SoilSCAPE Wireless Sensor Network: Demonstration of Energy Efficiency, Extensibility, and NASA Mission Cal/Val Support

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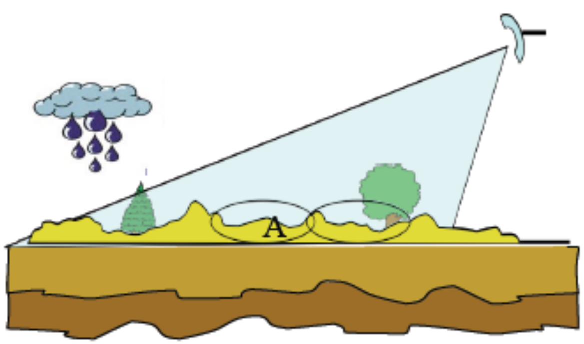
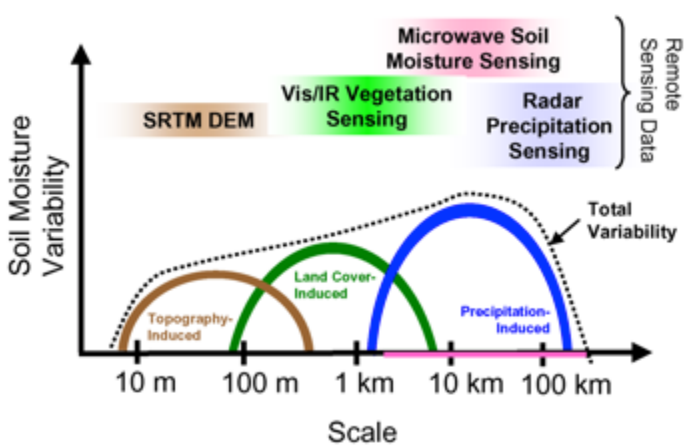
Background and Objectives (1)

Soil moisture Sensing Controller And oPtimal Estimator (SoilSCAPE)





Develop technologies for near real-time validation of multiscale spaceborne remote sensing products, such as soil moisture estimates from the Soil Moisture Active and Passive (SMAP) mission.

Soil moisture varies on spatial scales of meters to tens of kilometers, and temporal scales of minutes to days.

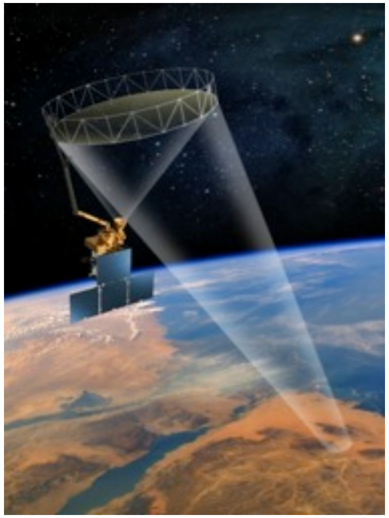
SMAP radar and radiometer each observe soil moisture, but with different spatial resolutions. Both capture lots of landscape heterogeneity due to large pixel sizes.

Validation of these multi-scale measurements requires adaptive temporal and spatial sampling strategies and upscaling method.

Data also used for AirMOSS EVS-1 mission validation.

Background and Objectives (2)

SMAP Facts



Objectives:
- Global high-resolution mapping of soil moisture and freeze-thaw state
- Link terrestrial water, energy, and carbon cycle processes
- Estimate global water and energy fluxes at the land surface

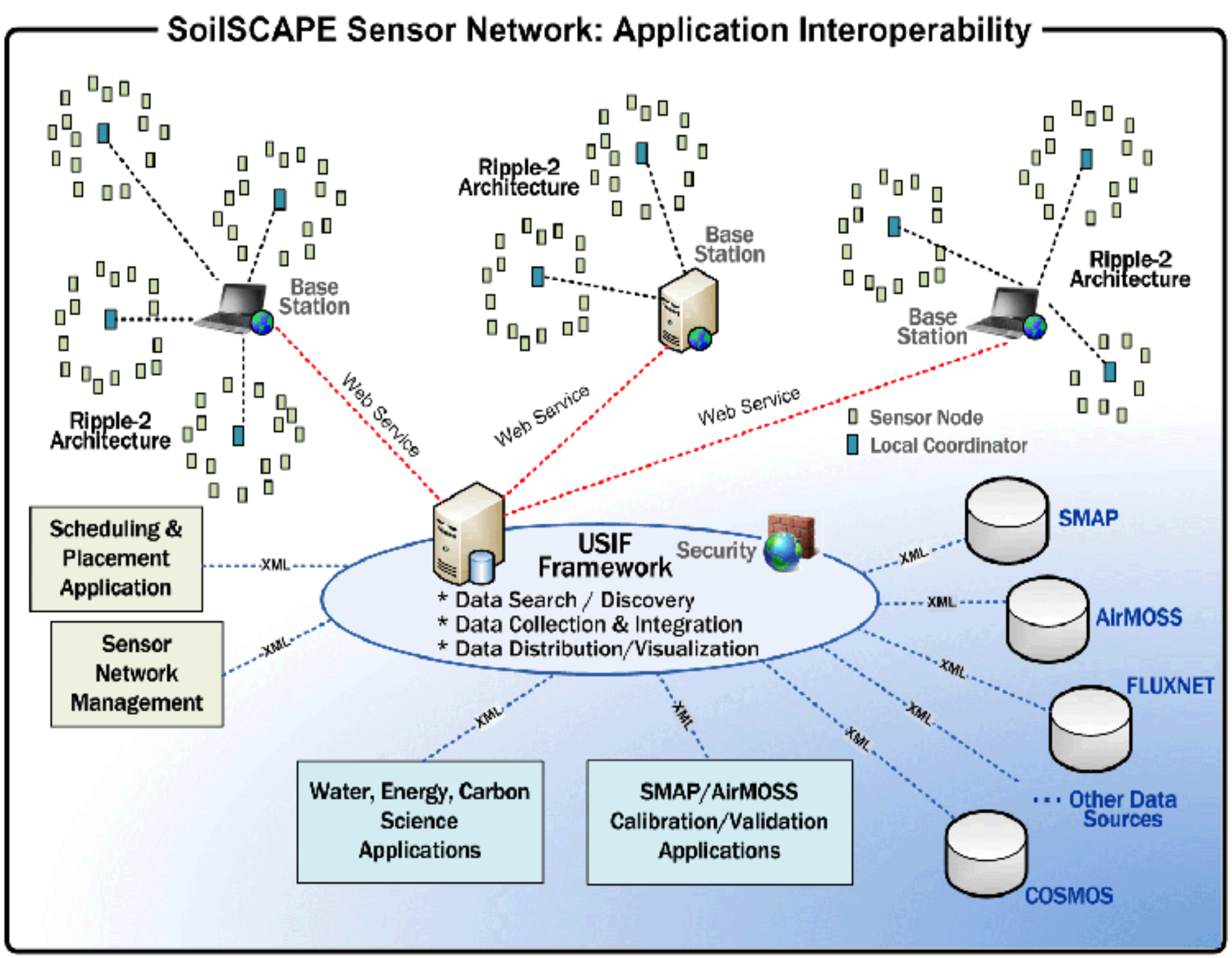
Instrument and Measurement Approach:
- L-band radiometer (36 km), L-band radar (3 km)
- Common 6m rotating antenna for 3-day global repeat coverage
- Merge radar and radiometer data for high-accuracy, mid-resolution, soil moisture

Mission Status:
- Launched successfully, January 2015
- Radar failed, July 2015; radiometer working well
- Validated Level 1 and 2 radar (3 km), radiometer (36 km), and joint (9 km) products released

Cal/val Plan:
- Take advantage of several cal/val "partners"
- Number of cal/val sites is ~20
- Core validation sites must meet spatial sampling criteria, data quality requirements, scaling function, and have easy & rapid data access
- SoilSCAPE is a cal/val site for SMAP and was first to provide near-real-time data

Background and Objectives (3)

Generalized SoilSCAPE Framework



Background and Objectives (4)

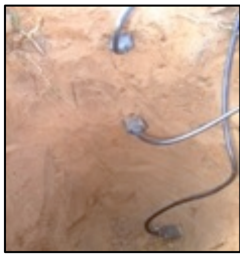
Specific Objectives of SoilSCAPE:

- Generalized wireless network Framework
  - Support large number of nodes in sparse network
  - Flexible network energy management to meet Earth science mission lifetime requirements
  - Energy-efficient nodes and devices
  - Sustained network reliability and reduced costs
  - Extensible network architecture; deployable in diverse environments
  - Adaptive scheduling of sensor nodes to maximize longevity
  - Accurate geophysical parameter process estimation

- Unified Science Information System Framework
  - Distributed Search/Discovery
  - Data Collection & Integration
  - Data Dissemination for science support (visualization and analysis)

Network architecture design

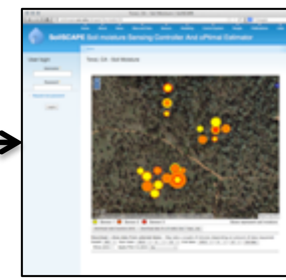
3 or 4 soil moisture sensors* at different depths (e.g., 5, 20 and 50 cm) called End Device (ED)






Wirelessly send data to Local Coordinator (LC) using custom 'BETS' protocol


Send back to USC lab from custom hardware via SMS or 3/4G

Decompress and add to MySQL database, accessible via website

* Decagon EC-5 or 5TM

Technology Overview (2)

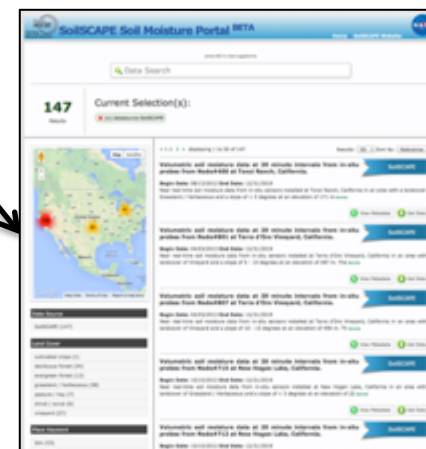
Network architecture design

Send data back using custom RPi H/W to USC lab via SMS or 3/4G

Decompress and add to MySQL database, accessible via website Soilscape.usc.edu

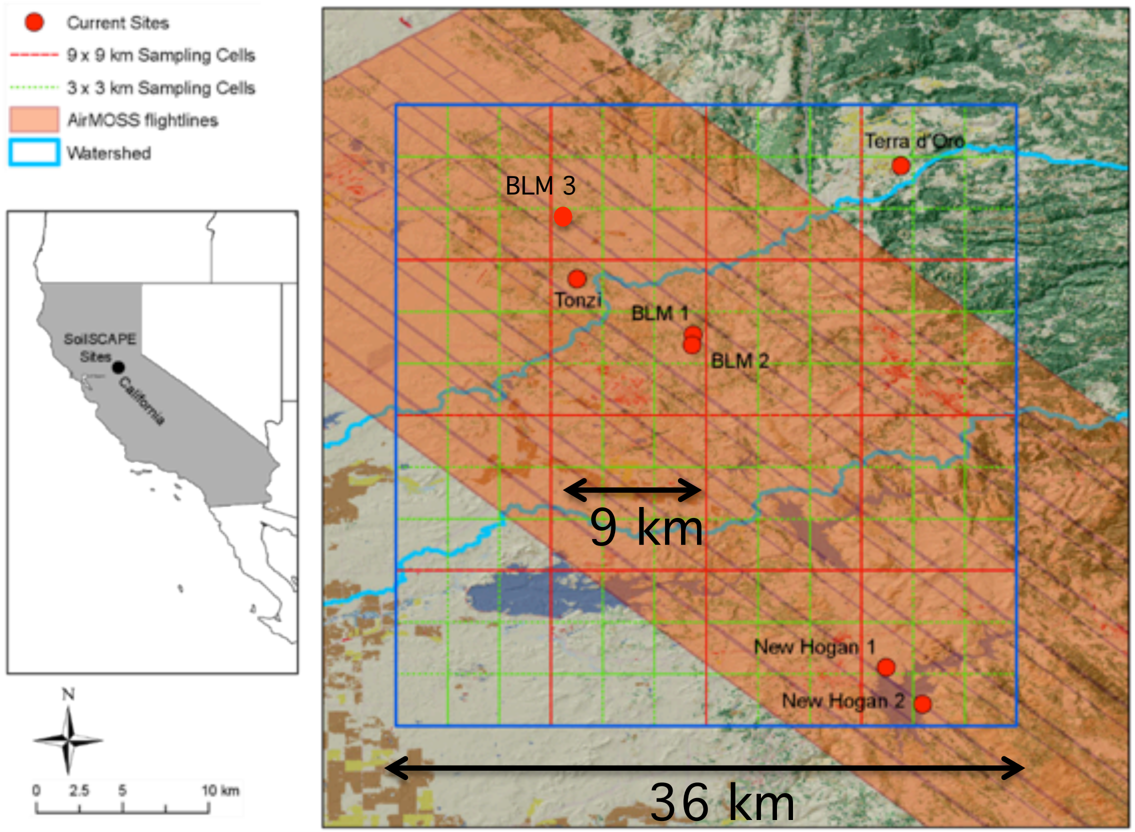
SMAP Data System at JPL

Search and discovery portal at ORNL



Files containing the last 7 days of data are created every hour for automatic pull by SMAP Cal/Val team at JPL

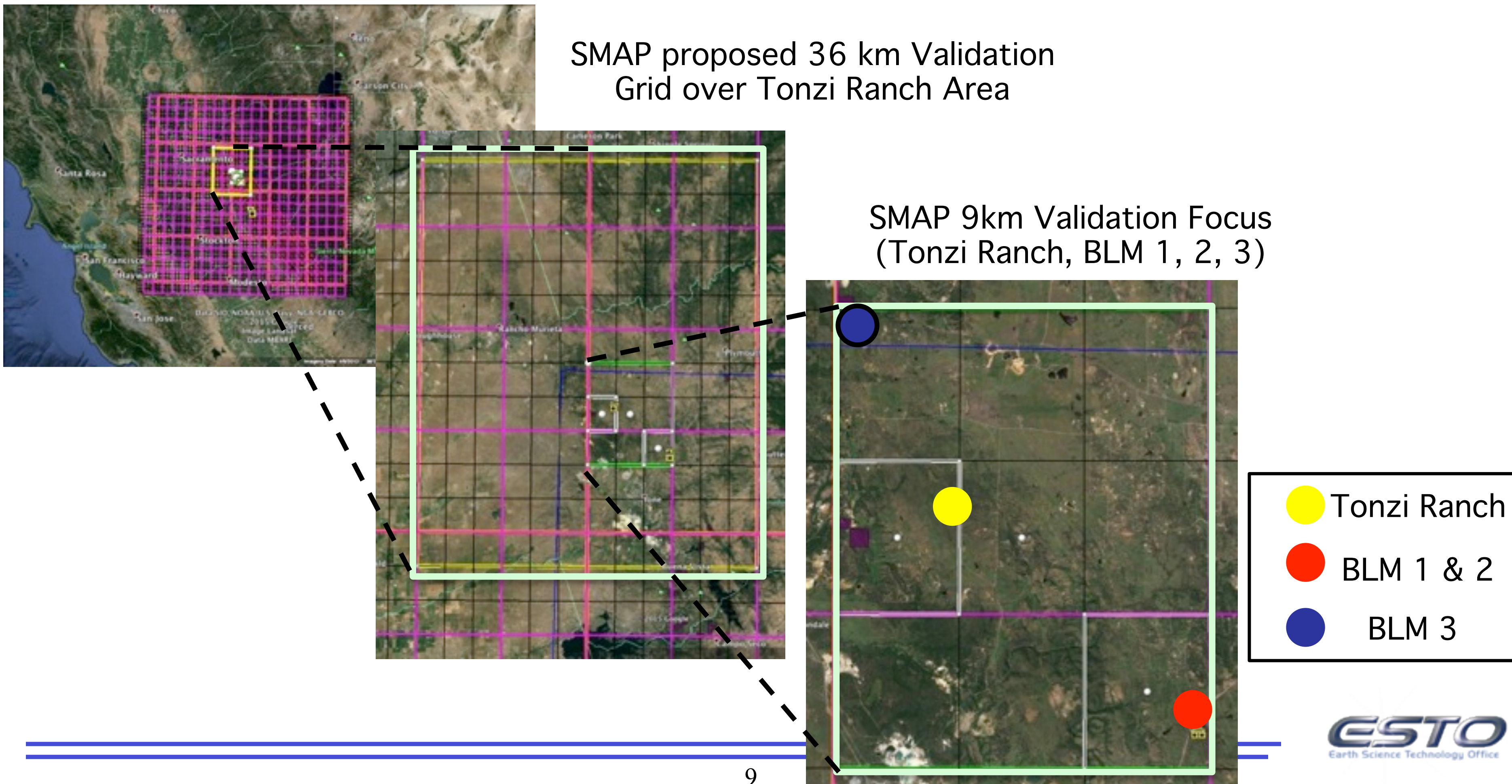
Network node distribution in SMAP cal/val site in CA (1)



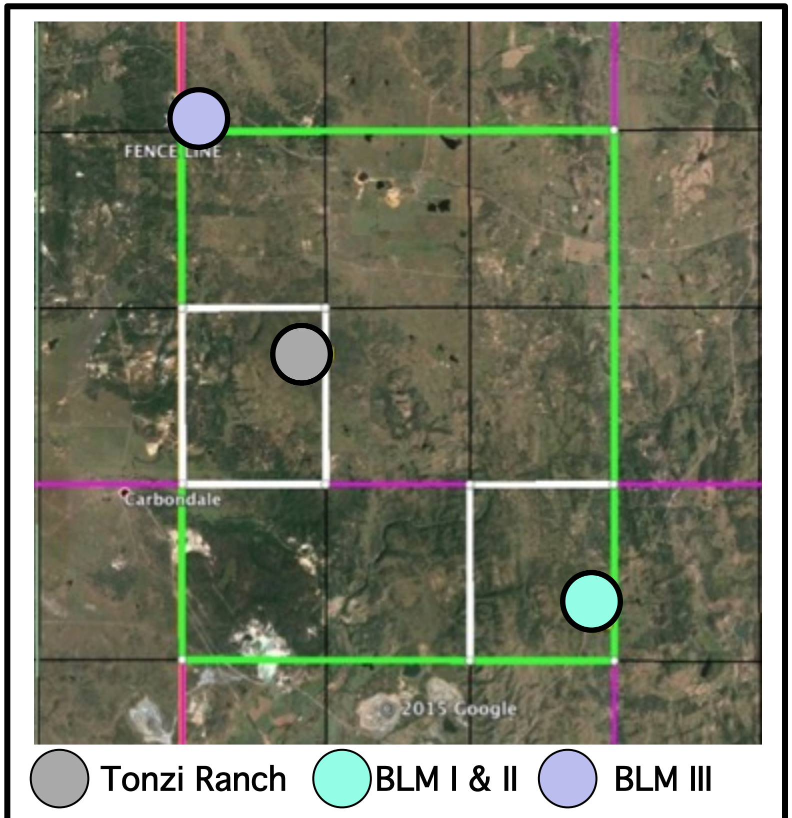
- 116 nodes operational over 7 sites
- Data available in near-real-time from soilscape.usc.edu
- SMAP nested pixel has 1 km, 3 km, 9 km, and 36 km scales

Network node distribution in SMAP cal/val site in CA (2)

- Network Distribution to support SMAP nested soil moisture pixels
  - Initial deployment focused on 3 km and 9 km cal/val pixels
  - With loss of SMAP radar, focusing also on 36 km pixel.



Network node distribution in SMAP cal/val site in CA (3)



- CA site total count is at 116
- Meeting SMAP sampling requirements for the 9 km validation pixel

Site	Location	# of Sensors	Land Cover*
Tonzi Ranch	North-Central California	18	Savanna
BLM I		17	Woody Savanna
BLM II		14	Woody Savanna
BLM III		5	Woody Savanna
New Hogan I		19	Open Shrubland
New Hogan II		14	Savanna/Grass
Terra d'Oro		28	Vineyard
Lucky Hills	Southern Arizona	8	Open Shrubland
Kendall		10	Grassland
Canton	Oklahoma	22	Pasture/Grassland
Total		156	

*Savanna & Woody Savanna represent ~ 15% of global land cover; Grasslands & Shrubs ~27%

Network node distribution in SMAP cal/val site in CA (4)

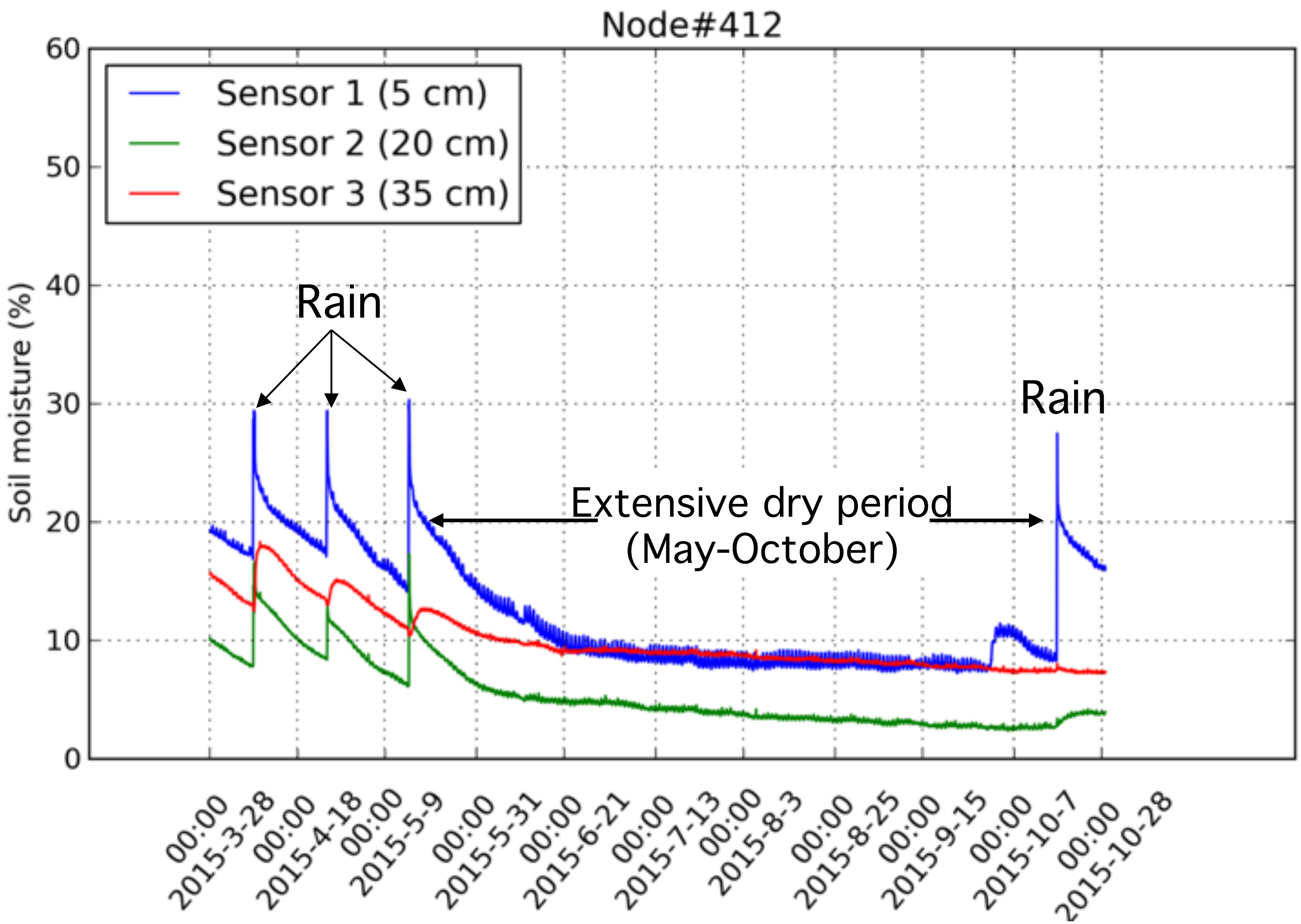
- What is the impact of SMAP radar failure on utility of SoilSCAPE network data?

  - SMAP radar failed on July 7, 2015
  - Main purpose of the radar was to enable medium-resolution (9 km) soil moisture products using an algorithm that used both the radiometer (36 km) and the radar (3 km) data
  - The radiometer products at 36 km are still being produced
  - Alternate methods are being investigated to get the 9 km product (other radar data, statistical methods, time-series data, etc.)
  - The SoilSCAPE 3 km and 9 km cells still used:

    - To validate the joint radar/radiometer 9 km product and the 3 km radar product for the 2.5 months when radar data were available; important for algorithm development and validation in the long run
    - To validate new algorithms for disaggregating the 36 km product to 9 km
    - To validate the 36 km product using our recent upscaling method
    - To validate the 36 km product using the SoilSCAPE stations that already exist but are not in the 9 km box

Network node distribution in SMAP cal/val site in CA (5)

"Textbook" Soil Moisture Response from Tonzi Ranch

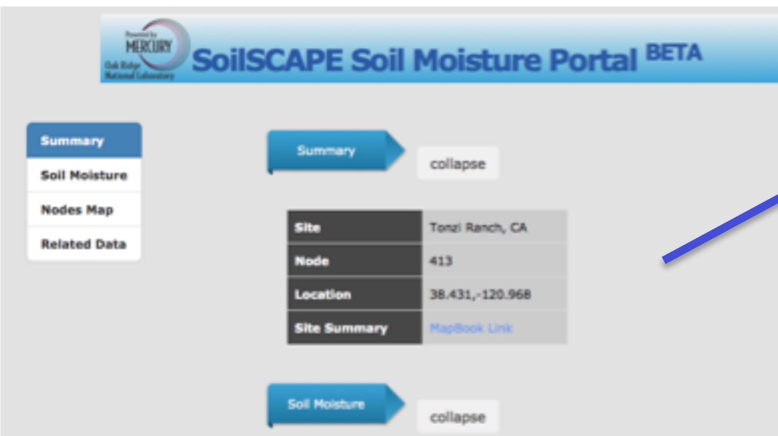


Jitters aren't noise, but rather diurnal soil moisture variation.

SoilSCAPE Data Portal: Visualizations

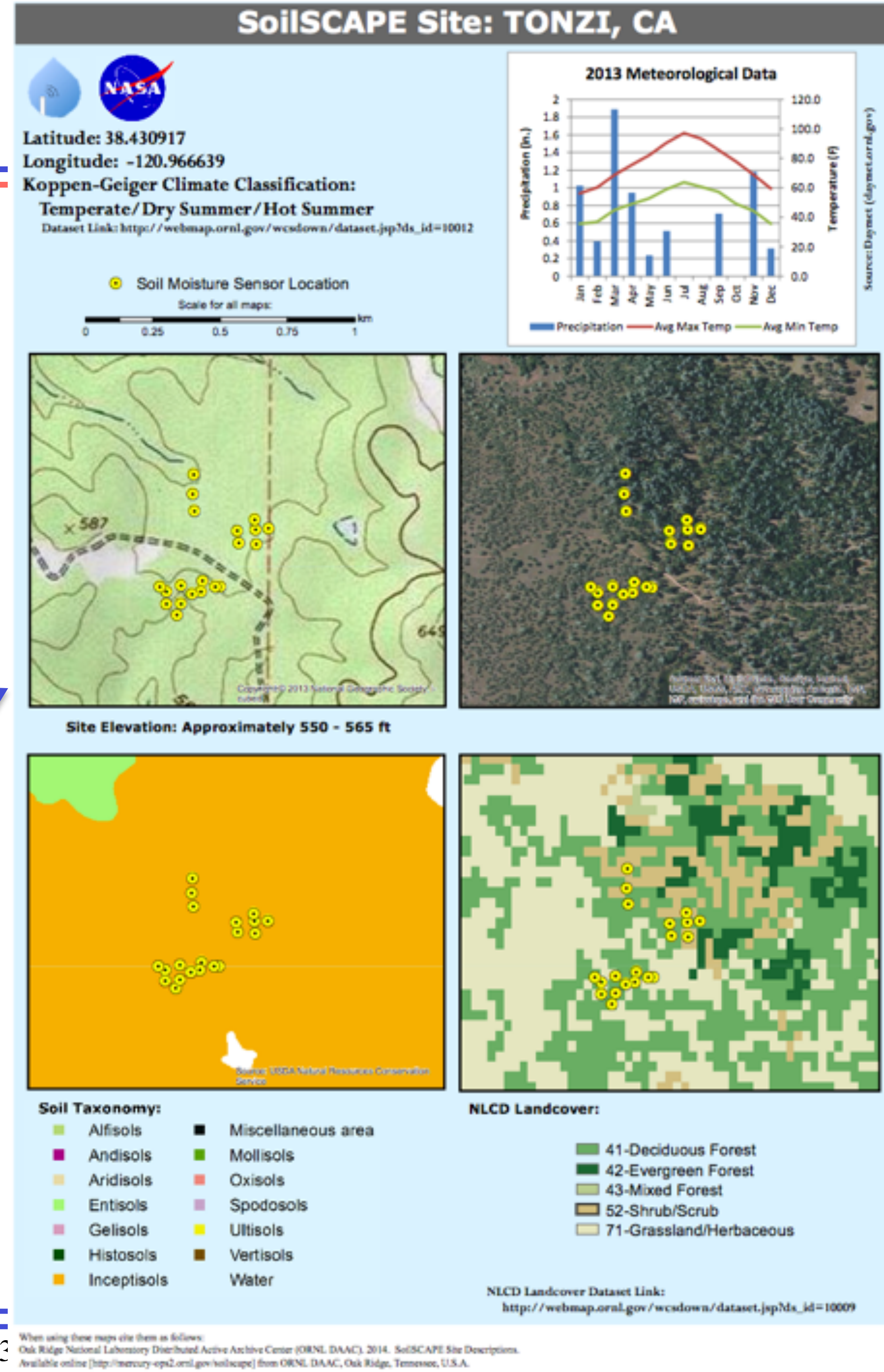
- Site summary info available for each site in a .pdf "MapBook" page

- More than 1200 page views since Jan 2015



http://mercury.ornl.gov/soilscape

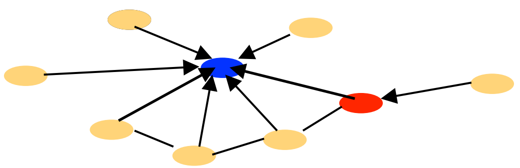
Slide courtesy of Alison Boyer and ORNL DAAC team



“Ripple”-series Architectures (1)

Ripple-1architecture:

- Sensor nodes (end devices) in star-shape multihop arrangement
- Base station (3G) at center, indoor, plugged in
- Xbee Pro SOC module to serve as MCU and radio
- Rechargeable batteries at end devices
- Longevity: days to months
- Sensor nodes per infrastructure node: ~8
- Heat/cold performance: poor



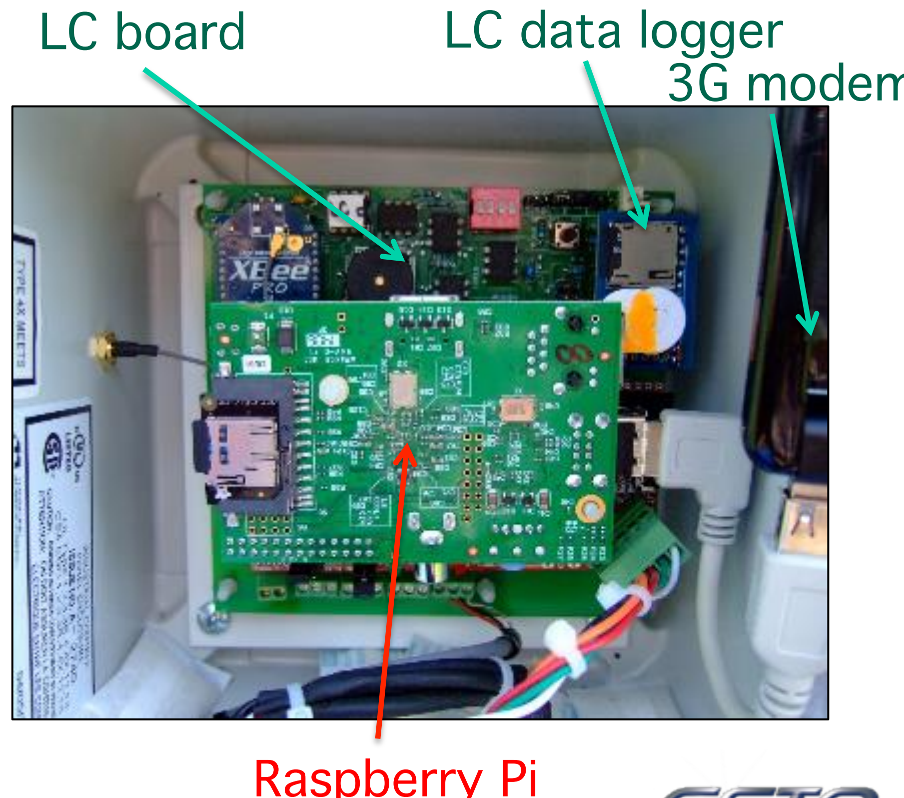
Ripple-2 and Ripple-3 architectures:

- End device → Local coordinator → SMS/3G/4G
- Nothing is plugged in; no indoor infrastructure (all unattended except the lab gateway)
- Raspberry Pi single board Linux computer and 3G modem
- Dual-freq network
- Non-rechargeable batteries at end devices
- Home-made protocol: “best-effort time slot (BETS)” alloction
- Longevity: 2 years+
- Sensor nodes per infrastructure node: ~60
- Heat/cold performance: excellent

"Ripple"-series Architecture (2)

Ripple-2 architecture

- All sites employ LC-RPi-3G: LC module + Raspberry Pi + 3G modem
  - ED-LC communication: 900MHz or 2.4GHz
  - New LC board version supports adaptive scheduling
  - Robustness: RPi/modem crash recovery



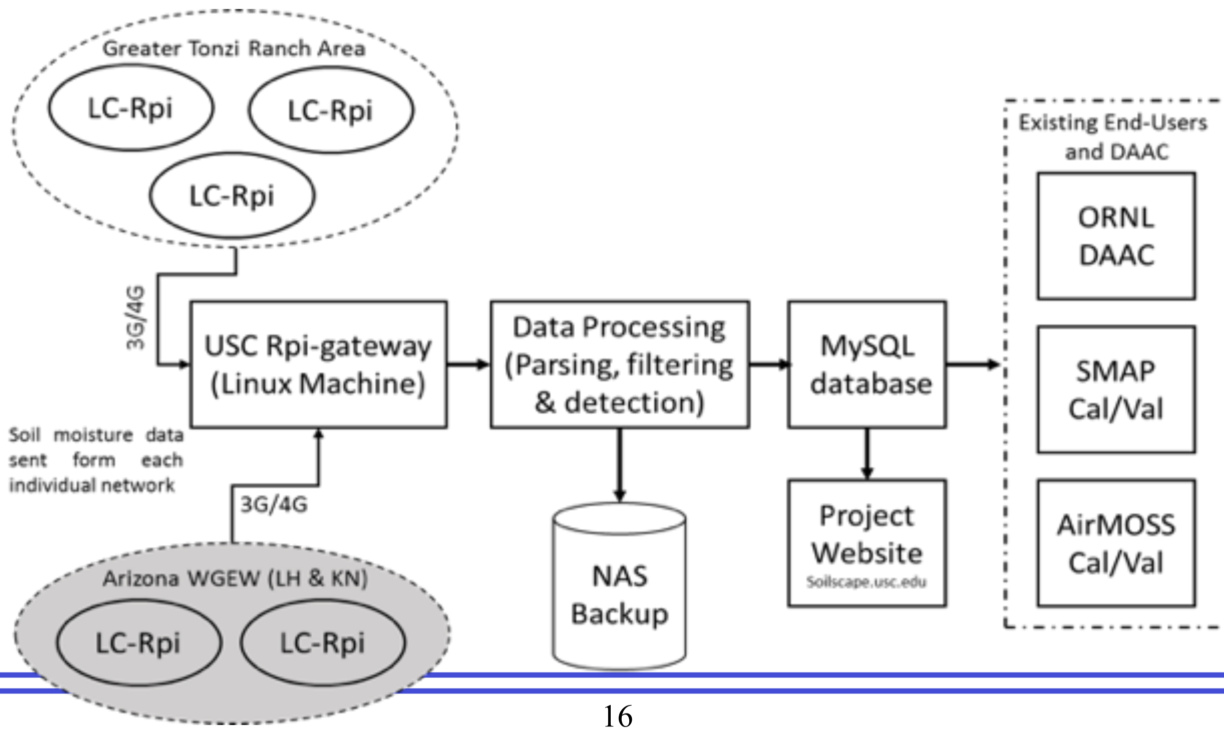
- All California SoilSCAPE sites employ Ripple2D+ ED nodes

- EC-5 probes made more robust

Ripple-3 architecture: latest SoilSCAPE upgrade

- Significant End-Device hardware upgrades and improvements
  1. On-board short-term memory (~ 1 month)
  2. Multi-level data redundancy: End-Device, Local Coordinator, Raspberry Pi, Database
  3. Intelligent Sensing: probe fault/short detection and flagging
  4. Dual sensor mode compatible: Analog (Decagon EC-5) & Digital (Decagon 5TM)

- All upgrades have been implemented & operational since 08/18/2015

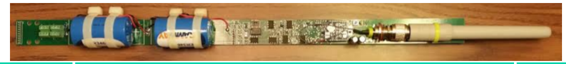


"Ripple"-series Architecture (4)

Ripple3 End Device Enhancements

- **Reliability**
  - Significant number of Ripple2 maintenances due to EC-5 probe fault: impact on the ED node (battery) and on data quality (noisy/bad data)
- **Data redundancy**
  - Measurements are saved in 4 places: ED node, LC module, RPi module, and at the Data Server
- **Support for modern digital probes**
  - Ripple3 supports 5TM digital probe
  - Can be software-adapted to support the SDI-12 specification
- **Future: Extensibility and converting Ripple3 into a low-cost datalogger**
  - To be used to cover very large areas
  - LC+ED integrated; no LC-ED network
  - Implementation: Ripple3 + Rpi + 3G modem + power module
  - Multiple soil measurements during the day
  - Few 3G transmissions to the Data Server (application-specific)
  - No solar panel and lifetime ~1 year

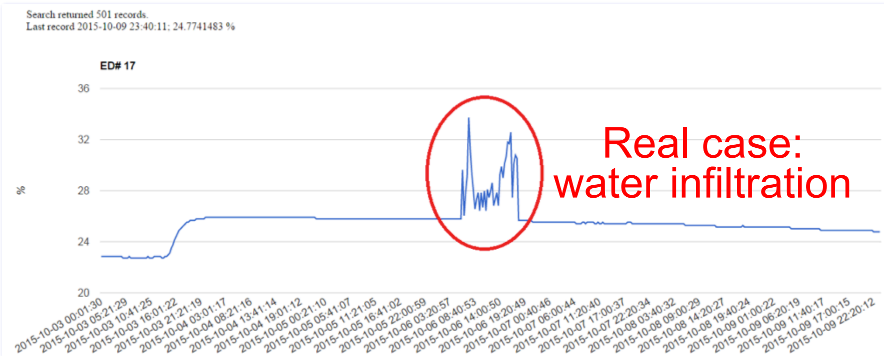
"Ripple"-series Architecture (5)



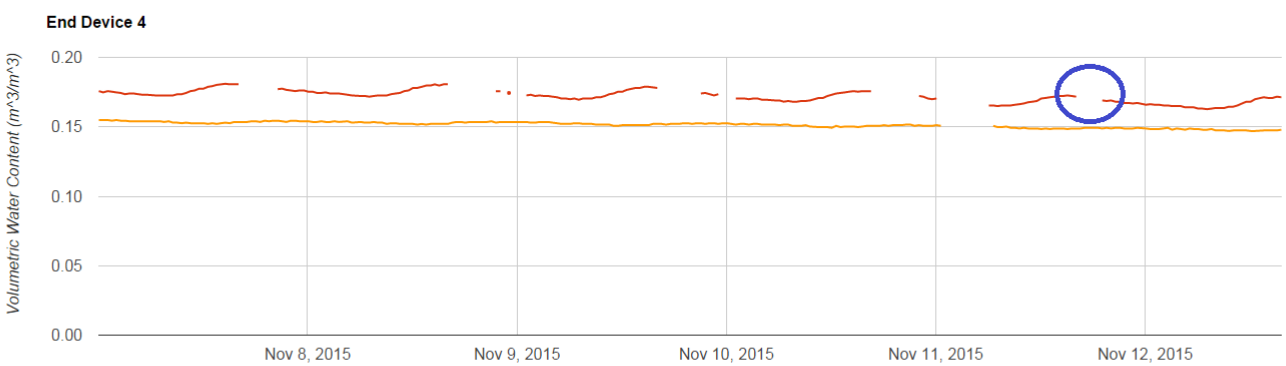
Feature	Ripple-1 thru 2D	Ripple2D+	Ripple3
Energy Management	Rechargeable battery ED&LC; plugged in base station	Non-rechargeable battery at ED, solar at LC	Non-rechargeable battery at ED, solar at LC
Longevity	Days to weeks	2+ years	3+ years expected
# of Sensor ports per ED	3 (analog)	4 (analog)	8 (4 analog, 4 digital)
Isolated power lines	No	No, shared	Yes, 8 isolated lines
User-defined probe power profile*	No	No	Yes
User-defined probe measurement valid range*	No	No	Yes
Detection/isolation of short-circuited probes*	No	No	Yes
Detection of unresponsive probes	No	No	Yes, for digital probes
Internal datalogger	No	No	Yes (128k B)

* Not available in any existing commercial hardware

"Ripple"-series Architecture (6)



Can a sensor node auto-flag its own measurements?



Data-server algorithms become more efficient in reconstructing missed/flagged data

Ripple-3 has this "intelligent sensing" feature:

- All data still transmitted but bad data are flagged
- Criteria: power consumption signature, valid data range, spatio-temporal soil moisture gradient heuristic (user-defined and uploaded to the node)

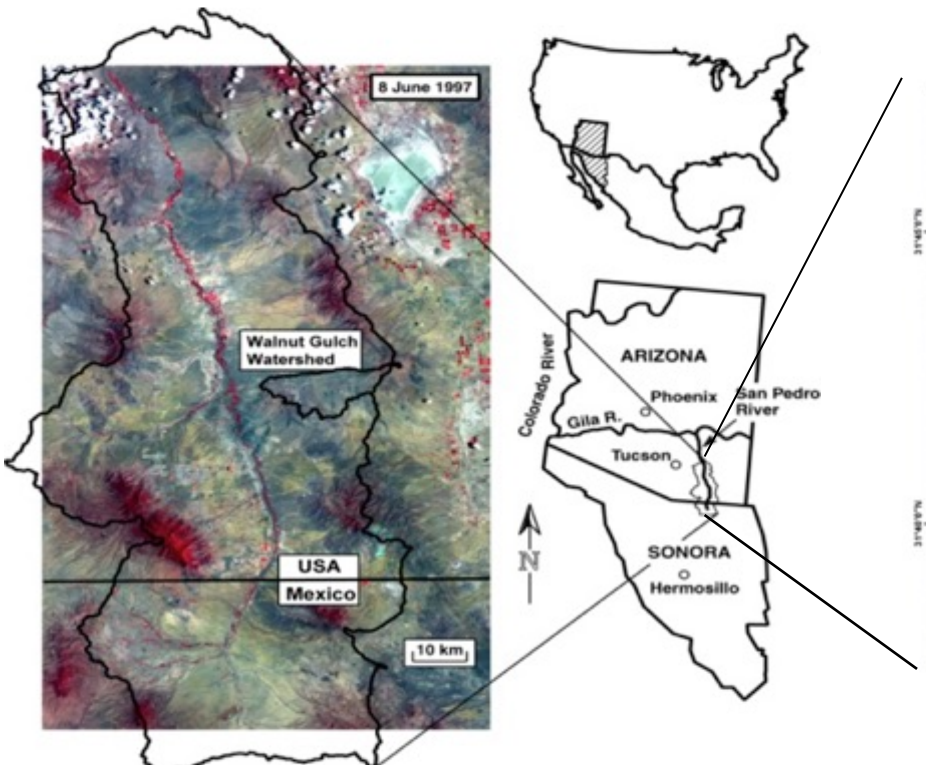
Sensor and Node Deployment Statistics

State	Site	Number of Nodes	Node Density (nodes ha^{-1})	Maximum distance from LC (m)
California	Tonzi Ranch	19	1.45	340
	New Hogan 1	14	1.66	257
	New Hogan 2	18	1.05	346
	Terra d' Oro	27	1.50	317
	BLM 1	17	4.73	207
	BLM 2	16	5.09	145
	BLM 3	3		50
Arizona*	Lucky Hills	7		200
	Kendall	10		480

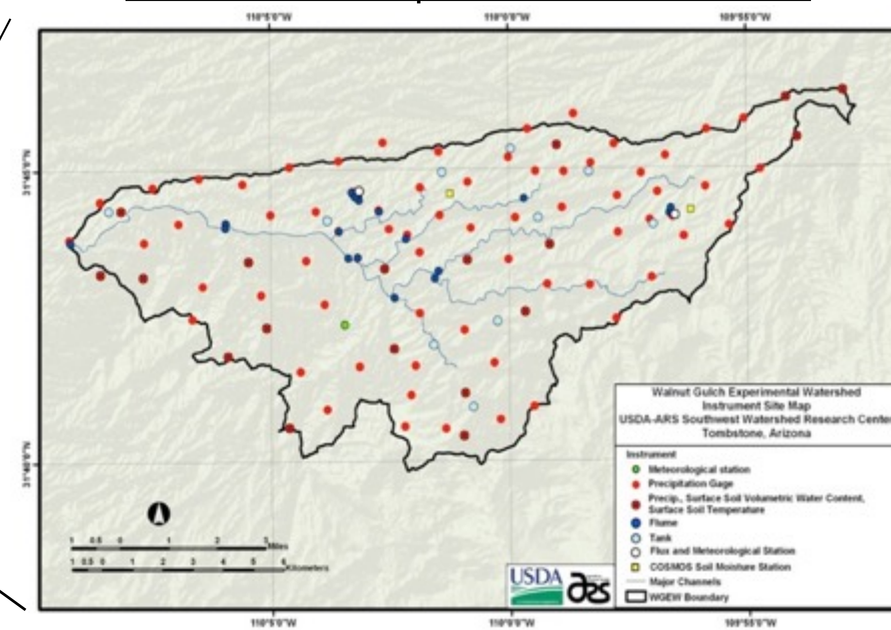
* Upgraded to Ripple 3 for Arizona.

Expansion to Walnut Gulch, AZ (1)

- New network site in Tombstone, Arizona: deployed August 2015
- Science objectives
  1. Support ongoing SMAP Cal/Val activities in Walnut Gulch Experimental Watershed* (WGEW)
  2. Support regional & small scale studies in WGEW
  3. Technology expansion & adaptation



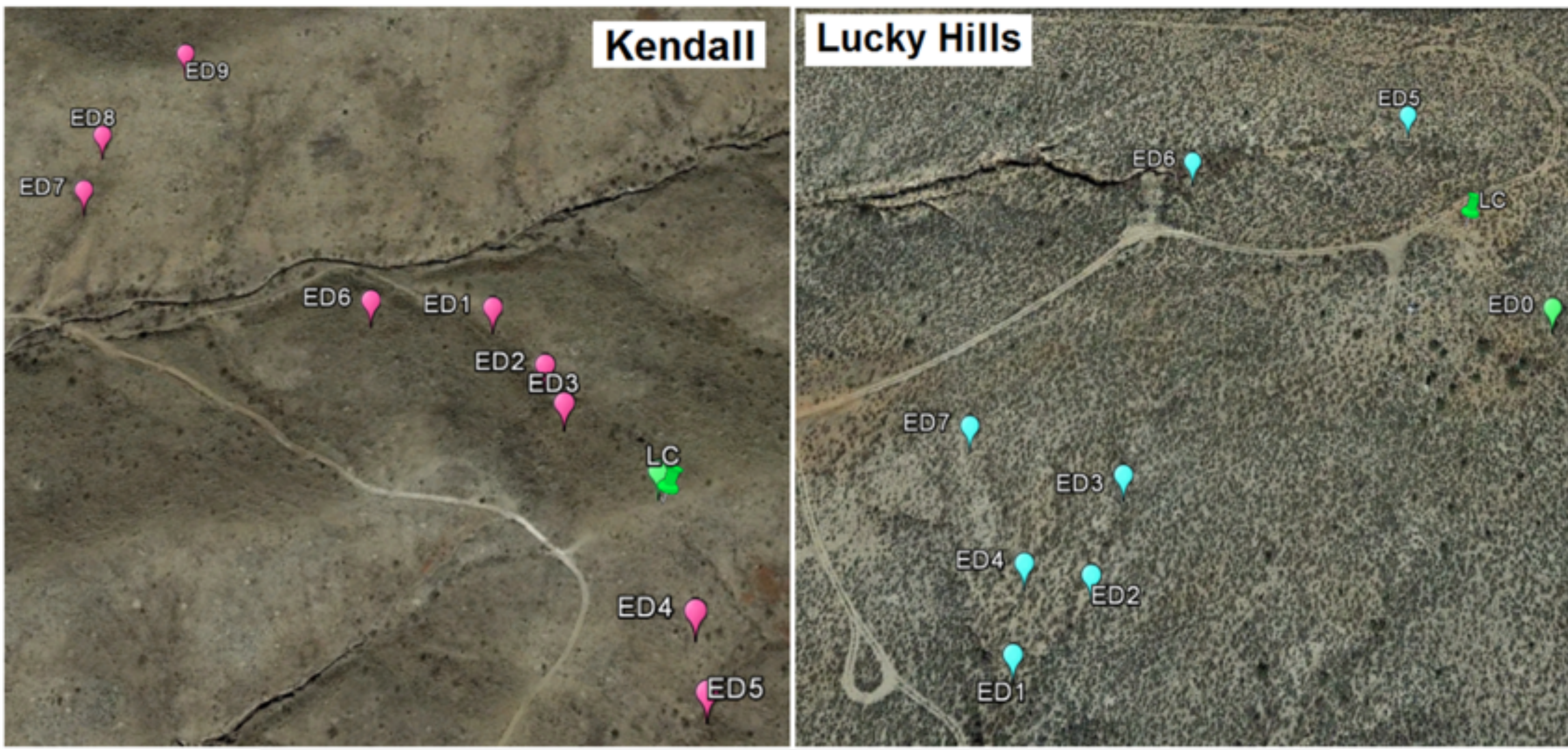
Walnut Gulch Experimental Watershed



*The USDA-ARS Walnut Gulch Experimental Watershed (WGEW) is operated by the Southwest Watershed Research Center (SWRC) is a 150 km² watershed. It has been extensively studied since 1953 and is one of the most intensively instrumented semiarid experimental watersheds the world.

Expansion to Walnut Gulch, AZ (2)

- Two new sites identified, with help from local USDA-ARS research teams*
- Lucky Hills (LH)
  - Open shrubland
  - 8 End Devices
  - Sensors from 5cm to 75cm
- Kendall (KN)
  - Grassland
  - 9 End Devices
  - Sensors 5cm to 50cm
- Long term, both LH & KN have been heavily monitored (TDR, Flux towers, etc.)

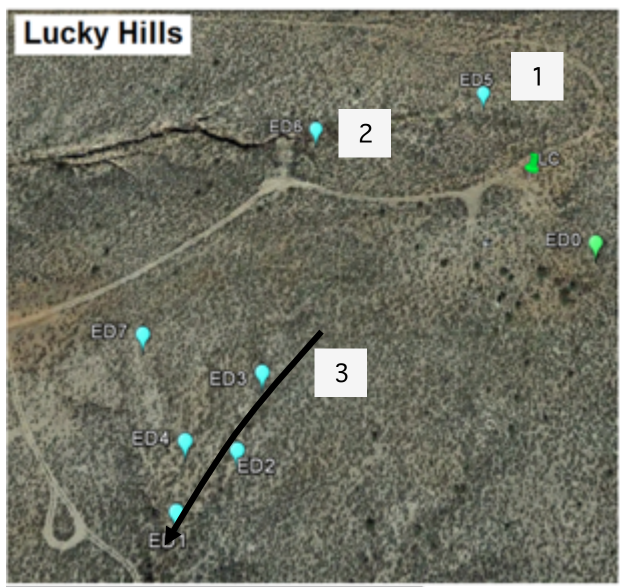


* Special thanks to: John Smith, Russ Scott, Joel Biederman, Leland Sutter from USDA-ARS and UA

Expansion to Walnut Gulch, AZ (3)

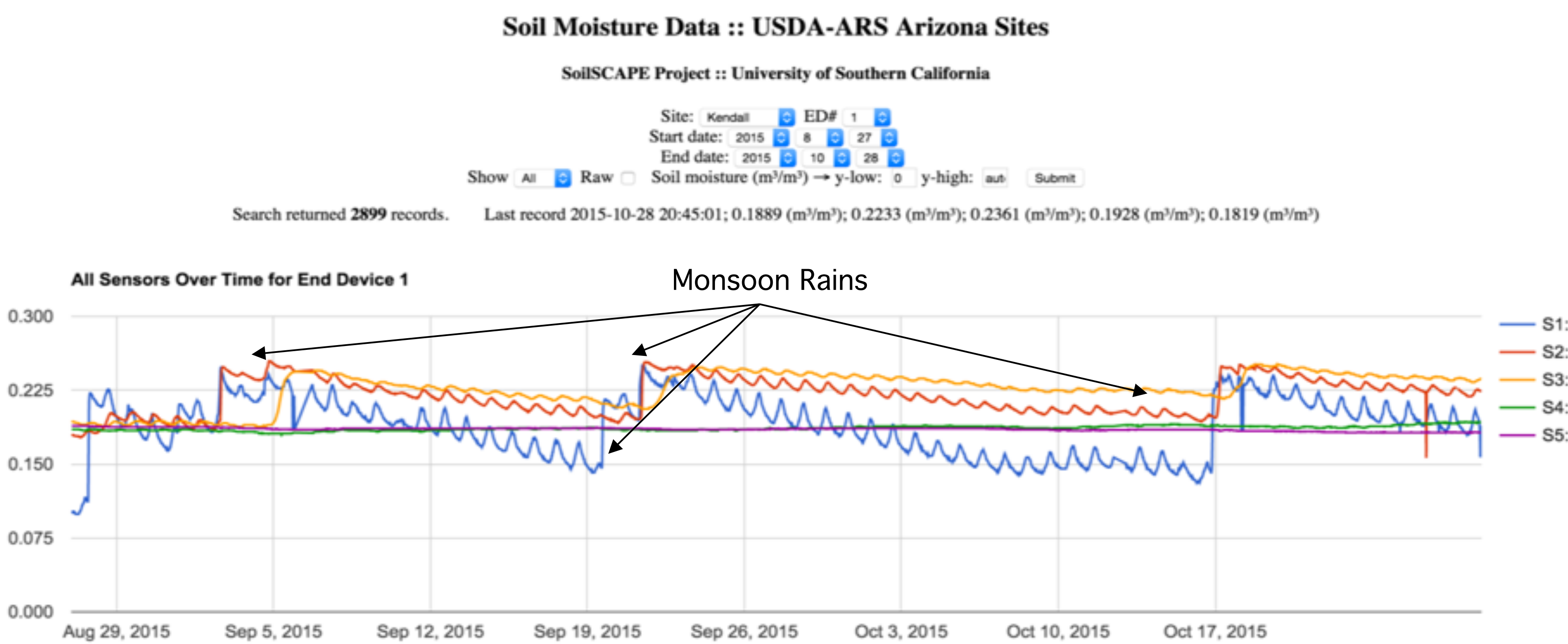
- Existing soil moisture infrastructure
  - Very limited and over a decade old
  - Does not quantify soil moisture variations at the sub 500m scales
  - Affects understanding controls on ecohydrological state and fluxes within the watersheds

- SoilSCAPE Impacts
  - Capturing local soil moisture heterogeneity due to topography, soil type, and solar aspect variation
  - Better understanding of channel erosion and soil moisture with sensors in proximity



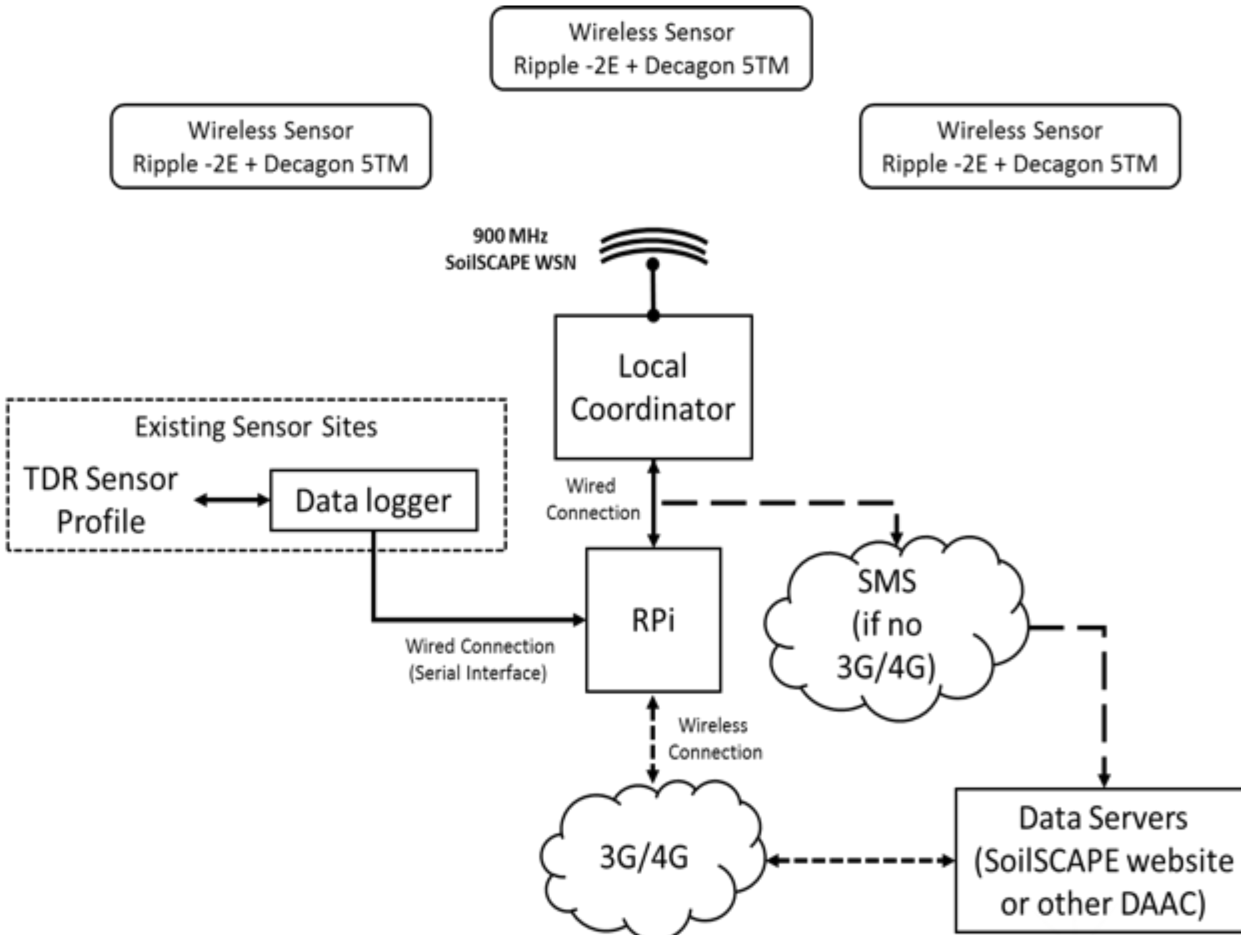
Expansion to Walnut Gulch, AZ (4)

- Near-real time data delivery (30min sampling schedule)
- Web-based visualization (beta) and free data download
- Continued integration with ORNL DAAC



Interface with legacy hardware

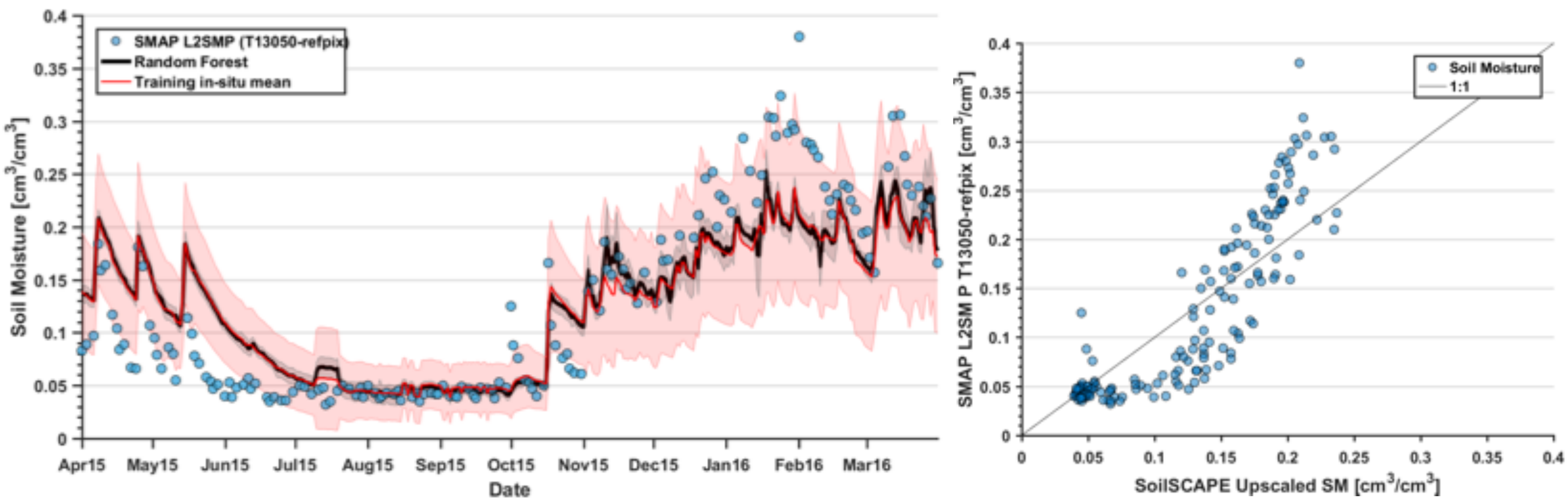
- Legacy technology integration and demonstration at a 3rd site underway: SoilSCAPE network as add-on to existing sensors and dataloggers
- Database and web interface improvements
- Forwarding and data integration within ORNL DAAC



Cal/Val Utilization of SoilSCAPE Data (1)

- SMAP and AirMOSS calibration and validation (Cal/Val)
- California data used in all SMAP data product cal/val activities
  - Radar-only at 3km, Radiometer-only at 36 km, and Radar-Radiometer at 9 km
  - Overall excellent agreement with SMAP products

SMAP Radiometer-only Soil Moisture vs. Up-scaled SoilSCAPE Soil Moisture (April 1st 2015 – March 31st 2016)

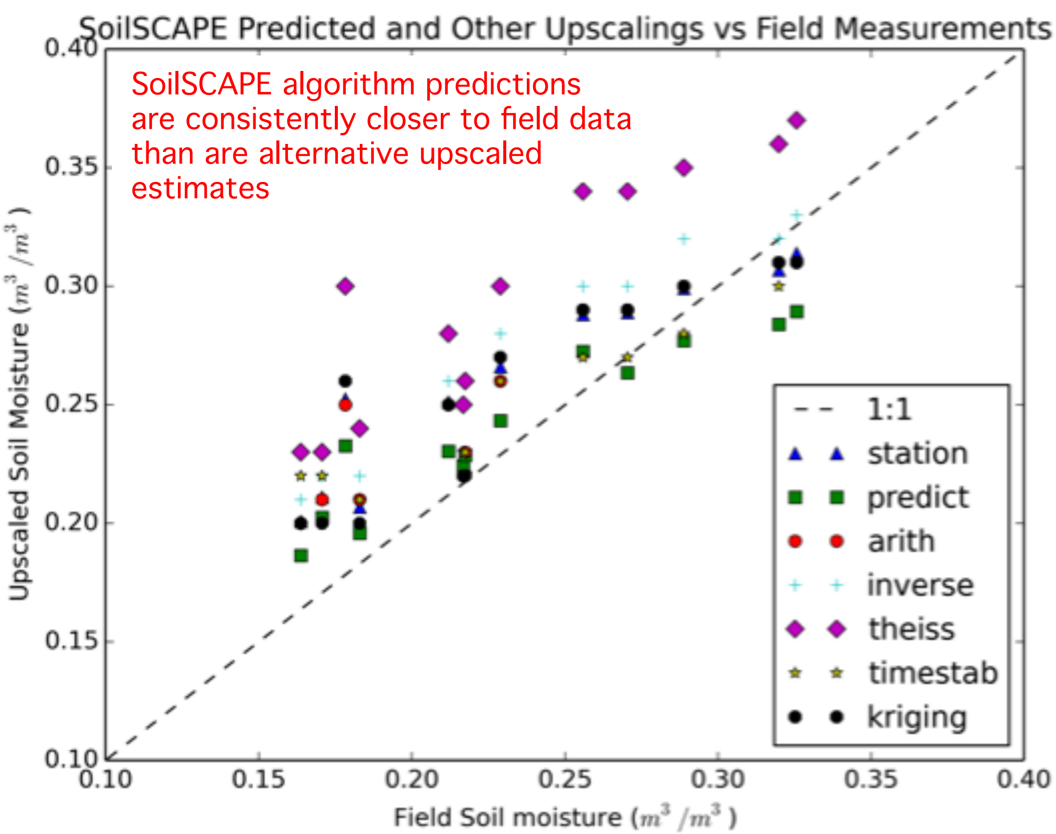


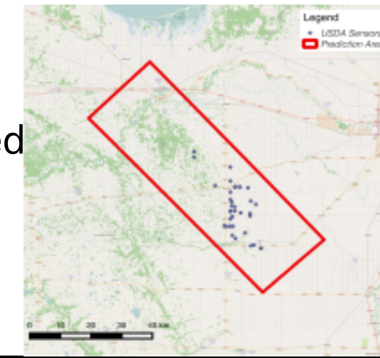
Errors (cm³/cm³)	RMSE	Bias	ubRMSE
RF vs. SMAP	0.045	-0.003	0.0448

Cal/Val Utilization of SoilSCAPE Data (2)

Scaling analysis: Validation Results

SoilSCAPE Random-Forests-based scaling algorithm produces significantly improved soil moisture mean estimation relative to alternative upscaling techniques





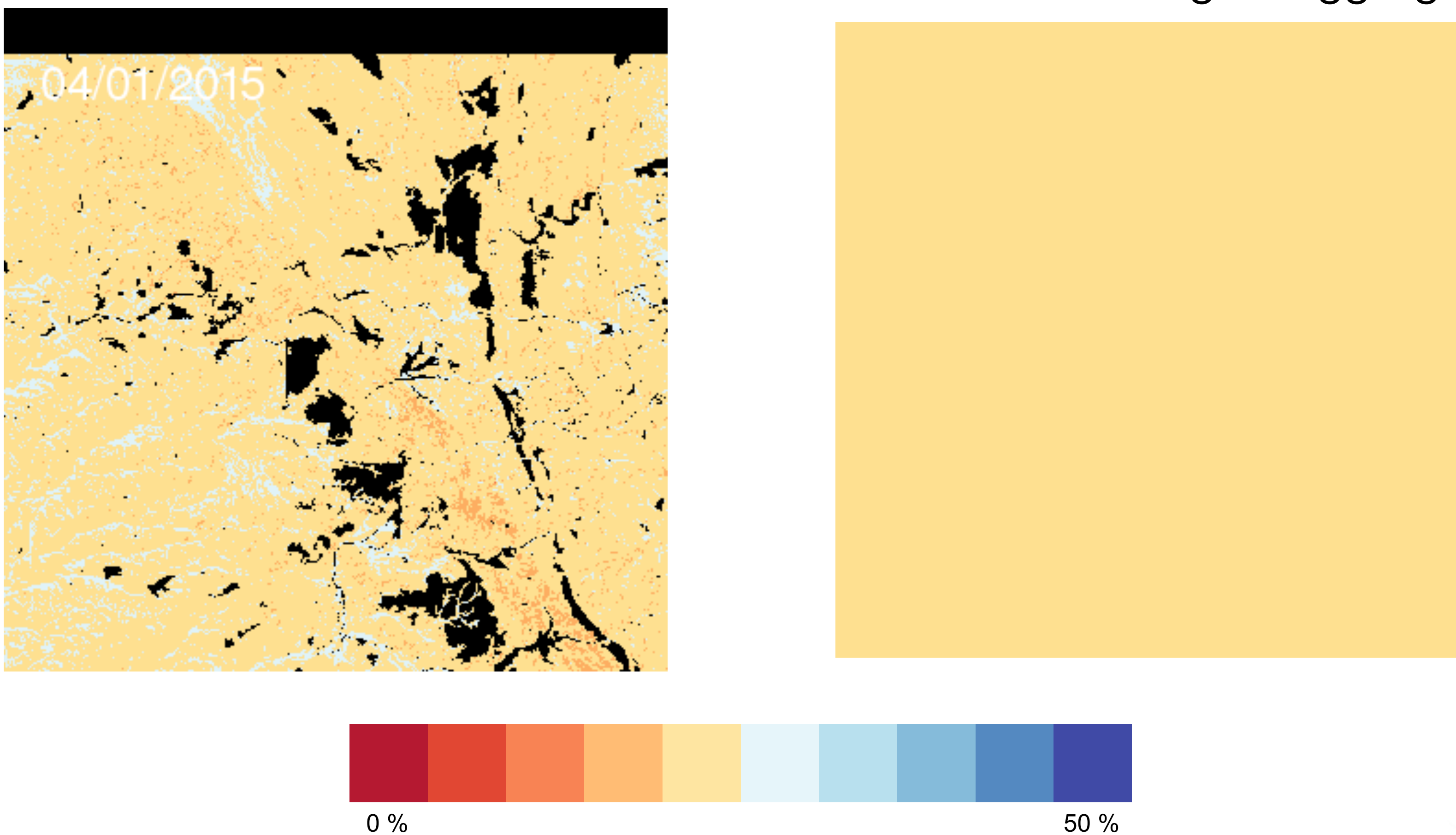
Method	RMSE (m^3/m^3)	Bias (m^3/m^3)
Station	0.033	0.023
SoilSCAPE (Random Forest)	0.026	0.008
Arithmetic Average	0.032	0.023
Inverse Distance	0.041	0.034
Theissen	0.067	0.063
Timestab	0.036	0.021
Kriging	0.033	0.022

Cal/Val Utilization of SoilSCAPE Data (3)

Up-scaled Soil Moisture: Greater Tonzi Ranch Area

RF 100m Estimates

RF 9km EASE grid Aggregates



Summary

- Networks at Tonzi ranch, CA, have demonstrated continuous operation for well over two years
- Technology demonstration expanded and extensibility shown in Walnut Gulch, Arizona, with significant device upgrades
- Have designed, implemented, and demonstrated operation of open architecture
- Continued support of SMAP and AirMOSS cal/val activities
- Plans for near future: Boreal and arctic science support (esp. permafrost for ABoVE campaign)

http://soilscape.usc.edu/