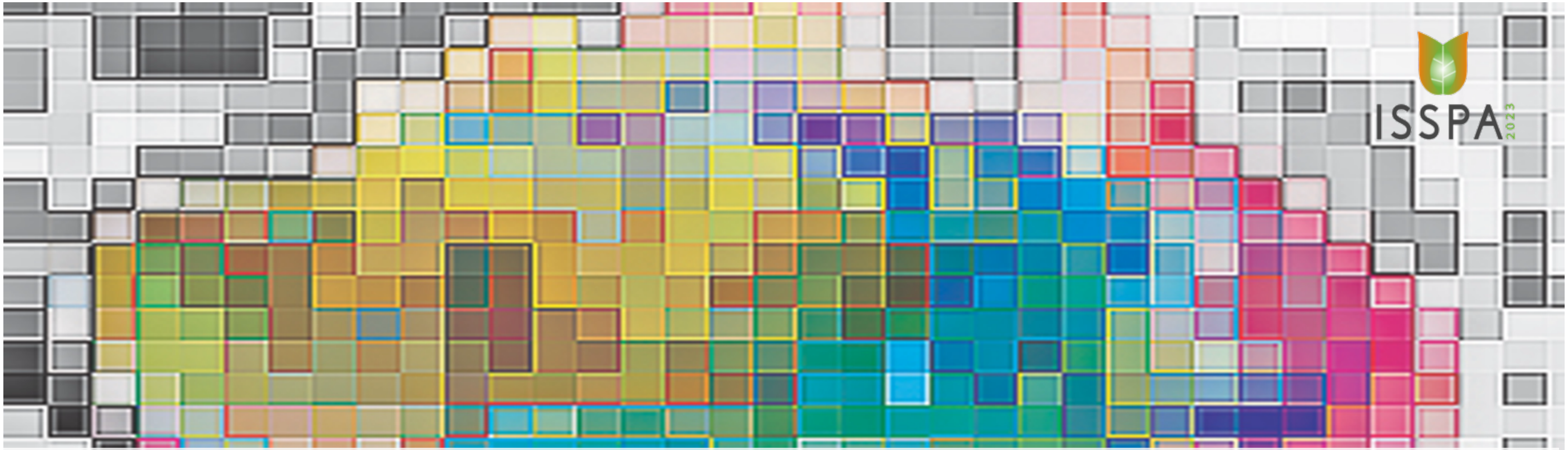

It makes sense to *soil sense* for environmental sustainability

Raphael VISCARRA ROSSEL
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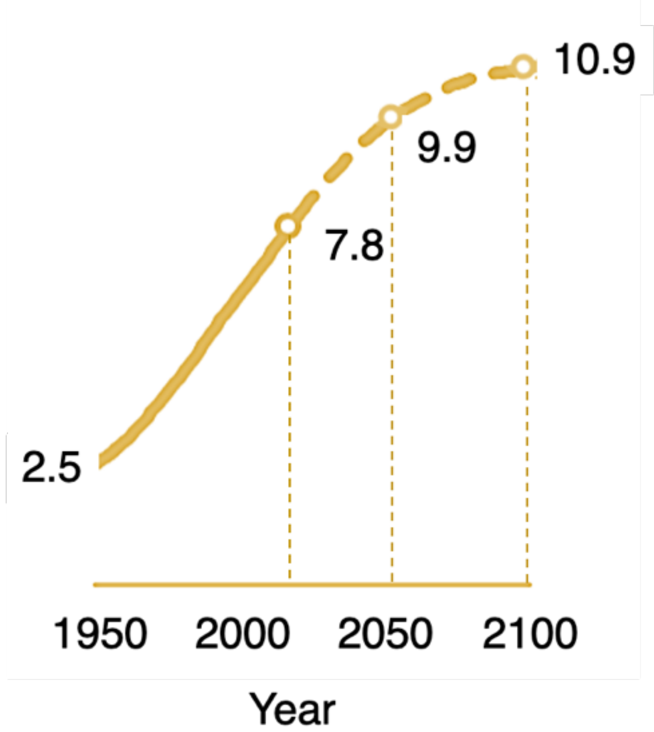
17th International Symposium on Soil and Plant Analysis ISSPA
21–24 March Concepción, Bio-bio region, Chile

soil & landscape science lab
Curtin University

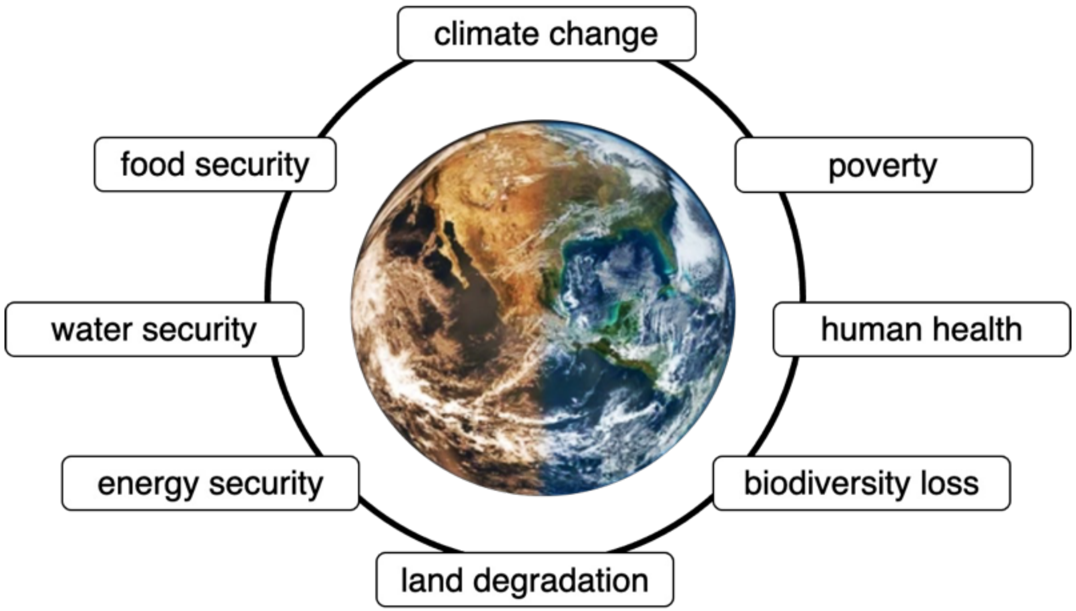
Global environmental challenges

World Population
(billions)



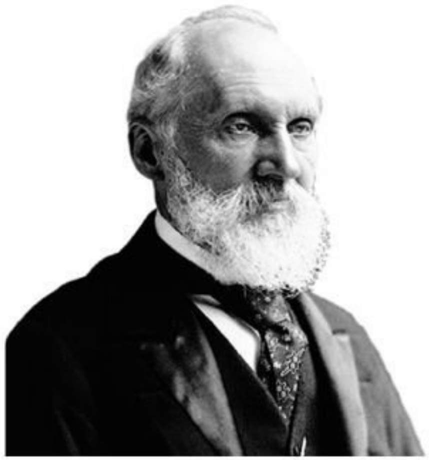
Impact on environment

- consumption of resources
- production of wastes



Soil measurement is key to addressing environmental challenges

Soil measurement is central in the development of scientific solutions to improve soil health and promote sustainable development

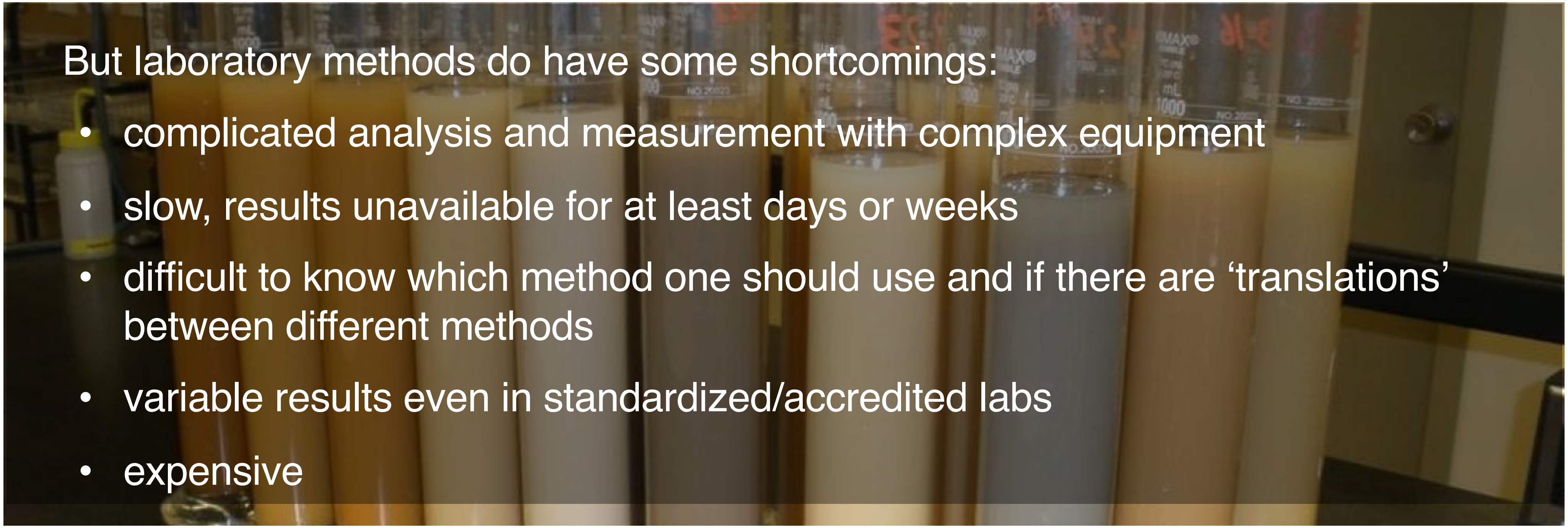


Thomson (1889)

'…when you can measure what you are speaking about, and express it in numbers, you know something about it; but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely, in your thoughts, advanced to the stage of science, whatever the matter may be.'

Shortcoming of current soil laboratory analyses

Our understanding of soil is gained through soil survey and chemical, physical, mineralogical and biological laboratory analysis

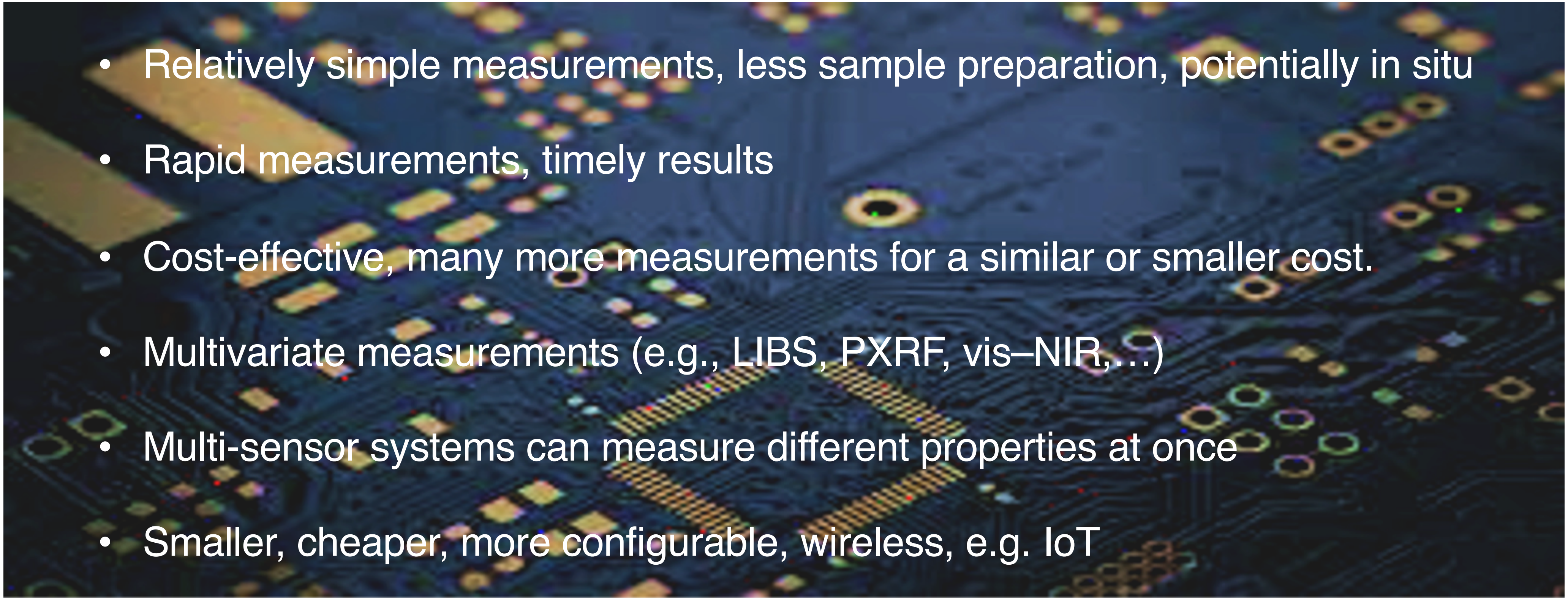


But laboratory methods do have some shortcomings:

- complicated analysis and measurement with complex equipment
- slow, results unavailable for at least days or weeks
- difficult to know which method one should use and if there are ‘translations’ between different methods
- variable results even in standardized/accredited labs
- expensive

Soil sensing must be an essential part of the solution

Soil sensing can help to overcome the limitation of conventional methods



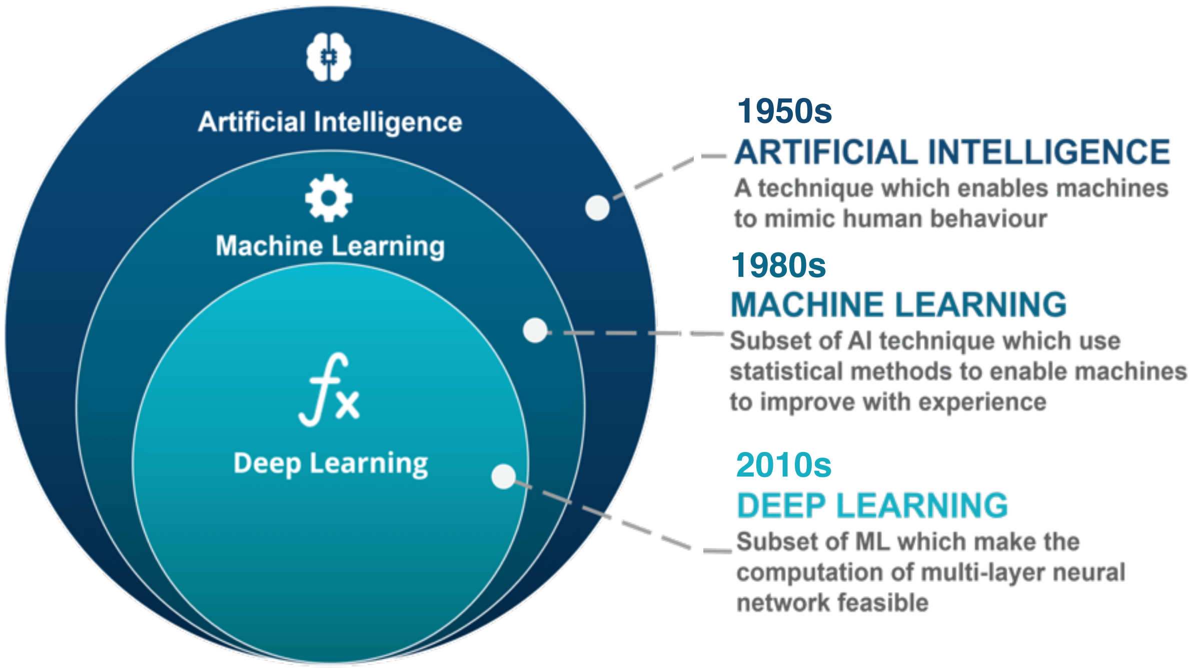
- Relatively simple measurements, less sample preparation, potentially in situ
- Rapid measurements, timely results
- Cost-effective, many more measurements for a similar or smaller cost.
- Multivariate measurements (e.g., LIBS, PXRF, vis–NIR,…)
- Multi-sensor systems can measure different properties at once
- Smaller, cheaper, more configurable, wireless, e.g. IoT

We need soil sensing but not to replace conventional methods

These are important advantages as there is a growing demand for inexpensive spatial, temporal soil information.

The point is not to completely replace conventional lab methods, but to supplement them with sensing

AI will revolutionize soil sensing and analyses



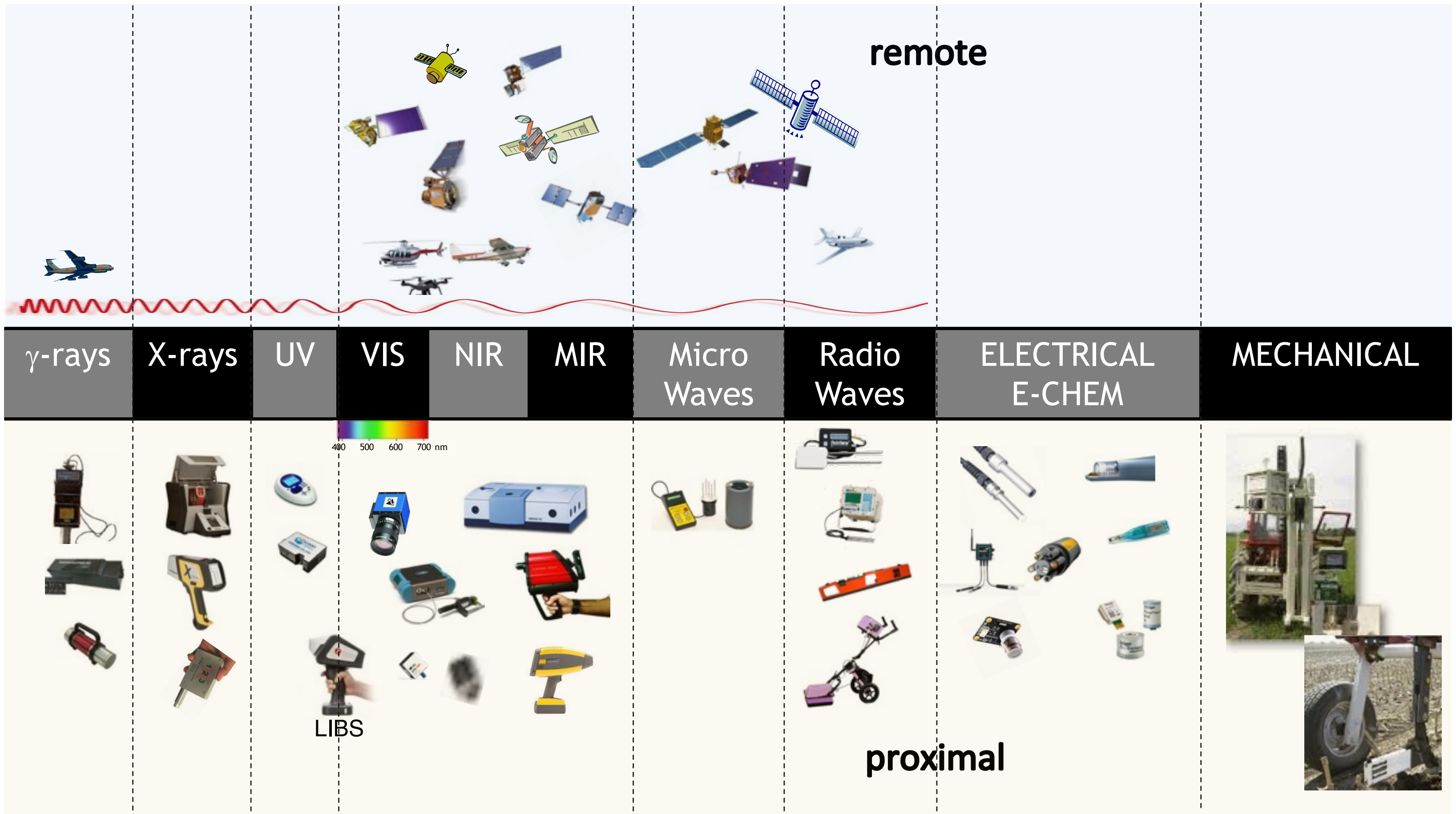
- Identify and 'untangle' complex patterns and relationships from multiple sensors
- Optimise sensor measurements/placement and calibration
- Accurate predictions of soil properties and their response to environmental change

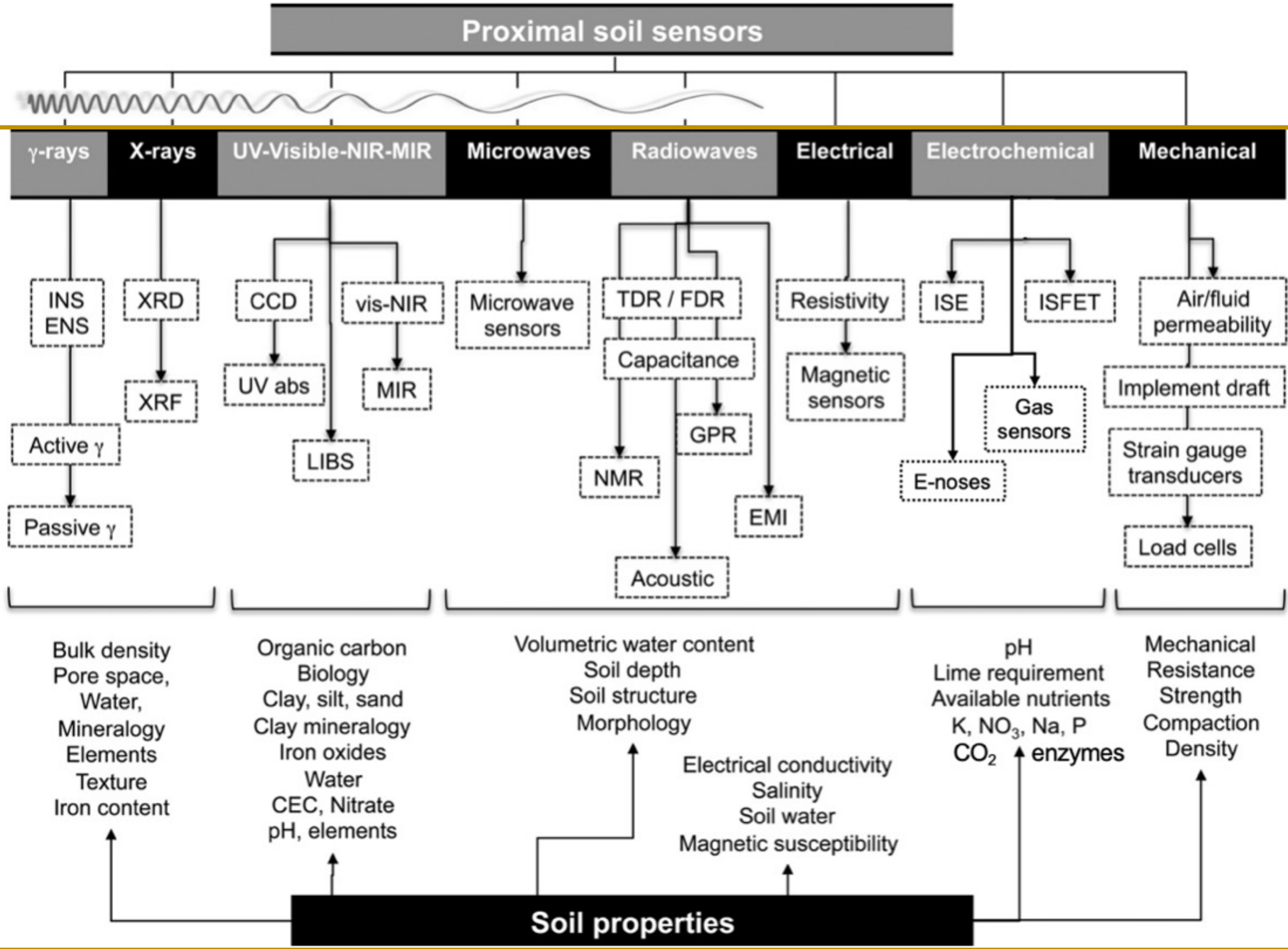
- Ultimately **sensing + AI** will help to reinvent the ways we analyse soil

Which sensors can we use to measure soil properties?

…many possibilities exist for measuring soil properties with sensors.

Some are well-developed while others are being developed

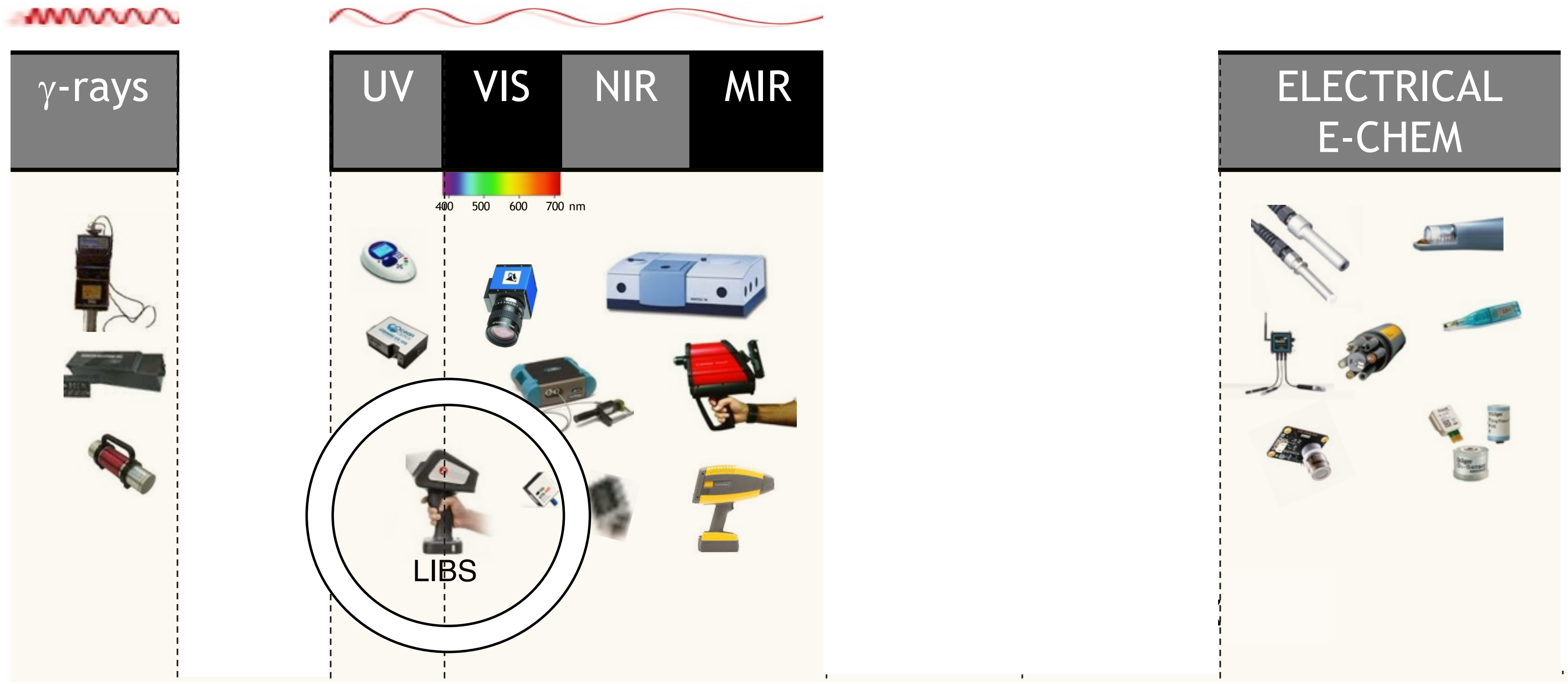




Proximal soil sensors
γ-rays
X-rays
UV-Visible-NIR-MIR
Microwaves
Radiowaves
Electrical
Electrochemical
Mechanical
INS ENS
Active γ
Passive γ
XRD
XRF
CCD
UV abs
vis-NIR
MIR
LIBS
Microwave sensors
TDR / FDR
Capacitance
GPR
NMR
EMI
Acoustic
Resistivity
Magnetic sensors
ISE
ISFET
Gas sensors
E-noses
Air/fluid permeability
Implement draft
Strain gauge transducers
Load cells
Bulk density
Pore space,
Water,
Mineralogy
Elements
Texture
Iron content
Organic carbon
Biology
Clay, silt, sand
Clay mineralogy
Iron oxides
Water
CEC, Nitrate
pH, elements
Volumetric water content
Soil depth
Soil structure
Morphology
Electrical conductivity
Salinity
Soil water
Magnetic susceptibility
pH
Lime requirement
Available nutrients
K, NO_3, Na, P
CO_2 enzymes
Mechanical
Resistance
Strength
Compaction
Density
Soil properties

Some examples

Sensors that are compatible because they measure uniquely different properties

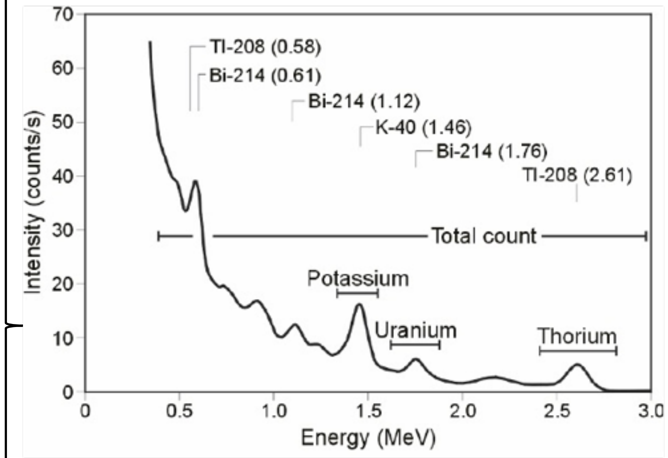


Passive gamma sensors

Sensor mounted on a vehicle, equipped with RTK GPS

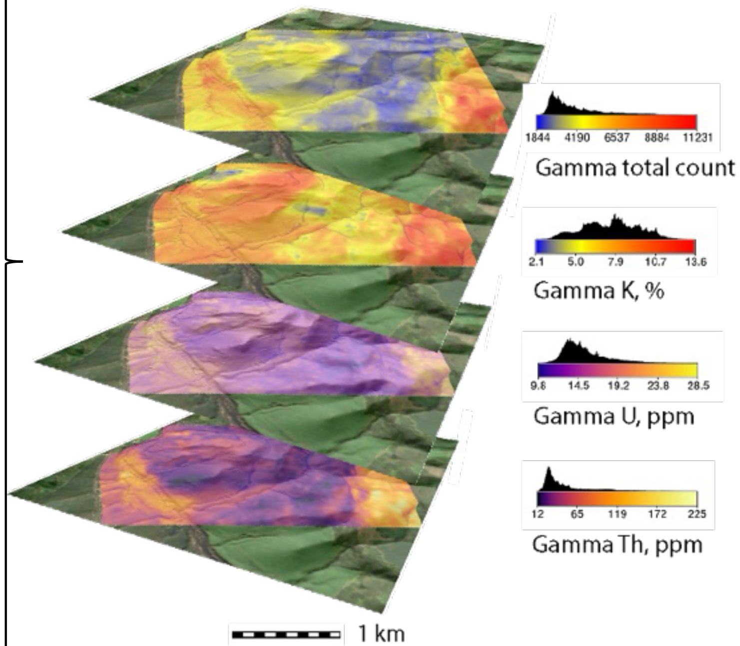
Usually, data collected at 1 Hz

A gamma spectrum recorded at every sensing location



Spectrum measures naturally occurring isotopes of K, U, Th in topsoil and the integrated total count, which is related to mineralogy

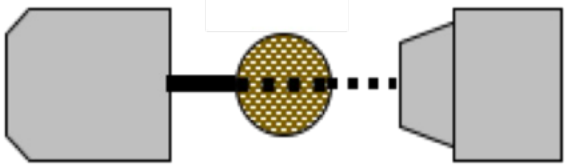
Interpolated maps useful for understanding soil variability: mineralogy, water, texture



Active gamma attenuation: densitometer

Measures the attenuation of gamma radiation passing through a soil core

Source ^{137}Cs | Soil core | Detector e.g., NaI

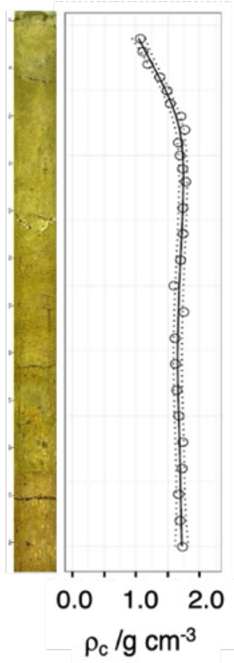


Attenuation is defined by Beer–Lambert's law

$$\frac{I}{I_0} = \exp\left[-x\left(\mu_s\rho_s + \mu_w\rho_w\theta\right)\right]$$

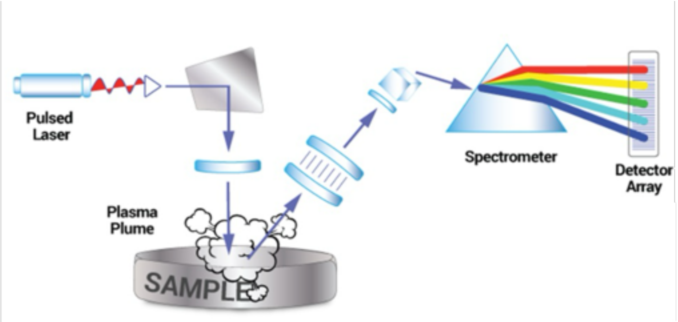
Direct measure of BD

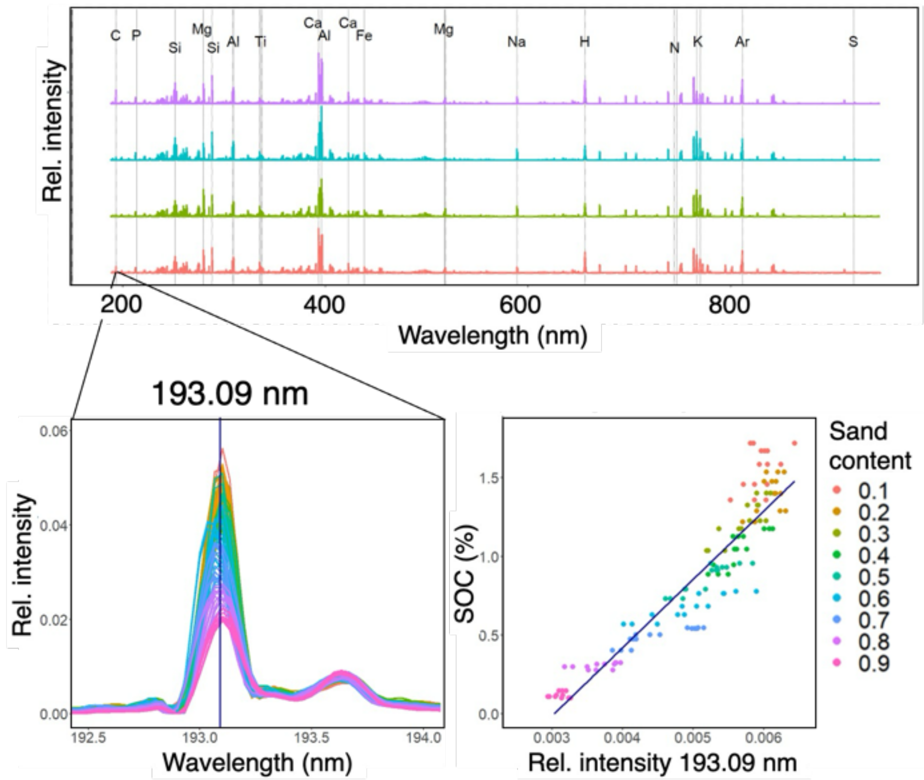
$$\rho_b = \frac{1}{x\mu_s}\ln\left(\frac{I_0}{I}\right) - \frac{\mu_w}{\mu_s}\rho_w\theta$$



Enables rapid, direct, accurate measurement of bulk density to depth

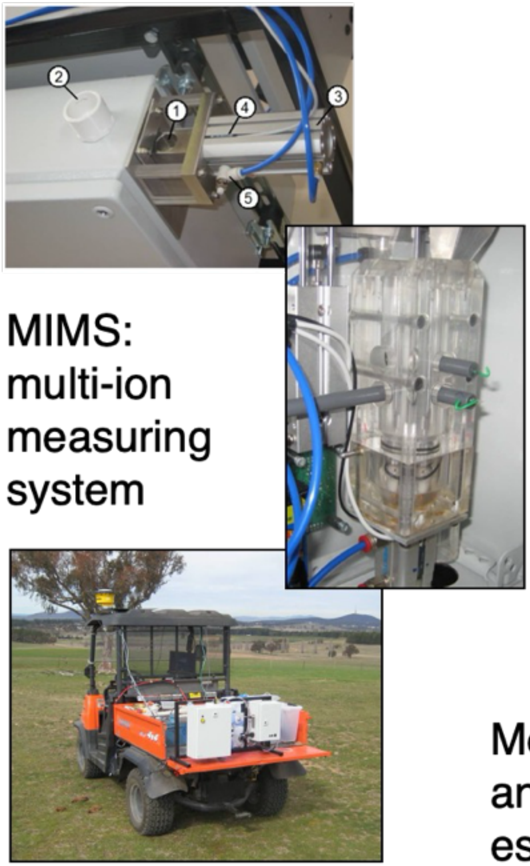
Laser induced breakdown spectroscopy (LIBS)





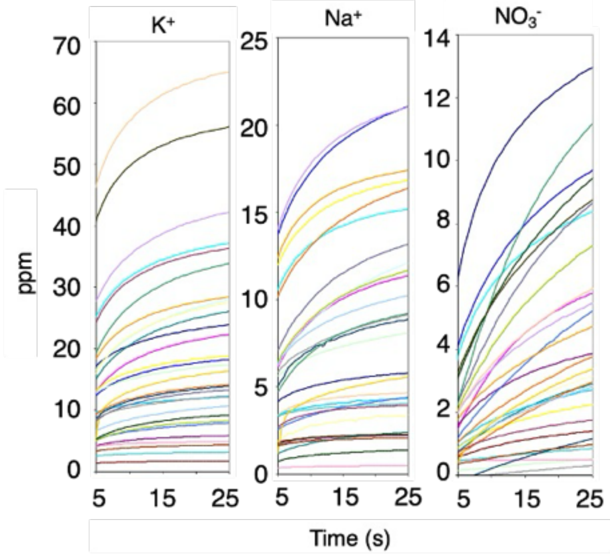
- A high energy laser pulse ablates a small amount of sample in to transient plasma, as the plasma cools, elements emit light at characteristics wavelengths, which are measured by a spectrometer.
- Elements are detected from emission peaks of particular wavelength, and the intensity of the peak is correlated to the element content.
- In a single spectrum can measure all elements present in the sample.
- Advantage over PXRF is that it can measure lighter elements, e.g., C

Electrochemical sensing of pH and plant available nutrients



MIMS: multi-ion measuring system

Reaction kinetics can be modelled

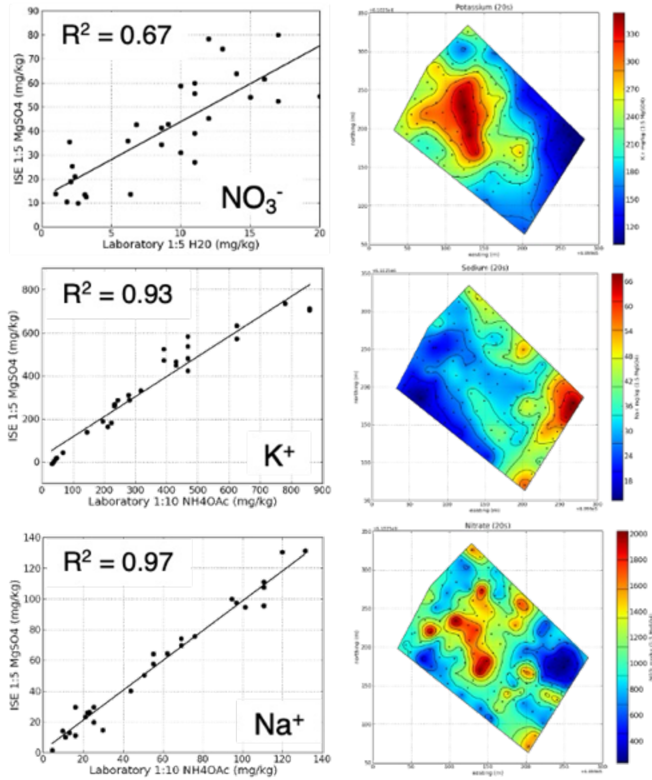


$$E = E_{eq} + \frac{1}{At + B}$$

Buffle & Parathasarathy (1977)

Measuring for 25 s, considering kinetics and sensor characteristics can accurately estimate reaction equilibrium

Validation against conventional methods and interpolated maps

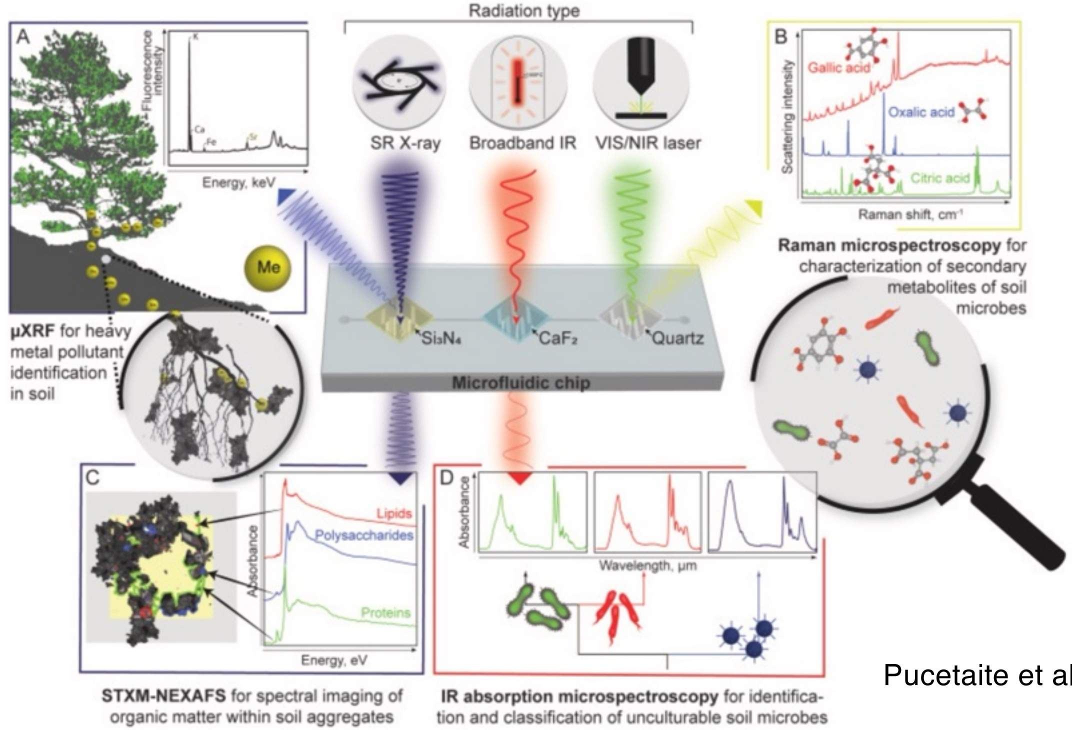


Sensors and what they measure: a summary from the literature

	Soil property	γ-rays	X-ray	CCD	UV–VIS–NIR–MIR	LIBS	Microw. / Radar	Acoustic / Radio	EMI	E-chem.	E-noses	Mech.
Chemical	Organic C and fractions	I		I	I	I			I		I	
	Bioavailable nutrients		I		I	I				D	I	
	pH	I	I		I	I				D		
	CEC	I	I		I	I			I	I		
	Salinity/sodicity		I	I	I	I			I	D		
	Mineralogy	D	I	I	D	I						
Physical	Water storage	D		I	D		D	I	I			
	Bulk density	D			I			I				I
	Clay, silt, sand	i	I	I	I	I		I	I			
	Aggregation			I	I							
	Penetration resistance							I				I
Biological	Microbial activity									I	I	
	Microbial biomass				I						I	
	Respiration/GHG									D	D	
	Diversity/composition				I							
	Enzyme activity				I					I		
	Earthworms/fauna			I				I				

Sensing soil-on-a-chip

	Soil property	Lab-on-a-chip
Chemical	Organic C and fractions	
	Bioavailable nutrients	
	pH	
	CEC	
	Salinity/sodicity	
	Mineralogy	
Physical	Water storage	
	Bulk density	
	Clay, silt, sand	
	Aggregation	
	Penetration resistance	
Biological	Microbial activity	
	Microbial biomass	
	Respiration/GHG	
	Diversity	
	Enzyme activity	
	Earthworms/fauna	



Pucetaite et al. (2021)

Integrating microfluidics and miniature sensors in a chip, allows inexpensive, real-time, in-situ, high-throughput soil analyses and monitoring, e.g., microbial and interfacial processes

What can we gather from the summary table?

No single sensor system that can measure all properties, but soil spectroscopy can measure many chemical, physical and some biological properties

	Soil property	γ-rays	X-ray	UV–VIS–NIR–MIR	LIBS	Microw. / Radar	Acoustic / Radio	EMI	E-chem.	E-noses	Mech.	Lab-on-a-chip
Chemical	Organic C and fractions											
Physical	Water storage											
	Bulk density											
	Clay, silt, sand											
	Aggregation											
	Penetration resistance											
Biological	Microbial activity											
	Microbial biomass											
	Respiration/GHG											
	Diversity											
	Enzyme activity											
	Earthworms/fauna											

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No single sensor system that can measure all properties

Some sensor systems measure directly but many measure indirectly and most need calibration

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Chemical	Organic C and fractions											
	CEC											
	Mineralogy											
Physical	Water storage											
	Earthworms/fauna											

There is no single sensor system that can measure everything

Some sensor systems measure directly but many require calibration

Combining a carefully selected set of sensors offers several advantages

- increase information content
- improved accuracy and reliability
- provide redundancy
- increase versatility
- cost-effectiveness

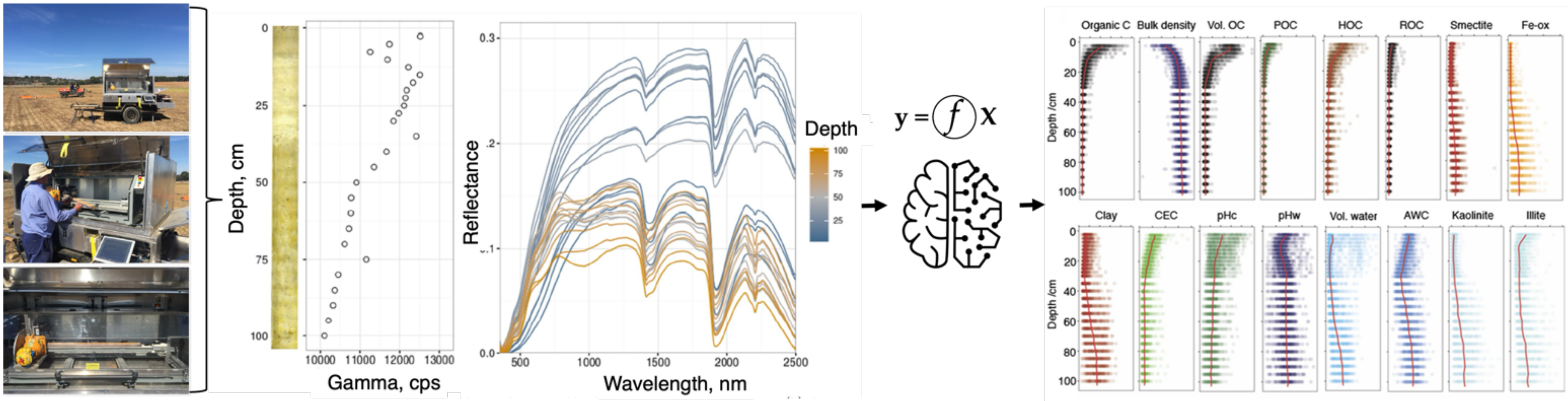
A multi-sensor platform: SCANS for measuring soil condition

Automated soil core sensing with embedded computer

Sensors
- vis and IR cameras
- γ-densitometer
- vis–NIR spectrometer
- 4G comms

Data analytics and ML

Measurements characterize soil variability (x,y,z) at a fine spatial resolution



Measurements taken at 5 cm depth increments from 1 m soil cores in total of 20 minutes

Final remarks

Our general need to innovate to sustainably meet the world's needs for food and environmental quality is served by the adoption of soil sensing

Using proximal soil sensors will help to farmers fine-tune enterprise management and balance production with environmental quality, including the preservation of soil

Sensing can empower farmers and land managers everywhere to instantly and continuously focus management on their own specific conditions, effectively enabling the implementation of sustainable soil management practices

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Thank you for your attention.