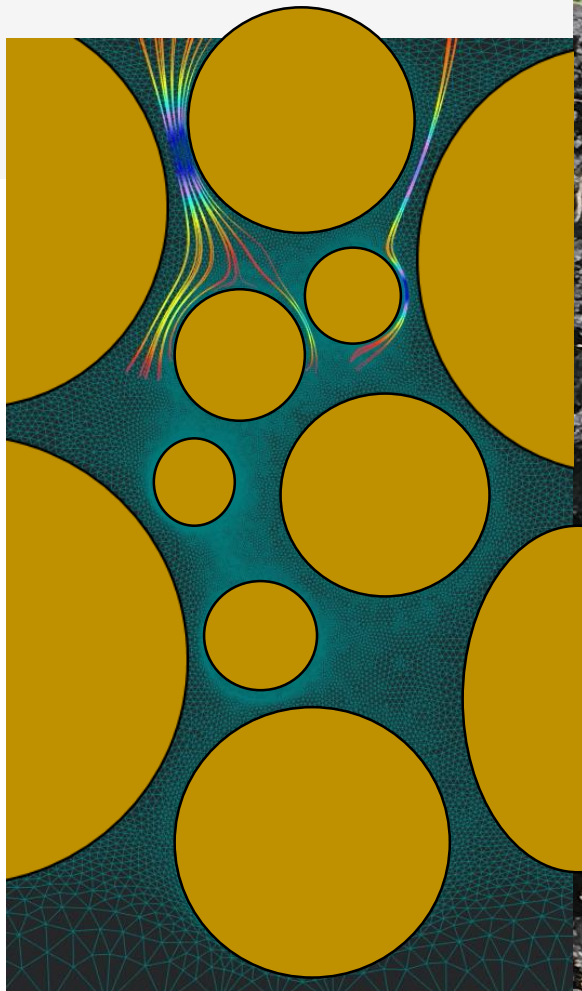
Getting precise with measuring soil water

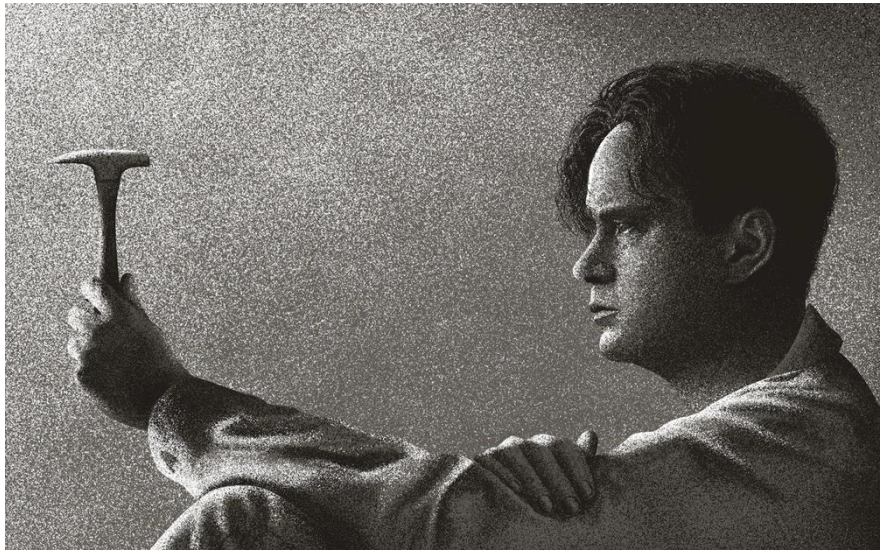
In-situ to remote sensing and their interpretations

Aaron Lee M. Daigh, PhD
Associate Professor
Soil Physics and Hydrology



Cartoons created in Bitmoji; Photo and Simulation by Aaron Daigh

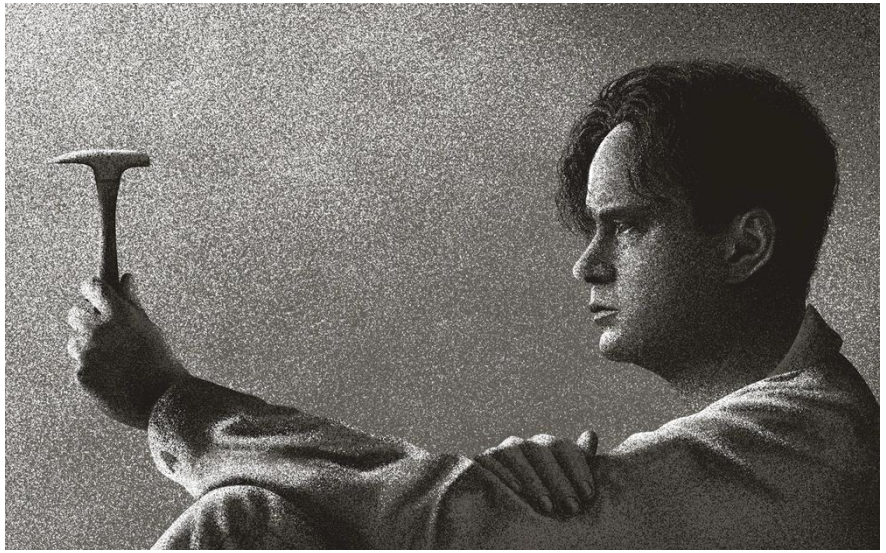
What’s the Tool?



What’s it Operating On?

Images from Tanmay Konnur; Castle Rock Entertainment, Marvel Studios

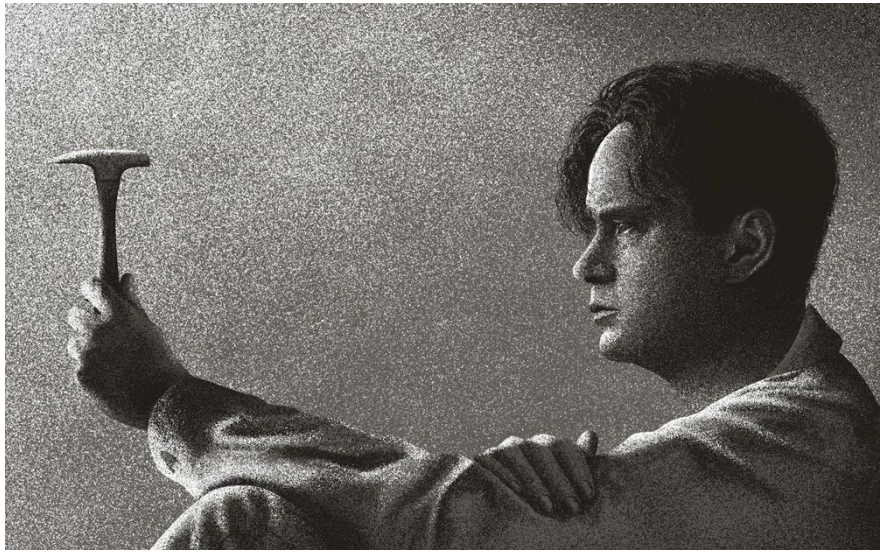
What’s the Tool?



What is Success?

Images from Tanmay Konnur; Castle Rock Entertainment, Marvel Studios

What’s the Tool?

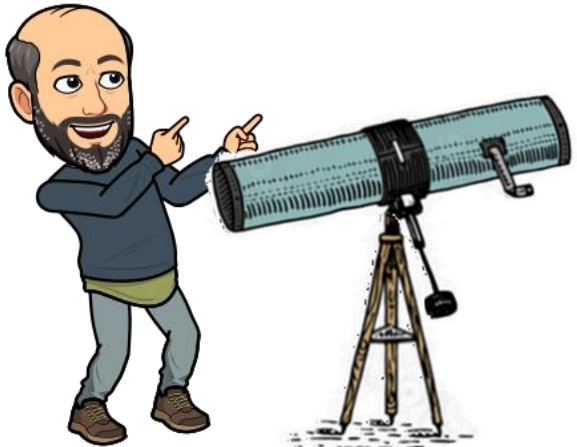


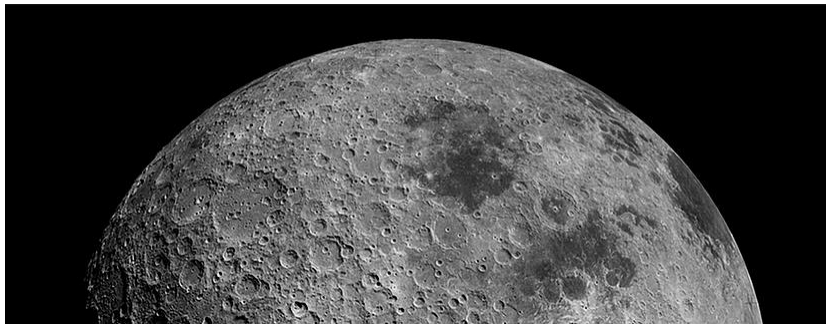
What is Not Ideal?

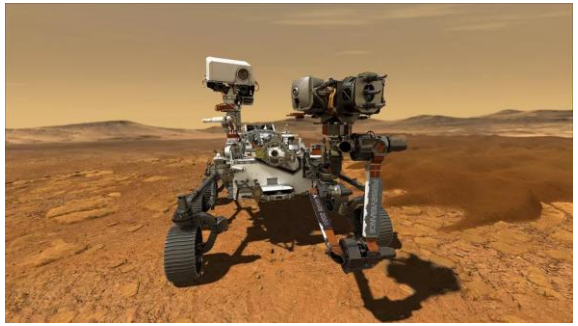
Images from Tanmay Konnur; Castle Rock Entertainment, Marvel Studios

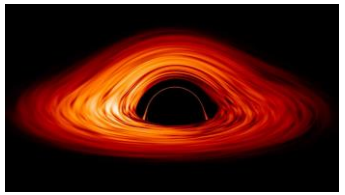
Over the next 40 minutes…

- Discuss just how variable soil water is across the landscape
- Clarify what soil water sensors and technologies actually do
- Share some implications to help calibrate our expectations





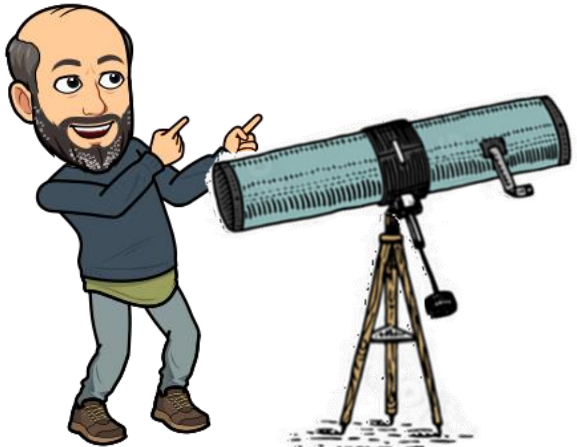


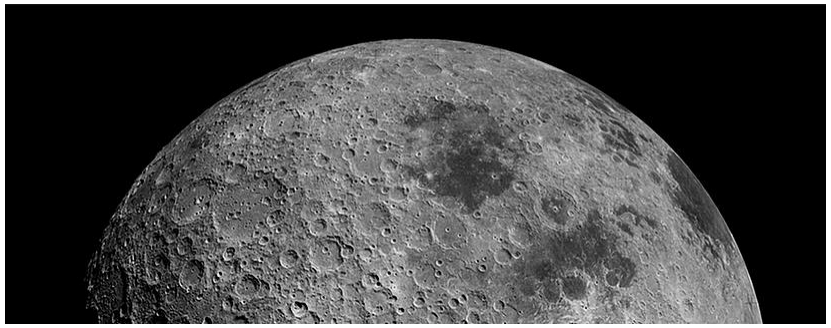


Images from NASA, JPL-Caltech, Goddard SPC, and Bitmoji

First up…

- What is your water content?
- Just how variable soil water is across the landscape?
- What conditions affect this variability?





Images from NASA, JPL-Caltech, Goddard SPC, and Bitmoji


CANADA
MONTANA
NORTH DAKOTA
SOUTH DAKOTA
Williston
Minot
Devils Lake
Fort Union Trading Post National Historic Site
Lake Sakakawea
Knife River Indian Villages National Historic Site
Theodore Roosevelt National Park
Dickinson
Bismarck
Missouri
Jamestown
James
Grand Forks
Fargo
Crookston
Moorhead
Red
© WWW.FREEWORLDMAPS.NET
CANADA
Rainy
International Falls
Voyageurs NP
Upper Red Lake
Lower Red Lake
Cass Lake
Lake Winnibigoshish
Bemidji
Leech Lake
Ely
Virginia
Eagle Mt.
2299 ft / 701 m
Lake Superior
Duluth
Brainerd
Mille Lacs Lake
St. Croix
MINNESOTA
Lake Traverse
St. Cloud
Mississippi
Willmar
Minneapolis
St. Paul
Lakeville
Minnesota
Faribault
Mankato
Des Moines
Rochester
Winona
Albert Lea
WISCONSIN
SOUTH DAKOTA
IOWA
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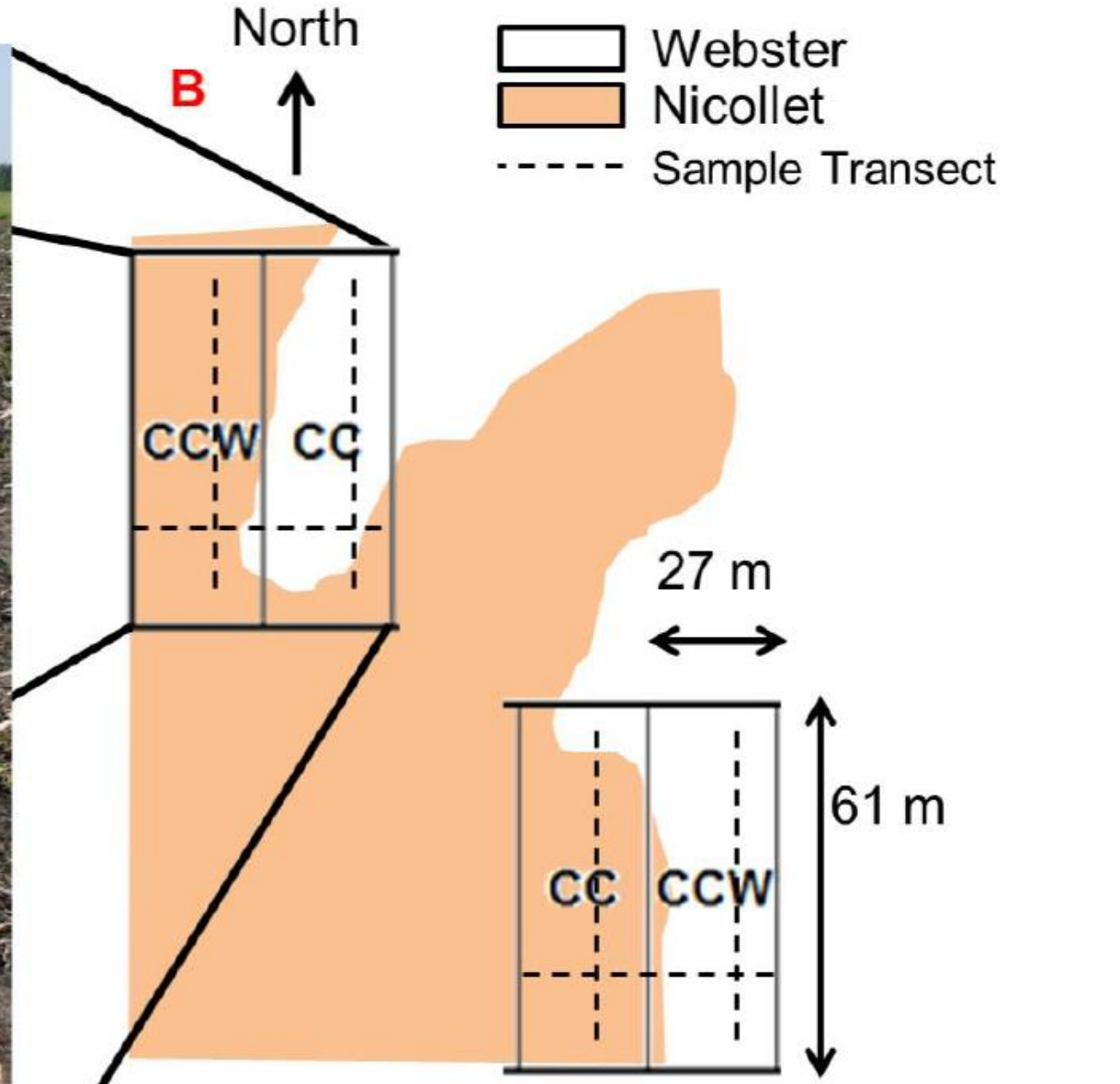
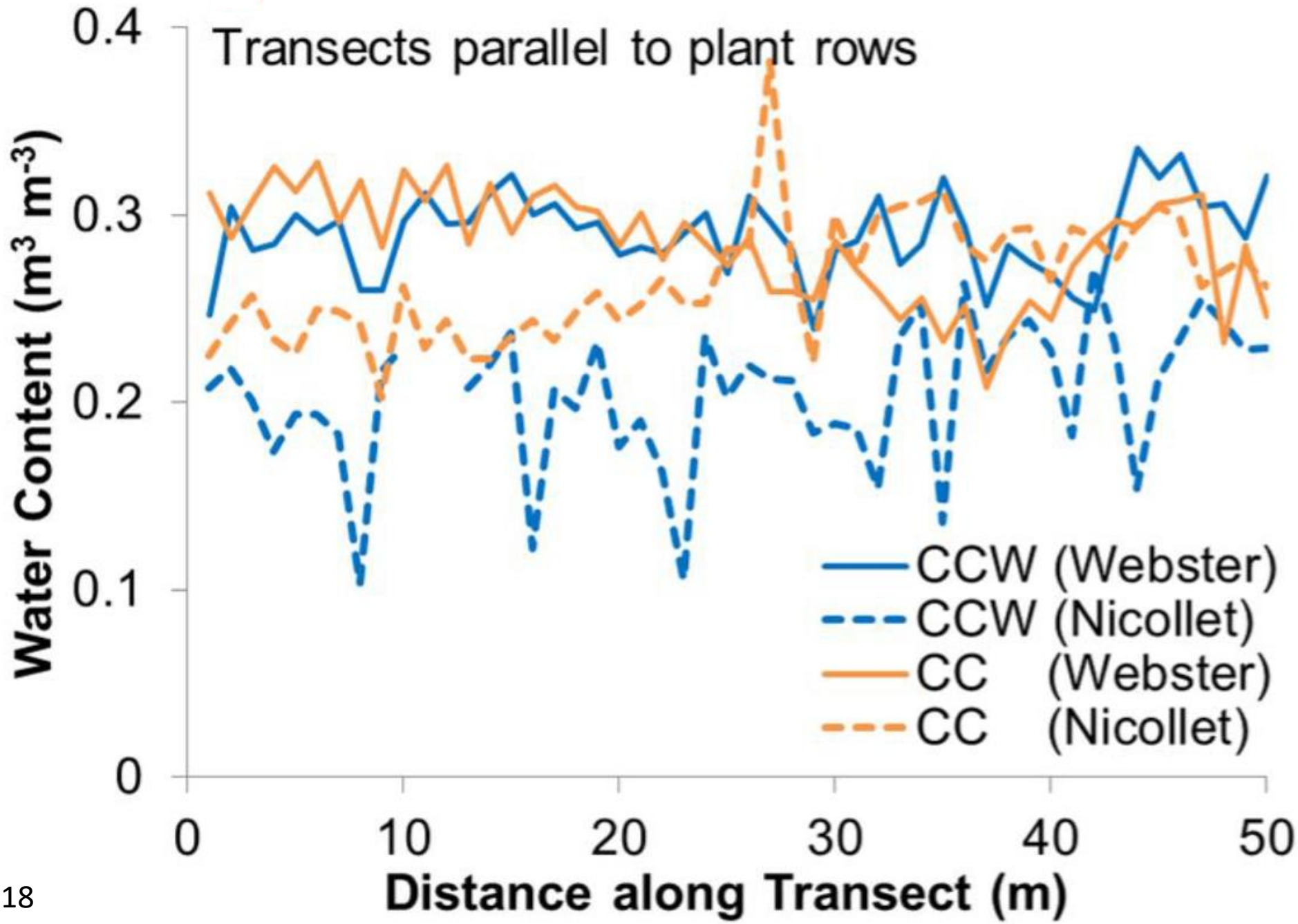
Images by Derby and Daigh, 2019

Daigh et al., 2018

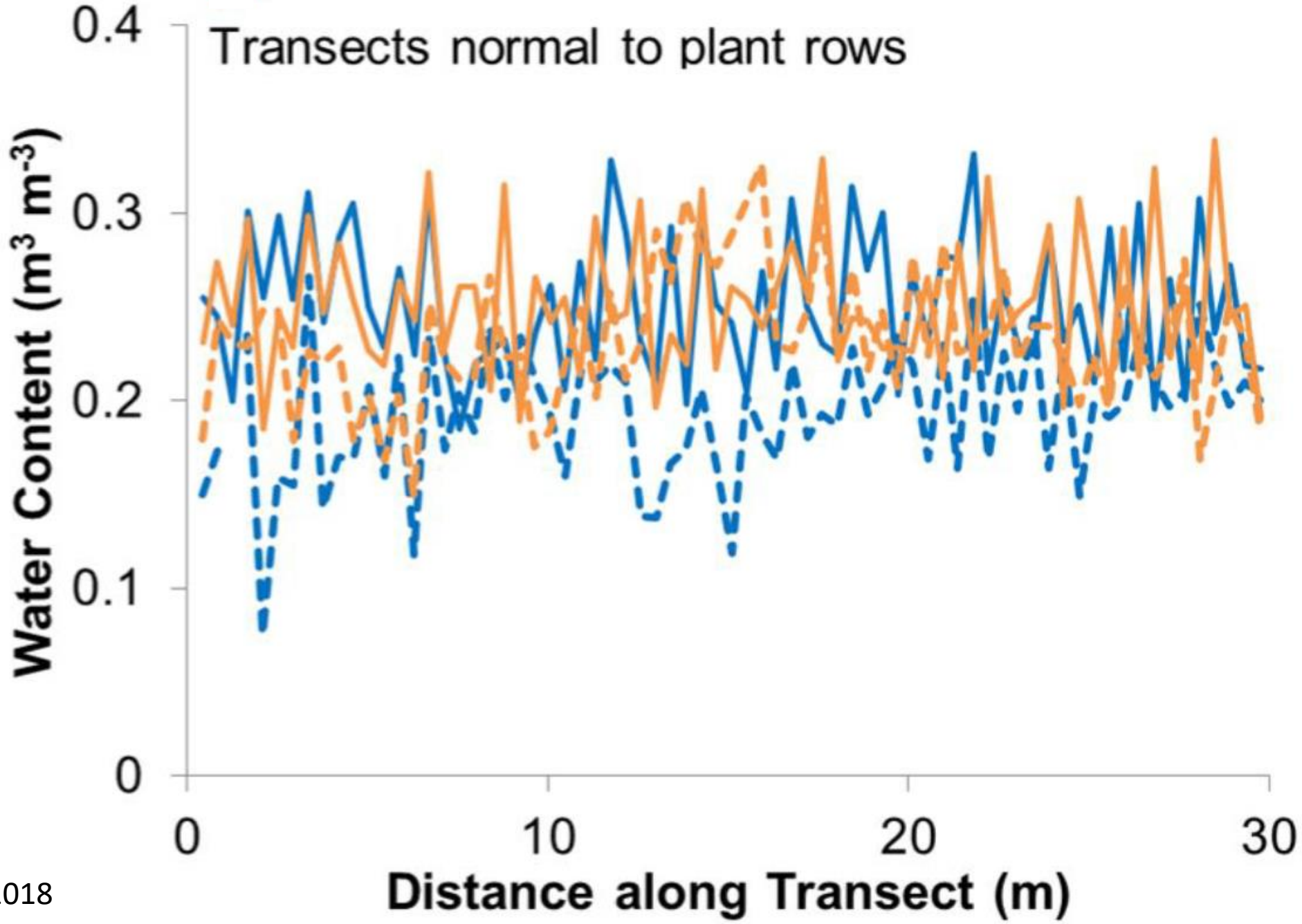


CC Continuous Corn (grain + stover harvest)
CCW Continuous Corn (grain + stover harvest) with winter cover crop

Daigh et al., 2018



Daigh et al., 2018



Daigh et al., 2018

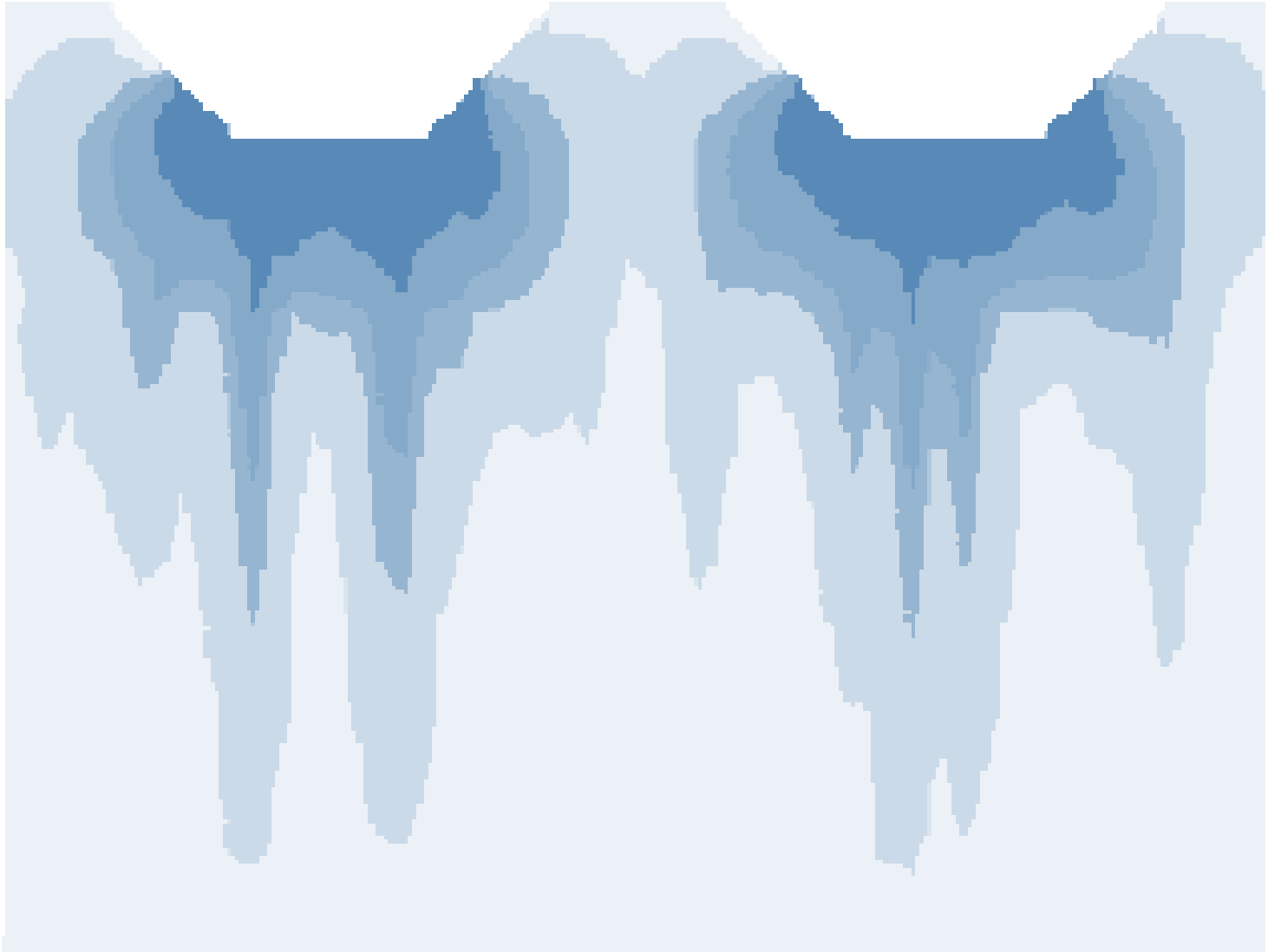
When the soil is Homogenous

Vogel et al., 2000

But introduce large pores from soil structure….

Vogel et al., 2000

You gain a lot of small scale variability….



Vogel et al., 2000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0.352
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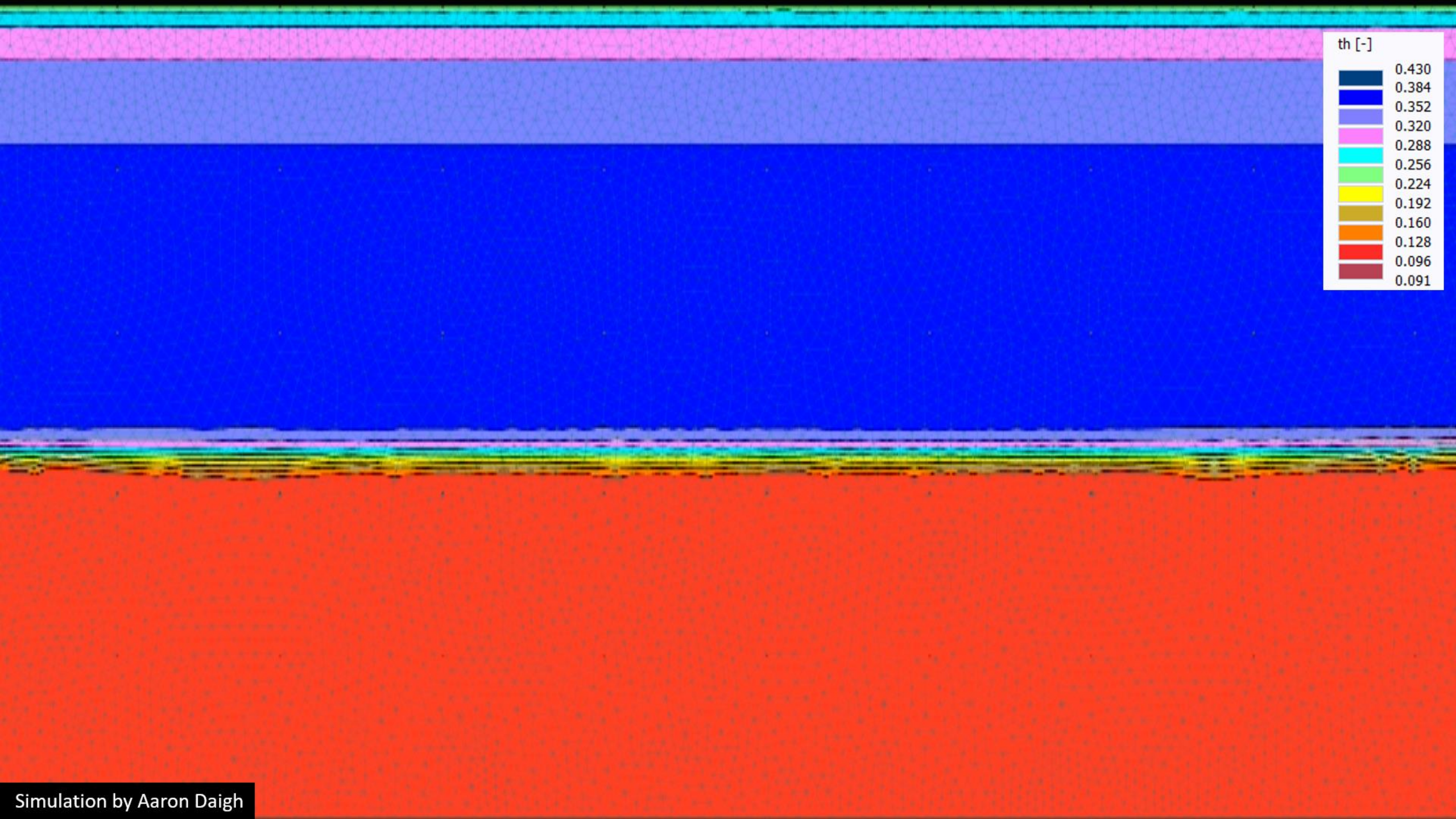
0.288
0.256
0.224
0.192
0.160
0.128
0.096
0.091
Simulation by Aaron Daigh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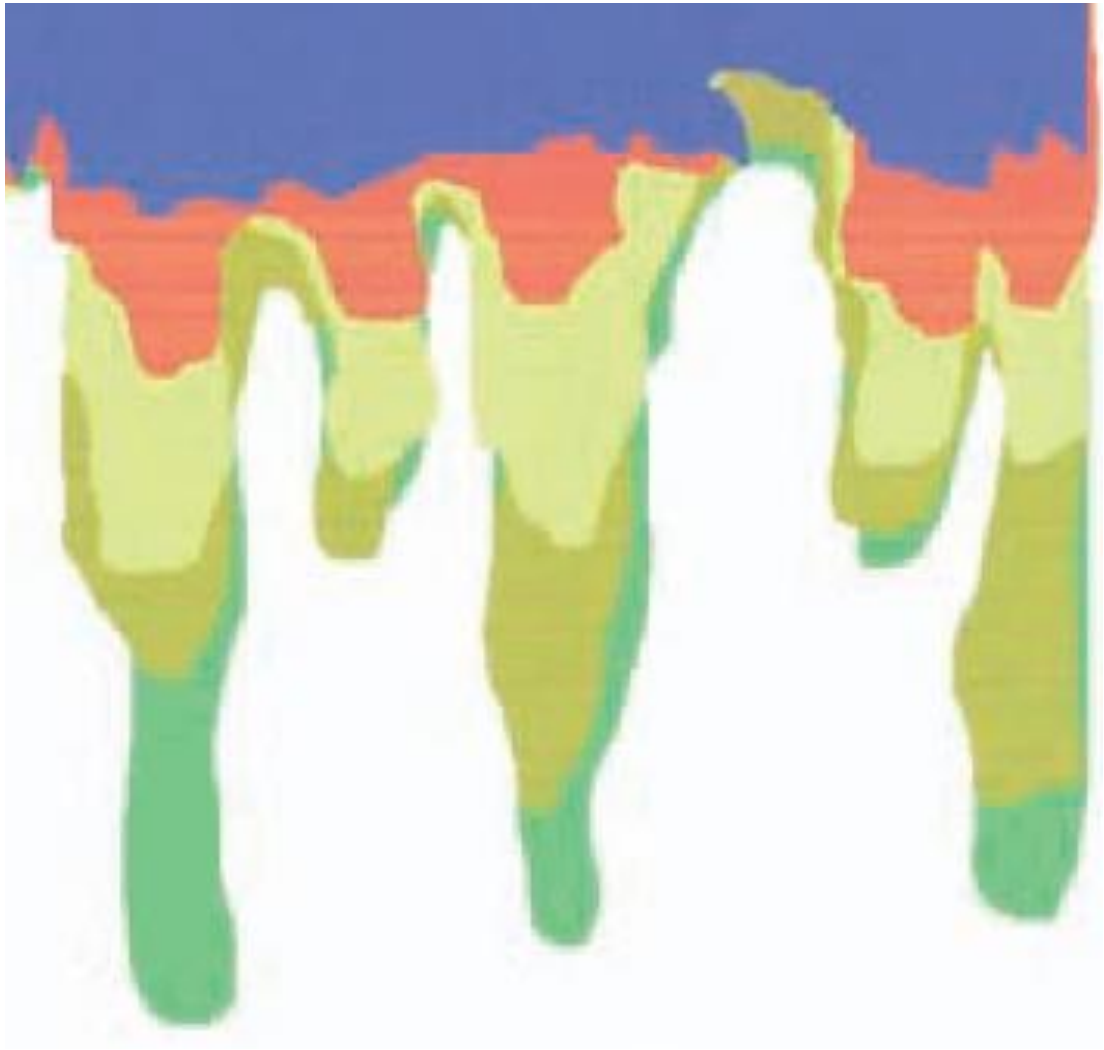
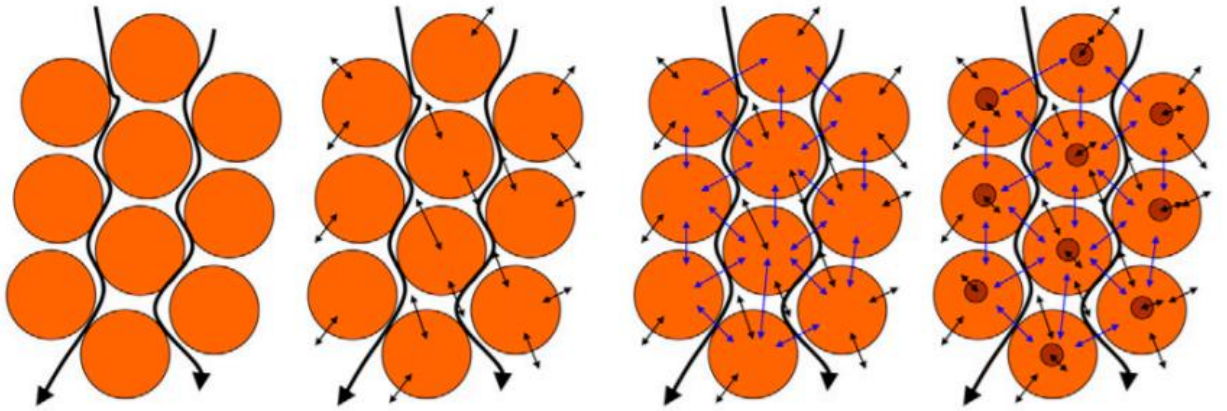


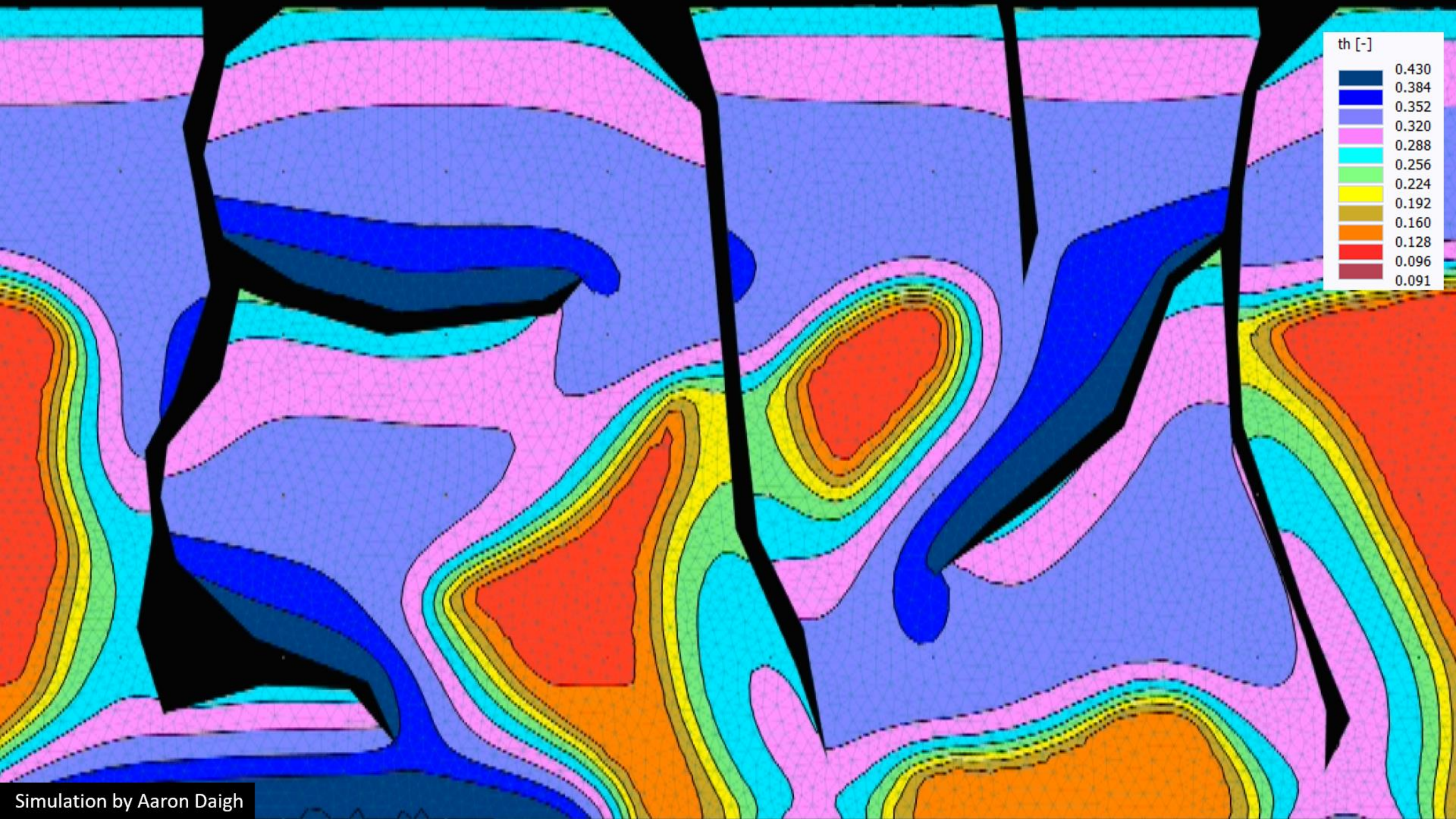
$$K(S_e) = K_s \frac{(w_1 S_{e1} + w_2 S_{e2})^1 \left\{ w_1 \alpha_1 \left[1 - \left(1 - S_{e_1}^{1/m_1} \right)^{m_1} \right] + w_2 \alpha_2 \left[1 - \left(1 - S_{e_2}^{1/m_2} \right)^{m_2} \right] \right\}^2}{(w_1 \alpha_1 + w_2 \alpha_2)^2}$$



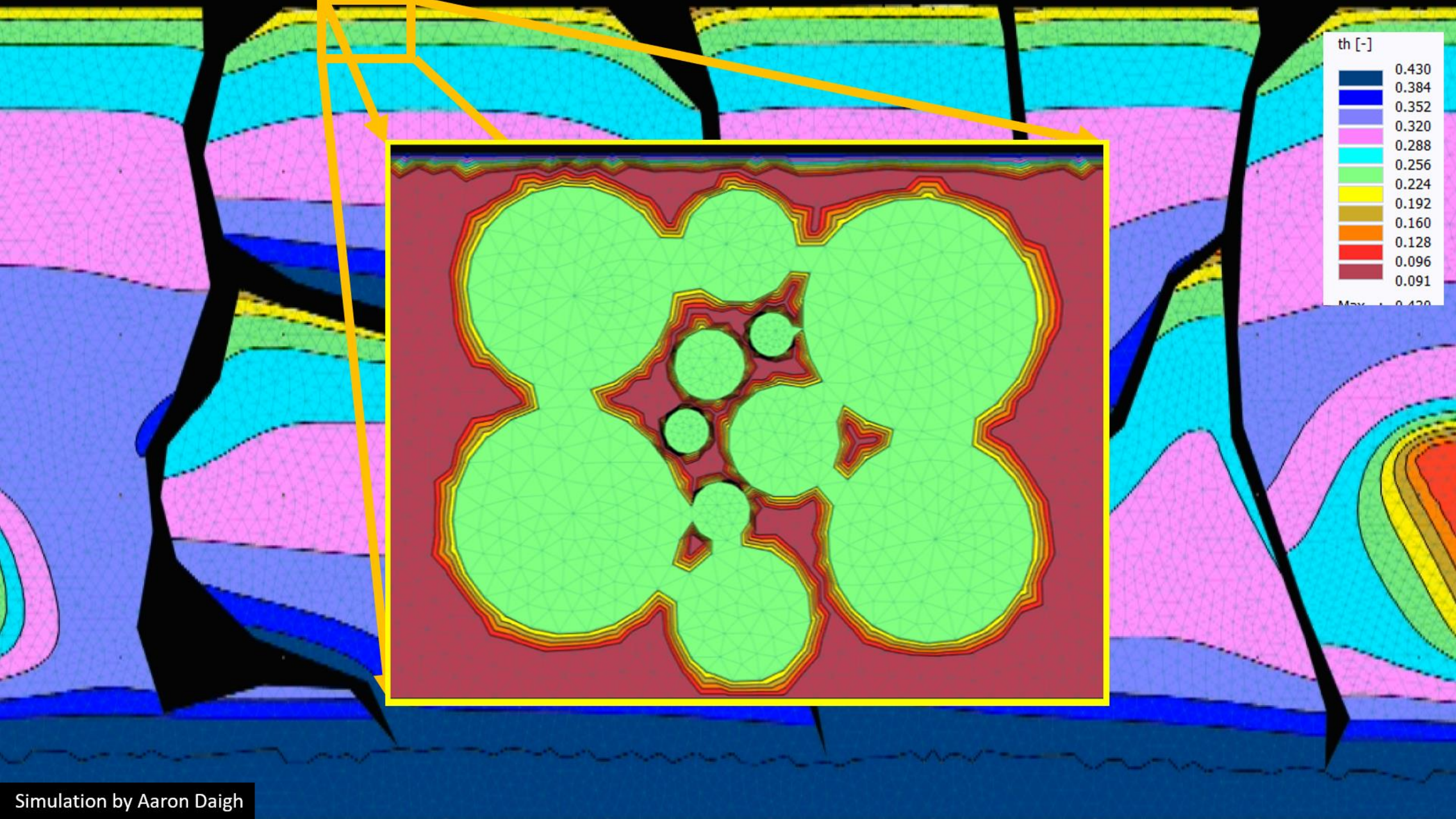
a. Uniform Flow
b. Mobile-Immobile Water
c. Dual-Porosity
d. Dual-Permeability
e. Dual-Permeability with MIM

Jury et al., 2003; Šimůnek and van Genuchten, 2008

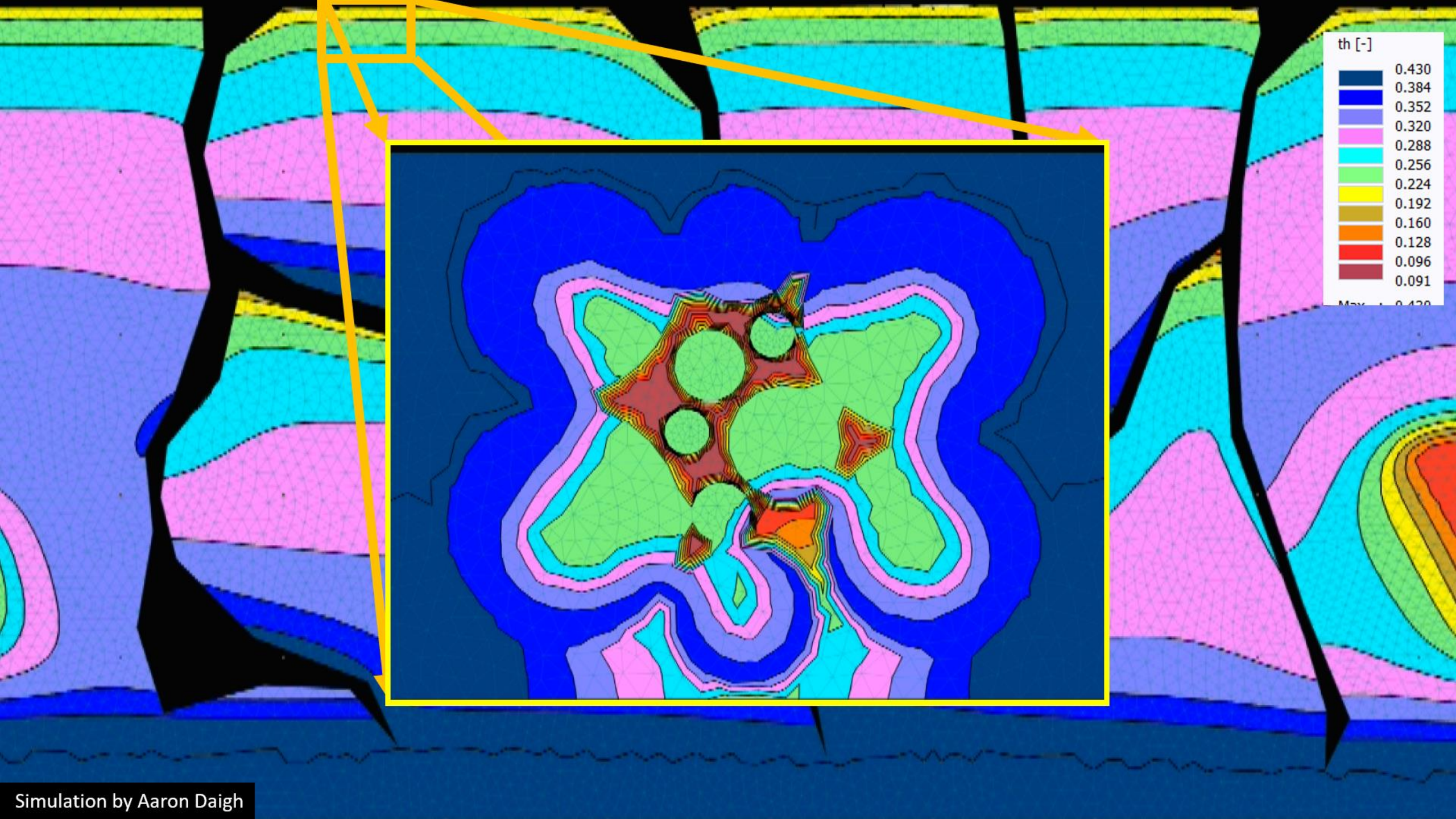
Simulation by Aaron Daigh



Simulation by Aaron Daigh



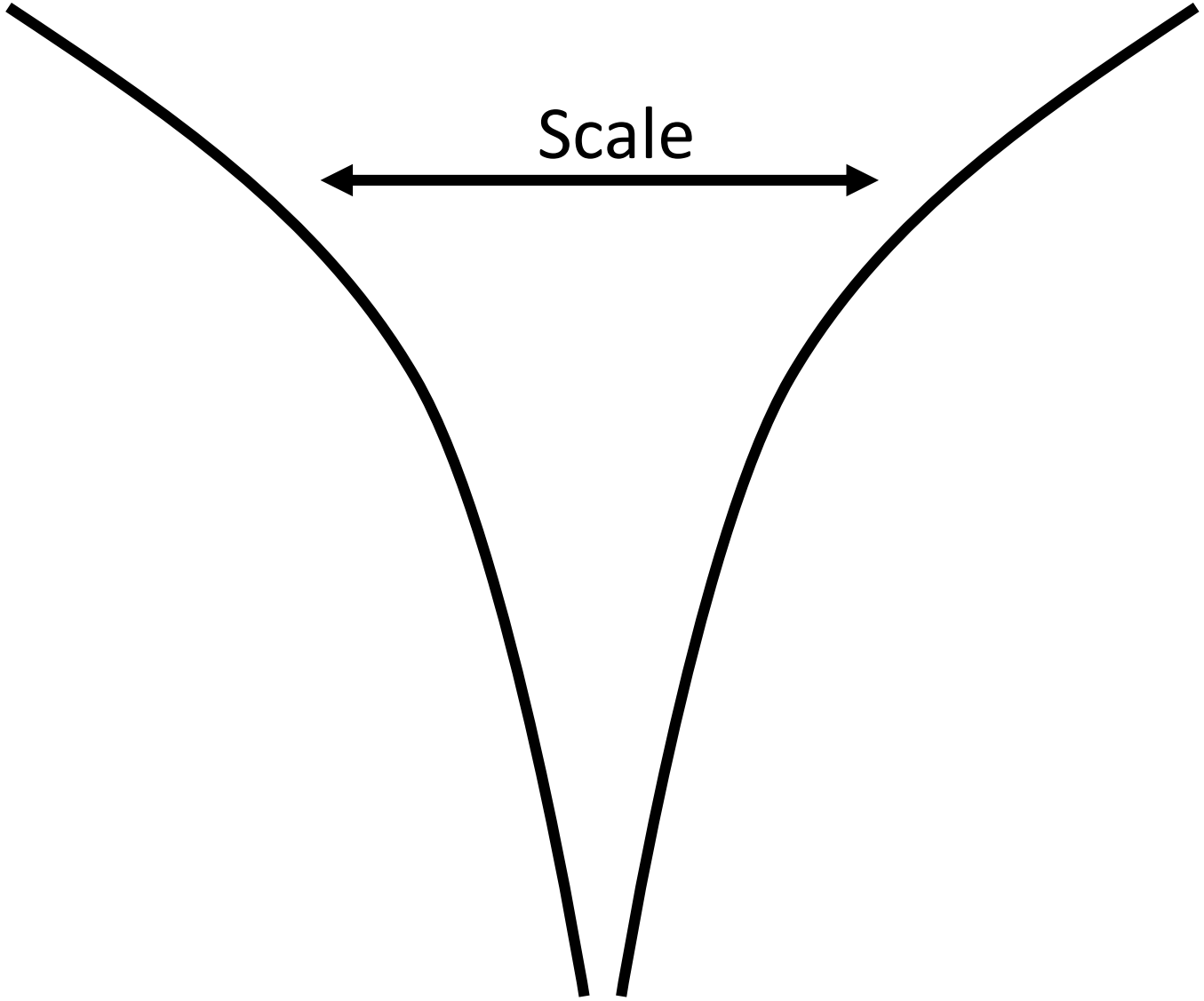
Simulation by Aaron Daigh



Simulation by Aaron Daigh

What is the water content of:

- North Dakota?
- Your farm?
- Your field?
- This pass of the tractor?
- This side of the hill?
- Within reach of this plant?
- In the seedbed?
- Deeper in the soil?
- Handful of soil aggregates?
- Inside a soil aggregate?
- Inside one pore?



What is the Point?

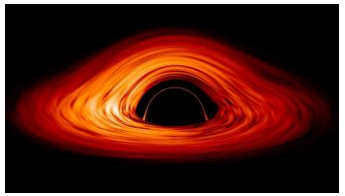
Knowing what you are measuring [and its context] can help us be more realistic about:

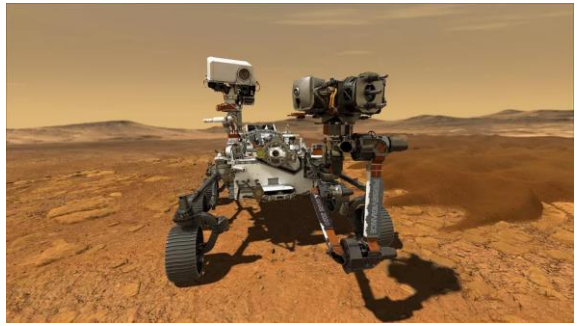
- Our expectations from that data
- Our role in the process (open vs. closed box systems)

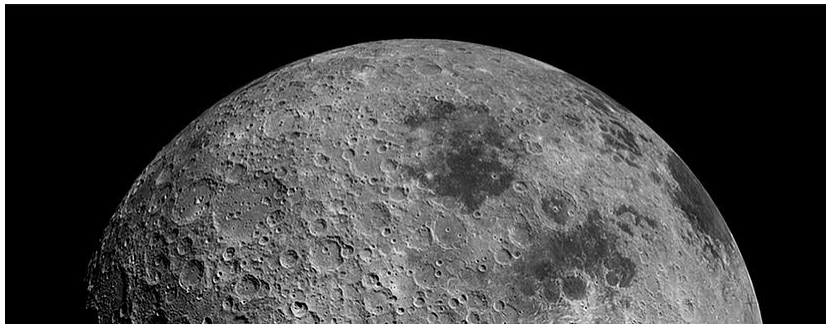
…Good ingredients when applying management practices

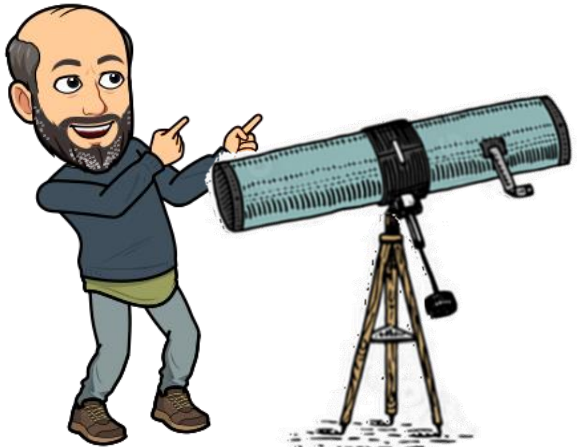
Next up…

- What options exist to measure soil water content?
  - Ground sensors
  - Remote sensors





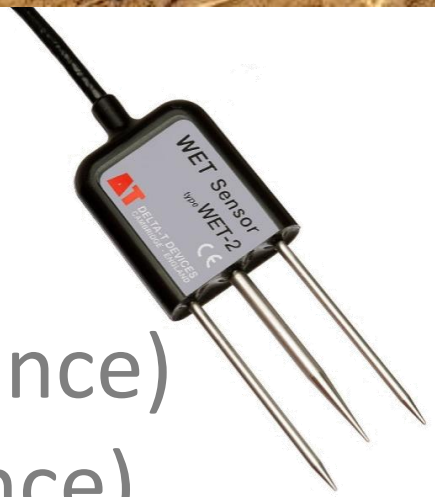




Images from NASA, JPL-Caltech, Goddard SPC, and Bitmoji

Ground Soil Water Sensors

- All are "Indirect Methods"
  - Neutron Thermalization
  - Gamma-Ray attenuation
  - Time-Domain Reflectometry
  - Frequency-Domain Reflectometry (Capacitance)
  - Amplitude-Domain Reflectometry (Impedance)
  - Electrical Resistance



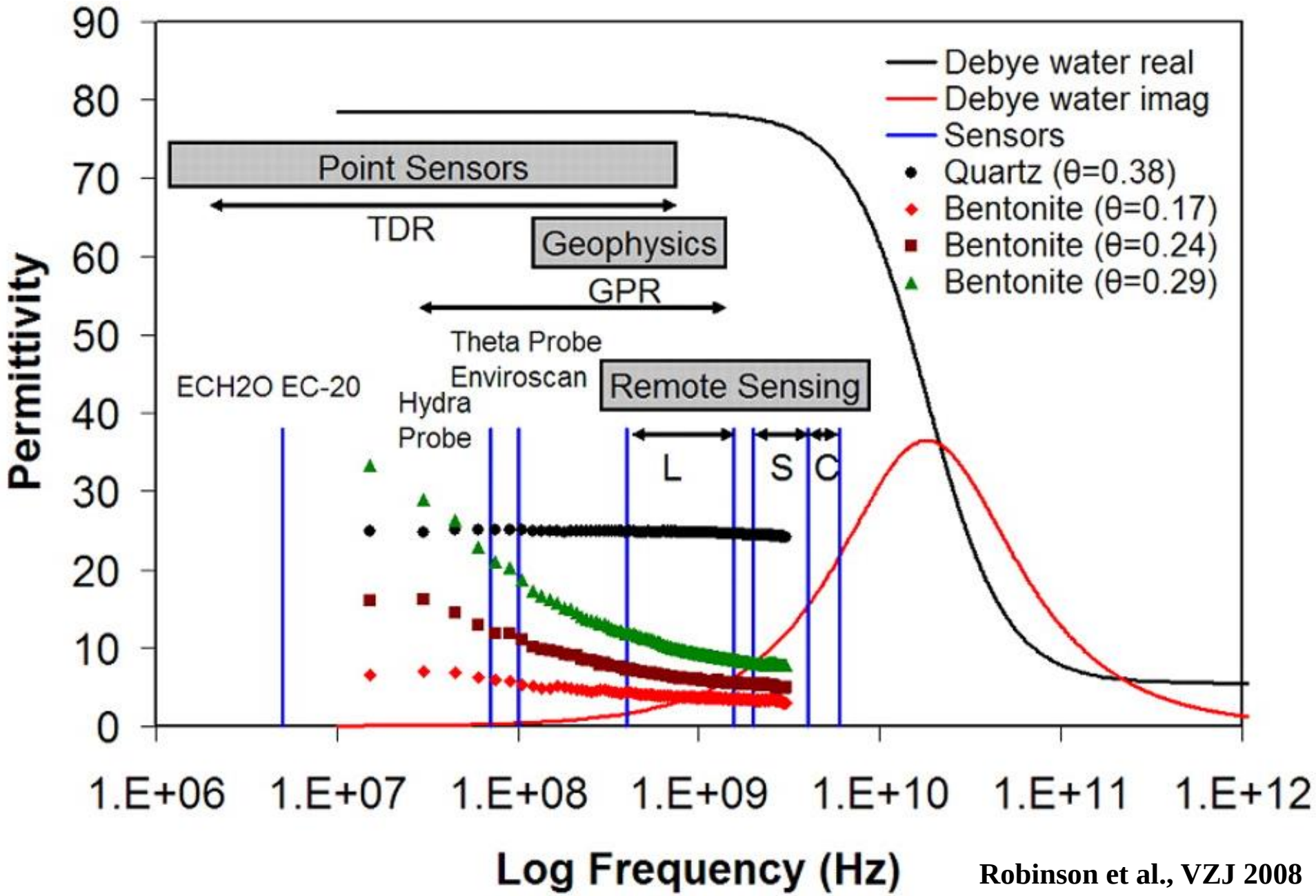
Dielectric permittivity

- Dielectric permittivity is a measure of how susceptible a material is to being polarized in the presence of an electrical field.
- A material with a high dielectric permittivity is generally polar.
- Because the individual atoms do not polarize or align instantly, there is a delay. Consequently, permittivity is frequency-dependent.

Dielectric Permittivity

Material	Relative permittivity ε_r
vacuum	1.0
air	1.0006
hexane	1.9
charcoal	1.5
wood (dry)	2-6
cereal grain	3-8
sand	3-5
water	**80**
ice	3

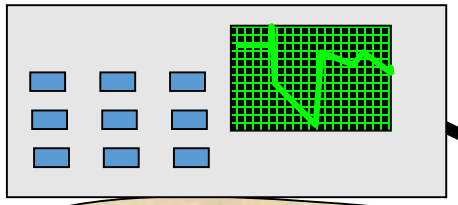
Around 20 °C and 1 kHz



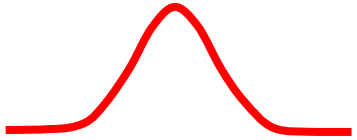
Robinson et al., VZJ 2008

TDR setup

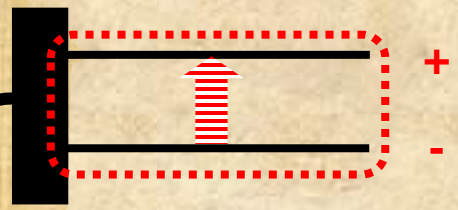
Cable Tester



1) A pulse is sent through the cable to the probe



2) The material between the needles is subjected to an EM gradient



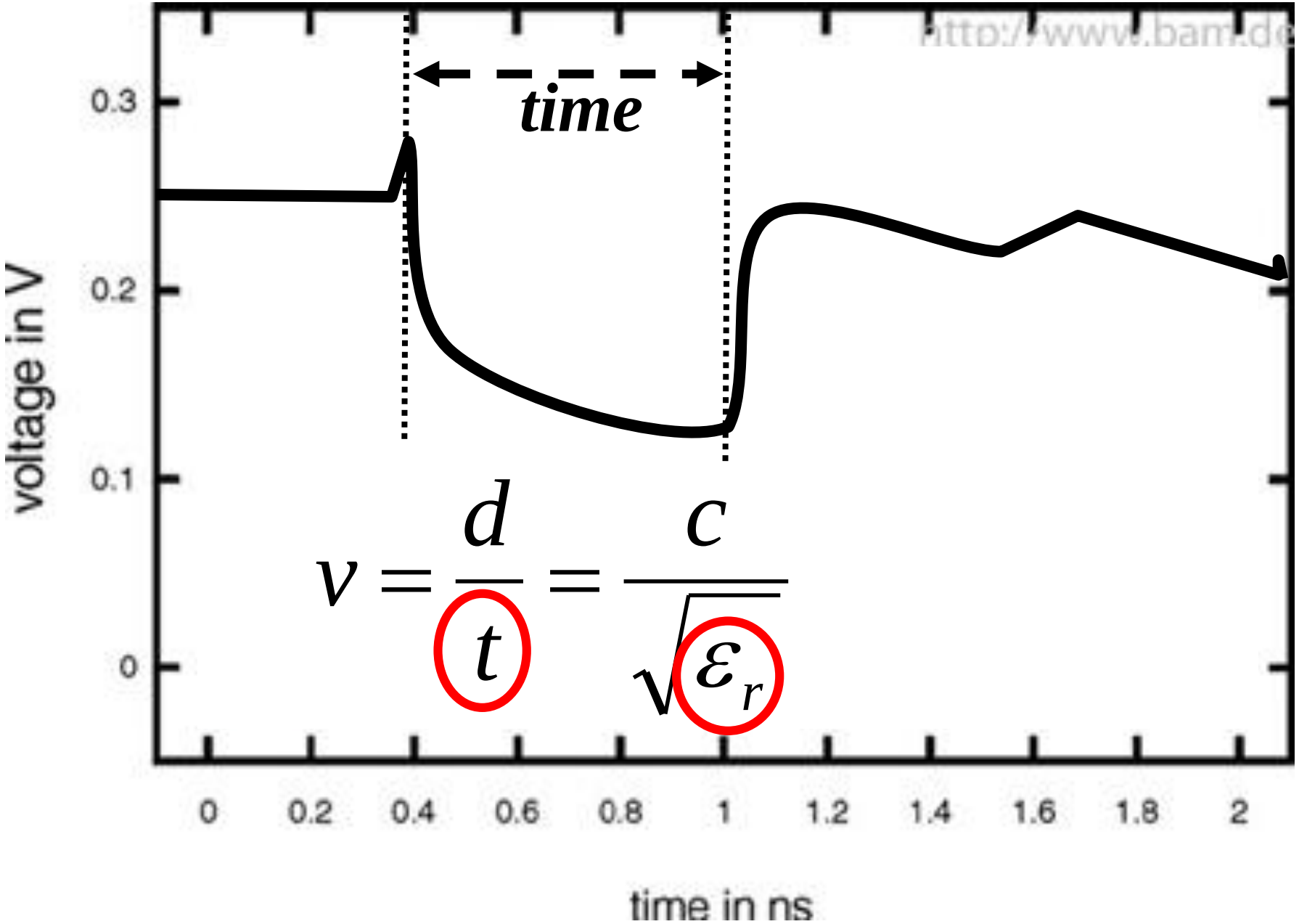
3) The pulse reflects off the ends of the needles.

4) The pulse also propagates through the soil at a velocity

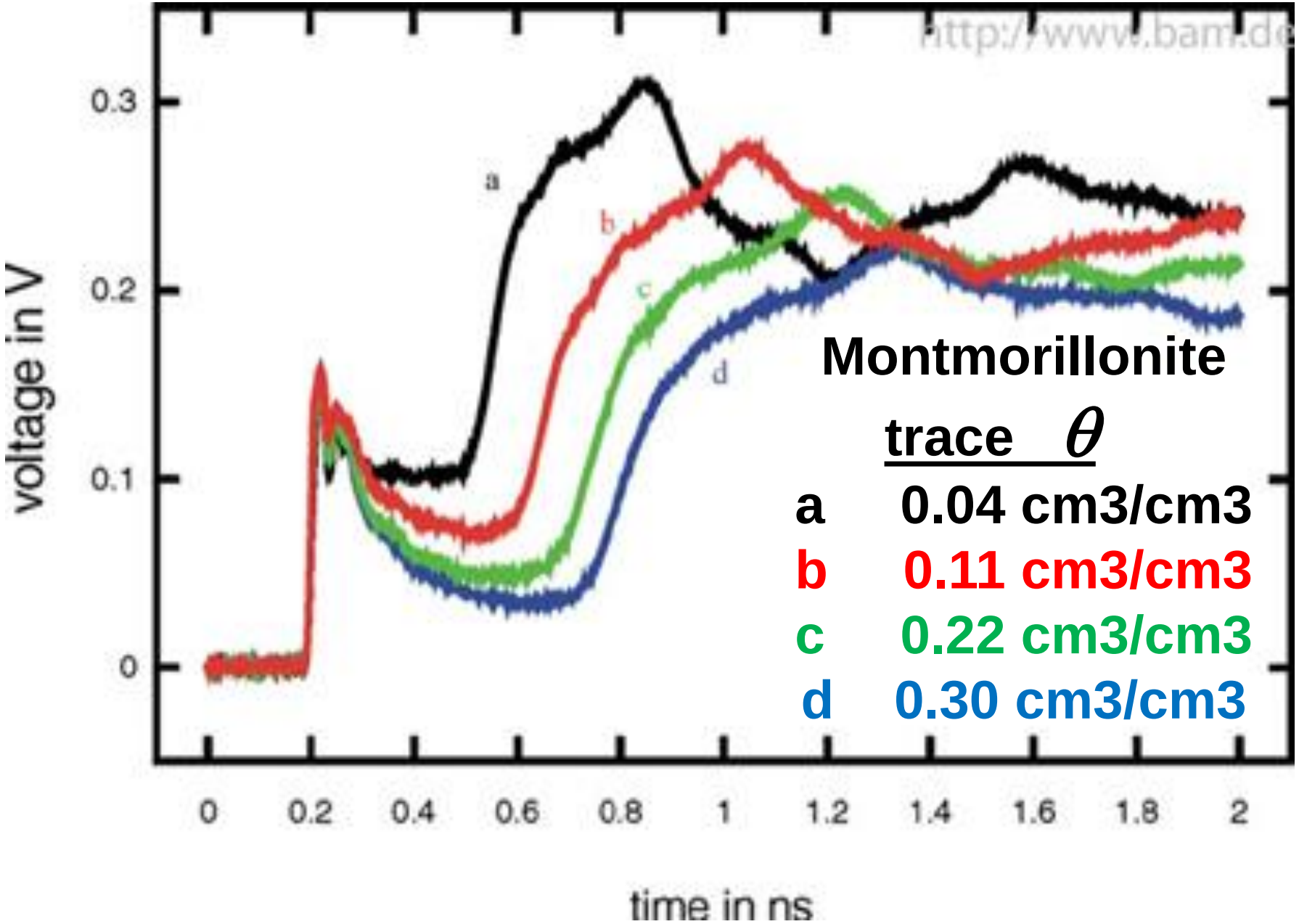
$$v = \frac{c}{\sqrt{\varepsilon_r}}$$

5) The returned pulse shows the effect of this delay

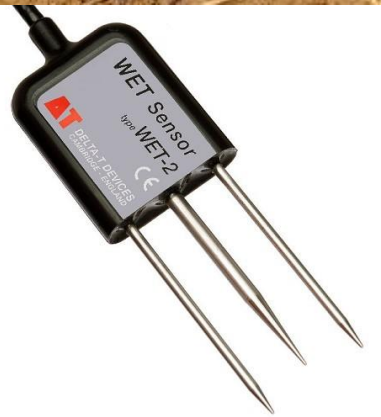
Animation courtesy of Dr. Dan Russell, Kettering University



$$v = \frac{d}{t} = \frac{c}{\sqrt{\varepsilon_r}}$$

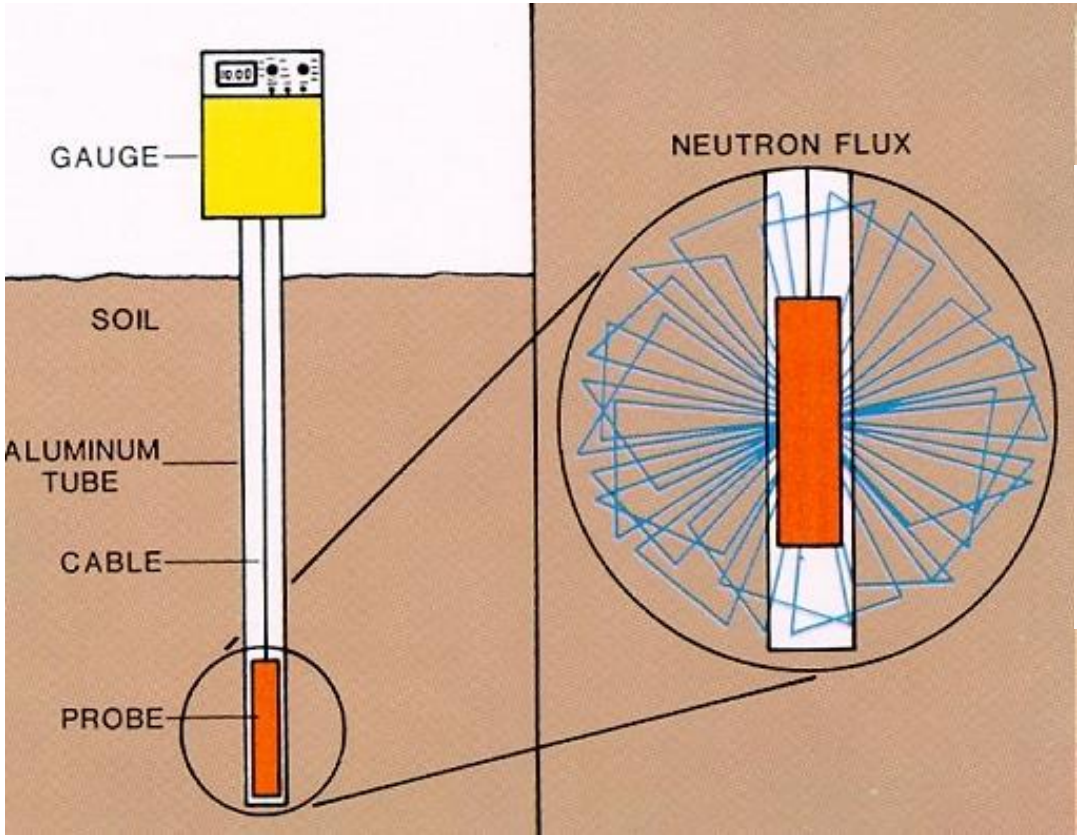

http://www.bam.de
voltage in V
0.3
0.2
0.1
0
a
b
c
d
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
time in ns
Montmorillonite
trace θ
a 0.04 cm3/cm3
b 0.11 cm3/cm3
c 0.22 cm3/cm3
d 0.30 cm3/cm3

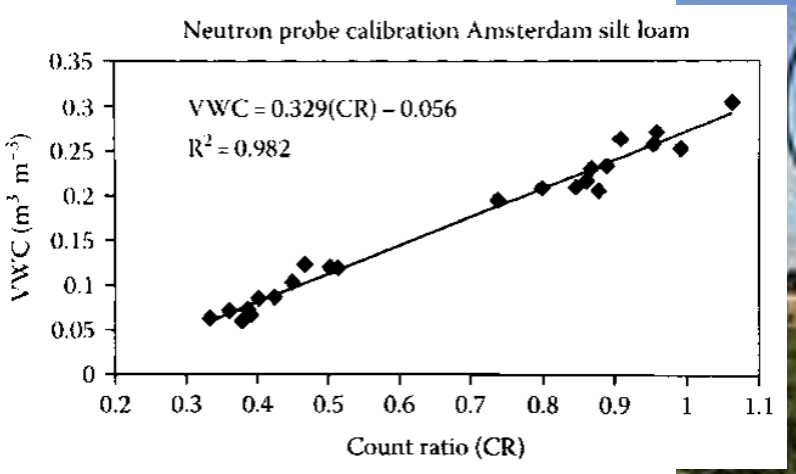
Time Domain
Frequency Domain
Amplitude Domain

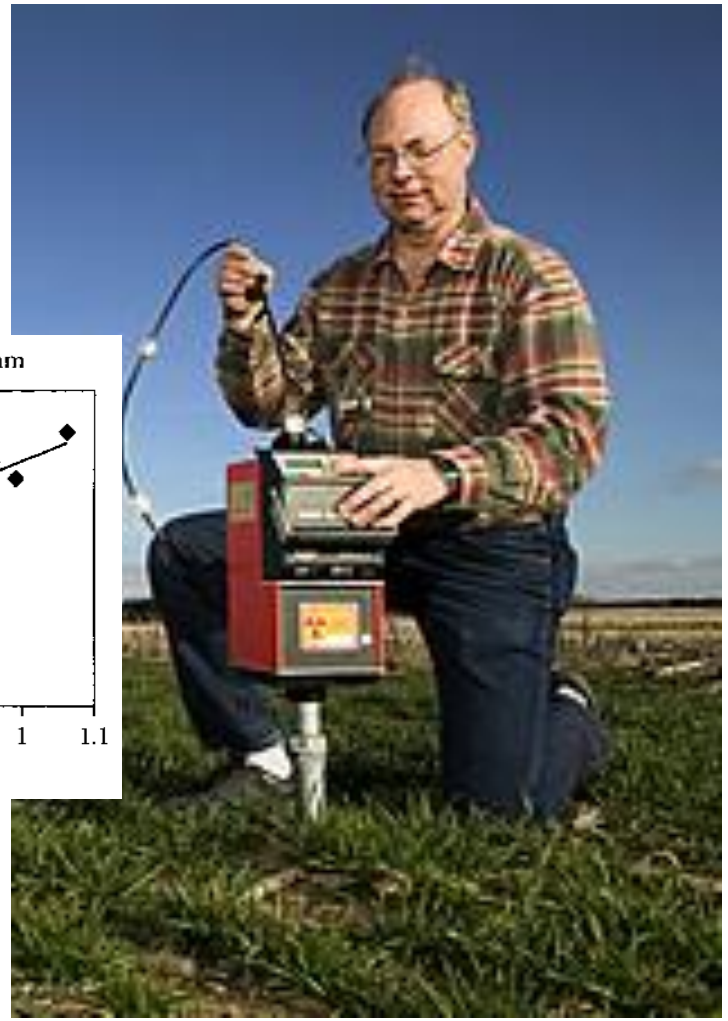


Neutron Scattering/Thermalization

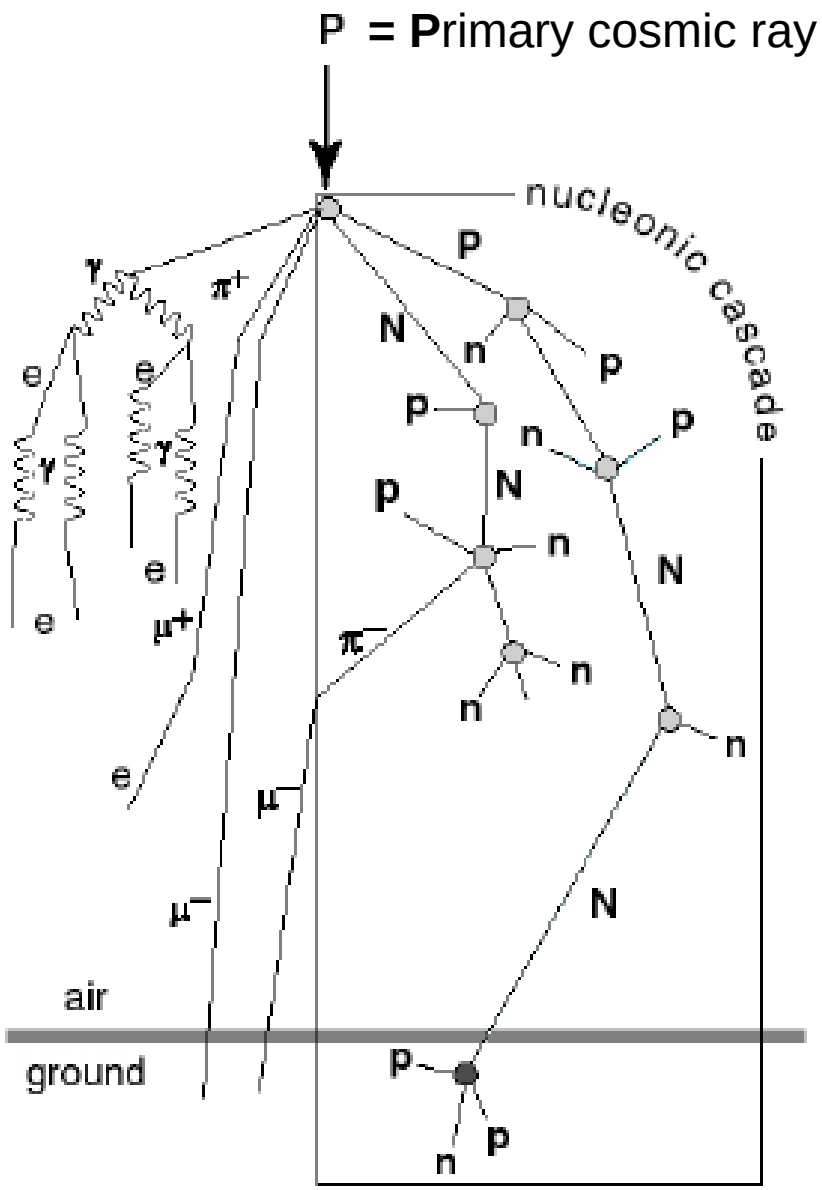
- Emits fast neutrons (1000 miles per second!)
- Impacts with hydrogen atoms thermalizes neutrons (1.7 miles per second)
- Record the count ratio
- Convert to soil water content

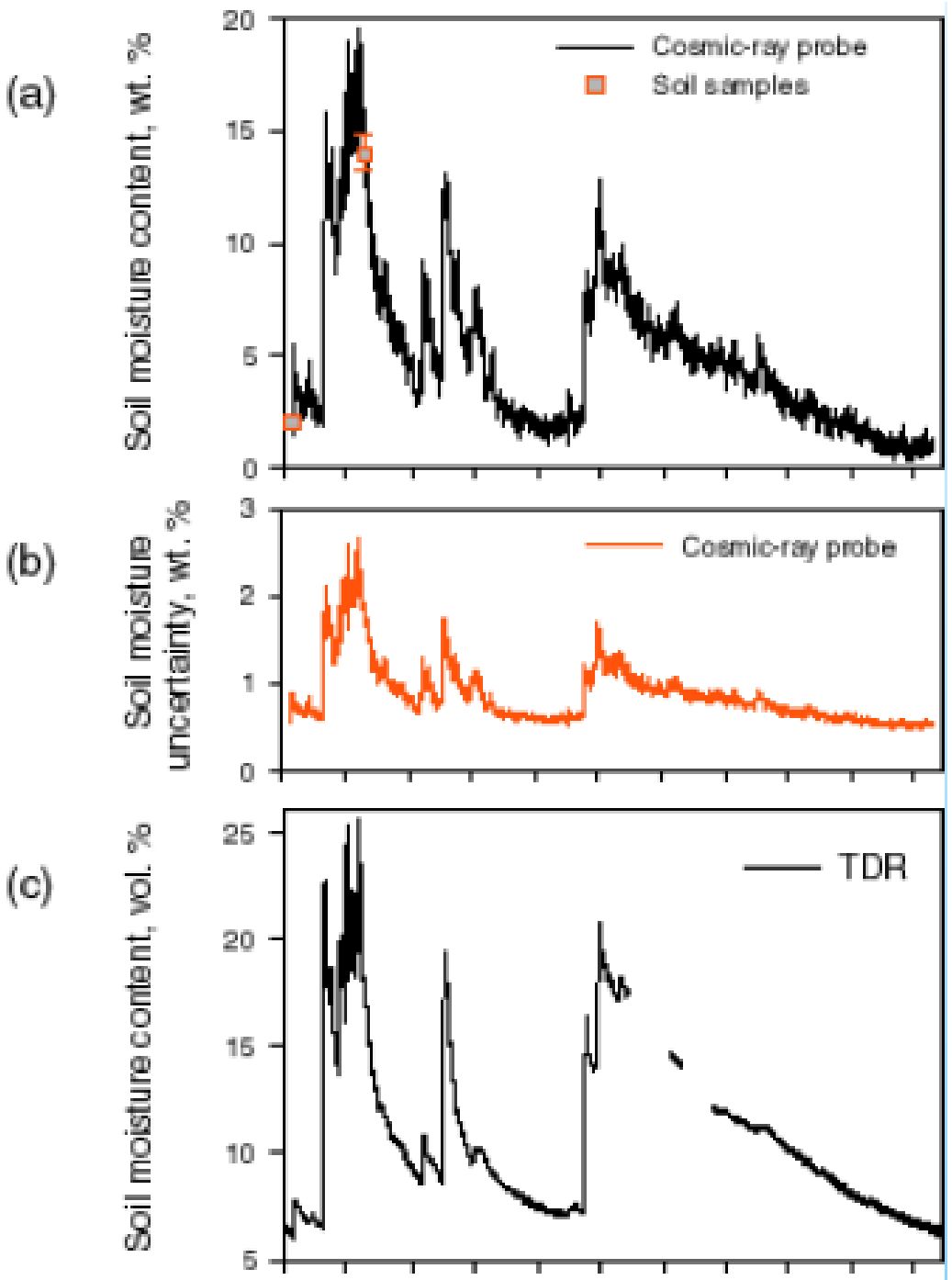






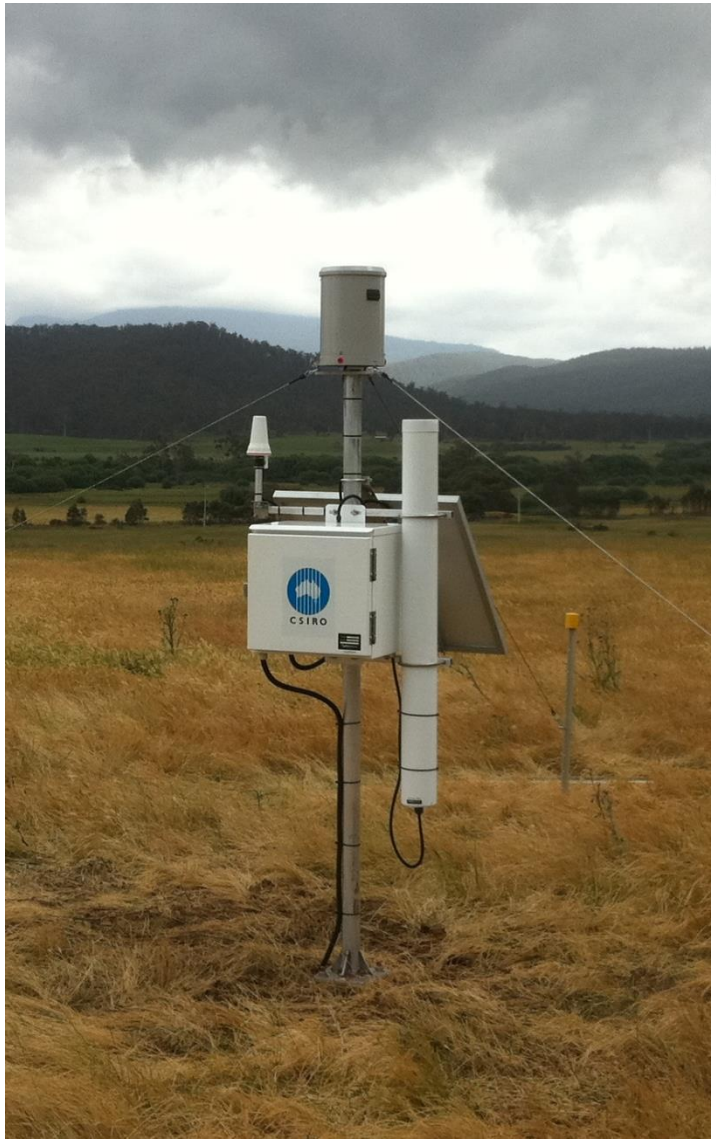
The New Way to use Neutrons

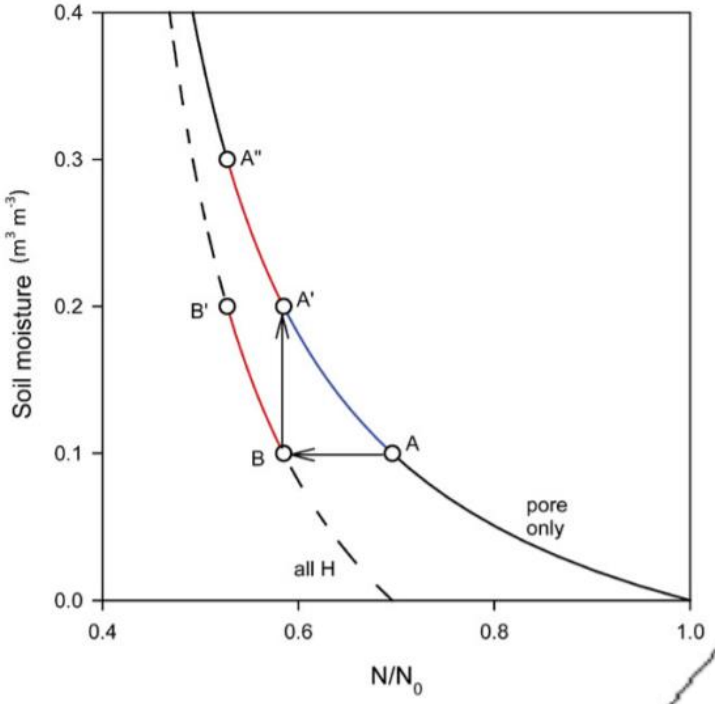




Zreda et al

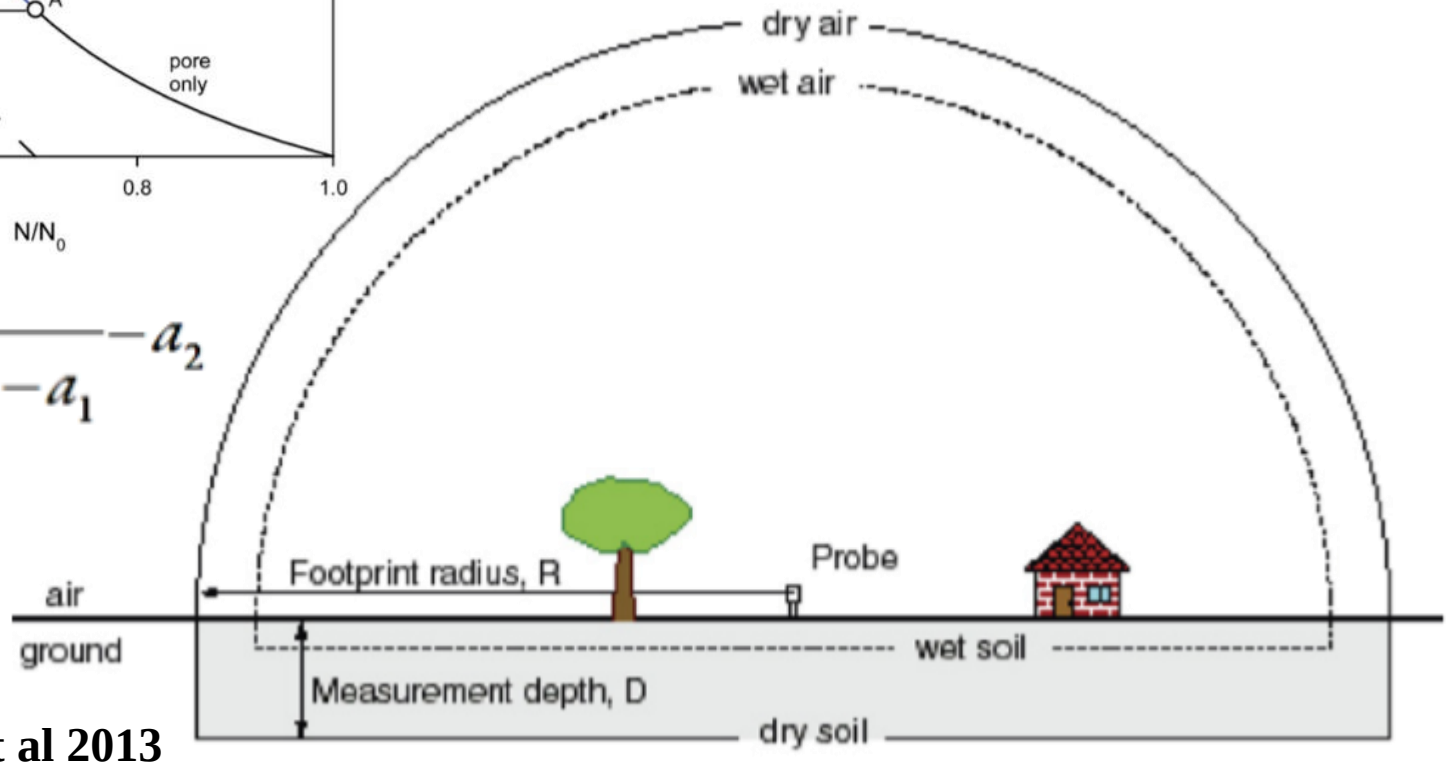
The New Way to use Neutrons





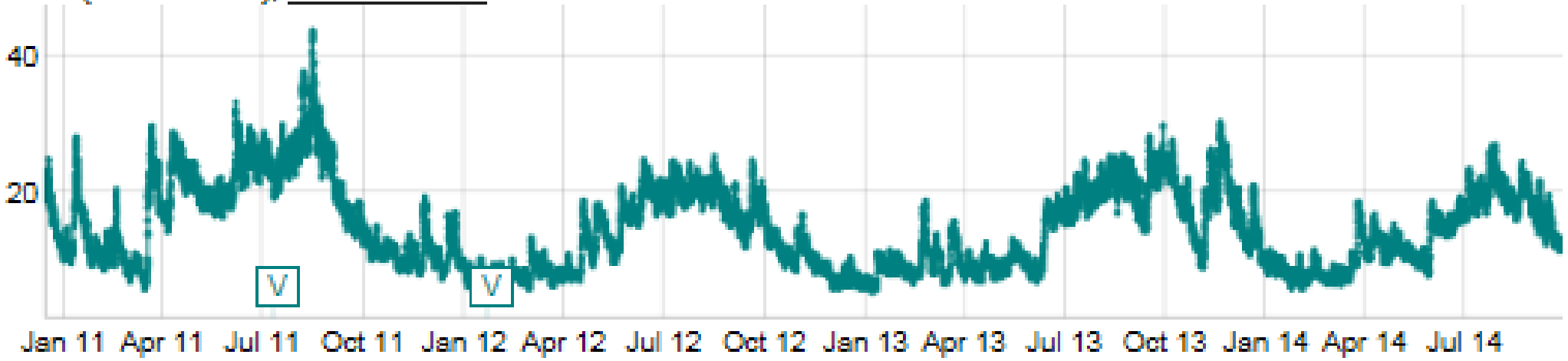
$$\theta = \frac{a_0}{(N/N_0) - a_1} - a_2$$

- Installs above ground
- Aerial average
- Footprint about 80 acres
- Needs calibration
- Measures more than water

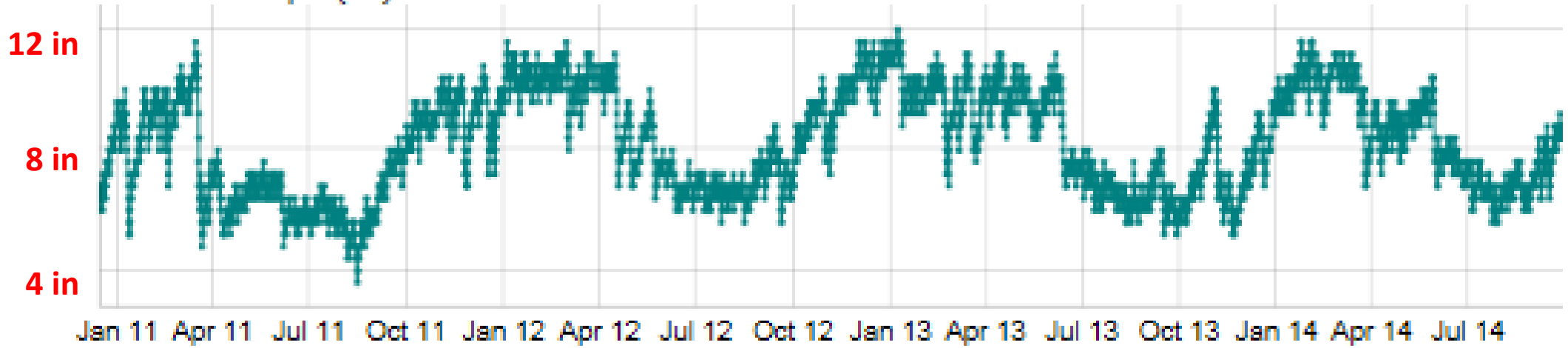


Ochsner et al 2013

Soil Moisture (% Volumetric), Calibration Data



Effective Measurement Depth (cm)



Level 1 Data (Plots) Level 2 Data Level 3 Data Data Levels Excel (.xls) Matlab (.mat) Python (.pkl)

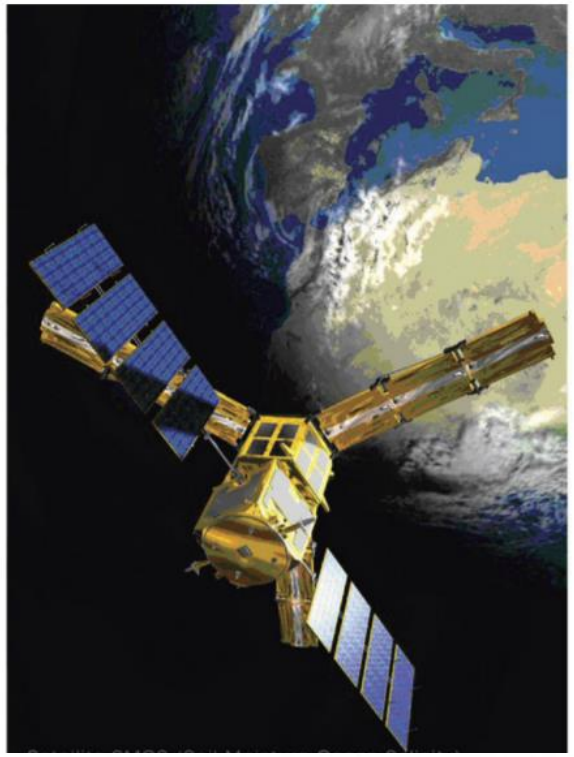
COSMOS data is research level and subject to change.

Remote Sensors for Soil Water

Several main satellites used:

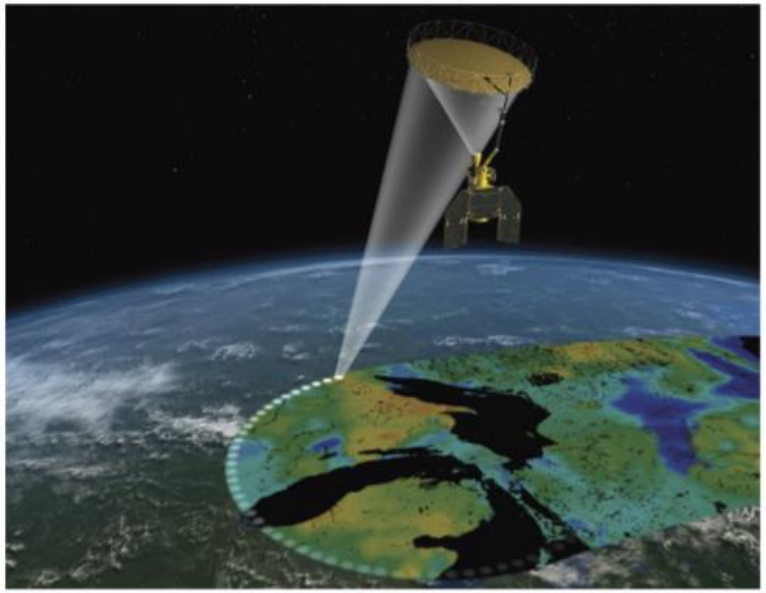
Soil Moisture and Oceanic Salinity (SMOS)

- 2009 launch
- Passive observation of L-band EM frequency (1.4 GHz)
- Pixels of 25 by 25 miles
- 3-day retrieval

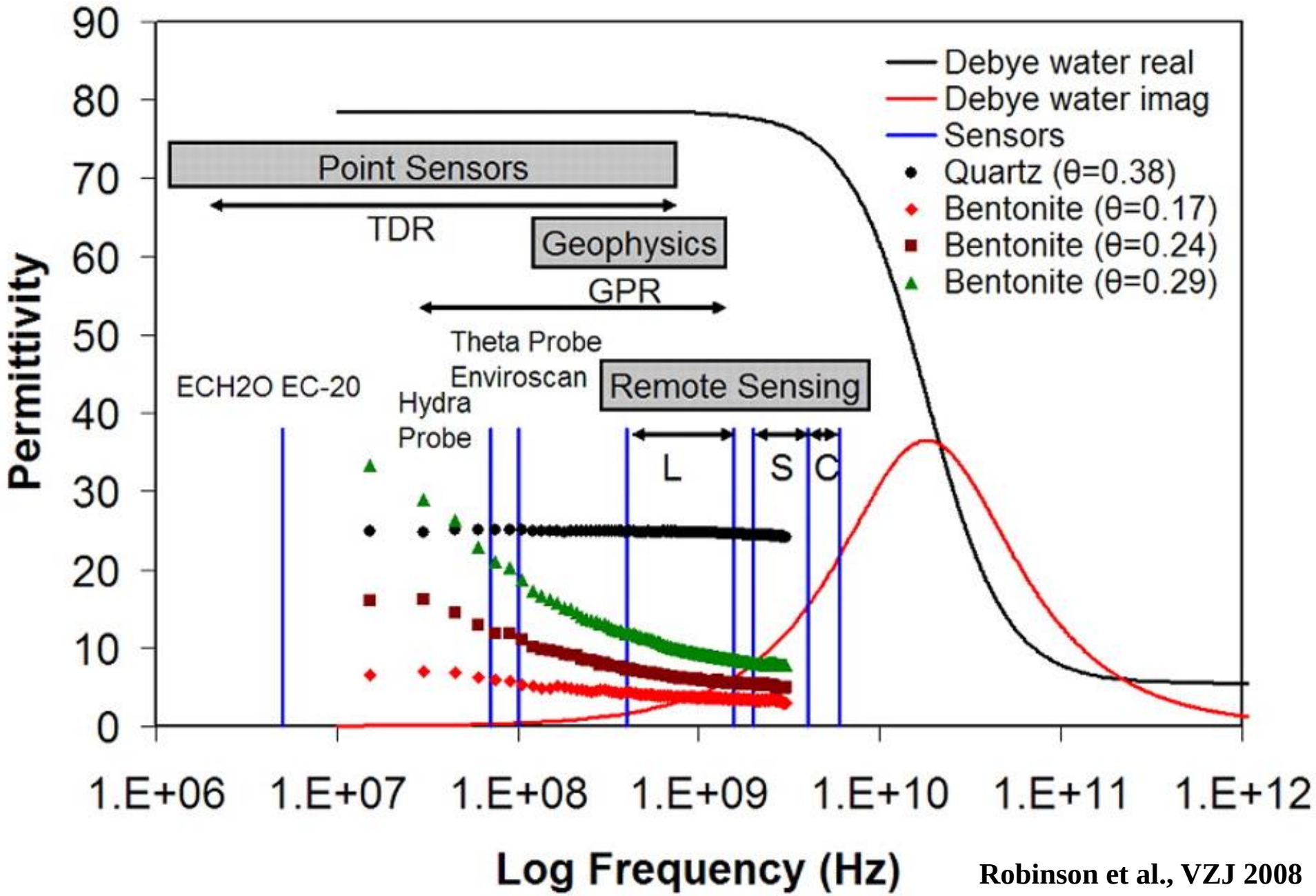


Soil Moisture Active/Passive (SMAP)

- 2015 launch
- Includes Active L-band EM sensor
- Pixels of 6 by 6 miles
- 3-day retrieval



Sources: Ochsner 2013; Centre d'Etudes Spatiales de la BIOsphere, [CESBIO]



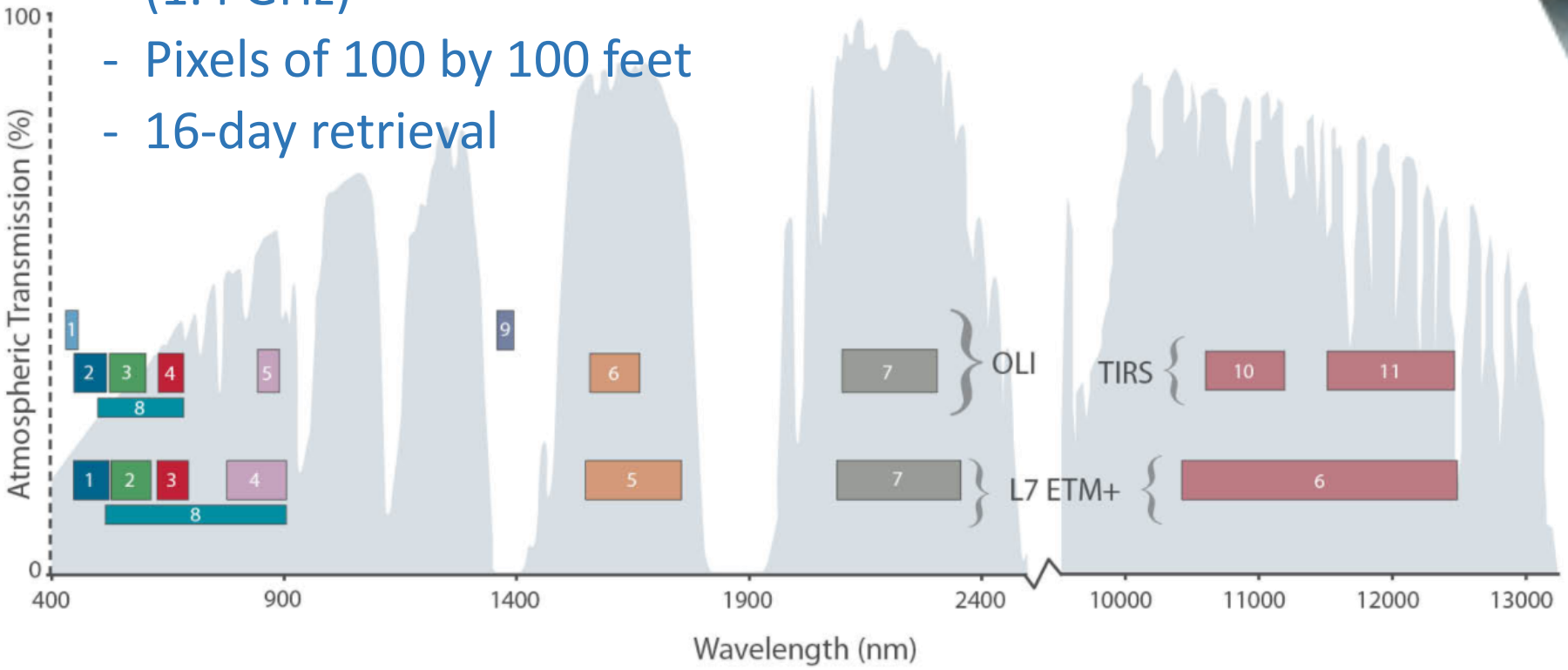
Robinson et al., VZJ 2008

Remote Sensors for Soil Water

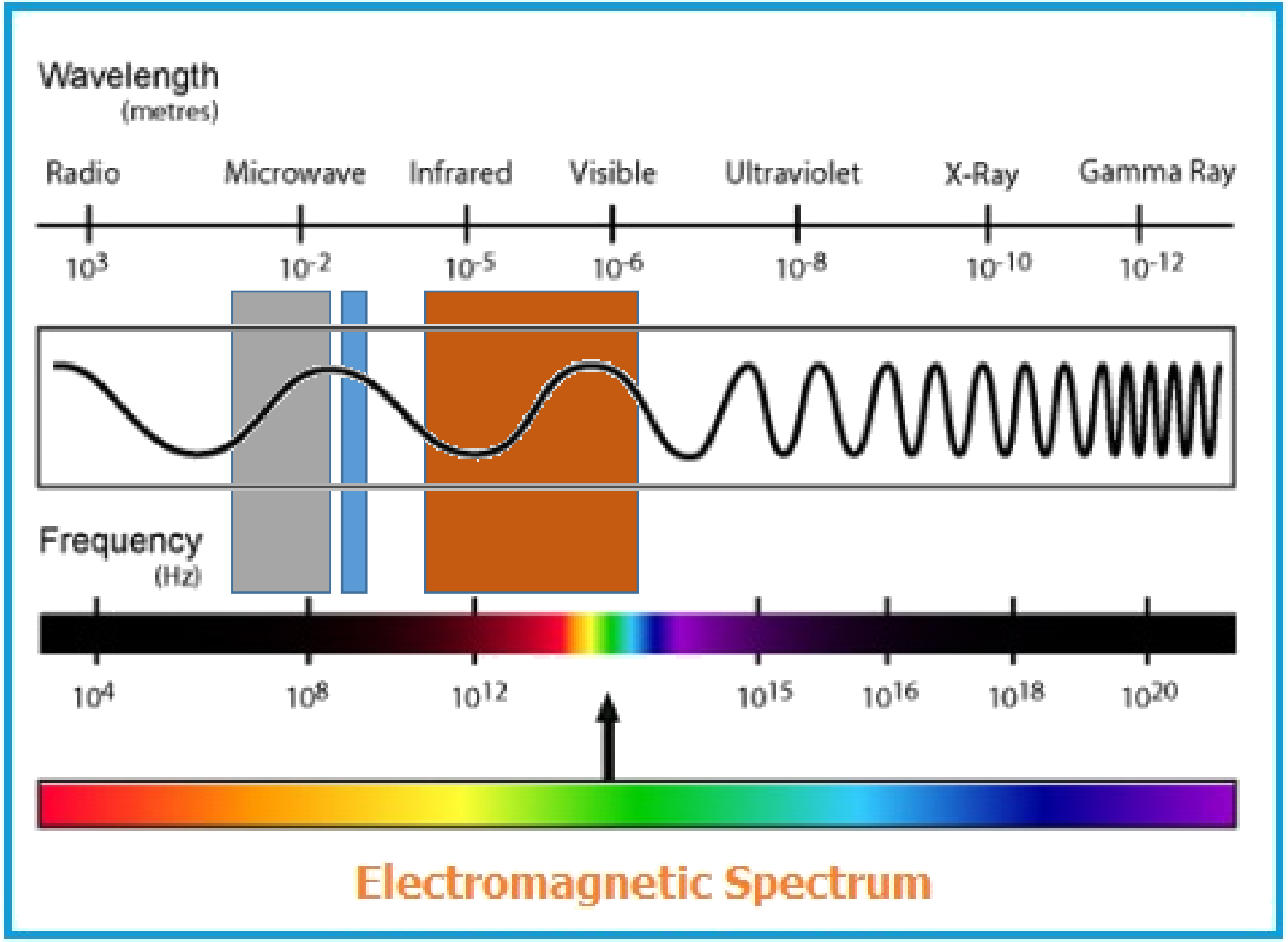
Several main satellites used:

Landsat (9 satellites so far)

- Landsat 8 launch in 2013; Landsat 9 launch in Sept 2021
- Passive observation of 11 different bands EM frequency (1.4 GHz)
- Pixels of 100 by 100 feet
- 16-day retrieval



Sources: L.Rocchio and J.Barsi, NASA



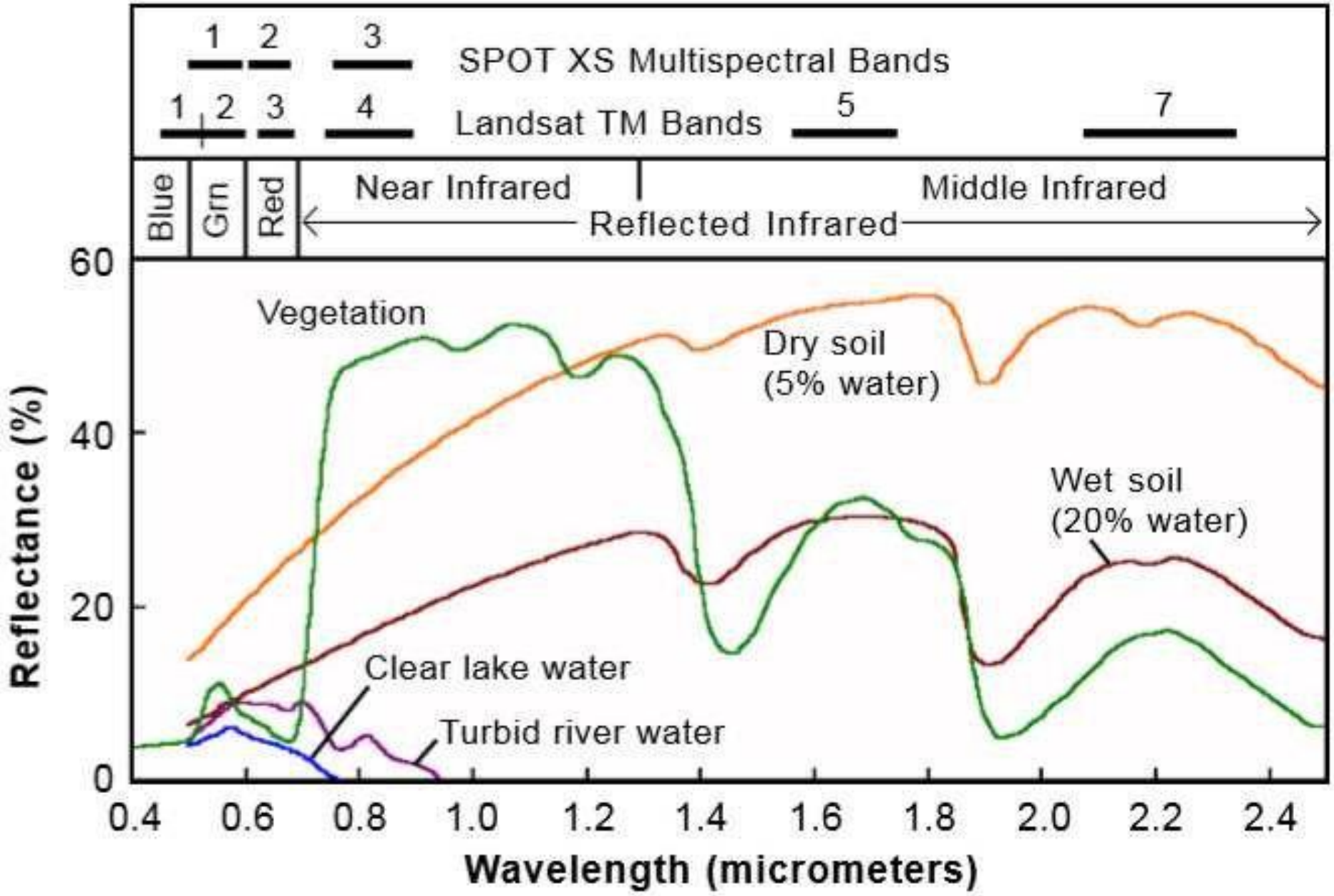
Ground sensors

SMOS, SMAP

Landsat

- Microwave range is sensitive to changes in soil moisture and has deeper soil penetration than shorter wavelengths
- Visible and Infrared ranges are susceptible to attenuation due to the atmosphere and vegetation

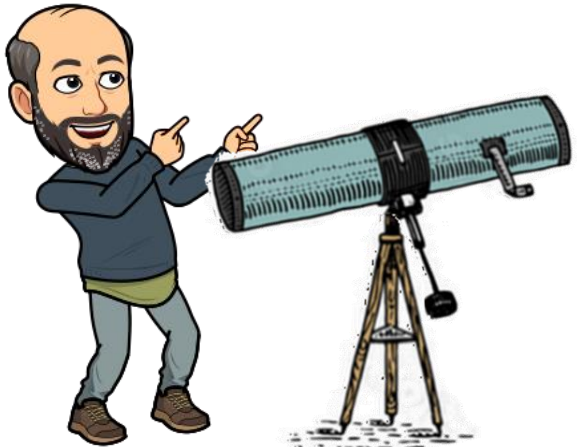
Source: Mondal 2018

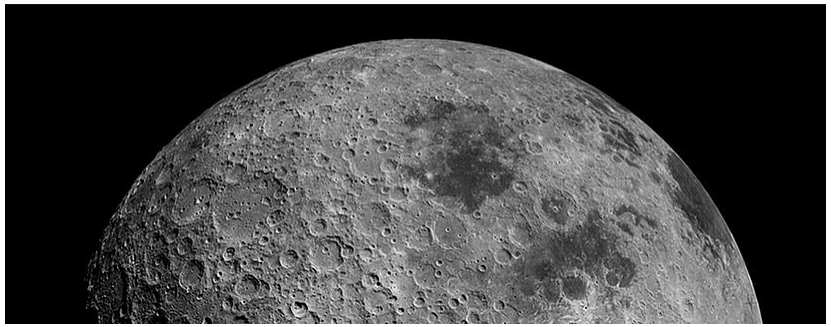


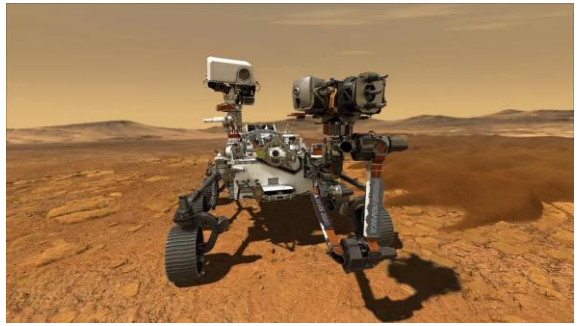
Source: Mondal 2018

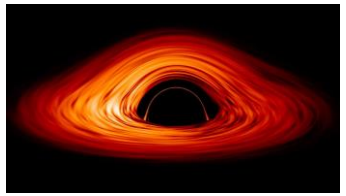
To finish up…

- Calibrating ourselves for realistic expectations out of precision systems?

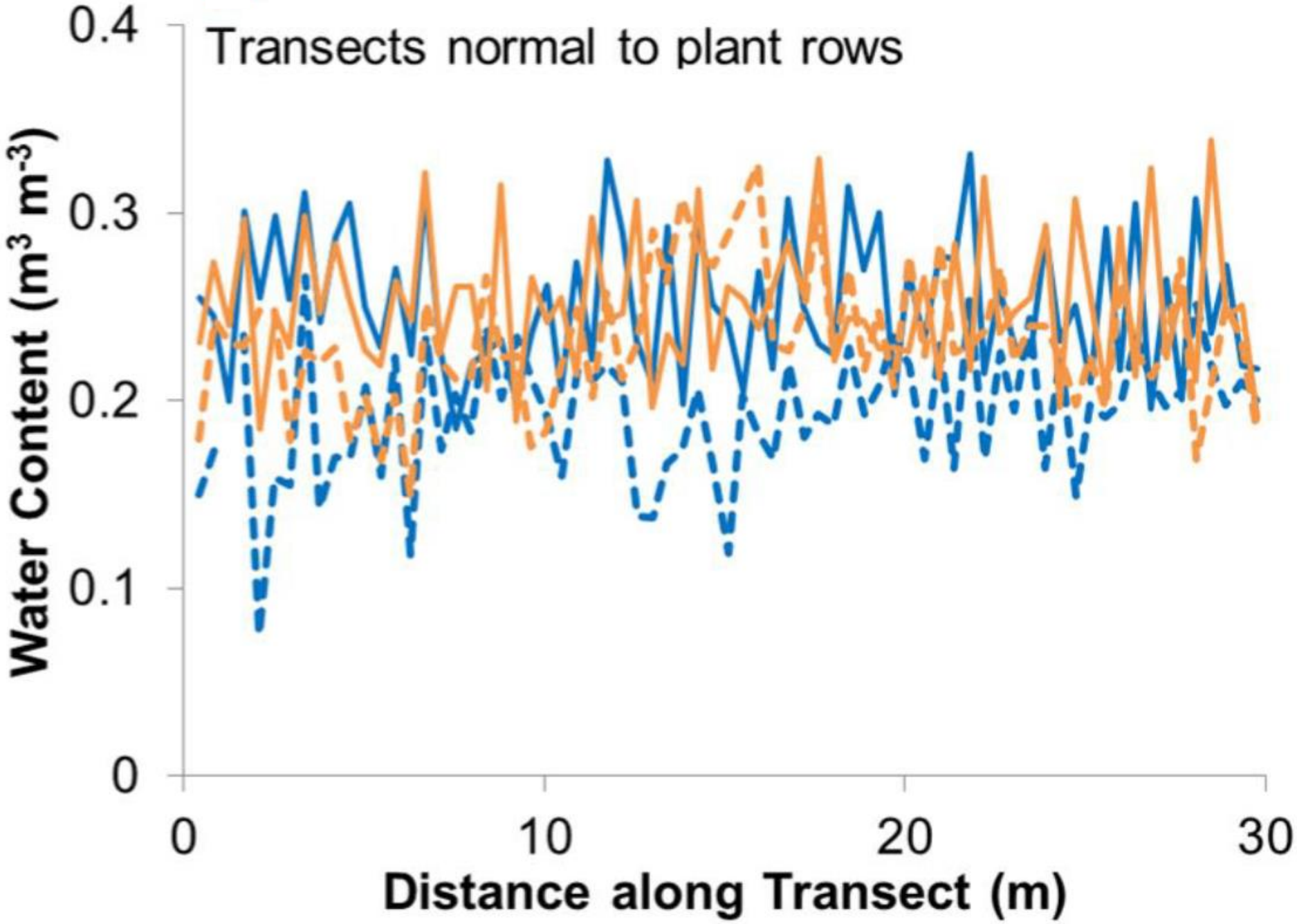


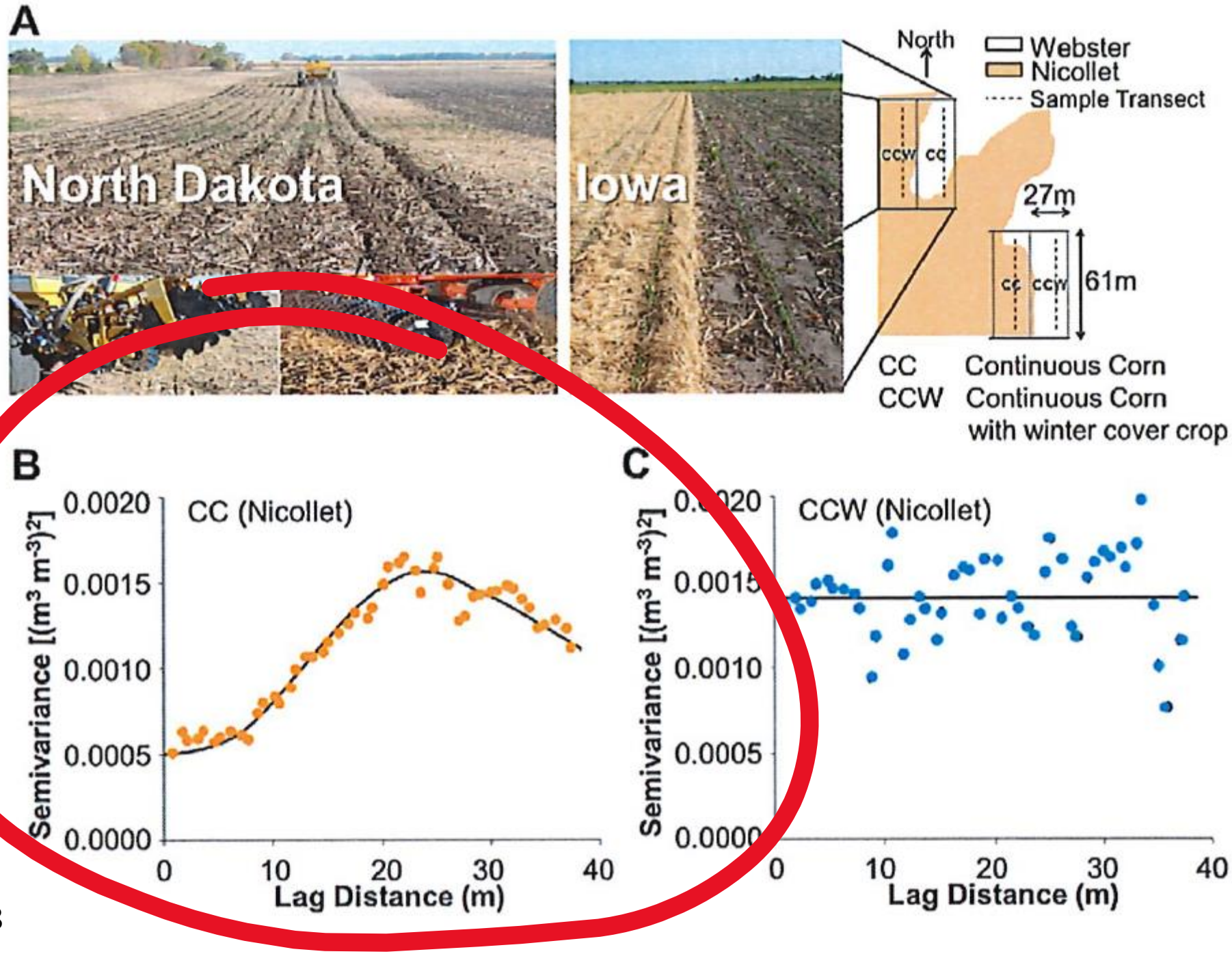






Images from NASA, JPL-Caltech, Goddard SPC, and Bitmoji

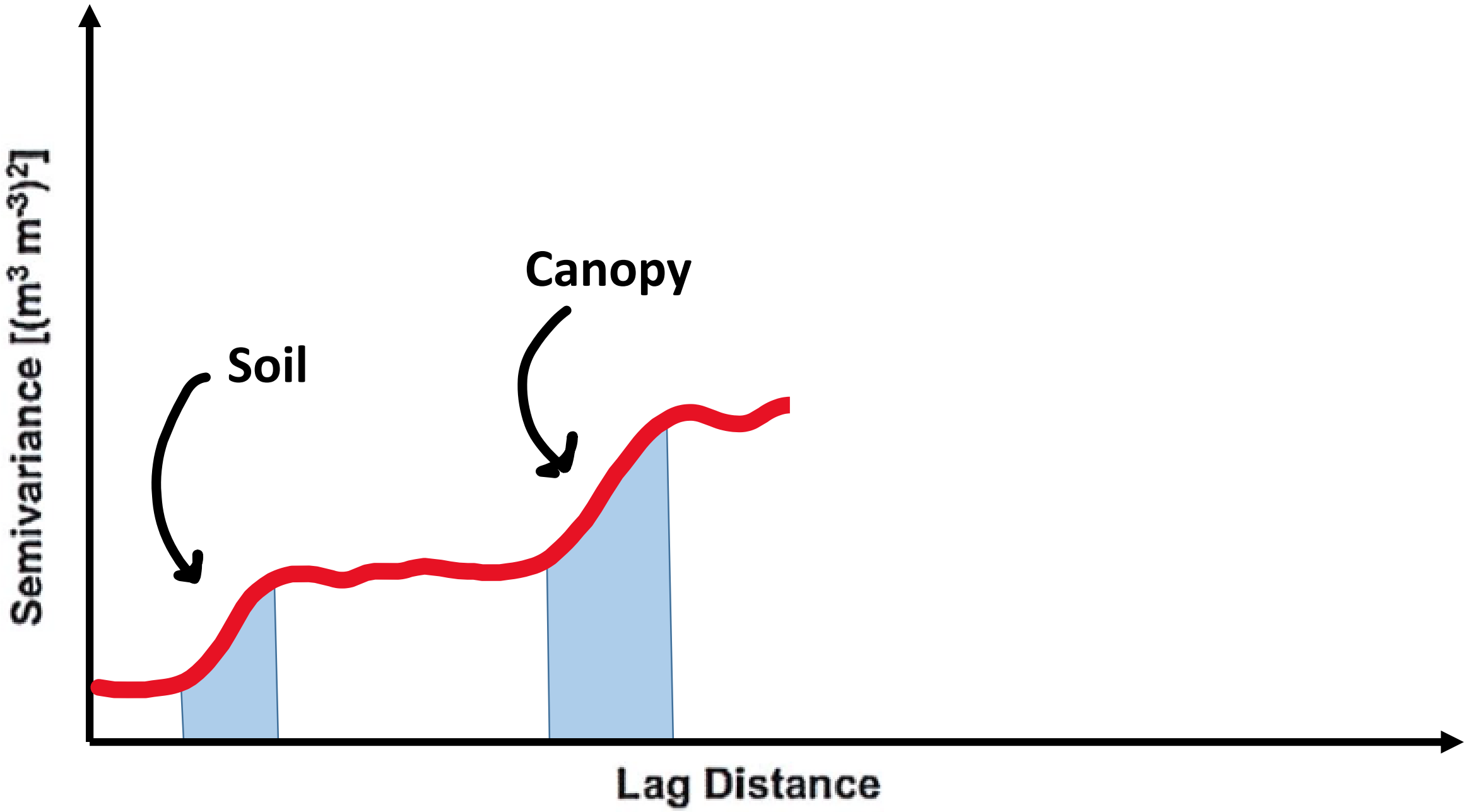

Transects normal to plant rows
Water Content (m3 m-3)
0.4
0.3
0.2
0.1
0
0
10
20
30
Distance along Transect (m)

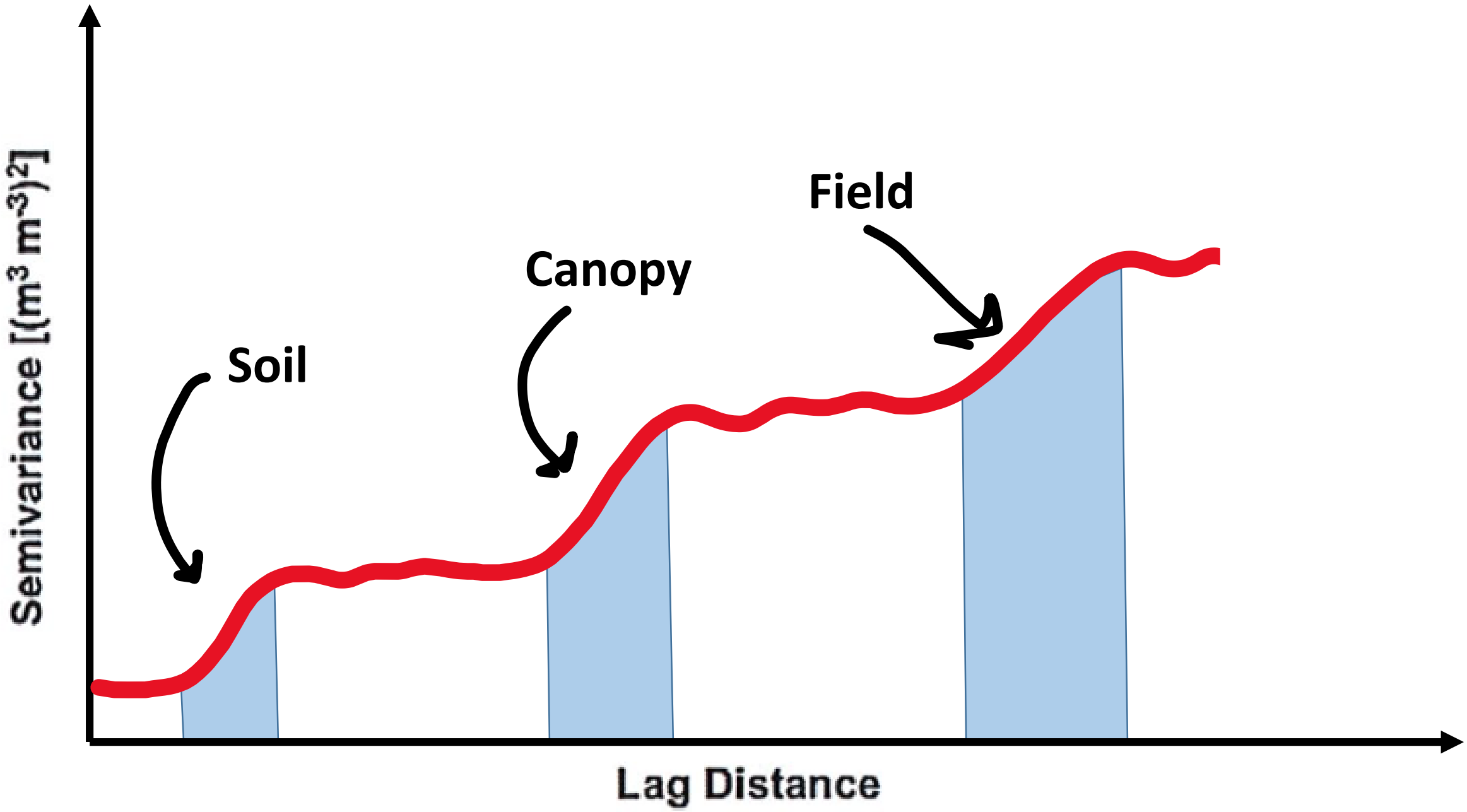


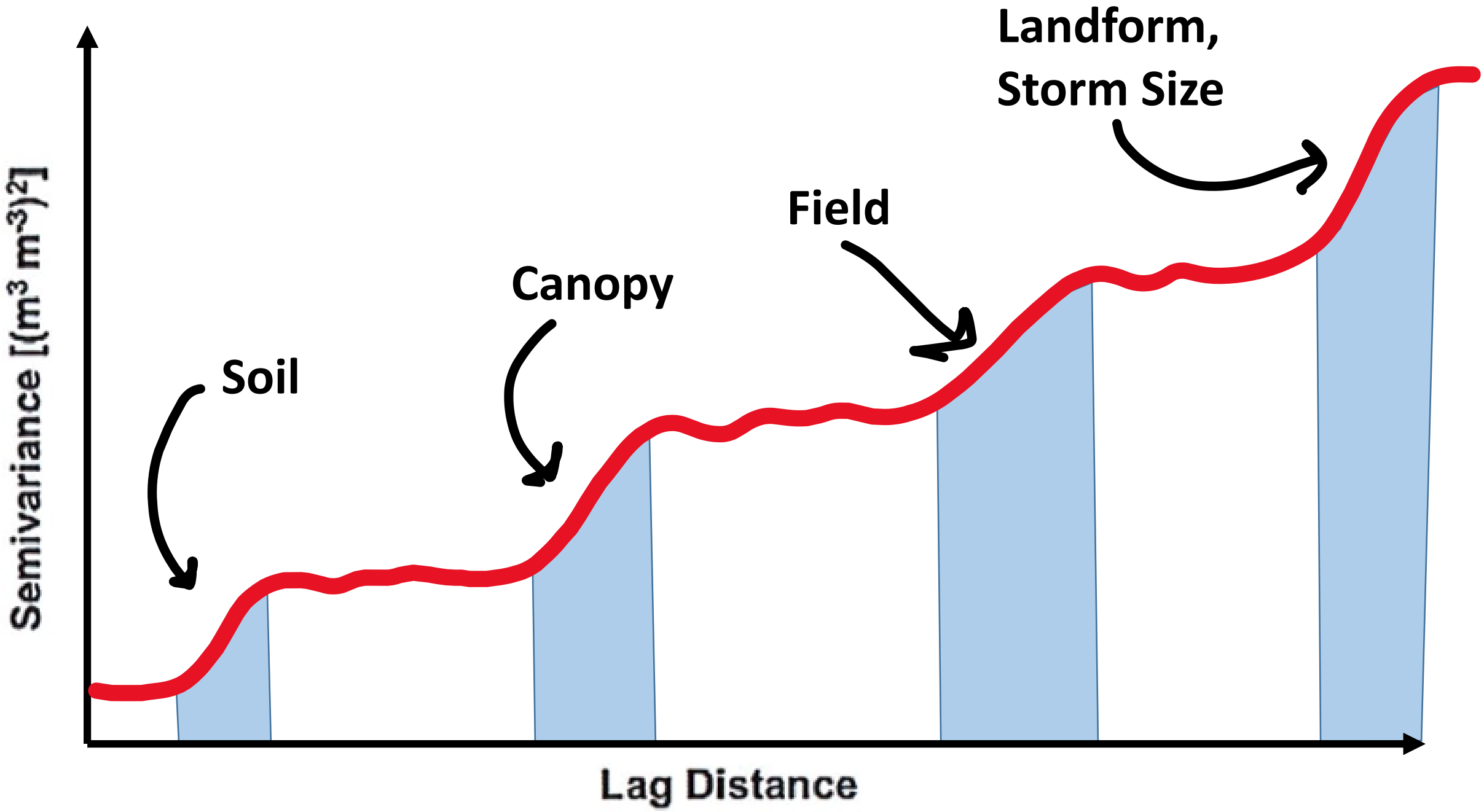
Daigh et al., 2018

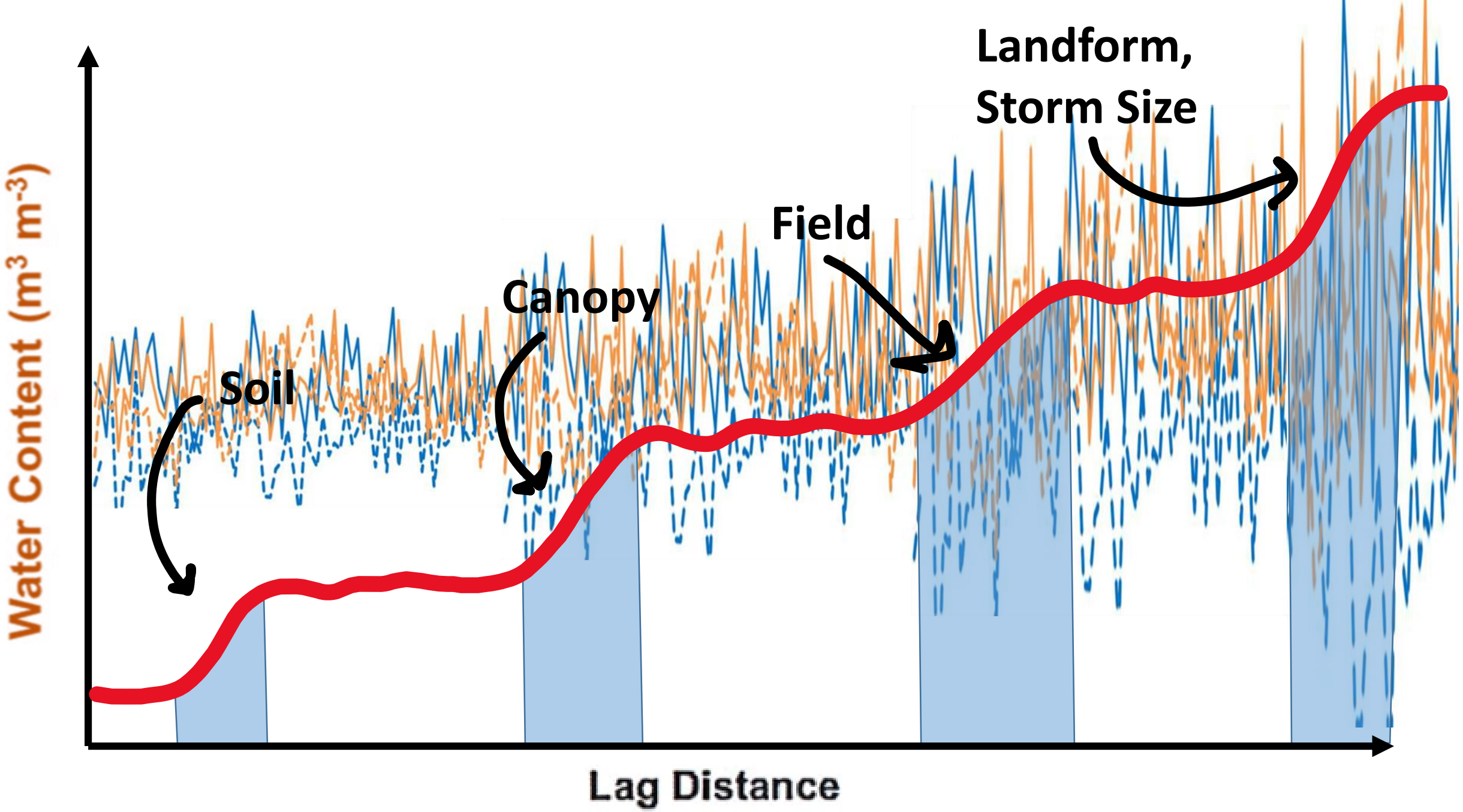

Semivariance [(m3 m-3)2]
Soil
Lag Distance


Semivariance [(m³ m⁻³)²]
Soil
Lag Distance


Semivariance [(m³ m⁻³)²]
Soil
Canopy
Lag Distance


Semivariance [(m³ m⁻³)²]
Soil
Canopy
Field
Lag Distance


Landform,
Storm Size
Field
Canopy
Soil
Semivariance [(m³ m⁻³)²]
Lag Distance


Landform,
Storm Size
Field
Canopy
Soil
Water Content (m^3 m^{-3})
Lag Distance

Perspectives to take with you:

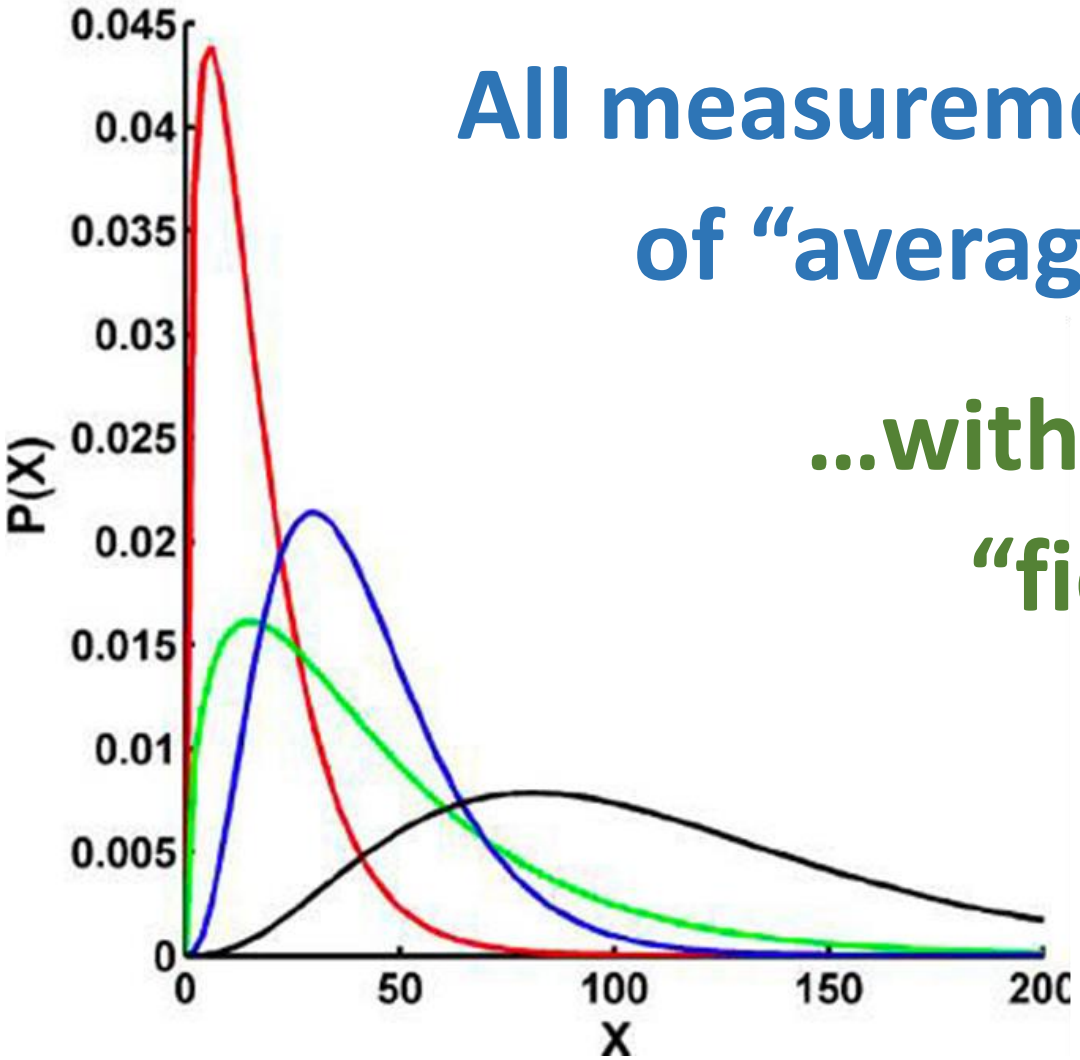
- **A single point measurement tells you little about soil water**

  …because it is naturally variable across spatial scales.

  …asking for exactness from an innately spatially variable scaling system is like asking what is south of the South Pole.

  …it is more like asking the percent of grey hairs on our heads. The extent (or scale) of your inquiry matters a lot.

Perspectives to take with you:



All measurements are innately a form of "averaging" or "weighting"

…within the method's "field of view"

Source: Kozak 2020

Perspectives to take with you:

- **We innately want precision and accuracy**

  …but we almost always "over-fit" our expectations when we operate on closed-box systems

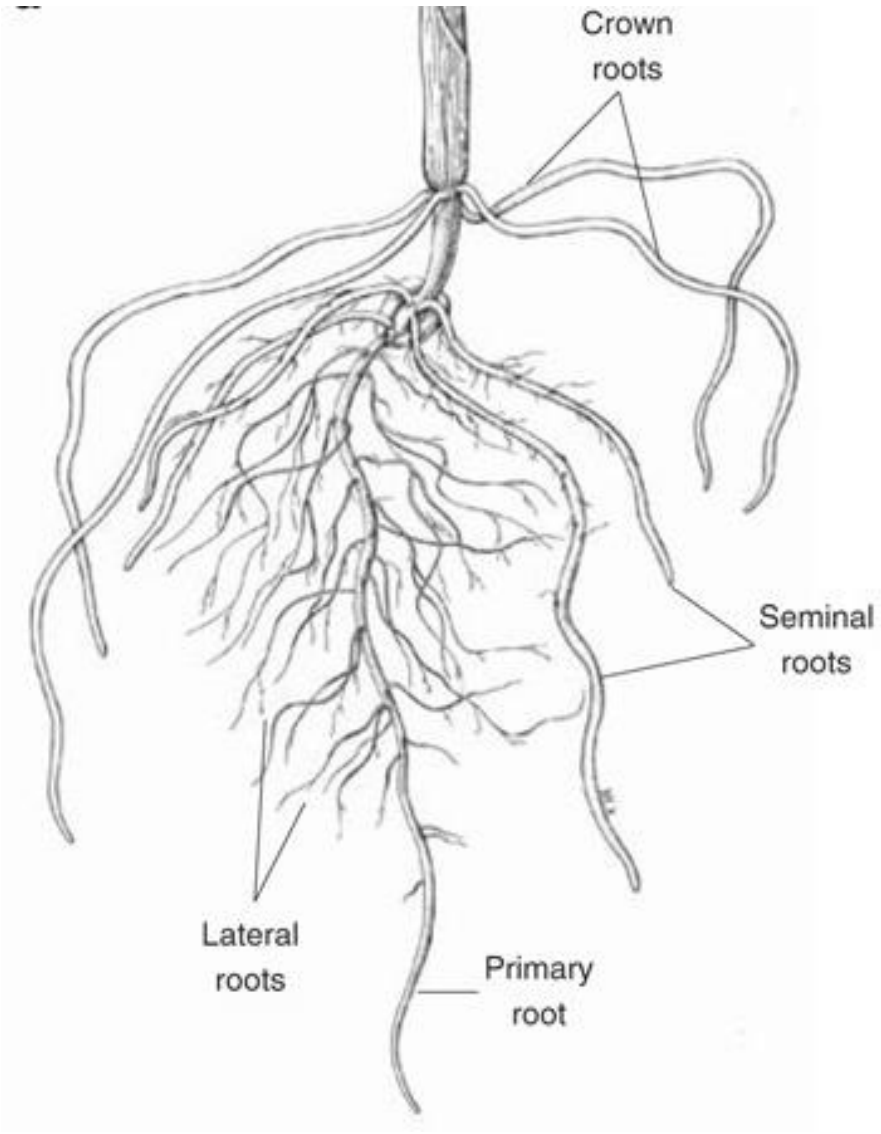
Source: Twitter; unknown creator

Perspectives to take with you:

- **What scale matters to you?**

  …Individual plants have a generally large root zone that can "compensate" for surpluses and deficient in the root zone

  …Equipment passes are largely influenced by vertical stratification of water and hillslope positions



Source: Hochholdinger 2009

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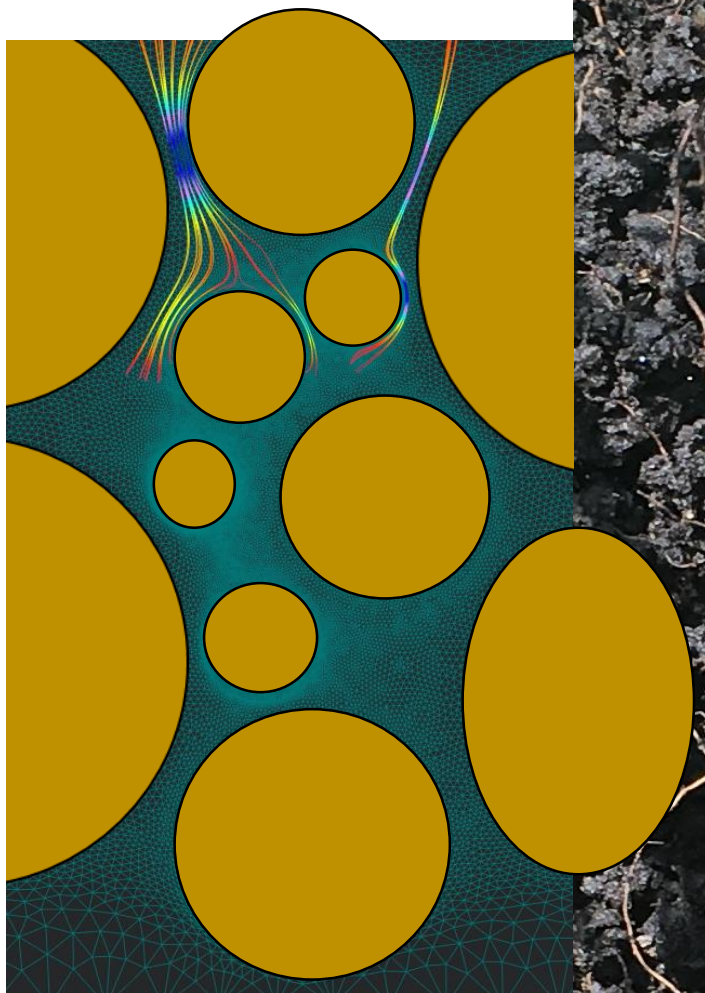

Cartoons created in Bitmoji; Photo and Simulation by Aaron Daigh