USING ISFETS FOR PROXIMAL SENSING IN PRECISION AGRICULTURE

D.J.J. Walvoort, J. Bouma, and P.D. Peters

Laboratory for Soil Science & Geology
Wageningen University
Wageningen, The Netherlands

J.J. de Gruijter

Alterra
Wageningen University and Research Centre
Wageningen, The Netherlands

ABSTRACT

Site- and time-specific fertilizer application requires detailed data on various soil and crop properties. Proximal sensing techniques offer cost-efficient ways to collect these data. In this paper the Ion Sensitive Field-Effect Transistor (ISFET) pH sensor is evaluated for sensing 'on-the-go' subject to the standard Dutch protocol for pH analysis. It can be concluded that at this stage, proximal sensing 'on-the-go' by means of the ISFET pH sensor is not yet possible. First, some technological hurdles have to be taken. Once these issues have been solved, the ISFET seems a promising sensor, because it is accurate, robust, and has a relatively quick response time. Furthermore, some preliminary results showed that the strict standard Dutch protocol for pH analysis can be simplified without losing too much accuracy. This increases the potential of using ISFETs 'on-the-go'.

Keywords: Proximal sensing, ISFET, lime requirement, pH_{KCl}

INTRODUCTION

Conventional agricultural management systems often lead to unacceptable losses of nutrients and agrochemicals to the environment. Systems based on precision agriculture offer an opportunity to reduce these losses by taking within-field spatial and temporal variation of soil and crop properties into account. At the

department for Soil Science and Geology of Wageningen University in The Netherlands, precision agricultural research has been focused on a forward-looking approach, in which management decisions are made pro-active rather than reactive (Bouma, 2000). In this approach, models are used to predict current and future soil and crop conditions so that appropriate measures can be taken to turn adverse effects (Van Alphen, 2000). These models need large amounts of data on various soil and crop properties. Remote and proximal sensing techniques offer cost-efficient ways to collect these data (Booltink and Epinat, 2000).

In this paper, attention has been focused on proximal sensing, i.e., data gathering by means of sensors that are in or near the soil or near the crop. The aim of this paper is to evaluate the performance of the Ion Sensitive Field-Effect Transistor (ISFET) pH sensor for 'on-the-go' proximal sensing when the Dutch standard protocol for pH analysis is taken into account. The ISFET is more robust and has a faster response time than the traditional glass-calomel pH electrode (Viscarra Rossel and McBratney, 1997). In a case study, the pH measurements obtained with the ISFET are used as inputs to a model for computing site-specific liming rates.

MATERIALS AND METHODS

Study area

The research is performed at the Van Bergeijk farm near Zuidland in the western part of the Netherlands. The total farm is approximately 100 ha and is mainly used for growing potatoes, sugar beets, and winter wheat. For our liming research we selected a 16 ha field with a pronounced $CaCO_3$ gradient ranging from $CaCO_3$-poor soils in the south-east to $CaCO_3$-rich soils in the north-west. Soil texture varied from heavy marine clay in the south-east to lighter textured marine clay in the north-west.

Sampling scheme

A total number of 200 samples were taken of the top soil (0-25 cm). All sampling points were located using a differential GPS. Half of the samples were taken according to centroid sampling which is a special case of the sampling design mentioned in Brus et al. (1999) and Walvoort and De Gruijter (1999). The aim of centroid sampling is to distribute k sampling points evenly over a field. The algorithm is as follows: a field is discretized into many small subareas (in our case square subareas with an area of 4 m^2 each), whose spatial co-ordinates are clustered by a non-hierarchical clustering method like k-means (Hartigan, 1975). The resulting k cluster centroids are evenly distributed over the field and can be used as sampling points.

The remaining 100 samples were taken along 20 transects. There were two reasons for sampling along transects. First, to quantify short range spatial variation, and second to decrease sampling effort. Each transect consists of 6 points that were not equidistant, but taken according to an optimal Golomb 5 ruler. Formally speaking, a Golomb ruler refers to a set of non-negative integers such that no two distinct pairs of numbers from the set have the same difference.

Conceptually, this is similar to a ruler constructed in such a way that no two pairs of marks measure the same distances (Anon., 1999). An optimal Golomb ruler is the shortest ruler possible for a given number of marks. The optimal Golomb 5 ruler has marks at 0, 1, 4, 10, 12, and 17 distance units and includes all integer distances between 1 and 17 units, save for 14 and 15 units.

The transects have distances units equal to 1 m or 1.5 m, resulting in 10 transects with a length of 17 m and 10 transects with a length of 25.5 m respectively. Since a large number distances are available which are multiples of 1 m or 1.5 m, the transects provide a lot of information on short range spatial variation. The sampling layout is given in Fig.1.

Laboratory analyses

Soil pH_{KCl} was measured according to Buurman et al. (1996) which is based on the Dutch standard protocol NEN 5750. A soil suspension was created by adding 25 ml 1M KCl to 5.0 g of air dry soil. The suspension was shaken for 2 hours, after which it was allowed to settle. The pH_{KCl} was measured in the supernatant. pH-analysis was performed in batches of 26 samples, including two standard soil samples, i.e., Labex 19 and WEPAL-ISE 921. The standard soil samples serve to guarantee the quality of the laboratory procedures as their variation in pH_{KCl} is accurately known. The standards were representative for the range in pH_{KCl} found at the Van Bergeijk farm.
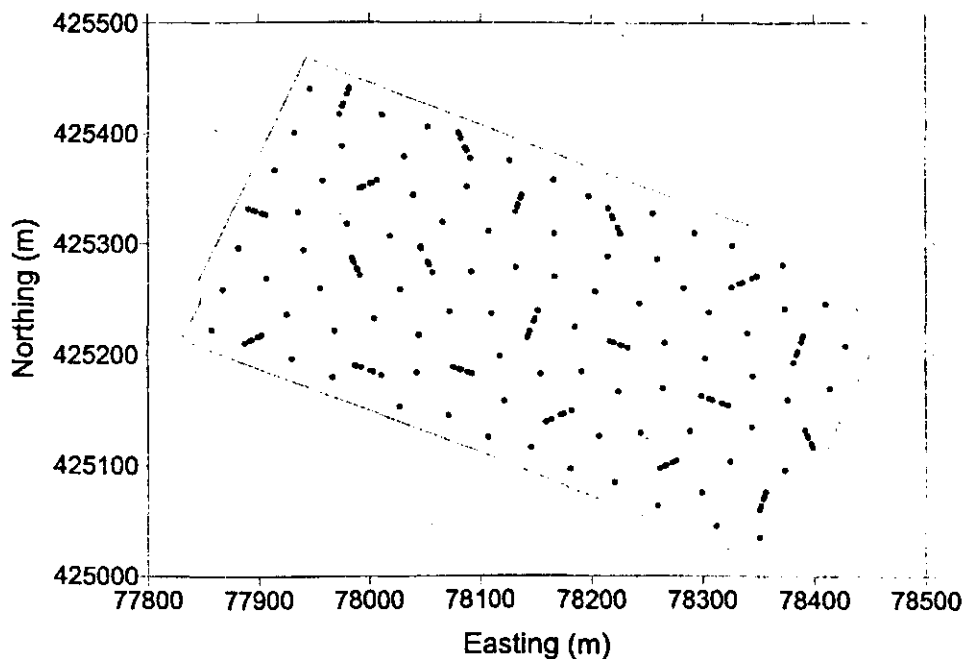

Fig. 1. Sampling layout for estimating pH_{KCl}.

Calculation of site-specific liming rates

Lime requirement is computed by means of the IKC-method (IKC, 1992, 1994). It is the standard procedure in the Netherlands for computing lime requirement. It is envisaged that by using this methodology for site-specific management rather than by following a · different procedure will accelerate acceptance by farmers and agricultural authorities. According to the IKC-method, lime requirement is a function of crop rotation and soil type. The primary data needed for computing lime requirement for the marine clays at the Van Bergeijk farm are the actual pH_{KCl}, the organic matter content OM (weight%), the weight percentage of the particle size fraction smaller than 16 µm (P_{16}), and the application depth d_a (m). The secondary data are derived from the primary data and are the dry bulk density of the soil _ (g/cm^3), the target pH^*_{KCl} and the relative base contents at pH^*_{KCl} (rb^*) and pH_{KCl} (rb). The relative base content is defined as the base content relative to the base content at pH_{KCl} 6.4. The difference between rb^* and rb is denoted by _rb. Lime requirement (kg CaO/ha) is computed by entering these quantities in the following expression:

$$LR = \begin{cases} 0 & \text{if } pH_{KCl} > pH^*_{KCl} \\ LR_1 & \text{if } pH_{KCl} < 6.4 \text{ and } pH^*_{KCl} < 6.4 \\ LR_2 & \text{if } pH_{KCl} \geq 6.4 \text{ and } pH^*_{KCl} \geq 6.4 \\ LR_1 + LR_2 & \text{otherwise, with } \Delta pH_{KCl} = 6.4 - pH_{KCl} \text{ and } \Delta rb = rb^* - 1 \end{cases}$$

with

$$LR_1 = 1120\rho(0.25P_{16} + OM)\Delta pH_{KCl}\, d_a$$

$$LR_2 = 560\rho(0.25P_{16} + OM)\Delta rb$$

The primary and secondary data used in the IKC-method and their dependencies are schematically depicted in Fig. 2.

A lime prescription map was computed by first applying the IKC-model at the observation points, followed by ordinary kriging (Deutsch and Journel, 1998) of the estimated lime requirements to a dense grid.
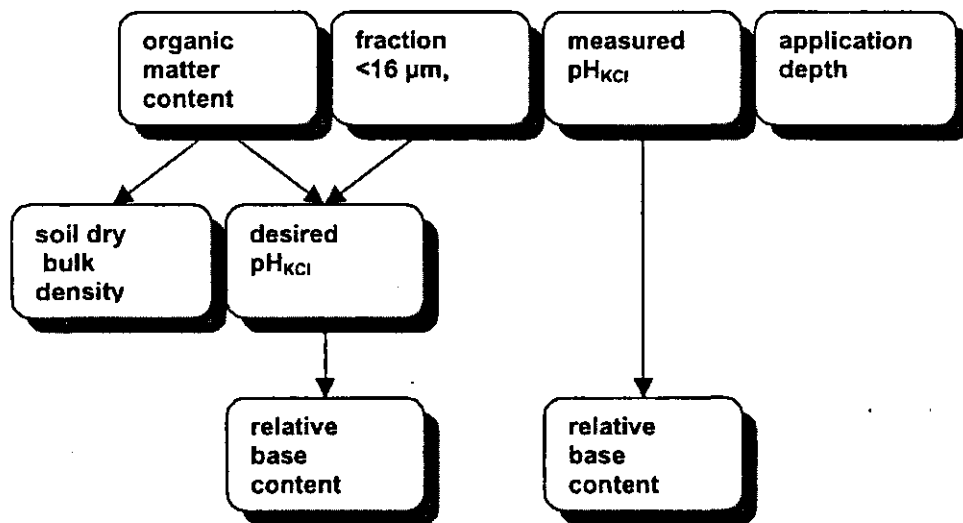
Fig. 2. Primary (top row) and secondary data for computing lime requirement according to the IKC method and their relations.

Particle size estimation

In order to apply the IKC model, P_{16} has to be known. However, the soil data base of the Van Bergeijk farm only contains particle size classes 0-2 μm (clay), 2-50 μm (silt), and 50-2000 μm (sand). To estimate P_{16}, we used the similarity approach (Nemes et al., 1999) in conjunction with loglinear interpolation. Given a cumulative particle size distribution with an unknown weight percentage P_x of the particle size smaller than limit x, the similarity procedure selects 10 cumulative particle size distributions from a vast reference database that are similar to the distribution of interest. Furthermore, the selected distributions also contain P_x. The average P_x of these distributions is then an estimate of the unknown P_x of the distribution of interest.

The reference database used in our study is a subset of a database compiled by the department of Agricultural Chemistry and Soil Science of The University of Sydney, Australia (Minasny, 2000, pers. com.). It contains particle size distributions from several international databases, i.e., GRIZZLY, UNSODA, USDA-NRCS Soil Survey Laboratory, and databases from several locations in Australia. A subset of this database was taken that at least contained the $x=2$ μm and $x=50$ μm particle size limits that were also available in the Van Bergeijk database. Since only 67 out of 2564 distributions in the reference database contained the limit $x=16$ μm, and all distributions contained $x = 20$ μm, we used loglinear interpolation between $x=2$ μm and $x=20$ μm to estimate P_{16} when $x=16$ was not available:

$$P_{16} = P_2 + (P_{20} - P_2)\frac{\varphi_2 - \varphi_{16}}{\varphi_2 - \varphi_{20}} = P_2 + (P_{20} - P_2)\log_{10}(8)$$

where $\_x = -\log_2(0.001x)$ a scale that is common in sedimentology.

RESULTS AND DISCUSSION

pH measurements

An appropriate sensor for proximal sensing 'on-the-go' should at least be able to produce accurate results. In order to test the performance of the ISFET and the reproducibility of the measurements, 2 standard samples were subsampled and analyzed in 11 batches. The results show that the measurements were reproducible and that the ISFET measurements are within the same ranges as those of traditional probes. These results comply with those obtained by Viscarra Rossel and McBratney (1997).

Another requirement is that the sensor should be free of instrumental drift, at least during the time of operation in the field. A preliminary test by measuring pH$_4$ and pH$_7$ buffer solutions just before and after analyzing a batch (a time span of approximately one hour) showed no evidence of instrumental drift.

Another important requirement is that the total time needed for sample preparation and measurement should be done in a limited time span. If the sensor is mounted on a vehicle that drives with a speed of 5 km/h over a field and if the sampling points are 10 m apart, then sampling, soil preparation and measurement should be done within 14 seconds. This time may be increased when technological solutions are taken into account, like multiple sensors, and temporary storage facilities on the vehicle to allow suspensions to equilibrate. However, according to the protocol we used (Buurman et al, 1996) the samples have to shake for 2 hours to reach equilibrium pH$_{KCl}$, a time span that makes 'on-the-go' proximal sensing with ISFETs impracticable. However, for estimating lime requirement, it is not always necessary to estimate pH very accurately. Depending on the position on the crop response curve, an accuracy of about 0.25 pH units is usually sufficient (Viscarra Rossel, 2000, pers.com.). Therefore, we monitored the process of achieving equilibrium pH$_{KCl}$ on a mechanical shaker for two hours after adding 1M KCl. During the first hour, measurements were taken at time intervals of 5 minutes, while during the second hour time intervals of 10 minutes were used. The results show that 2 hours shaking time for equilibration is rather excessive (Fig. 3). Equilibrium pH is in most cases achieved within 5 or 10 minutes. Preliminary measurements on only three samples showed that even for time spans less than 5 minutes (ranging from 25 seconds to 3 minutes) the pH$_{KCl}$ stabilizes very quickly (0.1 or 0.2 pH units from equilibrium pH). The excessive amount of 1M KCl in a 1:5 soil:solution suspension expels protons very quickly from the adsorption complex. It is expected that pH$_{KCl}$ stabilizes even faster in sandy soils.
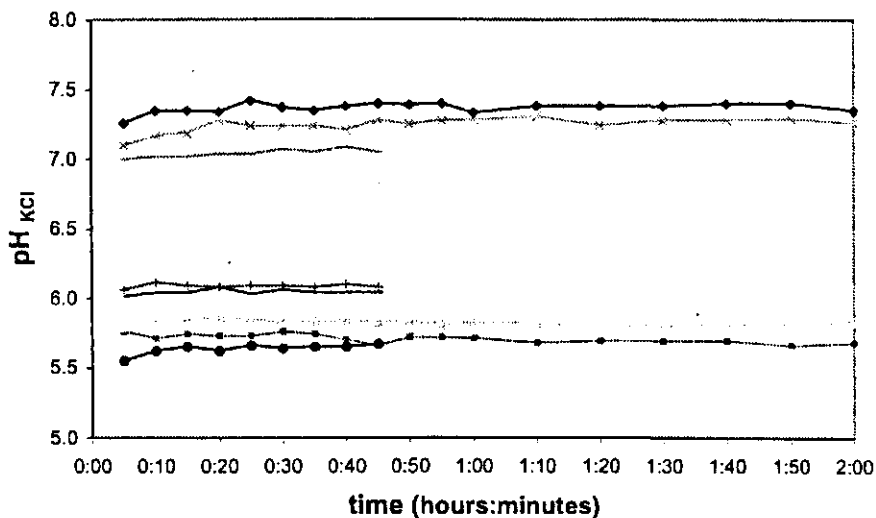
Fig.3. pH$_{KCl}$ as a function of time after adding 1M KCl

It can therefore be concluded that once a technological solution has been found for sampling, soil preparation, and temporary sample storage, ISFETs are appropriate for estimating pH$_{KCl}$ 'on-the-go'

Particle size estimation

The similarity procedure in conjunction with loglinear interpolation was validated by estimating P_{16} of an independent validation set which contained all particle size distributions from the reference database that have P_{16} ($n=67$). The accuracy of the similarity procedure in conjunction with loglinear interpolation as expressed by the root mean squared error (RMSE) was 4.9%, as opposed to a RMSE of 7.7% when only loglinear interpolation was applied.

The similarity procedure in conjunction with loglinear interpolation was applied to estimate P_{16} of the particle size distributions in the Van Bergeijk database. The results are used for computing site-specific lime requirement.

Site-specific lime requirement

The following data were available for computing a site-specific lime requirement map: 199 sampling points where the pH$_{KCl}$ was known, and 71 soil survey points in the Van Bergeijk database where OM, P_{16}, and d_a were known. Since the soil survey points and pH$_{KCl}$ points were sampled during different field campaigns and with different aims, the points do generally not coincide.

Therefore, we first interpolated pH$_{KCl}$ to the 71 soil survey points. Since pH$_{KCl}$ is not additive, it was converted into H$^+_{KCl}$ prior to interpolation, and

converted to pH_{KCl} again afterwards. The resulting pH_{KCl} map is given in Fig 4. The pH_{KCl} ranges from 5.6 to 7.5 and is lower in the south-east than in the north-west. After running the lime requirement model for the 71 soil survey points, the estimated lime requirements were interpolated to a dense grid. The resulting map is given in Fig. 5 and applies to an application depth 25 cm to 30 cm.
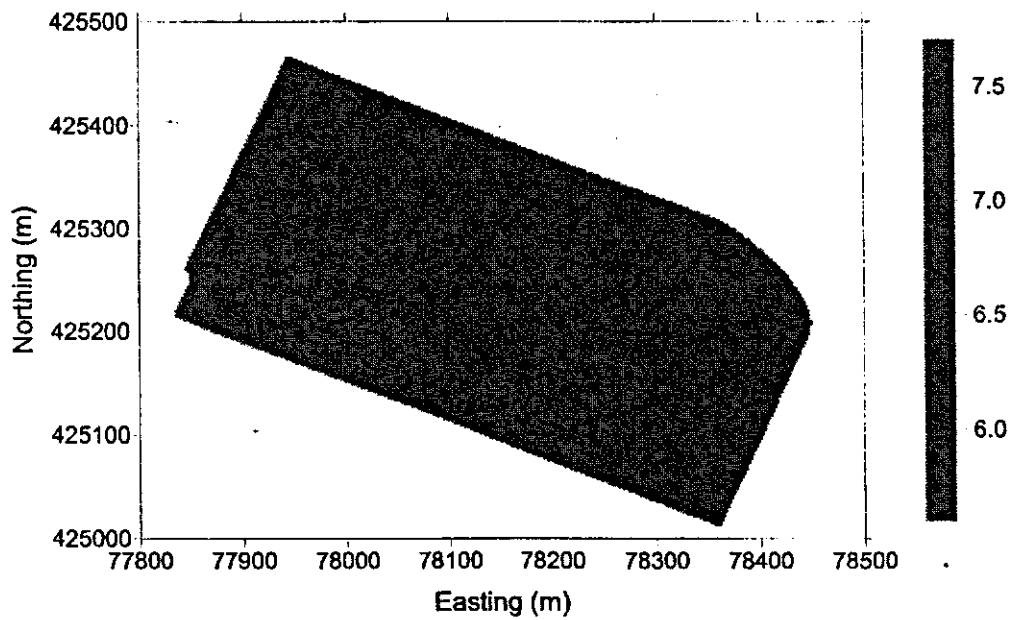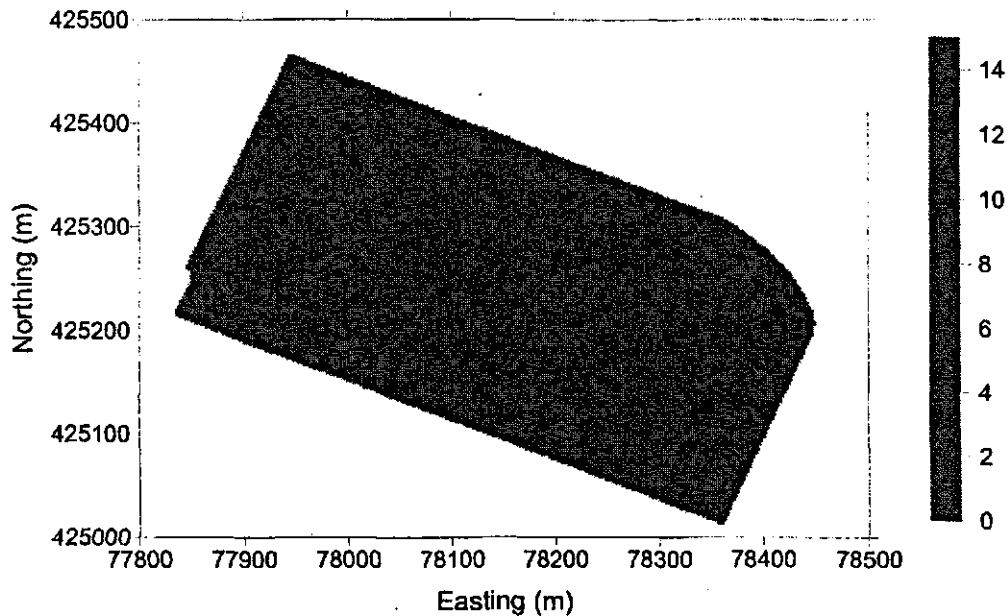
Fig.4. pH_{KCl} of the top soil (0-25 cm).

Fig.5. Lime requirement map for an application depth of 0.25m-0.30m (in 1000 kg CaO/ha).

CONCLUSIONS

At this stage, proximal sensing 'on-the-go' by means the ISFET pH sensor is not yet possible. First, some technological hurdles have to be taken. Among these are the development of a methodology for taking soil samples and making soil:KCl suspensions 'on-the-go', and the development of some kind of temporary storage facility on the vehicle to allow the suspensions to equilibrate.

Our research showed that the standard Dutch protocol for pH_{KCl} analysis can be simplified, because the prescribed equilibration time of 2 hours turned out to be rather excessive. A preliminary test showed that equilibration times of less than 5 minutes are generally sufficient. When the total time needed for sampling, sample preparation, sample equilibration, and pH measurement, can be further decreased, the ISFET seems a promising sensor for proximal sensing 'on-the-go' since it is robust, accurate, and has a relatively quick response time.

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