Precision AGRICULTURE

Site-Specific Management of Soil pH (FAQ)

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Site-specific management of soil pH is a precision agriculture practice that can provide positive economic and environmental impacts on modern crop production. This publication addresses several frequently asked questions related to the meaning of soil pH, lime requirement, and quality of data used to prescribe site-specific management of soil pH.

What is soil pH?

The term "pH" is defined as the negative logarithm of the hydrogen ion activity, and values range from 1 (very acidic) to 14 (very basic). A neutral solution, such as pure water at 23 ^{0}C, has a pH of 7.0. Soil pH is a major characteristic of the crop-growing environment as it affects nutrient availability, microbial activity, and the potential for toxicity problems. Soil acidification may be caused by acid-forming fertilizers, removing bases with harvested crops, leaching nitrate and basic elements, and organic material decomposition (*Management Strategies to Reduce the Rate of Soil Acidification,* NebGuide 03-1503).

In general, optimal soil pH varies with the crop. When soil pH falls below the desired level, soil acidification may cause toxic concentrations of aluminum and manganese. The activity of soil micro-organisms that affect nitrogen, sulfur, and phosphorus availability may be altered as well. Calcium may be deficient when the percent base saturation, and usually cation exchange capacity (CEC), of the soil is extremely low (as in sandy soils). Acidic soils may be poorly aggregated with poor tilth, especially for low organic matter soils. The availability of phosphorus and other nutrients also is frequently reduced. On the other hand, a high soil pH may reduce the availability of phosphorous and certain micronutrients, and injury or carryover with some classes of herbicides.

How is soil pH measured?

A pH measurement is normally made by either colorimetric or electrometric methods. The former involves suitable dyes or acid-base indicators, the colors of which change with hydrogen ion activity. The latter involves a glass electrode paired with a reference electrode attached to a suitable meter for measuring electromotive force (emf) in proportion to the pH. The colorimetric method is not reliable and provides much lower accuracy. In the United States, soil pH is commonly determined using an ion-selective electrode in a solution obtained by mixing soil and water together in a 1:1 ratio.

The most common procedure for measuring soil pH in a laboratory consists of five primary steps:

1. Calibrate the pH meter over the appropriate range using a minimum of two standard buffer solutions, typically having pH 7 and 4 (and/or 10 for alkaline soils).
2. Measure a sample of air-dried, crushed and sieved soil into a cup (5, 10 or 20 g are recommended).
3. Add distilled or double-deionized water, or another extracting solution (e.g., 0.01M $CaCl_2$), to the sample to bring the solution to a weight-to-weight ratio of 1:1.
4. Stir vigorously for 5-10 seconds and let stand for 10-30 minutes.
5. Place the electrode in the slurry, swirl carefully, and read the pH.

How can I raise low soil pH?

Liming is a common practice used to neutralize soil acidity. Lime requirement is defined as the amount of agricultural limestone or other basic material needed to increase soil pH from an unacceptably acidic condition to a value that is considered optimum for the desired use of the soil. Lime rates usually range between 1 and 3-4 ton per acre (greater rates should be split between two or more applications). Soil pH indicates the need for lime but buffer pH is needed to estimate the amount of exchangeable acidity to be neutralized and, therefore, the amount of lime required to raise the soil pH to the desired level. Lime requirement is affected by soil properties, including parent material, clay and organic matter contents, the cation exchange capacity, forms of acidity present, and initial and final pH of soil (*Lime Use for Soil Acidity Management*, NebGuide G03-1504).

Currently, three methods are used to estimate the amount of exchangeable acidity that must be neutralized to raise the pH to the desired level. The first involves estimating the lime requirement from soil properties such as soil pH, texture, type of clay, and organic matter content. The second method is direct titration of soils with $Ca(OH)_2$. The third and most common procedure uses buffer methods to estimate the lime-test index. Numerous buffer methods have been developed over the years. The SMP and Woodruff single-buffer methods for rapid measurement of lime requirement have been adopted by many soil-testing laboratories, including those in Nebraska.

The most common alternatives to buffers are some sort of an estimate of the lime requirement based on soil pH and a measured, or recorded, factor that is associated with soil buffering capacity. Examples include soil organic matter content, estimated CEC, and soil series. Many experiment stations and soil-testing laboratories have determined the recommendations for computing lime requirements of the major soil series and types in the areas they serve. Once this has been done, knowledge of the pH and the soil type will make an immediate liming recommendation possible.

Most current recommendations provide application rates for a given effective calcium carbonate equivalent (ECCE), relative neutralizing value, effective neutralizing material, or similar characteristic of liming material, which vary with its quality (purity and fineness). Therefore, it is necessary to adjust application rates for the quality of material actually being applied. In addition, lime recommendations are based on the assumption that lime will be incorporated to a depth of 6 to 9 inches (4 inches in the case of no-till) following the application. Thus, the application rate should be adjusted for the actual depth of lime incorporation.

How variable is soil pH?

With the advent of precision agriculture, soil variability within an agricultural field has become the focus of many studies. It has been shown that the natural variation in field landscape (including terrain, parent material, surface water movement, etc.) and past and/or present management can cause significant variation in soil pH, lime requirement, and other soil properties. For example, *Figure 1* illustrates the distribution of soil pH within three Nebraska fields. In these fields the coefficients of variation (one of the indicators of relative variability) were 4%, 9%, and 8%, respectively. This means that the majority of a field with an average pH of 6.0 may have soil pH varying between 5.0 and 7.0. Small areas with a soil pH outside this range are not uncommon.

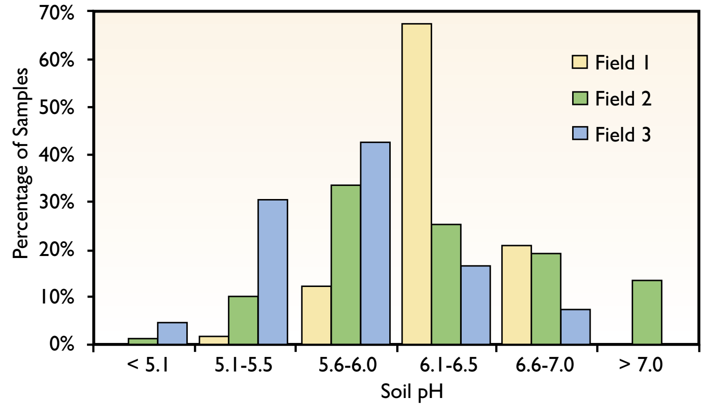


Figure 1. Distribution of soil pH within three agricultural fields in Nebraska (based on 182-186 soil samples collected in each field using a 1-acre grid pattern).

In general, soil pH is believed to have coefficients of variation ranging between 2% and 16%, which is low compared to soil nutrients or certain physical properties (e.g., saturated hydraulic conductivity). In addition, soil pH does not change abruptly, and soil samples taken close together tend to have smaller differences between pH measurements than samples collected farther apart. Therefore, soil pH has "spatial structure." Although the degree of this spatial structure changes from field to field, similarities in soil pH measurements can be observed at maximum distances of 60 - 900 ft.

What is site-specific management of soil pH?

One of the goals of precision agriculture is to manage agricultural inputs according to changing local field conditions in order to increase profitability and reduce environmental waste of agricultural inputs. According to many adopters, variable rate liming is one of the profitable and popular practices in site-specific crop management. In addition to acidic field areas, having knowledge of areas with alkaline soil conditions (high pH) can be useful to avoid lime application in these areas and also aid in the selection of crop varieties tolerant to problems associated with high pH (e.g., iron chlorosis).

Currently, variable rate lime prescription maps are generated based on soil samples collected manually and analyzed in laboratory conditions. These samples are usually obtained with a 2.5-acre sampling frequency (*Soil Sampling for Precision Agriculture,* EC00-154).

Is 2.5-acre grid sampling an adequate approach?

Figure 2 illustrates a common problem with creating a prescription map for applying variable rate lime using 2.5-acre grid sampling. In this case, 330- by 330-ft (2.5-acre) grid cells are superimposed on a bare-soil infrared image. The field has terraces which appear as dark lines so it is evident that there is a significant slope in this field. The white areas are eroded Nora soil, with alkaline (high pH) subsoil near the surface. The darker areas are less eroded, and more acid in the upper horizon.

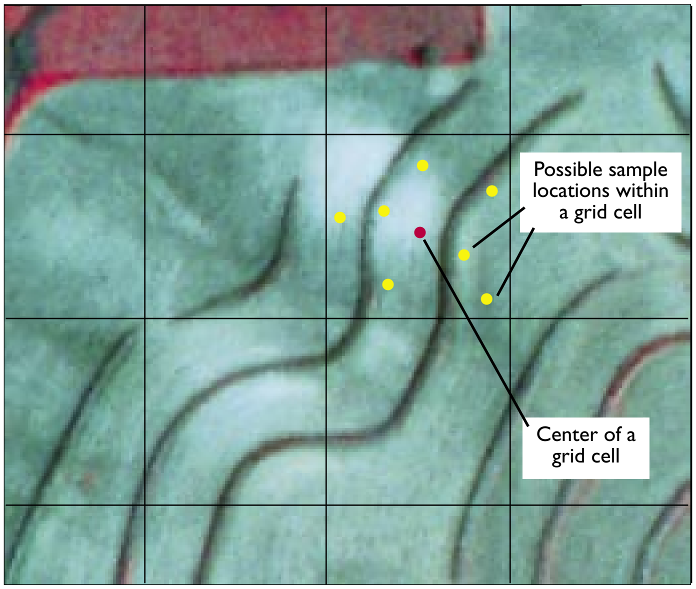


Figure 2. A field image with 2.5-acre grid sampling pattern.

If a few cores are taken near the center of a grid cell (red dot), the sample pH is likely to be greater than 7 since it is within the white area. As a result, the entire grid cell will receive no lime. If several cores are taken randomly throughout the grid cell, such as at the yellow dots, and then combined, the result will be nearer the average pH for the grid cell. However, the variability in this grid cell is likely to be as high as it is across the field, so little is accomplished. Using this method, it is likely that the grid cell will receive too little lime in the non-eroded portion, and too much lime on the eroded spot. Since the grid lines do not coincide with the patterns of variability, the variable rate application is not necessarily more appropriate than a uniform application. In this example, the analysis cost would be eight times as high as when a regular 20-acre composite sampling strategy is used. Overall, grid sampling with 2.5-acre grids increases analysis cost and often fails to adequately measure spatial pH variability, resulting in reduced profitability of variable rate liming.

The quality of prescription maps generated using a grid sampling can be improved by decreasing the grid size to 1 acre; however, the cost of the laboratory analysis for pH and buffer pH will increase. Although the procedure will not need to be repeated for five or more years and the cost can be prorated over that time, the profitability of variable rate liming using this sampling strategy remains questionable. Even in a 1-acre grid cell, a 50-ft lime spreader can make four passes with several different applied rates in each pass (more than 16 50 by 50-ft squares can be located within 1-acre grid cell). Therefore, the mapping method still does not match the application technique.

If the earlier mentioned spatial structure exists, certain map interpolation methods can be used to better predict lime application rates in unsampled locations. However, even with the best (from a scientific viewpoint) interpolation method, errors will remain. Any type of interpolation is ineffective when substantial soil variability can be found between nearest soil samples.

Could directed sampling be helpful?

Directed (also called guided) sampling according to relatively uniform required lime application zones is a promising approach for many fields. The zones are determined by considering the variations in the field that may affect lime requirement, including soil types, topographic position, past management, aerial images of bare soil and growing crops, spatial variation in historical yields, soil electrical conductivity maps and/or other data layers.

For example, *Figure 3a* represents an aerial photo of a soybean field in late July. The field is irrigated with a center pivot system. Stand loss and plant death have occurred in the southwest corner, which is not irrigated. The pH in the bare areas was below 4.5 due to a history of seed-corn production with relatively high nitrogen application rates. The irrigated parts of the field have pH above 5.5 due to better uptake of nitrogen in previous crop years and high amounts of calcium in the irrigation water. Compaction effects are also relevant because a disk-tillage pan was present on the west half but not on the east half, which was under ridge tillage. The most severely degraded areas are relatively level. This can be seen in *Figure 3b*, which shows the same photo viewed from the west, and overlaid on a digital elevation model (3-D view of field terrain). On the steep slopes, alkaline subsoil is exposed and roots grew through the tillage pan. In the relatively level area near a field entrance in the northwest corner (indicated by the red arrow), crop growth was affected by both compaction and low pH. In summary, the spatial variability of pH in this field is due to differences in past nitrogen use, calcium applied with irrigation water, and differences in soil type as influenced by slope. The effect of pH on crop growth also was influenced by tillage history. Therefore, enough information is available to create a useful directed sampling plan.

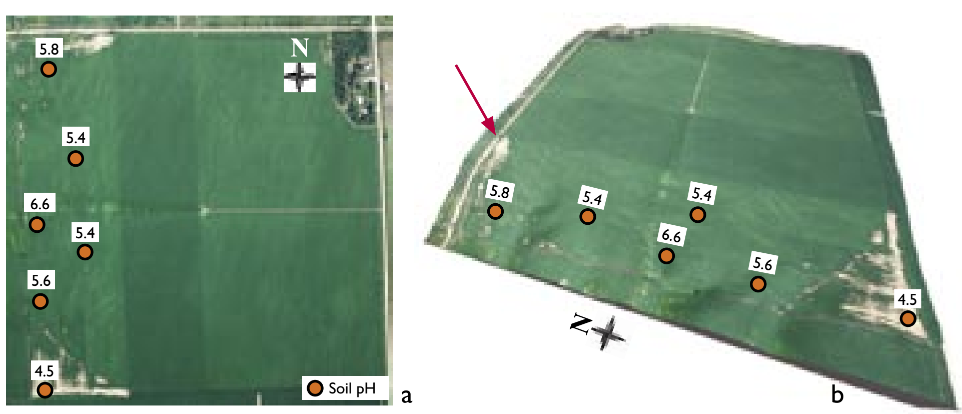


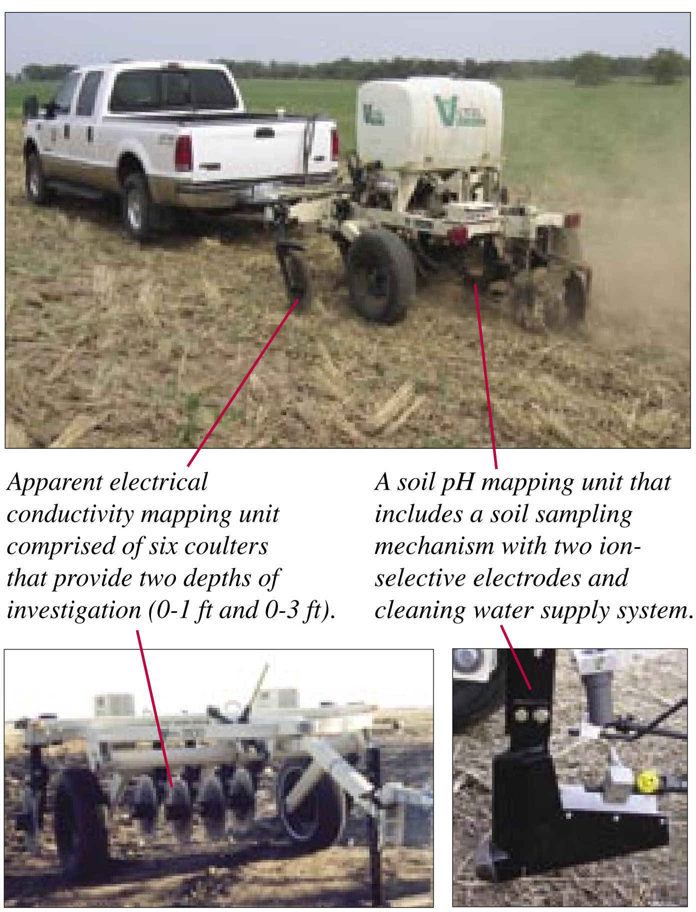
Figure 3. Soybean field with crop stress due to pH variability caused by past management represented as a) aerial photograph, and b) the same image combined with a 3D view of the terrain.

Usually the effects of soil pH on crop growth are more subtle than those seen in the example above. When soil pH deviates from the optimum range, root growth, legume nodulation, and phosphorous uptake may be reduced. Also, soil applied herbicides may be less effective in some cases. All of these effects can be caused by other factors, such as compaction, lack of rhizobium inoculants, or insect damage. Crop scouting observations are usually not adequate to detect these effects on plants and the cumulative impact is best measured by crop yield. Therefore, knowing soil pH is essential for preventing potential yield loss in the future.

How can the accuracy of soil pH maps be improved?

Since the beginning of precision agriculture approach, several researchers and manufacturers pursued the development of on-the-go soil sensors to accurately map pH (and other soil properties) at a relatively low cost (*On-the-Go Vehicle-Based Soil Sensors,* EC02-178). Based on research conducted at Purdue University and the University of Nebraska-Lincoln, Veris Technologies, Inc., based in Salina, Kan., launched production of the world's first automated on-the-go soil pH mapping system in the summer of 2003. This product is called the Mobile Sensor Platform (MSP). It consists of a widely used electrical conductivity (EC) mapping unit and a Soil pH Manager™ (*Figure 4*).

Figure 4. Veris® Mobile Sensor Platform (MSP).



During field operation, the Soil pH Manager™ automatically collects and measures a soil sample without stopping. While mapping a field, row cleaners remove crop residue. A hydraulic cylinder on a parallel linkage retracts to lower the cutting shoe assembly into the soil, and the cutting shoe creates a soil core which flows into the sampling trough. The previous core sample is discharged at the rear of the trough as it is replaced 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 sample in contact with two ion-selective pH electrodes (combination, gel-filled, epoxy-body, dome-glass membrane). During sampling, the electrodes are washed with two flat fan nozzles. Covering disks fill the soil trench and cover the track. Measurement depth is adjustable from 1.5 to 6 inches, typically with a 3-inch average effective measurement depth. Soil cores are brought into direct contact with the electrodes and held in place for 7-25 seconds (depending on the electrode response). Every measurement represents an average of the outputs produced by the two electrodes. Two independent measurements allow cross-validation of electrode performances and filtration of erroneous readings. The recorded electrode output is converted to pH values according to the selected electrode calibration parameters. Every measurement is geo-referenced using a Global Positioning System (GPS) receiver.

Figure 5 illustrates the results of comparisons between conventional laboratory analysis conducted on manually extracted soil samples and corresponding on-the-go measurements performed within a 25-ft radius. This comparison involved 14 fields in Kansas, Nebraska, Iowa, Illinois, and Wisconsin. Although the degree of correlation between the two methods is high, on-the-go measurements can have a standard error as high as 0.2 to 0.3 pH, which is slightly higher than usual in a selected commercial soil lab. On the other hand, on-the-go mapping allows for a significant increase in sampling density. *Table 1* illustrates the effect of travel speed and distance between passes on sampling density with the assumption that sampling occurs every 10 seconds.

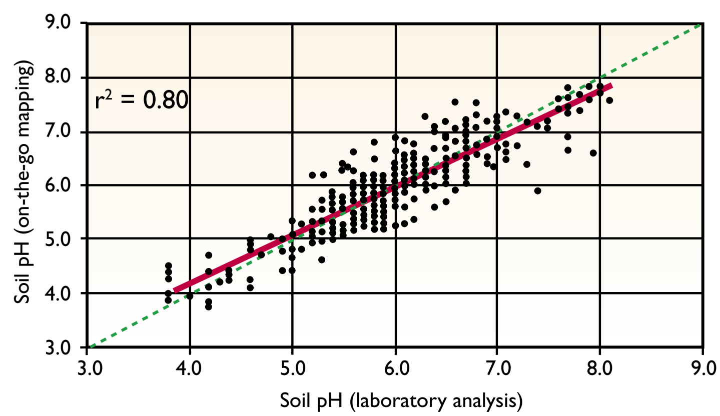


Figure 5. Comparison between on-the-go and laboratory measurements of soil pH.

Table 1. Sampling density (samples per acre) for on-the-go soil pH mapping

Travel speed (mph)	Distance between passes (ft) 20	40	60	80	100
4	37.1	18.6	12.4	9.3	7.4
6	24.8	12.4	8.3	6.2	5.0
8	18.6	9.3*	6.2	4.6	3.7
10	14.9	7.4	5.0	3.7	3.0

* - sampling density currently recommended by researchers and the manufacturer

This increase in sampling density frequently results in more accurate soil pH maps. For example, *Figure 6* illustrates a 60-acre Kansas field. The neutral soil band near the northwest field boundary (caused by an adjacent gravel road) and a fuzzy pattern of acidic soil in the middle of the field were hidden when the 2.5-acre grid sampling approach was applied. Laboratory analysis of 10 validation samples confirmed that the map based on on-the-go sensing was more accurate than the interpolated map based on 2.5-acre grid sampling.

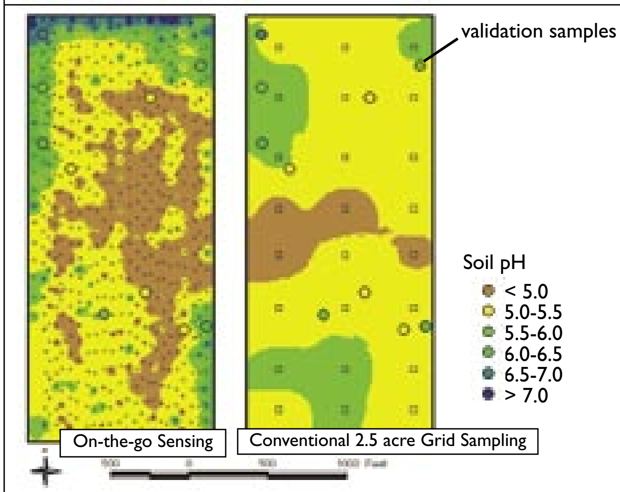


Figure 6. Comparison between soil pH maps obtained through on-the-go mapping and conventional 2.5-acre grid sampling.

Can on-the-go soil sensing be used directly to prescribe lime application rates?

Soil pH maps based on on-the-go measurements indicate the variability of soil acidity/alkalinity but need to be translated to lime application maps prior to variable rate liming. This is somewhat challenging as soil buffering capacity typically varies across the field, and the amount of lime needed to change soil pH by one unit is not constant. Therefore, the Veris® MSP combines soil pH and electrical conductivity mapping capabilities as electrical conductivity maps often reflect changes in soil texture (percentage of clay, silt, and sand), the major factor affecting soil buffering capability. Therefore, lime prescription maps can be calculated from the simultaneously obtained electrical conductivity and soil pH measurements.

For example, the calibration of lime requirement measurements can be done by using laboratory analysis of eight to 10 soil samples from parts of the field with either relatively low or high soil pH and co-aligning these results with corresponding on-the-go measurements of soil pH and EC. A multivariate regression approach can be applied to develop a field-specific equation for predicting the lime requirement based on a linear combination of soil pH and EC data collected on-the-go. Although this approach appears complex, a straight-forward technique is being developed to integrate soil sensor measurements with results from laboratory analysis of a few samples. This will make variable rate liming prescriptions easier to create in the future. Additional sources of spatial soil data might also be used to improve the quality of lime application maps. Currently under development, sensors for mapping soil optical reflectance (predictor of organic matter content) and conventional bare soil imagery also could serve as additional data sources.

Does variable rate liming pay?

As with other site-specific crop management strategies, the profitability of variable-rate liming depends on: 1) quality of information, 2) additional application cost and data collection and processing costs, and 3) the variability in lime requirement for the particular field.

For instance, variable-rate liming will not be profitable if lime requirement is uniform or soil acidity is not limiting the yield. Also, liming may require several years to impact the yield and should be considered a long-term investment. Finally, poor quality of information used to prescribe variable-rate liming may result in inappropriate changes of lime application rates and therefore increase (rather than reduce) soil pH variability at the farmer's expense.

In a recent University of Nebraska–Lincoln study of the value of soil pH maps, it has been shown that the expected net return (crop sale revenue) over cost of lime (NRCL) during a four-year corn-soybean growing cycle is affected by the errors associated with different mapping approaches. Based on the model developed, higher errors mean lower potential benefit (*Figure 7*).

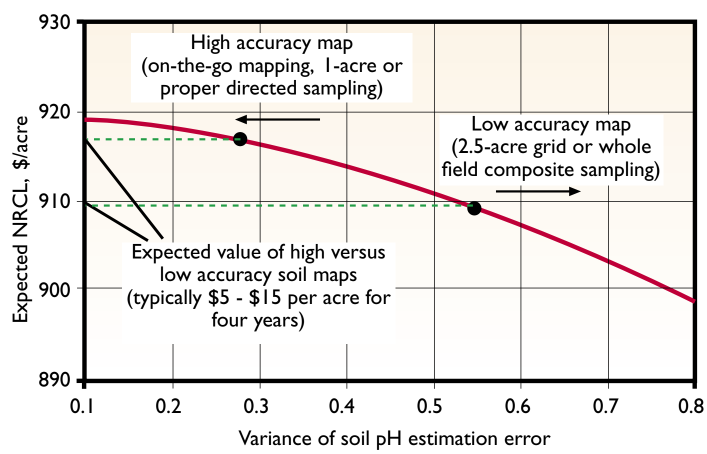


Figure 7. The effect of soil pH mapping quality on liming profitability (NRCL represents four years of corn and soybean crop revenue minus the cost of lime).

For the selected field conditions with slightly acidic (5.8 average pH) soil and 9% variability, "low accuracy map" means either a map obtained using 2.5-acre grid sampling or simply assuming that soil pH is constant across the field (composite field sampling). A "high accuracy map" can be obtained through 1-acre grid sampling, on-the-go mapping, or properly conducted directed sampling. The difference between expected NRCL corresponding to high and low accuracy maps represents the expected economic benefit that typically ranges between $5 and $15 per acre. Of course, this benefit should cover the difference in costs associated with both methods, which ranges between $0 and $20/acre. For example, the cost of on-the-go mapping can be similar to the 2.5-acre grid sampling, and the 1-acre grid sampling costs $20/acre more than the whole-field composite sampling.

Summary

When implementing different precision agriculture practices, site-specific management of soil pH has been shown to be one of the most promising strategies in fields with substantial variability in soil pH. Justification of variable-rate liming is complicated by the following: liming is a long-term investment; lime requirements across fields are not always highly variable; and the conventionally implemented 2.5-acre grid soil sampling does not provide the sampling density needed to accurately determine the variability of soil pH in many fields. The recently commercialized technology of on-the-go soil mapping provides a better basis of information about spatial variability of soil pH and other properties related to buffering characteristics (i.e., electrical conductivity). With proper consideration of all the information available, an optimized strategy for site-specific pH management can be developed and positive economic and environmental impacts can be achieved.

Additional recommended reading

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