EJP SOIL WEBINAR

INTRODUCTION TO SOIL SENSING

<u>INTRODUCTION TO PROXIMAL SENSING (18-1)</u>

INTRODUCTION TO REMOTE SENSING (2-2)

EJP SOIL
European Joint Programme

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INTRODUCTION TO PROXIMAL SENSING

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Outline

- Introduction
  - Definition
  - Overview of types and groups of sensor techniques and applications
- Focus on a couple of sensor techniques with examples of applications
  - Electrical conductivity
  - Soil spectroscopy (vis-NIR-MIR)
  - Gamma ray and PXRF
- Discussions and questions (20-30 min)

Proximal sensing, definition

"the use of field-based sensors to obtain signals from the soil when the sensor's detector is in contact with or close to (within 2 m) the soil"

Viscarra Rossel et al 2011

This definition exclude similar sensor being used on platforms for remote sensing (e.g. on satellites) and in the laboratory.

But it is recognized that for some sensors, development (and applications) are also done using laboratory settings. Will partly be included in this seminar.

Viscarra Rossel, R.A., V.I. Adamchuk, K.A. Sudduth, N.J. McKenzie, and C. Lobsey. 2011. Proximal soil sensing: An effective approach for soil measurements in space and time, Chapter 5. Adv. Agron. 113:237–283.

Why use proximal soil sensing?

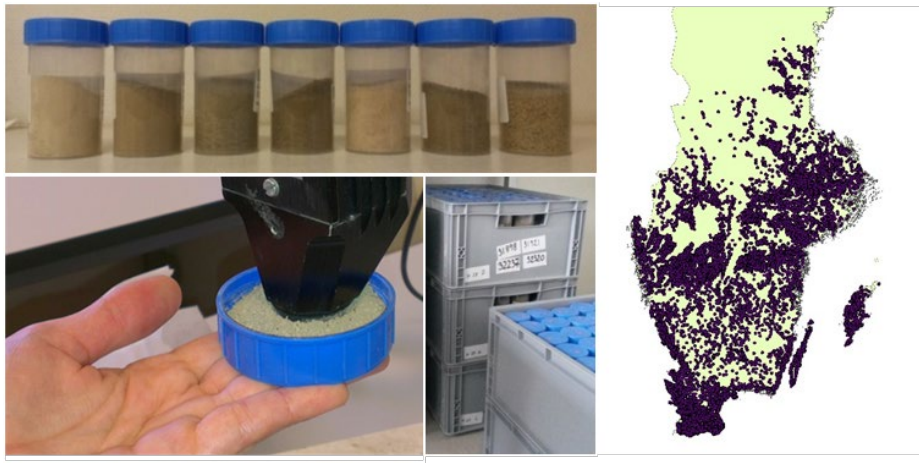
- The measurements are cheaper, faster and allow for more analyses.
- The sensors signals correspond to physical measures which can be related to soil properties.
  - Quite often through indirect inference ➡ a need for calibration models using sensor measurements and traditional analyses on soil samples.
- Each individual measurement might be less correct, but you get additional information by getting more measurements.
- The fact that some of the sensor measurements are affected by several soil properties also make them useful for estimating “over all soil variation” or even in some cases “soil fertility”.

What can proximal soil sensing be used for?

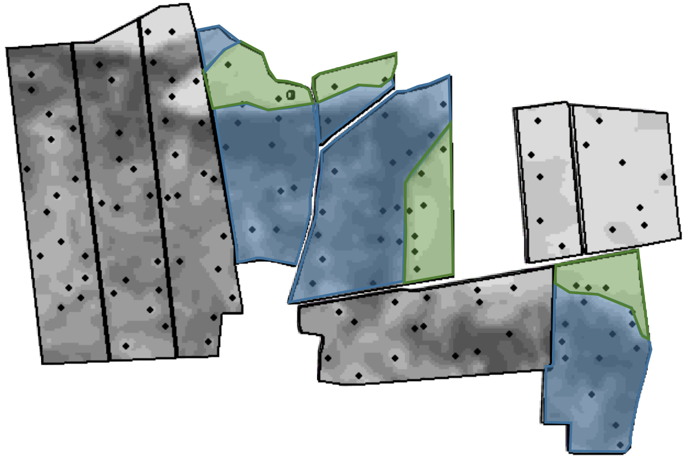
Scale:

Field measurements → field or farm scale

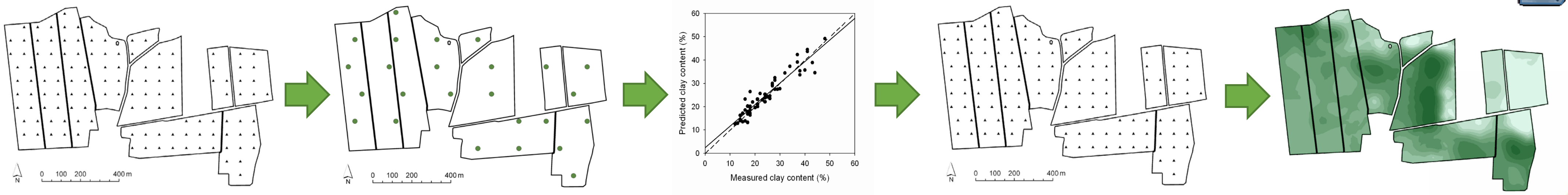
Laboratory measurements → field, regional, national, European scale



What can proximal soil sensing be used for?



- To guide soil sampling
- To delineate fields into management zones
- To increase the number of analysis



- To estimate soil properties
- To directly measure soil properties

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Proximal soil sensing – many types

Can be divided based on "**how**" they measure/operate …

Measurement	Energy	Operation	Inference
Non-invasive	Passive	On-the-go	Indirect
Invasive *In situ – ex situ*	Active	Stationary	Direct

Adopted from Viscarra Rossel et al., 2011

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Proximal soil sensing – many types

… and on "**what**" they measure.

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

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Proximal soil sensing – many types

… and on “**what”** they measure.

- Mechanical
  - Measures mechanical resistance in the soil, soil compaction
  - Draft force on regular soil cultivation machinery
  - Horizontal penetrometers

- Electrochemical
- Electrical and Electromagnetic
- Optical and Radiometric

Proximal soil sensing – many types

… and on “**what**” they measure.

- Mechanical
- Electrochemical
  - Ion-selective electrodes (ISE)
  - Measures the ion concentration in a solution using Ion-selective membranes

- Electrical and Electromagnetic
- Optical and Radiometric

Proximal soil sensing – many types

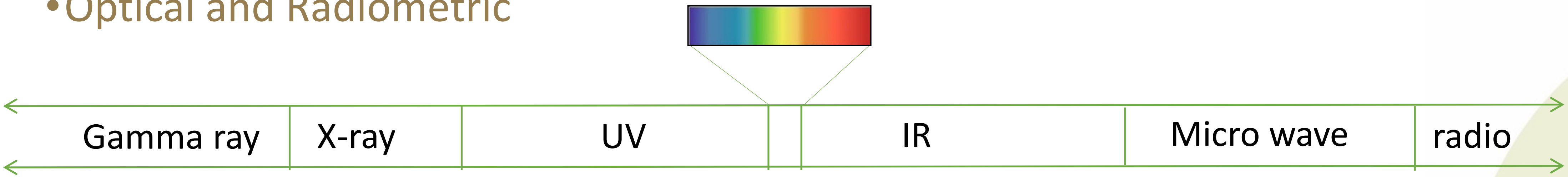
… and on “**what**” they measure.

- Mechanical
- Electrochemical
- Electrical and Electromagnetic
  - Measure electrical conductivity
  - Direct contact or through magnetic induction
  - *Kristin Person will talk more about this*
- Optical and Radiometric

Proximal soil sensing – many types

... and on “**what”** they measure.

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



Mats Söderström
will talk more about this

I will talk more about
this later

Ground penetrating
radar

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References and further reading

Overview of proximal soil sensing

- Viscarra Rossel, R.A., V.I. Adamchuk, K.A. Sudduth, N.J. McKenzie, and C. Lobsey. (2011). Proximal soil sensing: An effective approach for soil measurements in space and time, Chapter 5. Adv. Agron. 113:237–283. https://doi.org/10.1016/B978-0-12-386473-4.00005-1
- Adamchuk VI, Ji W, Viscarra Rossel R, Gebbers R, Tremblay N (2018) Chapter 9, Proximal Soil and Plant Sensing in Precision Agriculture Basics. D.K Shannon, D.E. Clay, and N. Kitchen (eds.) American Society of Agronomy, Crop Science Society of America, and Soil Science Society of America, 5585 Guilford Rd. Madison, WI 53711, USA.

Example of using mechanical sensors

- Bölenius, E., Wetterlind, J., Keller, T. (2018). Can within field yield variation be explained using horizontal penetrometer resistance and electrical conductivity measurements? Results from three Swedish fields. Acta Agriculturae Scandinavica, Section B — Soil & Plant Science, 68(8), 690-700. https://doi.org/10.1080/09064710.2018.1464201

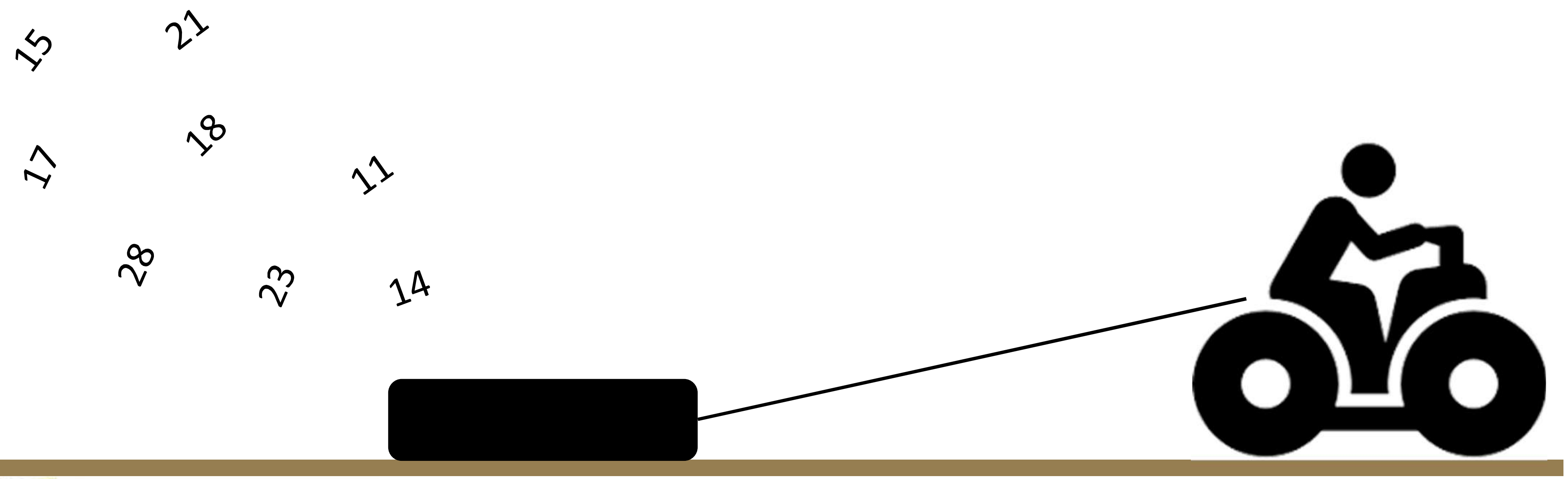
Example of using electrochemical sensors

- Kim, H., Hummel, J.W., Sudduth, K.A. and Motavalli, P.P. (2007), Simultaneous Analysis of Soil Macronutrients Using Ion-Selective Electrodes. Soil Sci. Soc. Am. J., 71: 1867-1877. https://doi.org/10.2136/sssaj2007.0002

Example of using ground penetrating radar

- Lombardi, F., Ortuani, B., Facchi, A.; Lualdi, M. (2022). Assessing the Perspectives of Ground Penetrating Radar for Precision Farming. Remote Sens. 14, 6066. https://doi.org/10.3390/rs14236066

Electrical conductivity sensors for *on-the-go* measurements



Two sensing techniques

Electromagnetic induction (EMI) method

Entity: Apparent (or bulk) Electrical Conductivity (ECa)

Unit: S m^{-1}

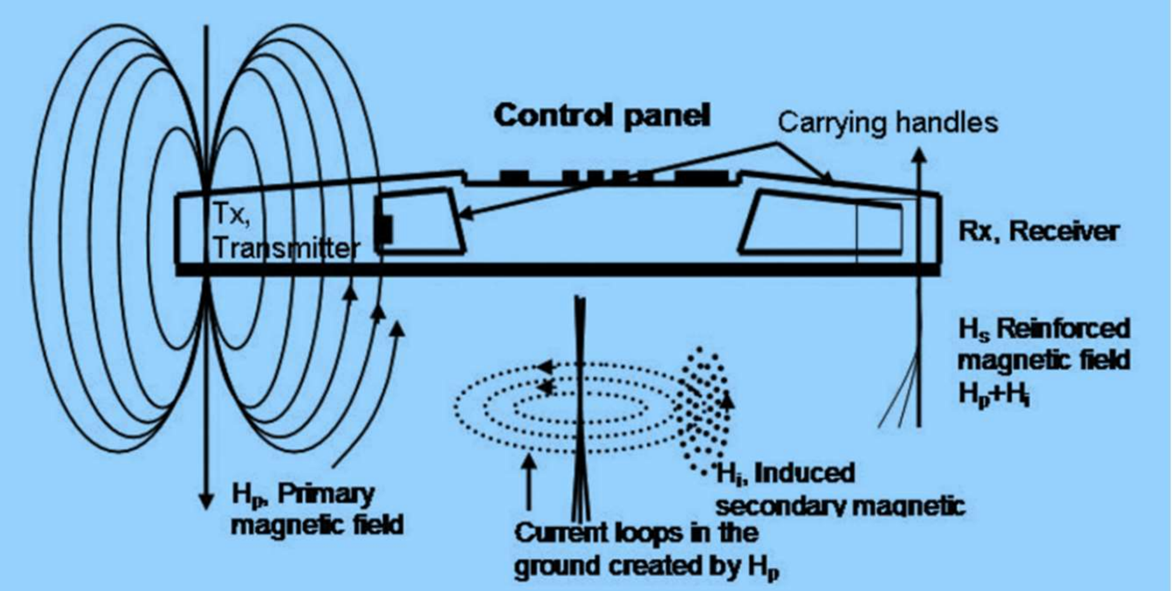


FIGURE 10-7. Schematic of the operation of electromagnetic induction equipment, using an EM-38.

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Direct current (DC) method

Entity: Electrical Resistivity (ER)

The inverse of ECa

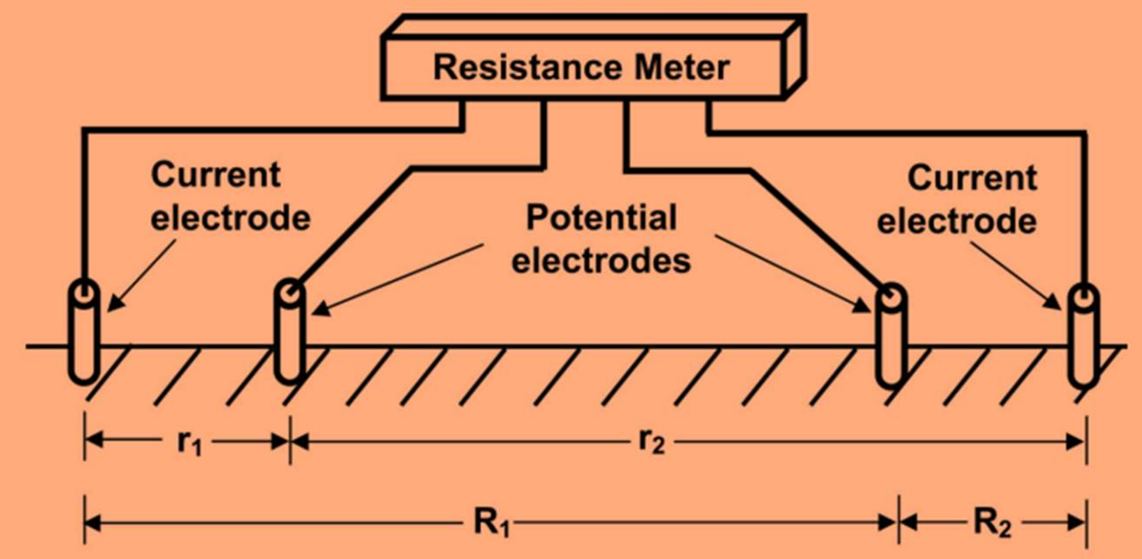

FIGURE 10-4. Schematic of four-electrode probe electrical resistivity used to measure apparent soil electrical conductivity. From Corwin and Hendrickx (2002).

Veris 3100

Kristin Persson, Swedish University of Agricultural Sciences (SLU), kristin.persson@slu.se

Figures: DOI: 10.1061/9780784411698.ch10

Two sensing techniques

Electromagnetic induction (EMI) method
Entity: Apparent (or bulk) Electrical Conductivity (ECa)
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DUALEM 21S

Direct current (DC) method
Entity: Electrical Resistivity (ER)
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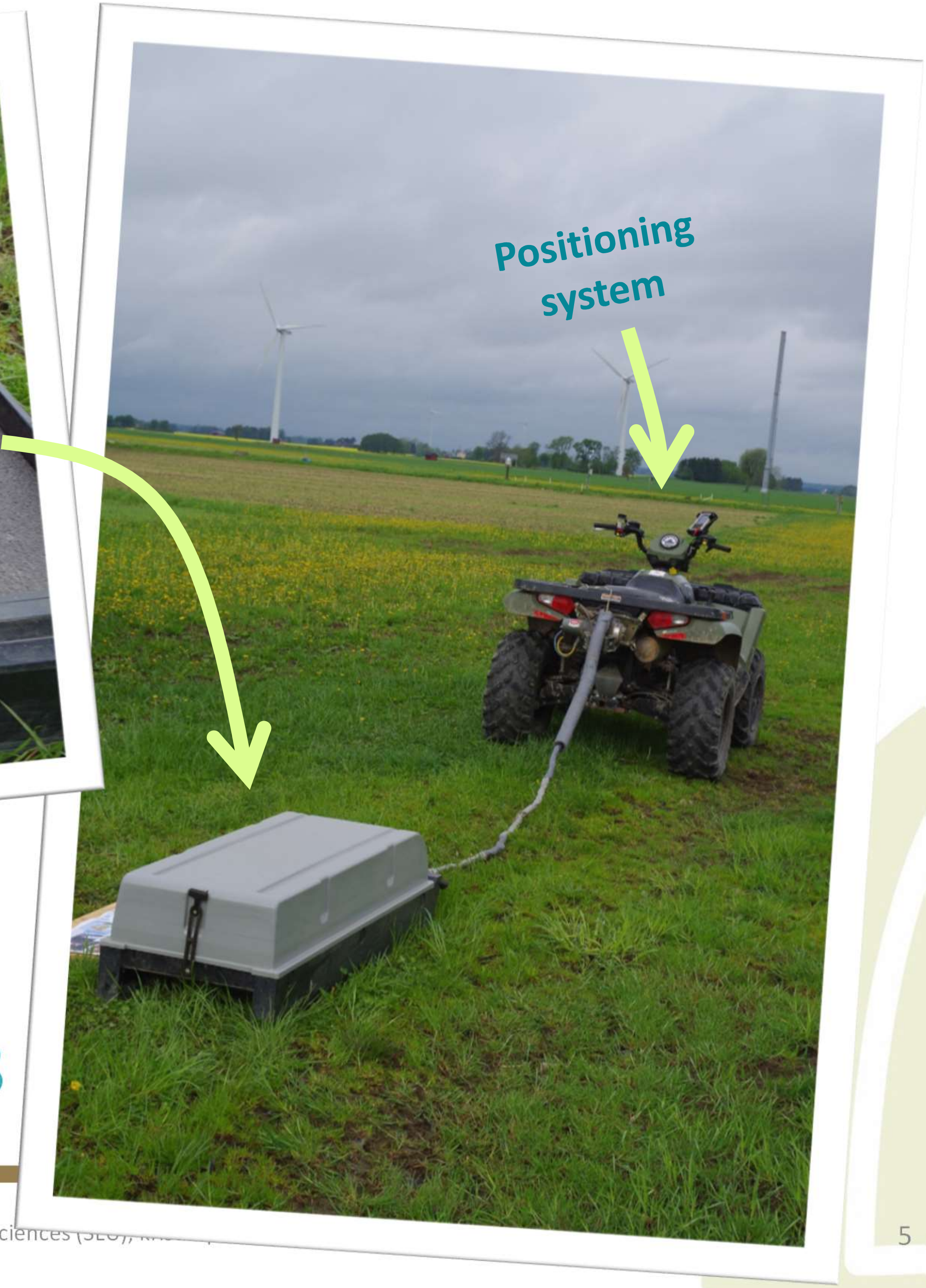
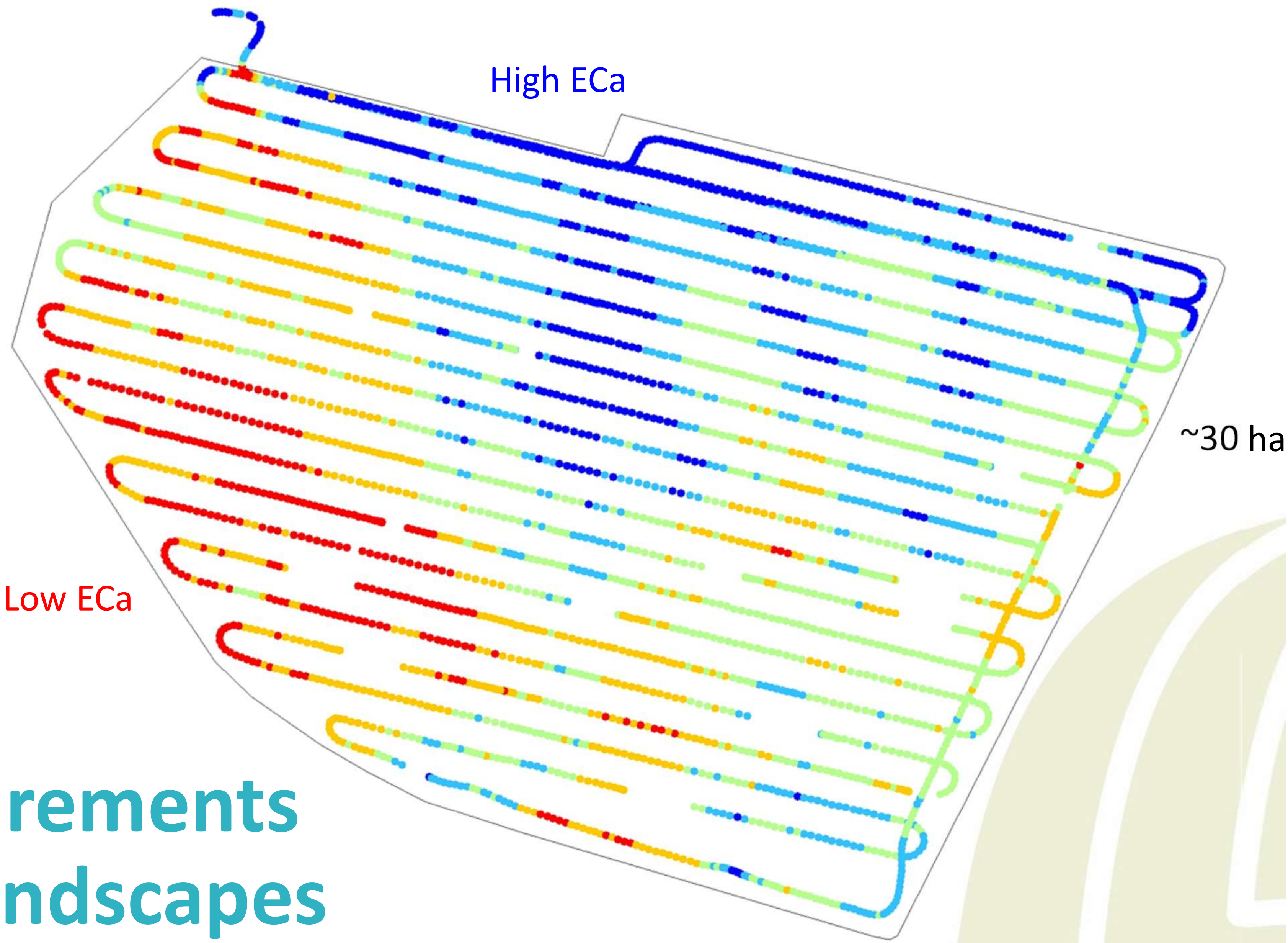


On-the-go measurements across fields or landscapes



On-the-go measurements across fields or landscapes

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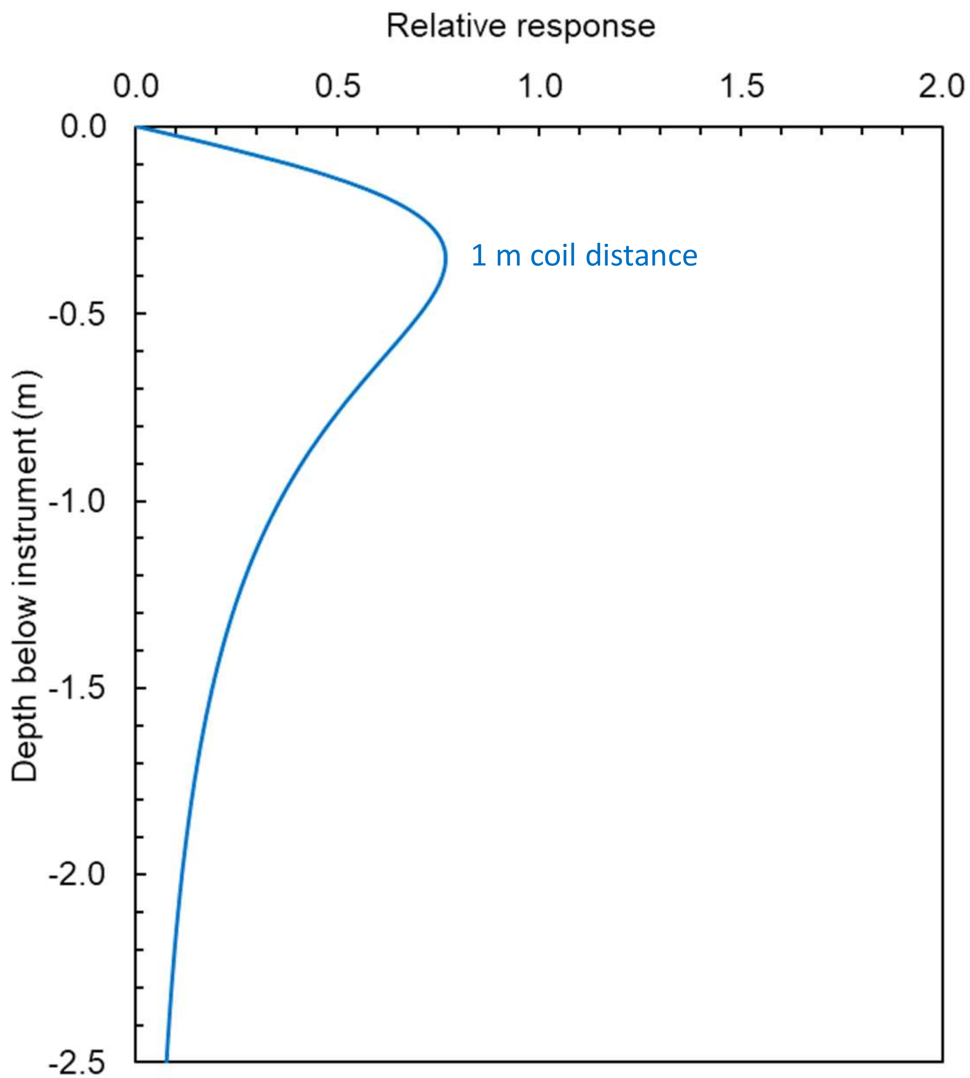
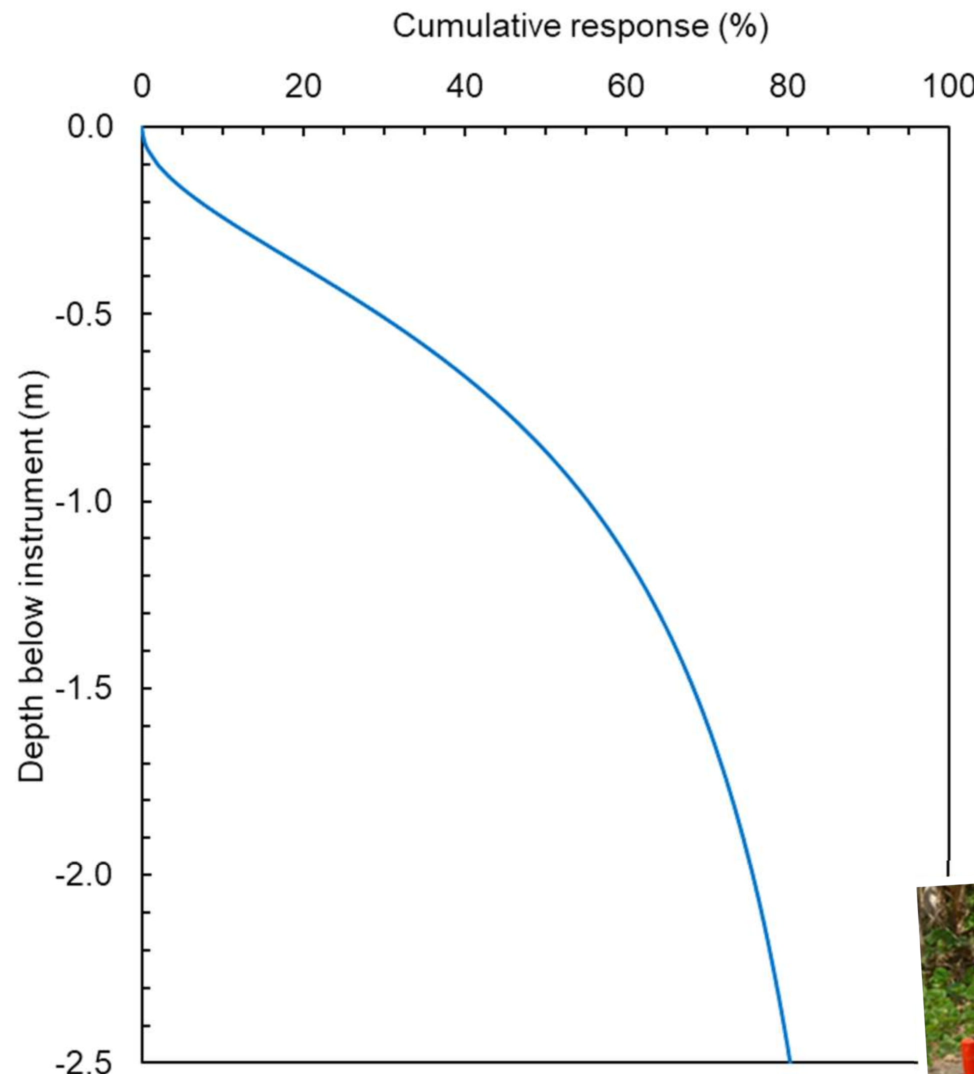
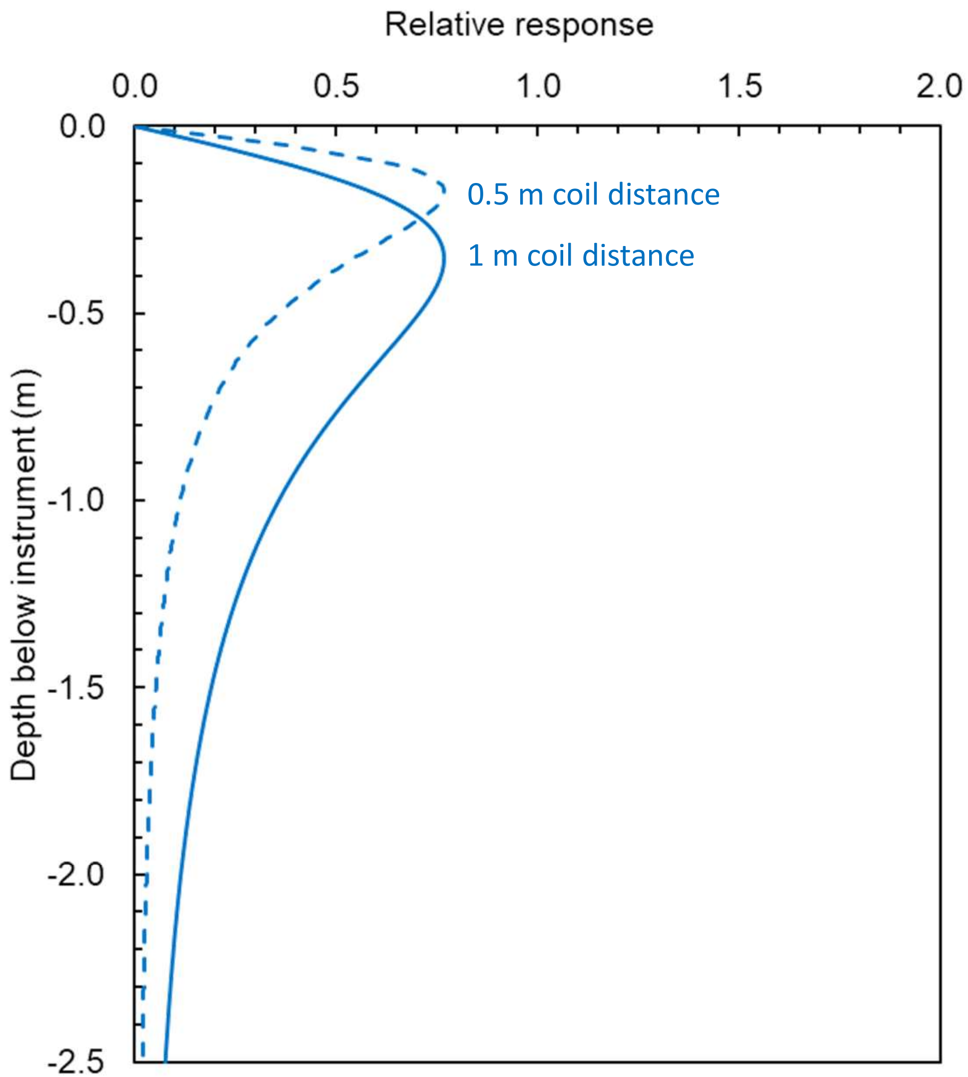
The depth response of an EMI sensor

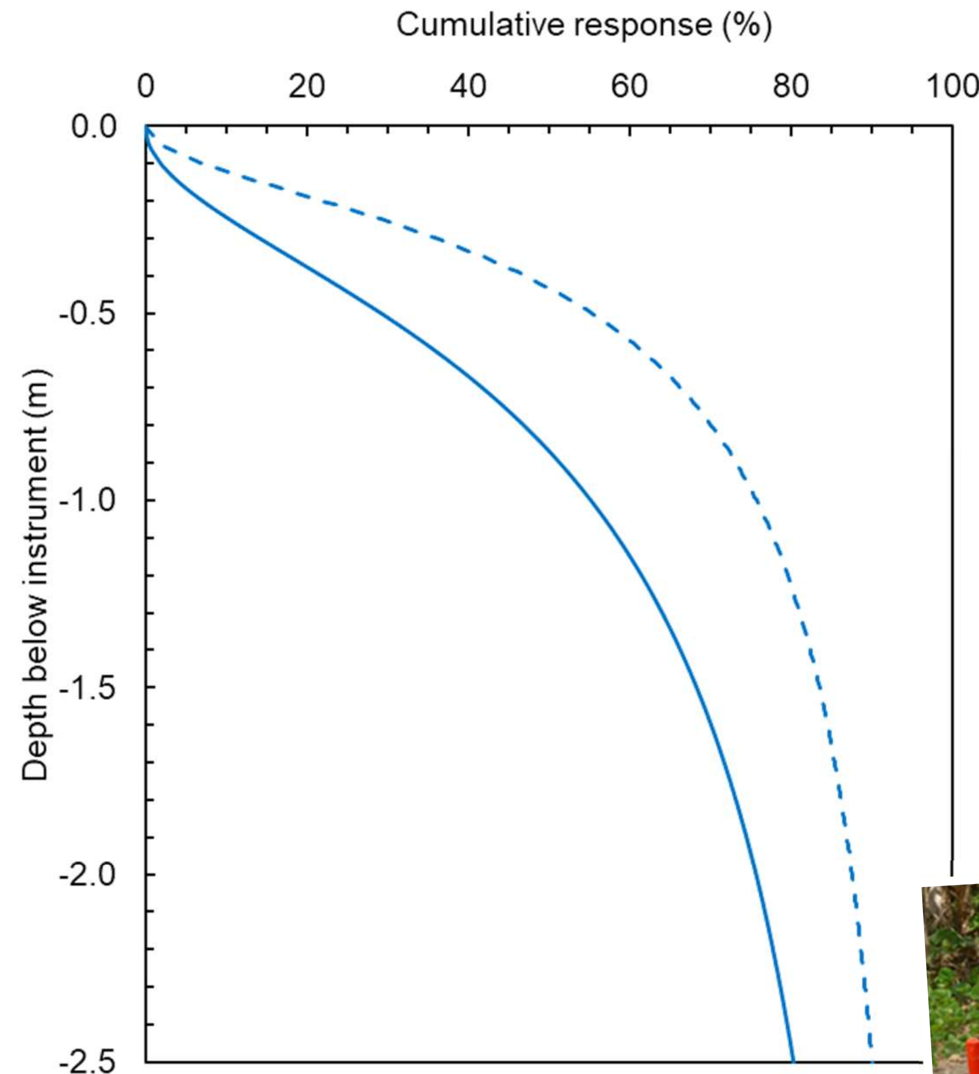




Geonics EM38 MK2

The depth response of an EMI sensor





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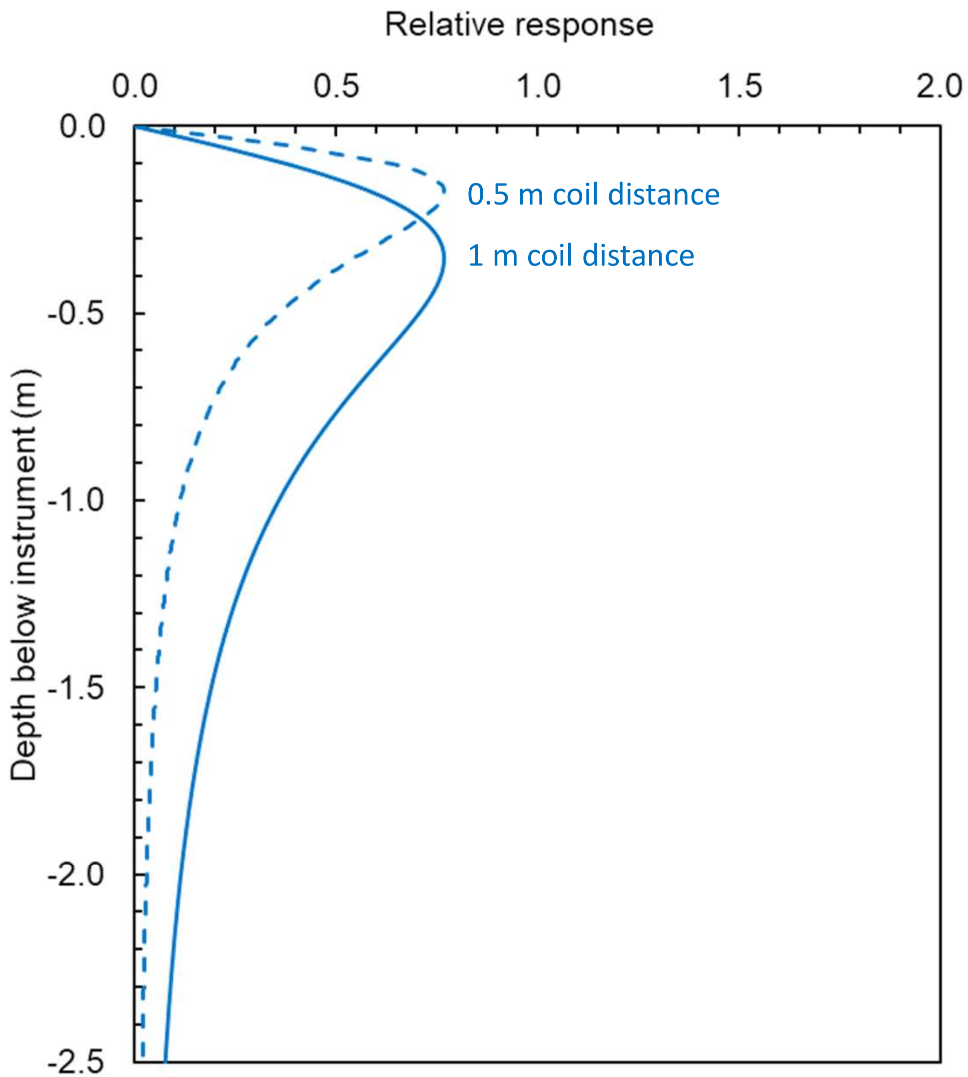

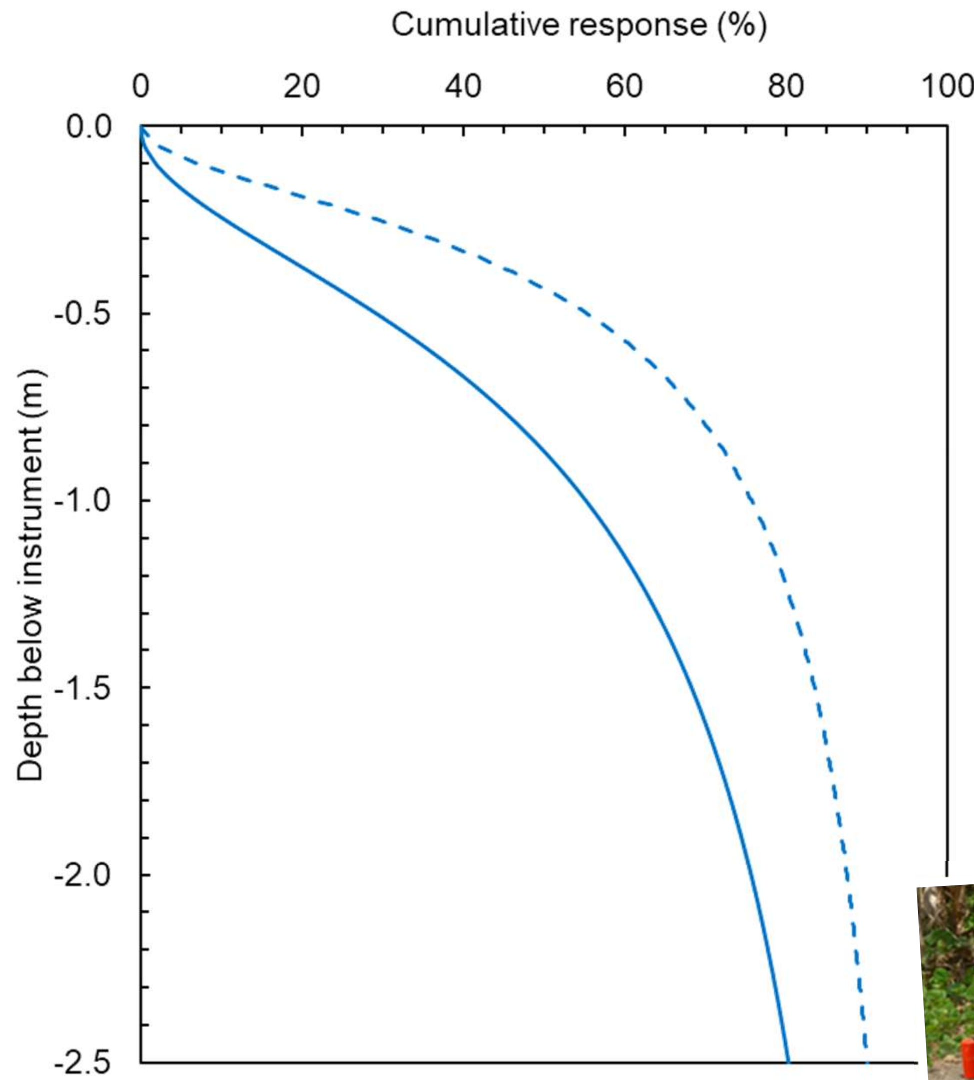

Geonics EM38 MK2

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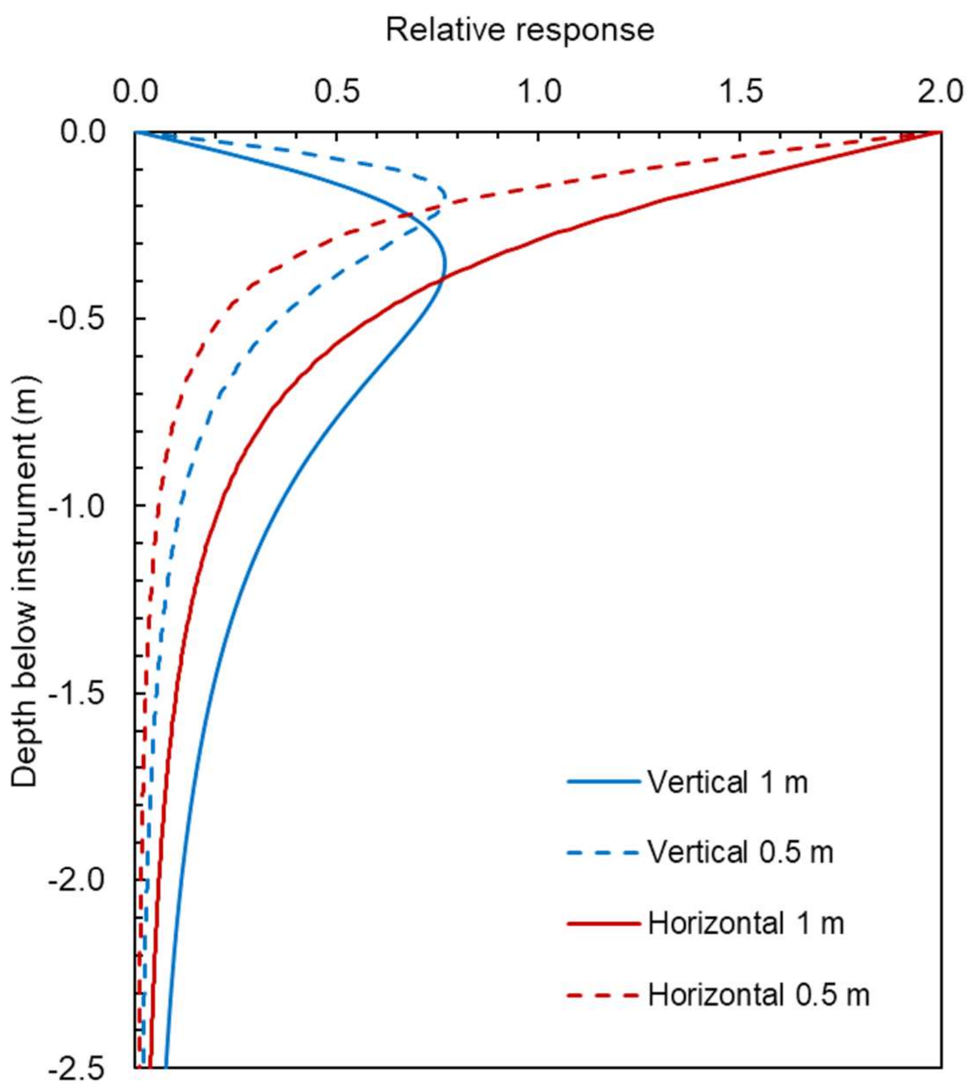
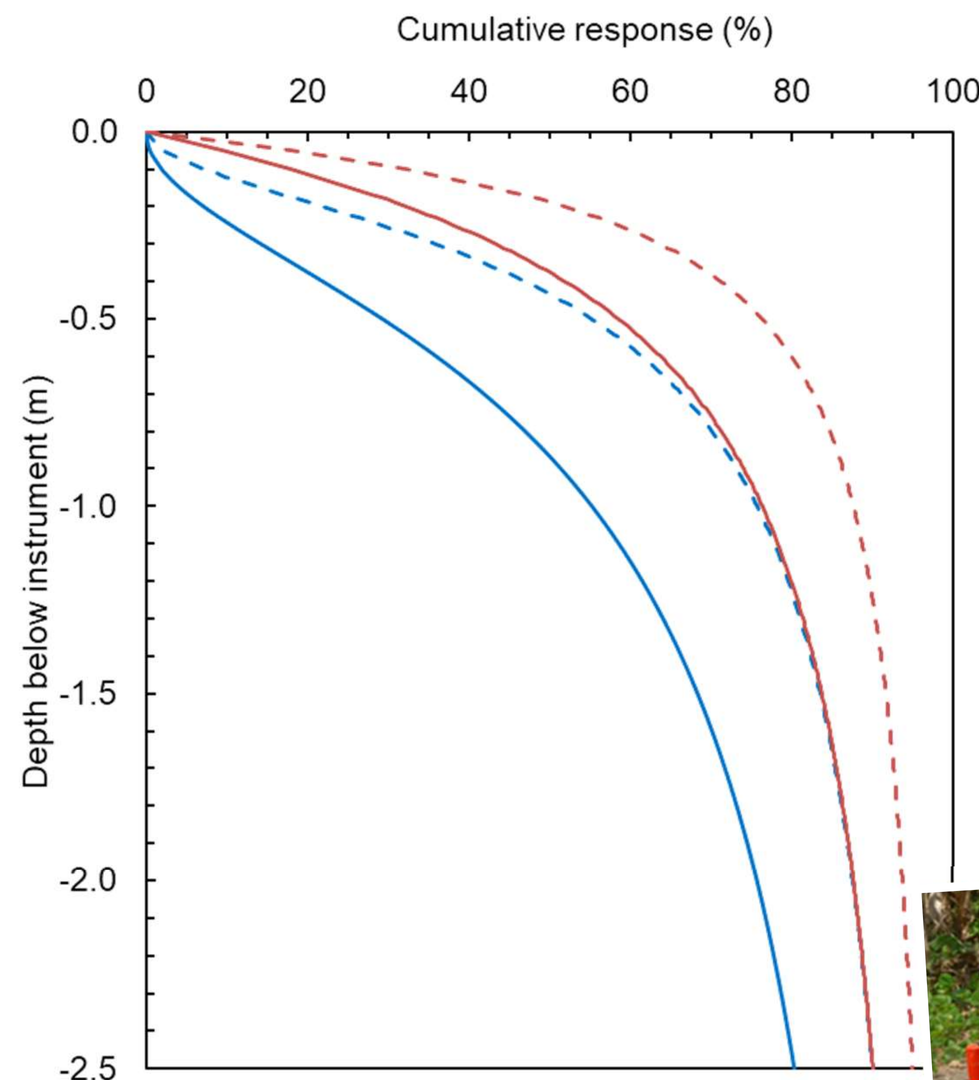
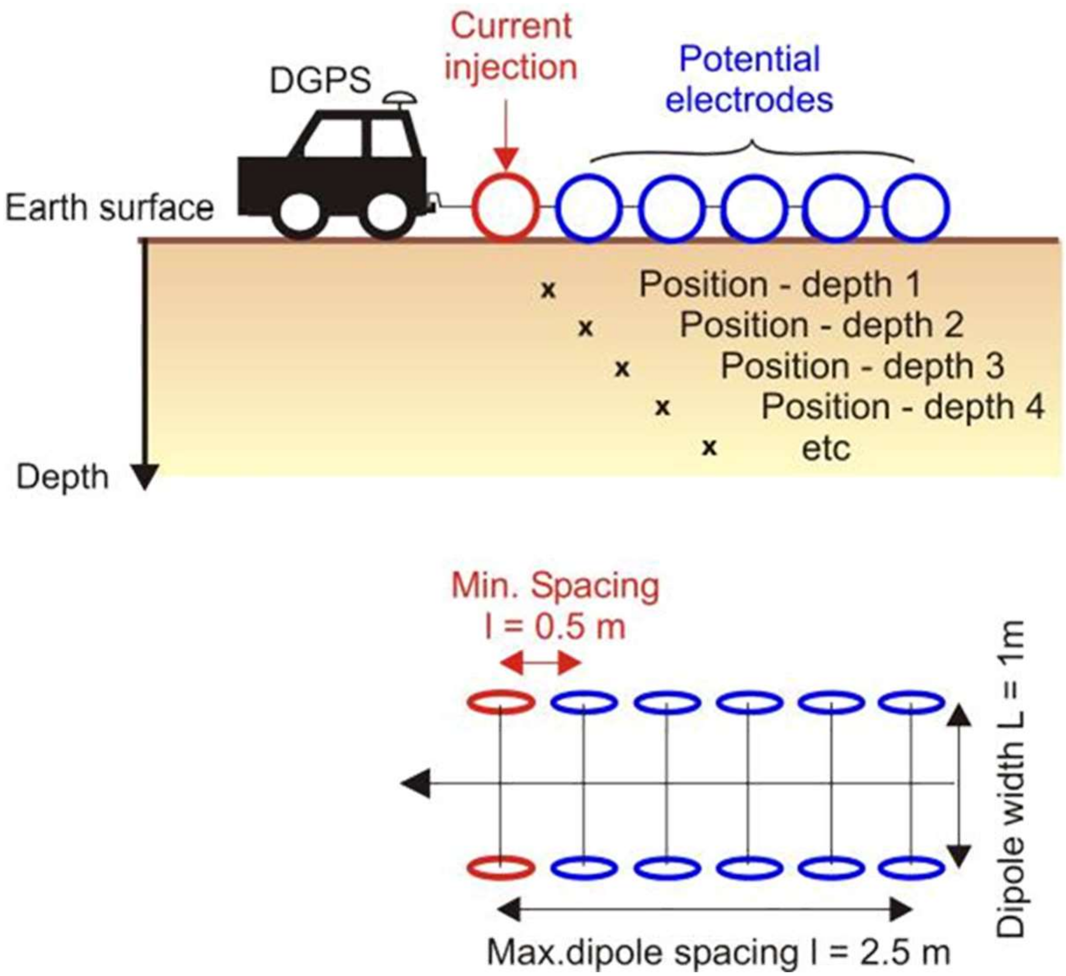
The depth response of an EMI sensor

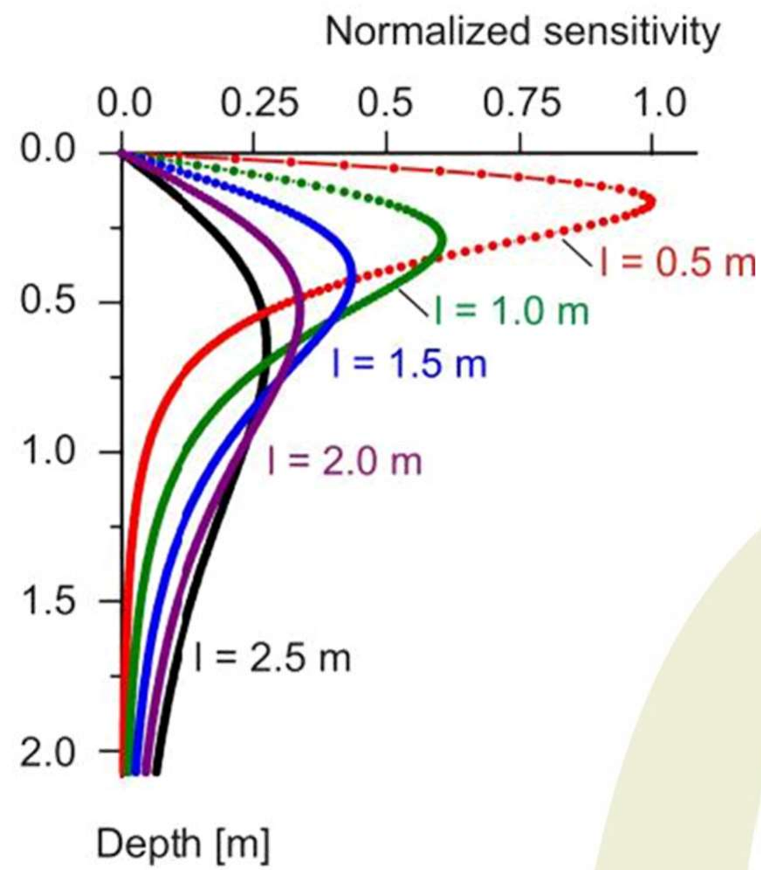




Geonics EM38 MK2

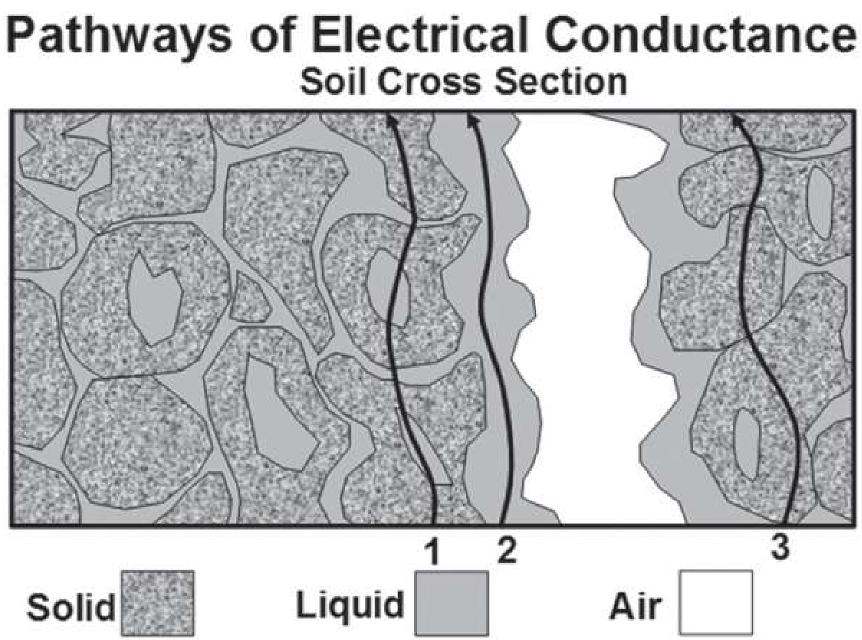
The depth response of a DC sensor



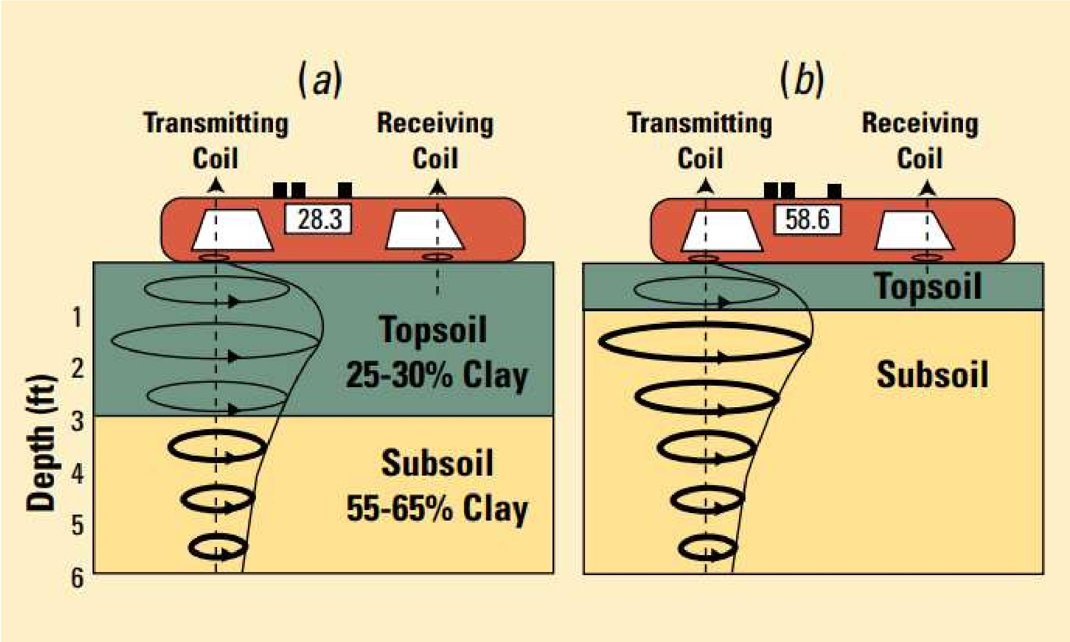


Lueck, E., & Ruehlmann, J. (2013). https://doi.org/10.1016/j.geoderma.2012.11.009

Also soil electrical properties varies with depth

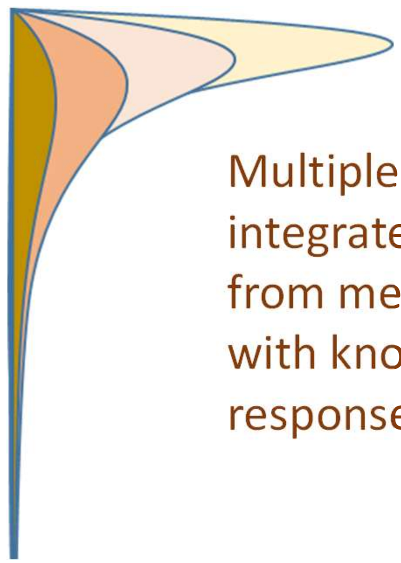


https://doi.org/10.1016/j.compag.2004.10.005

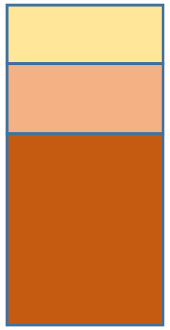


https://geonics.com/pdfs/casestudies/a38Kitchen.pdf

Also soil electrical properties varies with depth



Multiple depth-integrated ECa values from measurements with known depth-responses



Estimated ECa values in specific depth intervals

Theory explained: http://dx.doi.org/10.2136/sssaj2002.6730

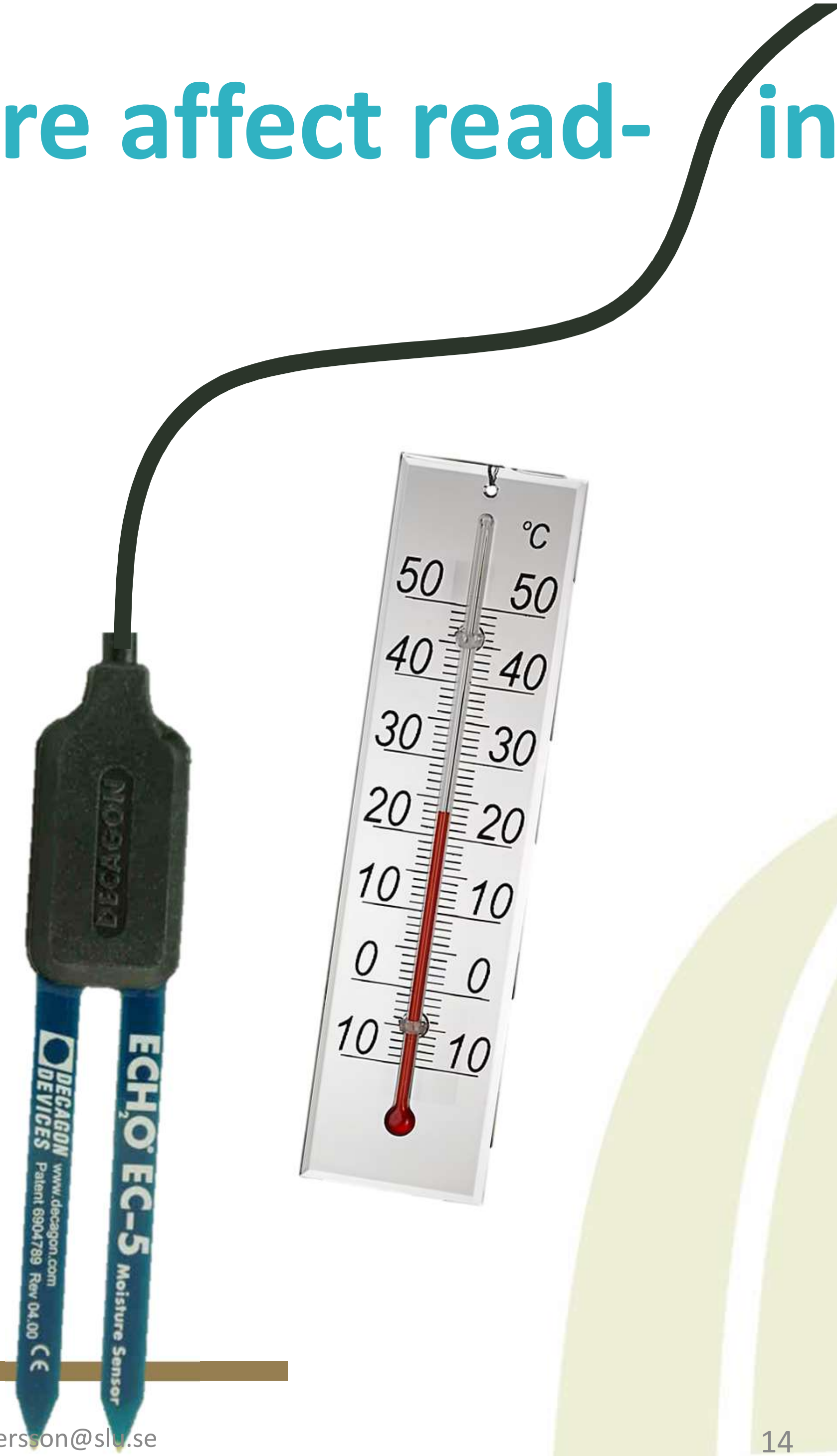
One of many examples: https://doi.org/10.2136/vzj2009.0088

Air temperature and soil moisture affect readings

EMI sensors are sensitive to temperature

ECa of soil depend on water content

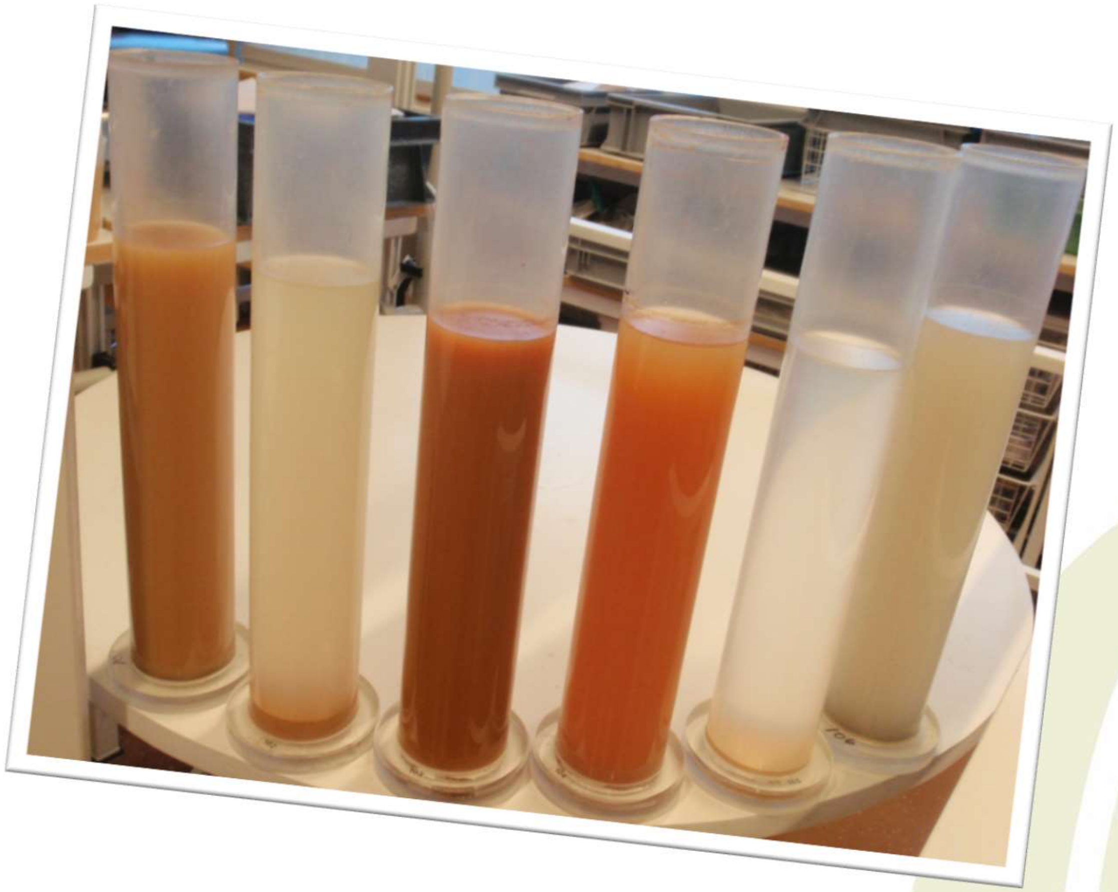
Better to measure closer to field capacity.



Agronomic relevance of ECa maps

Soil ECa depend on – or covariates with – several soil properties, e.g.:

- salinity
- clay content
- organic matter content
- macronutrient content (e.g. K and Mg)
- depth to layer with contrasting ECa (e.g. claypan or bedrock)



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- depth to layer with contrasting ECa
  (e.g. claypan or bedrock)

NB: Correlations are often time- and site-specific

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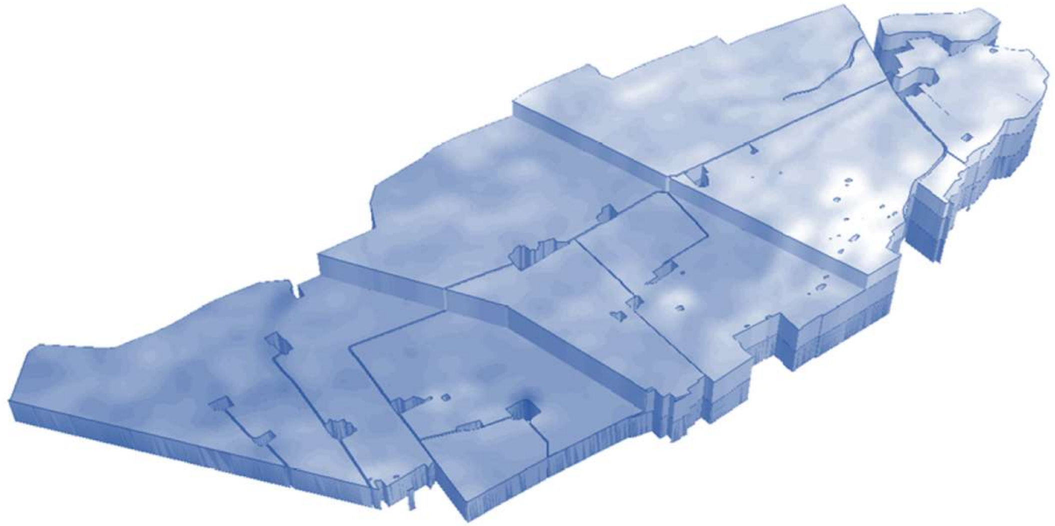
How to use ECa maps

- Guide soil sampling
- Delineation of management zones
- Salinity mapping
- Covariable for soil mapping (2D or 3D)

How to use ECa maps

One example



Multiple EMI readings on-the-go → Eca maps for three depth intervals → Soil property maps for three depth intervals → Modelling of P leaching

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https://doi.org/10.3920/978-90-8686-778-3_2

Summary

- ECa sensors can give information on soil property variation in 3D. ECa sensors are **easy to use for on-the-go** measurements over fields – landscapes and from sensor readings with different depth responses one **can infer ECa in specific depth layers**.

- EMI sensors sensitive to temperature and ECa of soil depend on water content and therefore **ECa varies over time**.

- ECa of soil depend on – or covariates with – several soil properties, e.g.: salinity, clay content, soil organic matter content, macronutrient content, and depth to layer with higher or lower ECa (e.g. claypan or bedrock). These **correlations are often time- and site-specific**.

- Common uses of ECa mapping are to: guide soil sampling, delineate of homogeneous zones, map salinity (Eca), use as a covariate for mapping of other soil properties (2D or 3D).

References and further reading

On 3D soil mapping and inversion or interpretation of depth-integrated ECa readings

Corwin, D. L., & Lesch, S. M. (2005). Apparent soil electrical conductivity measurements in agriculture. Computers and electronics in agriculture, 46(1-3), 11-43. https://doi.org/10.1016/j.compag.2004.10.005

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Triantafilis, J., & Santos, F. M. (2010). Resolving the spatial distribution of the true electrical conductivity with depth using EM38 and EM31 signal data and a laterally constrained inversion model. Soil Research, 48(5), 434-446.. https://doi.org/10.1071/SR09149

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Saey, T., Van Meirvenne, M., De Smedt, P., Cockx, L., Meerschman, E., Islam, M. M., & Meeuws, F. (2011). Mapping depth-to-clay using fitted multiple depth response curves of a proximal EMI sensor. Geoderma, 162(1-2), 151-158. https://doi.org/10.1016/j.geoderma.2011.01.015

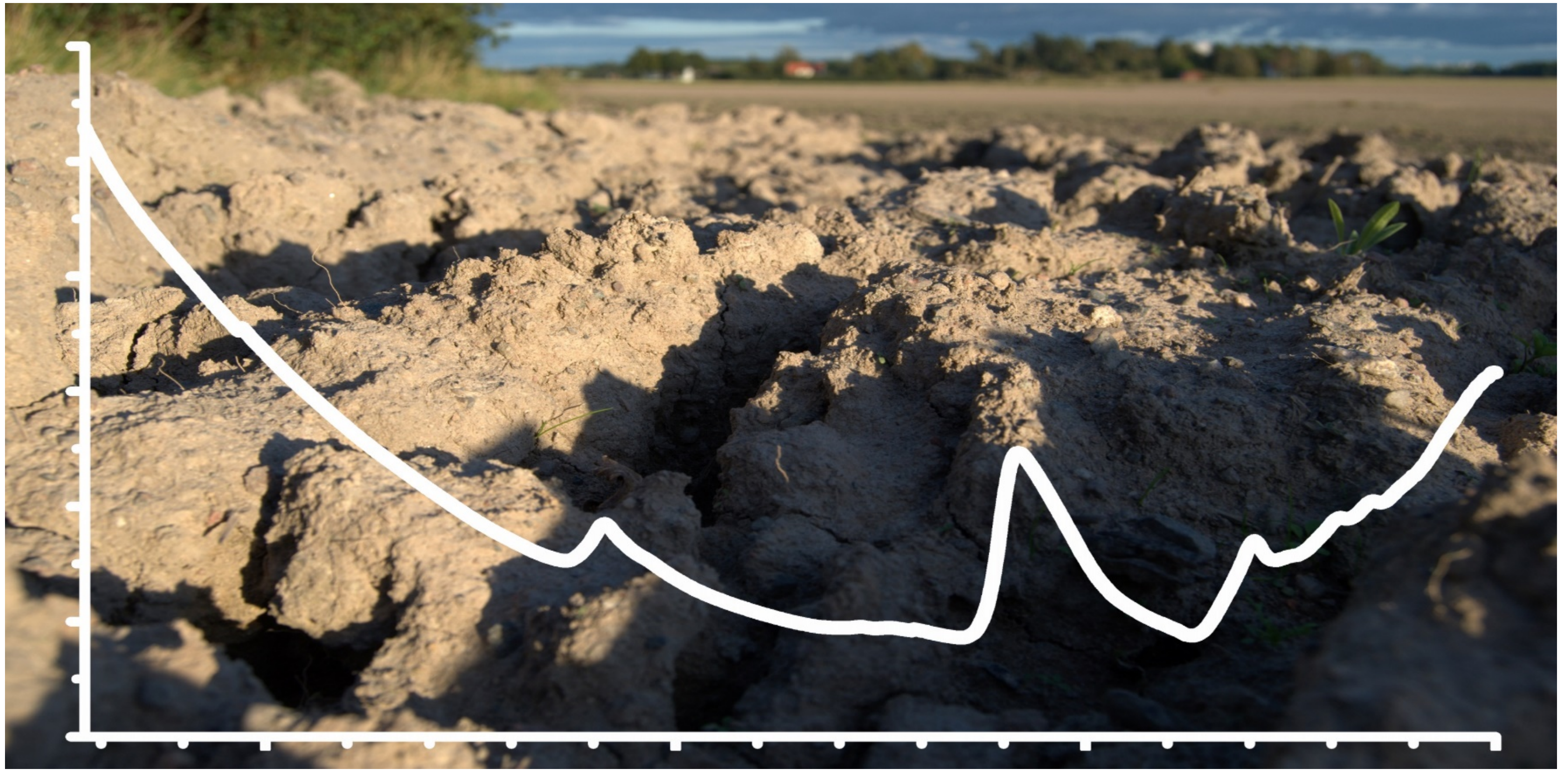
Sudduth, K. A., Myers, D. B., Kitchen, N. R., & Drummond, S. T. (2013). Modeling soil electrical conductivity–depth relationships with data from proximal and penetrating ECa sensors. Geoderma, 199, 12-21. https://doi.org/10.1016/j.geoderma.2012.10.006

On evaluation of model performance

Piikki, K., Wetterlind, J., Söderström, M., & Stenberg, B. (2021). Perspectives on validation in digital soil mapping of continuous attributes—A review. Soil Use and Management, 37(1), 7-21. https://doi.org/10.1111/sum.12694

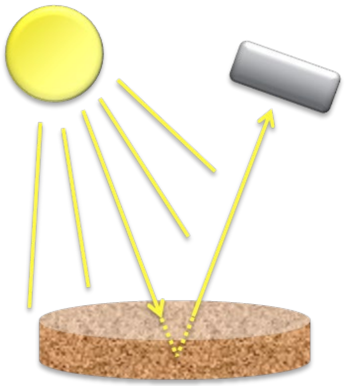
Piikki, K., Söderström, M., Eriksson, J., Muturi John, J., Ireri Muthee, P., Wetterlind, J., & Lund, E. (2016). Performance evaluation of proximal sensors for soil assessment in smallholder farms in Embu County, Kenya. Sensors, 16(11), 1950. https://doi.org/10.3390/s16111950

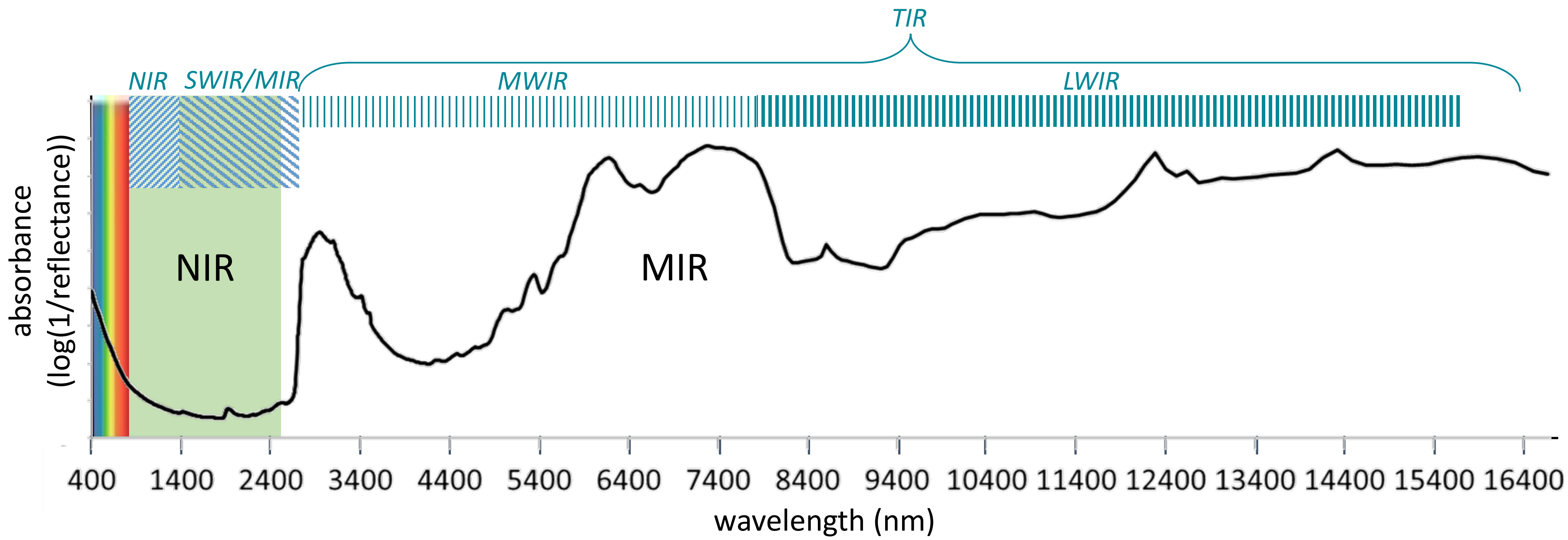
Vis-NIR-MIR sensors for soil sensing



Vis-NIR-MIR sensors for soil sensing

Passive or active sensors that measure reflectance in the visible, near and/or mid infrared wavelength ranges





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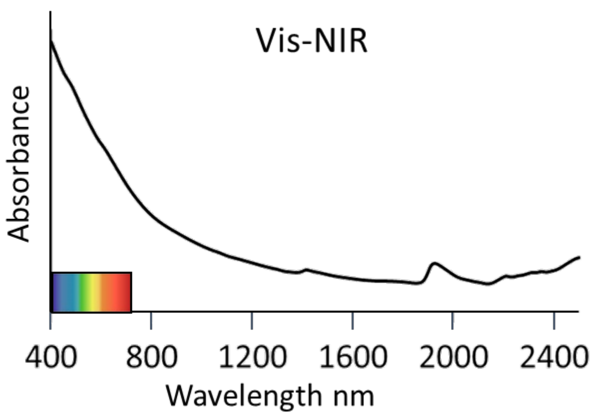
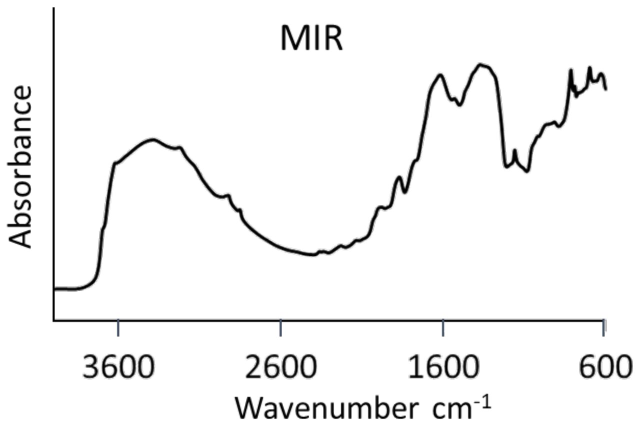
Vis-NIR-MIR sensors for soil sensing

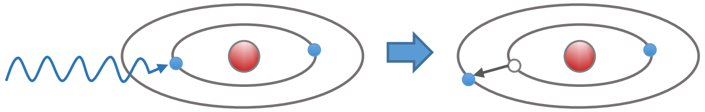




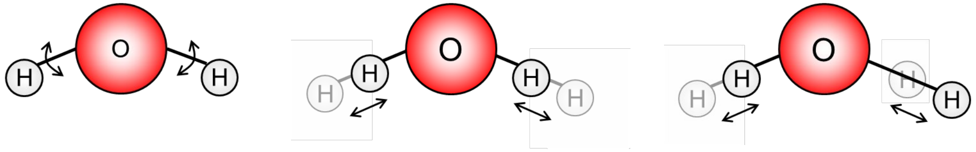
Can look at the spectra qualitatively

For quantitative analyses, multivariate calibrations are needed.

- In the visible region absorption is due to excitation of electrons.



- With longer wavelengths, the absorptions is due to vibrations in chemical bonds within molecules, with the fundamental absorption in the MIR and overtones and combinations in the NIR region.



Vis-NIR-MIR sensors for soil sensing

Reflectance spectra from soils primarily contain information related to **water, soil organic matter, clay minerals and soil texture**, and other soil parameters related to these (e.g. CEC).

Example:

It is not possible to directly relate the spectra to pH (H^+ concentration).

However, the spectra holds information on the buffering capacity (clay and organic matter content) and if pH is related to the buffering capacity it is possible to indirectly estimate pH. Or if the pH is related to carbonate content.

But, as with most indirect correlations they are often site specific. And cannot be moved to another context/site.

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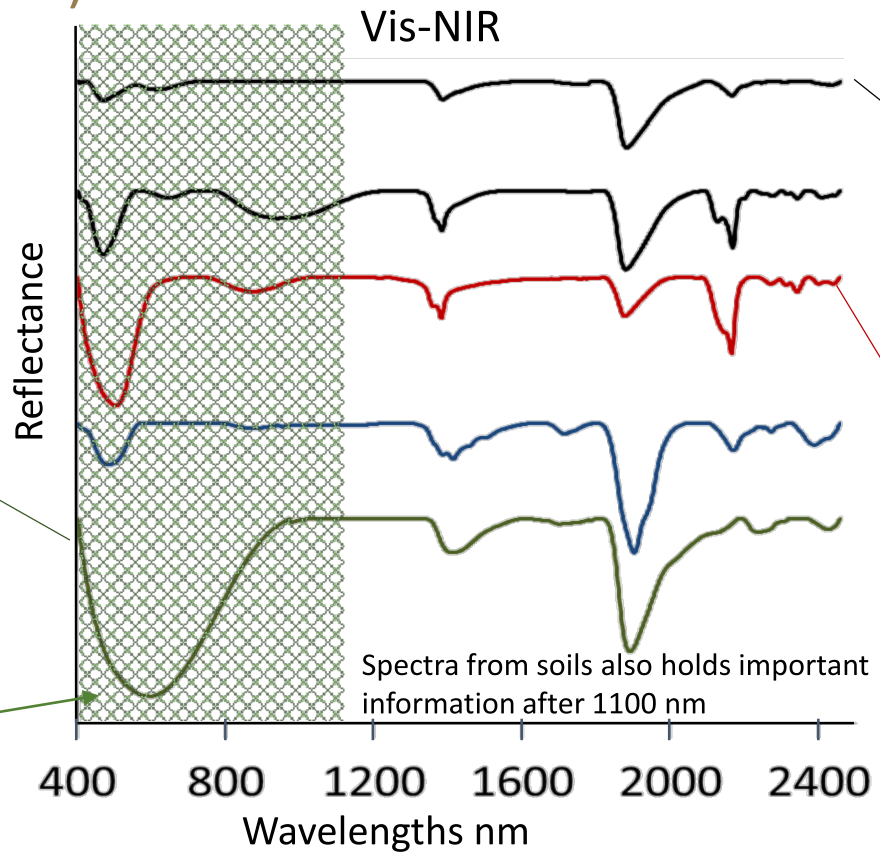
Vis-NIR-MIR sensors for soil sensing

Reflectance spectra from soils primarily contain information related to **water, soil organic matter, clay minerals and soil texture**, and other soil parameters related to these (e.g. CEC).

Organic soil

Spectral range often covered by sensors used for plant analysis



Comparably young illitic soil.

Older more weathered soil, containing kaolinite and iron oxides.

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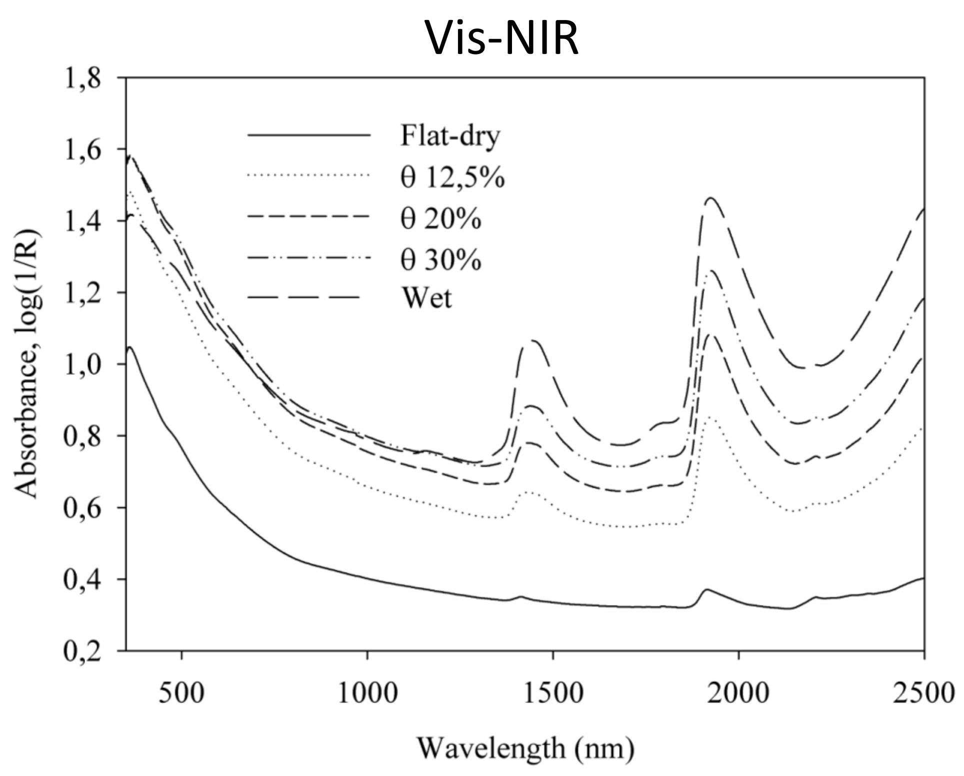
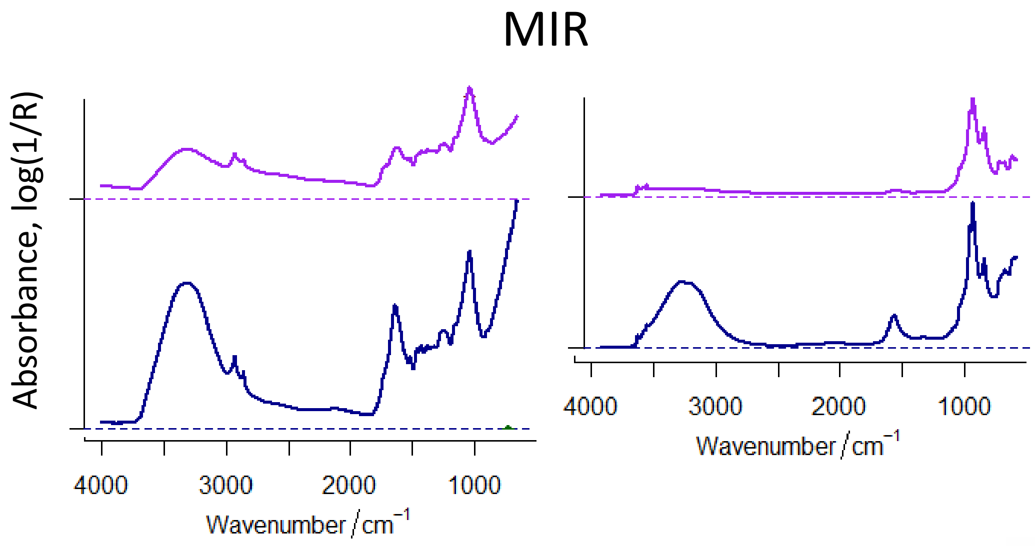
Strong influence of water





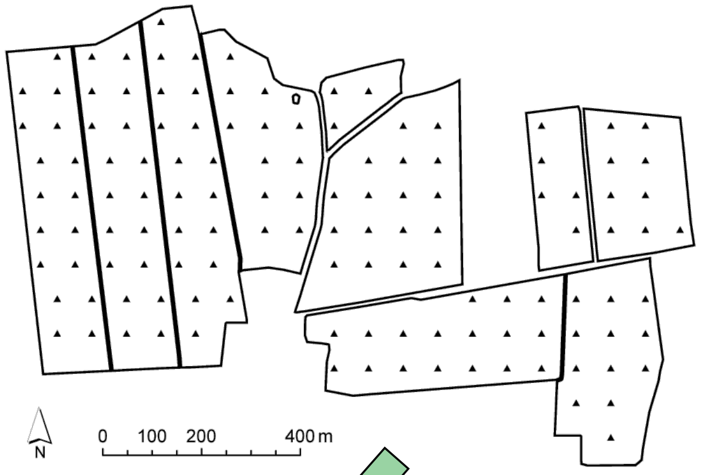
This affects *in-situ* measurements.

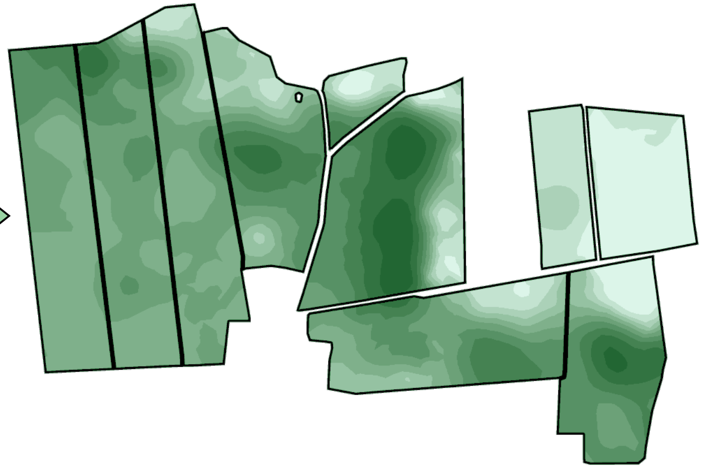
Laboratory and field instruments

- Easier to take vis-NIR measurements out into the field.
- MIR measurements usually require more sample preparation (grinding vs sieving) and are more sensitive to water.
- Many of the applications using NIR and MIR are lab analyses similar to other soil analyses, using calibrations based on large spectral libraries.
  However, cheap and with the possibility to get information on several soil properties from one measurement.
- There are instruments for field analyses also for MIR, and a growing number of really cheep NIR sensors with varying spectral ranges.

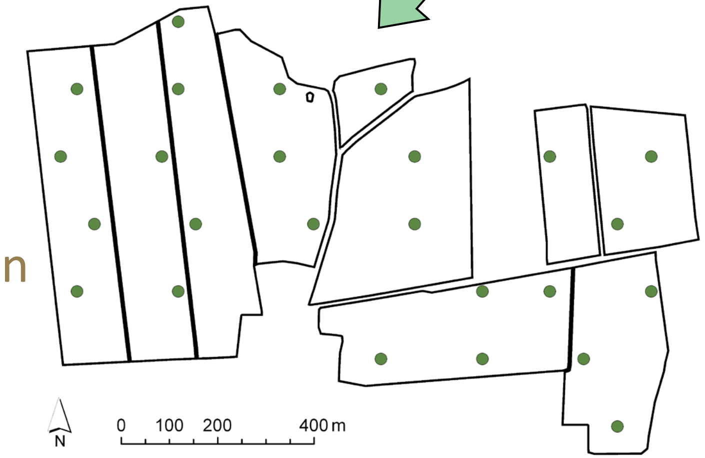
Example 1: Laboratory analyses vis-NIR *(local calibrations)*

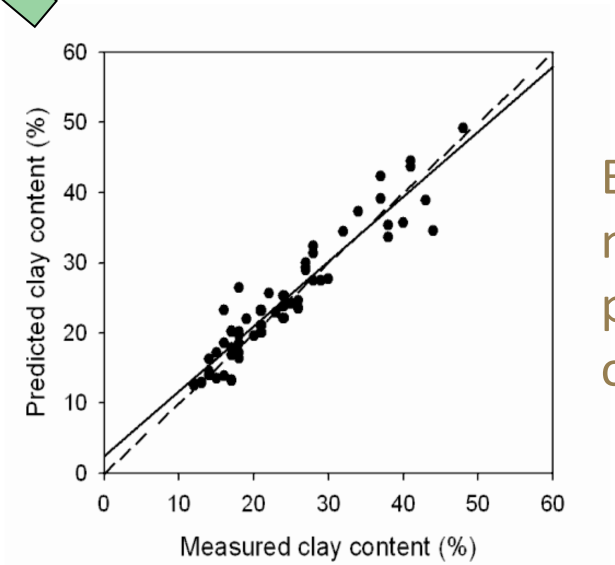
Farm soil sampling
1 sample/ha
But some analyses every third sample.





Analyse all samples using vis-NIR and select calibration samples.

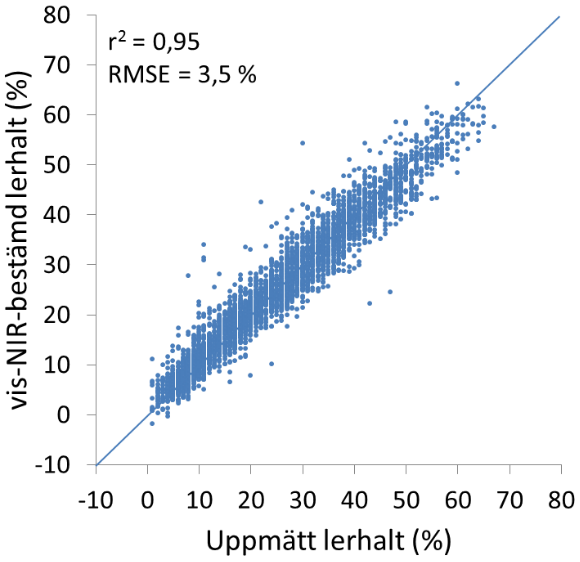


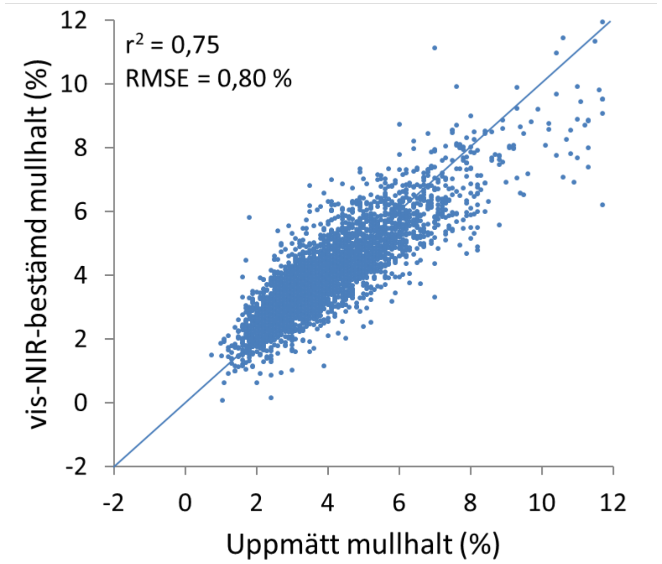


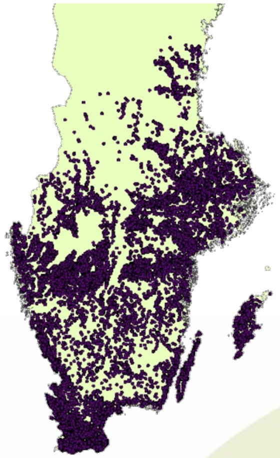
Build calibration model and predict the rest of the samples.

Example 2: Laboratory analyses vis-NIR *(national calibrations)*

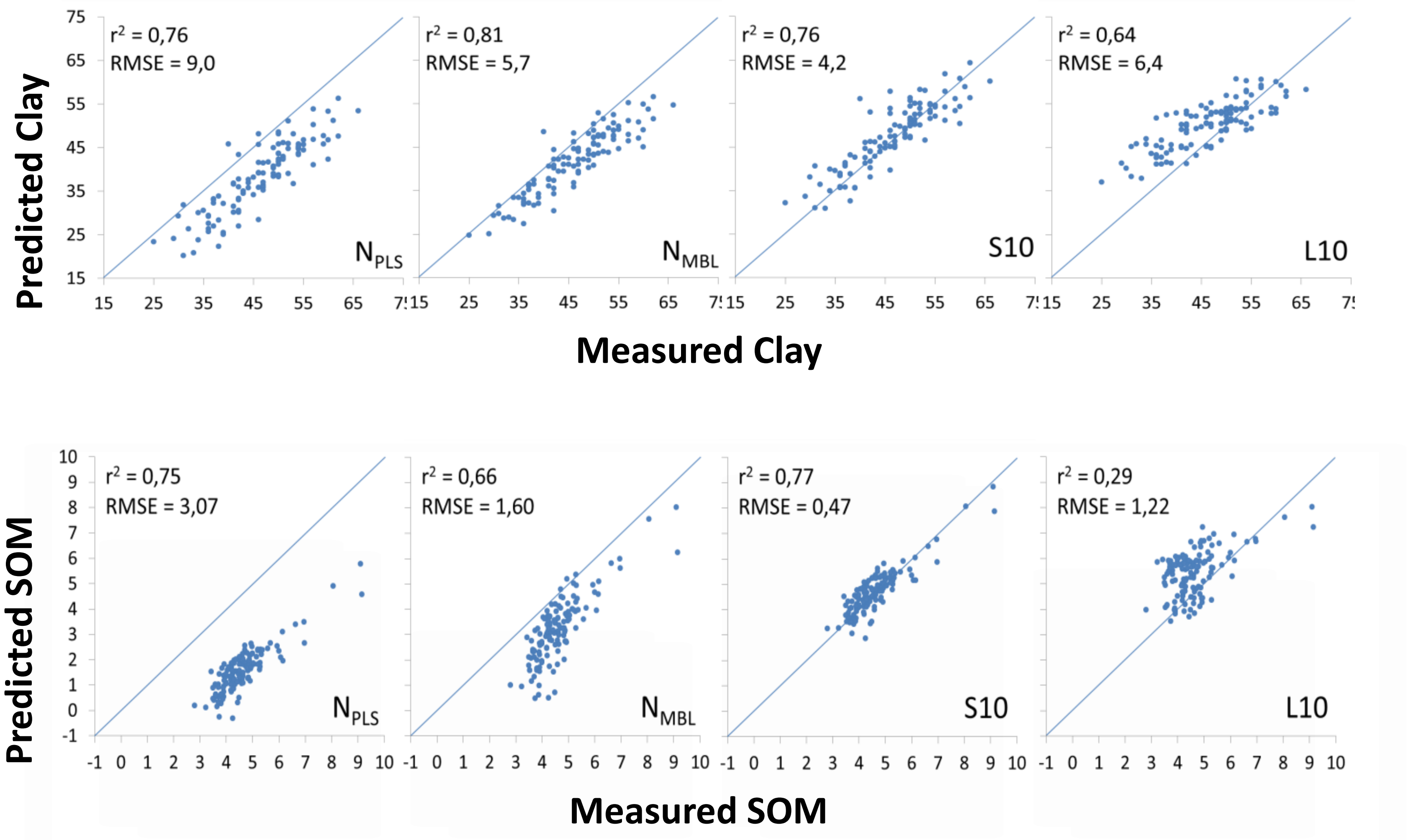
The Swedish national SSL ~12 000 samples
Agricultural top soil





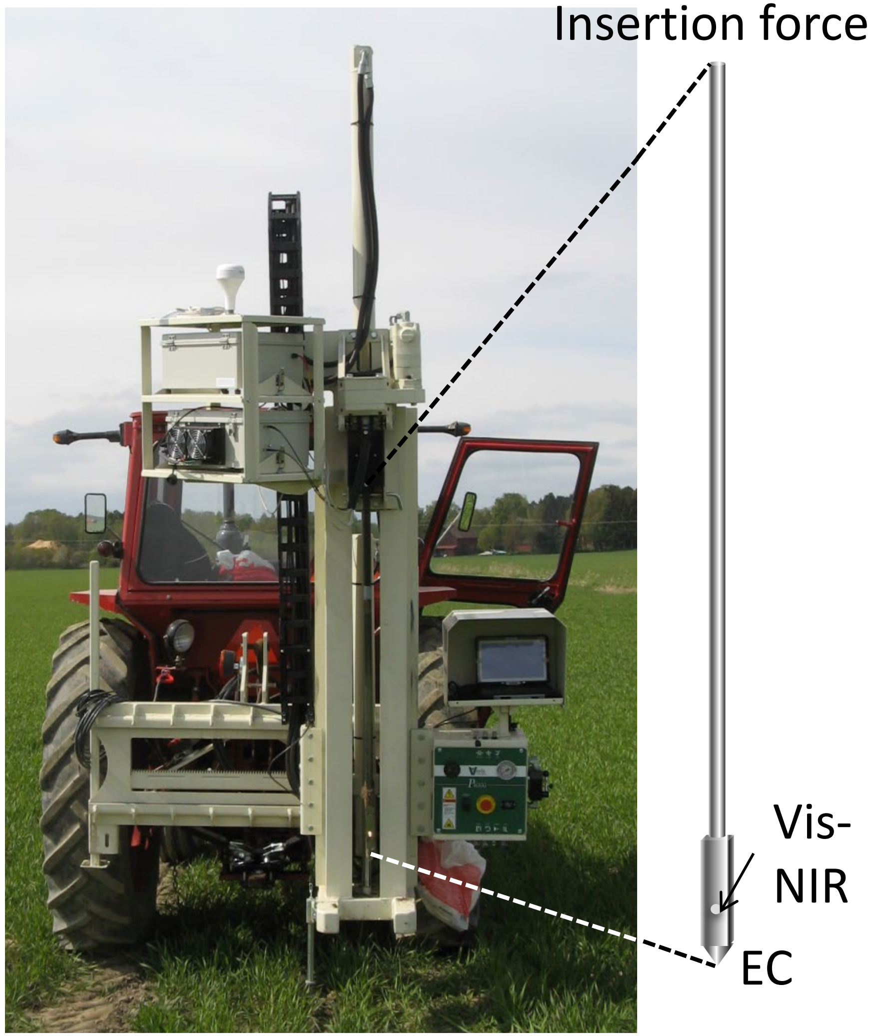


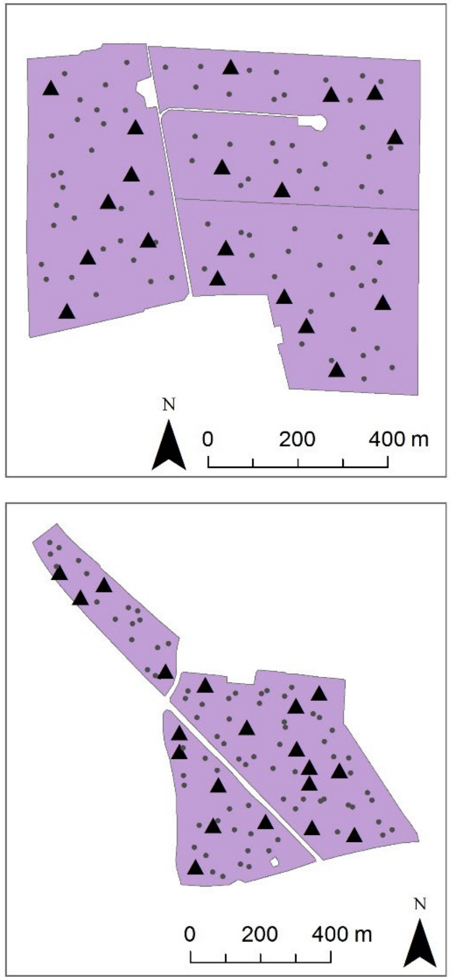
Example 2: Laboratory analyses vis-NIR *(national calibrations)*



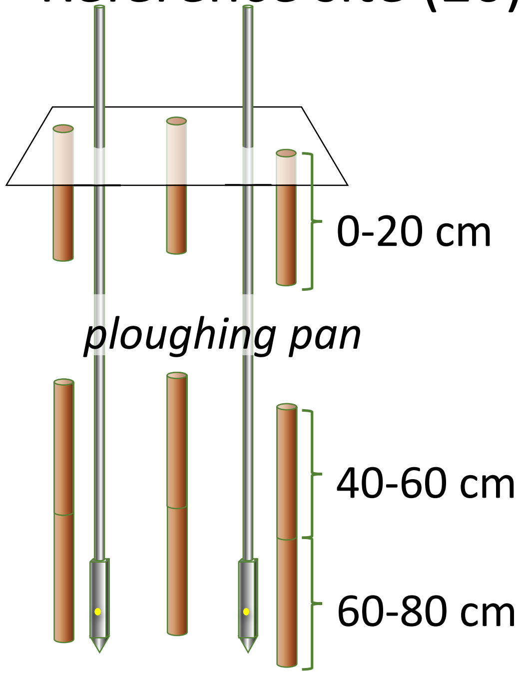
Local predictions
~100 ha farms

Example 3: *In-situ* analyses vis-NIR *(combining sensors)*





Reference site (20)



Clay
Sand
SOM

Example 3: *In-situ* analyses vis-NIR *(combining sensors)*

- In most cases, a combination of more than one sensor rendered the best calibration results.
- Rather small improvements but with little extra effort.
- vis-NIR was the best single sensor for all tested soil properties, however for clay ECa was almost as good.
  - NIR-range for clay and sand
  - vis-NIR-range for SOM content
- vis-NIR range in combination with IF rendered the best results for SOM content,
  while the NIR range combined with ECa gave the best results for clay and sand.
  But the differences differed between the two sites.

References and further reading

Reviews and basics

- Miller, C. E. (2001). Chemical principles of near-infrared technology. In P. Williams & K. Norris (Eds.), Near-infrared Technology in the Agri-cultural and Food Industries. Springer-Verlag New York, Inc.
- Soriano-Disla, J. M., Janik, L. J., Viscarra Rossel, R. A., Macdonald, L. M., & McLaughlin, M. J. (2014). The performance of visible, near-, and mid-infrared reflectance spectroscopy for prediction of soil physical, Chemi-cal, and biological properties. Applied Spectroscopy Reviews, 49(2), 139–186.
- Stenberg, B., Viscarra Rossel, R. A., Mouazen, A. M., & Wetterlind, J. (2010). Visible and near infrared spectroscopy in soil science. Advances in Agronomy, 107, 163–215.

Example 1. local models

- Wetterlind, J., Stenberg, B., Söderström, M. (2010). Increased sample point density in farm soil mapping by local calibration of near infrared prediction models. Geoderma 156(3-4), 152-160.

Example 2. adopting national calibrations to local sites

- Wetterlind, J., Stenberg, B. (2010). Near infrared spectroscopy for within field soil characterisation – Small local calibrations compared with national libraries augmented with local samples. European journal of soil sciences 61(6), 823-843.
  However, the data presented in the slides are using an updated (much larger) national spectral library.

Example 3. in-situ analysis

- Wetterlind, J., Piikki, K., Söderström, M., Stenberg, B. (2015). Exploring the predictability of soil texture and organic matter content with a commercial integrated soil profiling tool. European Journal of Soil Science, 66(4), 631-638

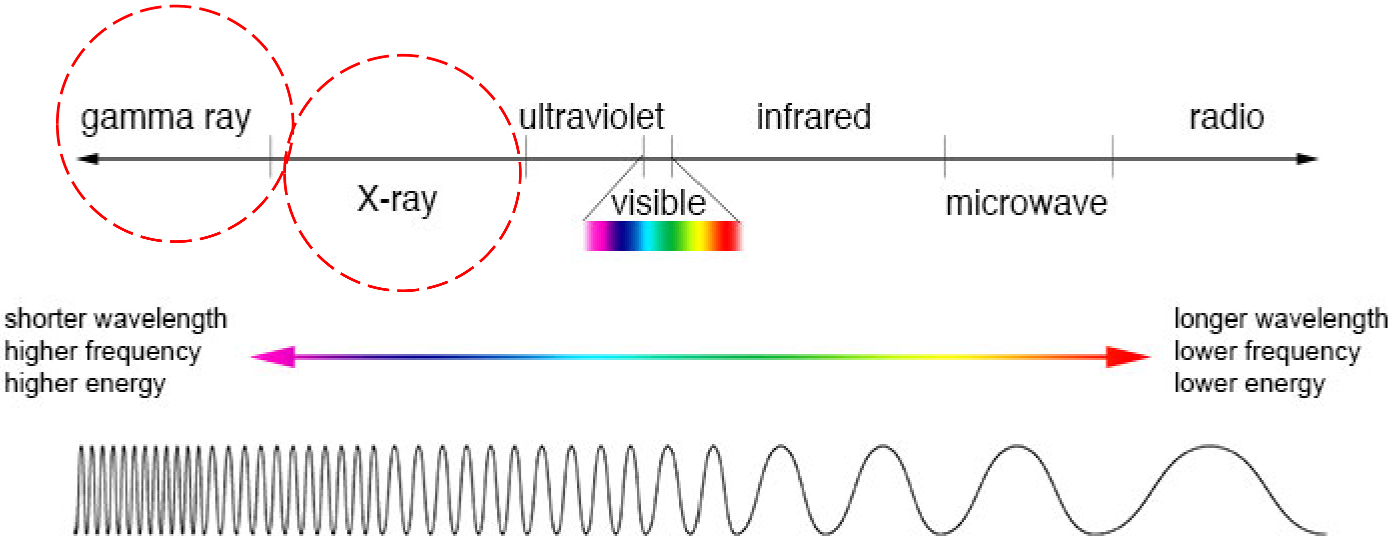
Gamma-ray spectrometry and Portable X-ray fluorescence

Proximal sensing of natural gamma radiation

Portable X-ray fluorescence - PXRF

Images: SoilOptix.com
Söderström, Stadig. 2015.
https://res.slu.se/id/publ/66439

Gamma-ray spectrometry and Portable X-ray fluorescence



Very short wavelengths – high energy

Image: NASA's Imagine the Universe

Gamma-ray spectrometry

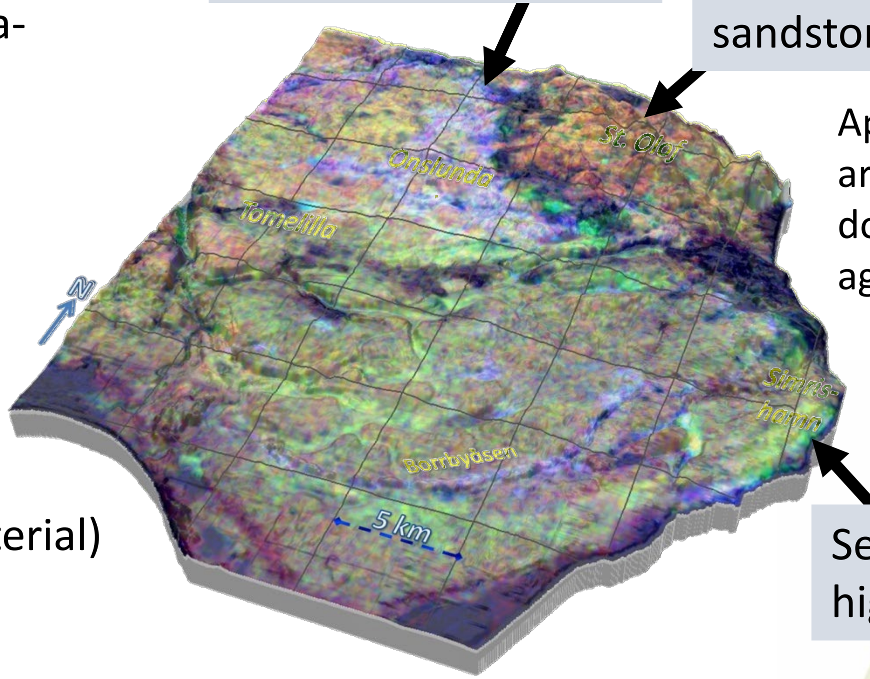
The three naturally occurring radioelements uranium (^{238}U), thorium (^{232}Th), and potassium (^{40}K) are measured in gamma-ray spectrometry, possibly also caesium (^{137}Cs) (which is man-made..)

Excellent for mapping of soil texture in the topsoil!

…and very useful in studies of:

- Soil parent material
- Various soil properties (related to texure and parent material)
- Soil water content
- Environmental surveys
- Geological surveys
- Radiation monitoring
- Erosion

etc…



Approx. 30 km^2 area in SE Sweden dominated by agricultural land

False-colour composite image from airborne gamma-ray spectrometry: ^{40}K (red) ^{232}Th (green) ^{238}U (blue)

Image: Söderström, Eriksson, 2014 Geoderma, 192, 323-334
https://doi.org/10.1016/j.geoderma.2012.07.014

More about gamma rays...

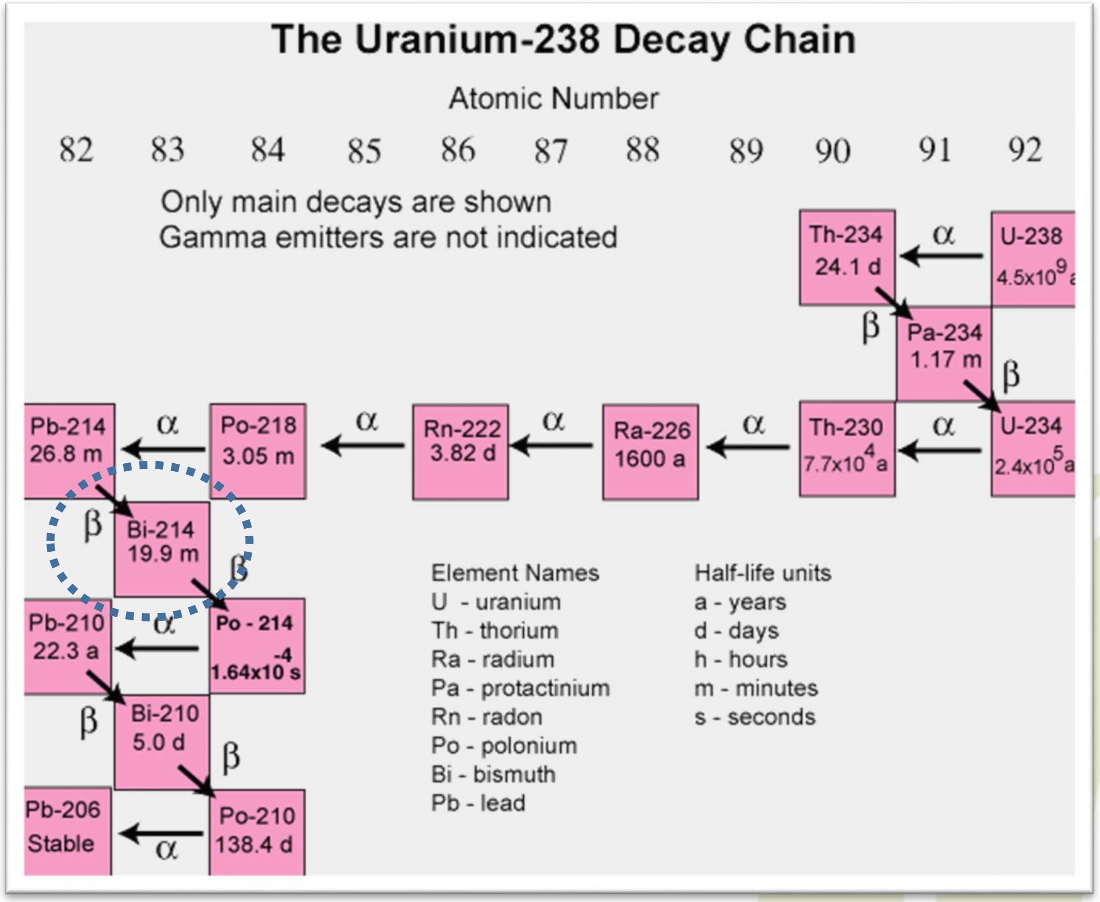
Radiation is produced by unstable atoms (radionuclides) that undergo radioactive decay

Radioactive decay is the emission of energy in the form of ionizing radiation.

The ionizing radiation can include alpha or beta particles, and/or gamma rays.

Gamma rays (γ) are weightless packets of energy called photons - similar to visible light, but with much higher energy.

Example of a decay chain – main gamma emitter encircled



Very long half-life….

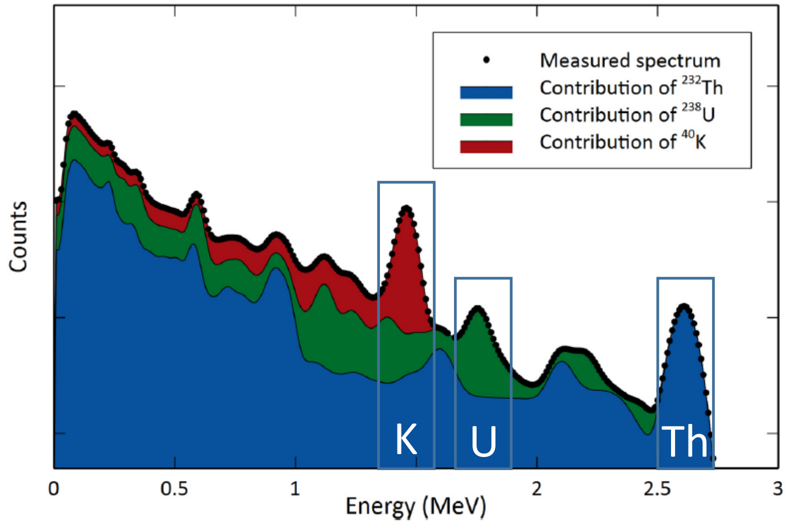
	Half-life (y)
^{40}K	1.3×10^9
^{238}U	4.46×10^9
^{232}Th	1.39×10^{10}

Source: IAEA, 2003.
https://www-pub.iaea.org/MTCD/Publications/PDF/te_1363_web.pdf

More about gamma rays...

Passive instruments, waiting for gamma interaction to occur in the detector volume

Most common are scintillation detectors – scintillating crystals emit low-energy photons when struck by gamma-rays, photomultiplier tubes collect the emitted photons and the energy in the gamma-rays can be determined. Can detect the gamma energy spectrum.



Typically the main peaks (*window analysis*) are analyzed, or the *full spectrum*, then converted to concentrations of K, U and Th

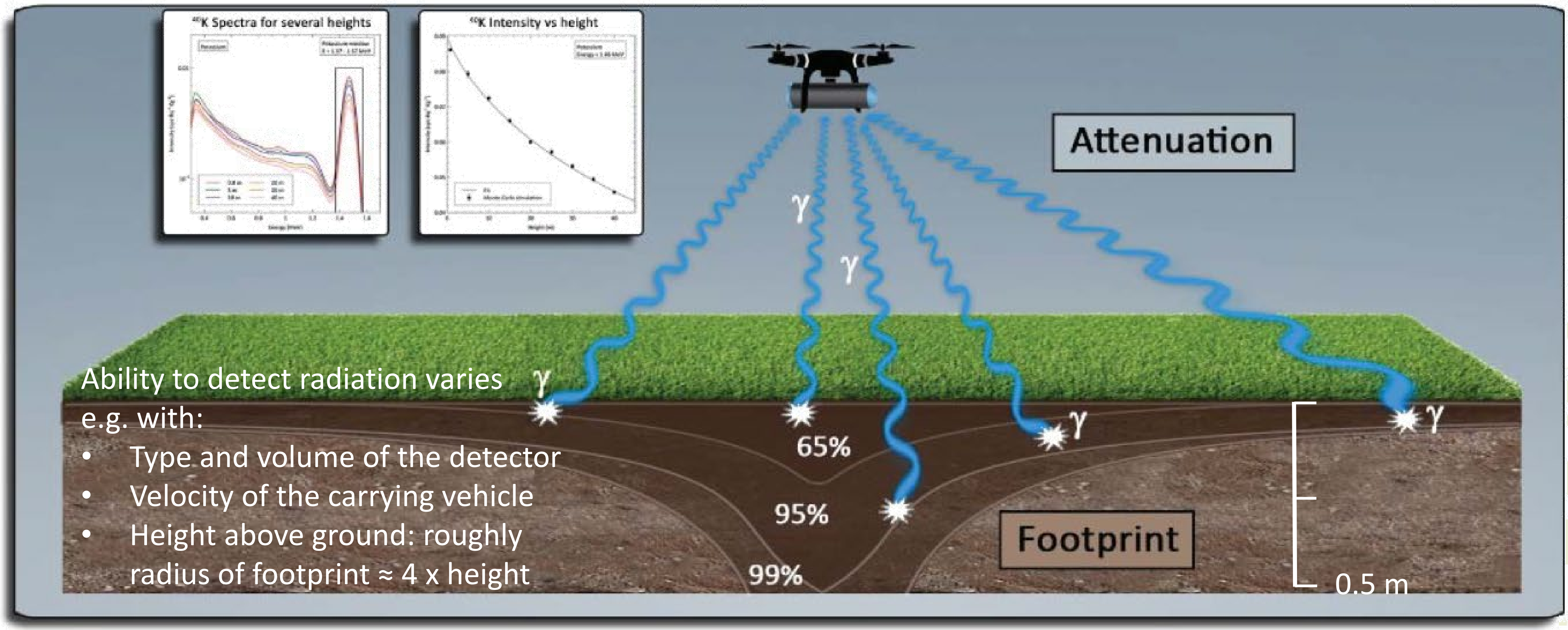
Image: van der Veeke, 2023, https://doi.org/10.33612/diss.261264637

Mass concentrations of radioelements in soil and bedrock are expressed in % (K) or ppm (Th, U)

Conversion of radioelement concentration to specific activity (Becquerel per kg):
1% K = 313 Bq/kg
1 ppm U = 12.35 Bq/kg
1 ppm Th = 4.06 Bq/kg

IAEA, 2003. Guidelines for Radioelement Mapping Using Gamma Ray Spectrometry Data
https://www-pub.iaea.org/MTCD/Publications/PDF/te_1363_web.pdf

Response area/volume of a gamma sensor....



Ability to detect radiation varies e.g. with:

- Type and volume of the detector
- Velocity of the carrying vehicle
- Height above ground: roughly radius of footprint ≈ 4 x height

From: van der Veeke et al. 2021, J Env Radioact., 237, 106717
https://doi.org/10.1016/j.jenvrad.2021.106717

Platforms for gamma-ray sensing...

Source

Low-flying airplane… 30-120 m

Source

Drone…

Source

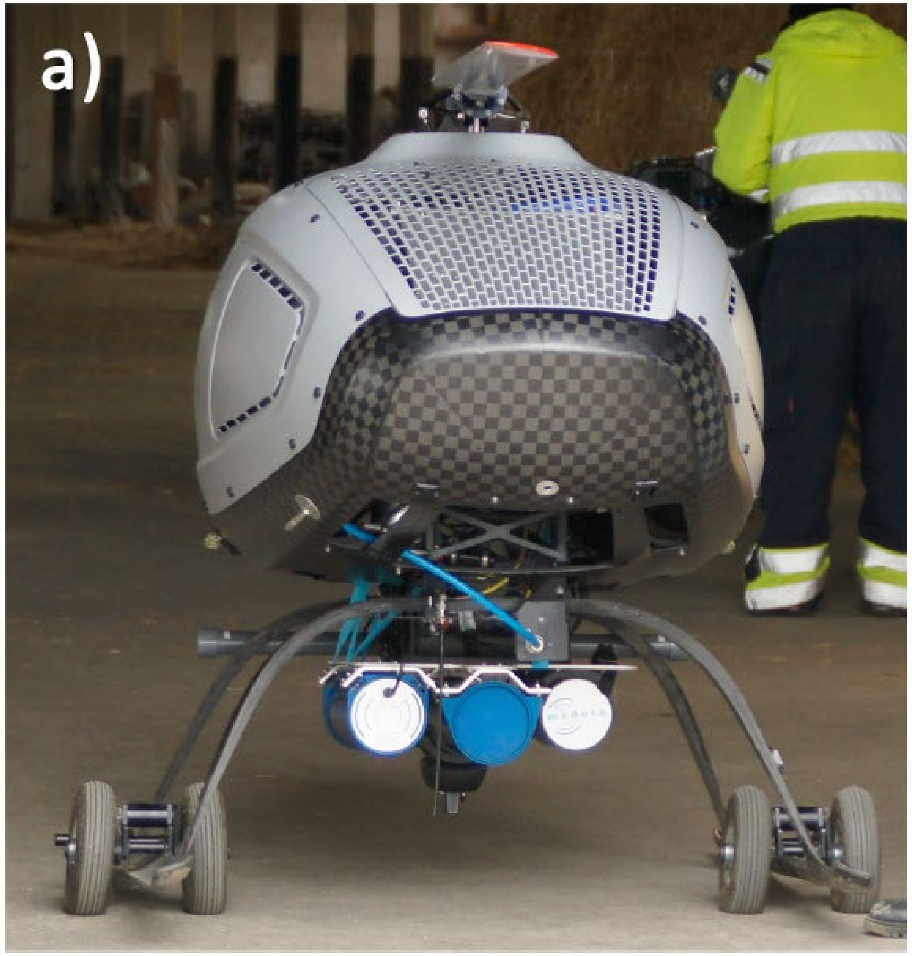
Quadbike, tractor etc.

…or walking…

Source

Example of gamma-ray sensing – correlation with soil texture

Drone-based scanning, three sensors, crystal volumes:



1000 ml (7 kg)

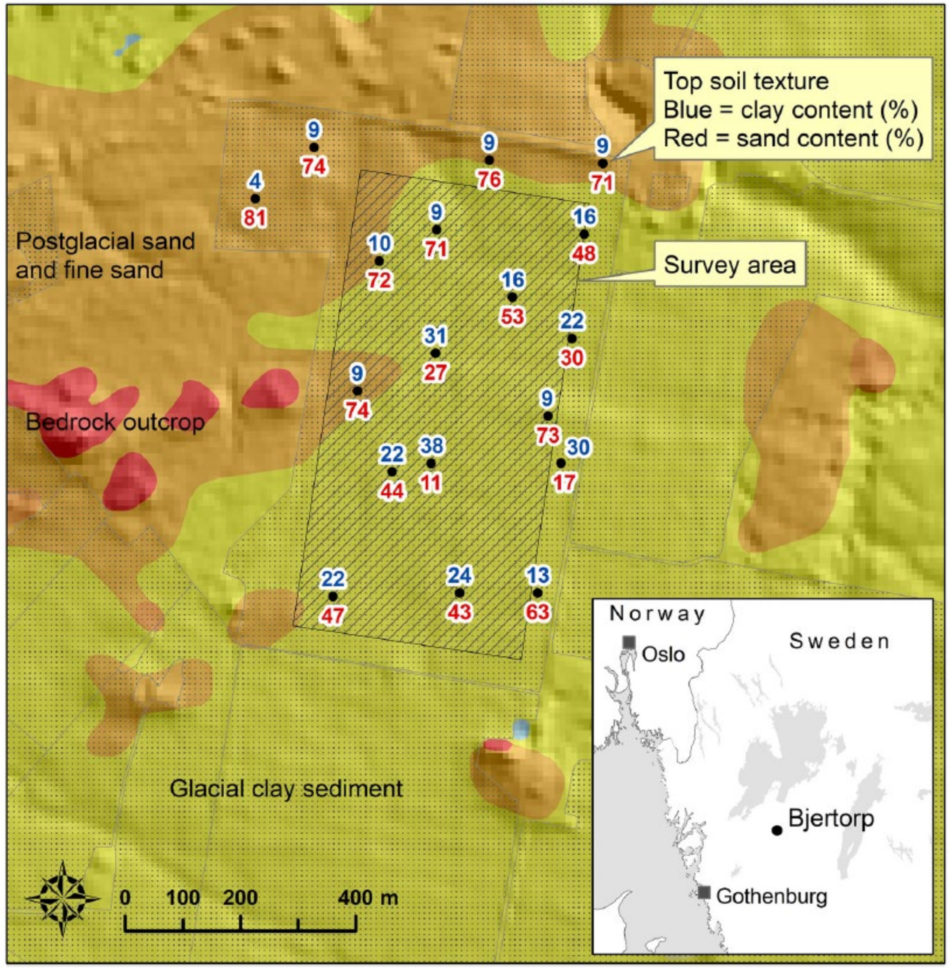
2000 ml (12 kg)

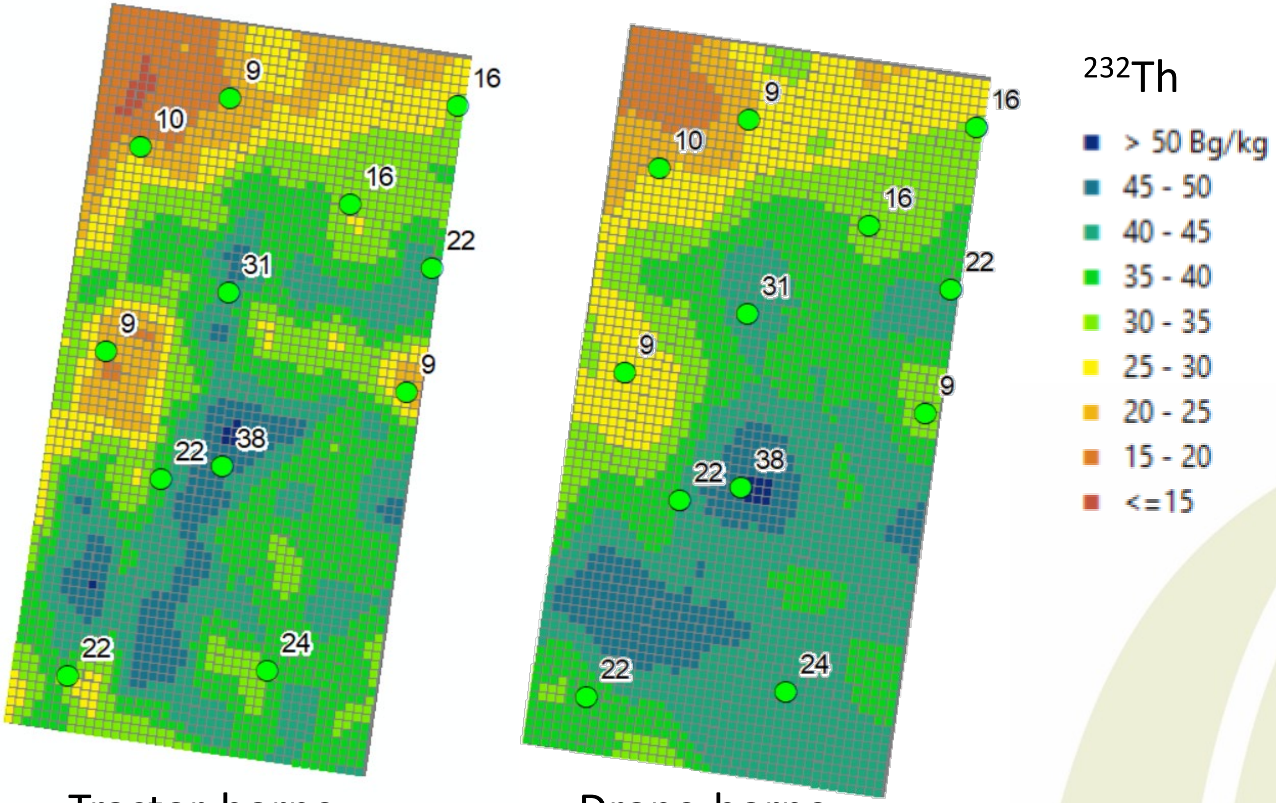
350 ml (2.2 kg)

Ground-based scanning, 2000 ml

From: van der Veeke et al. 2021, J Env Radioact., 237, 106717
https://doi.org/10.1016/j.jenvrad.2021.106717

Example of gamma-ray sensing – correlation with soil texture



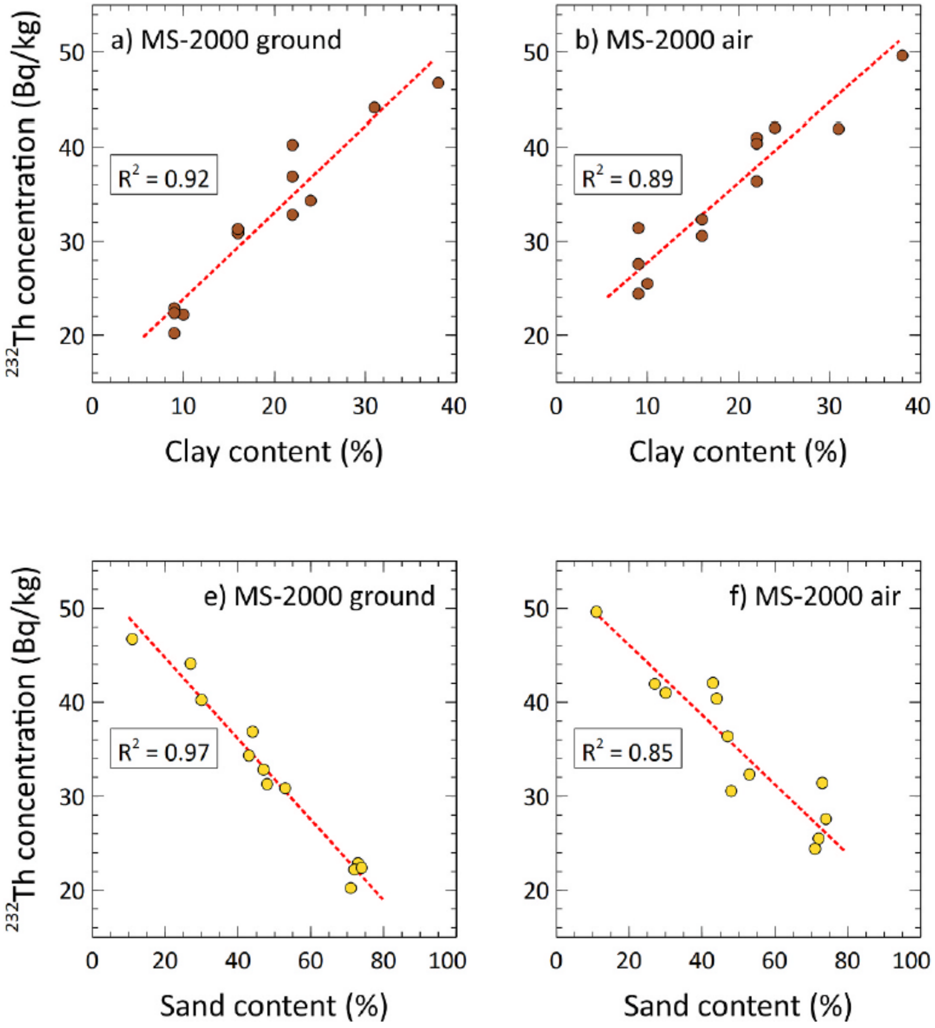


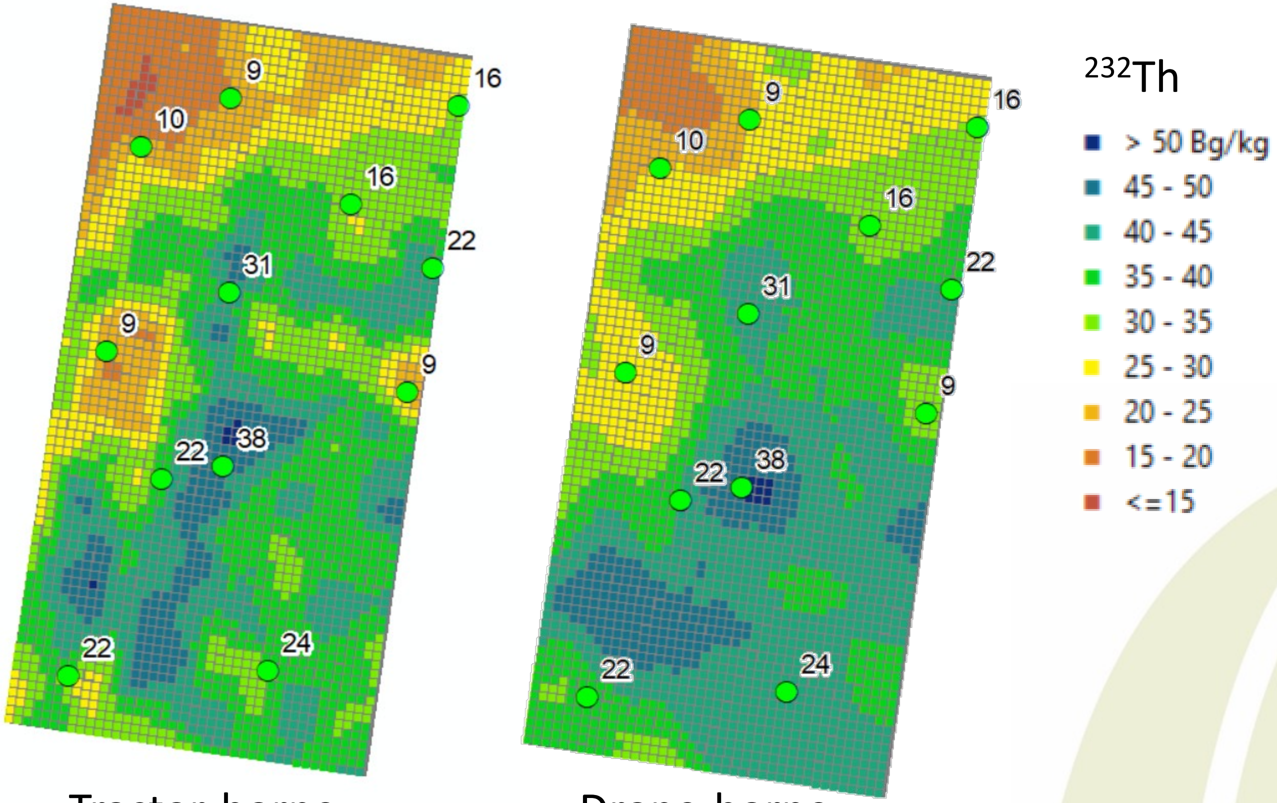
Tractor-borne
(2000 ml sensor)

Drone-borne
2000 ml sensor)

Adapted from: van der Veeke et al. 2021, J Env Radioact., 237, 106717
https://doi.org/10.1016/j.jenvrad.2021.106717

Example of gamma-ray sensing – correlation with soil texture





Tractor-borne
(2000 ml sensor)

Drone-borne
2000 ml sensor)

Adapted from: van der Veeke et al. 2021, J Env Radioact., 237, 106717
https://doi.org/10.1016/j.jenvrad.2021.106717

Local calibration may be needed...

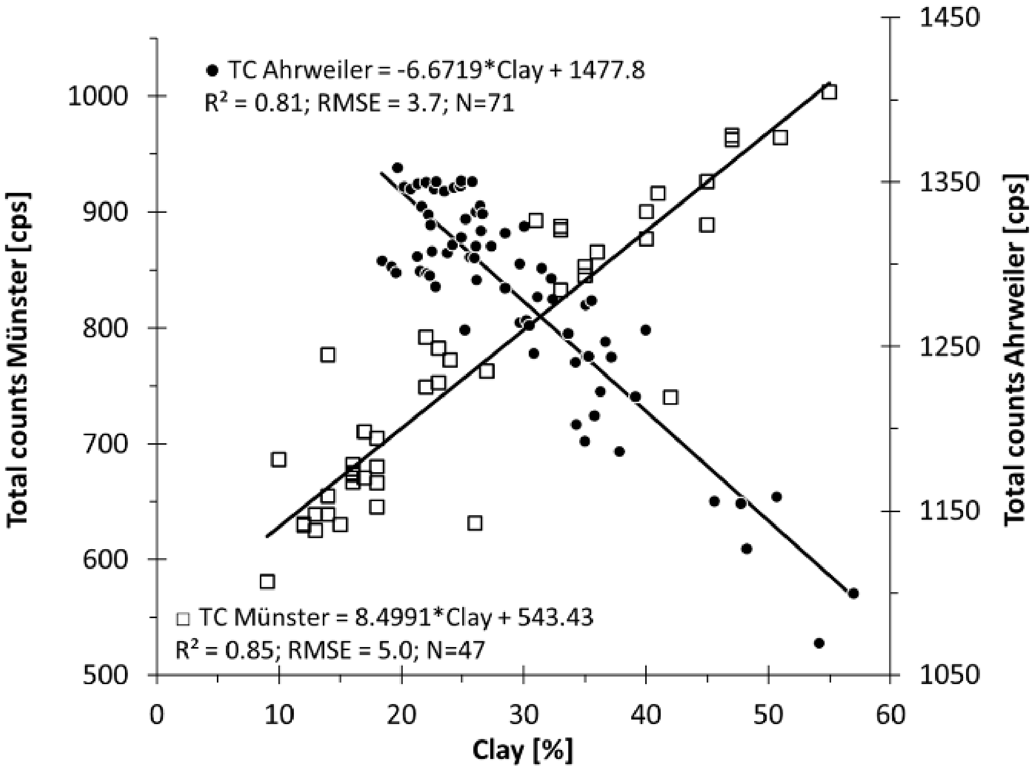


Figure 5. Correlation between clay content and total gamma counts (TC) at the study fields Münster and Ahrweiler. Fundamental differences in clay mineralogy led to the contrasting relationship between clay content and TC.

Example from:
Pätzold et al. 2020, Soil Systems, 4, 31
https://doi.org/10.3390/soilsystems4020031

Portable X-ray fluorescence – PXRF

Image: Söderström, Stadig. 2015.
https://res.slu.se/id/publ/66439

X-ray fluorescence (XRF) is the emission of energy from a material that has been excited by being bombarded with high-energy X-rays.

Widely used for elemental analysis and chemical analysis, particularly in the investigation of metals, glass, ceramics and building materials, and for research in geochemistry, forensic science, archaeology and art objects such as paintings.

Source: Wikipedia

PXRF – a portable instrument capable of in situ simultaneous multielement analysis…

PXRF measurements – both in the field and in the lab

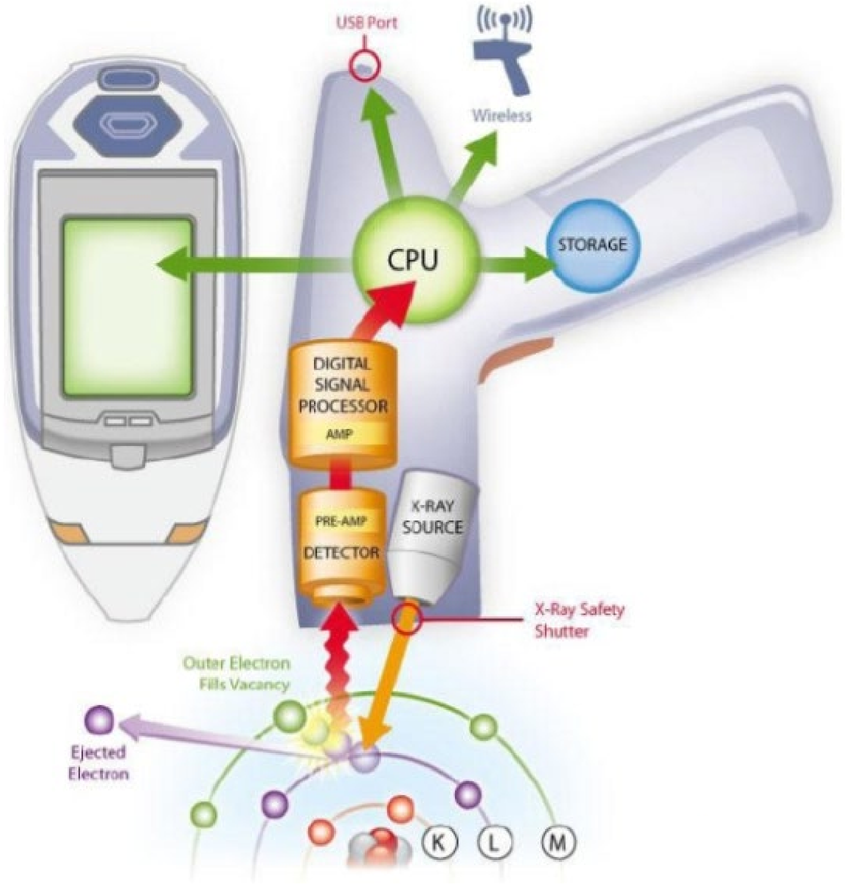


Image: Thermo Scientific

Elements detected depend on the instrument, and setup, and may include:

Mg, Al, Si, P, S, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Rb, Sr, Y, Zr, Nb, Mo, Ag, Cd, Sn, Sb, Ba, W, Au, Pb, Bi, La, Ce, Pr, Nd, Th, and U

Time of measurement required in soil may be 2-4 min (for analyzing a metal object, maybe a few seconds)

PXRF measurements – both in the field and in the lab

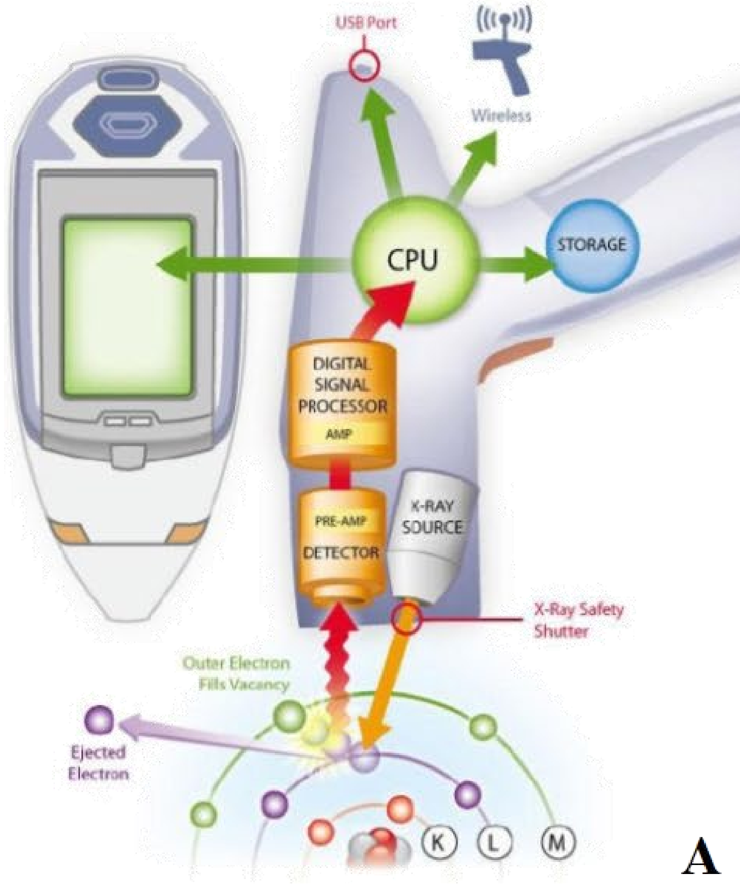
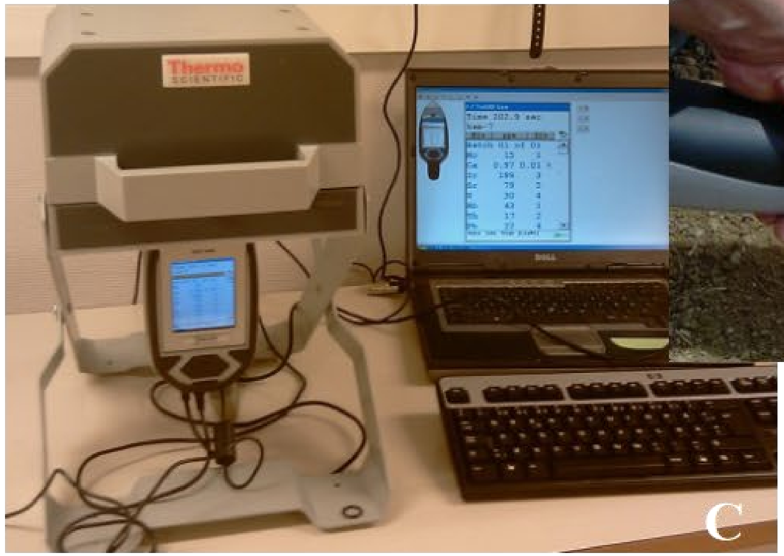


Image: Thermo Scientific

Lab setup



Homogenized, dried samples → more stable data analysis

Field measurements

Dry soil (SWC<20 %)
Small volume - representativity?
Safety/regulations?
Time…

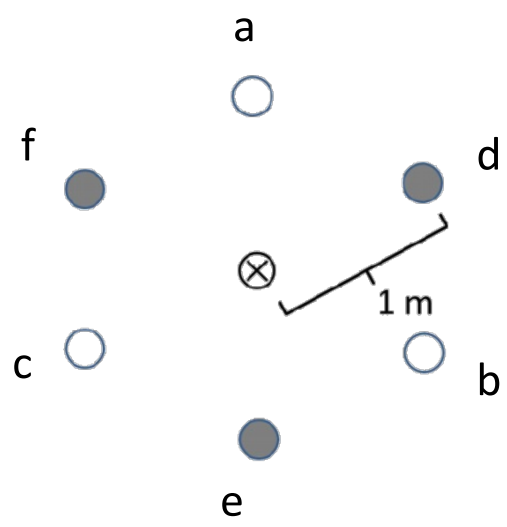
Images: Söderström, Stadig. 2015. https://res.slu.se/id/publ/66439

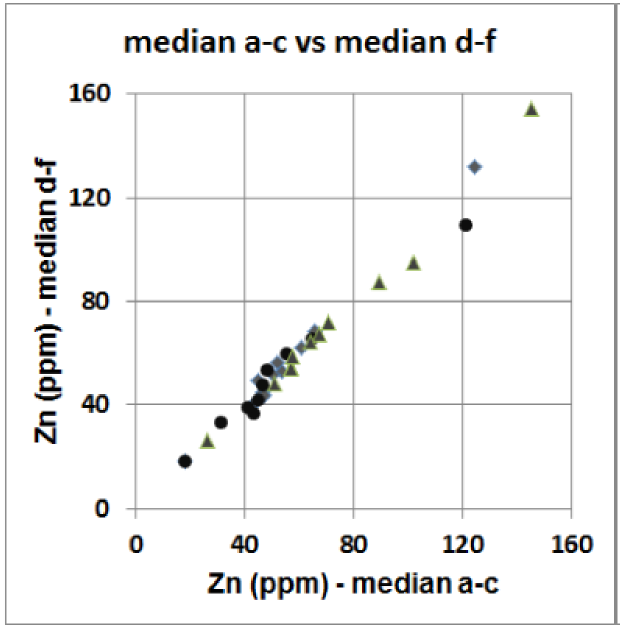
PXRF measurements – both in the field and in the lab

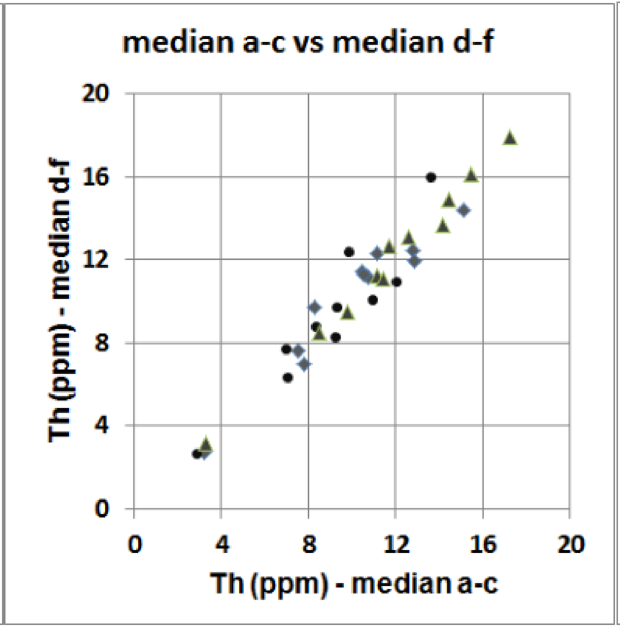
Is it possible to measure on soil directly in the field – and collect representative data?

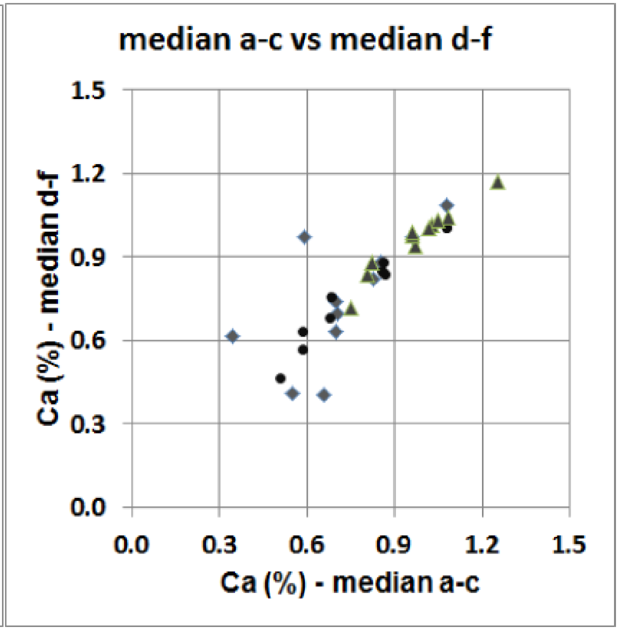
It could be… - plowed, harrowed, dry soil preferred, and several (at least 3?) ”subsamples”

Triangle = dry, homogenized, lab
Point = untreated sample in lab
Diamond = field



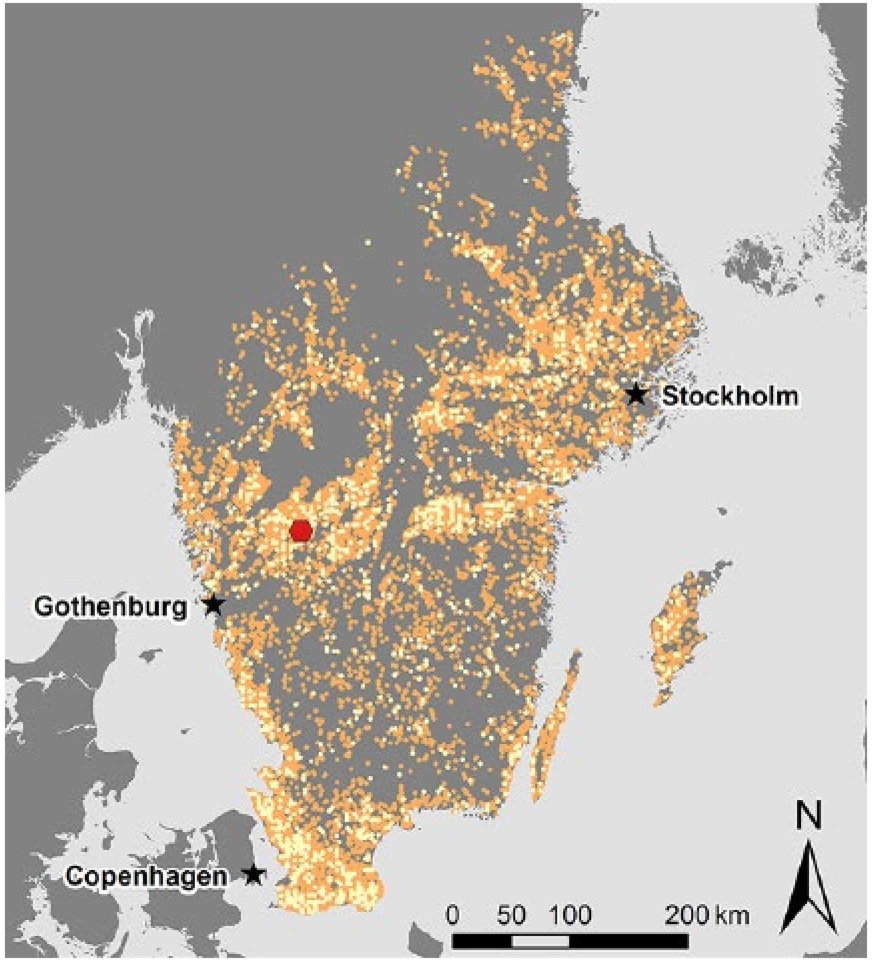




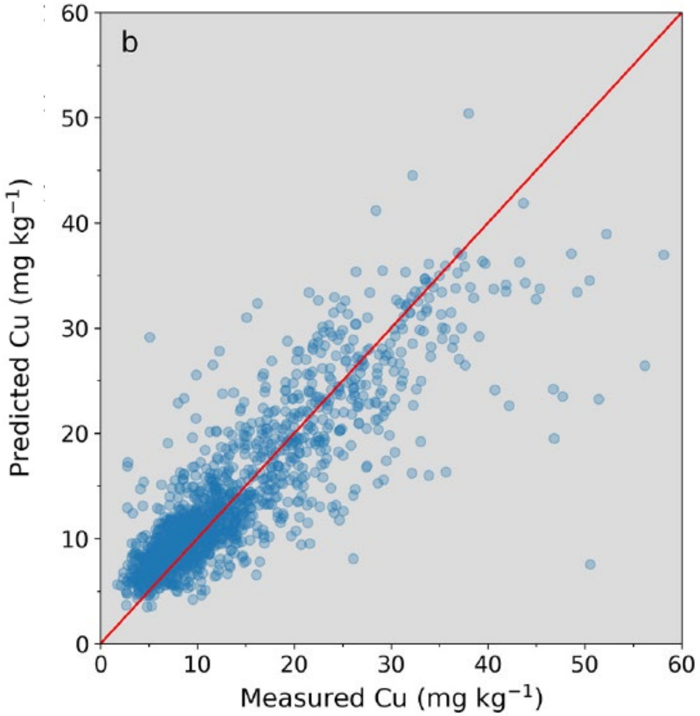


From: Söderström, Stadig. 2015. https://res.slu.se/id/publ/66439

Application example - PXRF combined with gamma
for national mapping of Cu in arable topsoil in Sweden



Lab analysed Cu in 1434 soil samples + PXRF
Only PXRF in 11093 soil samples



Cu in all 12527 samples

Example from: Adler et al. 2022. Geoderma Regional 30 e00562
https://doi.org/10.1016/j.geodrs.2022.e00562

Application example - PXRF combined with gamma
for national mapping of Cu in arable topsoil in Sweden

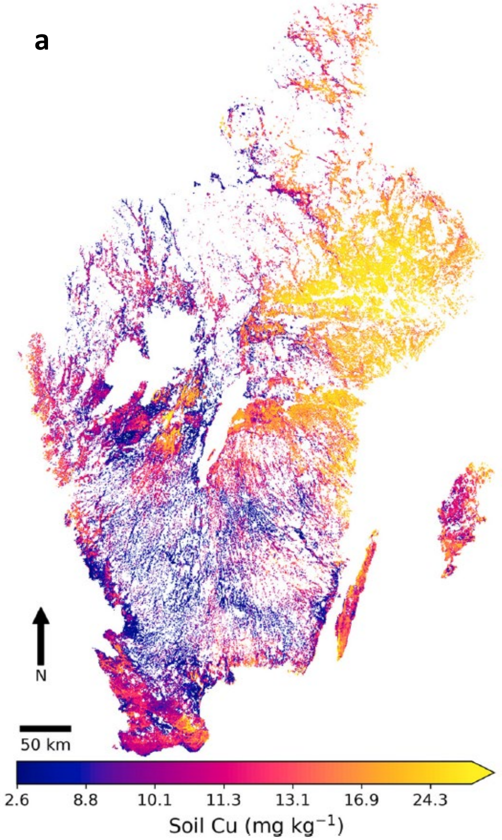
Long list of covariates, e.g. from airborne gamma scanning, covering the whole country (50 m pixels)

Covariate	Type	Source
U (mg kg^{-1})	Gamma radiation	SGU*
Th (mg kg^{-1})	Gamma radiation	SGU*
K (%)	Gamma radiation	SGU*
Dose rate (nGy hr^{-1})	Gamma radiation	Computed from U, Th and K
K/Th, K/U and Th/U	Gamma radiation	Computed from U, Th and K
TPI 5, 50 and 500	DEM	Computed from elevation*
Soil moisture	DEM	Ågren et al. (2021)
Elevation (m)	DEM	Lantmäteriet*
Precipitation, annual (mm)	Climate	SMHI (2015)
Precipitation, seasonal (MAM, JJA, SOM and DJF) (mm)	Climate	SMHI (2015)
Temperature, annual (°C)	Climate	SMHI (2015)
Temperature, seasonal (MAM, JJA, SOM and DJF) (°C)	Climate	SMHI (2015)
Soil texture classes (Clay, Clay till, Till, Silt, Sand and Other)	Soil texture	SGU*

+ Cu in 12527 samples

Machine learning model for mapping

Concentration map



Risk for deficiency

Example from: Adler et al. 2022. Geoderma Regional 30 e00562
https://doi.org/10.1016/j.geodrs.2022.e00562

Summary

Gamma-ray spectrometry

- Used from many platforms:
  - walking, vehicle, drones, airplane
- Excellent for topsoil texture mapping
- Many other uses – e.g. useful covariate in digital soil mapping of various properties
- Local calibrations needed

PXRF

- Direct analysis of a range of elements (from Mg and heavier…)
- *In situ* measurements possible
- Small soil volume, rather time consuming
- Best results in dry, homogenized soil
- Useful for ground truthing in combination with other sensors

Images: SoilOptix.com
Söderström, Stadig. 2015.
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Images: SoilOptix.com
Söderström, Stadig. 2015.
https://res.slu.se/id/publ/66439

Further reading

For example two PhD theses:

Gamma:
Steven van der Veeke. 2023. UAV-borne radioelement mapping: towards a guideline and verification methods for geophysical field measurements. University of Groningen, Netherlands. https://doi.org/10.33612/diss.261264637

PXRF:
Karl Adler. 2022. Digital soil mapping and portable X-ray fluorescence prediction of cadmium, copper and zinc concentrations as decision support for crop production. Swedish University of Agricultural Sciences. https://pub.epsilon.slu.se/27921/