

Development of soil pH and lime requirement maps using on-the-go soil sensors

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Abstract

Since conventional sampling and laboratory soil analysis do not provide a cost effective capability to obtain georeferenced measurements with adequate frequency, different on-the-go sensing techniques have been attempted. One such recently commercialized sensing system combines mapping of soil electrical conductivity and pH. The concept of direct measurement of soil pH has allowed for a substantial increase in measurement density. In this publication, the analysis of variable rate lime prescription maps is discussed. Liming rates generated from on-the-go measurements can result in improved prediction of liming requirement compared to the conventional 1 ha grid sampling (RMSE = 1354 versus 2506 kg/ha).

Keywords: on-the-go mapping, soil pH; variable rate liming; electrical conductivity.

Introduction

Site-specific crop management allows growers to improve management of agricultural inputs while taking into consideration the variability of soil attributes within their fields. Conventional geo-referenced soil sampling and laboratory analysis represent a popular technique to identify the variability of soil properties within fields (Whipker and Akridge, 2004). Sampling fields using a 1 ha grid pattern has become the most common strategy in many parts of the USA. To define soil test values for locations between the sampling points, various interpolation methods have been used. The interpolated values predicted for un-sampled areas are valid only if there is spatial dependence between the sample sites. Interpolation of a map based on unrelated soil test values is erroneous. Several studies have shown that the range of soil pH spatial dependency can be less than 100 m, the length of a 1 ha grid cell (McBratney and Pringle, 1997). For example, in some cases, semivariogram ranges (maximum distances of spatial dependency) as short as 21 m have been found (Wollenhaupt et al., 1997) while, in some fields, changes of 2 pH units have been observed over distances less than 12 m (Bianchini and Mallarino, 2002). Higher sampling density has been shown to be impractical because of the high sampling and analysis costs. Attempts have been made to improve spatial predictions from soil sampling using more rigorous geostatistical methods (McBratney et al., 1981; Laslett and McBratney, 1990). These approaches required sampling densities higher than the common 1 ha intensity and, therefore, have not been adopted commercially.

As an alternative, on-the-go soil sensors offer the potential to increase mapping density at a relatively low cost (Viscarra Rossel and McBratney, 1997). Based on the experience gained during the development of a field prototype system for mapping soil nitrate content and pH (Loreto and Morgan, 1996), a research study was initiated in 1997 to investigate the applicability of flat-surface combination ion-selective electrodes (ISEs) to measure soil properties (particularly pH) on moist soil samples directly (Adamchuk et

al., 2003). The initial results illustrated high correlation with conventional laboratory measurements ($r^2 > 0.92$), and a prototype automated system for mapping soil pH on-the-go was developed and tested (Adamchuk et al., 1999). Later, this technology was licensed (Veris Technologies, Inc., Salina, Kansas, USA), and a commercial implement (Soil pH Manager™) has been developed (www.veristech.com). While most operation parameters are selected by users, this sensor can be operated at 8 km/hr using 20 m transects (distance between passes) while conducting measurements every 10 s, which results in more than 20 measurements obtained from each hectare.

Although more accurate delineation of field areas requiring lime application was achieved, it was also known that lime requirements depend not only on soil pH, but also on soil buffering characteristics commonly assessed through buffer pH test or direct titration methods. Conventional apparent electrical conductivity (EC) maps have been shown to correspond to changes in soil types and therefore related to buffering characteristics (McBride et al., 1990). Therefore, the Soil pH Manager™ was integrated with the Veris® 3100 EC mapping unit to form the Veris® Mobile Sensor Platform (MSP). Currently, several MSP units (shown in Figure 1) are in commercial operation across the United States. Linear combinations between pH and EC measurements were used to define lime requirements. In addition, it has been reported that optical soil reflectance can be related to organic matter content that also affects soil buffering characteristics (Chen et al., 2000; Shepherd and Walsh, 2002). Therefore, Veris Technologies has developed a prototype near-infrared spectrometer (NIRS) sensor that could further extend applicability of MSP in the future (Christy et al., 2004).

The objectives of this paper were: 1) to report the results of the Soil pH Manager™ performance tests in different field conditions with respect to the standardized laboratory soil analysis, and 2) to illustrate the comparison between sensor-generated and sampling-based lime prescription maps.

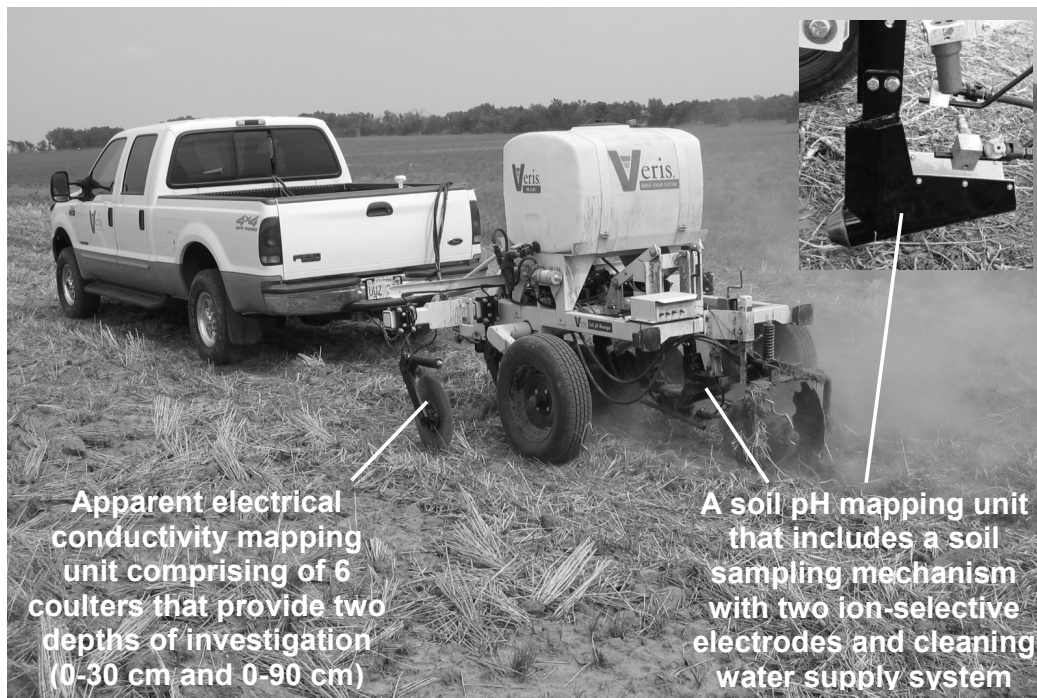


Figure 1. Veris® Mobile Sensor Platform (MSP).

Materials and methods

Automated mapping of soil pH

During field operation, the Soil pH Manager™ automatically collects and measures a soil sample without stopping and without any action from the operator. Measurement depth is adjustable from 4 to 15 cm. The direct soil measurements performed on-the-go are conducted by two combination, jell-filled, epoxy-body, dome-glass membrane, ion-selective pH electrodes. Soil cores are brought into direct contact with the electrodes and held in place for 7- 25 s (depending on the electrode response). Average cycle time is approximately 10 seconds. Every measurement represents an average of the outputs produced by two electrodes. This is done to cross-validate electrode performance and filter erroneous readings.

While mapping a field, optional row cleaners remove crop residue. A hydraulic cylinder on a parallel linkage retracts to lower the cutting shoe assembly into the soil thus cutting a soil core which flows into a sampling trough. The previous core sample is discharged out of the rear of the trough by the new sample core entering in the front. The hydraulic cylinder extends to raise the sampling trough containing the soil core out of the soil while bringing the new soil core into contact with two ion-selective pH electrodes in an electrode holder. During each raising and lowering cycle, the leading edge of the cutting shoe is cleaned by the cutting shoe scraper. The electrodes are washed with two flat fan nozzles while sampling a new core; water is held in a 378 L tank. Optional covering disks fill the soil trench and cover the track. An external electronic control module operates the sampling process, records the output of the ion-selective electrodes and sends these readings to a data storage and user interface module. The instrument processes electrode voltage output and converts it to pH. A two point calibration procedure is performed using standard buffer solutions corresponding to pH 4, 7, and (for alkaline soils) 10. Every measurement is georeferenced using a Global Positioning System (GPS) receiver.

Field evaluation

A pre-commercial prototype of Soil pH Manager™ was tested on more than 1200 ha across nine US states. Every field was mapped using transect widths of approximately 15-20 m, and field speeds ranging from 8 to 16 km/hr. This resulted in mapping density varying between 10 and 20 samples/ha. More than 15,000 measurements with two electrodes have been obtained. To validate the sensor measurements, 329 manually extracted soil samples were collected and analyzed in a commercial laboratory (Soil Testing Lab, Kansas State University, Manhattan, Kansas, USA) following the standard analytical procedure (Watson and Brown, 1998).

Sample locations were determined based on 0.4 ha or 1 ha systematic aligned grids, and/or adaptive sampling to target the areas of apparent homogeneity (based on EC and pH maps). At each of the sampling points, 8-10 soil cores were collected from a depth of 0-15 cm within a circle with 3 m radius. These cores were mixed prior to submitting to the laboratory. The results of the laboratory analysis were compared to the inverse-distance weighted average of two nearest on-the-go measurements performed within 7 m from the center of the manual soil sample location (a single on-the-go measurement was used when a second nearest measurement was farther than 7 m from the sampling

location). On-the-go sensor measurements were normalized to the field means of the laboratory results.

The coefficient of determination of linear regression between corresponding laboratory and on-the-go measurement of soil pH was the major indicator of overall field performance of the on-the-go soil pH mapping. Root mean squared error (RMSE) calculated as the root of squared difference between two corresponding measurements was used to quantify sensor's performance in individual fields. In this case the assumption of 1:1 relationship between two measurement methods was applied.

Lime requirement

In addition to on-the-go soil pH mapping, several fields were mapped using EC sensors and one field was mapped with pH, EC, and NIRS sensors. The EC measurements were obtained using traditional Veris[®] 3100 unit (Lund et al., 1998). Soil optical reflectance was determined using a newly designed shank-based NIRS system (Christy et al., 2004). This instrument recorded soil reflectance between 900 and 1700 nm.

Calcium and/or magnesium soil amendments (such as lime) are typically applied to neutralize acidic soil (low soil pH). In many regions, the quantity of required lime is found through an additional pH measurement of a buffer (typically SMP or Woodruff) extract. The lime requirement is affected by several factors: weathering, type of parent material, clay content, organic matter content, forms of acidity present, as well as the initial and the final soil pH (McLean and Brown, 1984). With crude approximation, soil buffering characteristic can be predicted based on soil texture. For example, Hoefl et al. (1996) recommend Illinois producers to apply lime recommendations based on soil pH and generic soil characteristics affected by primarily soil texture. Bulk soil electrical conductivity (EC) measured on-the-go has frequently been used as an indirect indicator of soil texture (Sudduth, et al., 2002). Soil optical reflectance usually correlates with organic matter (Chen, et al., 2000) can be associated with soil buffering as well. Therefore, integrating soil EC and optical reflectance mapping capability can potentially improve applicability of on-the-go soil pH mapping to derive lime prescription maps.

To evaluate the potential of on-the-go soil mapping for variable rate liming, four fields were mapped using the on-the-go soil sensors and sampled manually on a 1 ha grid. Manual samples were analyzed for soil pH as well as buffer pH (based on the conventional SMP buffer test). The buffer pH test results were used to define lime requirement based on existing Kansas State University (Manhattan, Kansas, USA) soil fertility recommendations. The following three major liming strategies have been compared: 1) uniform lime application rate based on the average of buffer pH measurements, 2) variable rate liming based on conventional 1 ha grid soil sampling results processed using the inverse-distance second-power interpolation, and 3) variable rate liming based on on-the-go soil sensors data. Lime prescription maps based on on-the-go mapping were developed using three levels of data: 1) soil pH maps only, 2) soil pH and EC maps, and 3) soil pH, EC and NIRS data combined. Simple linear regression was used to define buffer pH (and therefore lime requirement) as a function of soil pH or linear combination of soil pH and shallow (0-30 cm) EC measurements. A locally-weighted partial least squares regression analysis was used to predict buffer pH when NIRS sensor data was involved. The combination of all three data layers to predict buffer pH was available for only one production field.

Ten directed soil samples were used to determine the relationship between buffer pH measured in the laboratory and sensor outputs. Samples obtained using a 1 ha grid

pattern were used to validate lime requirement maps based on sensor data. On the other hand, the directed soil samples were used to validate conventional liming strategies (uniform management and variable rate liming based on manually collected grid sampling). The RMSE (root MSE) was calculated for each field and served as the major indicator of map quality. The MSE (mean squared error), which served as a variance of error estimate used to make statistical comparison (F-test), was defined as the averaged squared difference between lime requirements (based on laboratory buffer pH measurements) at validation points and corresponding values from lime prescription maps.

Results and Discussion

Soil pH measurements

The results of the comparison between soil pH measurements performed in the laboratory and in the field are summarized in Table 1. Although some fields demonstrated a lower degree of correlation between corresponding on-the-go and laboratory measurements, coefficient of determination values (r^2) greater than 0.4 have been observed in every field. Differences between the two measurement methods may be explained by on-the-go measurements and soil samples being up to 7 m apart, and by being from different depths. . The overall comparison (Figure 2) indicated relatively high correlation ($r^2 = 0.80$) with the slope of linear regression being close to one. The overall RMSE was found to be 0.38 and ranged from 0.28 to 0.55 pH for different fields.

Table 1. Summary of soil pH measurement comparison in 14 production fields.

Field ID	Area, ha	Number of measurements		r^2 *	RMSE*, pH
		On-the-go	Manual		
Illinois 1	30	260	10	0.76	0.30
Illinois 2	22	184	10	0.65	0.51
Illinois 3	30	272	10	0.85	0.36
Iowa	12	107	37	0.76	0.39
Kansas 1	20	598	34	0.76	0.34
Kansas 2	15	706	67	0.63	0.39
Kansas 3	32	456	10	0.86	0.33
Kansas 4	47	791	10	0.74	0.30
Kansas 5	32	333	15	0.78	0.28
Kansas 6	25	250	15	0.77	0.33
Kansas 7	10	199	26	0.77	0.39
Nebraska 1	30	286	42	0.40	0.41
Nebraska 2	11	250	22	0.42	0.55
Wisconsin	13	260	24	0.71	0.55
Overall	329	4952	332	0.80	0.38

*coefficient of determination and RMSE values were determined using linear regression model: $\text{Sensor pH} = \beta_0 + \beta_1 \cdot \text{Lab pH}$

Lime requirement

The ability to predict buffer pH based on pH only or linear combination of pH and EC is summarized in Table 2. As mentioned before, ten directed soil samples were used to derive this relationship in each field (despite the field area differences). Based on the coefficient of determination r^2 , soil pH measurements were rather well correlated to the buffer pH in three of four test fields. Adding electrical conductivity measurements has improved this correlation. Table 3 summarizes the lime requirement (LR) RMSE values calculated for every field and mapping approach. RMSE for uniform application was similar to the variable rate liming strategy that was based on 1 ha grid sampling. On the other hand, implementation of on-the-go soil pH mapping has significantly ($\alpha = 0.05$) reduced this error in two of four fields. Simultaneous mapping of soil pH and EC have made the RMSE still lower, especially on the Nebraska 2 site where the correlation between pH and buffer pH was relatively low (Table 2). The additional information about soil buffering capacity provided by the EC sensor made a large improvement in the prediction of lime requirement on that field, while on fields with an already strong relationship between pH and buffer pH, the benefit of EC information was less significant. RMSE reduction observed in Kansas 2 field was not shown to be statistically significant.

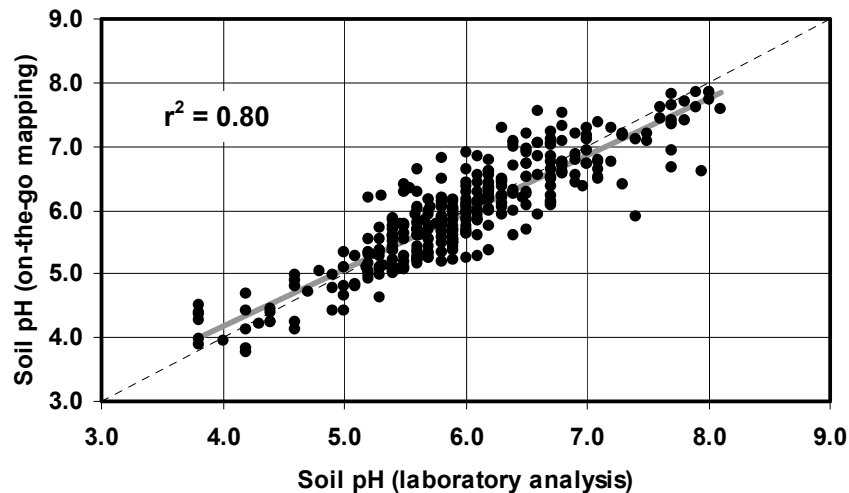


Figure 2. Correlation between soil pH measurements performed in the laboratory and on-the-go sensor measurements.

Table 2. Lime requirement (LR) (kg/ha) prediction based on pH only and pH with corresponding EC (mS/m) measurements.

Field ID	LR = $f(\text{pH})$		LR = $f(\text{pH}, \text{EC})$	
	Equation	R^2	Equation	R^2
Kansas 1	LR = 36124–5389·pH	0.92	LR = 35431–5516·pH+415·EC	0.92
Kansas 2	LR = 16675–2181·pH	0.95	LR = 18555–2566·pH+54·EC	0.96
Nebraska 2	LR = 31032–4923·pH	0.33	LR = 21854–1909·pH–297·EC	0.94
Wisconsin	LR = 28609–4086·pH	0.89	LR = 28663–4156·pH+141·EC	0.90

Table 3. Comparison of three liming strategies based on data obtained conventionally or using the on-the-go soil sensors.

Field ID	Number of validation samples*	Root mean squared error (RMSE)**, kg/ha			
		Uniform liming	Grid sampling	On-the-go mapping	
				pH only	pH and EC
Kansas 1	10 / 32	3550	3085	1117 ^{UG}	797 ^{UGP}
Kansas 2	10 / 57	1930	1745	1470	1450
Nebraska 2	10 / 12	2527	2088	2701	1120 ^{UGP}
Wisconsin	10 / 14	2900	2781	1400 ^{UG}	1444 ^{UG}
Overall	40 / 89	2857	2506	1354 ^{UG}	1259 ^{UG}

* – Ten targeted samples were used to validate uniform liming and grid sampling approaches in every field and grid samples were used to validate on-the-go mapping

** – RMSE values are shown for reference only, all comparisons were done using F-statistic performed on the estimates of error variance (MSE)

^U – significant ($\alpha = 0.05$) decrease of MSE compared to the uniform liming

^G – significant ($\alpha = 0.05$) decrease of MSE compared to the grid sampling

^P – significant ($\alpha = 0.05$) decrease of MSE compared to the on-the-go mapping of pH only

One of these fields (Kansas 1) was mapped using the NIRS sensor in addition to the pH and EC maps. Lime requirement maps generated based on the three sensors have further reduced RMSE (643 kg/ha) versus 1117 (significant at $\alpha = 0.05$) and 797 (insignificant at $\alpha = 0.05$) kg/ha when lime requirement maps were based on pH only and on the combination of pH and EC maps, respectively. Lime requirements determined using sensor data and in the laboratory are compared in Figure 3. In this field, the correlation between corresponding lime requirement estimates also increased when multiple on-the-go soil sensing techniques were used.

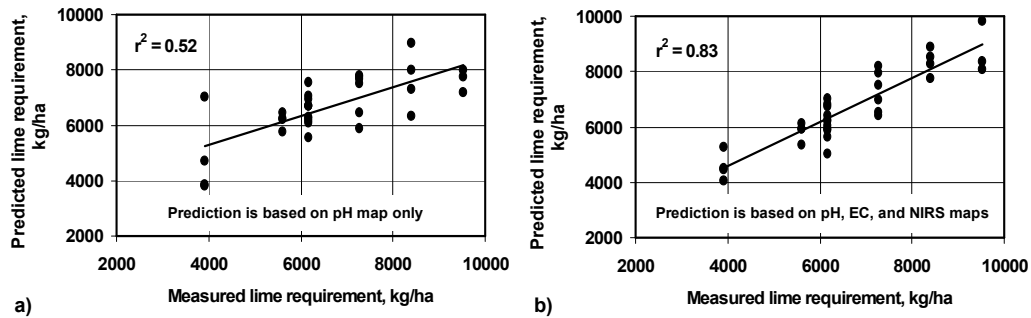


Figure 3. Comparison of lime requirement determined using buffer pH laboratory measurements and on-the-go soil sensors (a – pH only, b – pH, EC and NIRS) in a production field (Kansas 1).

Conclusions

Automated mapping of soil pH on-the-go has become available commercially. It has been found that the Soil pH Manager™ could produce 20 times more measurements than 1 ha grid sampling with a comparable effort. Validation sampling of sensor measurements resulted in acceptable correlation with conventional laboratory analyses. In addition, sensor-based lime prescription maps showed a reduced error in lime application rates. In selected fields, this improvement can be enhanced through incorporation of additional on-the-go soil sensors: conventional electrical conductivity sensor (commercial) and near-infrared spectroscopy (NIRS) sensors (under development).

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