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

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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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ABSTRACT

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 $CaCl_2$ pH (pH_{CaCl2}) and soil:lime requirement buffer (pH_{buffer}) reactions. Modelling of the pH_{buffer} reactions described their sequential, biphasic nature. A statistical methodology was devised to predict pH_{buffer} measurements using only initial reaction measurements at 0.5s, 1s, 2s and 3s measurements. The accuracy of the technique was 0.1 pH_{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_{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.

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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 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.

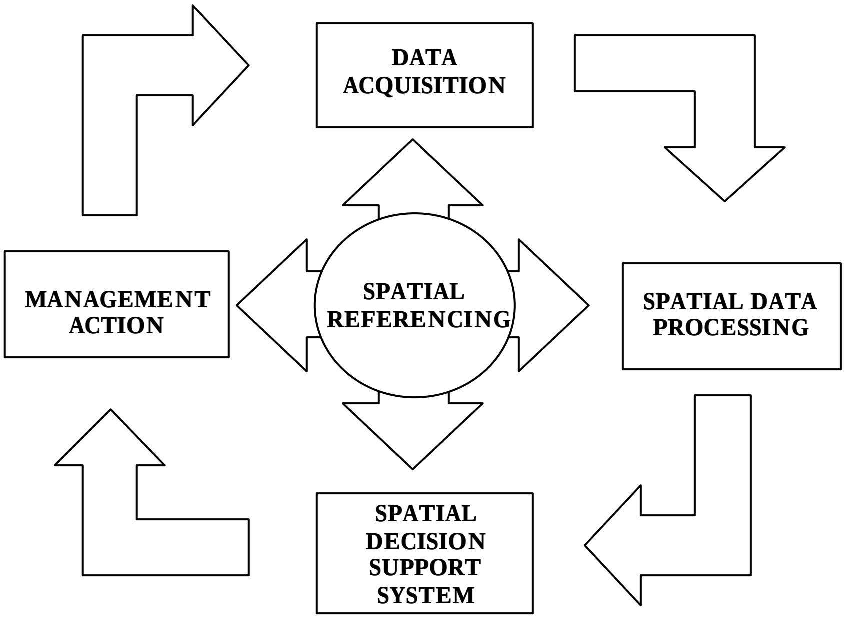

Figure 1 A continuous real-time precision agriculture (PA) management system

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.