CONDESA
CONVERGENCE OF NANO-ENGINEERED DEVICES FOR ENVIRONMENTAL AND SUSTAINABLE APPLICATIONS

Remote Sensing of Soil Moisture via Quantum Metrology

Maeve McCormick, Kyle Wright, Jorge Arteaga & Adityaa Bajpai

Outline

- Objective
- Motivation
- Existing Methods
- Proposed Methods
- Experiments
- Timeline

A roadmap and compass for you.

Objective:

Determine moisture content of soil.

Constraints:

Remote sensing

Quantum physics

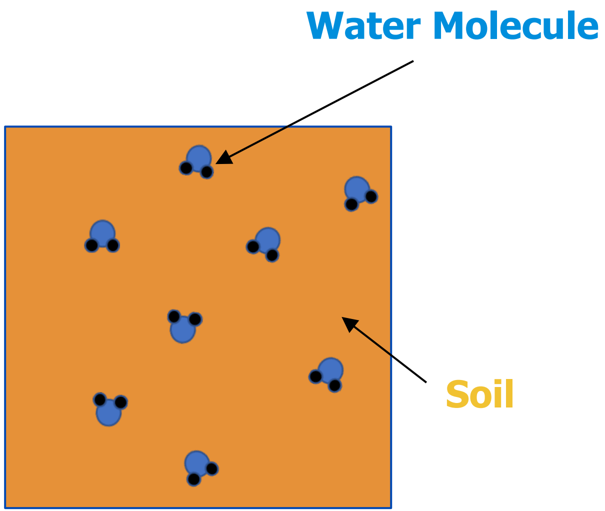


Diagram key

Aim: improve understanding of relationships among soil properties and SOC stability

- ❖ Why soil?
  - ➢ Soil Organic Carbon (SOC)
  - ➢ Microbial respiration

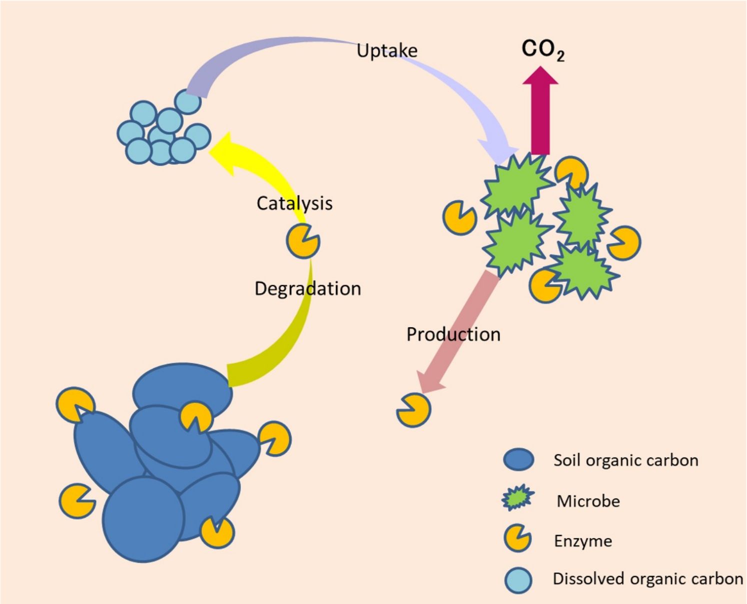
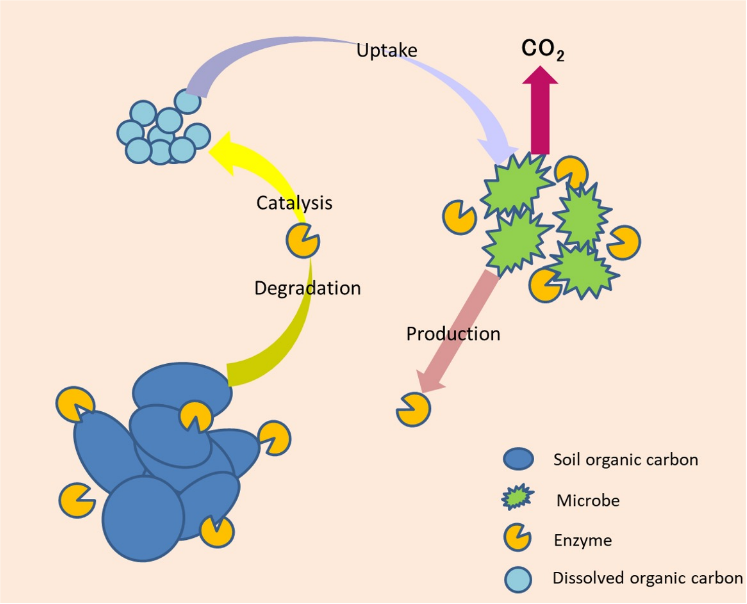


Image by Xia Zhang: Zhang, X., Xie, Z., Ma, Z., Barron-Gafford, G. A., Scott, R. L., & Niu, G.-Y. (2022). A microbial-explicit soil organic carbon decomposition model (MESDM): Development and testing at a semiarid grassland site. Journal of Advances in Modeling Earth Systems, 14, e2021MS002485. https://doi.org/10.1029/2021MS002485

Aim: improve understanding of relationships among soil properties and SOC stability

- ❖ Why soil?
  - ➢ Soil Organic Carbon (SOC)
  - ➢ Microbial respiration
- ❖ Where does water come in?
  - ➢ Regulating metabolic pathways



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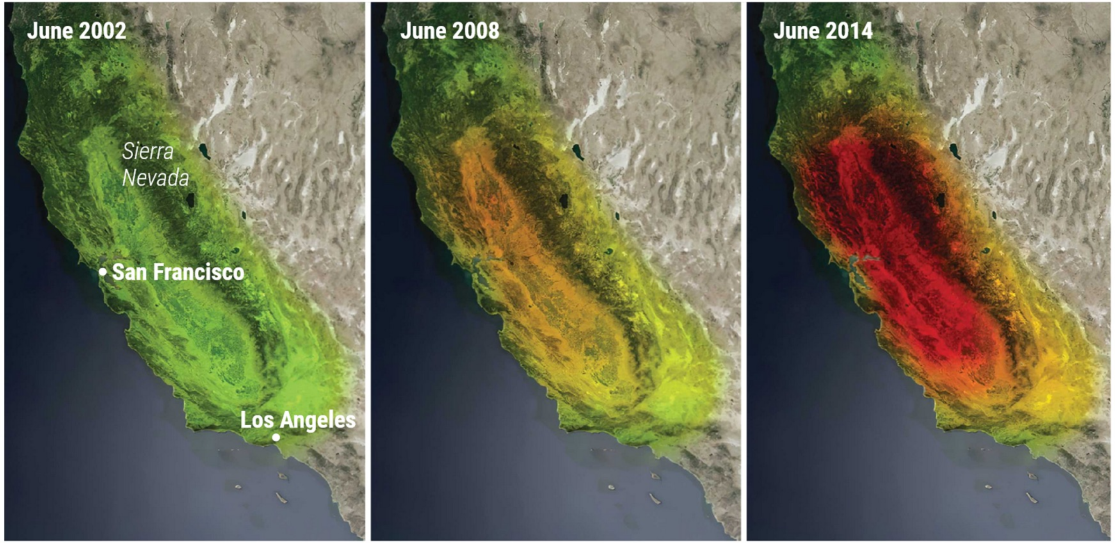
California is thirsty

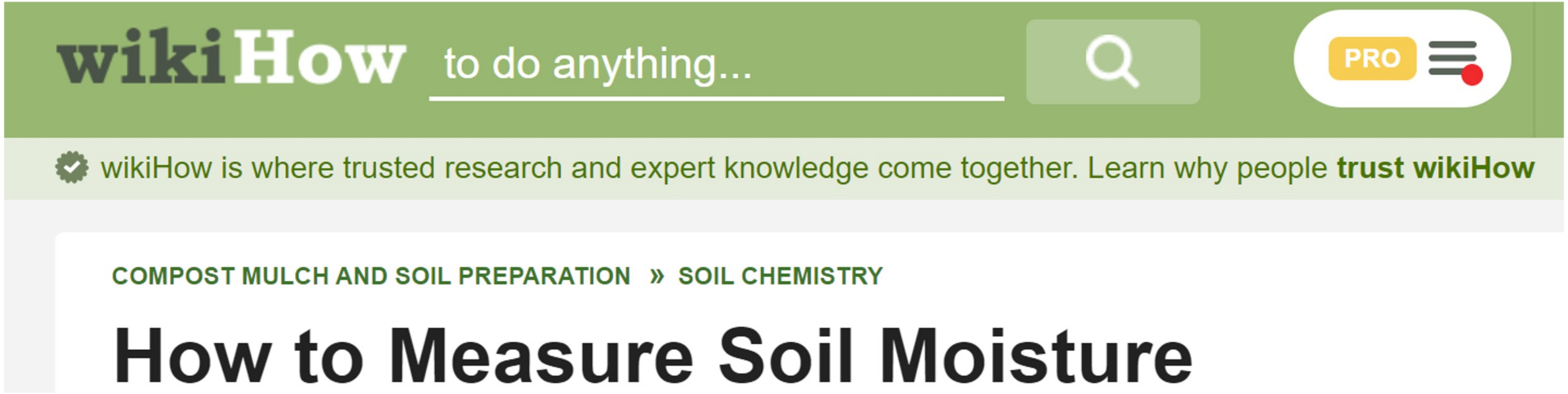
California drying

NASA's GRACE satellites detect the gravitational pull of water masses in aquifers, reservoirs, and snowpack. In 2014, GRACE data showing water loss (below, red indicates loss) helped dramatize the draining of aquifers and galvanize state lawmakers to protect groundwater.



Our interdisciplinary team is uniquely equipped to address this problem because our combined expertise informs our framing of and approach to the problem at hand.

- Soil physical properties and dynamics
- Intricacies and limitations of NMR
- Applications of functional modeling and machine learning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How to Measure Soil Moisture

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How to Measure Soil Moisture

Method 1

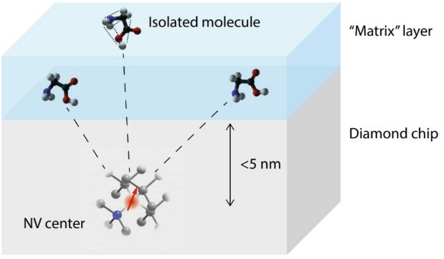
Estimating Soil Moisture by Look and Feel

Download Article

1 **Stick your finger 1–2 inches (2.5–5.1 cm) into the soil.** If the soil feels dry or if it falls off of your finger when you remove it, the soil may be dry. If the soil feels moist or if the soil sticks to your finger, the soil may be moist.[1]

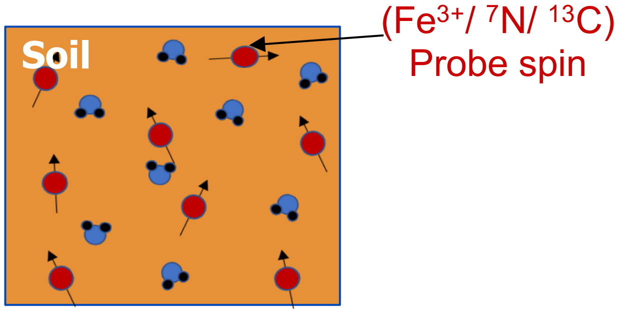
Step I: NV spin based detection

- Employ the nano-MRI technique to detect water using diamond chips with NV centers in lab setting
- Develop an ML algorithm that can detect the signature of water in the nano-MRI readout

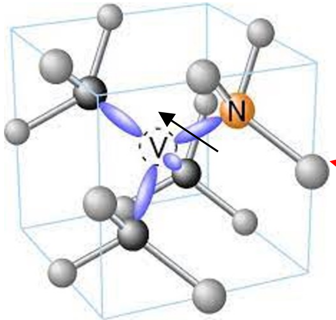


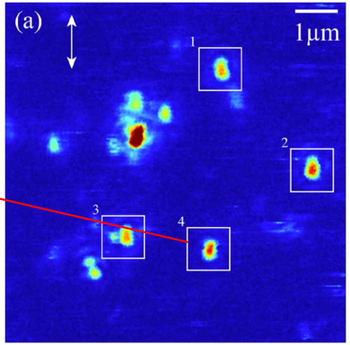
Step II: Nuclear spin based detection

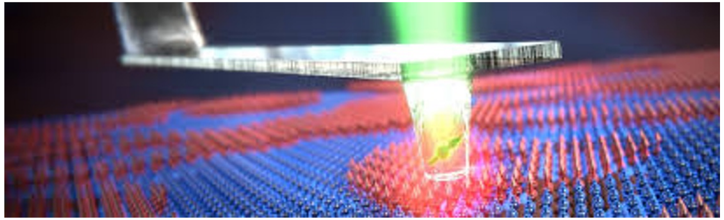
- Reproduce results obtained by NV centers with probe spins - Fe^{3+}/ ^{7}N/ ^{13}C - in the soil matrix
- Develop a portable device to resonantly excite and probe these spins to estimate the water content in the soil



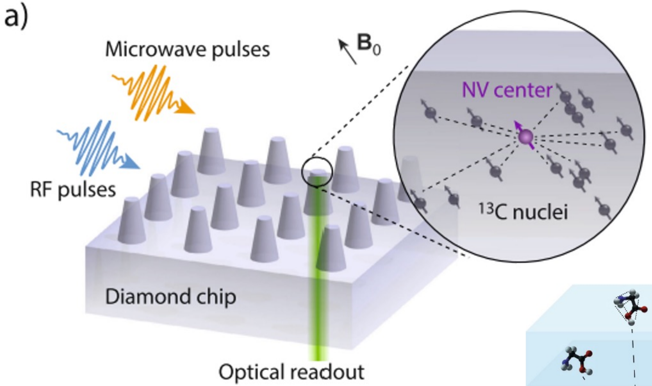
NV Centers

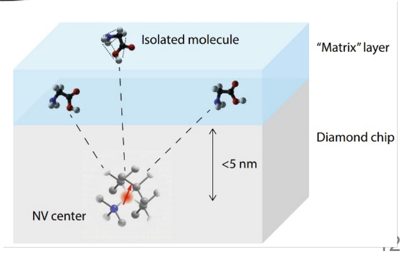






- Room-temperature experiments
- Fabrication ease
- Variety of application in magnetometry
- Recent developments in nuclear-spin mapping

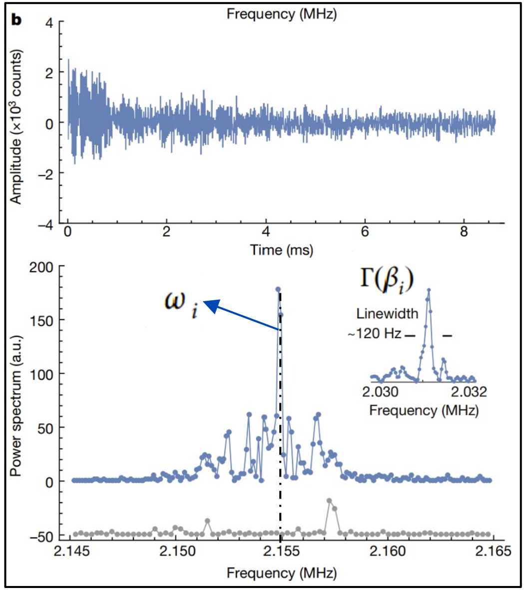


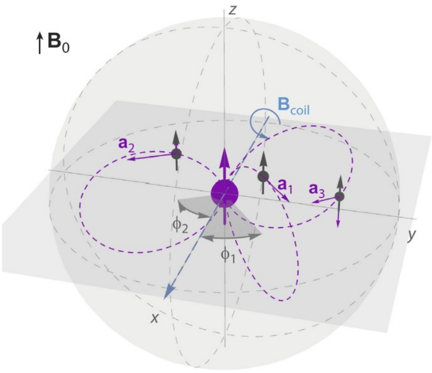


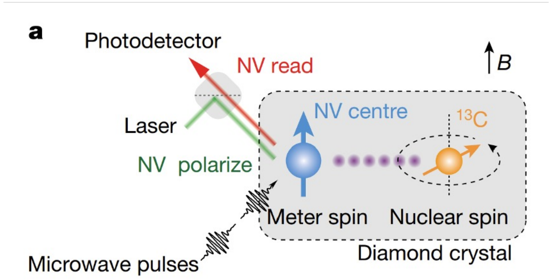
P. Dolan *et.al.* "Complete determination of the orientation of NV centers with radially polarized beams," Opt. Express 22, 4379-4387 (2014)

Cujia, K.S., Herb, K., Zopes, J. *et al.* Parallel detection and spatial mapping of large nuclear spin clusters. *Nat Commun* **13,** 1260 (2022)

NV Centers





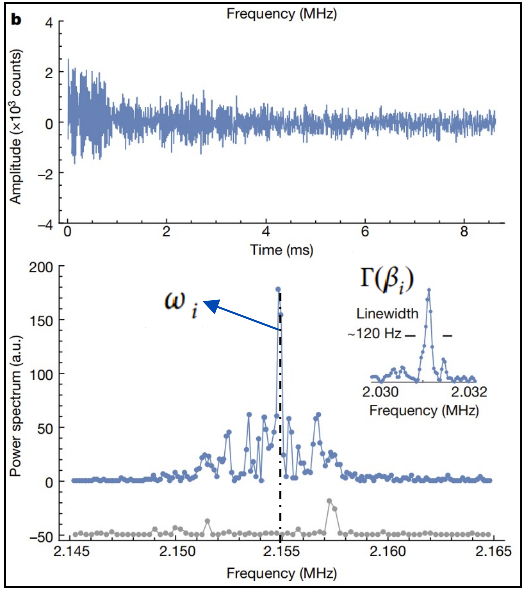


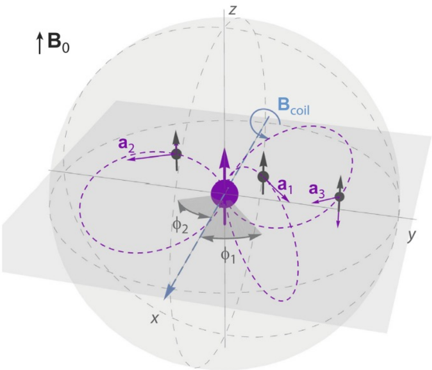
$$\omega_i \approx \omega_0 + \frac{1}{2} a_{||,i}$$

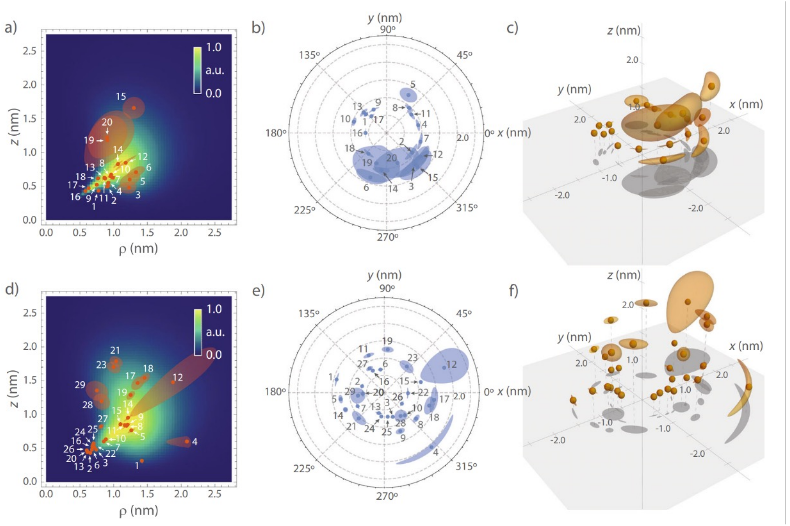
$$\Gamma(\beta_i) = \frac{a_{\perp,i}^2 t_\beta^2}{4 t_s \pi^2} + \frac{a_{||,i}^2 t_\ell^2}{2 t_s} + \frac{1}{T_{2,\mathrm{n}}^*}$$

Cujia, K.S., Herb, K., Zopes, J. *et al.* Parallel detection and spatial mapping of large nuclear spin clusters. *Nat Commun* **13,** 1260 (2022)

NV Centers







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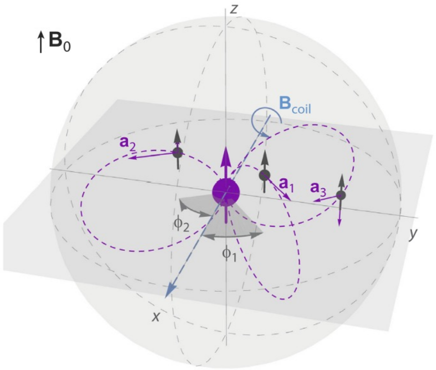
Nuclear spins can be mapped in the vicinity (< 5 nm) of a probe spin

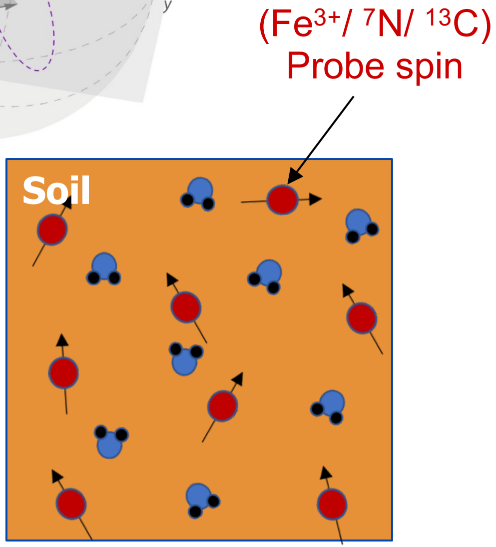
Overview

Water content of soil can be inferred using Nuclear Magnetic Resonance (NMR) measurements.

Why NMR:

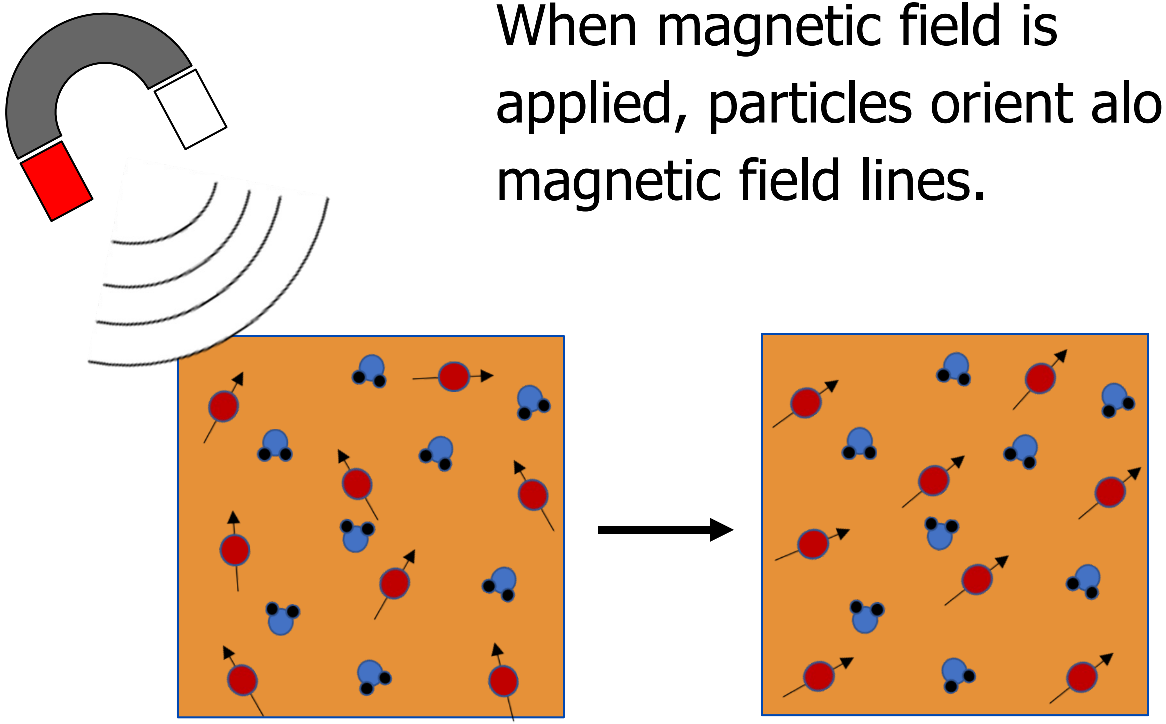
- ❖ Well studied
- ❖ Radio wave penetration of about a feet
- ❖ Completely remote measurement
- ❖ Can be used to study other species such as heavy metals





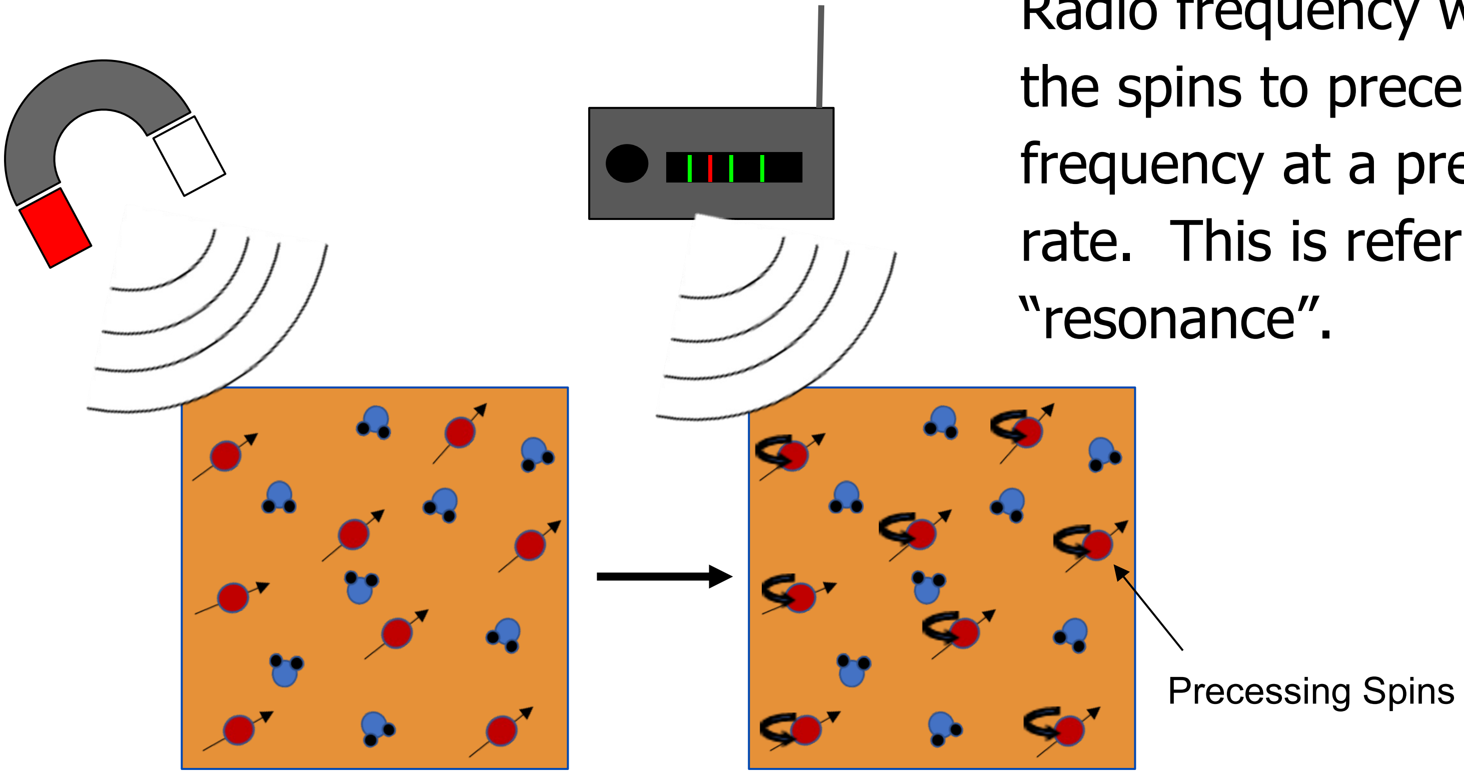
Applied Magnetic Field

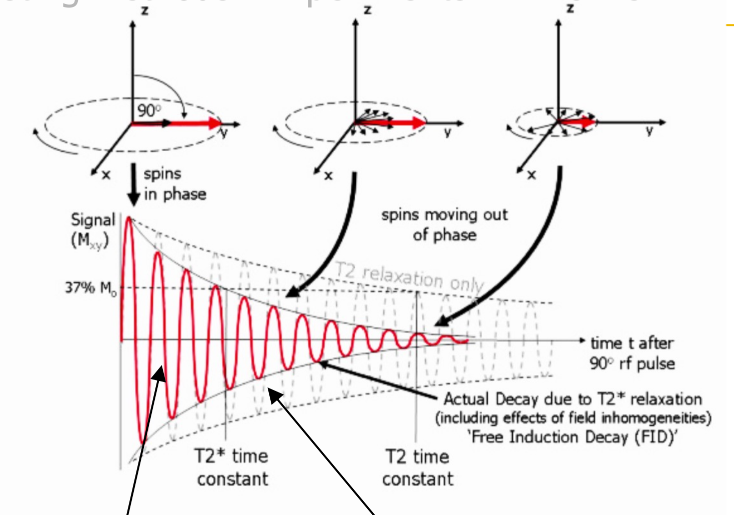
When magnetic field is applied, particles orient along magnetic field lines.



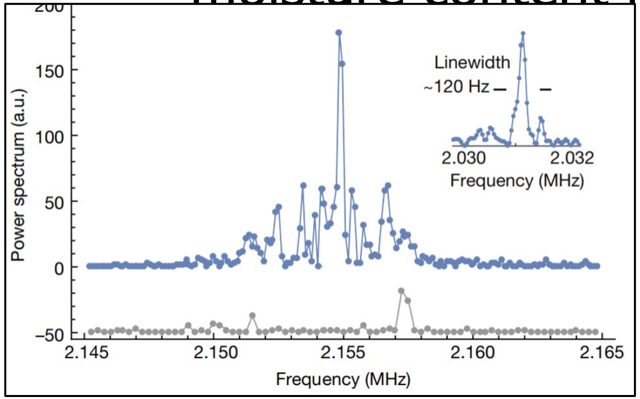
Radio Frequency Waves (100 MHz)

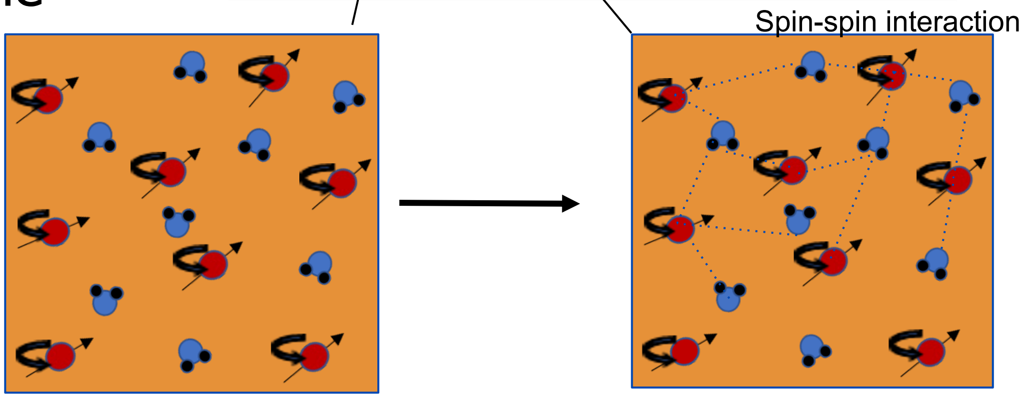
Radio frequency waves cause the spins to precess at a frequency at a predictable rate. This is referred to as "resonance".





- These decay rate due to spin-spin interaction can be used to estimate the moisture content in the

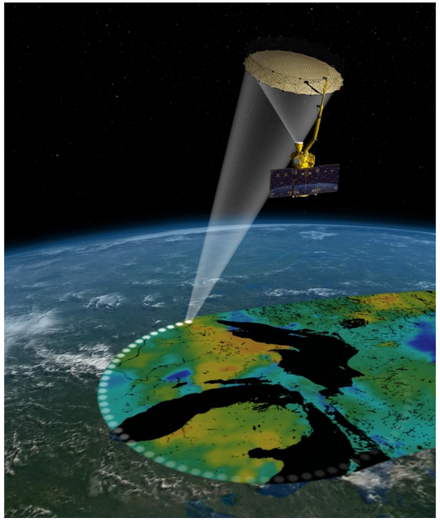




Moisture Sensing

- Gravimetric method
- Conductance
  - Probes up to 0.3m
- Neutron scattering method
  - ~30cm radius of source
- SMAP
  - ~10cm
- Direct NMR of water

A Campbell soil moisture probe.



https://www.jpl.nasa.gov/images/pia19133-soil-moisture-active-passive-satellite

NMR

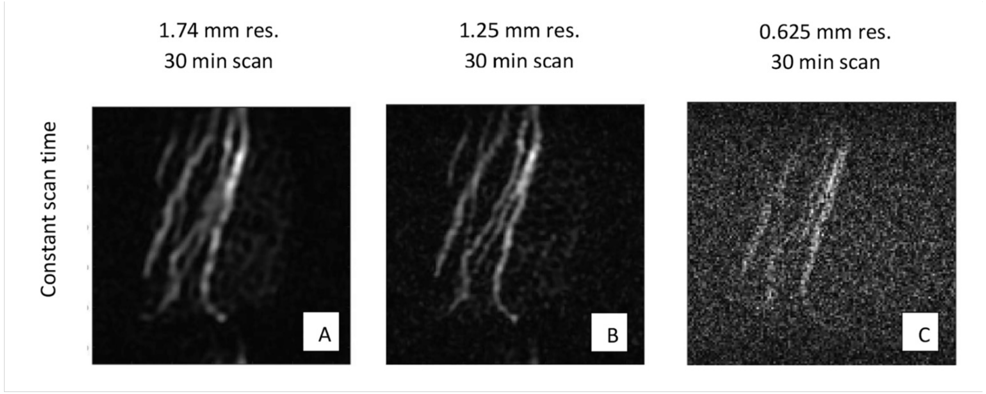
- Atoms in magnetic field are excited by radio waves into resonance
- Used to identify molecules and image sample
  - Used to directly measure soil water content
- NMR is usually done in lab setting with large superconducting magnets
  - ~20T (strongest Neodymium magnet ~1T)
- Bulky and expensive machine

R.F. Paetzold, G.A. Matzkanin, and A. De Los Santos, Soil Science Society of America Journal **49**, 537 (1985).

Low-field NMR

Often impractical to bring the large electromagnets needed for NMR into the field.

Low-Field NMR operates in the 1T to 10 mT range and can be implemented in the field



Low-field MRI of nodal roots under silt loam at 47 mT
Matthew Rosen *et. al.* Geoderma,Volume 370,2020,114356

Experimental Plan

1. Test NMR in mineral rich soil
   a. vary water concentrations: 0%,…,25%,…,50%,…,75%,…,100%
2. Model water concentration to give NMR output with and without soil parameters
   a. Training soil
   b. Testing soils with degrees of similarity
3. Repeat with various soil types
   a. Sand, clay, silt, loam, sandy loam
4. Investigate model differences and compare with parameter differences between soil types (for eg. study the dependence probe spin concentration on water estimation)

End Goal: Applications for environmental sensing in natural & agricultural systems.

Task/Goal	Year 1				Year 2				Year 3			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Literature Review	x	x	x	x								
Methods Comparison		x	x	x		x						
Application Modeling				x	x							
Tech Development						x	x	x	x	x		
Lab Experiments							x	x	x	x		
Field Experiments										x	x	x
Application Scaling												x

Thank you!

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CONVERGENCE OF NANO-ENGINEERED DEVICES FOR ENVIRONMENTAL AND SUSTAINABLE APPLICATIONS

Our Advisors:

Dr. Michael Scheibner

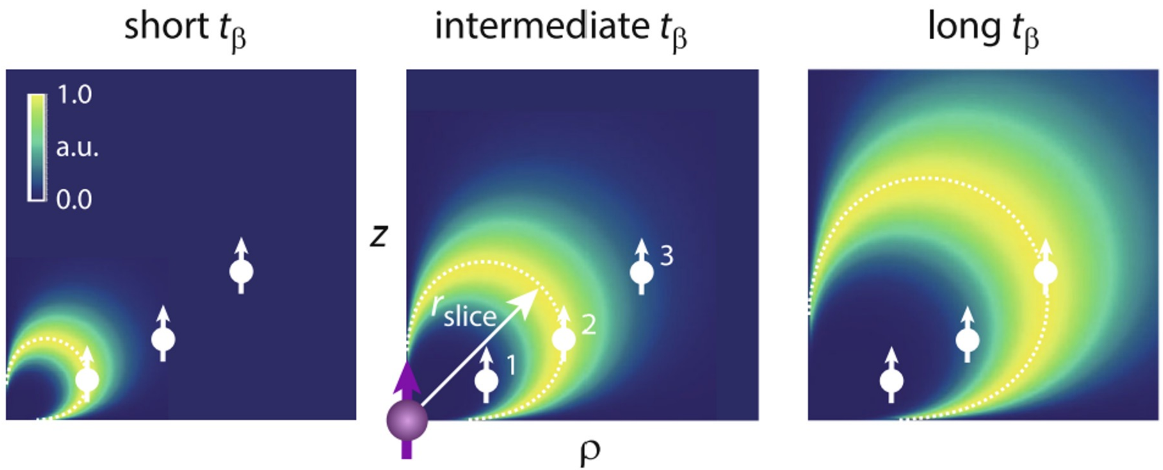
Dr. David Strubbe

Dr. Ryan Baxter

Dr. Teamrat Ghezzehei

Dr. Sayantani Ghosh

…and you, our peers, guests, and collaborators!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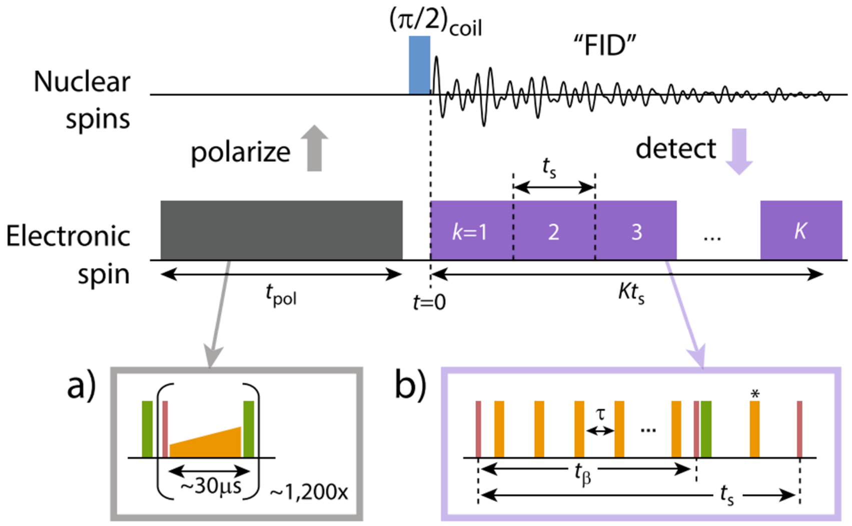
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