Development of On-the-Go Soil Sensor Systems

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Problem Statement

• The assessment of soil variability is one of the most important steps in site-specific management
• Conventional means to attain soil variability data are incapable of accurately identifying spatial inconsistency within a production field at an economically feasible cost
• There is a need to develop equipment for mapping soil attributes on-the-go

Sensor Use Approaches

Map-Based Approach

Integrated Approach
(Real-Time with Supplemental Base Map)

Agricultural Machine Systems

Tillage

Planting

Fertilization

Harvesting

Irrigation

Crop protection

Spatial data collection

On-the-go Soil Sensors

Electrical and Electromagnetic

Acoustic

Mechanical

Electrochemical

Optical and Radiometric

Pneumatic

Applicability of On-the-Go Soil Sensors

<table>
<thead>
<tr>
<th>Soil property</th>
<th>Good</th>
<th>OK</th>
<th>Some</th>
<th>Good</th>
<th>Some</th>
<th>Good</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil texture (clay, silt and sand)</td>
<td></td>
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<tr>
<td>Soil organic matter or total carbon</td>
<td></td>
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<tr>
<td>Soil water (moisture)</td>
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<tr>
<td>Soil salinity (sodium)</td>
<td></td>
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<tr>
<td>Soil compaction (bulk density)</td>
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<tr>
<td>Depth variability (hard pan)</td>
<td></td>
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<tr>
<td>Soil pH</td>
<td></td>
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<tr>
<td>Residual nitrate (total nitrogen)</td>
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<tr>
<td>Other nutrients (potassium)</td>
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<tr>
<td>CEC (other buffer indicators)</td>
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</tbody>
</table>
Electrical and Electromagnetic Sensors

**Electrical Conductivity/Resistivity Sensors**
- Soil type/texture
- Salinity
- Water content
- Organic matter content
- Depth variability
- Soil pH / nitrate content

**Capacitively-Coupled Resistivity Method**
- Volumetric water content
- Soil type/structure
- Subsurface soil impurities
- Iron

**Dielectric Sensors**
- Subsurface soil impurities
- Volumetric water content

**Magnetic Sensors**
- Soil type/structure
- Salinity

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**Galvanic Contact Resistivity Method**

Veris Technologies, Inc.
(Salina, Kansas)
http://www.veristech.com
- Veris® 3100 and MSP
  (0.3 and 0.9 m)

Geocarta (Paris, France)
http://www.geocarta.net
- Geocarta ARP
  (0.5, 1, and 2 m)

Crop Technologies, Inc.
(Spring, Texas)
http://www.soildoctor.com
- Soil Doctor® System
  (real-time approach)

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**Electromagnetic Induction Method**

Geonics Limited
(Mississauga, Ontario)
http://www.geonics.com
- Geonics EM-38
  horizontal – 0.75 m
  vertical – 1.5 m

Dualem, Inc.
(Milton, Ontario)
http://www.dualem.com
- DUALEM – 1S
  co-planar – 0.4 m
  perpendicular – 0.95 m

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**Capacitively-Coupled Resistivity Method**

Geometrics, Inc.
(San Jose, California)
http://www.geometrics.com
- Geometrics OhmMapper TR1

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**Example 1**
**Electrical Conductivity Map**

Improved Soil Type Separation
EC Map

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**Example 2**
**Electrical Conductivity Map**

Low Yielding Area
High Yielding Area
Yield Map
Example 3
Electrical Conductivity Map

Shallow EC  Deep EC  Shallow/Deep EC

Dielectric Sensor
UNL (Lincoln, Nebraska) – Retrokool (Berkeley, California) 2001-2003

- Silty clay loam soil
- Triple replicates
- Two tests

Dielectric Sensor Map

Soil Water Content

Gravimetric soil moisture

Sensor measurement

Laboratory measurement

Volumetric soil moisture

Sensor measurement

Gravimetric soil moisture

R² = 0.85

SE = 2.7%

0% 5% 10% 15% 20% 25% 30%

Sensor measurement

Laboratory measurement

Volumetric soil moisture

R² = 0.85

SE = 3.9%

0% 10% 20% 30% 40%

Sensor measurement

Laboratory measurement

Magnetic Sensor

Mapping spatial variations in Earth magnetic field (related to magnetic susceptibility)

Induced Magnetization (walls and ditches)

Thermoremanent Magnetization (iron, bricks)

Geocarta (Paris, France) http://www.geocarta.net

Geocarta AMP

Optical and Radiometric Sensors

Subsurface Soil Reflectance Sensors

Microwave Sensors

Ground Penetrating Radar

- Water content

Gamma Radiometer

- Water content

- Geophysical soil structure

- Organic matter (carbon) content
- Soil texture
- Cation exchange capacity (CEC)
- Soil water content
- Soil pH
- Mineral nitrogen and phosphorous

- Potassium
- Uranium
- Thorium

Small Scale Topography
**Example**

**Soil Mechanical Resistance Map**

- **Compact area**
- **Old roads**

**Yield Map**

**Soil Mechanical Resistance Map (20-30 cm)**

**Integrated Soil Physical Properties Mapping System**

- **UNL (Lincoln, Nebraska)**
- **Two wavelengths soil reflectance sensor**
- **Capacitor-based sensor**

**Soil mechanical resistance profiler with an array of strain gage bridges**

**Vertical Blade with Strain Gage Array**

- **Discrete Model**
- **Polynomial Model**

**Apparent Soil Profiles**

- **Plot B (disked)**
- **Plot C (chiselled and disked)**

**Integrated Load Comparison**

**Vertical Blade with Strain Gage Array**

**Discrete Model**

- **Polynomial Model**

**Linear Model**

**Tillage Plot**

- **Tillage Plot**

**Treatment**

- **A** plowed and double disked
- **B** disked
- **C** no-till with cultivation
- **D** chiselled and disked
- **E** double disked
- **F** no-till with cultivation
Soil Mechanical Resistance

Profile Average

Increase with Depth

5 – 30 cm depth

Bulk Density Prediction

Moisture

R^2 = 0.50

Soil Mechanical Resistance

R^2 = 0.19

Disc Coulter Sensor

Rotational Potentiometer

UNL (Lincoln, Nebraska)

Instrumented Tillage Implement

Laptop with DAQ Card

GPS Antenna

Signal Conditioning Unit

Load Cells

Custom Protective Shin

Custom Point

Variable Depth Tillage Concept

US Patent No. 7,028,554

Acoustic and Pneumatic Sensors

Soil Penetration Noise Sensors

Air Permeability Sensor

University of Illinois (Urbana-Champaign, Illinois)

University of Kentucky (Lexington, Kentucky)

- Soil clay content (type)
- Soil compaction
- Depth of hard (plow) pan
- Soil structure/tilth
- Water content
- Soil type
**Electrochemical Sensors**

- Ion-Selective Electrodes (ISEs)
- Ion-Selective Field Effect Transistors (ISFETs)

**Measurement Methods**

- Soil Solution Measurement
- Agitated Soil Measurement
- Direct Soil Measurement

**Activity of selected ions**

- Soil pH (H+)
- Potassium content (K⁺)
- Residual nitrogen (NO₃⁻-N)
- Sodium content (Na⁺)

**Automated Soil Testing**

- Purdue University (West Lafayette, Indiana)

**Soil/Buffer pH Mapping On-the-Go**

- The University of Sydney (Sydney, Australia)
- JTI (Uppsala, Sweden)

**Automated Soil pH Mapping Systems**

- Purdue University (West Lafayette, Indiana)

**Soil Sampling Mechanism**

- Soil Sample
- Travel Direction
- Removable Plates
- Water Nozzle
- Air Cylinder

**Soil pH Measurements On-the-Go**

- Data Set 1
- Data Set 2
- Laboratory

- Distance from the West End, m
Mobil Sensor Platform (MSP)

Veris Technologies, Inc. (Salina, Kansas)
http://www.veristech.com

Direct Soil Measurement

Purdue University (West Lafayette, Indiana)
Veris Technologies, Inc. (Salina, Kansas)
UNL (Lincoln, Nebraska)

Soil pH Manager

Example

Soil pH Mapping

Purdue University (West Lafayette, Indiana)
Veris Technologies, Inc. (Salina, Kansas)

Soil pH Maps of a Kansas Field

Evaluation Fields

<table>
<thead>
<tr>
<th>Field ID</th>
<th>Textural range</th>
<th>Max slope</th>
<th>Lab pH</th>
<th>EC (mS m⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IA1</td>
<td>Loam / silty clay loam</td>
<td>5%</td>
<td>5.18 (0.77)</td>
<td>9.26 (5.58)</td>
</tr>
<tr>
<td>IL1</td>
<td>Loam / clay loam</td>
<td>2%</td>
<td>6.28 (0.41)</td>
<td>11.44 (2.22)</td>
</tr>
<tr>
<td>IL2</td>
<td>Loam / clay loam</td>
<td>2%</td>
<td>6.52 (0.86)</td>
<td>14.88 (3.66)</td>
</tr>
<tr>
<td>KS1</td>
<td>Silt loam / silty clay loam</td>
<td>6%</td>
<td>5.34 (0.27)</td>
<td>3.17 (1.00)</td>
</tr>
<tr>
<td>KS2</td>
<td>Silty clay loam</td>
<td>3%</td>
<td>6.62 (0.68)</td>
<td>16.49 (4.6)</td>
</tr>
<tr>
<td>NE1</td>
<td>Silty clay loam</td>
<td>11%</td>
<td>5.95 (0.84)</td>
<td>25.86 (4.97)</td>
</tr>
<tr>
<td>OK1</td>
<td>Loamy fine sand</td>
<td>2%</td>
<td>6.16 (0.64)</td>
<td>0.96 (0.99)</td>
</tr>
<tr>
<td>WI1</td>
<td>Silt loam</td>
<td>18%</td>
<td>6.60 (0.47)</td>
<td>3.22 (1.08)</td>
</tr>
</tbody>
</table>

27-84 acre fields
12-34 grid samples (0.3-0.5 samples/acre)
250-598 MSP measurements (4-11 measurements/acre)
5 calibration samples & 5 validation samples

Mapping Alternatives

On-the-Go Sensing

Soil Sampling

Universal MSP pH

Adjusted MSP pH

Shifted MSP pH

Universal MSP pH = Intercept_universal + Slope_universal * MSP pH

Adjusted MSP pH = Intercept_adjusted + Slope_adjusted * MSP pH

Shifted MSP pH = Shift_adjusted * MSP pH

Soil pH Maps Evaluation

2.5 Acre Grid

Field Average

Raw MSP

Adjusted MSP

Universal MSP

Shifted MSP
**Numeric Agro-Economic Mode**

\[
\text{Income} = f(\text{Soil pH}) \quad \text{Soil pH} = f(\text{True pH, Lime, Probability})
\]

\[
\text{NRCL} = f(\text{Income, Cost}) \quad \text{True pH} = f(\text{Probability}) \quad \text{Lime} = f(\text{Estimated pH})
\]

\[
\text{Cost} = f(\text{Lime})
\]

\[
\text{Estimated pH} = f(\text{True pH, Probability})
\]

\[
\text{True pH} = f(\text{Probability})
\]

**Model Input Modules:**
- Categorized distributions
- Categorized functional relationships
- Multidimensional arrays

**Model Output**
- Net Return over Cost of Lime (NRCL)

\[
\text{NRCL} = \frac{P_c}{1 + d} Y_c + \frac{P_s}{1 + d} Y_s + \frac{P_c}{1 + d} Y_{C1} + \frac{P_s}{1 + d} Y_{S1} - C_l \cdot Q_l
\]

- \(d\) = annual discount rate
- \(P_c\) = price of corn
- \(P_s\) = price of soybean
- \(Y_c\) = corn yield
- \(Y_s\) = soybean yield
- \(C_l\) = cost of lime
- \(Q_l\) = prescribed lime application rate

**Value of Information**

How much is a map of soil pH worth?

- High accuracy soil map (on-the-go mapping, high-density or adaptive sampling)
- Low accuracy soil map (grid sampling, uniform field treatment)

Expected value of high versus low accuracy soil maps

\$10 to \$30 per ha (4 years)

**Portable Probe**

On-the-Spot Measurement of Soil pH

- Portable Probe
- Reference Lab

**Antimony Electrode**

Sandy and stony soils

**Integrated Direct Soil Measurement**

UNL (Lincoln, Nebraska)

15 Nebraska soils with fixed field water content

**UNL**

\(R^2 = 0.99\) (SE = 0.23)

\(R^2 = 0.35\) (0.61 means)

\(R^2 = 0.52\) (0.62 means)

\(R^2 = 0.93\) (0.96 means)

\(R^2 = 0.99\) (SE = 0.23)

**Soil pH**

- Glass Electrodes
- Antimony Electrodes

**Soil pH**

- Sandy and stony soils

\(pK\)

\(pNO_3\)
**Integrated Agitated Soil Measurement**

- **Motor-Stirrer**
- **Ion-selective Electrodes (ISE)**
- **Agitation Chamber and Stirrer**
- **Soil Sampler**

1. 1:1 solutions with 15 Nebraska soils

### Reference tests:
- Soil pH
  - Glass ion-selective electrode
  - RMSE = 0.05 pH
- Soluble potassium
  - Atomic absorption spectroscopy (AAS)
  - RMSE = 0.01 pK
- Residual nitrate
  - Cadmium reduction (CR)
  - RMSE = 0.02 pNO3

### Errors and Precision:
- **R2** = 0.87 (0.91 means)
- **RMSE (Precision)** = 0.15 pH
- **Reg. SE (Accuracy)** = 0.20 pH

### Errors and Precision:
- **R2** = 0.32 (0.40 means)
- **RMSE (Precision)** = 0.17 pNO3
- **Reg. SE (Accuracy)** = 0.22 pNO3

### Errors and Precision:
- **R2** = 0.54 (0.63 means)
- **RMSE (Precision)** = 0.10 pK
- **Reg. SE (Accuracy)** = 0.13 pK

### Errors and Precision:
- **R2** = 0.98 (0.99 means)
- **RMSE (Precision)** = 0.08 pH
- **Reg. SE (Accuracy)** = 0.09 pH

### Errors and Precision:
- **R2** = 0.48 (0.67 means)
- **RMSE (Precision)** = 0.13 pNO3
- **Reg. SE (Accuracy)** = 0.10 pNO3

### VRT Prescription

- **LR = f (buffer pH)**
- **Buffer pH = f (soil pH, CEC)**

### K rate = f (exchangeable K)
- **Exchangeable K = f (soluble K, CEC)**

### Integrated Multiple Data Layers

- **Soil pH**
- **Clay**
- **OM**

**Maps produced by Veris Technologies, Inc. (Salina, Kansas)**

### Status of Implementation

- **Commercial**
  - Electrical conductivity
  - Topography
  - Soil pH
  - Visual/near-infrared spectroscopy

- **Available solutions**
  - Implement draft
  - Ground penetrating radar
  - Magnetic field
  - Gamma-radiometry

- **Upcoming solutions**
  - Capacitance (moisture)
  - Residual nitrate and soluble potassium
  - Soil mechanical resistance
  - Machine vision
  - Small scale topography

- **Sensor fusion**
- **New applications**
Directed (Guided) Sampling

- Directed sampling should be used to calibrate and/or validate sensor data
- Directed samples should be collected from relatively homogeneous field areas away from the boundary and other transitional areas
- Directed samples should cover the entire range of sensor-based measurements, especially toward low and high ends
- Directed samples should be physically spread across the entire field
- It should be possible to process multiple sensor-based data layers

Currently Considered Criteria

- Homogeneity
- Neighborhood variability
- Even data spread
- D-optimality
- Even field coverage
- Spatial predictability

Example

Soil pH Mapping

- Property: Soil pH
- Instrument: Veris® Mobile Sensor Platform
- Field area: 23 ha
- Number of valid measurements: 598
- Number of guided samples: 10
- Different sets of samples considered: 63
  - Random selection: 20
  - Grid cell spread: 19
  - Even soil pH spread: 20
  - Maximum homogeneity: 1
  - Grid cell centers: 1
  - Subjunctive selection: 2

Soil pH Histogram

Complete Randomization

Soil pH
- <5.4
- 5.4–5.9
- 5.9–6.4
- 6.4–6.9
- 6.9–7.4
- >7.4
Grid Cell Spread

Even Soil pH Spread

Maximum Homogeneity

Grid Cell Centers

Subjunctive Selection

Z-Score Comparison
Summary

• On-the-go soil sensors can provide high density information about soil properties
• Many sensor approaches are past initial commercialization stage
• Sensor fusion provides the ability to separate various agronomic effects
• Site-specific sensor calibration and validation are essential steps of the mapping process
• Laboratory soil analysis remains a required supplementary practice
• Agro-economic value of selected sensor-based data layers is site-specific

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