First Global Workshop on High Resolution Digital Soil Sensing and Mapping (Sydney, Australia)
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Development of On-the-Go Soil Sensor Systems

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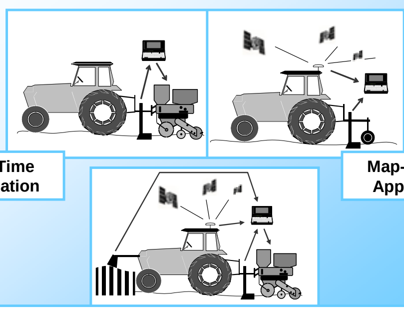
University of Nebraska-Lincoln

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



Real-Time Application

Map-Based Approach

Integrated Approach
(Real-Time with Supplemental Base Map)

Agricultural Machine Systems

Tillage

Planting

Fertilization

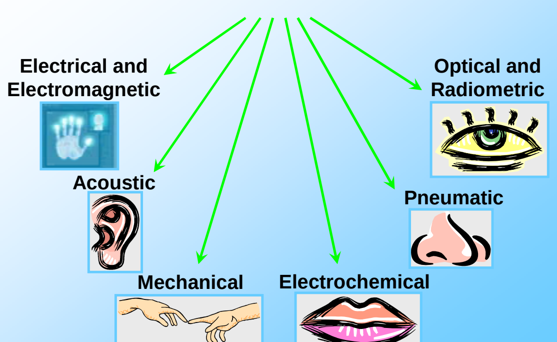
Harvesting

Irrigation

Crop protection

Spatial data collection

On-the-go Soil Sensors



Applicability of On-the-Go Soil Sensors

Soil property					
Soil texture (clay, silt and sand)	Good	OK		Some	
Soil organic matter or total carbon	Some	Good			
Soil water (moisture)	Good	Good			
Soil salinity (sodium)	OK				Some
Soil compaction (bulk density)			Good	Some	
Depth variability (hard pan)	Some		OK	Some	
Soil pH		Some			Good
Residual nitrate (total nitrogen)	Some	Some			OK
Other nutrients (potassium)		Some			OK
CEC (other buffer indicators)	OK	OK			

Electrical and Electromagnetic Sensors

Electrical Conductivity/Resistivity Sensors

Dielectric Sensors

Magnetic Sensors

Galvanic Contact Resistivity Method

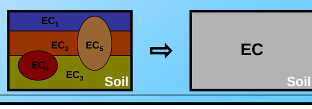
Electromagnetic Induction Method

Capacitively-Coupled Resistivity Method

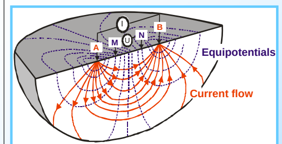
- *Soil type/texture*
- *Salinity*
- *Water content*
- *Organic matter content*
- *Depth variability*
- *Soil pH / nitrate content*

- *Volumetric water content*
- *Soil type/structure*
- *Salinity*

- *Subsurface soil impurities*
- *Iron*



Galvanic Contact Resistivity Method



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

Veris® 3100 and MSP
(0.3 and 0.9 m)

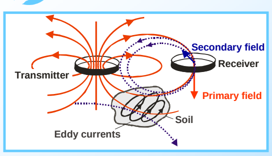
Geocarta (Paris, France)
http://www.geocarta.net

Geocarta ARP
(0.5, 1, and 2 m)

Crop Technologies, Inc.
(Spring, Texas)
http://www.soildoctor.com

Soil Doctor® System
(real-time approach)

Electromagnetic Induction Method



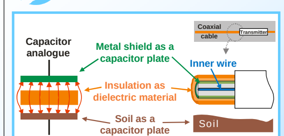
Geonics Limited
(Mississauga, Ontario)
http://www.geonics.com

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

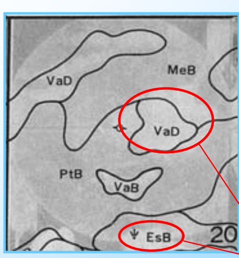
Capacitively-Coupled Resistivity Method

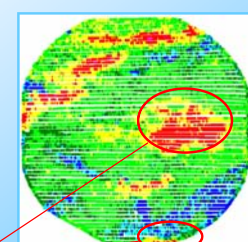


Geometrics, Inc.
(San Jose, California)
http://www.geometrics.com

Geometrix OhmMapper TR1

Example 1
Electrical Conductivity Map



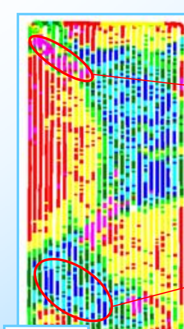


Soil Survey

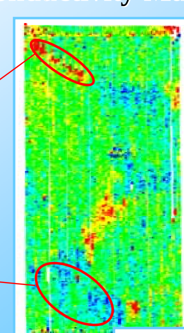
Improved Soil Type Separation

EC Map

Example 2
Electrical Conductivity Map



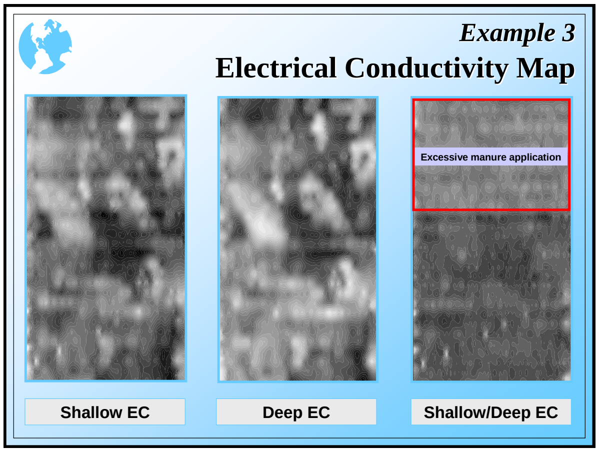
Low Yielding Area

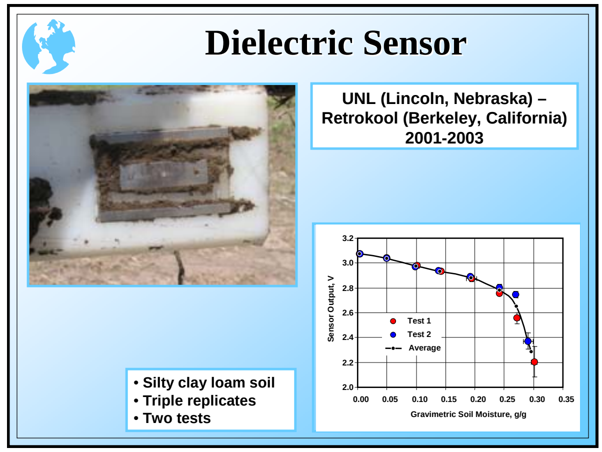


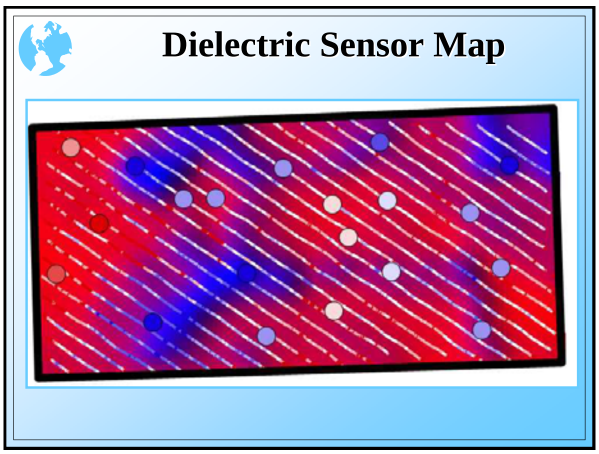
High Yielding Area

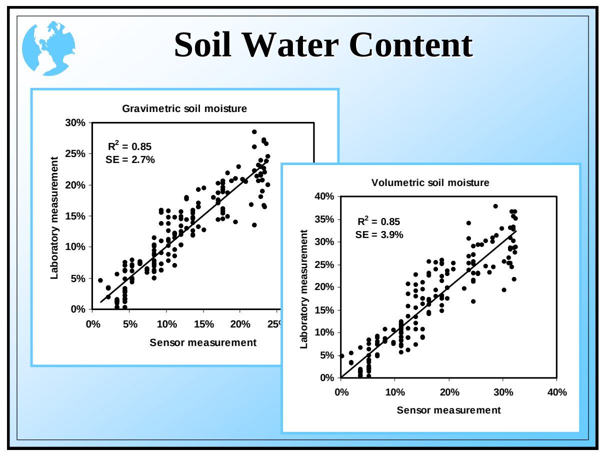
EC Map

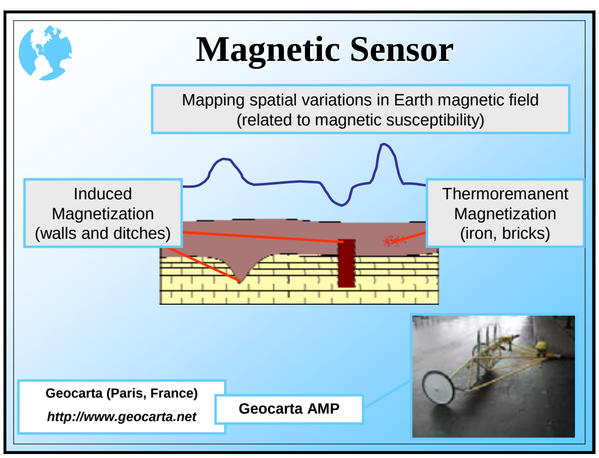
Yield Map

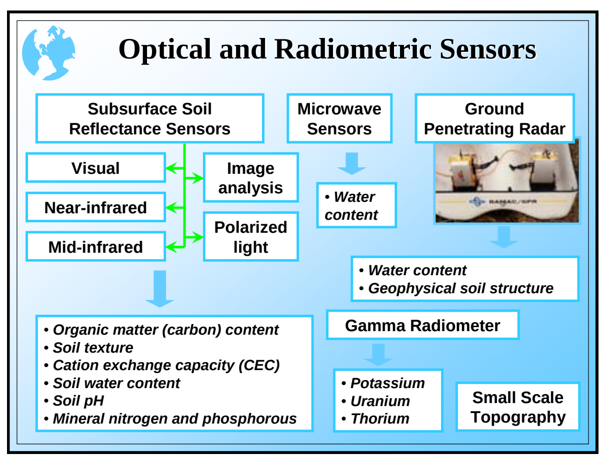

Example 3
Electrical Conductivity Map
Excessive manure application
Shallow EC
Deep EC
Shallow/Deep EC

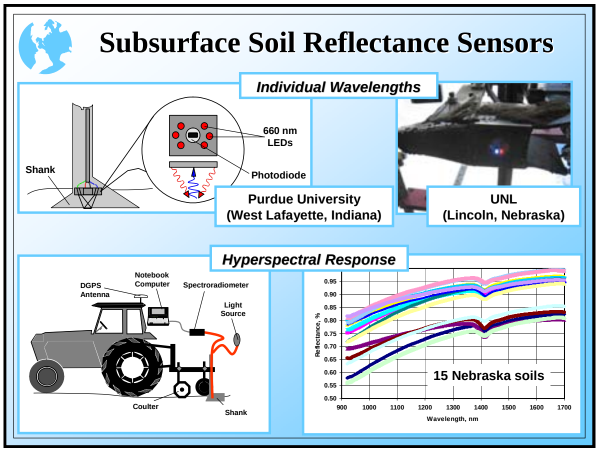

Dielectric Sensor
UNL (Lincoln, Nebraska) – Retrokool (Berkeley, California) 2001-2003
• Silty clay loam soil
• Triple replicates
• Two tests
Sensor Output, V
Test 1
Test 2
Average
Gravimetric Soil Moisture, g/g

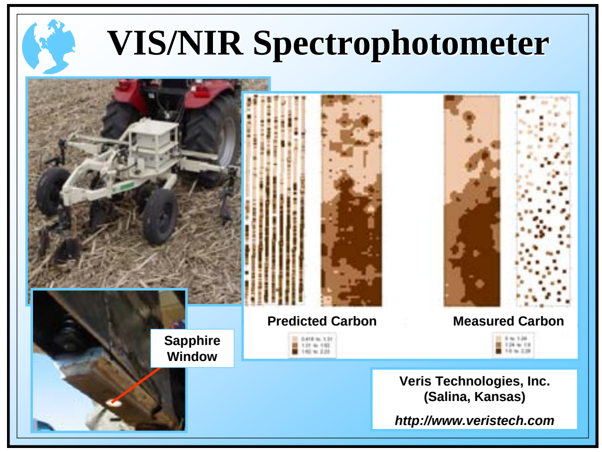

Dielectric Sensor Map

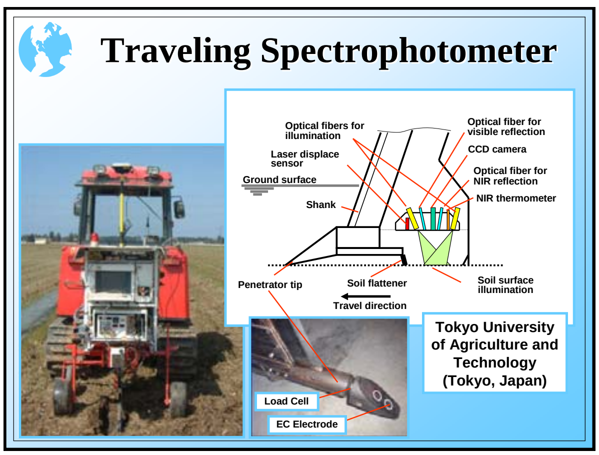

Soil Water Content
Gravimetric soil moisture
R² = 0.85
SE = 2.7%
Laboratory measurement
Sensor measurement
Volumetric soil moisture
R² = 0.85
SE = 3.9%
Laboratory measurement
Sensor measurement

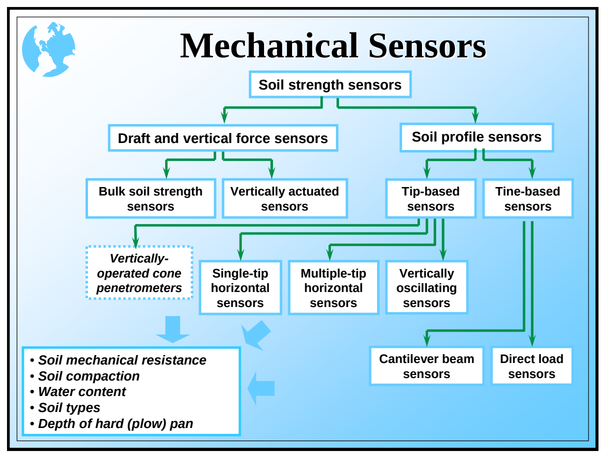

Magnetic Sensor
Mapping spatial variations in Earth magnetic field
(related to magnetic susceptibility)
Induced
Magnetization
(walls and ditches)
Thermoremanent
Magnetization
(iron, bricks)
Geocarta (Paris, France)
http://www.geocarta.net
Geocarta AMP

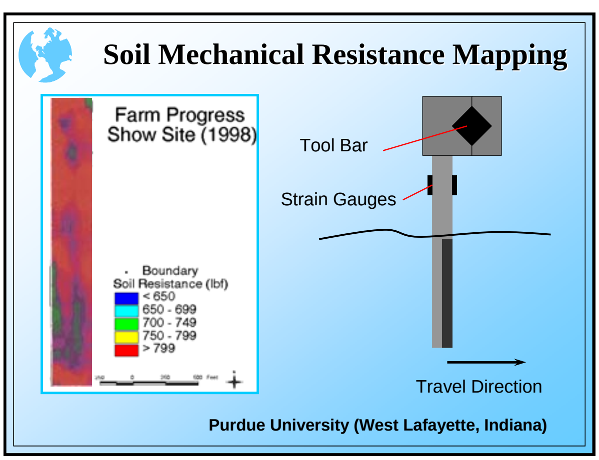

Optical and Radiometric Sensors
Subsurface Soil Reflectance Sensors
Microwave Sensors
Ground Penetrating Radar
Visual
Near-infrared
Mid-infrared
Image analysis
Polarized light
• Water content
• Water content
• Geophysical soil structure
• Organic matter (carbon) content
• Soil texture
• Cation exchange capacity (CEC)
• Soil water content
• Soil pH
• Mineral nitrogen and phosphorous
Gamma Radiometer
• Potassium
• Uranium
• Thorium
Small Scale Topography

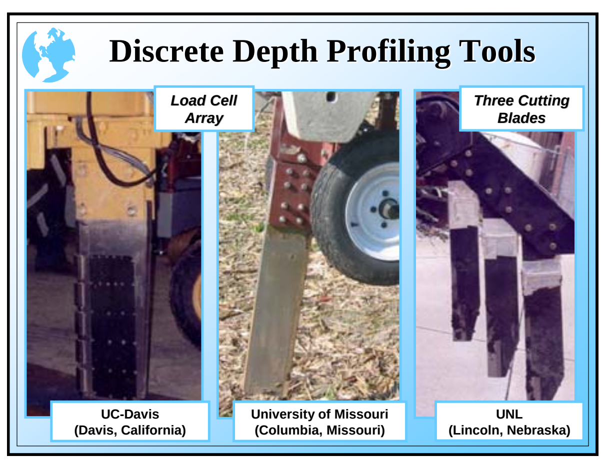

Subsurface Soil Reflectance Sensors
Individual Wavelengths
Shank
660 nm LEDs
Photodiode
Purdue University (West Lafayette, Indiana)
UNL (Lincoln, Nebraska)
Hyperspectral Response
DGPS Antenna
Notebook Computer
Spectroradiometer
Light Source
Coulter
Shank
Reflectance, %
15 Nebraska soils
Wavelength, nm

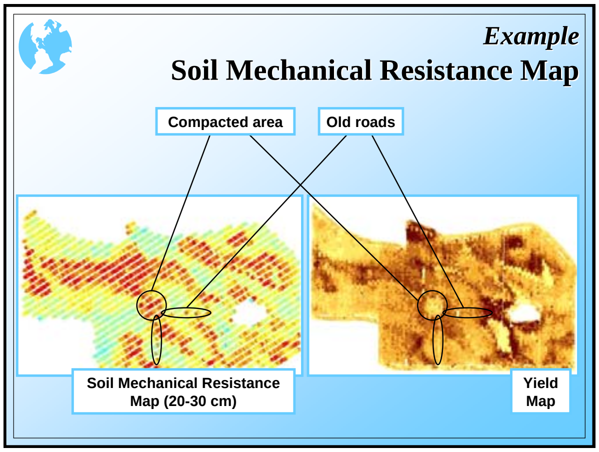

VIS/NIR Spectrophotometer
Sapphire Window
Predicted Carbon
Measured Carbon
Veris Technologies, Inc. (Salina, Kansas)
http://www.veristech.com

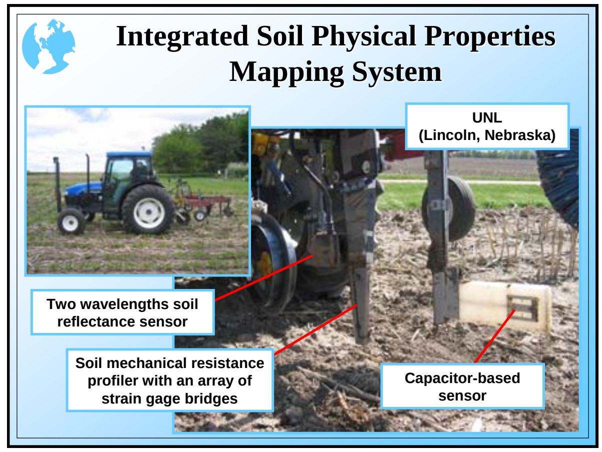

Traveling Spectrophotometer
Optical fibers for illumination
Optical fiber for visible reflection
Laser displace sensor
CCD camera
Ground surface
Optical fiber for NIR reflection
NIR thermometer
Shank
Penetrator tip
Soil flattener
Soil surface illumination
Travel direction
Load Cell
EC Electrode
Tokyo University of Agriculture and Technology (Tokyo, Japan)

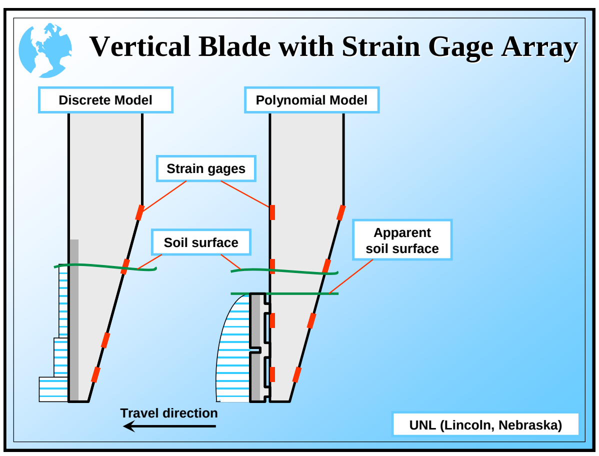

Mechanical Sensors
Soil strength sensors
Draft and vertical force sensors
Soil profile sensors
Bulk soil strength sensors
Vertically actuated sensors
Tip-based sensors
Tine-based sensors
Vertically-operated cone penetrometers
Single-tip horizontal sensors
Multiple-tip horizontal sensors
Vertically oscillating sensors
Cantilever beam sensors
Direct load sensors
• Soil mechanical resistance
• Soil compaction
• Water content
• Soil types
• Depth of hard (plow) pan

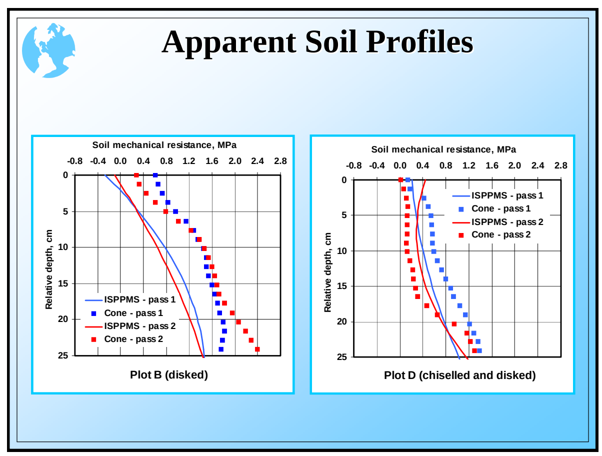

Soil Mechanical Resistance Mapping
Farm Progress Show Site (1998)
Boundary
Soil Resistance (lbf)
< 650
650 - 699
700 - 749
750 - 799
> 799
Tool Bar
Strain Gauges
Travel Direction
Purdue University (West Lafayette, Indiana)

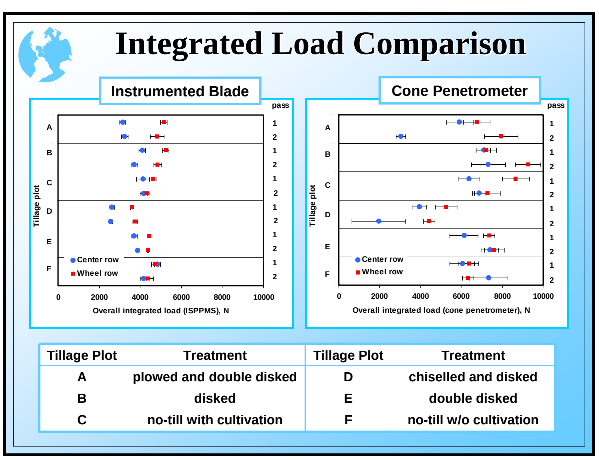

Discrete Depth Profiling Tools
Load Cell Array
Three Cutting Blades
UC-Davis (Davis, California)
University of Missouri (Columbia, Missouri)
UNL (Lincoln, Nebraska)

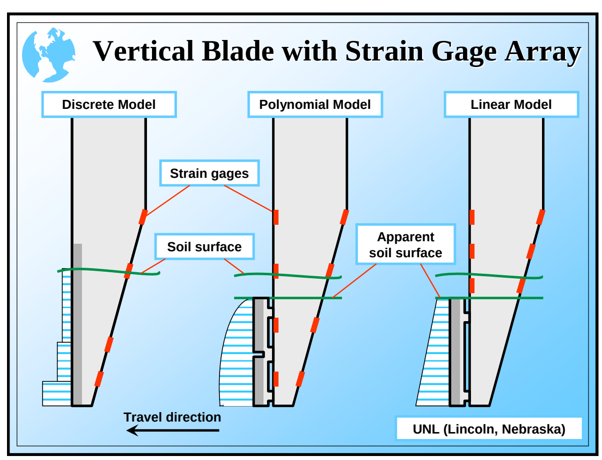

Example
Soil Mechanical Resistance Map
Compacted area
Old roads
Soil Mechanical Resistance Map (20-30 cm)
Yield Map

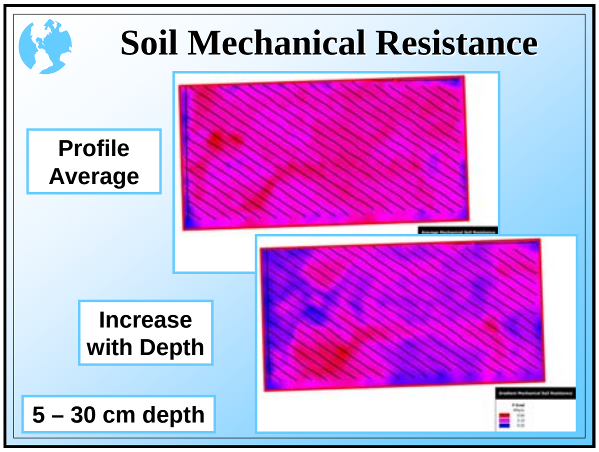

Integrated Soil Physical Properties Mapping System
UNL (Lincoln, Nebraska)
Two wavelengths soil reflectance sensor
Soil mechanical resistance profiler with an array of strain gage bridges
Capacitor-based sensor

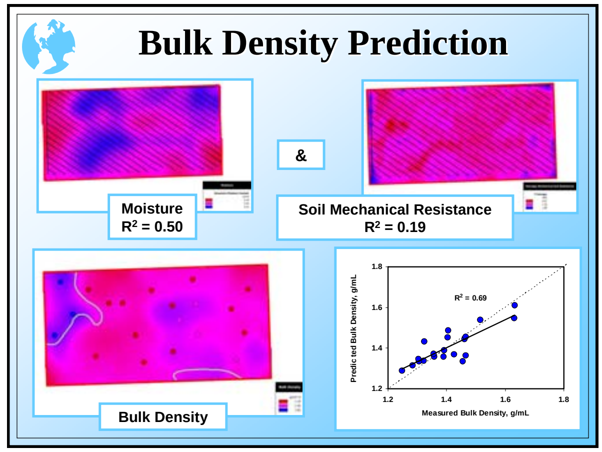

Vertical Blade with Strain Gage Array
Discrete Model
Polynomial Model
Strain gages
Soil surface
Apparent soil surface
Travel direction
UNL (Lincoln, Nebraska)

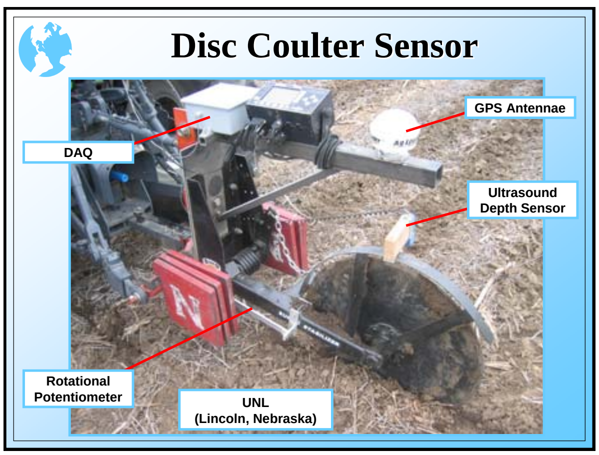

Apparent Soil Profiles
Soil mechanical resistance, MPa
Relative depth, cm
ISPPMS - pass 1
Cone - pass 1
ISPPMS - pass 2
Cone - pass 2
Plot B (disked)
Plot D (chiselled and disked)

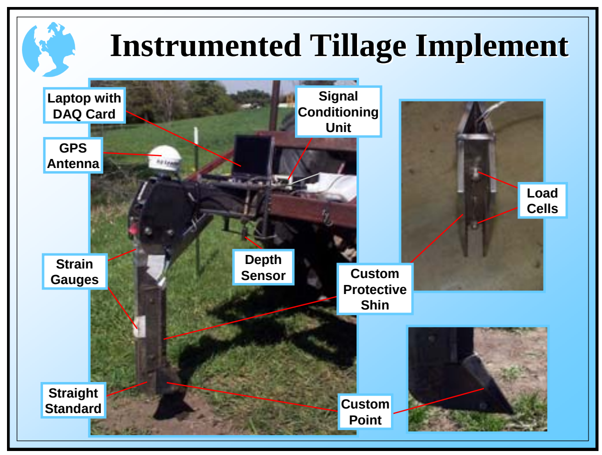

Integrated Load Comparison
Instrumented Blade
Cone Penetrometer
Tillage plot
pass
Center row
Wheel row
Overall integrated load (ISPPMS), N
Overall integrated load (cone penetrometer), N
Tillage Plot | Treatment | Tillage Plot | Treatment
A | plowed and double disked | D | chiselled and disked
B | disked | E | double disked
C | no-till with cultivation | F | no-till w/o cultivation

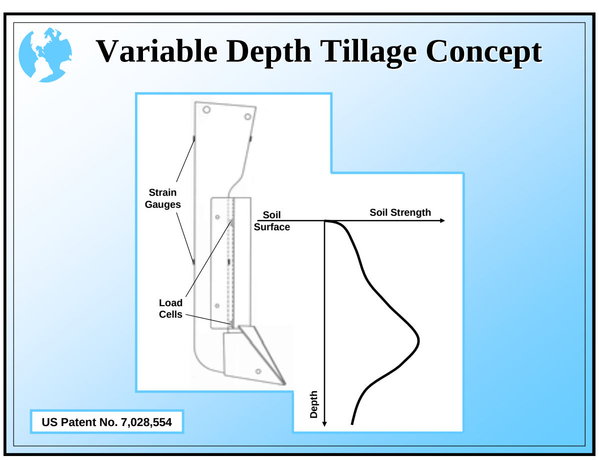

Vertical Blade with Strain Gage Array
Discrete Model
Polynomial Model
Linear Model
Strain gages
Soil surface
Apparent soil surface
Travel direction
UNL (Lincoln, Nebraska)

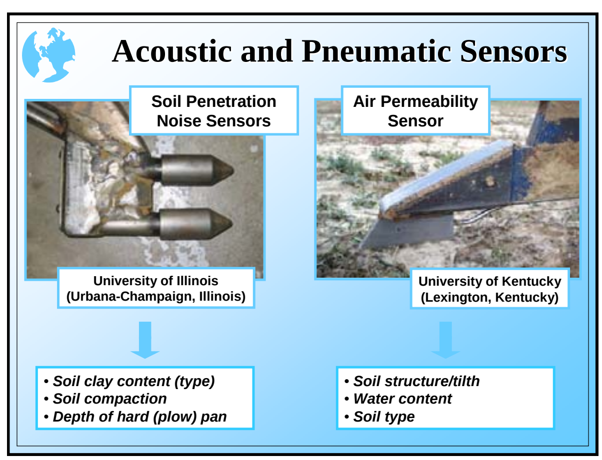

Soil Mechanical Resistance
Profile Average
Increase with Depth
5 – 30 cm depth

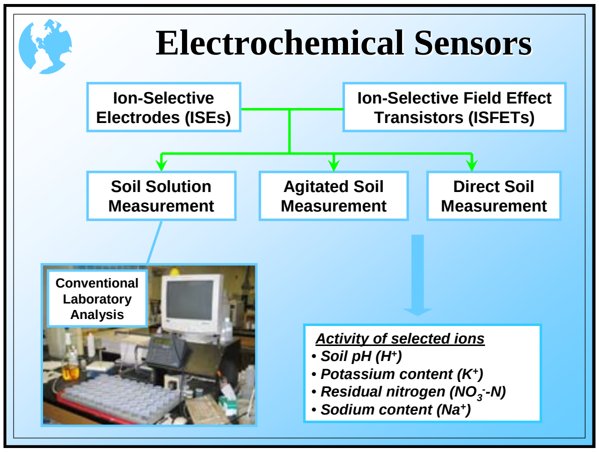

Bulk Density Prediction
Moisture
R² = 0.50
&
Soil Mechanical Resistance
R² = 0.19
Bulk Density
R² = 0.69
Predicted Bulk Density, g/mL
Measured Bulk Density, g/mL
1.2
1.4
1.6
1.8

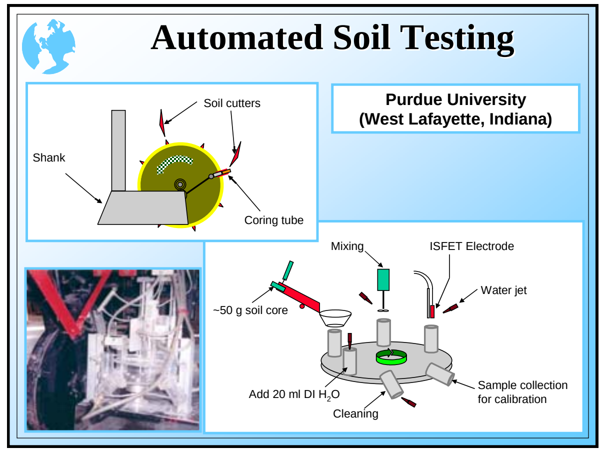

Disc Coulter Sensor
GPS Antennae
DAQ
Ultrasound Depth Sensor
Rotational Potentiometer
UNL
(Lincoln, Nebraska)

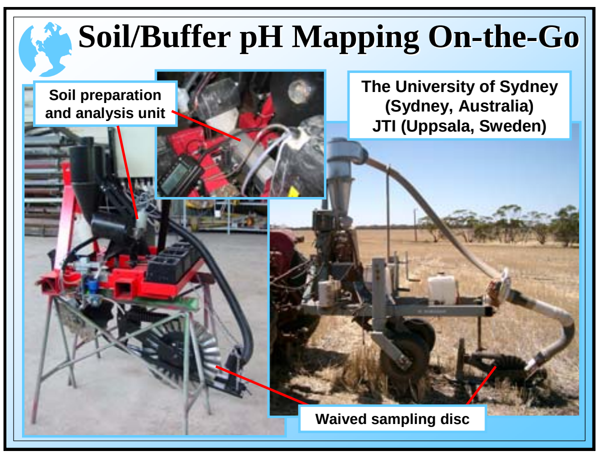

Instrumented Tillage Implement
Laptop with DAQ Card
Signal Conditioning Unit
GPS Antenna
Load Cells
Strain Gauges
Depth Sensor
Custom Protective Shin
Straight Standard
Custom Point

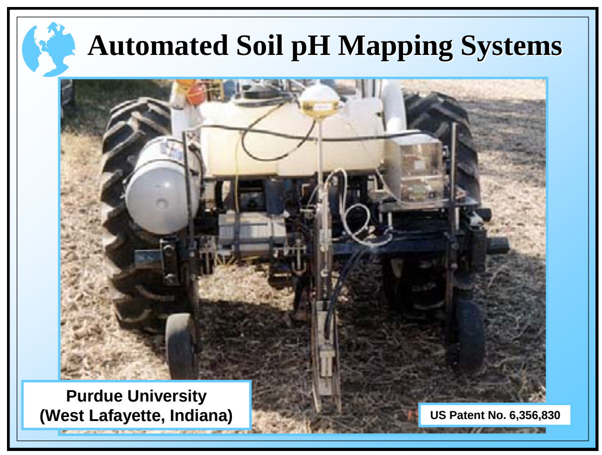

Variable Depth Tillage Concept
Strain Gauges
Soil Surface
Soil Strength
Load Cells
Depth
US Patent No. 7,028,554

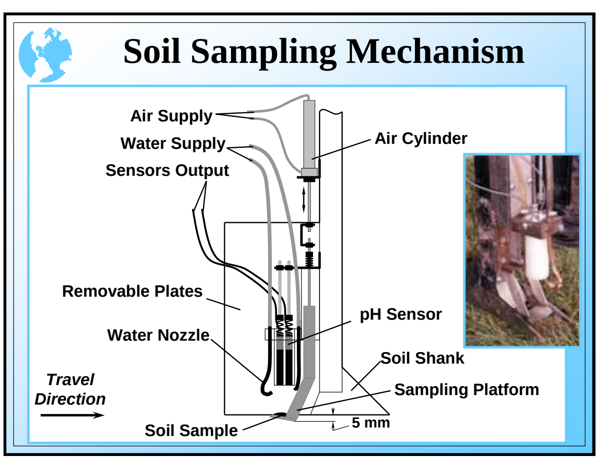

Acoustic and Pneumatic Sensors
Soil Penetration Noise Sensors
Air Permeability Sensor
University of Illinois
(Urbana-Champaign, Illinois)
University of Kentucky
(Lexington, Kentucky)
• Soil clay content (type)
• Soil compaction
• Depth of hard (plow) pan
• Soil structure/tilth
• Water content
• Soil type

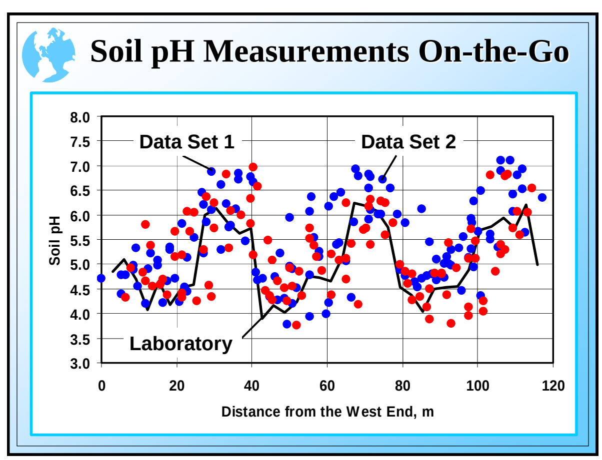

Electrochemical Sensors
Ion-Selective Electrodes (ISEs)
Ion-Selective Field Effect Transistors (ISFETs)
Soil Solution Measurement
Agitated Soil Measurement
Direct Soil Measurement
Conventional Laboratory Analysis
Activity of selected ions
• Soil pH (H^+)
• Potassium content (K^+)
• Residual nitrogen (NO_3^--N)
• Sodium content (Na^+)


Automated Soil Testing
Soil cutters
Shank
Coring tube
Purdue University
(West Lafayette, Indiana)
Mixing
ISFET Electrode
Water jet
~50 g soil core
Add 20 ml DI H_2O
Cleaning
Sample collection for calibration

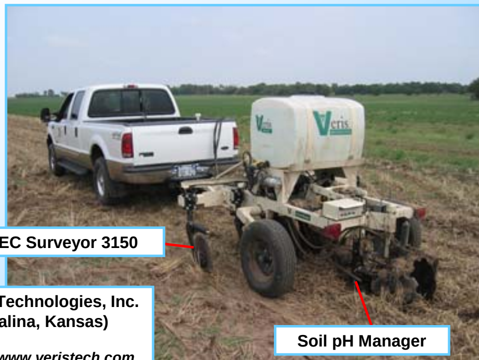

Soil/Buffer pH Mapping On-the-Go
Soil preparation and analysis unit
The University of Sydney
(Sydney, Australia)
JTI (Uppsala, Sweden)
Waived sampling disc


Automated Soil pH Mapping Systems
Purdue University
(West Lafayette, Indiana)
US Patent No. 6,356,830

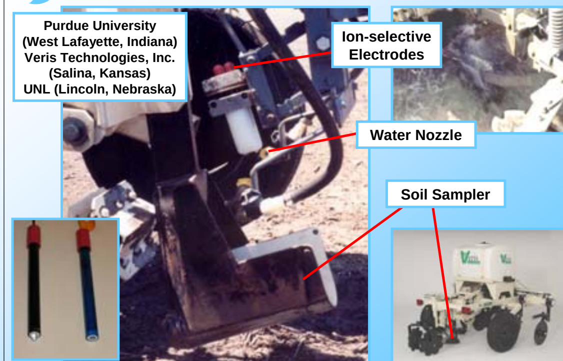

Soil Sampling Mechanism
Air Supply
Water Supply
Sensors Output
Air Cylinder
Removable Plates
Water Nozzle
pH Sensor
Soil Shank
Sampling Platform
Travel Direction
Soil Sample
5 mm


Soil pH Measurements On-the-Go
Data Set 1
Data Set 2
Laboratory
Soil pH
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
0
20
40
60
80
100
120
Distance from the West End, m

Mobil Sensor Platform (MSP)

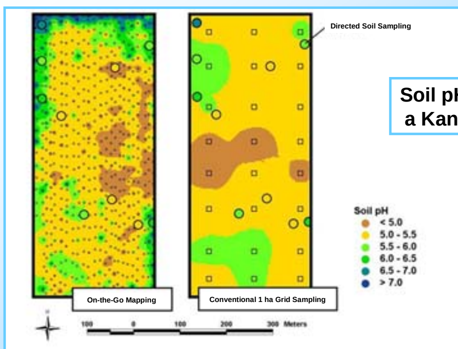


Direct Soil Measurement



Example

Soil pH Mapping



Soil pH Maps of a Kansas Field

Evaluation Fields

Field ID	Textural range	Max slope	Lab pH*	EC (mS m^{-1})*
IA1	Loam / silty clay loam	5%	5.18 (0.77)	9.26 (5.58)
IL1	Loam / clay loam	2%	6.28 (0.41)	11.44 (2.22)
IL2	Loam / clay loam	2%	6.52 (0.86)	14.88 (3.66)
KS1	Silt loam / silty clay loam	6%	5.34 (0.27)	3.17 (1.00)
KS2	Silty clay loam	3%	6.62 (0.68)	16.49 (4.6)
NE1	Silty clay loam	11%	5.95 (0.84)	25.86 (4.97)
OK1	Loamy fine sand	2%	6.16 (0.64)	0.96 (0.99)
WI1	Silt loam	18%	6.66 (0.47)	3.22 (1.08)

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 → MSP pH → Universal MSP pH, Adjusted MSP pH, Shifted MSP pH

Soil Sampling → Directed Sampling, Field Average, Interpolated Grid Map

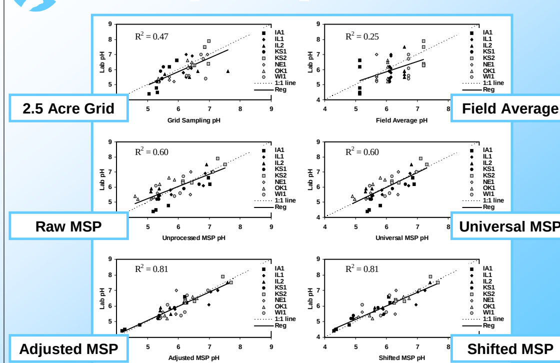
Directed Sampling → Adjusted MSP pH, Shifted MSP pH

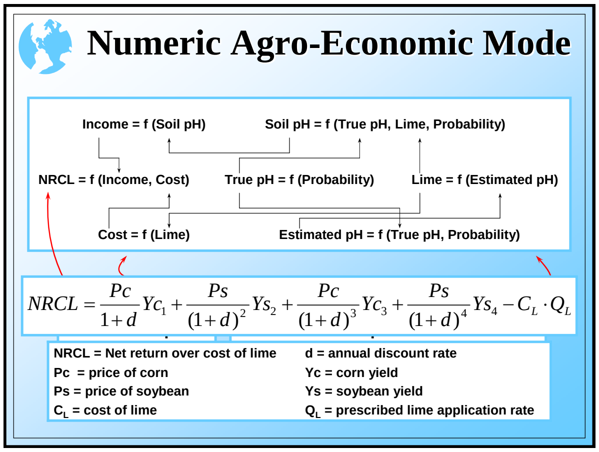
$$Universal\ \ MSP\ \ pH = Intercept_{Universal} + Slope_{Universal} \cdot MSP\ \ pH$$

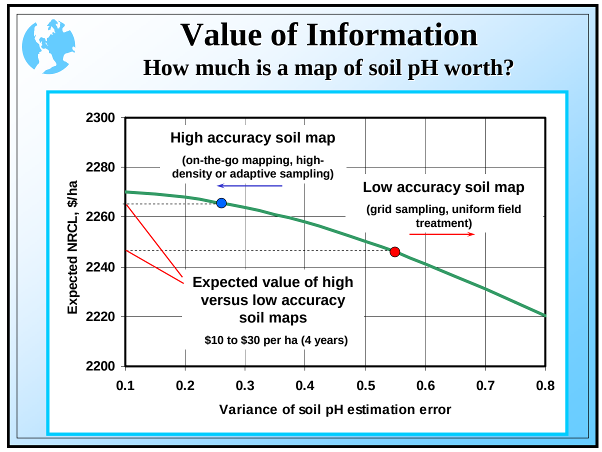
$$Adjusted\ \ MSP\ \ pH = Intercept_{Field-specific} + Slope_{Field-specific} \cdot MSP\ \ pH$$

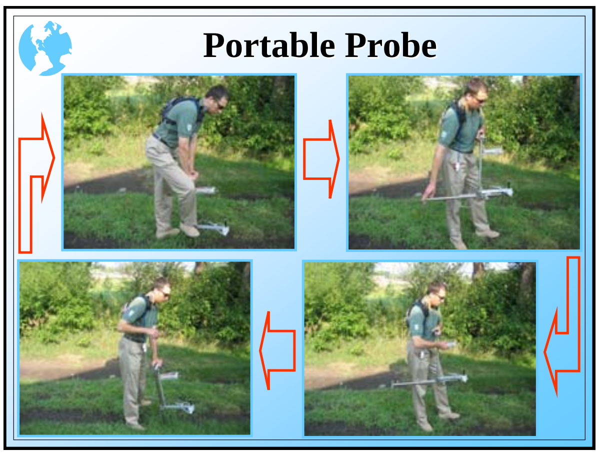
$$Shifted\ \ MSP\ \ pH = Shift_{Field-specific} + MSP\ \ pH$$

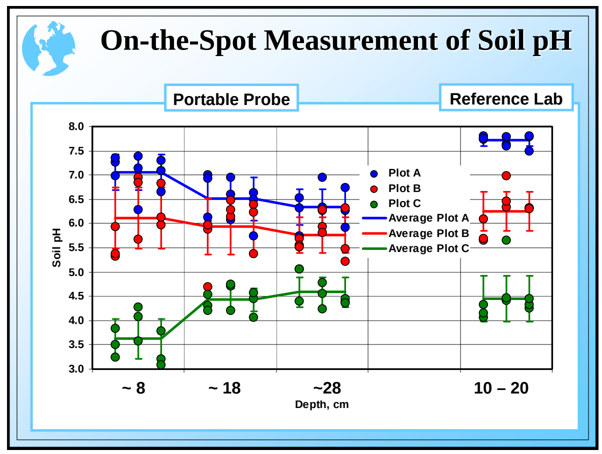
Soil pH Maps Evaluation

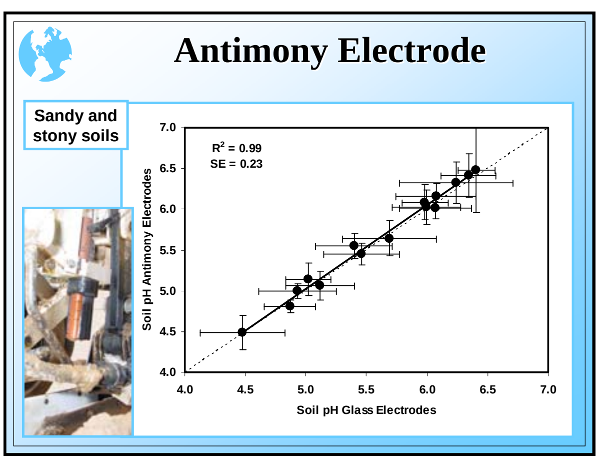


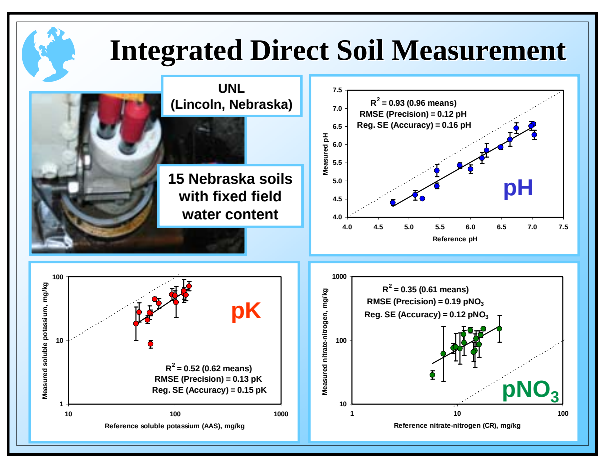

Numeric Agro-Economic Mode
Income = f (Soil pH)
Soil pH = f (True pH, Lime, Probability)
NRCL = f (Income, Cost)
True pH = f (Probability)
Lime = f (Estimated pH)
Cost = f (Lime)
Estimated pH = f (True pH, Probability)
$NRCL = \frac{Pc}{1+d}Yc_1 + \frac{Ps}{(1+d)^2}Ys_2 + \frac{Pc}{(1+d)^3}Yc_3 + \frac{Ps}{(1+d)^4}Ys_4 - C_L \cdot Q_L$
NRCL = Net return over cost of lime
d = annual discount rate
Pc = price of corn
Yc = corn yield
Ps = price of soybean
Ys = soybean yield
C_L = cost of lime
Q_L = prescribed lime application rate

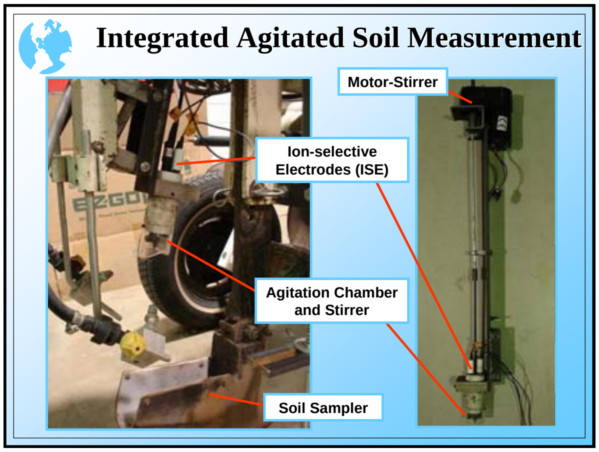

Value of Information
How much is a map of soil pH worth?
High accuracy soil map
(on-the-go mapping, high-density or adaptive sampling)
Low accuracy soil map
(grid sampling, uniform field treatment)
Expected value of high versus low accuracy soil maps
$10 to $30 per ha (4 years)
Expected NRCL, $/ha
Variance of soil pH estimation error

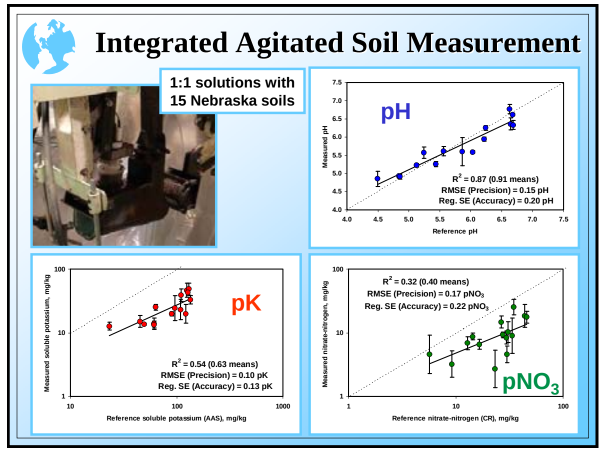

Portable Probe

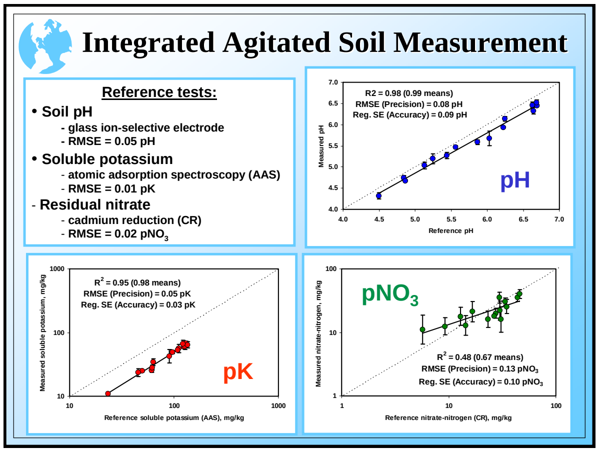

On-the-Spot Measurement of Soil pH
Portable Probe
Reference Lab
Plot A
Plot B
Plot C
Average Plot A
Average Plot B
Average Plot C
Soil pH
~ 8
~ 18
~28
10 – 20
Depth, cm

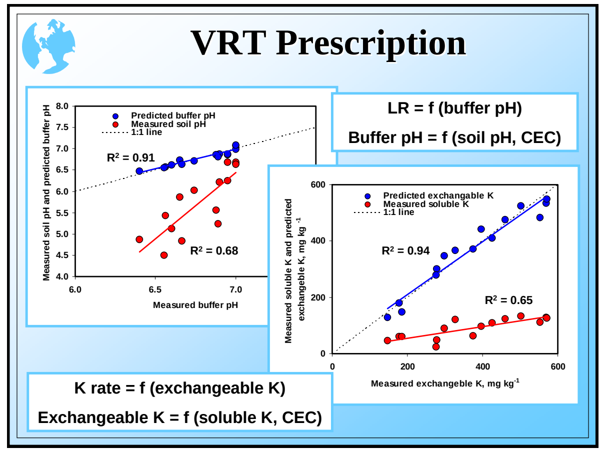

Antimony Electrode
Sandy and stony soils
R^2 = 0.99
SE = 0.23
Soil pH Antimony Electrodes
Soil pH Glass Electrodes

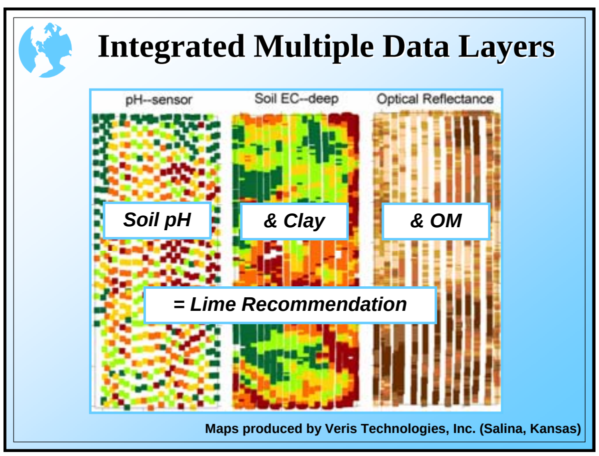

Integrated Direct Soil Measurement
UNL
(Lincoln, Nebraska)
15 Nebraska soils with fixed field water content
R^2 = 0.93 (0.96 means)
RMSE (Precision) = 0.12 pH
Reg. SE (Accuracy) = 0.16 pH
pH
Reference pH
pK
R^2 = 0.52 (0.62 means)
RMSE (Precision) = 0.13 pK
Reg. SE (Accuracy) = 0.15 pK
Reference soluble potassium (AAS), mg/kg
R^2 = 0.35 (0.61 means)
RMSE (Precision) = 0.19 pNO_3
Reg. SE (Accuracy) = 0.12 pNO_3
pNO_3
Reference nitrate-nitrogen (CR), mg/kg

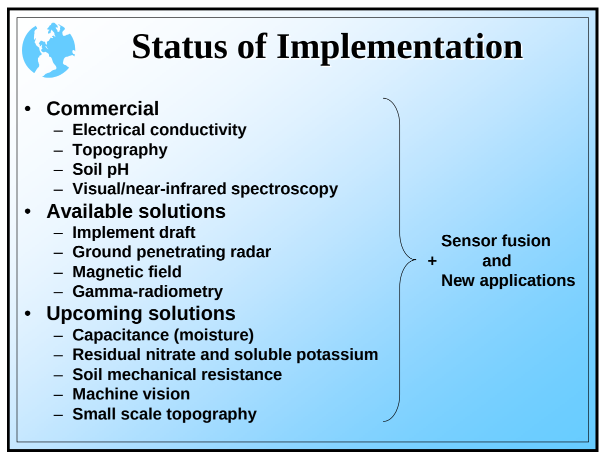

Integrated Agitated Soil Measurement
Motor-Stirrer
Ion-selective Electrodes (ISE)
Agitation Chamber and Stirrer
Soil Sampler


Integrated Agitated Soil Measurement
1:1 solutions with 15 Nebraska soils
pH
R^2 = 0.87 (0.91 means)
RMSE (Precision) = 0.15 pH
Reg. SE (Accuracy) = 0.20 pH
Reference pH
Measured pH
pK
R^2 = 0.54 (0.63 means)
RMSE (Precision) = 0.10 pK
Reg. SE (Accuracy) = 0.13 pK
Reference soluble potassium (AAS), mg/kg
Measured soluble potassium, mg/kg
R^2 = 0.32 (0.40 means)
RMSE (Precision) = 0.17 pNO_3
Reg. SE (Accuracy) = 0.22 pNO_3
pNO_3
Reference nitrate-nitrogen (CR), mg/kg
Measured nitrate-nitrogen, mg/kg


Integrated Agitated Soil Measurement
Reference tests:
• Soil pH
- glass ion-selective electrode
- RMSE = 0.05 pH
• Soluble potassium
- atomic adsorption spectroscopy (AAS)
- RMSE = 0.01 pK
- Residual nitrate
- cadmium reduction (CR)
- RMSE = 0.02 pNO_3
R2 = 0.98 (0.99 means)
RMSE (Precision) = 0.08 pH
Reg. SE (Accuracy) = 0.09 pH
pH
Reference pH
Measured pH
R^2 = 0.95 (0.98 means)
RMSE (Precision) = 0.05 pK
Reg. SE (Accuracy) = 0.03 pK
pK
Reference soluble potassium (AAS), mg/kg
Measured soluble potassium, mg/kg
pNO_3
R^2 = 0.48 (0.67 means)
RMSE (Precision) = 0.13 pNO_3
Reg. SE (Accuracy) = 0.10 pNO_3
Reference nitrate-nitrogen (CR), mg/kg
Measured nitrate-nitrogen, mg/kg


VRT Prescription
Predicted buffer pH
Measured soil pH
1:1 line
R^2 = 0.91
R^2 = 0.68
Measured buffer pH
Measured soil pH and predicted buffer pH
LR = f (buffer pH)
Buffer pH = f (soil pH, CEC)
Predicted exchangeable K
Measured soluble K
1:1 line
R^2 = 0.94
R^2 = 0.65
Measured exchangeble K, mg kg^{-1}
Measured soluble K and predicted exchangeble K, mg kg^{-1}
K rate = f (exchangeable K)
Exchangeable K = f (soluble K, CEC)


Integrated Multiple Data Layers
pH--sensor
Soil EC--deep
Optical Reflectance
Soil pH
& Clay
& OM
= Lime Recommendation
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 and 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

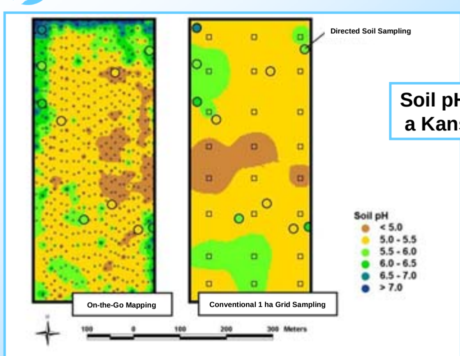
Homogeneity → Neighborhood variability

Even data spread → D-optimality

Even field coverage → Spatial predictability

Example

Soil pH Mapping

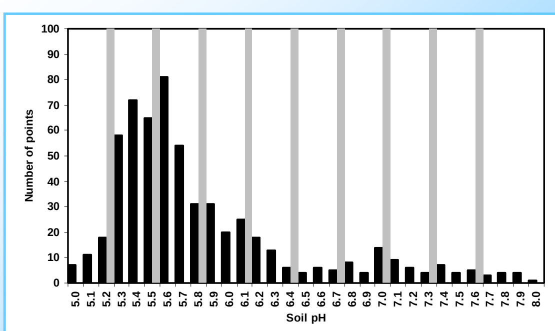


Soil pH Maps of a Kansas Field

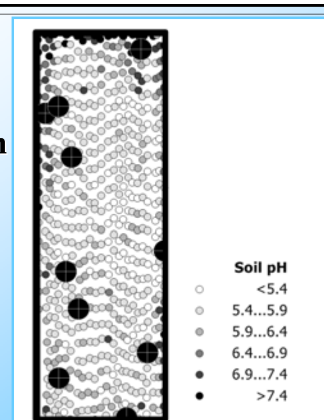
Example

- 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

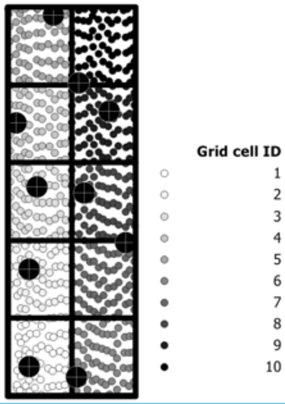
Soil pH Histogram



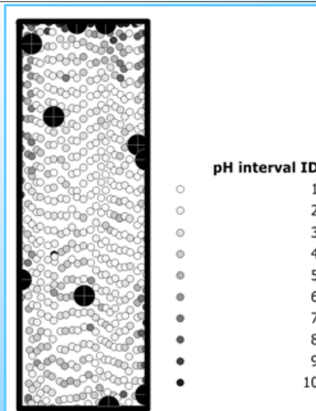
Complete Randomization



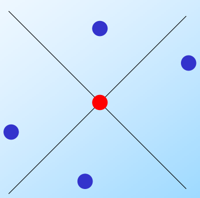
Grid Cell Spread

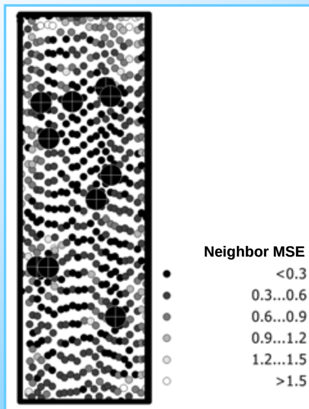


Even Soil pH Spread

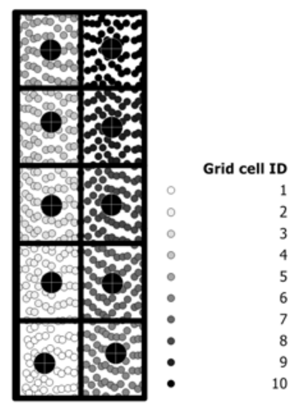


Maximum Homogeneity

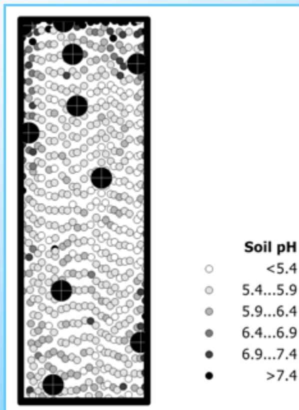




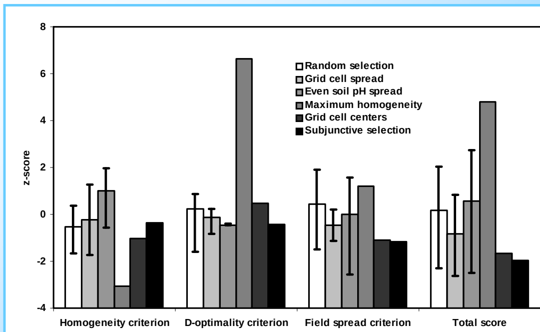
Grid Cell Centers



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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