measurements at 0.5s, 1s, 2s and 3s measurements. The accuracy of the technique was 0.1 pH\textsubscript{buffer} units and the bias was low. Finally, the chapter describes a framework for the development of a prototype soil pH and lime requirement sensing system and the creative design of the system.

The final section relates to the management of acid soil by liming. Chapter eight describes the development of empirical deterministic models for rapid predictions of lime requirement. The response surface models are based on soil:lime incubations, pH\textsubscript{buffer} measurements and the selection of target pH values. These models are more accurate and more practical than more conventional techniques, and may be more suitably incorporated into the spatial decision-support system of the proposed real-time continuous system for the management of acid soil. Chapter nine presents a glasshouse liming experiment that was used to authenticate the lime requirement model derived in the previous chapter. It also presents soil property interactions and soil-plant relationships in acid and ameliorated soil, to compare the effects of no lime applications, single-rate and variable-rate liming. Chapter X presents a methodology for modelling crop yields in the presence of uncertainty. The local uncertainty about soil properties and the uncertainty about model parameters were accounted for by using indicator kriging and Latin Hypercube Sampling for the propagation of uncertainties through two regression functions; a yield response function and one that equates resultant pH after the application of lime. Under the assumptions and constraints of the analysis, single-rate liming was found to be the best management option.
# TABLE OF CONTENTS

Abstract ........................................................................................................................................... v
Table of Contents ............................................................................................................................... vii
List of Figures ..................................................................................................................................... xv
List of Tables ...................................................................................................................................... xxi

## Conceptual Basis of the Research and Aims

<table>
<thead>
<tr>
<th>Conceptual Basis</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Land Degradation in Australian Agriculture</td>
<td>3</td>
</tr>
<tr>
<td>Managing Acid Soil</td>
<td>4</td>
</tr>
<tr>
<td>Precision Agriculture</td>
<td>5</td>
</tr>
<tr>
<td>Data Collection for Precision Agriculture</td>
<td>6</td>
</tr>
<tr>
<td>Advantages of ‘On-the-Go’ Proximal Sensing Systems</td>
<td>7</td>
</tr>
<tr>
<td>Aims of the Research</td>
<td>8</td>
</tr>
</tbody>
</table>

## Chapter I: Precision Agriculture: Convergence of Threads

| 1.1 INTRODUCTION | 15 |
| 1.2 WORLD POPULATION AND FOOD SECURITY | 16 |
| 1.3 ARABLE LAND AREA | 17 |
| 1.4 DEVELOPING NATIONS | 19 |
| 1.5 ENVIRONMENTAL AWARENESS | 20 |
| 1.6 WORLD ECONOMICS | 21 |
| 1.7 ADVANCES IN SCIENCE AND TECHNOLOGY IN AGRICULTURE | 23 |
| 1.7.1 The Green Revolution | 24 |
| 1.7.2 Developments in Studies of Soil Spatial Variability | 26 |
| 1.8 INFORMATION AND COMMUNICATION TECHNOLOGY | 28 |
| 1.8.1 Computers – Hardware and Software | 28 |
| 1.8.2 Satellite Systems | 29 |
| 1.8.3 Geographical Information Systems (GIS) | 30 |
| 1.9 TOTAL QUALITY MANAGEMENT AND VERTICAL INTEGRATION | 31 |
| 1.10 PRECISION AGRICULTURE | 33 |
| 1.11 REFERENCES | 34 |

## Chapter II: Quantifying Soil Spatial Variability and the Practice of Precision Agriculture: A Review of the Literature

<p>| 2.1 INTRODUCTION | 41 |
| 2.2 QUANTIFYING SOIL VARIABILITY | 41 |
| 2.2.1 Classical Description of the Spatial Variability of Soil pH | 42 |
| 2.2.2 Geostatistics | 43 |
| Regionalised Variables and Random Functions | 44 |
| Stationarity | 46 |
| Structural Analysis | 48 |</p>
<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>II</td>
<td>A CONTINUOUS MANAGEMENT SYSTEM FOR ACID SOIL</td>
<td></td>
</tr>
<tr>
<td></td>
<td>R. Viscarra Rossel</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Experimental Semi-Variograms</td>
<td>49</td>
</tr>
<tr>
<td></td>
<td>Theoretical Semi-Variograms</td>
<td>49</td>
</tr>
<tr>
<td></td>
<td>The Spatial Variability of Soil pH</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>Prediction using Kriging Algorithms</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>Stochastic Simulation</td>
<td>61</td>
</tr>
<tr>
<td></td>
<td>Techniques with Properties Intermediate to Kriging and Simulation</td>
<td>63</td>
</tr>
<tr>
<td>2.4</td>
<td>PRECISION AGRICULTURE</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>2.4.1 Spatial Referencing</td>
<td>65</td>
</tr>
<tr>
<td></td>
<td>2.4.2 Data Acquisition</td>
<td>69</td>
</tr>
<tr>
<td></td>
<td>2.4.3 Spatial Data Analysis and Prediction</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td>2.4.4 Data Management and Decision Support</td>
<td>76</td>
</tr>
<tr>
<td></td>
<td>Geographic Information Systems for Precision Agriculture</td>
<td>76</td>
</tr>
<tr>
<td></td>
<td>Spatial Decision Support Systems for Precision Agriculture</td>
<td>77</td>
</tr>
<tr>
<td>2.4.5</td>
<td>Implementation of Management</td>
<td>81</td>
</tr>
<tr>
<td>2.5</td>
<td>DATA ACQUISITION FOR PRECISION AGRICULTURE</td>
<td>82</td>
</tr>
<tr>
<td></td>
<td>2.5.1 Discrete Sampling</td>
<td>83</td>
</tr>
<tr>
<td></td>
<td>2.5.1.1 Simple Random Sampling</td>
<td>83</td>
</tr>
<tr>
<td></td>
<td>2.5.1.2 Stratified Random Sampling</td>
<td>84</td>
</tr>
<tr>
<td></td>
<td>2.5.1.3 Systematic Sampling</td>
<td>84</td>
</tr>
<tr>
<td></td>
<td>2.5.1.4 Stratified Systematic Unaligned Sampling</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>2.5.1.5 Zone (Direct) Sampling</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>2.5.1.6 Purposive Sampling Schemes</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>2.5.1.7 Automated Mechanisms for Discrete Soil Sampling and Analysis</td>
<td>86</td>
</tr>
<tr>
<td>2.6</td>
<td>COMPLETE ENUMERATION</td>
<td>87</td>
</tr>
<tr>
<td></td>
<td>2.6.1 Remote Sensing</td>
<td>88</td>
</tr>
<tr>
<td></td>
<td>2.6.1.1 Aircraft Imagery</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>2.6.1.2 Satellite Imagery</td>
<td>93</td>
</tr>
<tr>
<td></td>
<td>2.6.2 Proximal Soil Sensing Systems</td>
<td>97</td>
</tr>
<tr>
<td></td>
<td>2.6.2.1 Soil Water</td>
<td>98</td>
</tr>
<tr>
<td></td>
<td>2.6.2.2 Soil Nitrate</td>
<td>101</td>
</tr>
<tr>
<td></td>
<td>2.6.2.3 Soil Organic Matter</td>
<td>102</td>
</tr>
<tr>
<td></td>
<td>2.6.2.4 Soil pH</td>
<td>104</td>
</tr>
<tr>
<td></td>
<td>2.6.2.5 Soil Electrical Conductivity</td>
<td>105</td>
</tr>
<tr>
<td></td>
<td>2.6.2.6 Soil Physical Properties</td>
<td>107</td>
</tr>
<tr>
<td></td>
<td>2.6.2.7 Different Soil Properties using Various Techniques</td>
<td>109</td>
</tr>
<tr>
<td>2.7</td>
<td>CONCLUDING REMARKS</td>
<td>111</td>
</tr>
<tr>
<td>2.8</td>
<td>REFERENCES</td>
<td>112</td>
</tr>
</tbody>
</table>

**Chapter III: Description of the Experimental Field: Soil Sampling, Analysis and the Spatial Variability of Surface Soil Chemical Properties**

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1</td>
<td>FIELD SITE DESCRIPTION</td>
<td>127</td>
</tr>
<tr>
<td>3.1.1</td>
<td>The Landscape and Soil of the Experimental Field</td>
<td>129</td>
</tr>
<tr>
<td>3.2</td>
<td>DISCREET SAMPLING STRATEGY</td>
<td>132</td>
</tr>
<tr>
<td>3.3</td>
<td>SOIL ANALYSIS</td>
<td>134</td>
</tr>
<tr>
<td>3.4</td>
<td>SURFACE SOIL PROPERTY STATUS</td>
<td>135</td>
</tr>
<tr>
<td>3.4.1</td>
<td>Soil Chemical Properties</td>
<td>135</td>
</tr>
<tr>
<td>3.4.2</td>
<td>Soil Physical Properties</td>
<td>136</td>
</tr>
<tr>
<td>3.5</td>
<td>SPATIAL VARIABILITY OF FIELD SOIL CHEMICAL PROPERTIES</td>
<td>137</td>
</tr>
<tr>
<td>3.6</td>
<td>CONCLUDING REMARKS</td>
<td>139</td>
</tr>
<tr>
<td></td>
<td>Chapter III: Description of the Experimental Field: Soil Sampling,</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Analysis and the Spatial Variability of Surface Soil Chemical</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Properties</td>
<td></td>
</tr>
</tbody>
</table>
### Table of Contents

#### 3.7 REFERENCES ................................................................. 139

#### Chapter IV: Precision Agriculture and its Implications for Soil Sampling and Analysis ............................ 141

- **ABSTRACT** .................................................................................. 143

- **4.1 INTRODUCTION** ...................................................................... 143

- **4.2 IMPLICATIONS OF SOIL SAMPLING ON ANALYTICAL RESULTS** ................................................................. 145
  - 4.2.1 An Interim Approach to Sampling for Precision Agriculture ................................................................. 147
  - 4.2.2 Sample Collection and Handling ................................................................................................................. 148

- **4.3 ROUTINE SOIL CHEMICAL TESTS FOR PRECISION AGRICULTURE** ............................................................ 149
  - 4.3.1 Soil pH .................................................................................. 149
  - 4.3.2 Organic Matter (OM) .................................................................. 149
  - 4.3.3 Mineral Nutrients - Particularly N, P, K ........................................................................................................ 150
  - 4.3.4 Cation Exchange Capacity (CEC) ................................................................................................................. 150

- **4.4 ACCURACY AND PRECISION OF LABORATORY METHODS** ............................................................... 150
  - 4.4.1 Spatial Variability of Field Soil Chemical Properties ......................................................................................... 152
  - 4.4.2 Short-range or “Nugget” Variation ................................................................................................................ 152

- **4.5 CURRENT COST OF ANALYTICAL TECHNIQUES** ............................................................... 155

- **4.6 EFFECT OF SAMPLING INTENSITY ON MAP PRODUCTION** ................................................................. 156
  - 4.6.1 Sampling Intensity and Lime requirement ........................................................................................................ 157

- **4.7 INTENSIVELY COLLECTED SOIL DATA USING THE VERIS 3100** ...................................................... 163
  - 4.7.1 Correlations of VERIS EC Measurements with Soil Properties ............................................................................ 171

- **4.8 CONCLUDING REMARKS** ........................................................... 174

- **4.9 REFERENCES** ................................................................. 175

#### Chapter V: Spatial Modelling and Mapping Methods for Sparsely Sampled Soil that exhibits Spatial Drift ........................................................................ 179

- **ABSTRACT** .................................................................................. 181

- **5.1 INTRODUCTION** ...................................................................... 181
  - 5.1.1 Review of Prediction Methods used in this Work ............................................................................................. 184
    - Generalised Additive Models .................................................................................................................................. 184
    - Trend-Surface Regression Models .......................................................................................................................... 184
    - Local Trend Surface Polynomial Regression Models .................................................................................................. 185
    - Ordinary Kriging and Local Ordinary Kriging ........................................................................................................ 186
    - Intrinsic Random Function of Order \( k \) .................................................................................................................... 186
    - Regression Residual-Kriging Methods ....................................................................................................................... 188

- **5.2 METHODS** ............................................................................... 189
  - 5.2.1 Study Site and Experimental Design ............................................................................................................... 189
  - 5.2.2 Exploratory Data Analysis ............................................................................................................................... 190
  - 5.2.3 Comparison of the Methods Tested by Cross Validation ................................................................................ 190
  - 5.2.4 Modelling of the Spatial Trend .......................................................................................................................... 190
  - 5.2.5 Indices used to determine the Accuracy of Predictions .................................................................................... 191

- **5.3 RESULTS AND DISCUSSION** .................................................... 192
  - 5.3.1 Exploratory Data Analysis ............................................................................................................................... 192
  - 5.3.2 Structural Analysis ............................................................................................................................................. 195
  - 5.3.3 Modelling of the Spatial Trend .......................................................................................................................... 198
  - 5.3.4 Comparison of Prediction Methods .................................................................................................................. 201

- **5.4 CONCLUDING REMARKS** ........................................................... 208

- **5.5 REFERENCES** ................................................................. 211
Chapter VI: Soil Acidity and Acidification: A Prospective Management System for Acid Soil

6.1 INTRODUCTION

6.2 SOIL ACIDITY

6.2.1 Soil Acidification

6.3 PRIMARY CAUSES OF AGRICULTURAL SOIL ACIDIFICATION

6.3.1 Leaching of Nitrate-Nitrogen

6.3.2 Accumulation of Organic Matter

6.3.3 Removal of Agricultural Produce

6.3.4 Inefficient use of Fertilisers

6.4 PRINCIPAL CONSEQUENCES OF SOIL ACIDIFICATION

6.4.1 Soil Biological Consequences

6.4.2 Soil Chemical Consequences

6.4.3 Soil Physical Consequences

6.5 MANAGEMENT OF ACID SOIL

6.5.1 Site-Specific Soil Management

6.5.2 Liming

6.5.3 Acid-Tolerant Plant Species

6.5.4 Efficient use of Water and Fertilisers

6.5.5 Supplementary Management Practices

6.6 THE EXTENT OF SOIL ACIDITY

6.6.1 Global Distribution of Acid Soils

6.6.2 Distribution of Acid Soil in Australia

6.6.3 Distribution of Acid Soil in New South Wales

6.7 A CONTINUOUS MANAGEMENT SYSTEM FOR ACID SOIL

6.8 CONCLUDING REMARKS

6.9 REFERENCES

Chapter VII: Development of an 'On-the-Go' Proximal Soil pH and Lime Requirement Sensing System

ABSTRACT

7.1 INTRODUCTION

7.2 ASSESSMENT OF FOUR POTENTIOMETRIC SENSORS

7.2.1 Comparison of Accuracy and Precision

7.2.2 Comparison of Response Times

7.3 ION SENSITIVE FIELD-EFFECT TRANSISTORS

7.3.1 From FET to ISFET

7.3.2 Developments in pH ISFET Technology

7.3.3 Proposed Mechanisms of ISFET Operation

7.3.4 Evaluation of a pH ISFET sensor

7.4 Analytical Methodology

7.5 Determination of Drift and Hysteresis

7.6 REFERENCES
# Table of Contents

Determination of Response Time ......................................................... 268  
Quality Control ..................................................................................... 269  

7.3.5 Results ......................................................................................... 269  
Sensor Characteristics - Sensitivity, Drift and Hysteresis ................. 269  
Response Time of the ISFET Sensor ............................................... 271  
ISFET Quality Control ......................................................................... 277  

7.4 THE ANALYTICAL SYSTEM ................................................................. 279  
7.4.1 Flow Injection Analysis Systems ................................................. 280  
7.4.2 Flow Injection Analysis Systems for Soil Analyses ................. 282  
7.4.3 Sequential Injection Analysis Systems ........................................... 283  
7.4.4 An Analytical System for Field Operation .................................... 284  

7.5 KINETICS OF ION EXCHANGE REACTIONS ...................................... 287  
7.5.1 Methodology ................................................................................. 288  
Kinetic Methodology ........................................................................... 288  
Description of the Kinetics of pH\textsubscript{buffer} Reaction .................. 289  
Prediction of Equilibrium pH\textsubscript{buffer} Values ............................. 289  
7.5.2 Results .......................................................................................... 290  
Kinetics of Soil:0.01M-Calcium Chloride (pH\textsubscript{CaCl\textsubscript{2}}) Reactions 291  
Kinetics of Soil:Lime-Requirement Buffer (pH\textsubscript{buffer}) Reactions 292  
Description of the Kinetics of pH\textsubscript{buffer} Reaction ....................... 294  
Characterising the pH\textsubscript{buffer} Reactions using Double Exponential Models 296  
Comparison between the Kinetic Models .......................................... 298  
Interpretation of the Biphasic Kinetics of pH\textsubscript{buffer} Reactions .... 299  
Prediction of Equilibrium pH\textsubscript{buffer} Values .................................. 301  

7.6 FRAMEWORK FOR THE DEVELOPMENT OF THE SENSING SYSTEM 306  
7.7 CREATIVE DESIGN OF THE SENSING SYSTEM ................................ 308  
7.7.1 Sampling Component .................................................................... 308  
7.7.2 Data Processing System ................................................................. 309  

7.8 CONCLUDING REMARKS ................................................................. 310  
7.9 REFERENCES ..................................................................................... 312  


ABSTRACT ............................................................................................. 321  
8.1 INTRODUCTION ................................................................................. 321  
8.2 A BRIEF REVIEW OF THE LITERATURE ON LIMING ...................... 323  
8.2.1 Predictions of Lime Requirement using Multivariate Functions .... 323  
8.2.2 Predictions of Lime Requirement using Buffer Methods ............... 325  
  The Woodruff Buffer (WRF) ................................................................. 325  
  The Shoemaker, McLean and Pratt Buffer (SMP) ............................... 326  
  The Mehlich Buffer (MCH) ................................................................. 326  
  The New Woodruff Buffer (NWRF) .................................................... 326  
  Previous Comparative Research on Lime-Requirement Buffers ......... 327  
8.2.3 Lime Requirement Based on Exchangeable Aluminium ............ 330  
8.2.4 Site-Specific Predictions of Lime Requirement ............................ 331  
8.3 METHODOLOGY .............................................................................. 332  
8.3.1 Analytical Methods ...................................................................... 332  
  Soil:CaCO\textsubscript{3} Incubations ............................................................ 332  
  pH\textsubscript{buffer} measurements .......................................................... 333  
8.3.2 Statistical Methods ....................................................................... 334
Incubation Lime Requirements .......................................................... 334
Multivariate Functions ........................................................................... 335
Conventional Calibrations ........................................................................ 335
Single-Factor Response Surface Models .................................................. 335
Two-Factor Response Surface Models ....................................................... 336
Comparison and Validation of Lime Requirement Predictions ..................... 336

8.3.3 Spatial Methods .............................................................................. 337
Uncertainty of Response Surface Models ................................................ 337
Geostatistical Analysis of Lime Requirements, Aluminium and Calcium ...... 337
Comparison between Single-Rate and Site-Specific Liming .......................... 338

8.4 RESULTS AND DISCUSSION ............................................................. 338
8.4.1 Properties and Lime Requirements of Incubated Soils ......................... 340
8.4.2 Conventional Regression Equations ................................................ 344
8.4.3 Single-Factor (pH\(_{buffer}\)) Response Surface Models ............................ 346
8.4.4 Two-Factor (pH\(_{buffer}\) and pH\(_{CaCl_2}\)) Response Surface Models .......... 349
8.4.5 Comparison and Validations of Lime Requirement Predictions ............... 353
8.4.6 Uncertainty of the Response Surface Models ....................................... 355
8.4.7 Spatial Analysis of Lime Requirement, Aluminium and Calcium ........... 356
8.4.8 Comparison between Single-Rate and Site-Specific Liming ..................... 365

8.5 CONCLUDING REMARKS ............................................................... 366
8.6 REFERENCES .................................................................................... 368

Chapter IX: A Glasshouse Liming Experiment ............................................ 371
ABSTRACT .............................................................................................. 373
9.1 INTRODUCTION ................................................................................ 373
9.2 METHODS ........................................................................................ 375
9.2.1 Sample Selection and Analyses ......................................................... 375
9.2.2 Experimental Design and Trial Preparation ........................................ 376
Fertilisation .............................................................................................. 376
Mass of Soil used in Each Pot and Lime Requirement .................................. 378
Watering ................................................................................................. 379
Planting and Harvesting ........................................................................... 379

9.3 RESULTS AND DISCUSSION ............................................................. 380
9.3.1 Soil Property Comparisons between Treatments .................................... 382
9.3.2 Important Soil Property Interactions in Acid Soil ................................ 383
Soil Property Correlations ....................................................................... 384
Soil pH and Lime Requirement .................................................................. 384
Soil pH and Aluminium .......................................................................... 386
Aluminium and Lime Requirement .......................................................... 388
Soil pH, Aluminium and CEC ................................................................. 389
Soil pH, Aluminium and Calcium ............................................................ 390
9.3.3 Crop Yield Comparisons between Liming Treatments .......................... 392
9.3.4 Agronomic Interactions in Acid Soil .................................................. 394
Yield Response to Soil pH ...................................................................... 395
Yield Response to Aluminium .................................................................. 396
Yield Response to Calcium and CEC ........................................................ 397

9.4 CONCLUDING REMARKS ............................................................... 399
9.5 REFERENCES .................................................................................... 400
# ABSTRACT  
0.1 INTRODUCTION  
0.2 THEORY  
0.2.1 Modelling Local Uncertainty using Indicator Kriging  
0.2.2 Propagation of Uncertainty  
0.3 MATERIAL AND METHODS  
0.3.1 Analytical Methodology  
0.3.2 Geostatistical Methodology  
0.3.3 Profitability  
0.3.4 Optimisation of Site-Specific Lime Requirement  
0.3.5 Sensitivity Analysis  
0.4 RESULTS AND DISCUSSION  
0.4.1 No-lime Application  
0.4.2 Single-Rate Lime Application  
0.4.3 Site-Specific Liming Scenario – Optimising Net Profit  
0.4.4 Economic Comparison of Scenarios  
0.4.5 Optimising to Ensure 100% Probability of Making a Profit  
0.4.6 Sensitivity Analysis  
0.5 CONCLUDING REMARKS  
0.6 REFERENCES  
Conclusions and Future Work
### LIST OF FIGURES

#### Conceptual Basis of the Research and Aims

1. A continuous real-time precision agriculture (PA) management system ......................... 6

#### Chapter I: Precision Agriculture: Convergence of Threads

1.1 World population from 1950 to 2100. ............................................................................. 17
1.2 The cycle of soil degradation and its adverse effects on environmental quality, agricultural sustainability and the socio-economical aspects of human society........................................... 21
1.3 Logarithmic population curves through history, showing effects from the cultural, agricultural and scientific/industrial revolutions............................................................. 24
1.4 Trends in world population, world-average yields of wheat and rice. ................................. 26
1.5 Continual improvements in productivity and quality applying the Demin or Shewart wheel to Kaizen, the continual desire to improve................................................................. 32

#### Chapter II: Quantifying Soil Spatial Variability and the Practice of Precision Agriculture: A Review of the Literature

2.1 Bounded and unbounded semi-variogram models of soil properties.............................. 53
2.2 Positioning accuracy of the Global Positioning System (a.) with selective availability and (b.) without selective availability.............................................................................. 67
2.3 Operational configuration of a real-time Differential Global Positioning System.............. 68
2.4 Conceptual diagram of a management cycle and decision support system (DSS)............. 78
2.5 Field-based automated soil sampler and nitrate analysis system....................................... 86
2.6 The electromagnetic spectrum. .......................................................................................... 87
2.7 Reflectance spectra for soil, vegetation and water ............................................................. 88
2.8 Tine-mounted soil organic matter sensor (a.) mounting system on a variable-rate herbicide applicator, and (b.) red-light (660 nm) emitters and sensor................................................. 103
2.9 Operation of the VERIS 3100, an ‘on-the-go’ proximal soil EC sensing system.............. 105
2.10 The Mobile Electromagnetic Induction Sensing System for EC measurements............. 107
2.11 Photograph of NASA’s Micro-rover ‘Sojourner’ operating on a Martian landscape..... 111

#### Chapter III: Description of the Experimental Field: Soil Sampling, Analysis and the Spatial Variability of Surface Soil Chemical Properties

3.1 The experimental site located at Kelso, NSW .................................................................... 127
3.2 Monthly climatic averages for the Kelso / Bathurst area showing (a.) average rainfall and evaporation, and (b.) average maximum and minimum temperatures........................... 128
Chapter IV: Precision Agriculture and its Implications for Soil Sampling and Analysis

4.1 Management systems and required sampling schemes: Uniform, selective and continuous soil and crop management ................................................................. 148

4.2 Experimental variograms with fitted exponential models for (a.) LR(6.5) 40 m grid, (c.) 80 m grid, and (e.) 120 m grid. Point kriged maps shown in (b.) 40 m grid, (d.) 80 m grid, and (f.) 120 m grid ................................................................. 159

4.3 Difference maps between point kriged estimates of the different grid sample sizes (a.) 80 m – 40 m and (b.) 120 m – 40 m .................................................. 161

4.4 Sensed soil electrical conductivity measurements 0 – 30 cm ................................ .......................... 163

4.5 Block kriged map of VERIS 3100, surface soil (0 – 30 cm) electrical conductivity data, and elevation contours ................................................................. 165

4.6 Sensed soil electrical conductivity measurements 30 – 90 cm .............................................................. 169

4.7 Block kriged map of VERIS 3100 30 – 90 cm electrical conductivity data, and elevation contours ................................................................. 171

Chapter V: Spatial Modelling and Mapping Methods for Sparsely Sampled Soil that Exhibits Spatial Drift

5.1 (a.) Angle of coordinate rotation (?= -8.5º), and (b.) field layout showing two sampling points 1 m apart at each of the 119 nodes .................................................. 189

5.2 Histograms and summary statistics of soil (a.) pH_{CaCl_2} and (b.) OC in the experimental field ................................................................. 192

5.3 Classed maps of soil (a.) pH_{CaCl_2} and (b.) OC data .............................................................. 193

5.4 Averaged soil pH and OC data in the northern (a. & c.) and eastern (b. & d) directions respectively................................................................. 195

5.5 The four principal directional semi-variograms for (a.) pH and (b.) OC .......................... 196

5.6 Isotropic experimental semi-variograms for soil (a.) pH and (b.) OC ............................................................. 197

5.7 Semi-variograms of the residuals from the pH (a.) GAM, (b.) LTS 2, (c.) TS 2, and the organic carbon residuals for the (d.) GAM, (e.) LTS 2, (f.) TS 2 fitted models................................................................. 200

5.8 Maps of soil pH: (a.) generalised additive model, (b.) global ordinary kriging using an exponential semi-variogram, (c.) local ordinary kriging with a spherical variogram, and (d.) intrinsic random function of order 1 ................................................................. 205

5.9 Maps of soil organic carbon showing the general trend in prediction accuracy of the methods tested: (a.) quadratic local trend surface, (b.) global ordinary kriging using a linear
List of Figures

Chapter VI: Soil Acidity and Acidification: A Prospective Management System for Acid Soil

6.1 Change in the pH profile of the surface 20 cm of soil over 12 years as a result of dryland agricultural management practices ................................................................. 220
6.2 World distribution of acid soils with pH$_{H_2O}$ values smaller than 5.5.............................. 235
6.3 Distribution of acid soils (0 – 10 or 0 – 15 cm) and soils at risk of becoming strongly acidic in NSW ............................................................................................................. 241
6.4 Agricultural lime use in NSW, 1975 to 1995 ..................................................................... 243
6.5 A real-time continuous management system for acid soil .............................................. 244

Chapter VII: Development of an ‘On-the-Go’ Proximal Soil pH and Lime Requirement Sensing System

7.1 Schematic diagrams of the complete electrochemical systems of (a.) a MOSFET and (b.) an ISFET ........................................................................................................... 259
7.2 Schematic representation of SENTRON ISFET sensor used in experiments .................. 265
7.3 Injection chamber with a capacity of 6 ml ........................................................................ 266
7.4 The pH measurement process as a function of time for determination of sensor sensitivity and hysteresis ...................................................................................... 267
7.5 Calibration of the Al$_2$O$_3$-gate pH ISFET ...................................................................... 269
7.6 Drift characteristics of the Al$_2$O$_3$-gate ISFET tested in (a.) standard pH buffer pH 7, and (b.) lime-requirement buffer pH 7 ........................................................................... 270
7.7 A typical hysteresis curve .............................................................................................. 271
7.8 ISFET response time: static, stirred at 1000 rpm and injected at 3 ml s$^{-1}$ ................ 272
7.9 Continual pH measurements in standard pH buffers .................................................... 273
7.10 Continual pH measurements in (a.) 1:5 soil:0.01M CaCl$_2$ extracts and (b.) soil:lime requirement buffer extract ....................................................................................... 274
7.11 Continual response time curves of soil collected from the experimental field in (a.) 1:5 soil:0.01M CaCl$_2$ and (b.) soil:lime-requirement buffer extracts ................................ 276
7.12 Comparison between the continually measured (a.) pH$_{CaCl_2}$ and (b.) pH$_{buffer}$ values and pH measured using conventional methods ......................................................... 277
7.13 (a.) Average and (b.) range control charts for the continual soil pH measurements in soil:0.01M CaCl$_2$ extracts, using the ISFET sensor ..................................................... 278
7.14 (a.) Average and (b.) range control charts for the continual soil pH measurements in soil:lime-requirement buffer, using the ISFET sensor ........................................ 279
7.15 A simple flow injection analysis system manifold ........................................................ 280
7.16 A simple sequential injection analysis system manifold ............................................... 283
7.17 Analytical manifold for ‘on-the-go’ soil pH and lime requirement measurements .......... 285
7.18 (a.) pH measurements during the soil:0.01 M CaCl$_2$ reactions at various time intervals over a 30 minute period, and (b.) changes in pH during the first five minutes of the reactions, for eight different soil types ................................................................. 292

7.19 (a.) pH$_{buffer}$ measurements during the soil:lime-requirement buffer reactions at various time intervals over a 60 minute period, and (b.) changes in pH$_{buffer}$ during the reactions, for nine different soil types ................................................................. 293

7.20 First-order biphasic kinetic plots used to pH$_{buffer}$ reactions of all of the soils tested ...... 295

7.21 Plots of double exponential models used to describe the pH$_{buffer}$ reactions of all of the soils tested ................................................................. 297

7.22 pH$_{buffer}$ measurements against the log$_{10}$ of their corresponding reaction times .......... 302

7.23 Prediction of reaction equilibrium using only initial pH$_{buffer}$ values and according 0.5 s, 1 s, 2 s and 3 s measurements for sample S22 ................................................................. 304

7.24 Plot of (a.) predicted equilibrium pH$_{buffer}$ values versus actual equilibrium pH$_{buffer}$ values and (b.) plot of respective lime requirements ................................................................. 306

7.25 Flow chart for the optimal design and efficient development of an ‘on-the-go’ proximal soil pH and lime requirement sensing system prototype ................................................................. 307

7.26 Creative design of the ‘on-the-go’ proximal soil pH and lime requirement sensing system showing soil tilth implements, the sampling, analytical and sensing components of the system ................................................................. 308

7.27 The operating system for the ‘on-the-go’ proximal soil pH and lime requirement sensing system showing data inputs and outputs ................................................................. 310

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8.1 Variable-rate liming map ................................................................. 331

8.2 Soil sampling sites across the southwestern wheat-belt of NSW ................................................................. 333

8.3 Soil buffer (titration) curve for the Kelso field sample ................................................................. 334

8.4 Relationships between (a.) soil pH$_{CaCl_2}$, (b.) pH$_{H_2O}$ and lime requirement to a target pH of 6.5 ................................................................. 340

8.5 Relationships between (a.) exchangeable calcium, (b.) exchangeable aluminium and (c.) buffering capacity and lime requirement to a target pH of 6.5 ................................................................. 342

8.6 Soil titration curves showing the range in buffering capacities of the soils used in the incubation experiment ................................................................. 343

8.7 Relationships between soil pH$_{buffer}$ and lime requirements to attain a soil pH$_{CaCl_2}$ of 6.5 for (a.) the Shoemaker, McLean & Pratt (SMP) buffer; (b.) the Woodruff (WRF) buffer; (c.) the New Woodruff buffer (NWRF); and (d.) the Mehlich (MCH) lime-requirement buffers ................................................................. 345

8.8 (a.) The Woodruff (WRF) buffer single-factor response surface and (b.) WRF model fit ................................................................. 346

8.9 (a.) The Shoemaker, McLean & Pratt (SMP) buffer single-factor response surface and (b.) SMP model fit ................................................................. 347

8.10 (a.) The New Woodruff (NWRF) buffer single-factor response surface and (b.) NWRF model fit ................................................................. 348
8.11  (a.) The Mehlich buffer single-factor response surface and (b.) MCH model fit........... 349
8.12  Woodruff buffer two-factor (pH\text{buffer} and pH\text{CaCl}_2) response surface............. 351
8.13  Mehlich buffer two-factor (pH\text{buffer} and pH\text{CaCl}_2) response surface..................... 352
8.14  Block kriged (a.) Woodruff (WRF) pH\text{buffer} and (b.) lime requirement map to a target pH of 6.5................................................................. 359
8.15  Block kriged (a.) Mehlich (MCH) pH\text{buffer} and (b.) lime-requirement map to a target pH of 6.5................................................................. 361
8.16  Maps of (a.) exchangeable aluminium and (b.) exchangeable calcium......................... 363
8.17  Resultant pH\text{CaCl}_2 values if lime is applied uniformly across the field at a rate of 7.46 Mg/ha. .......................................................................................... 365

Chapter IX: A Glasshouse Liming Experiment

9.1  Field location and pH\text{CaCl}_2 values of soil samples used in the pot trial..................... 375
9.2  Relationships between (a.) pH\text{CaCl}_2 and lime requirement to a target pH\text{CaCl}_2 of 7.0 and (b.) pH\text{H}_2\text{O} and LR(7.0)........................................................................ 384
9.3  Relationships between (a.) pH\text{CaCl}_2 and exchangeable aluminium, and (b.) pH\text{CaCl}_2 and Al saturation of the CEC. (c.) and (d.) illustrate corresponding relationships between pH\text{H}_2\text{O} and Al................................. 387
9.4  Relationships between (a.) exchangeable aluminium and lime requirement to a target pH of 7 and (b.) aluminium saturation and LR(7.0)........................................................................ 388
9.5  Relationships between (a.) pH\text{CaCl}_2 and CEC, and (b.) aluminium saturation and CEC. 389
9.6  Relationships between (a.) pH\text{CaCl}_2 and exchangeable calcium and (b.) pH\text{CaCl}_2 and calcium saturation.................................................................................. 391
9.7  Relationships between (a.) aluminium saturation and exchangeable calcium and (b.) aluminium saturation and calcium saturation of the CEC ........................................... 392
9.8  Analysis of Variance between no lime application, single-rate liming and variable-rate liming ................................................................................................................. 393
9.9  Wheat yield as a function of (a.) pH\text{CaCl}_2 and (b.) pH\text{H}_2\text{O} .............................................. 395
9.10 Wheat yield as a function of (a.) exchangeable aluminium and (b.) aluminium saturation ....................................................................................................................... 397
9.11 Wheat yield as a function of (a.) calcium saturation and (b.) CEC.................................. 398

Chapter X: Geostatistical Assessment of the Production and Economic Risks of Site-Specific Lime Applications

10.1 Histogram of pH\text{buffer} and descriptive statistics ............................................................ 411
10.2 Flowchart of the assessment and propagation of uncertainty using indicator kriging and Latin Hypercube Sampling of probability distributions........................................... 414
10.3 Maps of (a.) the E-type estimates of pH\text{buffer} and (c.) its conditional variance and their respective distributions. Histograms and summary statistics of their distributions are shown in (b.) and (d.) respectively ......................................................... 415
10.4 (a.) response-surface of pH\textsubscript{$\text{CaCl}_2$} as a function of pH\textsubscript{buffer} and lime requirement and (b.) wheat yield as a function of soil pH\textsubscript{$\text{CaCl}_2$} ............................................................ 417
10.5 (a.) Map of pH\textsubscript{$\text{CaCl}_2$} estimates, (b.) histogram and descriptive statistics, (c.) map of wheat yield estimates, and (d.) histogram and descriptive statistics, for the no lime scenario .. 419
10.6 (a.) Map of pH\textsubscript{$\text{CaCl}_2$} estimates, (b.) histogram and descriptive statistics, (c.) map of wheat yield estimates, and (d.) histogram and descriptive statistics for the single-rate liming scenario ........................................................................................................ 421
10.7 (a.) Map of optimal variable-rate lime requirement and (b.) histogram showing descriptive statistics.................................................................................................................. 423
10.8 (a.) Map of pH\textsubscript{$\text{CaCl}_2$} estimates, (b.) histogram and descriptive statistics, (c.) map of wheat yield estimates, and (d.) histogram and descriptive statistics for the variable-rate liming scenario ........................................................................................................ 425
10.9 Maps of expected net profit and probability of making a profit respectively, for (a.) and (b.) no-lime application; (c.) and (d.) single-rate liming; (e.) and (f.) variable-rate liming ........................................................................................................ 429
10.10 (a.) Map of expected optimal variable-rate lime requirement and (b.) histogram with statistics.................................................................................................................. 431
10.11 (a.) Map of pH\textsubscript{$\text{CaCl}_2$} estimates, (b.) histogram and descriptive statistics, (c.) map of wheat yield estimates, and (d.) histogram and descriptive statistics for the variable-rate liming scenario ........................................................................................................ 433
10.12 Map of expected net profit for variable-rate liming .............................................................................. 435
10.13 Sensitivity analysis for the adoption of site-specific liming in the experimental field at Kelso, NSW ........................................................................................................ 437
# LIST OF TABLES

## Chapter I: Precision Agriculture: Convergence of Threads

1.1 Total land area and arable land area by continent ........................................ 18

## Chapter II: Quantifying Soil Spatial Variability and the Practice of Precision Agriculture: A Review of the Literature

2.1 Classical statistical descriptions of the spatial variability of soil pH ................. 45
2.2 Isotropic semi-variogram models and parameter values for soil pH ................... 56
2.3 Comparison of a sample data set (considered as reality) to estimation and simulation models .......................................................... 62
2.4 Yield monitoring systems and methods of operation for a variety of crops .......... 71
2.5 Provisional recommendations for spatial prediction methods to be used for precision agriculture with relation to sample size and intensity ............................................. 74
2.6 Examples of remote sensing techniques and their use ...................................... 89
2.7 Radiometric and spatial resolution characteristics of the Multispectral Scanner ........ 94
2.8 Radiometric and spatial resolution characteristics of the LANDSAT 5 Thematic Mapper and LANDSAT 7 Enhanced Thematic Mapper Plus sensors ....................... 94
2.9 Radiometric and spatial resolution characteristics of the SPOT sensors .............. 95
2.10 Potentially useful satellite-based sensors for precision agriculture .................... 96
2.11 Possible proximal soil sensing systems for various important properties .......... 99

## Chapter III: Description of the Experimental Field: Soil Sampling, Analysis and the Spatial Variability of Surface Soil Chemical Properties

3.1 Profile description: upper slope: Red Chromosol .............................................. 131
3.2 Profile description: lower slope: Brown Kurosol .............................................. 131
3.3 Surface soil chemical properties and recommended ranges for plant growth ........ 136
3.4 Surface soil physical properties ................................................................. 137
3.5 Description of the spatial variability of soil chemical properties in the experimental field .......................................................... 138

## Chapter IV: Precision Agriculture and its Implications for Soil Sampling and Analysis

4.1 Published analytical variances for soil chemical analyses ............................... 151
4.2 Comparative summary of variogram models, nugget variances and analytical variances for a number of soil chemical properties ...................................................... 154
4.3 Examples of sample spacing and analytical cost in Australia and the United States to perform kriging to a sufficient accuracy .......................................................... 156
4.4 Correlations between VERIS EC measurements and soil properties ...................... 173

Chapter V: Spatial Modelling and Mapping Methods for Sparsely Sampled Soil that Exhibits Spatial Drift

5.1 Models compared. Generalised additive model; quadratic trend surface; linear and quadratic local trend surfaces; global ordinary kriging with spherical, exponential, Gaussian, linear and power function semi-variograms; local ordinary kriging with both spherical and exponential semi-variograms; and intrinsic random function of orders 1 and 2 ................................................................................................................................. 190
5.2 Summary statistics for prediction and validation data sets ........................................ 198
5.3 Transitive and unbounded semi-variogram models and parameters fitted to the pH and OC data .................................................................................................................. 199
5.4 Spherical semi-variogram parameters used for kriging of the residuals resulting from the generalised additive models, quadratic trend surface, local linear trend surface, and local quadratic trend surface regression models, for both soil pH and OC ........................................ 201
5.5 Comparison of spatial prediction methods for soil pH ............................................. 202
5.6 Statistics of soil pH predictions derived from the best predictors from each of the groups tested ......................................................................................................................... 203
5.7 Comparison of spatial prediction methods for soil OC ............................................. 207
5.8 Statistics of soil organic carbon predictions derived from the best predictors from each of the groups tested ........................................................... 208

Chapter VI: Soil Acidity and Acidification: A Prospective Management System for Acid Soil

6.1 Equivalent amounts of lime (CaCO$_3$) required to replace the alkali removed in farm produce of north-eastern Victoria, Australia ......................................................... 224
6.2 Rates of soil acidification expected from various forms of nitrogenous fertilisers .... 225
6.3 World acid soils by land use by main region .................................................................. 237
6.4 Extent of acid agricultural soils in Australia with pH$_{CaCl_2}$ values < 4.8 ............... 239

Chapter VII: Development of an ‘On-the-Go’ Proximal Soil pH and Lime Requirement Sensing System

7.1 Characteristics and properties of the four sensors evaluated, namely a glass electrode, a glass microelectrode, an antimony electrode and an ISFET ........................................ 254
7.2 Accuracy and precision of pH measurements in standard buffer, soil:0.01M CaCl$_2$, soil: H$_2$O and soil:lime-requirement buffer extracts, using the four potentiometric sensors ......................................................................................................................... 255
List of Tables

7.3 Response-times in standard buffer, soil:0.01M CaCl$_2$, soil:H$_2$O and soil:lime-requirement buffer extracts, using four potentiometric sensors ................................................................. 256
7.4 Reported characteristics of inorganic membrane materials used in pH ISFETs .......... 261
7.5 Reported time responses of common inorganic membrane materials used in pH ISFETs ................................................................................................................................. 264
7.6 Flow Injection Analysis system application to soil analysis........................................ 283
7.7 Descriptive statistics of pH in 0.01M-CaCl$_2$ (pH$_{CaCl_2}$), pH in lime-requirement buffer, OC, CEC, clay content and lime requirement for the nine soil samples used in the experiments ................................................................................................................................. 290
7.8 Apparent rate coefficients $k_{\text{fast}}$ and $k_{\text{slow}}$ for the pH$_{\text{buffer}}$ reactions whose first-order kinetic plots are shown in Figure 7.20.......................... 296
7.9 Apparent exponential model parameters and rate coefficients $k_{(1)\text{fast}}$ and $k_{(2)\text{slow}}$ for the pH$_{\text{buffer}}$ reactions shown in Figure 7.21................................................................. 298
7.10 Linear regressions fitted to the linear portions of the graphs in Figure 7.22 and respective $R^2$ values......................................................................................... 303
7.11 Linear regressions fitted to the first four initial pH$_{\text{buffer}}$ points of all each of the nine soils and their $R^2$......................................................................................... 305


8.1 Literature review of methodologies used to determine the lime requirement of soil...... 328
8.2 Soil property statistics for soils used in incubation............................................................... 339
8.3 Correlation matrix for incubation lime requirements and soil properties................. 341
8.4 Lime requirement regressions to attain target pH values of 5.5, 6 and 7.................... 344
8.5 Comparison between incubation lime requirements and model-based predictions of lime requirements to target pH values of 5.5, 6, 6.5 and 7 ........................................ 354
8.6 Statistical description of the Woodruff and Mehlich pH$_{\text{buffer}}$ data, corresponding lime requirements to target pH 6.5 and 95 % confidence intervals data for the soil in the field at Kelso ............................................................... 355
8.7 Semi-variogram models and parameters for the Woodruff and Mehlich pH$_{\text{buffer}}$ values, and corresponding lime requirement estimates to a target pH of 6.5.................... 356
8.8 Descriptive statistics of the kriged Woodruff and Mehlich pH$_{\text{buffer}}$ and lime requirement to target pH of 6.5 data, exchangeable calcium and exchangeable aluminium .............. 357

Chapter IX: A Glasshouse Liming Experiment

9.1 Pot trial design consisting of three treatments, no-lime, single-rate lime and variable-rate lime applications..................................................................................................... 376
9.2 Recommended rates of fertiliser application ........................................................................ 377
9.3 Factors used to determine the amount of soil and lime to use in the pot trial ............ 380
9.4 Soil chemical property description prior to the application of treatments .................. 381
9.5 Soil nutrient status post-fertilisation (and pre-liming) for the pots in each of the three treatment groups .......................................................................................................................................................... 382
9.6 Descriptive statistics for soil properties in each of the three treatment groups after the application of lime ...................................................................................................................................................... 382
9.7 Cation saturation of the CEC after no lime applications, single-rate liming and variable-rate liming ......................................................................................................................................................... 383
9.8 Correlations between soil properties for the soils used in the experiment .................................................................................................................................................................................. 385
9.9 Wheat yield comparisons between the three treatments ............................................................................................................................................................................................ 394

Chapter X: Geostatistical Assessment of the Production and Economic Risks of Site-Specific Lime Applications

10.1 Sensitivity analysis for the adoption of site-specific liming ................................................................................................................................................................................................. 437
Conceptual Basis of the Research and Aims
CONCEPTUAL BASIS OF THE RESEARCH AND AIMS

CONCEPTUAL BASIS

This work describes research towards the development of an ‘on-the-go’ proximal soil pH and lime requirement sensing system, and the methodology required to manage acid soil using a real-time continuous precision agriculture (PA) management system.

Soil acidity is quantified in terms of pH. Soil pH is a most informative soil property that is frequently measured because it is also a good indicator of soil quality. The management of acid soil is important in crop and pasture systems because its incidence is not only detrimental to plant growth and agricultural production, it also has socio-economic implications and may affect human health e.g. through the increased concentration of aluminium in water supplies. Soil acidity is a form of land degradation that affects approximately 33 Mha of agricultural land in Australia, and approximately 900 Mha worldwide. Its management is important.

LAND DEGRADATION IN AUSTRALIAN AGRICULTURE

Over the past two decades there has been increased awareness of environmental issues associated with conventional agriculture. The issues of greatest concern pertain to the environmental impact of agricultural systems and the degradation of agricultural land, particularly soil, water and vegetation resources. Such environmental degradation, and the reduced productivity from degraded land, is testimony to the inadequacy and inefficiency of conventional production systems that may have once been thought to be sustainable.

Land degradation may be defined as any natural or anthropogenic factor or combination of factors that disrupt the chemical, physical and biological balances of an agro-ecosystem, and which restrict its use and productive capacity. Soil degradation is a principal component of land degradation because it adversely changes the pedosphere. Soil degradation in Australian agriculture pertains to the deterioration of soil chemical, physical and biological properties. For example, soil chemical degradation resulting from the depletion of carbon and nitrogen sources in the soil, as well as the widespread soil acidification and salinisation that occurs in many productive regions of Australia. The
deterioration of soil physical condition has caused reduced infiltration, higher incidence of compaction and/or the formation of a hard-setting layer throughout the cultivated horizons. A decline in structural stability has resulted in increased runoff and erodibility of Australian soil. Soil biological degradation has reduced the capability of the soil to cycle nutrients. The build-up of chemical residues in soil may be a consequence of the reduced biology that is required to decompose and cycle the increased amounts of residues generated by conventional agricultural management. Cultivation and fallow systems reduce faunal and microbial populations, indicating a decline in soil quality.

The notion that agriculturally productive land may be treated as a relatively homogeneous resource at the within-field scale is a common factor of these problems. This assumption and the subsequent uniform application of planting material, chemicals and/or tillage effort may result in zones within a field being under- or over-treated. Arising from these are problems associated with the inefficient use of input resources, economically significant yield losses, excessive chemical costs, gaseous or percolatory release of chemicals, unacceptable long-term retention of chemicals and a less than optimum growing environment. The environmental impact of crop production systems is substantial.

In this millennium, three important issues for scientists and agrarian communities to address are the need to efficiently manage agricultural land for sustainable production, the maintenance of soil and water resources and the environmental quality of agricultural land.

**MANAGING ACID SOIL**

Liming is the most rapid and effective method used to manage acid agricultural soil. Currently in Australia, agronomic management of acid soil by liming consists of low single-rate lime (CaCO$_3$) applications over an entire area of management – generally this area is contained within field boundaries regardless of size. Recommendations are based on either conjectural evidence, or only one and sometimes a few discrete observations that are averaged to derive the application rate.

Inevitably such single-rate applications of lime result in some areas of the field where the resource has been over-applied and other areas where under-applications have occurred. Intuitively the consequences of such actions are agronomically and economically unsound. Excessive applications of lime are uneconomical and may affect crop growth by inhibiting the availability of certain plant macro- and micronutrients. Conversely when
Conceptual Basis of the Research and Aims

Lime is insufficiently applied amelioration is not accomplished and the availability of nutrients such as manganese and elements like aluminium may reach toxic levels, then affecting physiological processes in the growing crop.

The inadequacies of conventional whole-field management systems arise from the fact that soil is an inherently variable medium. Precision agriculture and site-specific liming are offered as more efficient alternatives to uniform agronomic methods of acid soil management, particularly now that much of the technology is readily available to producers.

**Precision Agriculture**

Precision agriculture refers to the application of information technologies to agriculture. It is an agricultural management system that aims to identify soil and crop attribute variability, and manage it accordingly in an accurate and timely manner for near-optimal crop production. Unlike conventional agricultural management where an averaged whole-field analytical result is employed for decision-making, management in PA is based on site-specific soil and crop information. That is, resource application and agronomic practices are matched with variation in soil attributes and crop requirements across the field or management unit.

Conceptually PA makes economic and environmental sense, optimising gross margins and minimising the environmental impact of crop production systems. Although the economic justification for PA can be readily calculated, concepts such as environmental containment and the safety of agrochemicals in soil are more difficult to estimate. Nevertheless, it may be argued that if PA lessens the overall agrochemical load in agricultural and non-agricultural environments, then its value as a management system for agriculture increases substantially.

Presently, a PA management system requires collection and spatial referencing (using the Global Positioning System (GPS)) of environmental parameters such as soil and crop attribute information, databasing, spatial data analysis and mapping in a Geographical Information System (GIS), modelling and decision making in a spatial decision support system (SDSS), followed by the implementation of optimal and timely management (Figure 1). The implementation and outcome of management may then be recorded and used as input in a new cycle the following season.
The PA management system (Figure 1) may be used to devise agronomically sensible management strategies which, depending on the degree of variability present in the field, crop response models, uncertainty models and economic models, etc. may be either uniform or differential. The ultimate objective of PA is to carry out all four phases in a single pass over the field ‘on-the-go’ and in real-time. This type of management system is referred to as continuous. However the four phases of the cycle are at different stages of development and real-time continuous operation is not yet possible. Thus the PA system must be applied and implemented using the GPS for spatial positioning during the data collection and management phases. Research is needed to device more efficient methods of data collection, and to develop SDSSs for continuous PA management.

**Data Collection for Precision Agriculture**

Data acquisition for PA involves more intensive sampling (i.e. at much higher resolutions) than that needed for conventional management. Routine soil maps, especially those at 1:100 000 readily available in Australia, are clearly inadequate for this purpose. Interim approaches between uniform and continuous site-specific management are currently being used.

A technique employed by users of PA combines grid or random sampling with digital elevation models and various other environmental data, and use geostatistics to
interpolate. The production of accurate soil property maps then relies upon choosing a suitable grid resolution, quantitative soil analysis, and an appropriate spatial modelling and mapping technique. The size of the grid depends on the variable of concern and the trade-off between accuracy and cost. The production of accurate soil maps using an appropriate grid resolution is often laborious, time-consuming and much too costly for farmers to adopt. Conversely, if the resolution of the grid is too large, costs may be lowered but the loss of information results in inaccurate maps.

Zone or patch management techniques have been developed, whereby fields are stratified into smaller zones for sampling and management, based on the variability of exhaustive ancillary data sets such as yield, elevation, etc. Fuzzy clustering algorithms have also been used to divide fields into smaller management units.

Although these approaches may reduce the number of samples to collect, soil sampling and analysis is still much too laborious and expensive for the majority of Australian farmers since large areas are often involved. The development of ‘on-the-go’ proximal soil sensing systems that are timely, reduce the labour and lower the expense of soil sampling and analysis are imperative.

**ADVANTAGES OF ‘ON-THE-GO’ PROXIMAL SENSING SYSTEMS**

The implementation of PA at the farm or field level requires amongst other factors, the development of ‘on-the-go’ proximal sensing systems to collect the large amounts of soil information needed for management, with minimal labour, cost and effort. Research towards the development of ‘on-the-go’ proximal sensing systems to quantify soil variability and produce the information required for site-specific management in real-time is particularly important for the wide-scale adoption of PA.

The perceived advantages of such soil sensing systems are:

i. Elimination of costly and tedious sampling and analysis

ii. Efficient acquisition of fine spatial resolution continuous or continual data

iii. Real-time availability of results and the possibility for their integration with other field operations, e.g. variable-rate resource applications

iv. Minimal sample handling, i.e. no need for transport and storage

v. Elimination of laboratory induced variability
vi. Little expertise needed to operate the system after initial set-up.

AIMS OF THE RESEARCH

The conceptual basis of this work may be elucidated from the previous discussion. Its aims are as follows:

1. Describe the factors that converged in the development of precision agriculture

2. Provide a thorough literature review on topics that are relevant to the concept of precision agriculture and techniques used for the quantification of soil spatial variability, and the acquisition of soil data

3. Describe the geography, land use, vegetation and soil of the experimental site, with particular attention to the spatial variability of soil properties. Also describe the sampling strategy employed

4. Discuss the implications that precision agriculture has on current methods of soil sampling and analysis, and compare how sampling intensity affects map production

5. Compare various statistical and geostatistical methods for the analysis and mapping of non-stationary soil data

6. Review soil acidity and acidification and describe the components of a real-time continuous management system for acid soil

7. Conduct research towards the development of an ‘on-the-go’ proximal soil pH and lime requirement sensing system by:
   
   i. Evaluating the suitability of four potentiometric pH sensors for ‘on-the-go’ acquisition of soil pH and lime requirement information,
   
   ii. Investigating and assessing the electrochemical characteristics of a pH ion-sensitive field-effect transistor (ISFET) for its use as the sensor component in the proximal sensing system
   
   iii. Designing the analytical apparatus of the sensing system for ‘on-the-go’ field operation
   
   iv. Conducting kinetic experiments to describe the soil:0.01M CaCl$_2$ pH (pH$_{CaCl_2}$) and soil:lime-requirement buffer pH (pH$_{buffer}$) reactions, and devise a statistical
methodology that may be used to predict equilibrium pH measurements at shorter
time intervals than those suggested in the literature

v. Outlining the framework for the development of the sensing system

vi. Proposing the creative design of the ‘on-the-go’ proximal soil pH and lime
requirement sensing system which includes the design for an ‘on-the-go’ soil
sampling mechanism, and the data processing system to be used.

8. Derive a lime requirement calibration model using various soil types from
southeastern New South Wales, that may be incorporated into the spatial decision
support of a real-time continuous management system for acid soil. The model
should be flexible and allow the use of data from the sensing system for real-time
predictions of lime requirement

9. Conduct a glasshouse experiment to verify the use of the model derived in aim 8 and
the rationale behind site-specific liming management

10. Assess the production and economic risks of liming using geostatistical uncertainty
modelling

Each of the following ten chapters, in turn, addresses the aforementioned aims. Each
chapter also encompasses topical conclusions. A general concluding statement with
suggestions for future work is given at the end.