Development of an On-The-Go Soil Sensing System for Determinations of Soil pH and Lime Requirement

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ABSTRACT

This work describes the development of an on-the-go soil pH and lime requirement sensing system prototype and methodology implemented to determine soil pH and estimate the lime requirement of acid soil in real-time. The soil pH and lime requirement sensing system is made up of: (a.) a soil sampling and sieving mechanism, (b.) a soil analytical and sensing component, (c.) data collection and measurement algorithms. The sensing system is controlled and automated using a control I/O system and custom designed software. This paper details the soil analytical and sensing component and the methodologies used for determinations of soil pH and estimations of lime requirement. It only briefly describes aspects of its technological development.

INTRODUCTION

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 on 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. Liming acid soil has been suggested as the best method to attain and maintain a suitable pH for the growth of a variety of crops (e.g. Coventry et al., 1997). The lime requirement of acid soil is defined as the amount of $CaCO_3$ needed to raise the pH of the top 200 mm of the profile from an initial acid state to a pre-determined higher pH for near-optimal crop growth. Viscarra Rossel & McBratney (2000) suggested site-specific liming as more efficient than conventional 'blanket' applications and described a calibration model that may be used as part of the decision support tool of an 'on-the-go' soil pH and lime requirement sensing system. This work describes the development of one such sensing system and methodology that may be implemented 'on-the-go' to determine soil pH and the lime requirement of acid soil.

Research towards the development of mobile, 'on-the-go' sensing systems to quantify the spatial variability of various soil properties is ongoing worldwide. Their primary aim is to allow the collection of soil information at much finer spatial resolutions than those possible using discrete sampling procedures. The information collected by the sensors may then be more aptly used for site-specific crop management. 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 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. Some that are currently commercially available include a spectrometric soil organic matter sensor (Shonk et al., 1991), a soil electrical conductivity (EC) sensing system called the Soil Doctor® (Colburn Jr., 1998), the VERIS 3100 (Lund et al., 1999), the Mobile Electromagnetic Induction Sensing System (MESS) (Triantafilis & McBratney, 1998) and a soil pH sensing system (Adamchuk et al. 1999).

The soil pH and lime requirement sensing system described in this paper is made up of: (a.) a soil sampling and sieving mechanism, (b.) a soil analytical and sensing component, (c.) data collection and measurement algorithms. The sensing system is controlled and automated using a control I/O system and custom designed software. The aim of this paper is to describe the soil analytical and sensing components and the techniques used for determinations of soil pH and estimations of lime requirement. The technological development of the sensing system is described in detail by Thylén et al. (2004).

METHODS

The soil analytical and sensing component

The soil analytical system comprises a batch-type mixing chamber with two inlets for: (i) chemical solution (lime requirement buffer/ 0.01M $CaCl_2$) and (ii) water. Two pumps are used to pump solution into the chamber. The chemicals are pumped into the system using a peristaltic pump at about 6 ml/second. For cleaning water is pumped with a windshield washer pump with a capacity of 25ml/s. The mixing chamber, adapted from a coffee machine, uses a pinch valve to control the waste outlet. Within the mixing chamber there is a flat spinning disc ensuring efficient mixing of the chemical and the soil. A pH Ion Sensitive Field Effect Transistor (ISFET) is used for sensing. For specific details refer to Thylén et al. (2004). The pH ISFET was calibrated using standard pH buffer solutions at pH 4 and 7. The sensitivity of the ISFET was calculated from a linear regression fitted to the measured pH values of the buffer solutions. The sensitivity of the pH ISFET is 59.2 mV pH^{-1}, which is very much the same as ideal Nernstian sensitivity of glass electrodes. The range of the pH sensor extends from pH 0 to 14 and its precision is 0.001 pH units. Its response time ranges from less than 0.5 s to 2 s and hysteresis and drift have been reported to be low (Viscarra Rossel & McBratney, 1997).

Measurements of soil pH in 0.01M $CaCl_2$ (pH_{Ca})

The kinetics of soil pH_{Ca} reactions were characterised in the laboratory using 91 soil samples from around Australia. The experiments involved placing 3 g of sieved soil together with 15 ml of 0.01 M $CaCl_2$ solution into the mixing chamber of the analytical and sensing component. A calibrated pH ISFET connected to an A/D converter and data logging software were used to quantify changes in pH (at 10 Hz) from the initial contact between soil and solution, the progression of the reactions up to 60 s reaction time. From these data we are able to suggested suitable times for rapid field measurements based on the expected accuracy (calculated using the root mean square error (RMSE) and R^2 value) of soil pH measurements at various times during the chemical reactions.

We run the sensing system using 0.01M $CaCl_2$ on a 20 ha field in Uppsala, Sweden. pH_{Ca} measurements were made at a speed of about 2.5 m/s on 24 metres tramlines and approximately 40 m between measurements. This gives a capacity of 20 ha/h. In subsequent testing we will reduce the measurement time to less than 10 s.

Estimates of soil Mehlich buffer pH (pH_{buffer}) and lime requirement

The kinetics of soil Mehlich (Mehlich, 1976) lime requirement buffer pH (pH_{buffer}) reactions were characterised for ninety-one soil samples from around Australia. This involved placing 3 g of sieved soil together with 6 ml of a 1:1 mixture of Mehlich buffer solution and deionised water into the mixing chamber of the sensing system. As before a calibrated pH ISFET was used to quantify changes in pH. On average these reactions reached equilibrium at 12 minutes (Viscarra Rossel & McBrratney, 2003) and were characterised using triphasic exponential models, which accurately described the ion exchange reactions. Based on these data, a non-linear fitting algorithm was derived for the estimation of equilibrium pH_{buffer} at much shorter times, suitable for 'on-the-go' operation. The methodology uses pH_{buffer} measurements of the initial portion of the reactions to estimate equilibrium values.

Experiments were conducted in the laboratory to ascertain a suitable time for on-the-go field determinations of pH_{buffer} equilibrium. Once these values are estimated, they are then used in a response-surface regression model for predictions of lime requirement to a desired target pH_{Ca} value. The statistical methodology for this was proposed by Viscarra Rossel & McBratney (2000, 2001). In this instance the LR model is based on fifty-seven soil-$CaCO_3$ incubations. Both algorithms for estimating pH_{buffer} and subsequently lime requirement were implemented in Labview (National Instruments).

We analysed eighty widely varying Australian soils using the analytical and sensing component of the sensing system three times to test the reproducibility of results. Data was logged up to a reaction time of 30 s and we compared pH_{buffer} estimates at various times (i.e. < 30 s) to determine a suitable time for field measurements. Their respective lime requirements were also compared. We performed similar experiments using eighty-four soil samples from a 17 ha agricultural field in NSW, Australia. Maps of laboratory measured lime requirements and estimated lime requirements were drawn up for comparison.

We were unable to run the sensing system with Mehlich buffer in the field before the due date for the submission of this paper. As this is an on-going- project, we plan to do so in the following months.

RESULTS

The 'on-the-go' soil pH and lime requirement sensing system prototype is shown in Figure 1a, while Figure 1b shows it mounted on a tractor. Soil is collected continuously using a waved disc with a working depth of 20 cm (Figure 2a), sieved to a size fraction < 2mm and approximately 2 cm^3 of this sieved soil is measured and passed on to the soil analytical and sensing component for measurement and estimation of soil pH and lime requirement.

a. b.

Figure 1. (a.) The ‘on-the-go’ soil pH and lime requirement sensing system prototype: (i.) the waved soil sampling disc, (ii.) the soil transport tube, (iii.) the rotating sieve (iv.) the analytical and sensing component, and (v.) the controller box. (b.) the sensing system mounted on a tractor. The engineering development of the system is described in detail by Thylén et al. (2004).

The soil analytical and sensing component

The analytical and sensing component of the system is shown in Figure 2b.

a. b.

Figure 2. (a.) The waved sampling disc during field testing (b.) the soil analytical and sensing component consists of a mixing chamber, inlets for chemical solutions and water, a pH ISFET sensor and a spinning disc for mixing. Sieved soil is brought into the mixing chamber via a soil measuring unit. The waste outlet from the mixing chamber is controlled using a pinch valve.

An example of the data for determination of pH_{Ca} is shown in Figure 3a and that for estimating equilibrium pH_{buffer} in Figure 3b.

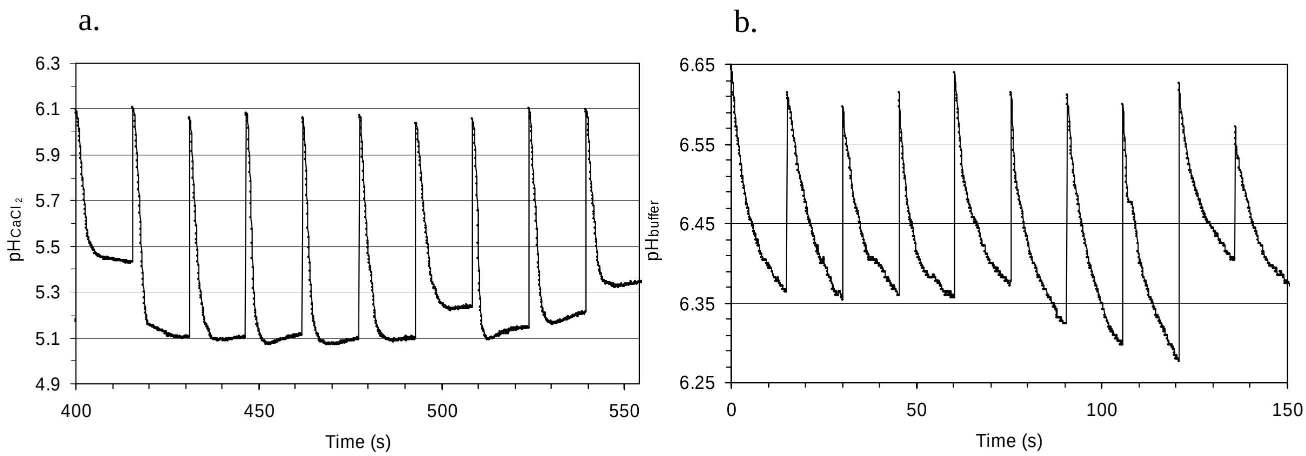


Figure 3. Examples of the data collected by the sensing system and used for determinations of (a.) soil pH_{Ca} and estimation of (b.) equilibrium soil pH_{buffer}. Signals shown for 15 s reaction times. Signal for pH_{Ca} measurements acquired during field testing while for pH_{buffer} during laboratory testing

Measurements of soil pH in 0.01M $CaCl_2$ (pH_{Ca})

Viscarra Rossel & Walter (2004) described the kinetics of soil pH reactions in both water and 0.01M $CaCl_2$, indicating that on average, 90 % of the pH reactions occur approximately within the first couple of minutes of the reaction. Figure 4 shows a plot of the RMSE and R^2 values of the pH_{Ca} determinations at various times up to a reaction time of 60 s. For example, the figure shows that 10 s sensing of pH_{Ca} will on average produce measurements with a RMSE of 0.2 pH_{Ca} units with an R^2 of 0.66. These results are similar to those by Viscarra Rossel & Walter (2003).

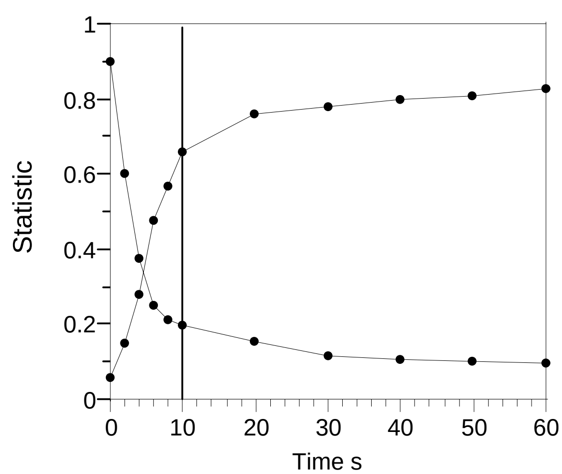
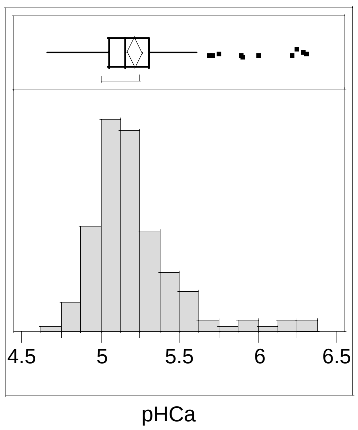


Figure 4. Root mean square error and R^2 values of soil pH_{Ca} measurements at various times during the soil pH reactions

The sensing system was tested in the field for 10 s determinations of pH_{Ca}. The distribution of the data is shown in Figure 5. The distribution of the sensed data is fairly typical of soil pH_{Ca}. The data is slightly skewed and appears to have a few outliers. The average pH of the field is 5.2 pH_{Ca} units with a standard deviation of 0.3 and a coefficient of variation of 5.6 % (Figure 5).



Quantiles		
100.0%	maximum	6.31
99.5%		6.31
97.5%		6.23
90.0%		5.58
75.0%	quartile	5.30
50.0%	median	5.16
25.0%	quartile	5.05
10.0%		4.93
2.5%		4.81
0.5%		4.68
0.0%	minimum	4.68

Moments	
Mean	5.22
Std Dev	0.29
Std Err Mean	0.02
upper 95% Mean	5.26
lower 95% Mean	5.17
N	138.00
Sum Wgt	138.00
Sum	719.80
Variance	0.08
Skewness	1.65
Kurtosis	3.65
CV	5.58
N Missing	0.00

Figure 5. Distribution and descriptive statistics of field sensed soil pH_{Ca} data

A classed plot of the 130 sensed field pH_{Ca} data is shown in Figure 6.

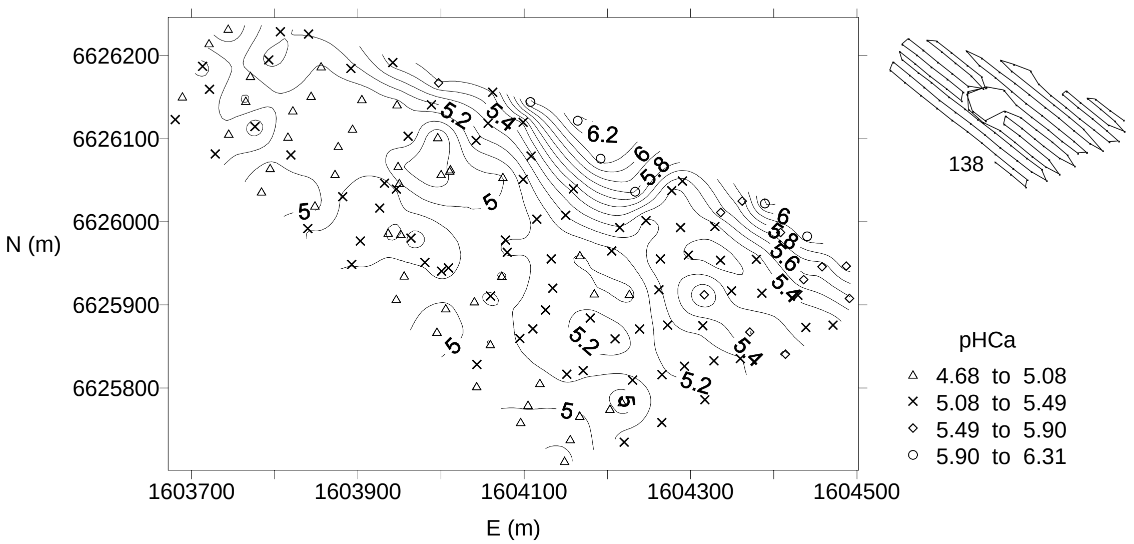


Figure 6. Classed plot map of soil pH_{Ca} data collected using the sensing system overlaid with its kriged contours

The map (Figure 6) is spatially structured with higher pH_{Ca} values in the north-eastern portion of the field and lower values in the north-western portion of the field. pH_{Ca} ranged from 6.3 to 4.7 units, respectively.

Measurements of soil Mehlich buffer pH (pH_{buffer}) and lime requirement

Determinations of lime requirement involve modelling the kinetics of the lime requirement buffer reactions to estimate reaction equilibrium times. For example, Figure 7a shows the kinetics of Mehlich lime requirement buffer reactions for five soils. By fitting triphasic exponential models to the initial portions of each of these curves we were able to estimate equilibrium pH_{buffer} values. These estimates are then inputted into a lime requirement model (Figure 7b) for predictions of lime requirement.

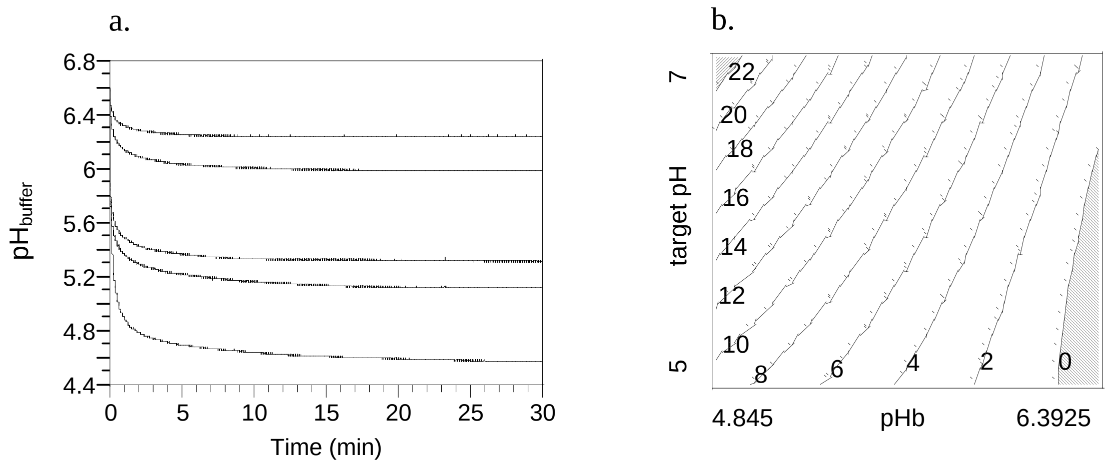


Figure 7. (a.) Example of soil pH_{buffer} kinetics for five different soils. Measurements in the Mehlich lime requirement buffer solution (b.) response-surface regression model for estimation of lime requirements

Figure 8a shows a plot of the RMSE and R^2 values of the pH_{buffer} estimates at various times up to a reaction time of 30 s for the eighty widely varying Australian soils. It shows that no significant improvements in estimation accuracy are gained after 15 s reaction time.

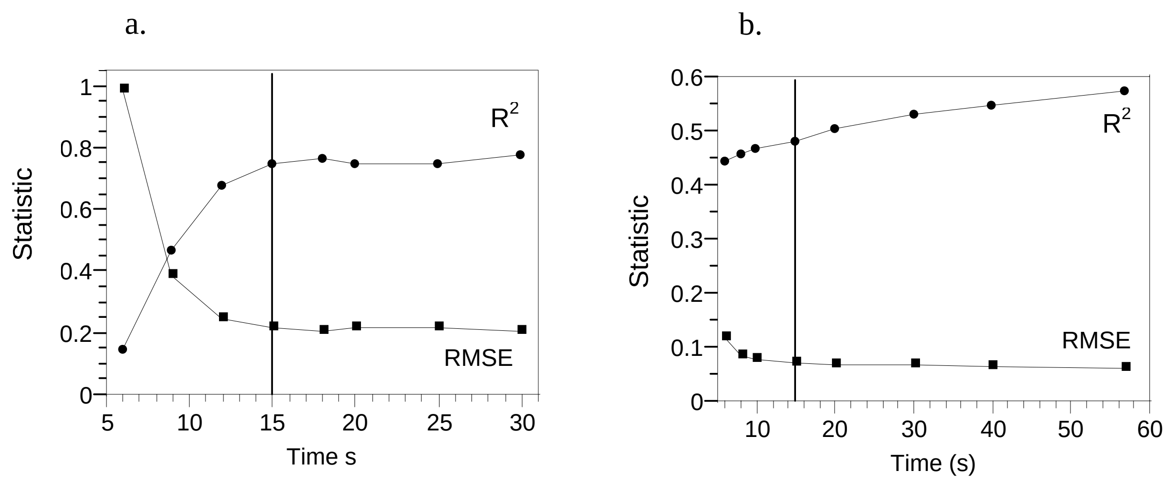


Figure 8. a. Expected worst-case scenario accuracy of 15 s pH_{buffer} estimates for a wide range of soils from Australia and (b.) accuracy of 15 s pH_{buffer} estimates for soil from a single field

Fifteen second estimates of pH_{buffer} for the eighty widely varying Australian soils and their corresponding estimates of lime requirement are shown in Figure 9a and 9b, respectively.

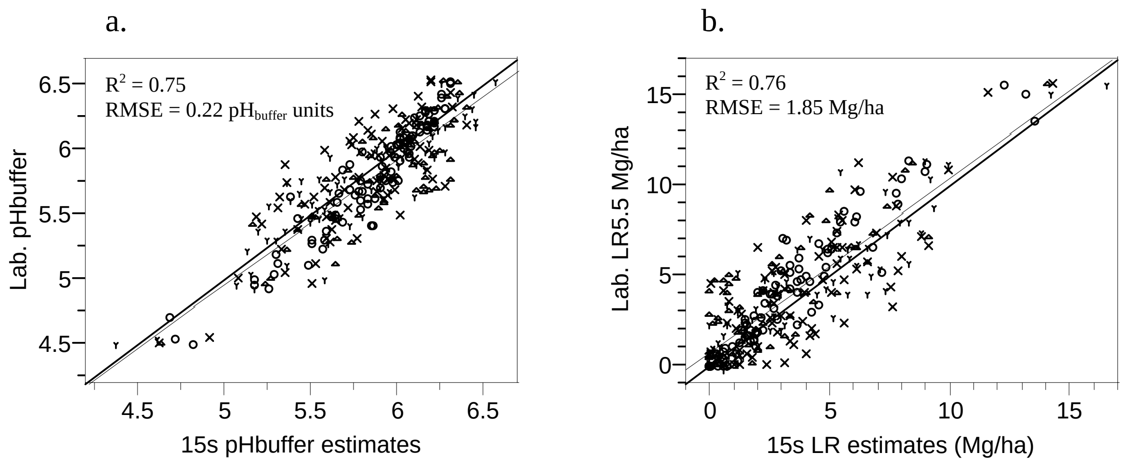


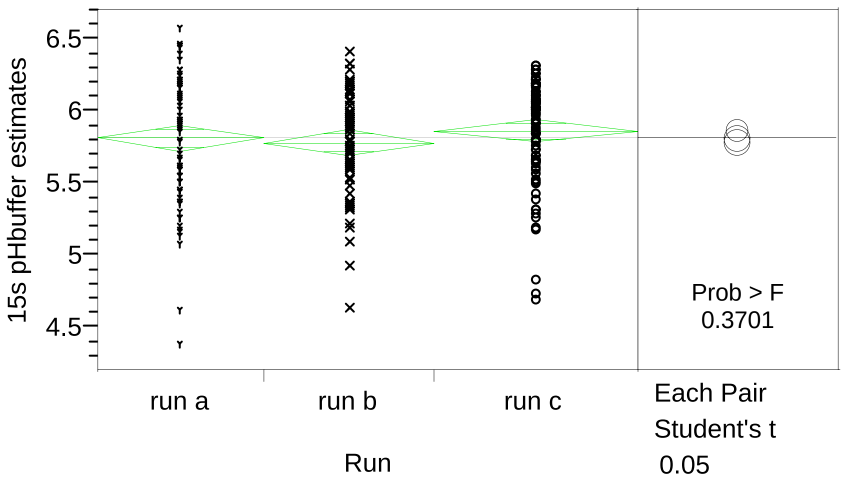
Figure 9. Comparison between laboratory measured and estimated (a.) 15 s pH_{buffer} measurements and (b.) respective lime requirement estimates for eighty Australian soils with widely varying properties. Measurements were replicated three times as shown by the different markers

The 15 s estimates of pH_{buffer} and lime requirement are predominantly unbiased and the range of the data was correctly estimated, however estimates they are somewhat imprecise (Figure 9). Although an accuracy (RMSE) of 1.85 Mg/ha (Figure 9b) may at first appear to be unacceptably low, we need to reflect on the fact that these soils originate from a wide geographic extent, were formed on very different parent materials, possess widely varying soil properties (Table 1) and show a very wide range of pH_{buffer} and lime requirement values. The sensing system will mostly be used on single fields within farms, where the soil will not be as variable and where the range of lime requirements should not be as wide as that shown on Table 1. Thus the data in Figure 9 may be said to represent a very worst-case scenario.

Table 1. Descriptive statistics of eighty Australian soils taken from every state, except the Northern Territory

	Mean	St. Dev.	Range
pH_{Ca}	4.74	0.74	3.60 – 6.65
pH_{buffer}	5.84	0.37	4.84 – 6.48
Buffering capacity Mg $CaCO_3$/20 cm soil/unit pH	5.25	4.34	1.14 – 23.10
Organic carbon dag/ kg	1.66	0.98	0.1 – 4.40
Clay dag/kg	20.08	10.81	6.27 – 52.43
Silt dag/kg	19.35	13.95	0.09 – 50.74
Sand dag/kg	48.83	30.01	7.20 – 92.56

The reproducibility of the results is shown in Figure 10. It shows that there were no statistically significant differences ($\alpha = 0.05$) between the 15 s estimates of each run.



Ordered differences between:		
run c	run b	0.083
run c	run a	0.050
run a	run b	0.033

Figure 10. Comparison between three replicate runs of the analytical and sensing component showing the reproducibility of the estimates using eighty Australian soils. There were no significant differences between the estimates of each run. Differences between the three runs are shown on the right part of the Figure.

As this is an on-going project, we were not yet able to run the sensing system in the field with the lime requirement buffer solution. However, we did perform further laboratory testing of the analytical and sensing component and estimation algorithms using soil from a single field. These results are shown in Figure 11. The coefficients of determination values for the estimates are not high ($R^2 = 0.49$); however their RMSEs are of acceptable magnitude (0.07 pH_{buffer} units and 0.6 Mg of lime per hectare) (Figure 11), particularly when considering the inefficiency of conventional lime applications (e.g. Evans et al., 1997). The distributions of estimation errors for pH_{buffer} and lime requirement are also shown in Figure 11. On average, the 15 s estimates of pH_{buffer} and lime requirement for soil from a single field were underestimated by 0.013 pH_{buffer} units and 0.13 Mg/ha, respectively (Figure 11). These results represent an average scenario where soil from a single field was analysed. We expect that these results will improve during field runs where samples will be taken continually and at shorter spatial intervals. Our hypothesis is that soils that are close to each other are more similar than those further apart and their spatial variation abides by some structure thus assisting our estimates of equilibrium pH_{buffer} and lime requirement when field soil is analysed on-the-go.

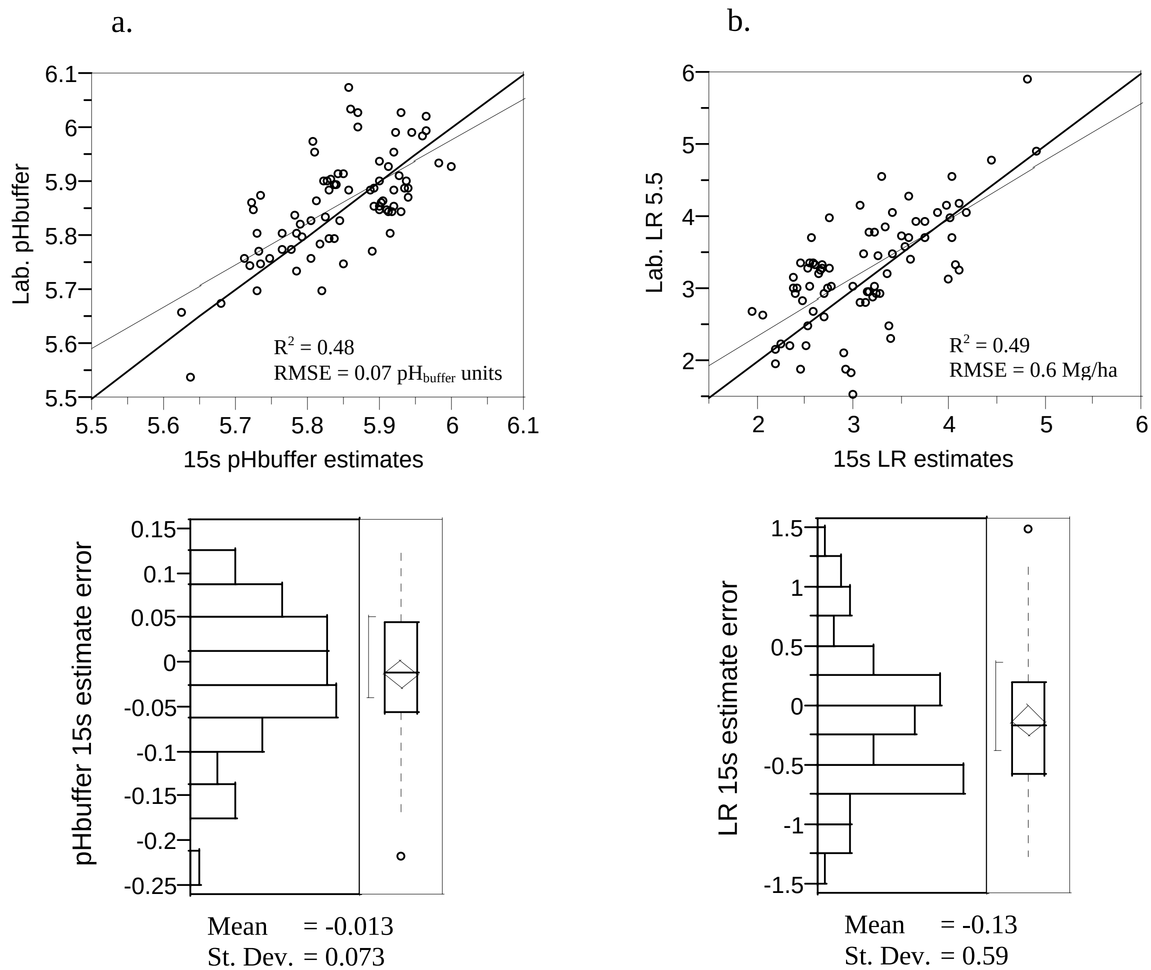
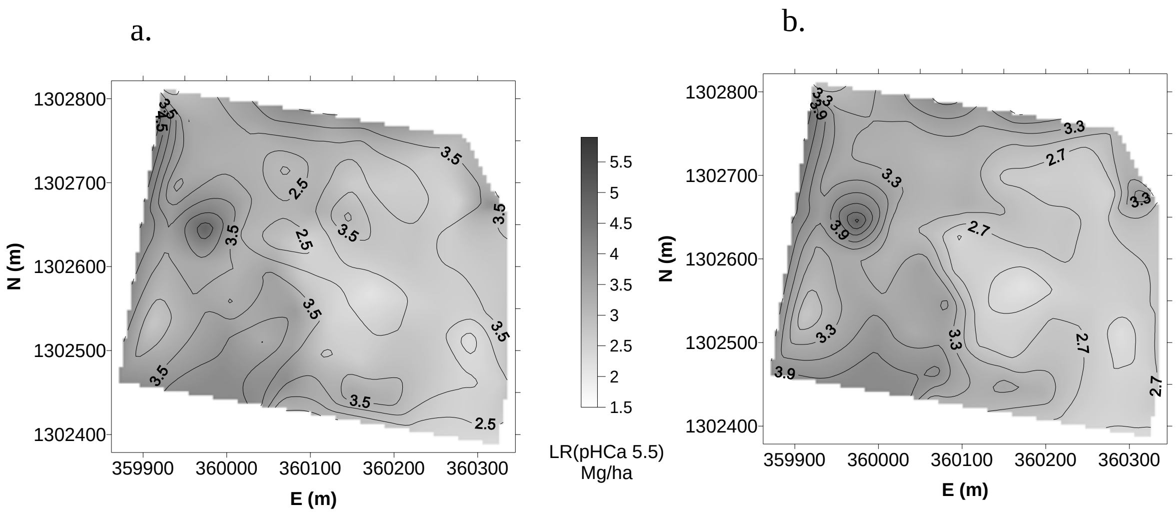


Figure 11. The RMSE of estimated (a.) equilibrium pH_{buffer} values and (b.) respective predictions of lime requirements at various times

Following from our single field scenario, we kriged both the conventional laboratory measurements of lime requirement and the estimated lime requirements (Figure 12). Both, conventional measurements and 15 s estimates of lime requirement produced maps that have a similar spatial structure (Figure 12). Low and high levels of lime requirement throughout the 17 ha field were correctly estimated. The mean laboratory estimate of lime requirement was 3.3 Mg/ha, while that estimated using the sensing system and 15 s data was 3.1 Mg/ha.



Mean = 3.3
St. Dev. = 0.78
Range = 1.5 – 5.9 Mg/ha

Mean = 3.1
St. Dev. = 0.65
Range = 1.9 – 4.9 Mg/ha

Figure 12. Kriged maps of (a.) lime requirements measured using conventional laboratory techniques and (b.) 15 s lime requirement estimates.

CONCLUSIONS AND FUTURE WORK

We developed the first prototype of a robust sensing system for on-the-go measurements of soil pH and lime requirement. We have also developed the methodology for accurate on-the-go determinations of soil pH and estimations of lime requirement, based on the kinetics of soil pH reactions. The algorithms form part of the decision support tool of our sensing system. We performed rigorous laboratory testing of various parts of this system and results are promising. Some of these are shown in this paper. As this is an on-going project, we have only field-tested the system for measurements of soil pH_{Ca}. The sensor signal and the 10 s determinations of soil pH_{Ca} look promising. Based on our laboratory data, we think that 6 s measurements are possible with only a small reduction on measurement accuracy. We have not yet performed field tests using the lime requirement buffer solution; however we plan to do this in coming weeks. Therefore future work will involve field testing of the sensing system for determinations of soil pH_{Ca} and estimations of lime requirement. We will also validate the sensed data with conventional laboratory measurements of both of these properties.

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