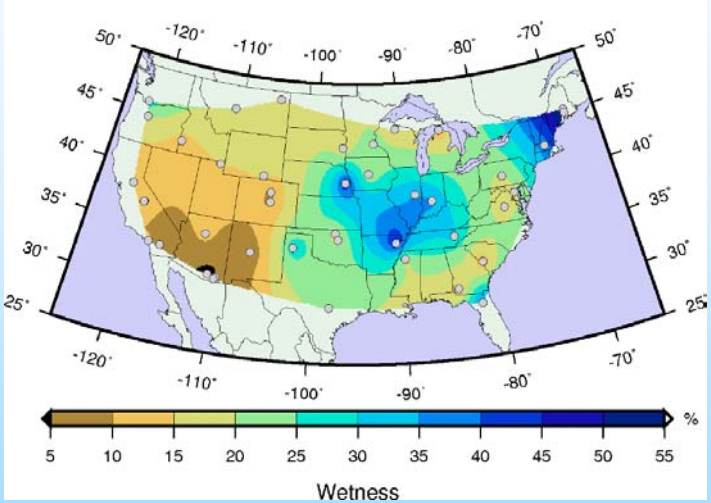
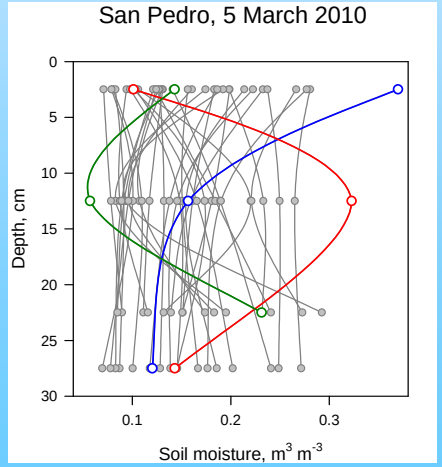
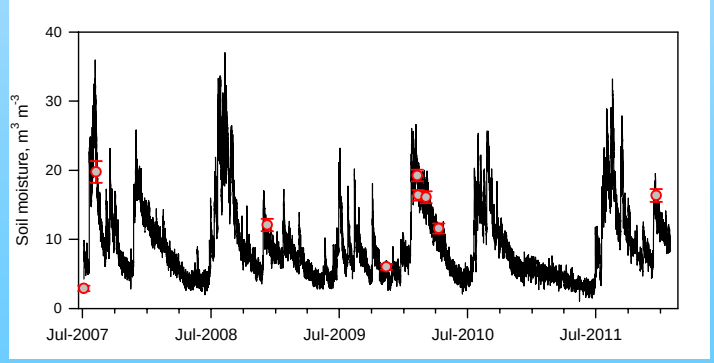
Soil moisture monitoring using cosmic-ray neutrons

Potential application to drought early warning

Marek Zreda, *(University of Arizona)*







Elements of presentation

(1) Brief description of purpose and applications of COSMOS

(2) Extent (including map)

- (i) COSMOS-US
- (ii) Global COSMOS

(3) Methods

- (i) Rationale and advantages
- (ii) Cosmic-ray neutron sensing

(4) Proposal specific to NIDIS-NOAA drought monitoring initiative

Purpose and applications of COSMOS

To create a US network that will provide consistent soil moisture data

To expand globally

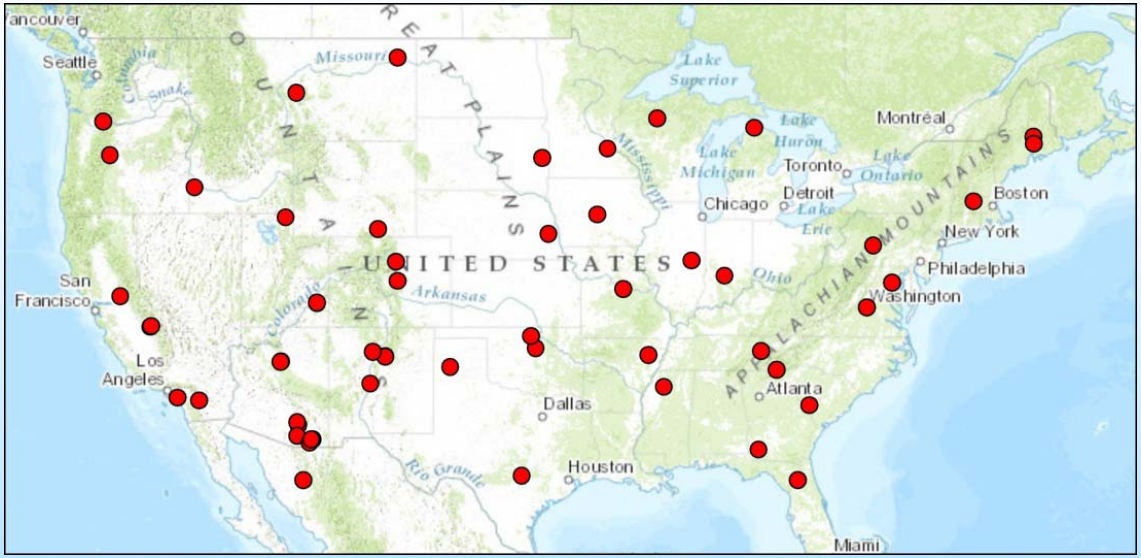
Applications include:

- Hydrology (recharge, drought, floods, hydraulic properties, snow water equivalent)
- Ecology (biomass, evapotranspiration)
- Weather forecasting (model initialization, data assimilation)
- Climate forecasting (seasonal, feedbacks, forcings, teleconnections)
- Agriculture (irrigation)
- Engineering (slope stability etc)
- Satellite remote sensing (cal/val)

Extent of COSMOS

USA

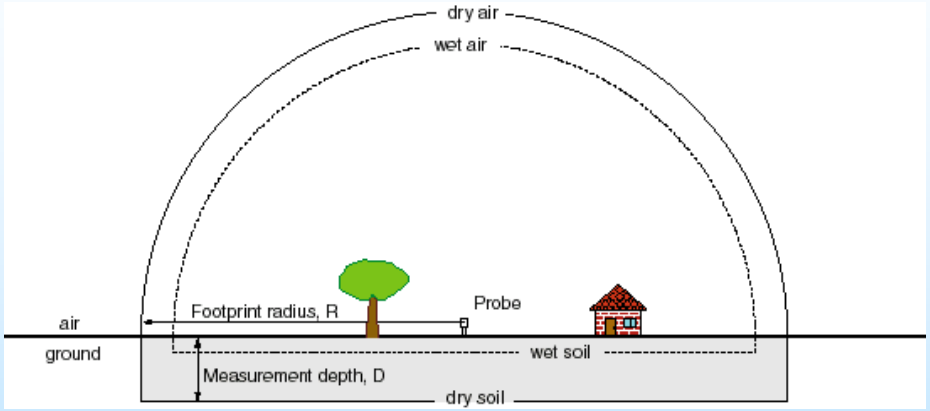
- Current: 56 stationary probes
- Goal: 500 probes
- Mobile sensing developed



Global

- Installed: 122+ probes
- New funded: 105+
- Proposals pending: 125+
- Mobile sensing: 2+

Measurement volume of cosmic-ray probe



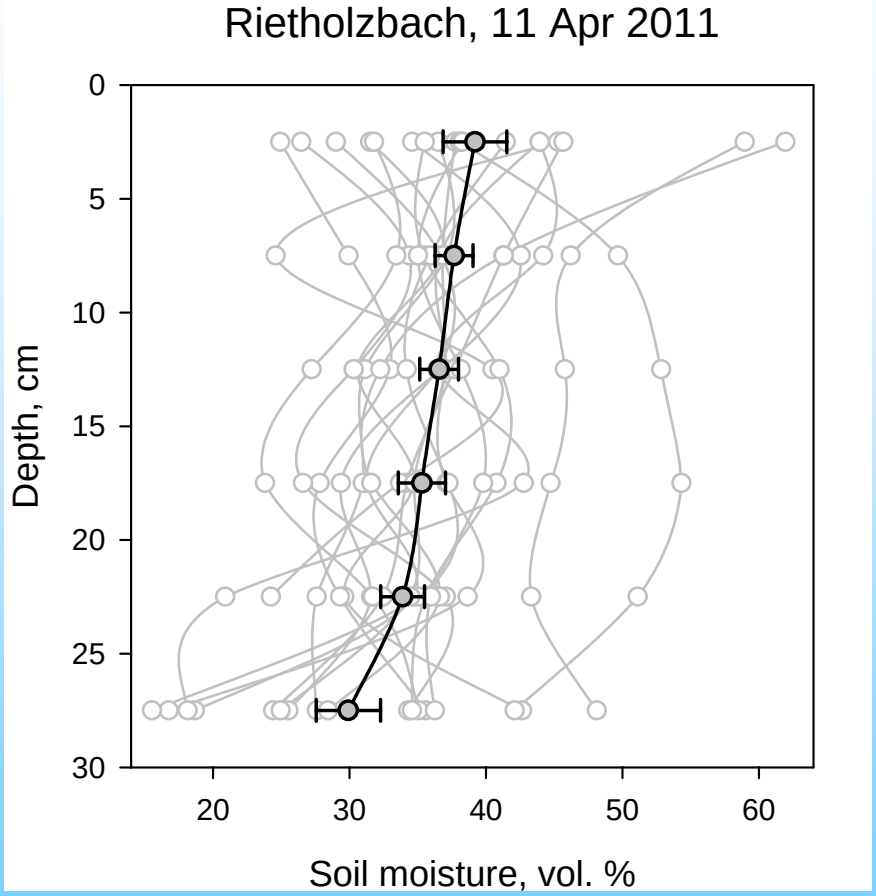
Horizontal footprint

- Circle, radius of ca. 300 m at sea level
- Nearly independent of soil moisture
- Increases with decreasing air density
- Decreases with increasing air humidity

Measurement thickness

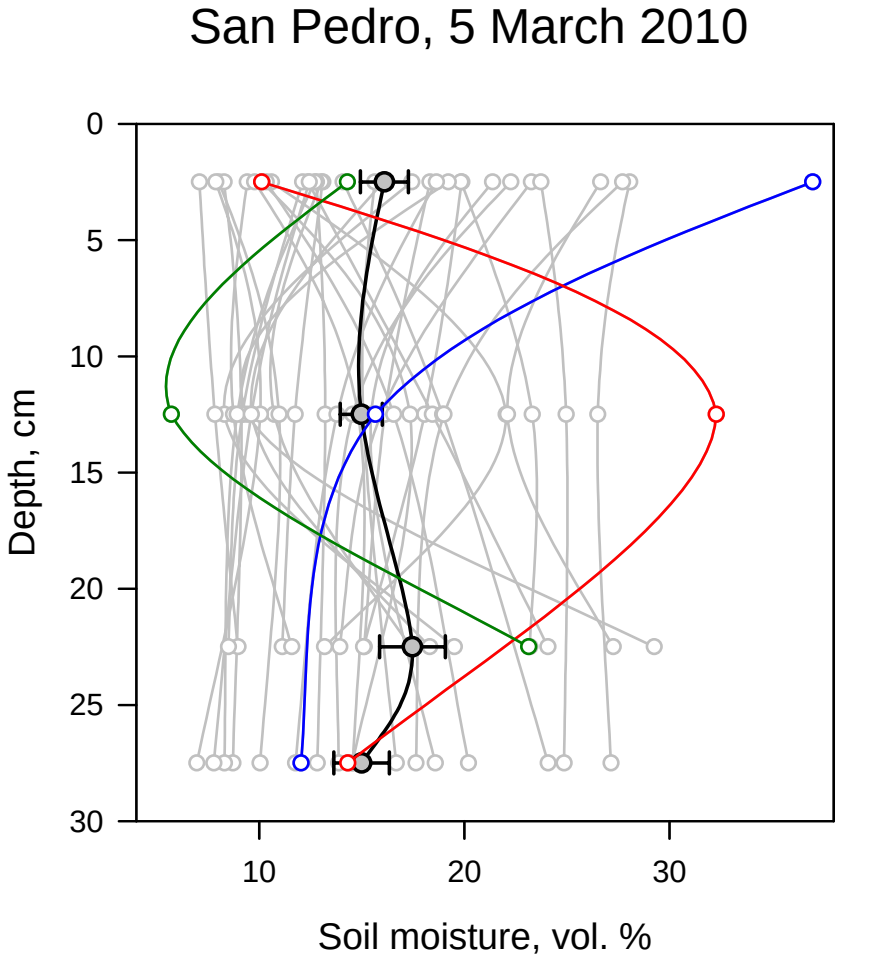
- 70 cm in dry soils (zero hydrogen)
- Decreasing to 12 cm in wet soils
- Independent of air density
- Independent of atmospheric humidity

Variations in soil moisture: circle, 400 m diameter

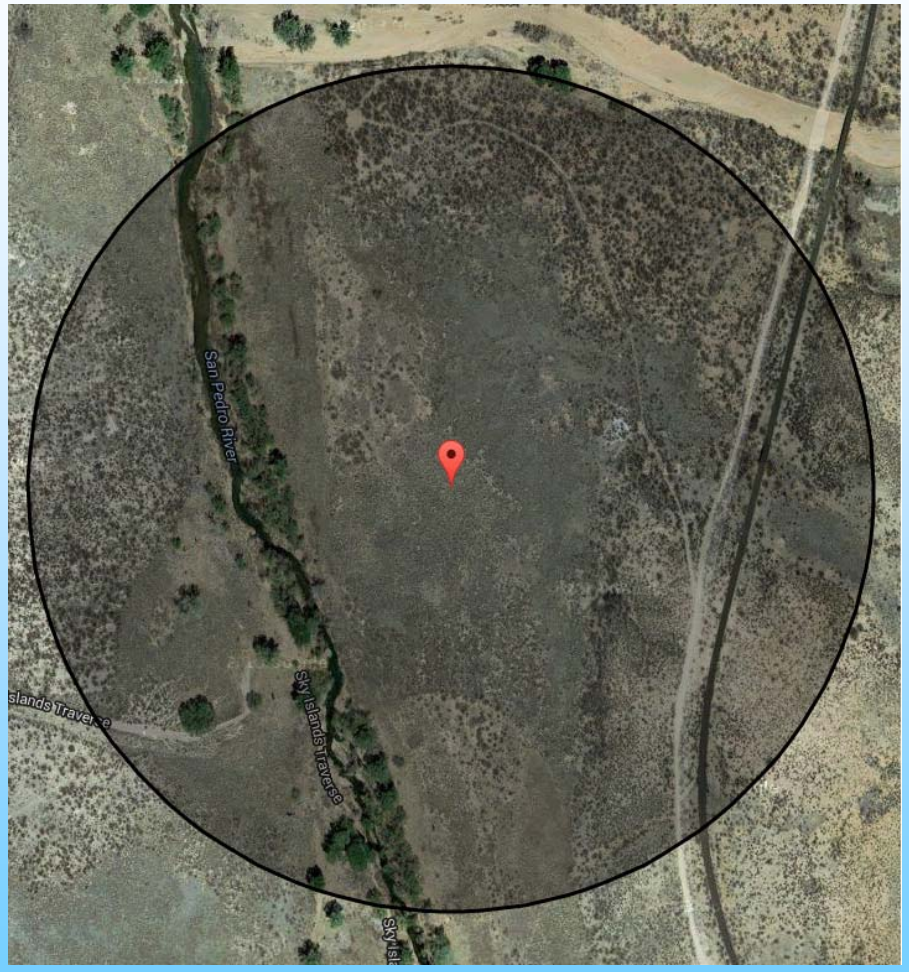


Footprint of the Rietholzbach COSMOS probe (cosmos.hwr.arizona.edu)

Variations in soil moisture: circle, 400 m diameter

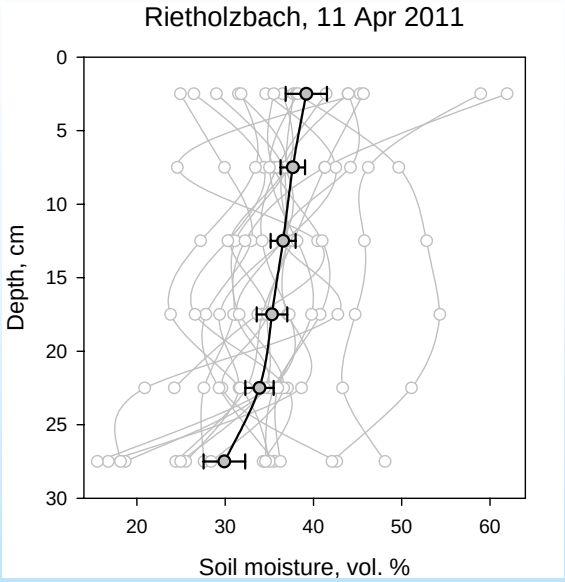


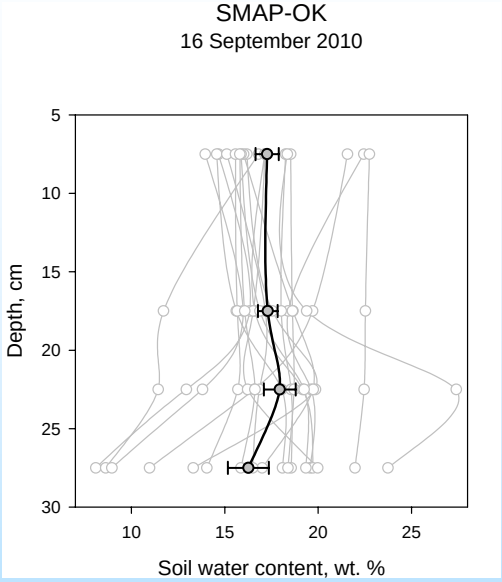
Zreda et al., 2012, HESS 16, 4079-4099.

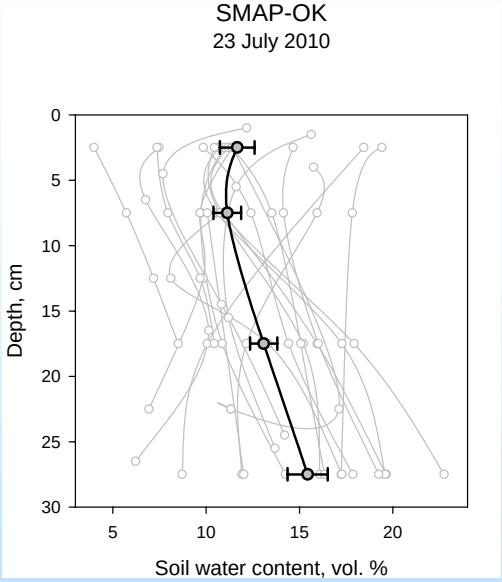


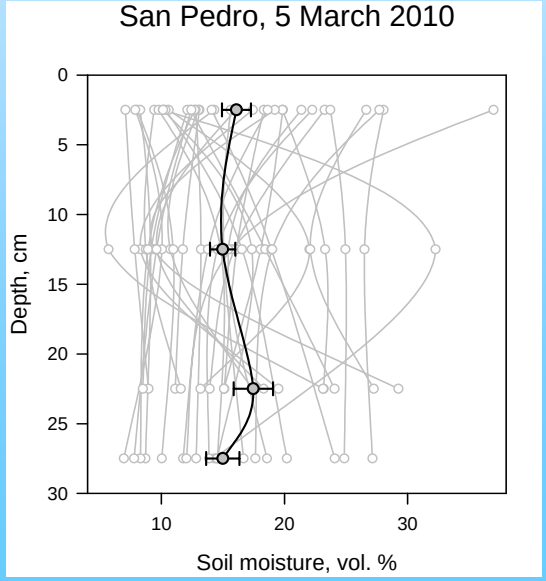
Footprint of the San Pedro COSMOS probe (cosmos.hwr.arizona.edu)

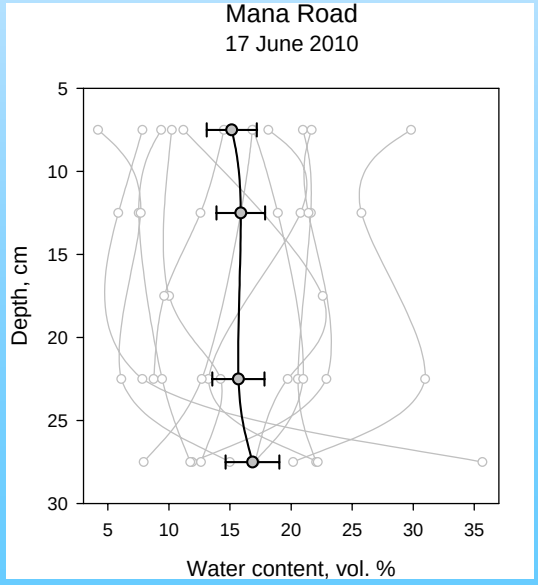
Variations in soil moisture: circle, 400 m diameter

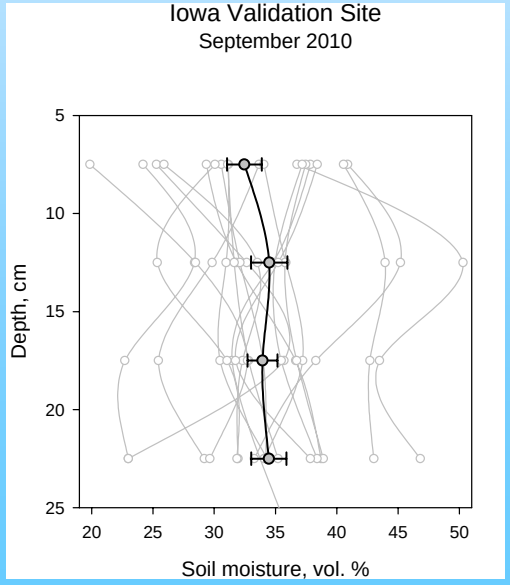




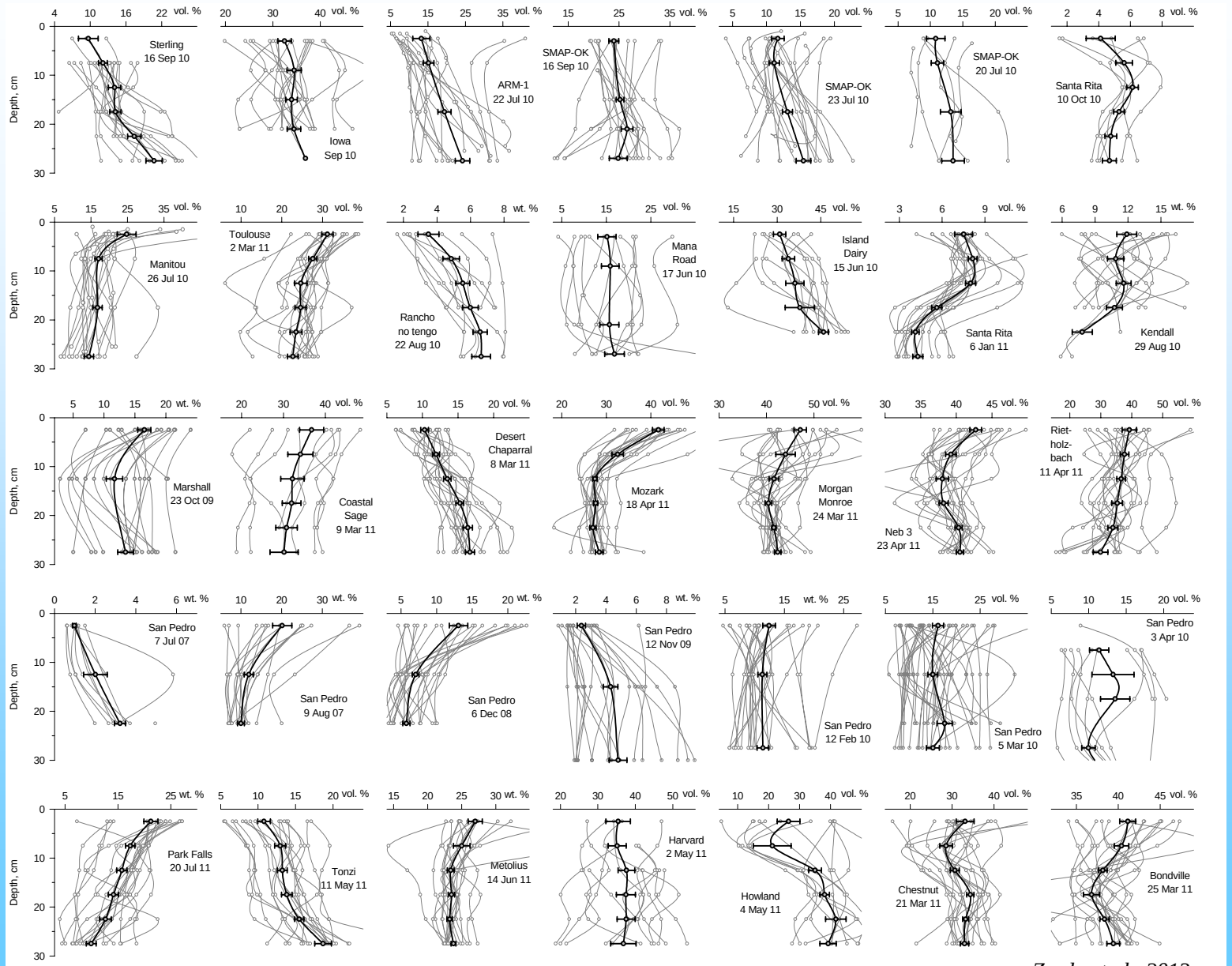






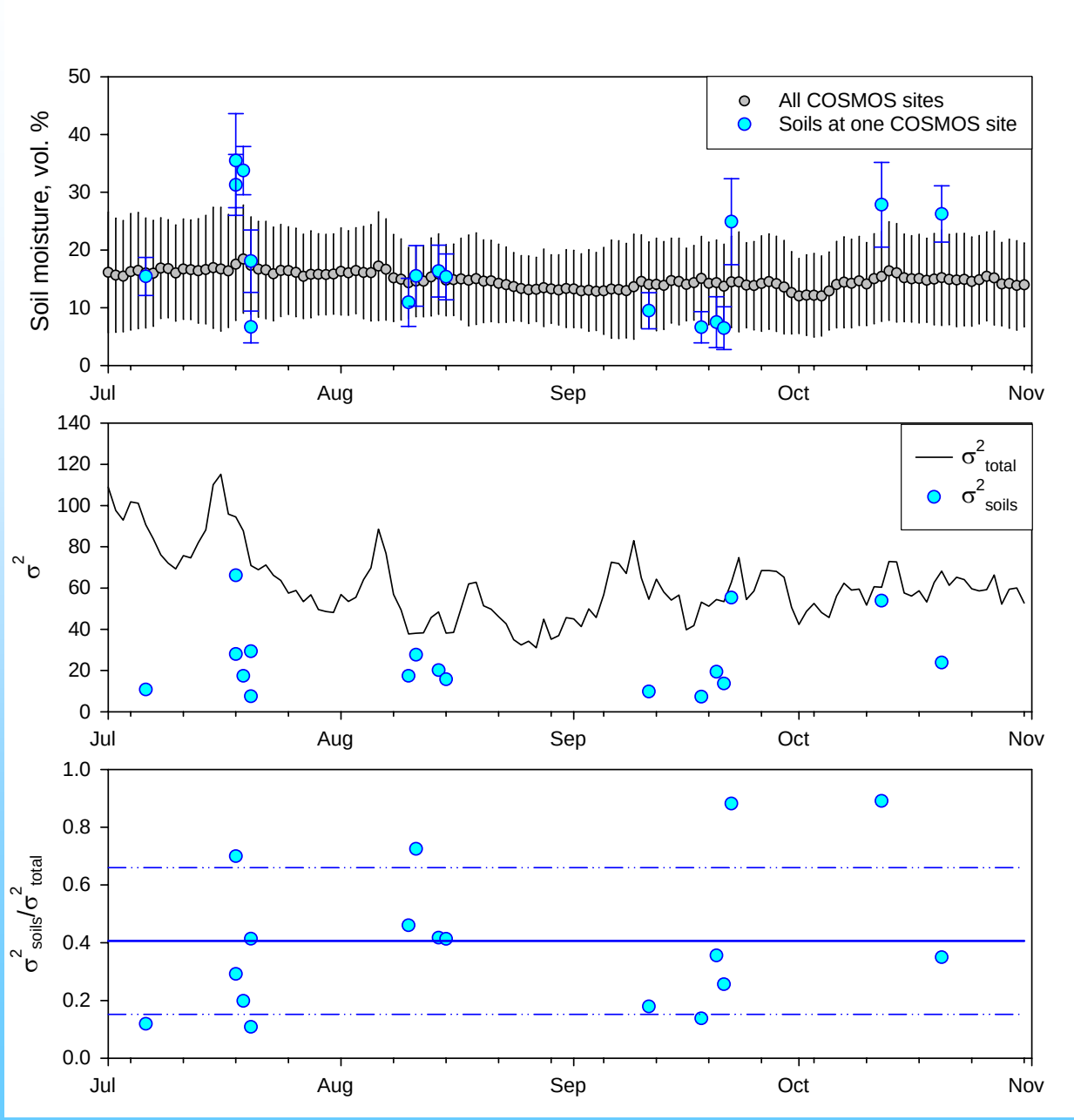


Variations in soil moisture: 35 COSMOS sites



Zreda et al., 2013.

Fraction of variance: 400 m vs. continental USA



Zreda et al., 2013.

Conclusions regarding horizontal variations in soil moisture

Soil moisture is highly variable in space.

Shapes of the profiles are as variable.

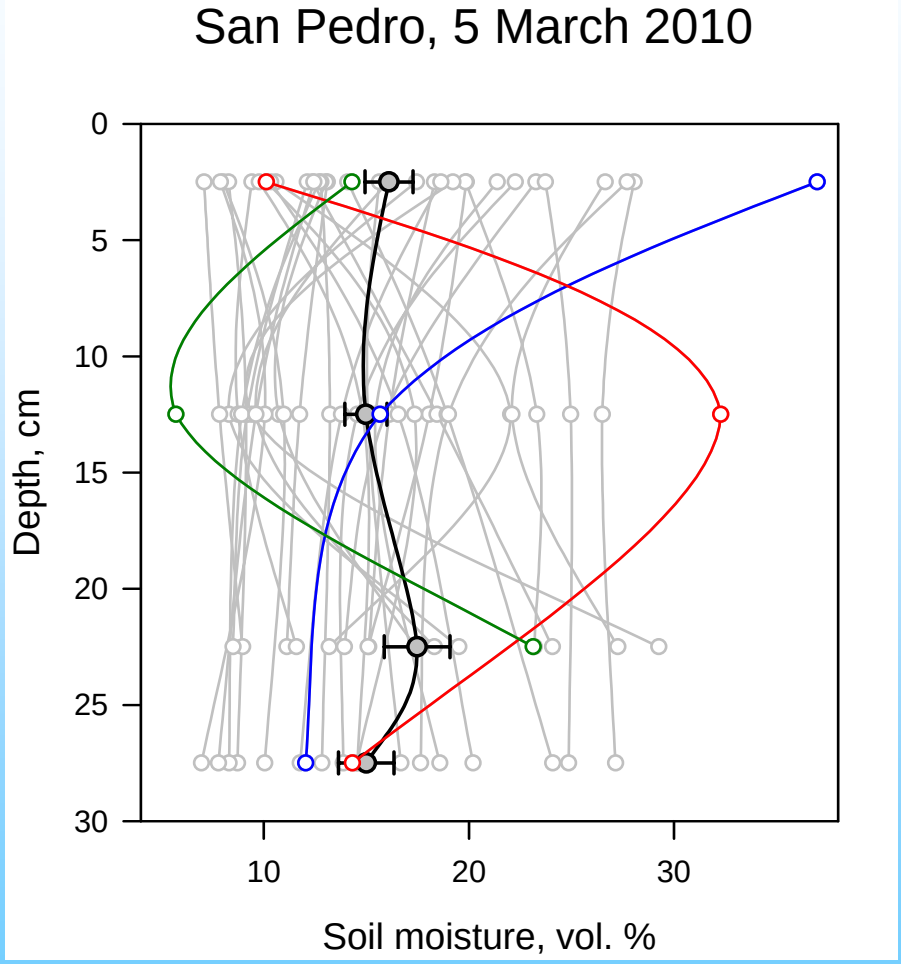
Neither single measurements nor profiles are representative of the surrounding area.

Small-scale variability makes up a large fraction of the continental variability.

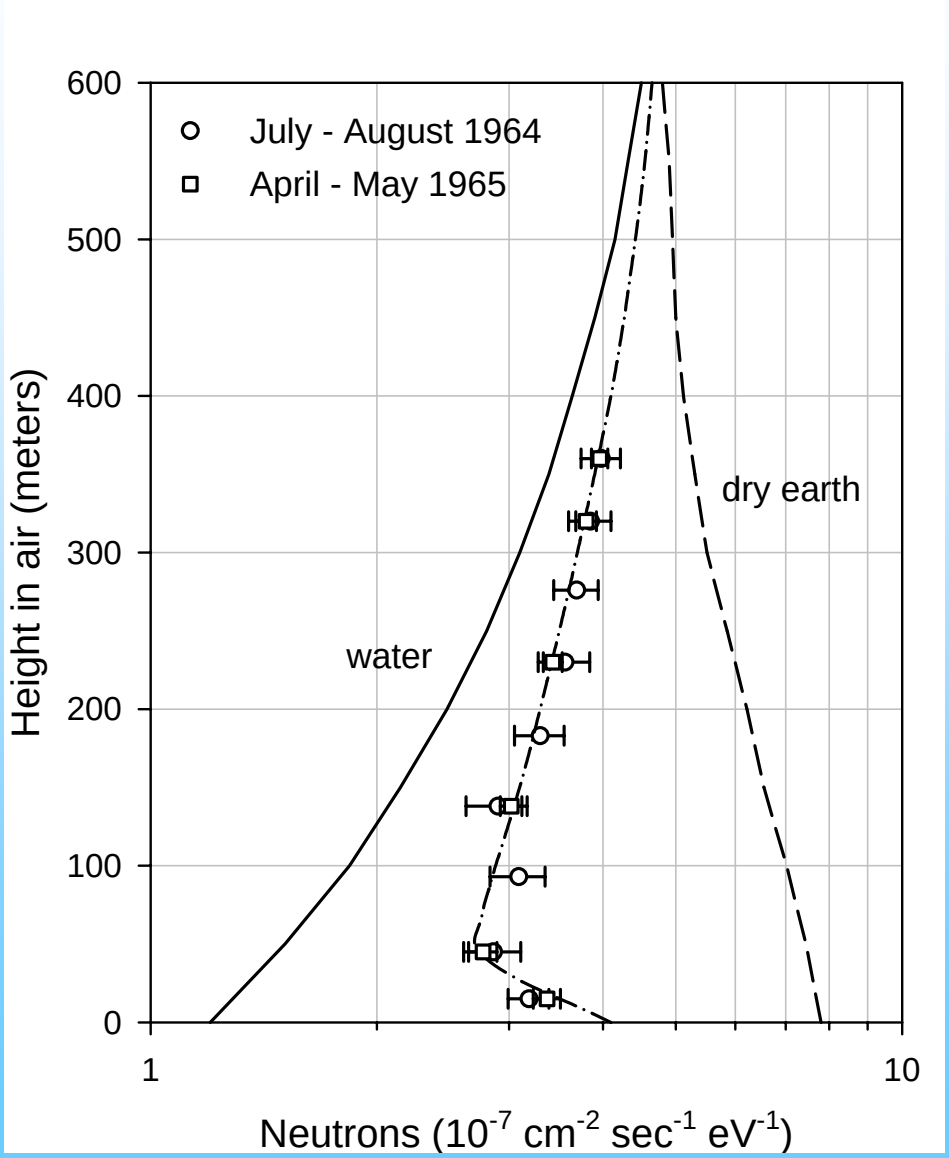
Therefore…

Point measurements of soil moisture are unreliable.

Need to shift to area-average measurements.



Cosmic-ray neutrons above the surface



Hendrick and Edge, 1966.

Production and removal of fast neutrons

Space:

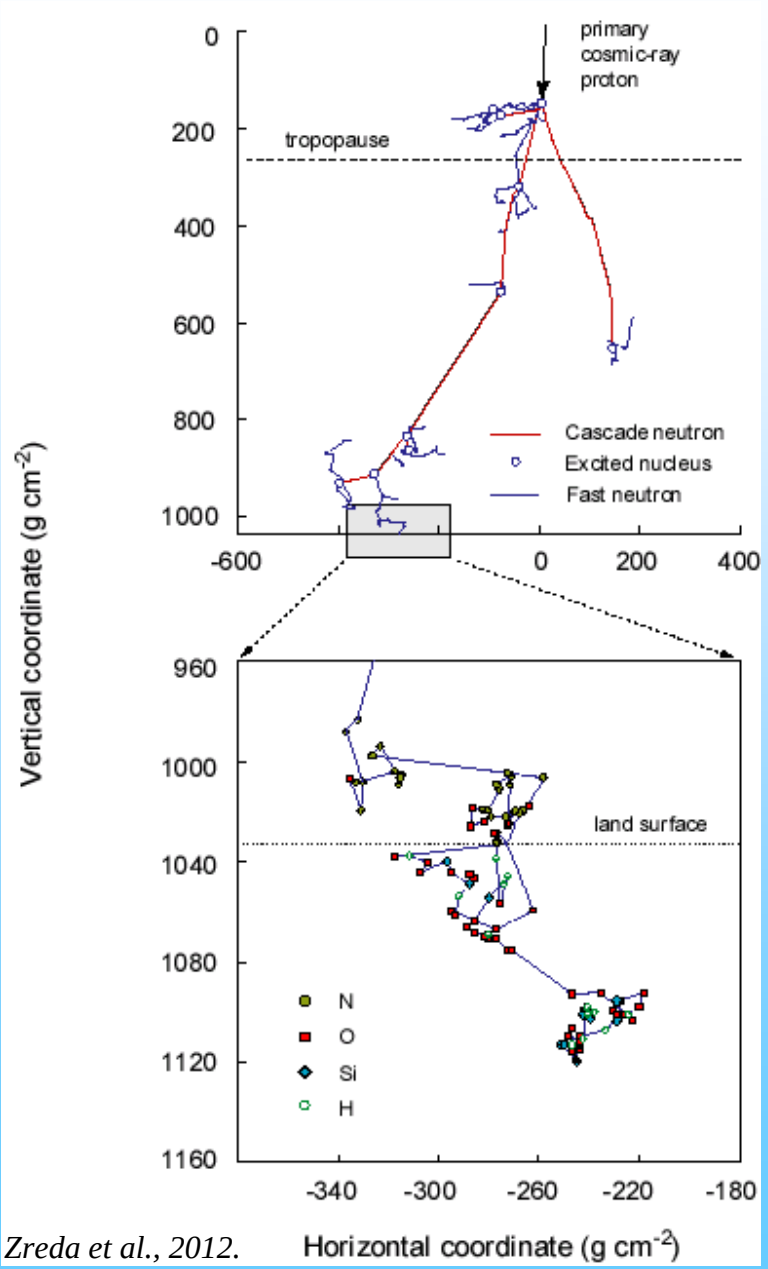
incoming high-energy cosmic-ray protons

Atmosphere:

generation of secondary cosmic rays

Ground:

scattering
thermalization
absorption

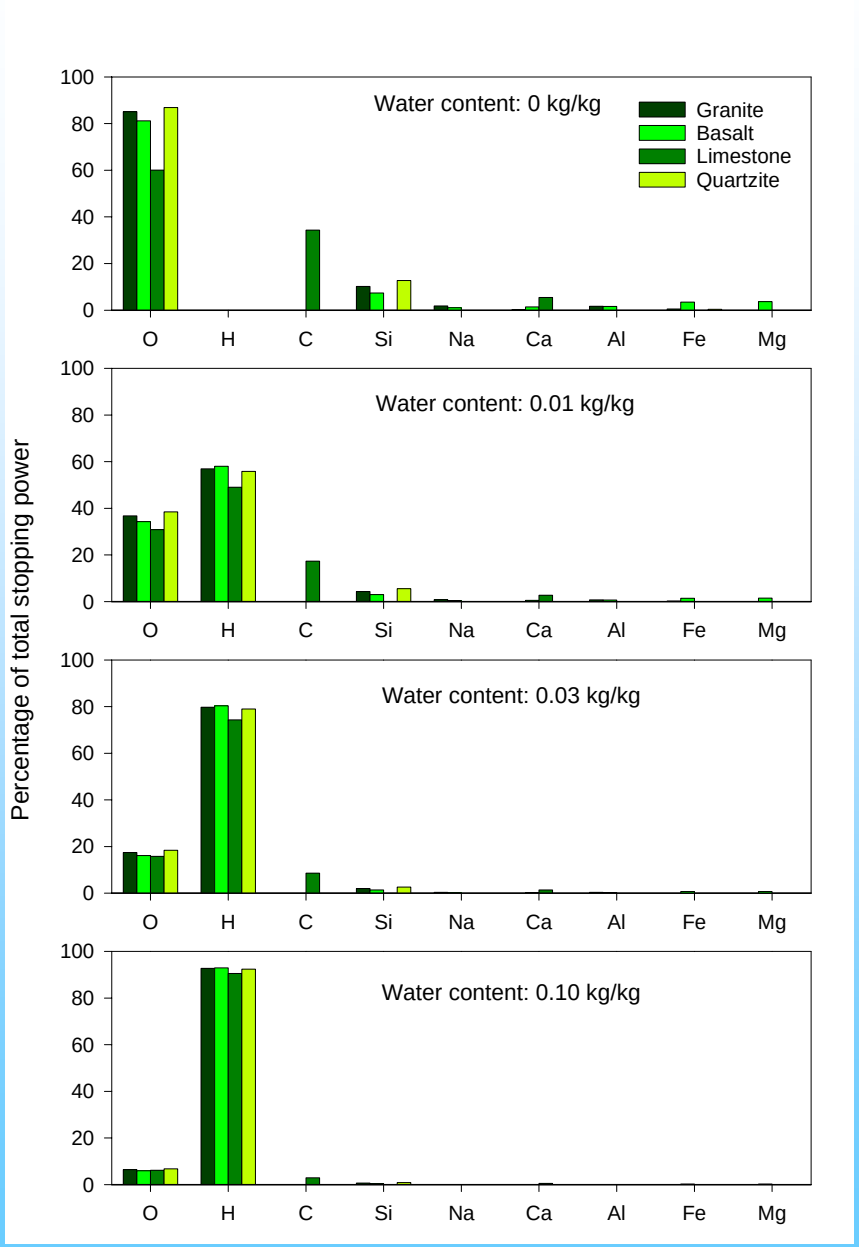


Zreda et al., 2012.

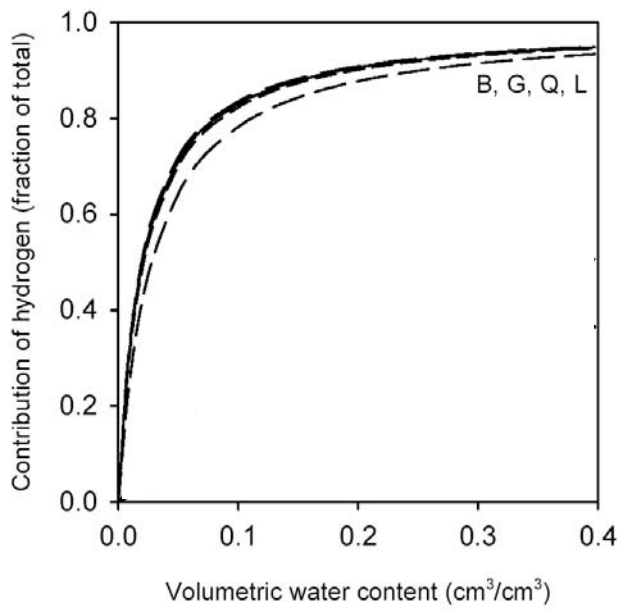
- Primary - mostly protons and alphas
- Interact with magnetic field
  - intensity depends on <u>solar activity</u> and <u>geomagnetic latitude</u>
- Interact with atmospheric nuclei
- Produce secondary particles - cascade
  - intensity depends on <u>barometric pressure</u>
- Produce fast neutrons
- Remove fast neutrons
  - slowing down by elastic collisions
  - leads to thermalization
  - and then absorption

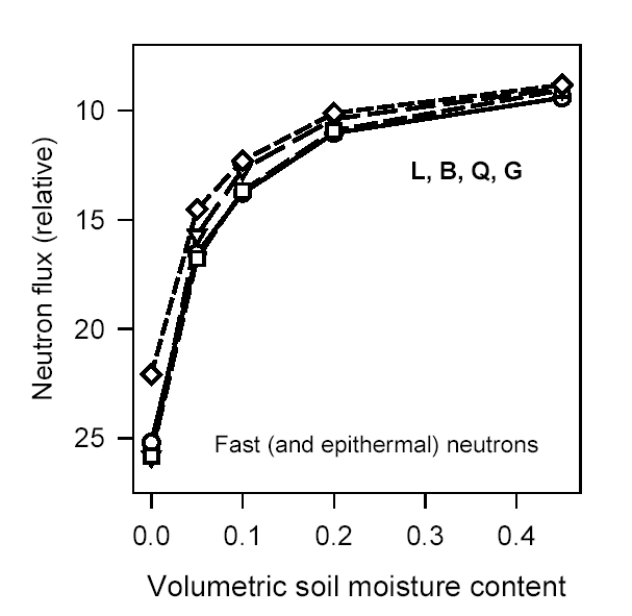
The last three processes depend on the <u>chemical composition</u> of the medium, in particular on its <u>hydrogen content</u>.

Moderating power of rocks & neutron flux



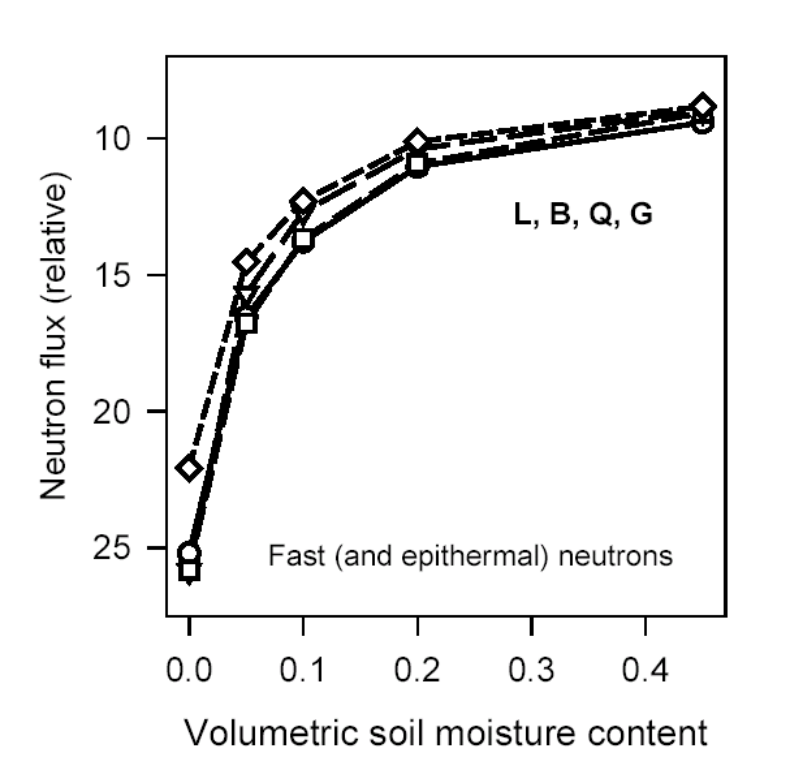
Zreda et al., 2012.





Zreda et al., 2008.

Moderating power and neutron intensity



$$\phi\,(E) = \frac{Q}{E\,[N_H \cdot \sigma_H \cdot \xi_H + \Sigma(N \cdot \sigma \cdot \xi)]}$$

ϕ (E) - flux of neutrons of energy E

Q - strength of source function

N - number of atoms of an element

σ_{sc} - scattering cross section for an element

ξ - log decrement of energy per collision

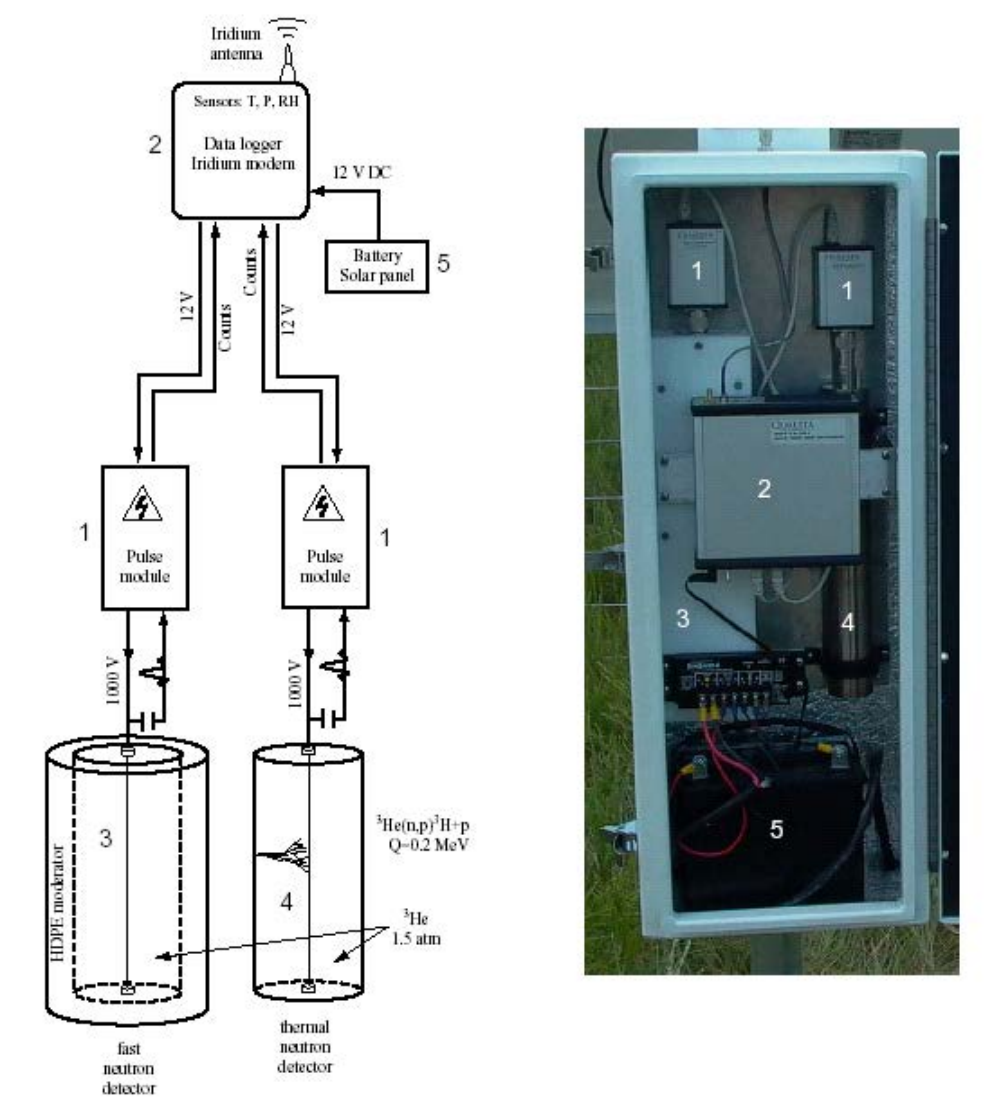
$\sigma \cdot \xi$ - slowing down power for an element

$N_H \cdot \sigma_H \cdot \xi_H + \Sigma(N \cdot \sigma \cdot \xi)$ - slowing-down power of the medium, separated into:

$\Sigma(N \cdot \sigma \cdot \xi)$ - slowing-down power of the medium minus hydrogen

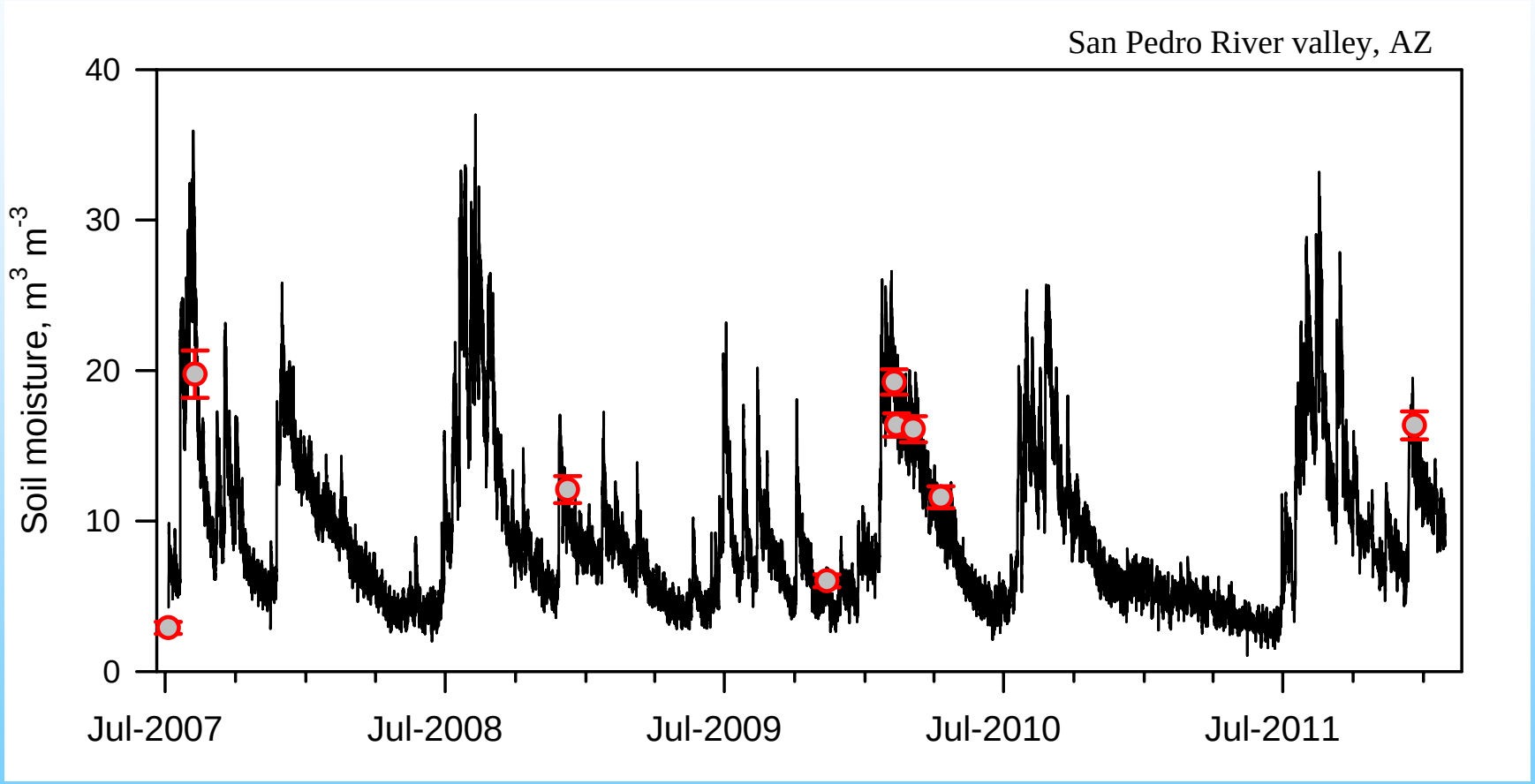
$N_H \cdot \sigma_H \cdot \xi_H$ - slowing-down power of hydrogen

Cosmic-ray probe



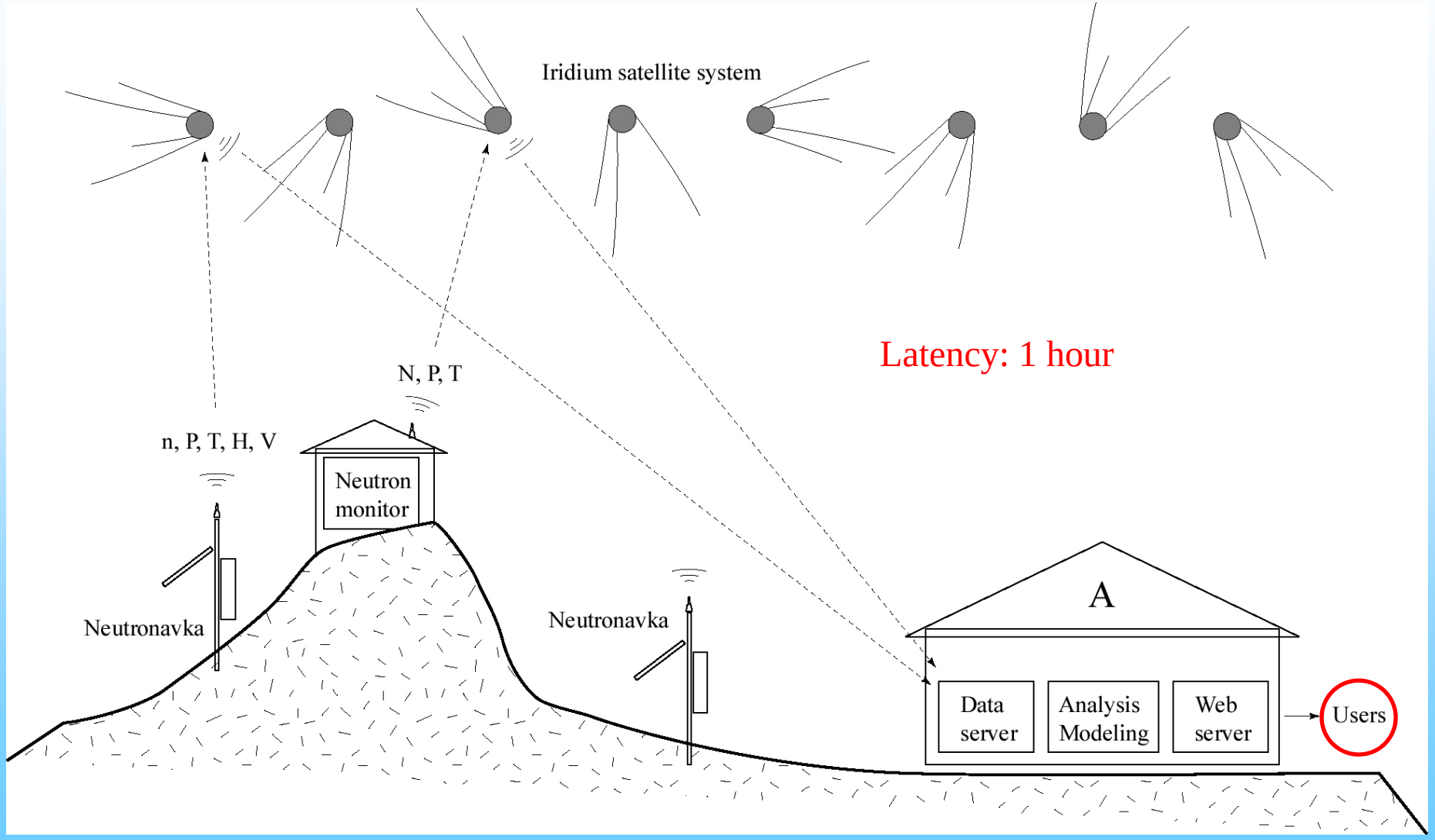
Zreda et al., 2012.

Testing calibration: repeated ground truthing



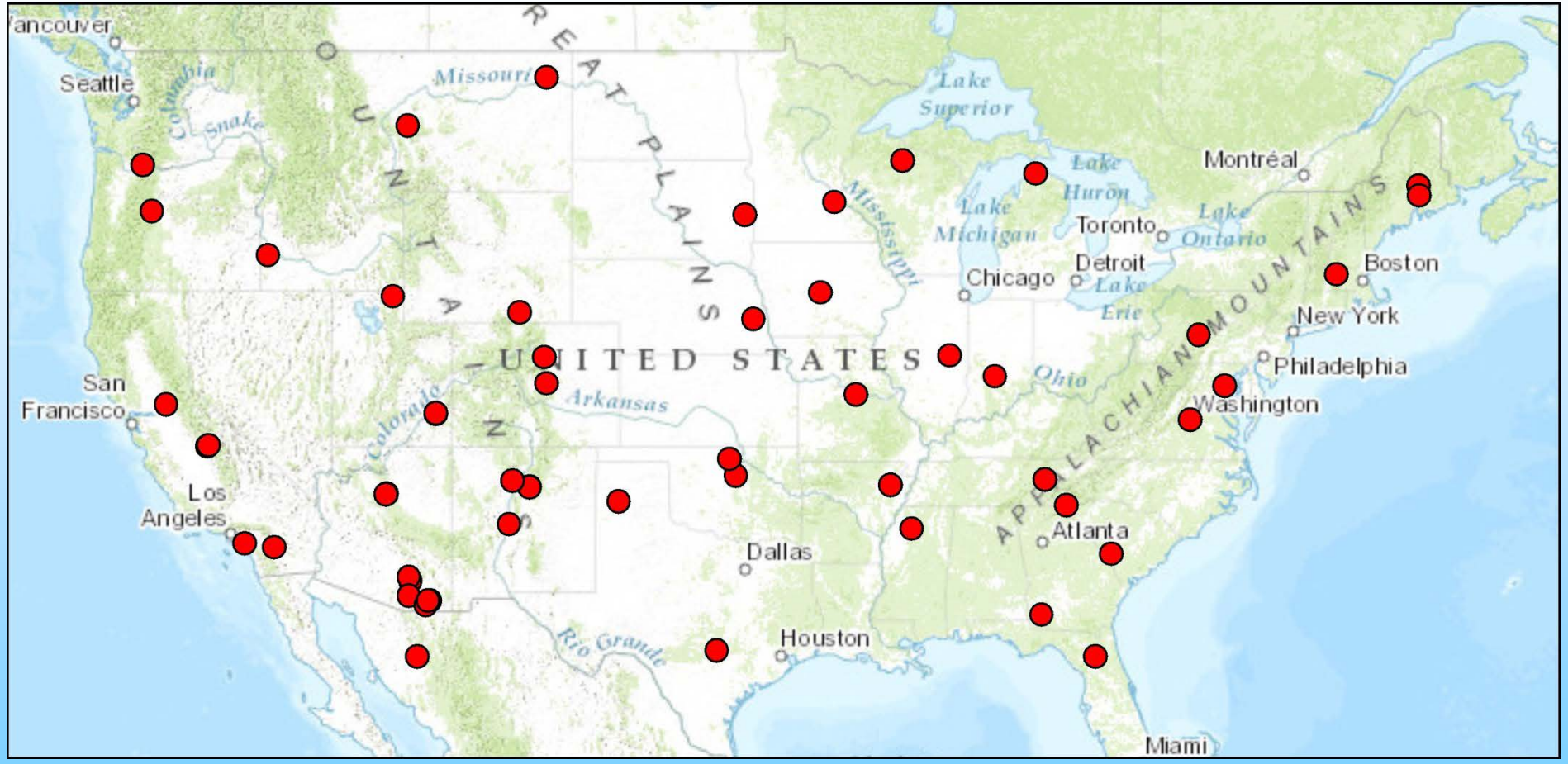
Zreda et al., 2012

COSMOS: Cosmic-ray soil moisture observing system



Zreda et al., 2012.

COSMOS sites



Main network: 54 probes in the 48 states

Additional probes: 2 in Hawaii and 5 abroad

Reliability: 95% uptime; 1 probe bad (due to lightning damage)

COSMOS web site: probe data

COSMOS | COSMOS Probe: Silver Sword

cosmos.hwr.arizona.edu/Probes/StationDat/012/index.php

» Home » Stations » **Station Information**

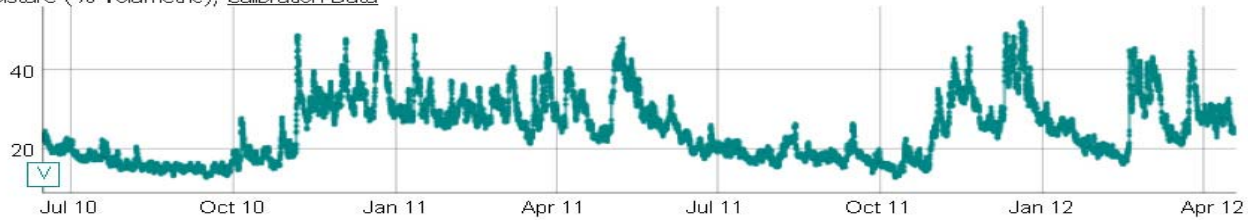
Silver Sword

Larger Photo Approx Footprint

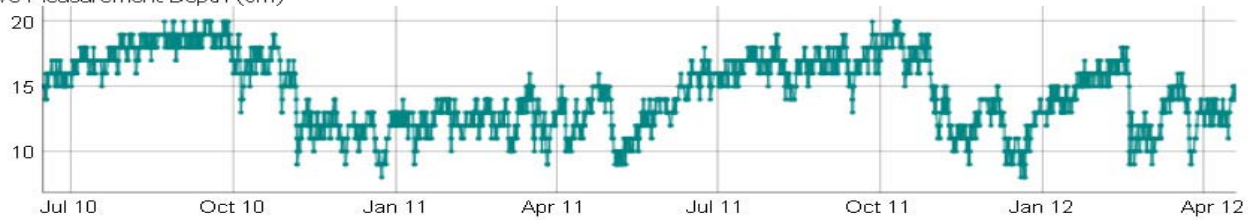
The site is co-located with the USDA National Resources Conservation Service 'Silver Sword' site. More information regarding the USDA site can be found at http://www.wcc.nrcs.usda.gov/nwcc/site?sitenum=2101&state=HI

Installation Date:	2010-06-15
Timezone (UTC):	-10
Cutoff Rigidity (GV):	12.87
Mean Pressure (mb):	725
Mean Bulk Density (g/cm^3):	0.78
Mean Lattice Water (% weight):	9.57
Max Count Rate (/hr):	2633

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.

COSMOS is supported by the Atmospheric and Geospace Sciences Division of the National Science Foundation

COSMOS public server: cosmos.hwr.arizona.edu

Mobile cosmic-ray probe (COSMOS rover)

Measures cosmic-ray intensity continuously using a probe in a vehicle.
Two modes:

(1) stop and measure (SAM);
(2) drive and measure (DAM).

Can do 1-D transects.
Can do 2-D maps (from multiple transects or multiple stops).
Has multiple large tubes for high count rates (fast measurements).
Has GPS to record positions.

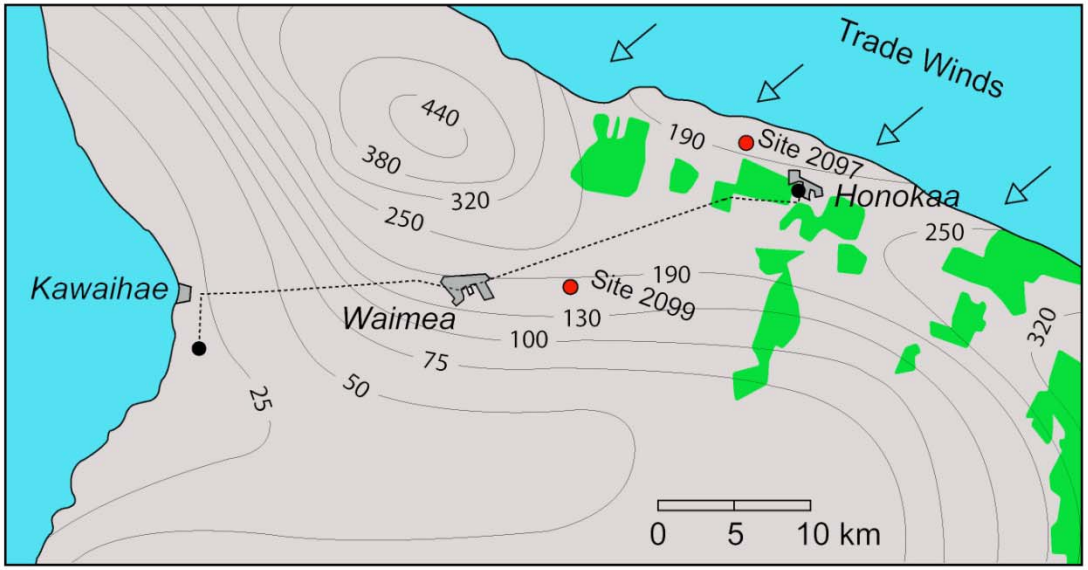
<u>Advantages:</u>

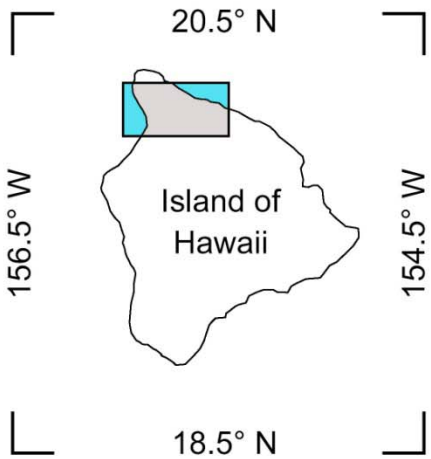
(1) Fast mapping of soil moisture over large areas and over variable terrains

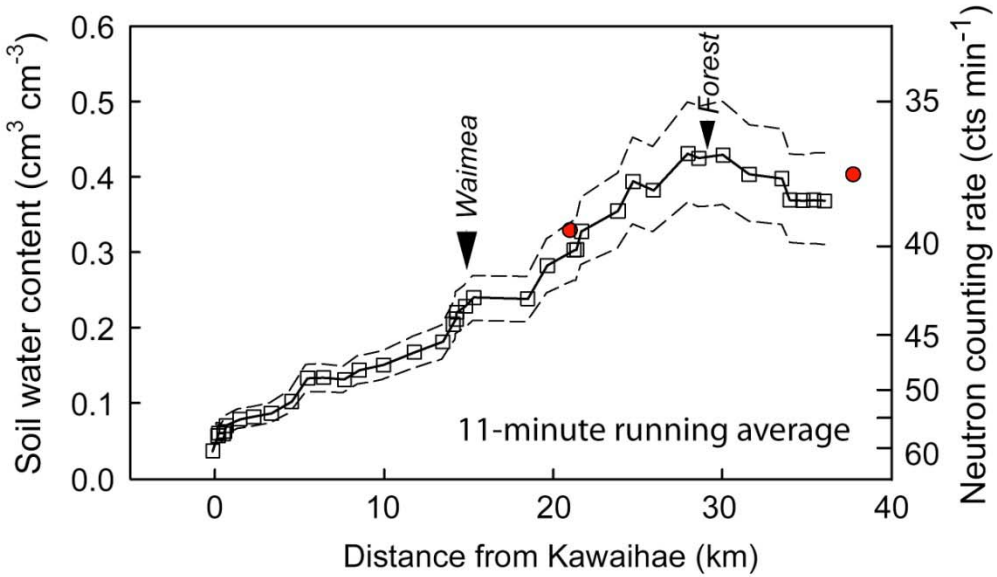
(2) Possible with different moving platforms:

- cars (done, working well)
- aircraft (in progress, likely to work)
- on foot (backpack rover, should work)
- **trains** (future, likely to work)

COSMOS rover: transect, Hawaii



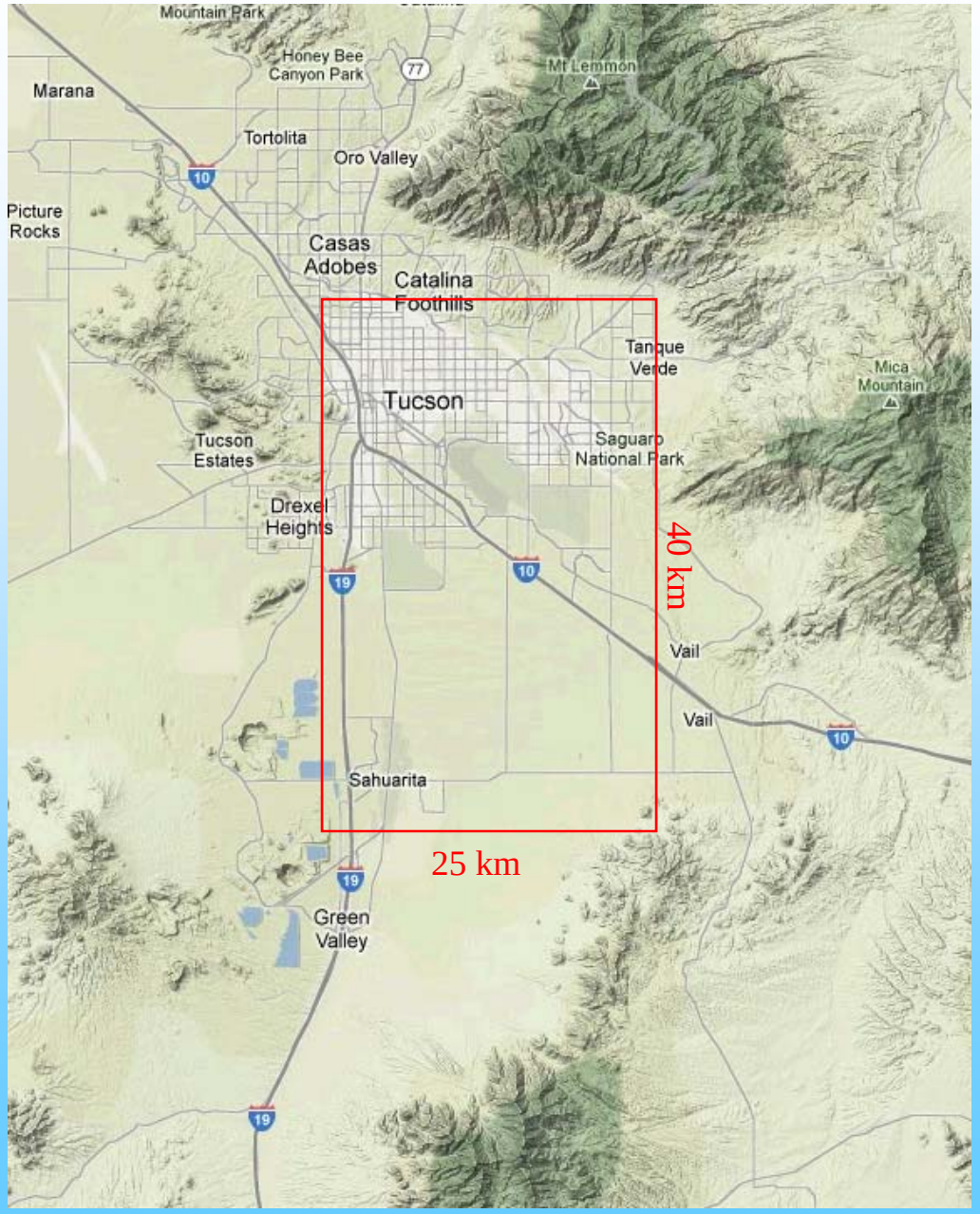




- Survey end point
- SCAN site
- Survey route
- Annual precipitation (cm)
- Dense Forest
- Urbanized Zone

Desilets et al., 2010

COSMOS rover: soil moisture in Tucson Basin



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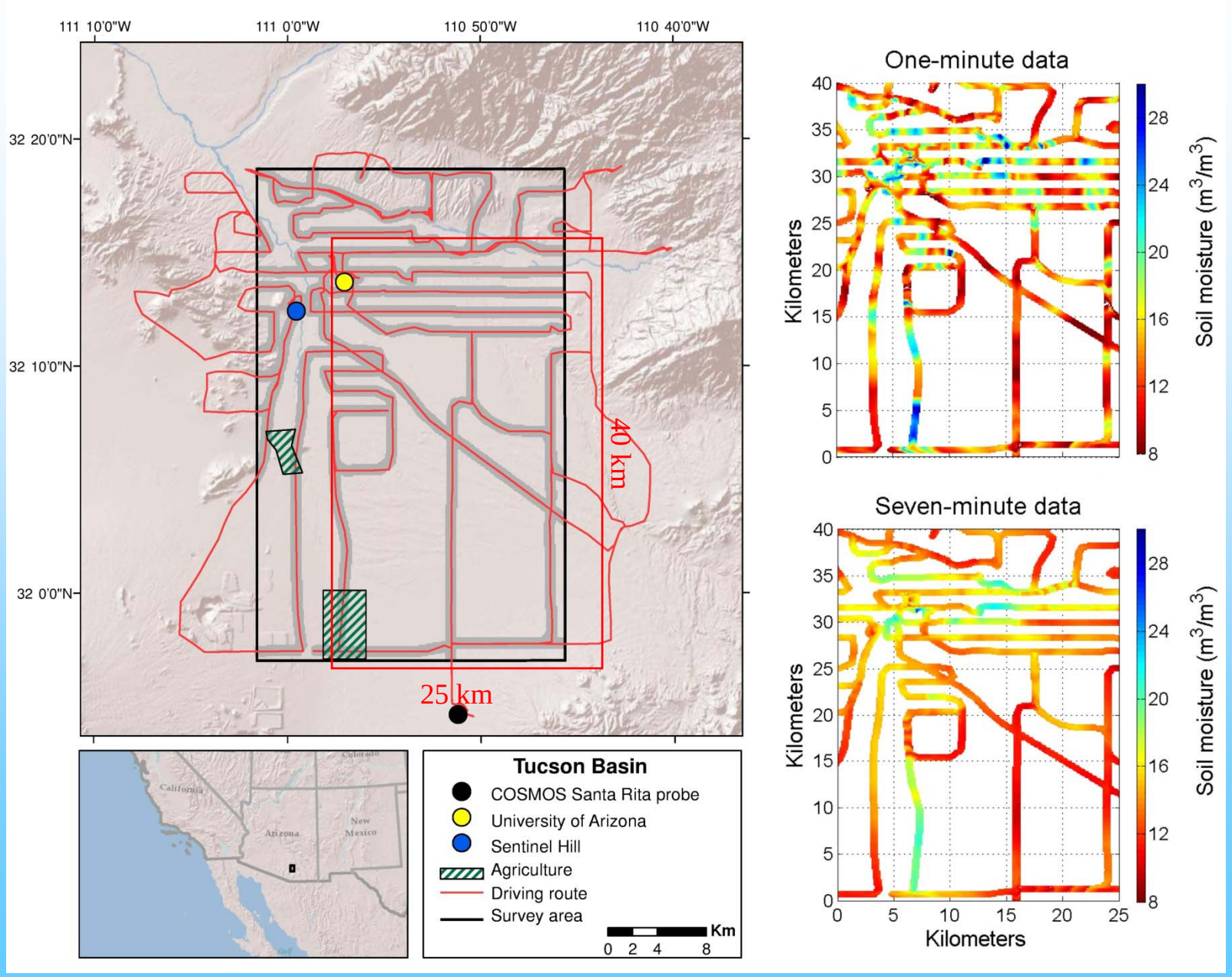

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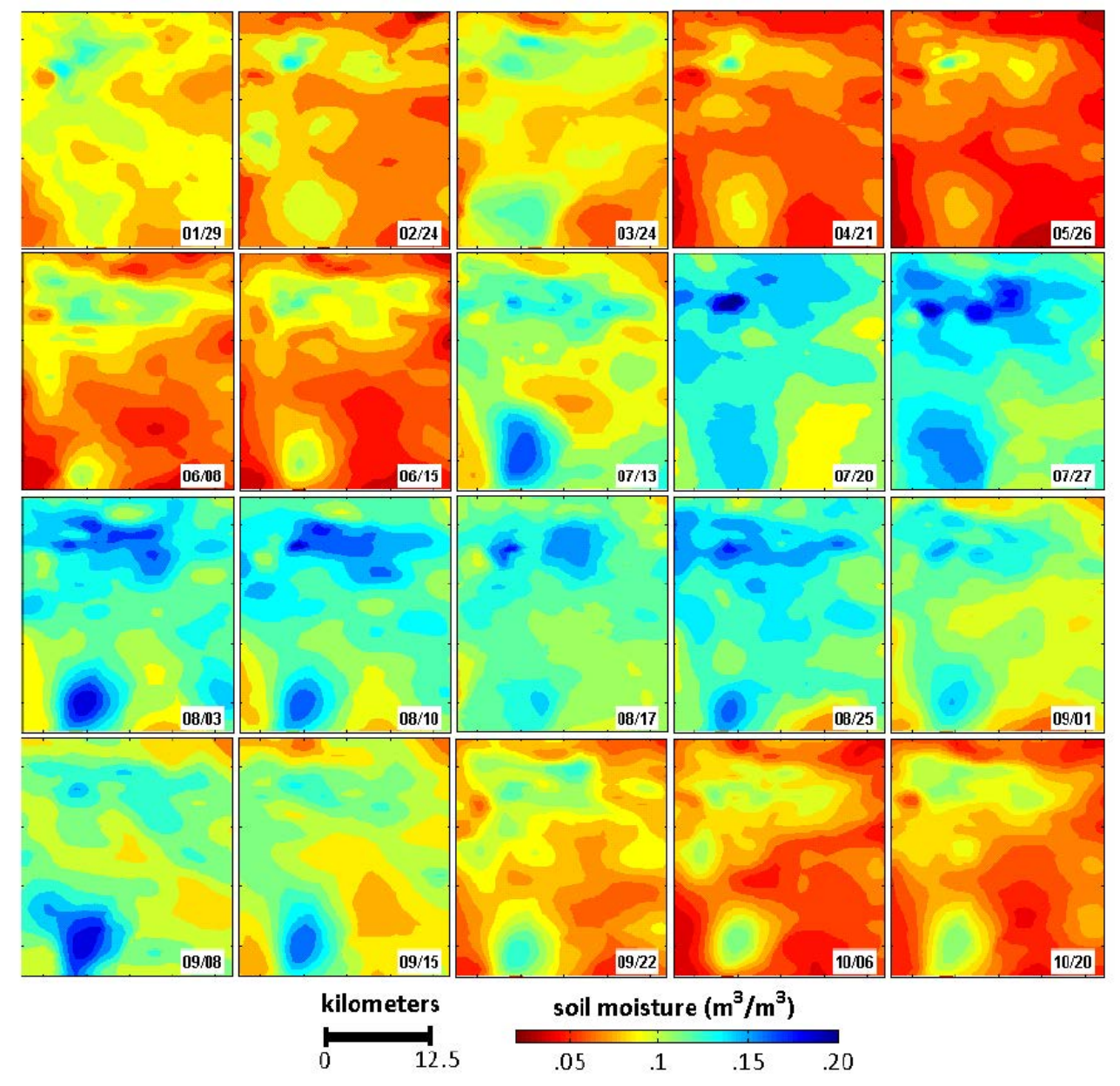
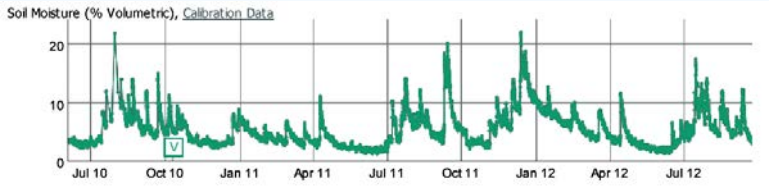
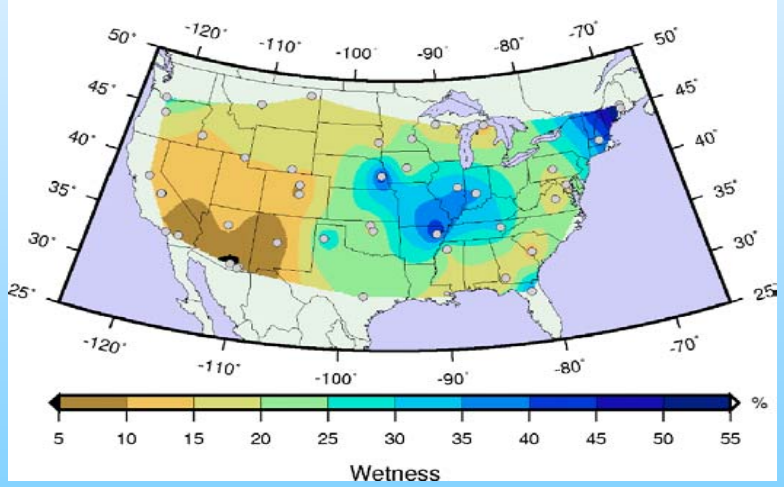


Possible use of COSMOS probes for drought monitoring

- Produce time series of area-average soil moisture data at COSMOS sites



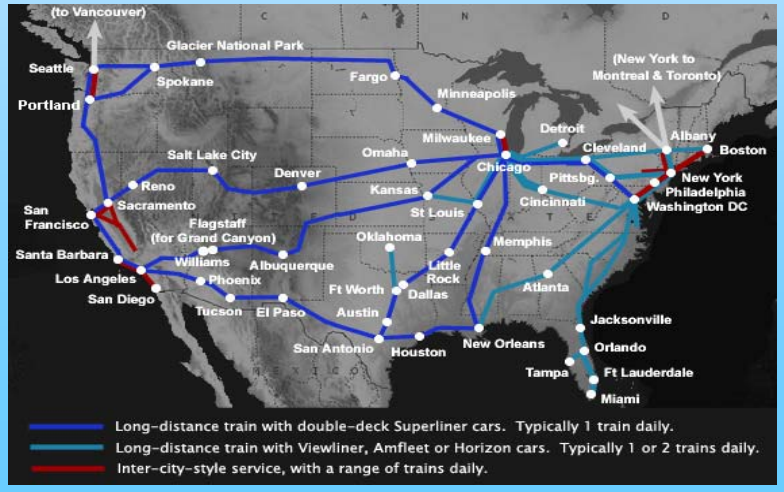
- Generate soil moisture maps using stationary COSMOS probes



- Determine soil properties from neutron data
- Compute water mass balance
- Separate evapotranspiration and biomass seasonal changes from neutron data
- Extract snow water equivalent from neutron data

- Connect COSMOS sites using COSMOS rover to enhance resolution and coverage

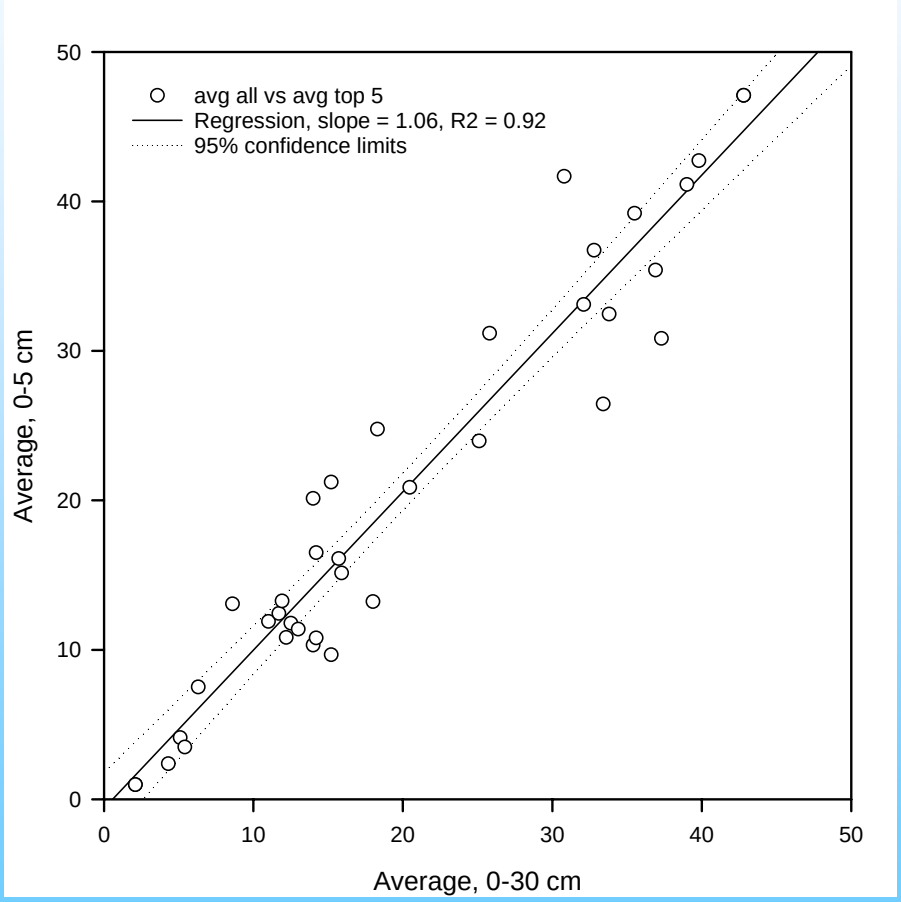
- Produce high-resolution mesoscale maps of soil moisture
- Use COSMOS rovers on trains to produce daily continental-scale soil-moisture transects



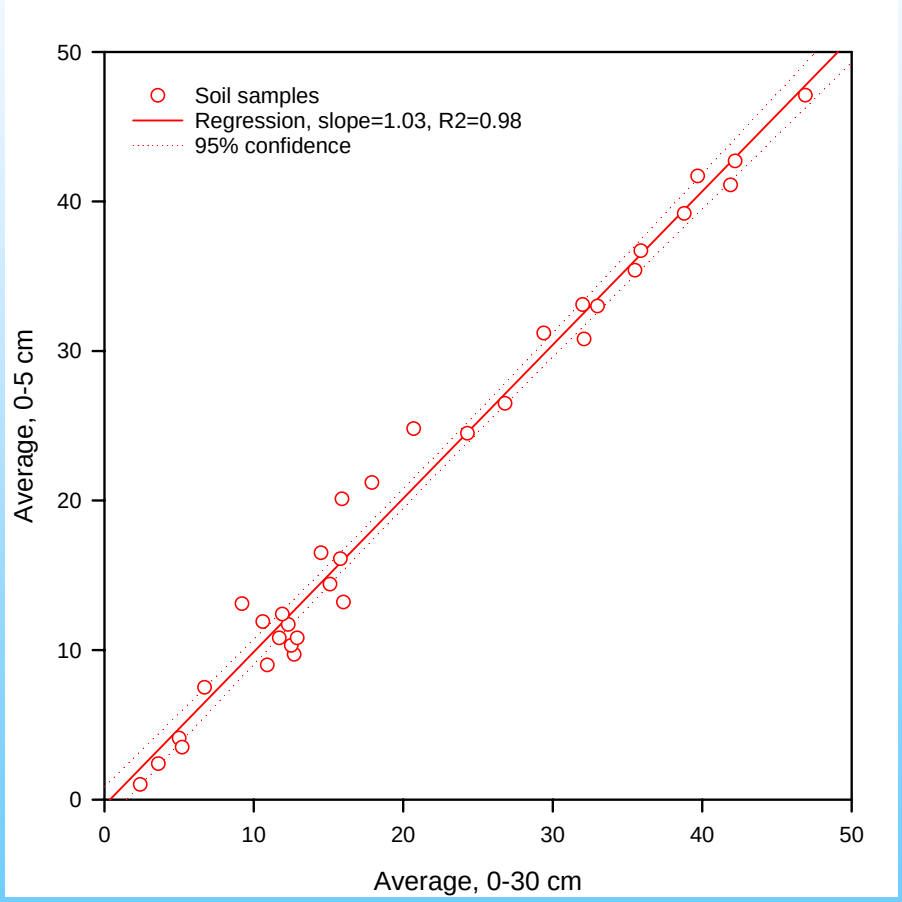
Correlation: soil moisture, 0-5 cm vs. 0-30 cm

Soil samples from cores at COSMOS sites in the continental USA

Raw (unweighted)



COSMOS-weighted (for depth)



Zreda et al., 2013.

Conclusions regarding vertical variations in soil moisture

Individual profiles are highly variable and unpredictable.

But **area-average profiles are less variable and more predictable**.

Strong **correlation (R2=0.98) between 0-5 cm and 0-30 cm** COSMOS-weighted soil moisture.

Therefore…

COSMOS data can be used to establish area-average **soil moisture profiles for drought monitoring**.

Future prospects: big picture

Big change: single-probe data vs. network data

- Research to date focused on single-probe data, such as soil moisture or biomass at the probe footprint (image)

- That research was necessary to build confidence in cosmic-ray measurements

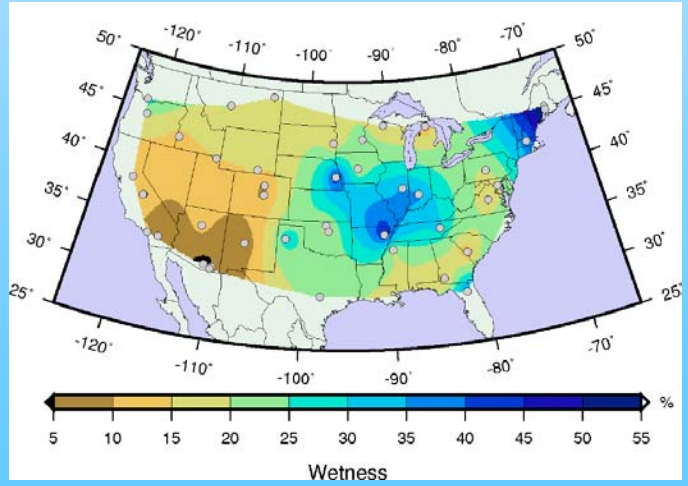
- Armed with that confidence, we are now ready to study processes that operate at mesoscale and larger scales

- Small-scale research at single sites will be transformed into large-scale research that uses the whole network, guided by the principle that <u>the whole is greater than the sum of its parts</u>

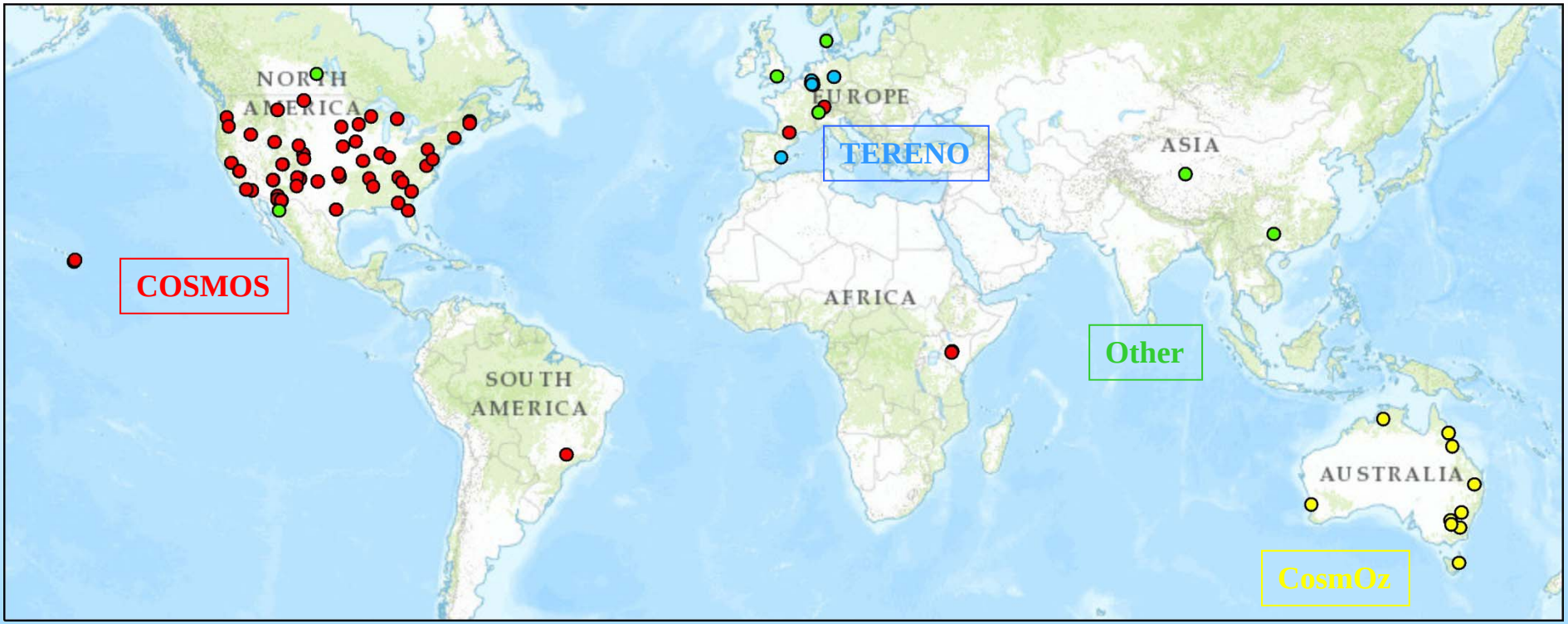
- The current network of 56 probes will be enlarged

- COSMOS probes will be collocated with other instruments and data analyzed jointly

- New applications will be developed

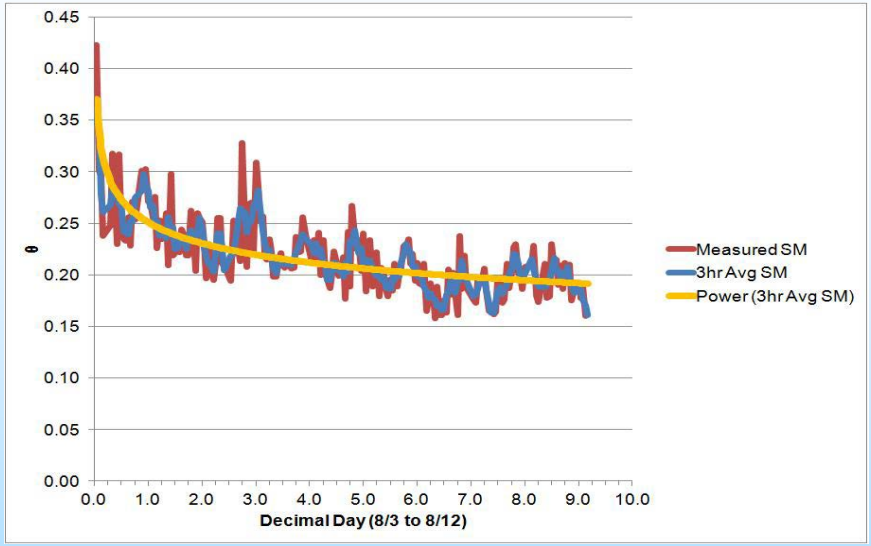
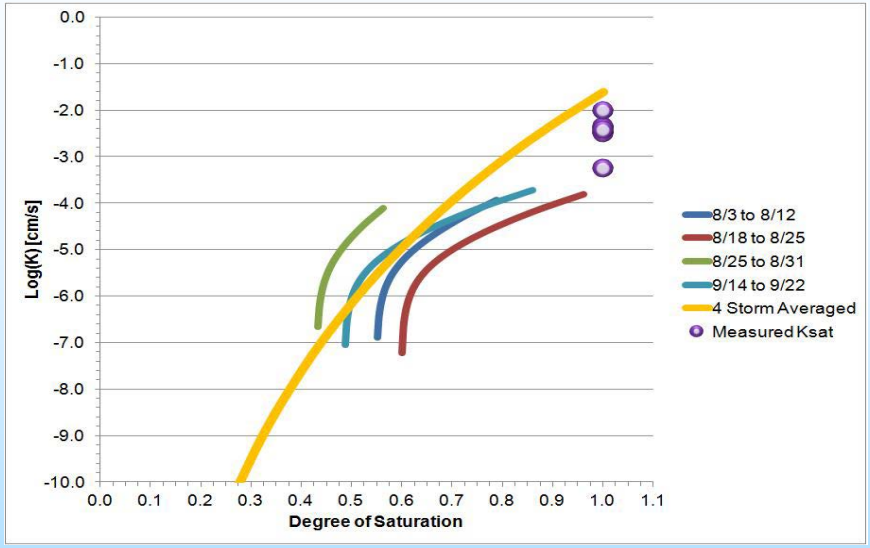
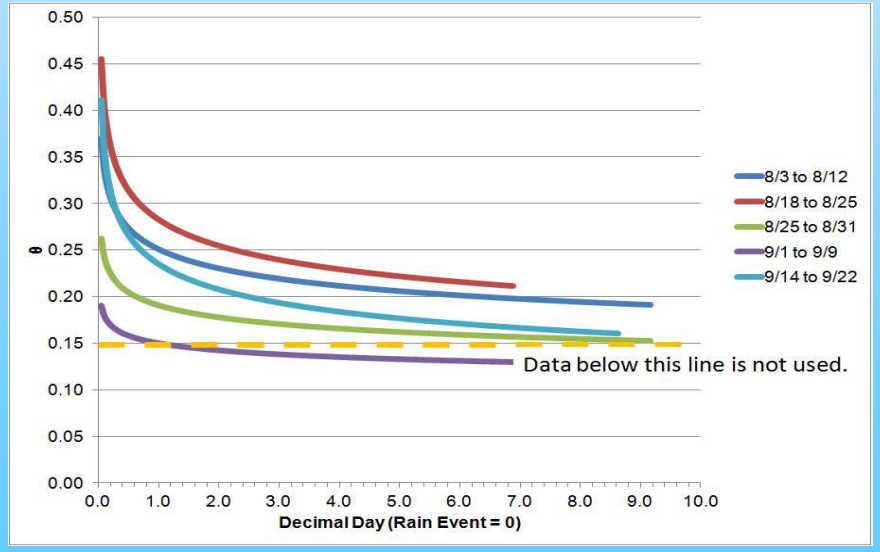
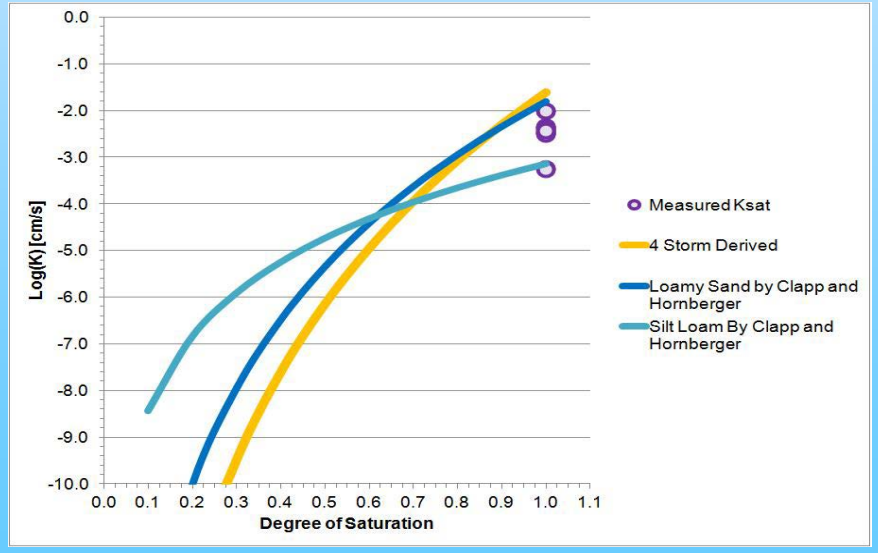


Growth of global COSMOS



Network	Current (installed)	New (funded)	New (proposals)
COSMOS (US)	61	---	---
CosmOz (Australia)	13	---	several
TERENO (Germany)	17	>61	---
CEH (UK)	5	40	---
Saudi COSMOS	---	---	125
Other	>26	4	hundreds
TOTAL	**>122**	**>105**	**>125**

Year 2008:
Probes: 1

Year 2013:
Existing probes: 122+
Probes funded: 105
Probes proposed: 125+

Area-average hydraulic conductivity derived from COSMOS data