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Presentation Outline

- Background
  - Problem statement and history of sensor development
  - Principle of commercial on-the-go mapping of soil pH
- Materials and Methods
  - Evaluation of alternative mapping approaches
  - Determination of lime requirement
- Results and Discussion
  - Comparison of alternative soil pH measurements and lime requirement estimates
  - Lessons learned from mapping several thousand hectares
  - On-the-spot measurement of soil pH
  - Summary and future development

Problem Statement

“Soil pH varied from 5.4 to 8.0 over distances of about 150 m in most transects. In some sections soil pH varied about 2 pH units over a 12 m distance...”


“It was concluded that a grid spacing of 30 m or less would be required to adequately assess the spatial variation of STP, STK, and soil pH. Sampling at this intensity would require approximately 11 times as many soil samples as the commonly used 100-m grid.”

Lauzon et al. (2005) Agronomy Journal 97:524-532

“Data points from large grids were too far apart to provide much information about the nature of pH or lime requirement change between adjacent sampling locations.”

Brouder et al. (2005) SSSA Journal 69:427-441

There is a need for on-the-go soil pH sensing technology

On-the-go Soil Sensors

- Electrical and Electromagnetic
- Optical and Radiometric
- Acoustic
- Mechanical
- Electrochemical
- Pneumatic

Conventional Soil Sampling

- Random
- Grid (Systematic) Sampling
  - Grid Point (Cluster) Method
    - Regular (Center)
    - Staggered and Random Start
    - Systematic Unaligned
    - Random
  - Grid Cell Method
- Adaptive
  - By Soil Types
  - By Management Zones

The Air Probe™

Automated soil sampling (20 containers)

Furrer FAB Designs
(Reynold, Indiana)
1999-2001
### Standard Soil pH Test

- **Preparation** (drying, crushing, sieving)
- **Solution**
  - 1:1 soil/water solution
- **Extraction**
  - DI water (soil pH)
  - SMP or Woodruff buffer solution (buffer pH)
- **Measurement**
  - Ion-selective electrode
  - Glass bulb

### Automated Soil Testing

- **Purdue University**
  - (West Lafayette, Indiana)
  - 1994-1996

### Direct Soil Measurement

- **Preparation**
  - Field conditions
- **Solution**
  - Naturally moist soil
- **Extraction**
  - Available ion activity
- **Measurement**
  - Ion-selective electrode
  - Flat (or dome) surface

### Automated Soil pH Mapping Systems

- **Purdue University**
  - (West Lafayette, Indiana)
  - 1997-2000

### Soil Sampling Mechanism

- **Removable Plates**
- **pH Sensor**
- **Sampling Platform**
- **Travel Direction**
- **Soil Shank**

### Pre-Commercial Sensor Development

- **Veris Technologies, Inc.**
  - (Salina, Kansas)
  - 2001-2003
Evaluation

On-the-Go Soil pH Mapping

Conventional Methods
- Uniform lime application rate based on the average of buffer pH measurements in a commercial laboratory
- Variable rate liming based on conventional 1 ha grid soil sampling results processed using the inverse-distance second-power interpolation

On-the-Go Methods
- Simple linear regression used to define buffer pH as a function of:
  - soil pH measurements only
  - linear combination of soil pH and shallow (0-30 cm) electrical conductivity measurements
  - locally-weighted partial least squares regression analysis of soil pH, electrical conductivity and hyper-spectral reflectance measurements

Validation
- Samples obtained using a 1 ha grid pattern were used to validate lime requirement maps based on sensor data. Ten directed soil samples from each field were used to determine buffer pH prediction equations and to validate conventional liming strategies. The RMSE (root MSE) was calculated for each field and served as the major indicator of map quality.

Results

On-the-Go Soil pH Mapping

<table>
<thead>
<tr>
<th>Field ID</th>
<th>Area, ha</th>
<th>Number of measurements</th>
<th>Mapping Density</th>
<th>pH only</th>
<th>pH and EC</th>
<th>RMSE, pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Illinois 1</td>
<td>250</td>
<td>18</td>
<td>Soil pH laboratory analysis</td>
<td>0.16 0.20</td>
<td>0.18 0.36</td>
<td>0.15 0.30</td>
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<td>18</td>
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<td>0.65 0.59</td>
<td>0.65 0.59</td>
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<tr>
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<td>18</td>
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<td>0.76 0.39</td>
<td>0.76 0.39</td>
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<td>0.76 0.39</td>
</tr>
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<td>0.76 0.39</td>
<td>0.76 0.39</td>
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<tr>
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<td>0.76 0.39</td>
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<td>0.76 0.39</td>
</tr>
<tr>
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<td>0.76 0.39</td>
<td>0.76 0.39</td>
</tr>
<tr>
<td>Kansas 6</td>
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<td>0.76 0.39</td>
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</tr>
<tr>
<td>Nebraska 1</td>
<td>250</td>
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<td>Soil pH laboratory analysis</td>
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<td>0.66 0.69</td>
<td>0.66 0.69</td>
</tr>
<tr>
<td>Nebraska 2</td>
<td>250</td>
<td>42</td>
<td>Soil pH laboratory analysis</td>
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<tr>
<td>Wisconsin 1</td>
<td>250</td>
<td>42</td>
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<thead>
<tr>
<th>Field ID</th>
<th>Number of validation samples</th>
<th>Uniform liming</th>
<th>Grid sampling</th>
<th>On-the-go mapping</th>
<th>pH only</th>
<th>pH and EC</th>
<th>RMSE, pH</th>
</tr>
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<tbody>
<tr>
<td>Kansas 1</td>
<td>10 / 32</td>
<td>2005</td>
<td>2005</td>
<td>1117 kg/ha</td>
<td>1259 kg/ha</td>
<td>0.18 0.36</td>
<td>0.18 0.36</td>
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<tr>
<td>Kansas 2</td>
<td>10 / 57</td>
<td>1930</td>
<td>2005</td>
<td>1470 kg/ha</td>
<td>1450 kg/ha</td>
<td>0.18 0.36</td>
<td>0.18 0.36</td>
</tr>
<tr>
<td>Nebraska 1</td>
<td>10 / 32</td>
<td>2527</td>
<td>2005</td>
<td>2701 kg/ha</td>
<td>2527 kg/ha</td>
<td>0.18 0.36</td>
<td>0.18 0.36</td>
</tr>
<tr>
<td>Nebraska 2</td>
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<td>2527</td>
<td>2005</td>
<td>2701 kg/ha</td>
<td>2527 kg/ha</td>
<td>0.18 0.36</td>
<td>0.18 0.36</td>
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<tr>
<td>Wisconsin 1</td>
<td>10 / 14</td>
<td>2900</td>
<td>2900</td>
<td>1400 kg/ha</td>
<td>1400 kg/ha</td>
<td>0.18 0.36</td>
<td>0.18 0.36</td>
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</tr>
</tbody>
</table>

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

- “–” significant (α = 0.05) decrease of MSE compared to the uniform liming
- “–” significant (α = 0.05) decrease of MSE compared to the grid sampling
- “–” significant (α = 0.05) decrease of MSE compared to the on-the-go mapping of pH only

Kansas 1 field was mapped using a near-infrared spectrometer sensor in addition to the pH and EC maps. Lime requirement map generated based on the three sensors had further reduced RMSE (645 kg/ha).
### Additional Observations

#### Rinsing Water Quality

1. In coarse sands, pH electrode response is typically slower than in heavier soils or with purified water.

2. On-the-go pH measurements using tap water may be noticeably affected by the pH of the water, spatial pattern frequently remains unchanged.

![Graph showing pH response time](image)

#### Repeatability of Soil pH Map Patterns

1. Soil pH values change due to:
   - pH temporal variability
   - alternative rinsing water sources
   - sampling depth
   - unknown factors

2. The pattern of pH variability remains consistent.

![Soil pH map patterns](image)

#### Some Causes of Soil pH Variability

1. Irrigation effects: lower pH within rain-fed field corners

2. Road effects: higher pH along gravel roads (limestone deposits)

![Soil pH map with road effects](image)

#### Indirect Prediction of Soil pH Variability

Relationships between pH and soil type (electrical conductivity) can be weak.

![Soil pH map with soil types](image)

#### Spatial Structure of Soil pH

Spatial structure of soil pH is variable from field to field.

![Soil pH map showing spatial variation](image)

#### Effect of Field Variability of Soil pH

<table>
<thead>
<tr>
<th>Field ID</th>
<th>SD</th>
<th>RMSE</th>
<th>RDP = SD/RMSE</th>
<th>F-stat</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Illinois 1</td>
<td>0.58</td>
<td>0.26</td>
<td>2.0</td>
<td>3.0</td>
<td>0.05</td>
</tr>
<tr>
<td>Illinois 2</td>
<td>0.74</td>
<td>0.26</td>
<td>2.7</td>
<td>1.1</td>
<td>0.66</td>
</tr>
<tr>
<td>Illinois 3</td>
<td>0.97</td>
<td>0.26</td>
<td>2.7</td>
<td>6.1</td>
<td>0.08</td>
</tr>
<tr>
<td>Iowa</td>
<td>0.61</td>
<td>0.26</td>
<td>2.4</td>
<td>3.3</td>
<td>0.06</td>
</tr>
<tr>
<td>Kansas 1</td>
<td>0.42</td>
<td>0.24</td>
<td>1.7</td>
<td>1.5</td>
<td>0.06</td>
</tr>
<tr>
<td>Kansas 2</td>
<td>0.61</td>
<td>0.24</td>
<td>1.5</td>
<td>1.5</td>
<td>0.06</td>
</tr>
<tr>
<td>Kansas 3</td>
<td>0.51</td>
<td>0.33</td>
<td>2.3</td>
<td>1.5</td>
<td>0.06</td>
</tr>
<tr>
<td>Kansas 4</td>
<td>0.46</td>
<td>0.26</td>
<td>2.5</td>
<td>1.5</td>
<td>0.06</td>
</tr>
<tr>
<td>Kansas 5</td>
<td>0.46</td>
<td>0.26</td>
<td>2.5</td>
<td>1.5</td>
<td>0.06</td>
</tr>
<tr>
<td>Kansas 6</td>
<td>0.38</td>
<td>0.23</td>
<td>2.3</td>
<td>0.5</td>
<td>0.07</td>
</tr>
<tr>
<td>Kansas 7</td>
<td>0.73</td>
<td>0.28</td>
<td>1.5</td>
<td>2.8</td>
<td>0.01</td>
</tr>
<tr>
<td>Nebraska 1</td>
<td>0.32</td>
<td>0.21</td>
<td>1.5</td>
<td>1.3</td>
<td>0.06</td>
</tr>
<tr>
<td>Nebraska 2</td>
<td>0.73</td>
<td>0.21</td>
<td>1.6</td>
<td>1.6</td>
<td>0.06</td>
</tr>
<tr>
<td>Wisconsin</td>
<td>0.54</td>
<td>0.21</td>
<td>1.6</td>
<td>2.2</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Fields with potential benefits from variable rate liming:

Assuming 0.3 pH measurement error, the standard deviation of a field that could benefit from variable rate liming is at least 0.6 pH (10% CV) if estimated based on 10 unbiased measurements.
On-the-Spot Measurement of Soil pH

Soil pH Demonstration Plots

Additional Observations
Field Capacity

Summary

Future Work

1. Growers, suppliers, and consultants are main users of the on-the-go pH mapping
2. Between 100 and 150 ha/day field capacity is typical
3. Approximately 5,000 ha/year has been accomplished by current users

• Automated mapping of soil pH on-the-go has become available commercially
• Soil pH Manager™ could produce 15-20 times more measurements than 1 ha grid sampling with a comparable effort
• Validation sampling of sensor measurements resulted in acceptable \( r^2 = 0.80 \) correlation with conventional laboratory analyses
• 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)
• Potential benefits of variable rate liming are site-specific and can be assessed using a low-cost measurement option

Future Work

• Integrating soluble potassium and residual nitrate mapping capability
• Fusion of optical reflectance and/or other spatial data for improved quality of recommendations
• Comprehensive evaluation of various lime prescription methods
• Numeric agro-economic evaluation of information value possessed by soil maps obtained on-the-go

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