Applications of soil infrared spectroscopy in Africa

From continental scale digital mapping to precision agriculture for smallholder farmers

Keith Shepherd, World Agroforestry Centre (ICRAF), Land Health Decisions, Nairobi, Kenya

Where it all began

Field spectrometry - Western Kenya Soils

Shepherd, Walsh (1999)
Instrument & spectral library developments

Spectral Libraries


Soil VNIR spectra Lake Victoria basin

(a) sediment samples
(b) sheet and rill eroded soils
(c) hardset soils
(d) gully eroded soils

Each horizontal line is a single spectrum, with wavelength increasing from left to right.

Bright colours indicate high reflectance values, whereas dark colours indicate low reflectance values.

Spectral Soil-Erosion-Deposition index (SEDI):
a measure of the distance in spectral data space of a soil from the population of sediment spectra

Walsh & Shepherd (2001)
Probability of being in an erosion phase

Erosion risk in relation to SEDI and vegetation cover at the start of the rainy season

Also infiltration capacity, $^{137}$Cs, nutrient content, maize yield correlated

Walsh & Shepherd (2001)
Spectral signatures respond to management induced changes at landscape level

Forest – cropland chronosequence, Kakamega forest, Kenya

Spectral signatures respond to management-induced changes in soil functional properties

NARL long-term experiment, Kenya

Table 2. Prediction success in an 18-year soil management experiment.

<table>
<thead>
<tr>
<th>Soil attribute</th>
<th>$r^2_{cal*}$</th>
<th>$r^2_{val*}$</th>
<th>SEP†</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exchangeable bases (cmol$_c$ kg$^{-1}$ soil)</td>
<td>0.90</td>
<td>0.81</td>
<td>0.796</td>
<td>6.3</td>
<td>12.8</td>
</tr>
<tr>
<td>Light fraction OM‡ (g kg$^{-1}$ soil)</td>
<td>0.89</td>
<td>0.78</td>
<td>0.288</td>
<td>0.8</td>
<td>8.2</td>
</tr>
<tr>
<td>Microbial biomass C (mg kg$^{-1}$ soil)</td>
<td>0.90</td>
<td>0.80</td>
<td>11.8</td>
<td>40</td>
<td>133</td>
</tr>
<tr>
<td>Bean yield§ (Mg grain ha$^{-1}$)</td>
<td>0.91</td>
<td>0.82</td>
<td>0.092</td>
<td>0.22</td>
<td>1.01</td>
</tr>
<tr>
<td>Maize yield§ (Mg grain ha$^{-1}$)</td>
<td>0.88</td>
<td>0.77</td>
<td>0.535</td>
<td>1.65</td>
<td>5.39</td>
</tr>
</tbody>
</table>

Africa Soil Information Service

Statistically sound sampling schemes
Sample diversity
Unbiased prevalence data

Main AfSIS workflow

Legend
- Operational
- Under development
- Planned
- Input data
- Process
- Database

Workflow features:
- Open source: R, Python, C++ ...
- Near-real-time input data updating
- HPC-ready (e.g. AWS-EC2)
- Code versioning on Github
- Standards compliant (e.g. OGC)
- Statistically defined uncertainty
- 5-star open data

Everything should be completely reproducible given past & current data!
On-line Spectral Prediction Engine
Bayesian Additive Regression Trees

http://spectpred.qed.ai

AfSIS

http://spectpred.qed.ai
Digital soil mapping of soil nutrients


https://soilgrids.org/
AfSIS – national level sampling & mapping

Acid cropland soils in Tanzania (in red, ~4.7 / 32.7 Mha)

Soils, Crop trials

EthioSIS, GhaSIS, NiSIS, TanSIS
Smallholder farm variability

Total N content (g/kg) of farm fields

Range 0.5 – 2.6 g/kg

Soil-Plant Spectral Technology

Mid-infrared spectrometer

- Soils properties
- Plant macro & micro nutrients
- Compost quality
- Fertilizer certification

Handheld x-ray fluorescence

- Digital mapping of soil properties
- Plant nutrition monitoring; large n trials
- Soil carbon inventory
- Agro-input and output quality screening
- Mining reclamation
Spectral lab network & capacity development

Transforming Lives and Landscapes with Trees

## Country Lab

<table>
<thead>
<tr>
<th>Country</th>
<th>Lab</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benin</td>
<td>AfricaRice</td>
</tr>
<tr>
<td>Cameroon</td>
<td>IITA; ICRAF</td>
</tr>
<tr>
<td>Cote D’Ivoire</td>
<td>CNRA; ICRAF</td>
</tr>
<tr>
<td>Ethiopia</td>
<td>ATA/NSTC (5); Mekelle Uni;</td>
</tr>
<tr>
<td>Ghana</td>
<td>CSIRO-SRI</td>
</tr>
<tr>
<td>Kenya</td>
<td>KARLO; One Acre Fund; CNLS, ICRAF</td>
</tr>
<tr>
<td>Madagascar</td>
<td>Antananarivo Uni (collaborative).</td>
</tr>
<tr>
<td>Malawi</td>
<td>CARS/ DARTS</td>
</tr>
<tr>
<td>Mali</td>
<td>IER</td>
</tr>
<tr>
<td>Morocco</td>
<td>Mohammed Vi Polytechnic /OCP (in progress)</td>
</tr>
<tr>
<td>Mozambique</td>
<td>IAMM</td>
</tr>
<tr>
<td>Nigeria</td>
<td>Obafemi Awolowo Un; IITA; IAR; FDMA&amp;RD (2)</td>
</tr>
<tr>
<td>South Africa</td>
<td>KwaZulu-Natal Dept A</td>
</tr>
<tr>
<td>Tanzania</td>
<td>SARI; Min Ag (4); Sokoine Uni</td>
</tr>
<tr>
<td>Outside Africa</td>
<td>Australia (CSIRO); China (YPC); India (CIMMYT; ISSS-ICAR); Peru (IIAP); UK (Rothamsted)</td>
</tr>
</tbody>
</table>
Application levels for spectral technology

- Digital mapping of soil constraints, crop nutritional deficiencies, spectral soil types
  - National scale
  - Refinement at county / district level
  - Local scale - UAV hyperspectral calibration / indices

- Cost effective soil-plant testing services for farmers
  - National labs
  - Rural soil-plant spectral testing labs – walk-in service to farmers
  - Mobile labs

- Low cost sensors for community knowledge workers, private enterprises
Soil organic carbon as a soil health indicator

• BUT – no one can tell you what is a good or poor level
• Relationship with soil functions varies with soil type – no universal relationship
Controls on soil organic carbon

Soil carbon concentration vs silt+clay content for different clay mineralogies

Low activity clays
High activity clays
Allophanic soils

Feller & Beare, 1979
MIR Spectral SOC Index

- Proposed SOC index = (actual level – lower limit) / (upper – lower limit) [0 to 1 scale]
- MIR characterization of mineralogy, texture, soil organic carbon

AfSIS library MIR calibrations (e.g. Sila et al 2016)
Management action determined by shape of functional relationship

Shape determines strategy:

(a) Increase SOC only on high risk soils (treat the afflicted)
(b) Increase SOC on all soils (reduce exposure of the whole population)

Conclusions

• Spectral data relates strongly to soil functional properties and their change due to land management, providing a rapid indicator of soil health
• Low cost spectrometers set to aid scaling of soil health monitoring +++
• New spectral indicators (e.g. soil vs sediment indicator) to avoid calibration to conventional soil properties
• Relation between soil functional properties and spectral indicators critical to advise on best management strategies
A new way of doing applied soil science

• Define and analyse stakeholder decisions in economic terms to know what soils information will have high value, and to demonstrate its relevance
• Define and sample the region of interest when making recommendations for valid inference
• Express uncertainty, maintain links to the data, and validate recommendations for reliable learning (Bayesian updating)
• Communicate uncertainty to users

Thank you!

http://worldagroforestry.org/landhealth
k.shepherd@cgiar.org

World Agroforestry (ICRAF),
United Nations Avenue, Gigiri,
P.O Box 30677-00100, Nairobi, Kenya
Phone: +254 20 722 4000
Fax: +254 20 722 4001
Email: icraf@cgiar.org
Website: www.worldagroforestry.org