Predicting and mapping soil properties using proximal/remote sensing

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Wet chemistry methods to extract soil properties are cost effective and time consuming. Accordingly, non-destructive technologies, such as field proximal sensors or remote sensing methods, can provide important vantages.
The capacity and potential of the proximal sensors / remote sensing on monitoring and mapping of some key functional properties of soil, such as soil moisture, organic matter and carbon.

- Effect on the interactions between soil and plants
- Related to soil quality

- Plays a leading role in surface water and energy balance
- Available for plant utilization
Soil moisture (土壤水分)

Variability in the moisture held in soil is a consequence of the continuous exchange of water between the land and atmosphere. Although soil only holds a small percentage of the total global budget, soil moisture plays an important role in the water cycle.

In the absence of a well-integrated program of sampling and scaling, the limited areal coverage over large land surface areas makes it difficult to use in situ measurements for studies more extensive than field-scale.
Remote sensing can be advantageous owing to its continuous temporal and spatial coverage. It is the most promising approach for soil moisture estimation involving large areas.

Launched in November 2009, the European Space Agency’s SMOS makes global maps of soil moisture every three days to improve our understanding of the water cycle, benefit to agriculture and water resource management, climate modeling, forecasting floods.
The Global Carbon Cycle (Pg C and Pg C/yr)

- Atmosphere: 730
- Accumulation: +3.2

Net terrestrial uptake: 1.4
Fossil fuels & cement production: 6.3
Net ocean uptake: 1.7

Atmosphere land exchange: 120
Atmosphere ocean exchange: 90
Runoff: 0.8

Vegetation: 500
Soils & detritus: 1,500
Ocean store: 38,000

Fossil organic carbon and minerals: Burial: 0.2

(1 Pg = 10¹⁵ g)

Ten soil properties will be predicted at each location. These are:

(1) total profile depth (cm)
(2) plant exploitable (effective) soil depth (cm)
(3) organic carbon (g/kg)
(4) pH
(5) sand (g/kg), (6) silt (g/kg)
(7) clay (g/kg)
(8) gravel (g/kg)
(9) bulk density (mg/m³)
(10) available water capacity (mm)

Additional soil properties:
(1) ECEC (cmolc/kg)
(2) EC (dS/m)
Maps can provide soil inputs (e.g., texture, organic carbon, and soil-depth parameters) to models predicting land-cover changes in response to global climatic and human disturbances.
Predictions of *organic matter* (Meuse data) visualized using polygons (KML)
Apply the right treatment in the right place at the right time

Variation in soils and crops

Soil and crop sensing

Relevant properties of soil productivity are soil moisture, clay content, organic matter content, nutrient availability, pH, bulk density.

Proximal soil sensing allows for a more direct detection of soil attributes than remote sensing (8). Three types of sensors are commercially available: electrical or electromagnetic sensors that measure electrical resistivity/conductivity or capacitance; optical sensors that obtain visible and near-infrared (Vis-NIR) spectra from within the soil; and electrochemical sensors that use ion-selective membranes to detect the activity of ions such as hydrogen, potassium, or nitrate. Soil compaction sensors for site-specific tillage will also be available in the near future.

Outlines

1. Introduction
2. Soil Proximal Sensors
3. Soil Remote Sensing
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<td>From lab to field 土壤光谱测试手段走向农田</td>
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</table>
Spectral signatures of materials are defined by their reflectance or absorbance, as a function of wavelength in the electromagnetic spectrum.

<table>
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<th>Wave number cm(^{-1})</th>
<th>0.1 nm</th>
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</table>

- **Scale**
  - γ 射线 Y ray
  - X 射线 X ray
  - 紫外 UV
  - 可见光 Vis
  - 红外 Infrared
  - 微波 microwave
  - 射频 Radio frequency

- **Interaction**
  - 核的跃迁 Nuclear transition
  - 内层电子跃迁 Electronic transition
  - 外层电子跃迁 Electronic transition

- **Spectral signatures of materials**
  - 分子振动 Molecular vibrations
  - 分子转动 Molecular rotation
  - 磁场中的自旋取向 Magnetic field spin orientation

- **Remote sensing techniques**
  - X射线荧光光谱 XRF
  - 激光感生击穿光谱 LIBS
  - 漫反射光谱 DRS
  - 发射率光谱 Emission spectrum
  - 土壤介电常数 Soil dielectric constant
  - 土壤有机质，质地，粘粒，水分 Soil organic matter, texture, clay, moisture
  - 土壤温度，水分 Soil temperature, moisture
  - 土壤粗糙度，水分，盐分 Soil roughness, moisture, salinity

[soil remote sensing and information technology](http://agri.zju.edu.cn)
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<thead>
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**Electromagnetic spectrum**

<table>
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<tr>
<th>EM Range</th>
<th>γ-rays</th>
<th>X-rays</th>
<th>UV – Visible – Infra red</th>
<th>Micro and Radio waves</th>
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<td>$10^{10}$</td>
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<td>Mech</td>
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2.1 Principal of electromagnetic spectrum

2.2 Soil spectral library in laboratory
   Standard, share  标准/规范/共享

2.3 Soil proximal sensors in field
   From lab to field  土壤光谱测试手段走向农田
Procedure of soil spectral library

**Soil reflectance spectroscopy → Diffuse reflectance spectroscopy (DRS)**

**Measurement**
- sampling
- standard
- share

**Pre-treatment**
- methods

**Calibration**
- modeling
- robust

Procedures of development and application of soil spectral library

Different soils can be characterized using Diffuse Reflectance Spectroscopy (DRS)?

Soil variation can be characterized using Diffuse reflectance spectroscopy (DRS)?

How can we make Global Soil Spectral Calibration of soil properties using existing data?

The global soil spectral library (GSSL)

GSSL (VIS/NIR, mid-IR)全球土壤光谱库

2008, Raphael A. Viscarra Rossel (CSIRO Land and Water) organized the “The Soil Spectroscopy Group”.

◎ 样品的典型性； ◎测试的规范性； ◎ 应用的可靠性

Different soils can be characterized using Diffuse Reflectance Spectroscopy (DRS)?

Soil variation can be characterized using Diffuse reflectance spectroscopy (DRS)?

How can we make Global Soil Spectral Calibration of soil properties using existing data?
16000+ spectra come from 90+ countries
All measured with vis-NIR and some with mid-IR

from Raphael VISCARRA ROSSEL
Spectroscopic calibration to soil TOC from GSSL

Calibrations to soil OC after clustering PLS scores

vis – NIR
TOC $R^2 = 0.77$

mid-IR
TOC $R^2 = 0.86$
First stages, The soil spectral library of China (SSLC) collected more than 2000 soil samples, built the linking network among several universities and institutions in China.
Soil sampling in Tibet (色季拉山、雅鲁藏布江等地)

4439米海拔，高山草甸(alpine meadow)

3893米海拔，高山冷杉(alpine fir)

4161米海拔，中大试验站，灌木(shrub)

3426米海拔，青稞田(hulless barley)
The soil spectral library of China (SSLC)

Spectral reflectance of some selected soils in China

Supported by Ministry of education of China (MOE)
The soil spectral library of China (SSLC)

The correlation coefficients between SOM content and spectral reflectance of different soils

Relationship between Soil OM and spectral reflectance
Multivariate calibrations

(1) Linear regressions
- Partial least squares regression (PLSR)
- Multiple linear stepwise regression (MSLR)
- Principal component regression (PCR)

(2) Data mining techniques
- Multivariate adaptive regression splines (MARS)
- Boosted regression trees (BT)
- Random forest (RF)
- Support vector machines (SVM)
- Artificial neural networks (ANN)
A hand portable, remote sensing FTIR spectrometer (Model 102F) is a type of Fourier transformed infrared spectrometers produced by Design& Prototypes company. (Design for *in situ* measurements)
Emissive spectra feature for different soil types
不同类型土壤的发射光谱特征

Emissive spectra feature for different soil water
不同含水量土壤的发射光谱特征

Emissive spectra feature for different soil’s OM contents
不同有机质含量土壤的发射光谱特征
Soil microwave dielectric properties

Soil dielectric constant was measured and analyzed using Vector Net Analyzer at different conditions.

Coaxial probe method directly calculates the microwave complex permittivity of a medium by measuring the reflection coefficient of the probe terminal.
Soil samples preparation

Install the test-bed

Set parameters:
**Frequency:** 500MHz-12GHz, concluding L S X C bands
**Bands:** 800
**Probe pressure:** according the drying condition of the samples

Measure the dielectric constant
The relationship of the soil dielectric constant and the frequency

- The real part of the dielectric constant is increasing with the increase of the soil water content and decreasing with the decrease of the frequency. This trend is obvious at high water content but hardly changing at low water content.
- The imaginary part of the dielectric constant increase with the increase of the water content at higher frequency.
The relationship of the dielectric and soil volumetric water content simulated by Topp model.

The relationship of soil dielectric constant and soil volumetric water content by Dobson model at different frequencies.
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Program:

*In situ* Characterization of SOM of Paddy Soil with vis-NIR Diffuse Reflectance Spectroscopy (DRS)

Objective:

To evaluate the feasibility of VNIR-DRS for *in situ* quantification of organic matter content of paddy soil
Paddy soil in China

China is the largest producer of rice in the world
In situ Characterization of SOM of Paddy Soil with vis-NIR Diffuse Reflectance Spectroscopy (DRS)

1. 20cm-deep-transect
2. optimize by spectralon panel
3. scanned by spectrometer
4. Moisture measurement
5. Soil collection
In situ Characterization of SOM of Paddy Soil with vis-NIR Diffuse Reflectance Spectroscopy (DRS)

Predicted model by MLSR method, Selected bands (454, 469, 404 nm)

\[ n = 75, R^2 = 0.701, \text{RMSE} = 0.215 \]

Soil OM Range [6.02-22.4 g/kg]
On-the-go measurement by vis-NIR DRS

Vis-NIR DRS probe module (Veris P4000)

Vis-NIR DRS shank module (Veris)
Soil proximal technology and sensors

National Program for Science and Technology Development in China (2006-2020)

Key fields:
- Precision agriculture, Agricultural IT
- Sensors and intelligent information processing

Area of priority:
- Agricultural Internet of things (IOT)
- Intelligent equipment or sensors
Agricultural sensors

- For laboratory, in situ field, on-the-go measurement
- Static and dynamic observation
- Robust, low power consumption, wireless communication

Plant
- Nutrient index: Chlorophyll, water, N, P, K, trace element etc.
- Physiology: Protein, amino acid, enzyme etc.
- Ecology: LAI, VI, shape, Leaf temperature, stem flow etc.

Soil
- Physics: moisture, water potential, temperature, tension, compaction, EC, salinity
- Chemistry: pH, organic matter, N, P, K, heavy metal

Environment
- Temperature, humidity, Solar radiation, CO2
Outlines

1. Introduction
2. Soil Proximal Sensors
3. Soil Remote Sensing
**Problems to soil remote sensing**

Going from point (spectrometer) to image spectrometry (remote sensing) is not only a journey from micro- to macro-scales but also a long stage that encounters problems such as dealing with data having a *low signal-to-noise level*, atmospheric interference, shade and shadow effects, mixtures of materials within pixels, the **BRDF** effect, variation in soil *moisture* content, and more.

(大气干涉、地面覆盖物阴影、粗糙地表的二向反射影响、混合像元、表土水分空间异质性等)
3.1 Soil OM/Carbon remote sensing

3.2 Soil moisture remote sensing

3.3 Application of soil remote sensing
### Soil OM/Carbon remote sensing

<table>
<thead>
<tr>
<th>Source image</th>
<th>Wavelengths</th>
<th>$R^2$</th>
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<tbody>
<tr>
<td>SPOT</td>
<td>R–G</td>
<td>0.22</td>
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<tr>
<td>Aerial photograph</td>
<td>B–G–NIR</td>
<td>0.22–0.28</td>
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<tr>
<td><strong>AVIRIS</strong></td>
<td>VIS–NIR</td>
<td><strong>0.72</strong></td>
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<td>Arial photograph</td>
<td>B–G–R</td>
<td>0.92</td>
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<td>Color slide</td>
<td>B–G–R</td>
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<td><strong>ATLAS</strong></td>
<td>R–NIR</td>
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<td>IKONOS</td>
<td>B–G–R</td>
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<td>Digital orthophotograph</td>
<td>B–G–R</td>
<td>0.08–0.16</td>
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<td>Hyperspectral image</td>
<td>VIS–IR</td>
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*ATLAS: digital aerial images by NASA ATLAS sensor

* AVIRIS: Airborne Visible / Infrared Imaging Spectrometer
b) 田间水分 (Filed moisture, FM), (c) 有机质 (OM), (d) 饱和含水量 (Saturated moisture, SM)

Validation results for the organic (left side) and inorganic (right side) carbon contents estimated from the HyMap image data. The red lines show the linear regression between the modelled and measured values. The dashed lines indicate a linear 1:1-relationship.

Thomas, J. et al. 2007. Proceedings of 5th EARSeL Workshop
3.1 Soil OM/Carbon remote sensing

3.2 Soil moisture remote sensing

3.3 Application of soil remote sensing
### Soil Moisture Retrieving by Remote Sensing

<table>
<thead>
<tr>
<th>Sensor types</th>
<th>Methods</th>
<th>Advantages and disadvantages</th>
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<td><strong>Optical remote sensing</strong></td>
<td>Statistical relational model-based</td>
<td>The relationship with the soil moisture spectral characteristics is not closely. Interfered by vegetation layer, weak ability to penetrate the surface, seriously affected by atmosphere and clouds, rarely applied in soil moisture detection</td>
</tr>
<tr>
<td><strong>Thermal infrared remote sensing</strong></td>
<td>(1) Bare soil or low vegetation coverage areas: Thermal inertia (2) High vegetation coverage areas: TVDI, CWSI</td>
<td>With the advantages of <strong>macro and high time resolution</strong>, it has superiorities in the large range of soil moisture detection and river basin drought early warning.</td>
</tr>
<tr>
<td><strong>Passive microwave remote sensing</strong></td>
<td>(1) Empirical model: Inversion soil moisture by using brightness temperature and establish a linear relationship (2) Theoretical model based on radiative transfer equation</td>
<td>With the definite rationale, <strong>high time resolution</strong> and relatively-low spatial resolution (about 10-50 km), it fits soil moisture monitoring by remote sensing on <strong>the regional even global scales</strong>.</td>
</tr>
<tr>
<td><strong>Active microwave remote sensing</strong></td>
<td>(1) Theoretical model: Kirchhoff, SPM, IEM (2) Semi-empirical model &amp; Empirical model: Oh Model, Dubois Model, Shi Model (3) The model of the high vegetation coverage areas: Water-Cloud Model, MIMICS Model</td>
<td>It has the quality of <strong>all-day and all-weather</strong> resistance to mist and weather, and high spatial resolution relative to passive microwave sensor, making the advantage on Soil moisture detection.</td>
</tr>
</tbody>
</table>
HyMap image from July 30th 2004 (RGB from bands 13/7/2). The red line depicts the boundaries of soil moisture measurements in the field.

Surface soil moisture from July 30th 2004 determined from (a) FDR (频域反射仪) field measurements and (b) HyMap-based ratio calculation (1288 vs. 1515 nm) based on the regression function for quaternary sand. The dashed line shows the part of the area being covered with quaternary sand.

Active microwave remote sensing

Multi-temporal SAR images - False color composite
R:2009-2-15 PALSAR HH  G:2009-5-14 PALSAR HH
B: 2009-8-18 PALSAR HH (Polarization)

Detected soil moisture based on ALOS/PALSAR
Synchronous field experiment

Ground measurement in situ

Equipments:
- TDR300 (USA, ST)
- W.E.T Sensor (UK, Delta-T)
- MiniTrase (USA, SEC)
- eKo PRO (USA, XBOW)

Soil moisture(%) Nov 21th 2010
North Area
- 18.90 - 25.00
- 25.01 - 30.40
- 30.41 - 36.20
- 36.21 - 42.80
- 42.81 - 52.50

Soil moisture(%) Nov 21th 2010
South Area
- 12.00 - 20.00
- 20.01 - 28.00
- 28.01 - 36.00
- 36.01 - 44.00
- 44.01 - 54.30

Supported by NSFC(40871100), 2009-2011
Inversion model 反演模型

Oh model

\[
\frac{\sigma_{HH}^o}{\sigma_{VV}^o} = \left[1 - \left(\frac{2m_v}{\pi}\right)^\frac{1}{3\sigma_v} \exp(-ks)\right]^2
\]

Soil moisture(%) 

High 80.00 

Low 0.00 

Supported by NSFC(40871100), 2009-2011
Thermal infrared remote sensing
热红外遥感

LST_EVI scatter diagram
Eigenspace
散点图、特征空间

Detecting soil moisture based on MODIS data

Time-series maps of soil moisture covered the whole Zhejiang province land in 2007
浙江省2007年1月、2月土壤相对含水量分布图
Detecting soil moisture based on multi-resource remote sensing

- Microwave Remote Sensing data (ALOS-PALSAR)
- Optical Remote Sensing data (ALOS-AVNIR)
- Infrared remote sensing data (MODIS/FY-2C)

1. Data preprocessing (Geometric correction, Denoising, Data Fusion, etc.)
2. Information extraction of variety vegetation indices, vegetation coverage, etc.
3. Backscattering coefficient model of bare surface soil
4. Backscattering coefficient model of sparsely vegetated topsoil
5. Soil moisture inversion model of bare and sparsely vegetated soil
6. Soil moisture inversion model of high vegetation coverage soil
7. Spatial distribution of soil moisture
8. LST inversion
9. The surface heat balance equation
10. Surface evapotranspiration calculation
11. Validation of soil moisture and surface evapotranspiration inversion model and precision analysis
12. Ground observation station synchronizing meteorological data (wind speed, precipitation, temperature, etc.)
13. Ground station synchronizing soil moisture and surface evapotranspiration data
3.1 Soil OM/Carbon remote sensing

3.2 Soil moisture remote sensing

3.3 Application of soil remote sensing
Using Temperature—Vegetation Dryness Index (TVDI) to predict the soil surface moisture. The remote sensing data include LST and EVI from MODIS data, also containing measured soil moisture over the same period.
The study of the integration system of flood forecasting

Application II: Flooding forecast

DEM and water conservancy data → soil type map → Ground hydrological and Meteorological observation → Space analysis technology and Statistical analysis → Hydrological and terrain parameters → Hydrological parameters of soil → Rainfall, Water level and Flow → Integration

Remote sensing
- Optical remote sensing
- Microwave
- Infrared remote sensing

DEM and water conservancy data → soil type map → Ground hydrological and Meteorological observation → Space analysis technology and Statistical analysis → Hydrological and terrain parameters → Hydrological parameters of soil → Rainfall, Water level and Flow

Soil remote sensing and information technology  http://rs.zju.edu.cn

Application III: DSM

combine soil spectral libraries, and other geo-referenced information, such as from digital terrain models and field observations, with information from multi- and hyper-spectral remote sensing imagery
Application III: DSM

County Level Digital Soil Mapping (1:50,000) Using Decision Tree Model

SCOPAN approach (McBratney et al., 2003)

$S = f(s, c, o, r, p, a, n)$

DT algorithm

ID3

CART

C4.5

SLIQ

SPRINT

Study area – Fuyang county

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Application III: DSM

County Level Digital Soil Mapping (1:50,000) Using Decision Tree Model

Zhou Y and Shi Z. Digital soil mapping technology. 2010
### Application III: DSM

#### County Level Digital Soil Mapping Using Decision Tree Model

<table>
<thead>
<tr>
<th>Predictor variables</th>
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<tbody>
<tr>
<td>Soil (s)</td>
<td></td>
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<tr>
<td>Soil classification map (categorical)</td>
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<tr>
<td>Landsat ETM band 1,3,6,7</td>
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<tr>
<td>Soil spectral data</td>
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<tr>
<td>Climate (c)</td>
<td></td>
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<tr>
<td>Mean annual rainfall (mm)</td>
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<td>Mean annual temperature (°C)</td>
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<tr>
<td>Organisms (o)</td>
<td></td>
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<tr>
<td>Landsat ETM band 2,4,5</td>
<td></td>
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<tr>
<td>Vegetation cover, NDVI, Wetness</td>
<td></td>
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<tr>
<td>Relief (r)</td>
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<tr>
<td>DEM, slope, relief, aspect</td>
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<tr>
<td>Parent materials (p) and age (a)</td>
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<tr>
<td>Geology</td>
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<tr>
<td>Land use</td>
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</tr>
</tbody>
</table>

**soil type map (1:50,000)**

**Geology map**

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Application III: DSM

County Level Digital Soil Mapping Using Decision Tree Model

Predictors data from DEM

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Application III: DSM

Predictors data from Landsat image (optical remote sensing)

- Normalized difference vegetation index (NDVI)
- Normalized difference water index (NDWI)
- Soil color index (SCI)

County Level Digital Soil Mapping Using Decision Tree Model
Application III: DSM

County Level Digital Soil Mapping Using Decision Tree Model

Predictors data from soil sampling and spectral measurement

Soil samples (n=3682) and spectral measurement in Lab (n=347)

Zhou Y and Shi Z. Digital soil mapping technology. 2010
Summary and discussion

The increasing number of new satellite or sensors now available and the higher spatial/spectral resolution along with shorter revisit intervals offers greater potential than ever improve the digital mapping of soil type and some functional soil properties.

- But, the knowledge of classical mapping is not replaced by the new digital technologies including remote sensing (RS) and proximal sensors (PS) which mostly provide the auxiliary information for DM nowadays.

- In spite of recent advances, development of robust methods for estimating soil properties using RS/PS has to be extremely complicated. We should further to research the theory behind of new technologies / modeling approaches, and do more extensive field calibration working in different soils under different agricultural practice.
Equipment
Acknowledgement

National scientific foundation of China (NSFC)

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Thanks and questions?

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