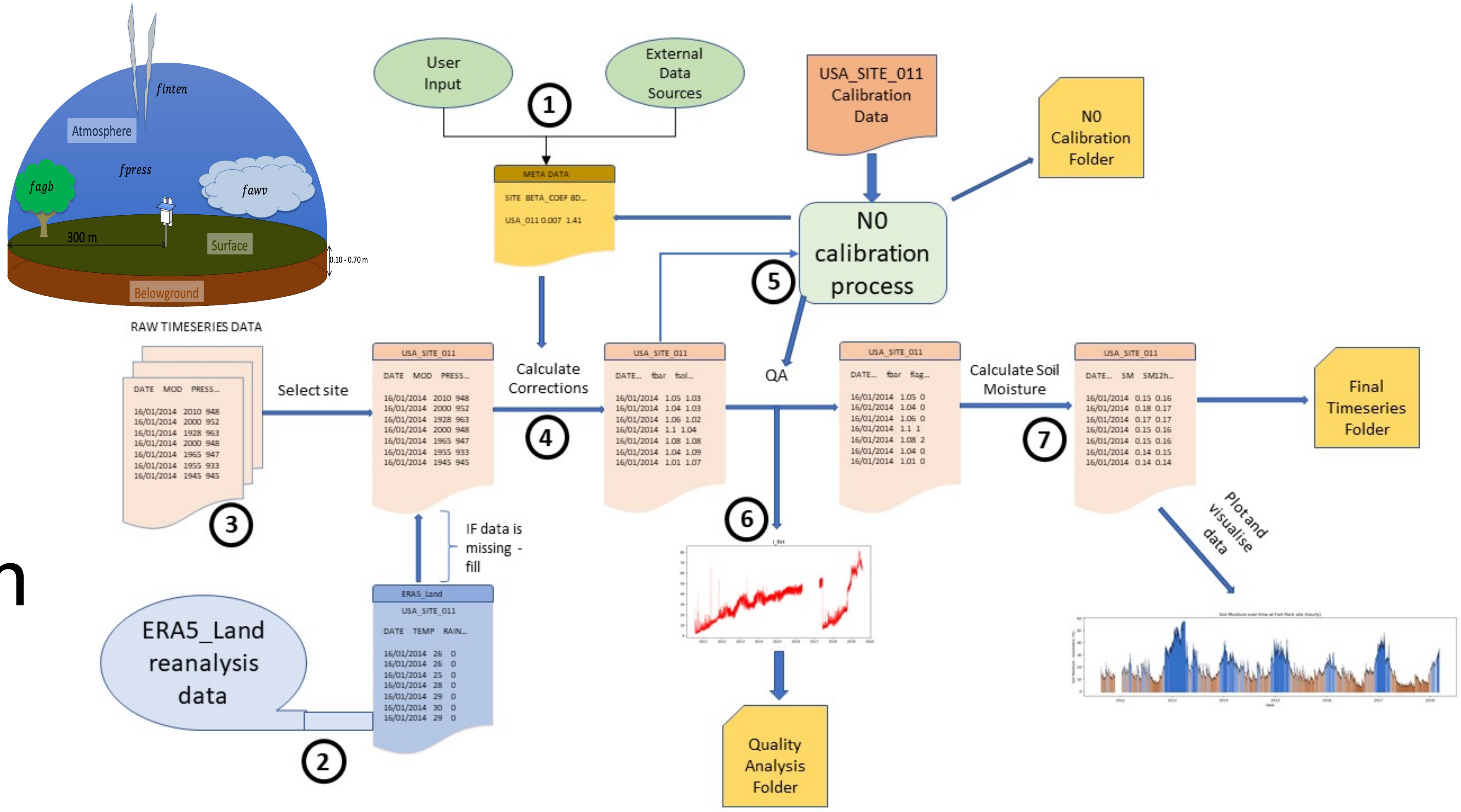
Efforts to a harmonized data processing approach for cosmic-ray neutron sensors



Rafael Rosolem

University of BRISTOL

At the end of this lecture, you should…

- Recognize national-scale networks of cosmic-ray neutron sensors for soil moisture networks
- Understand the current challenges related to the establishment of a global-scale network of cosmic-ray neutron sensors
- Be aware of current efforts to harmonize global datasets of cosmic-ray sensors and their important quality control and processing steps

A quick recap

Over the years, the community has learned more about the cosmic-ray neutron sensors

$$\theta_{VOL} = \left[\frac{a_0}{\frac{N_{pihv}}{N_0} - a_1} - a_2 - LW - SOC\right] \cdot \rho_{bd}$$

where

$$N_{pihv} = N_{raw} \cdot f_p \cdot f_i \cdot f_h \cdot f_v$$

Based on Franz et al. (2012), Rosolem et al. (2013); and Baatz et al. (2015?)

θ_{VOL} = volumetric water content (m^3 m^{-3})
N_{pihv} = fully-corrected measured neutron counting rate (counts per hour)
N_{raw} = raw measured neutron counting rate (counts per hour)
N_0 = site-specific calibration parameter
LW = lattice water content (g g^{-1})
SOC = soil organic carbon (g g^{-1})
ρ_{bd} = dry soil bulk density (g cm^{-3})
f_p = atmospheric pressure correction factor (-)
f_i = solar intensity correction factor (-)
f_h = atmospheric water vapor correction factor (-)
f_v = aboveground biomass correction factor (-)
a_0, a_1, a_2 = fixed coefficients (-)

The cosmic-ray neutron sensor signal is affected bby all sources of hydrogen within its support volume

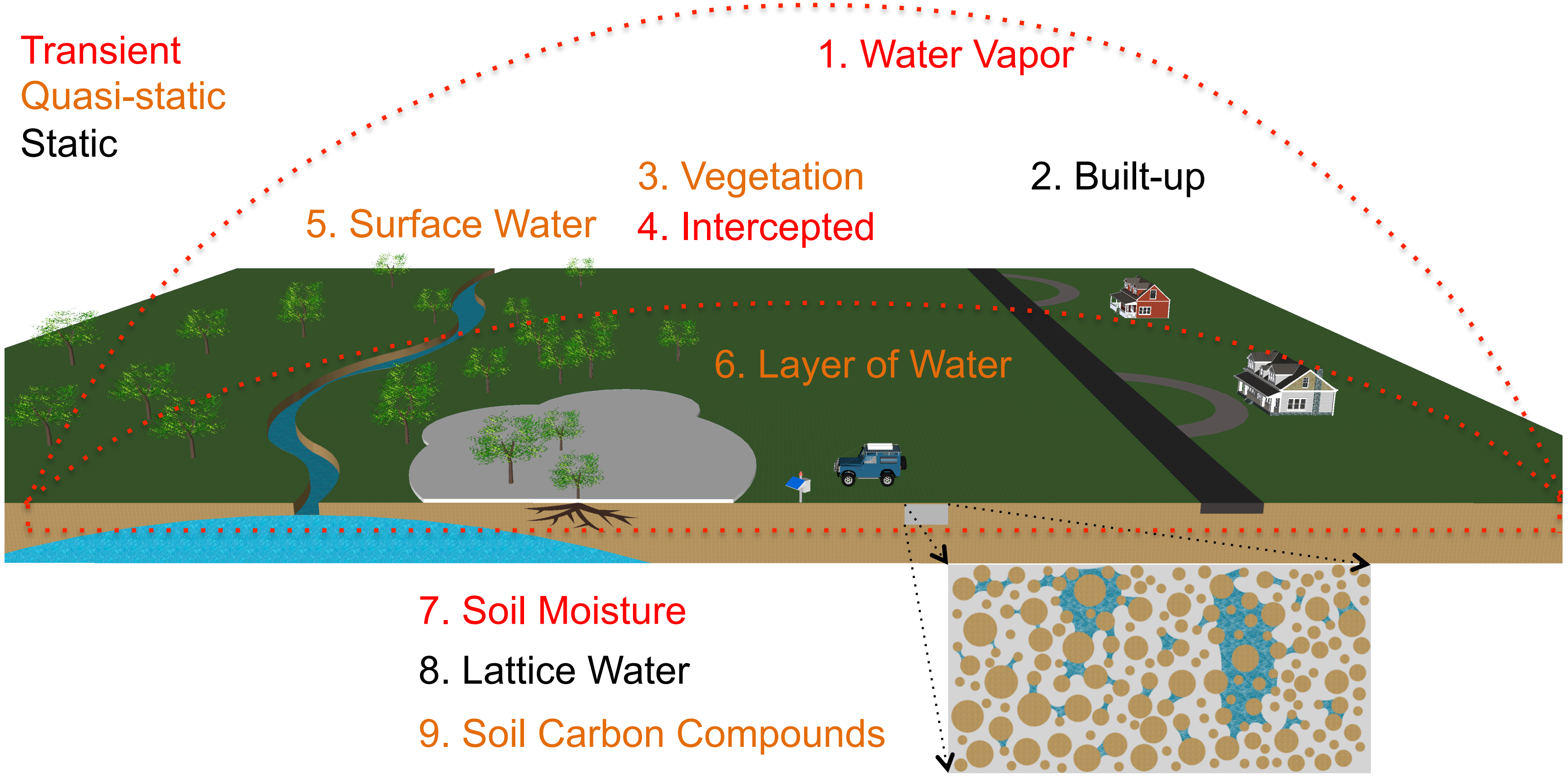
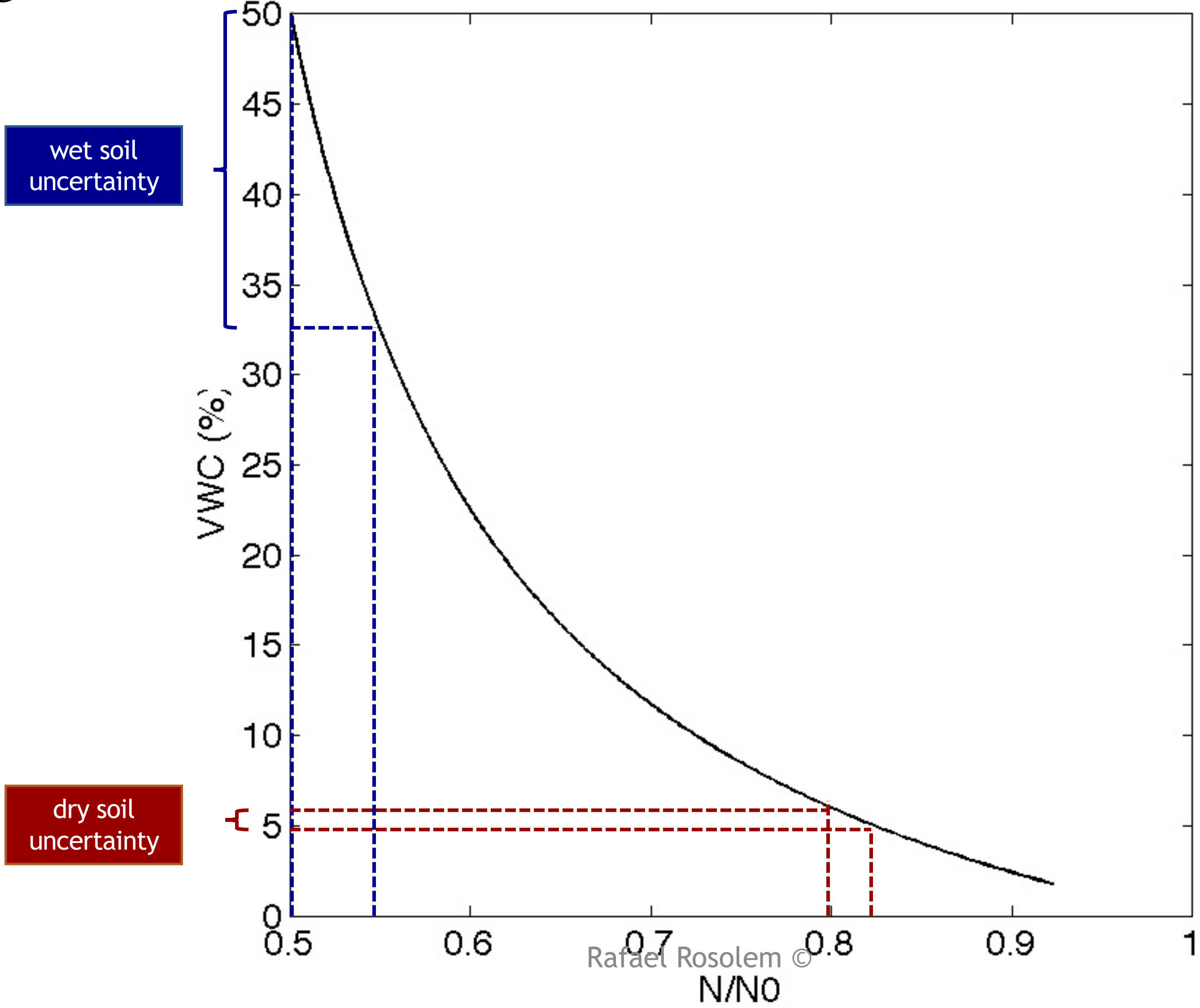


Image kindly provided by Trenton Franz (Nebraska-Lincoln)

Propagation of uncertainty: dry versus humid regions



In a humid region:

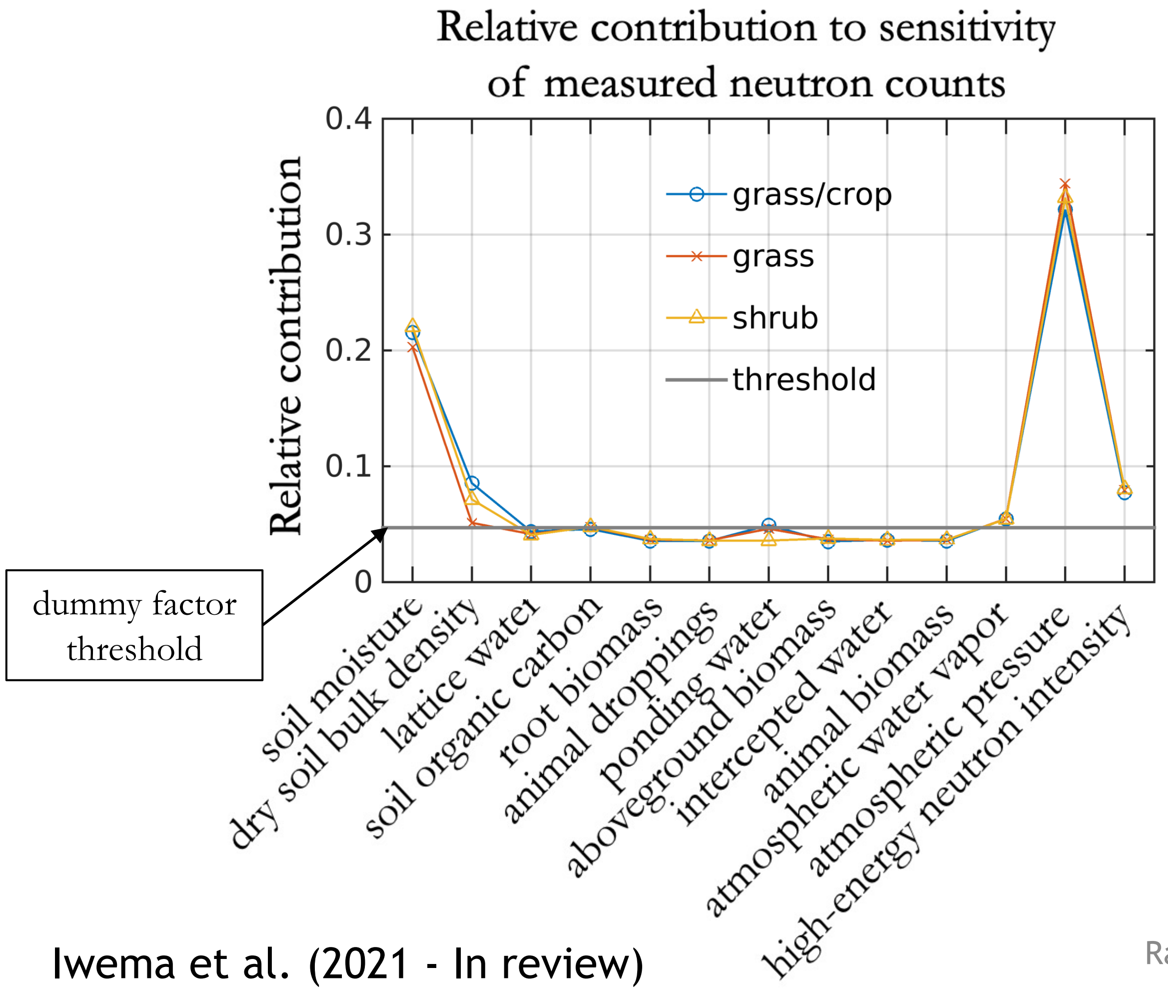
Uncertainty of neutron counts on the order of 5%

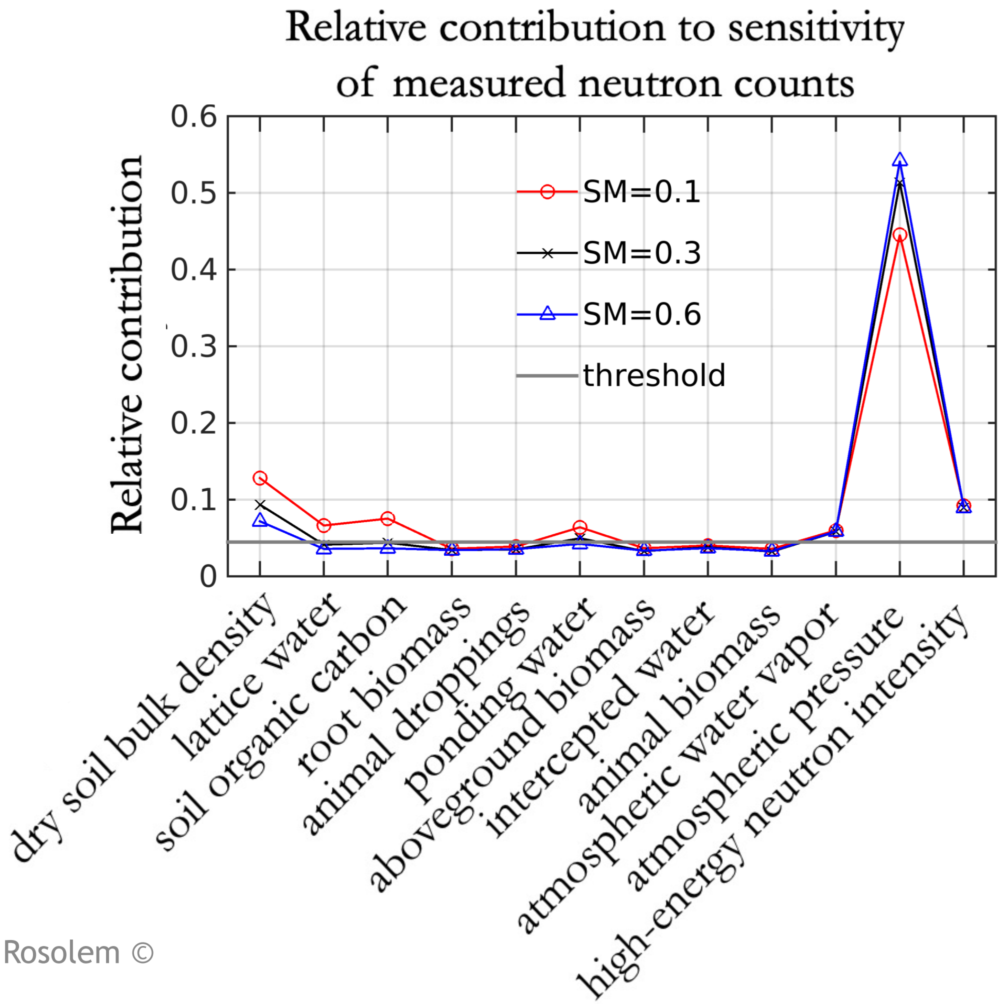
Do you know why?

Propagated uncertainty of soil moisture on the order of 17% vol.

Can you understand why?

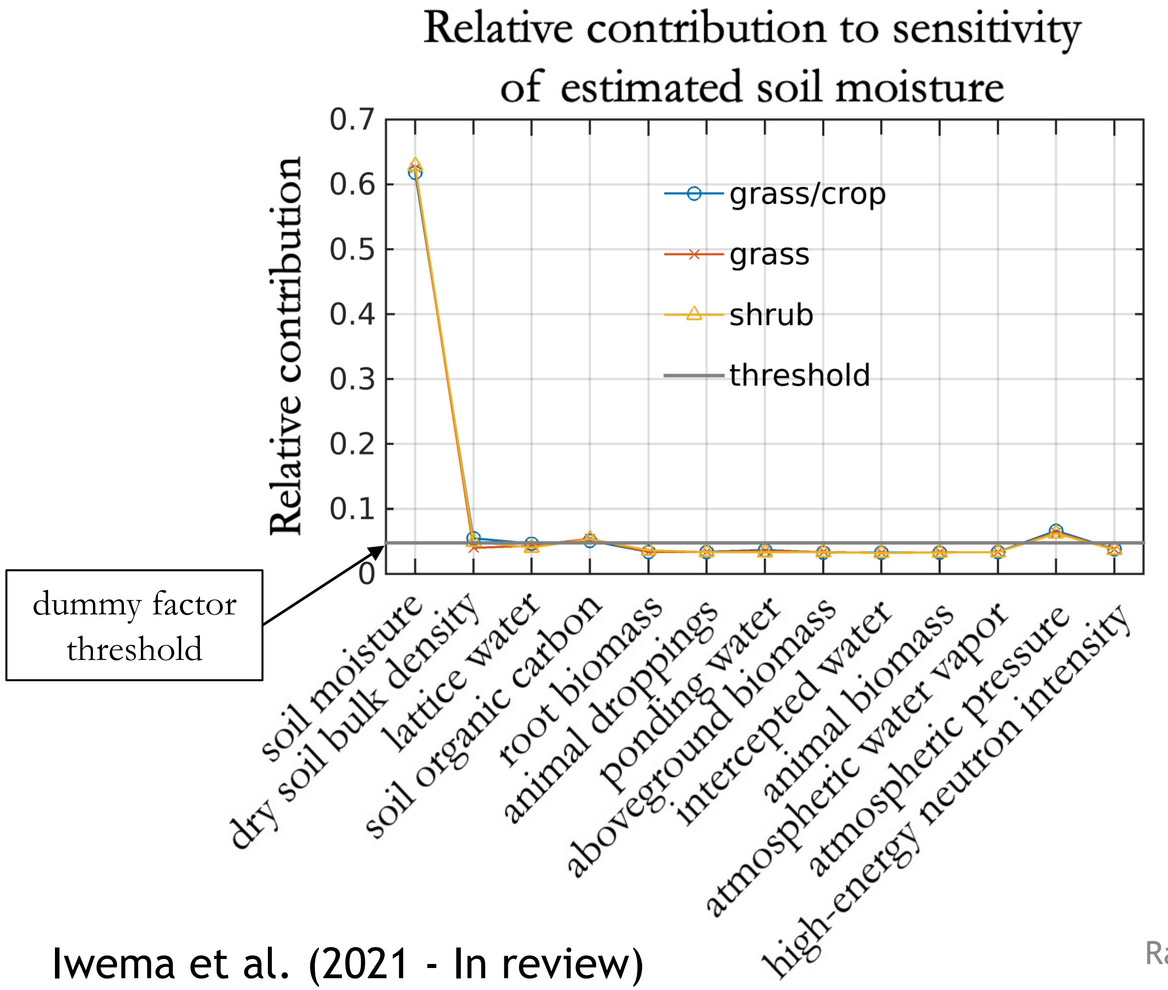
How does each factor influence the neutron signal?

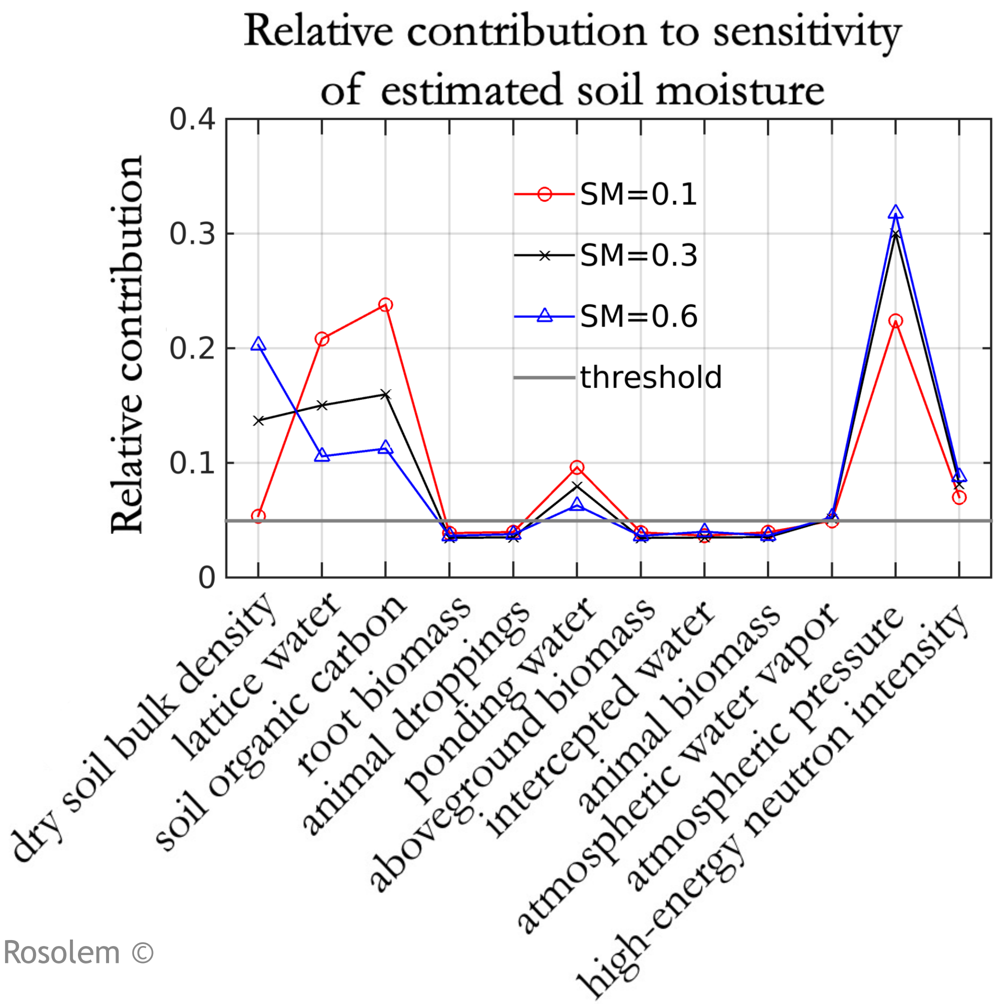




Iwema et al. (2021 - In review)

How is that propagated to the derived soil moisture estimation?

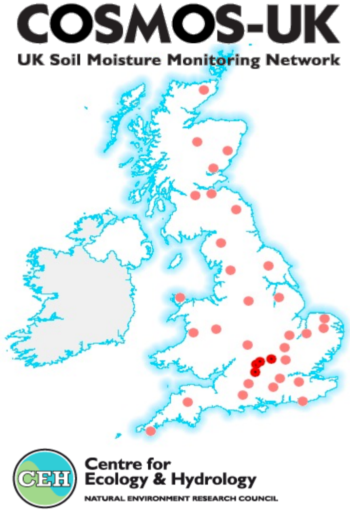


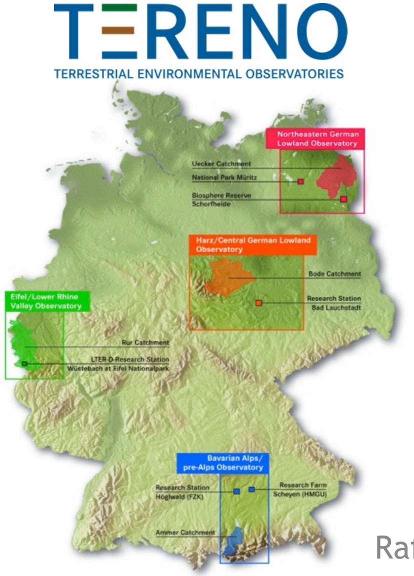


Iwema et al. (2021 - In review)

Expansion of cosmic-ray neutron sensor stations for soil moisture monitoring

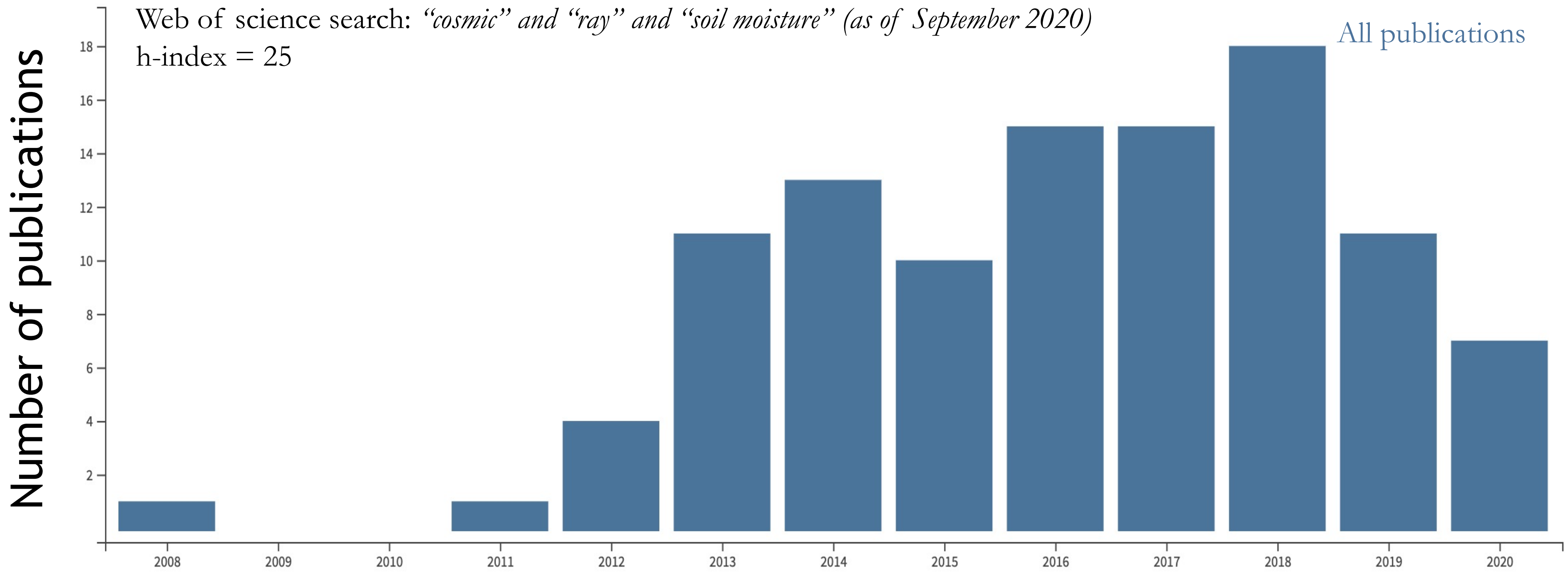
Since the US COSMOS, we have seen an increase in national-scale networks





Increase adoption of the technology from scientific publications

Total Publications
106 Analyze

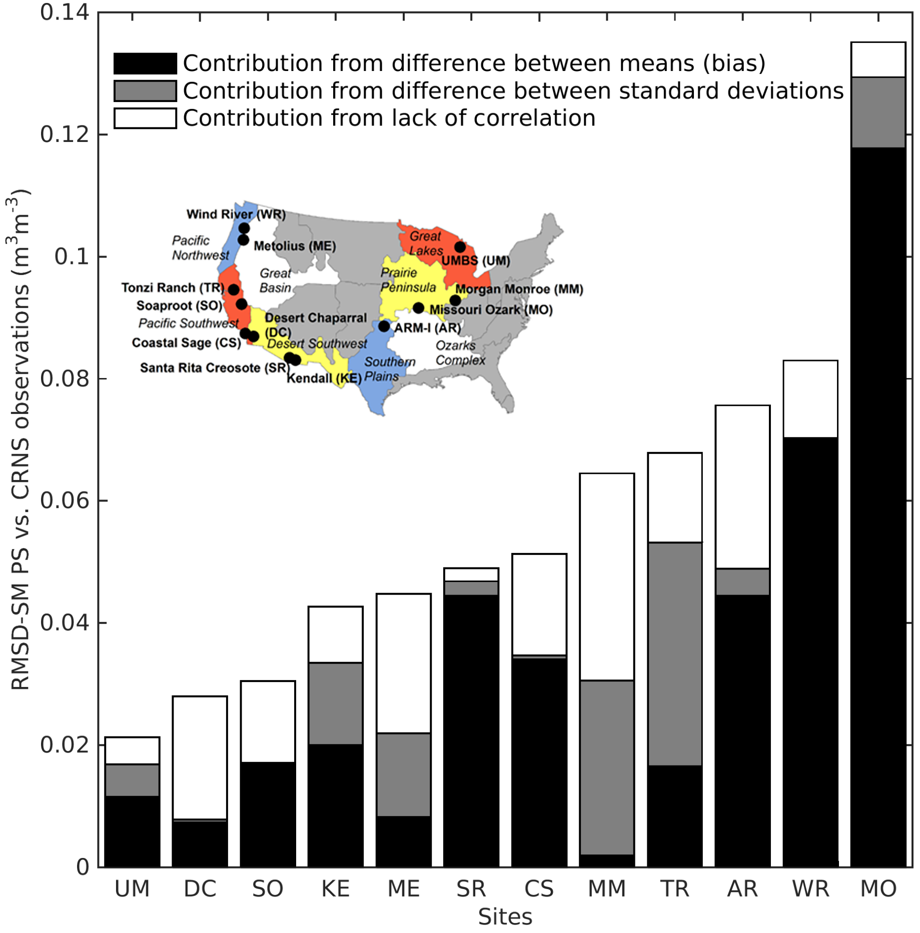


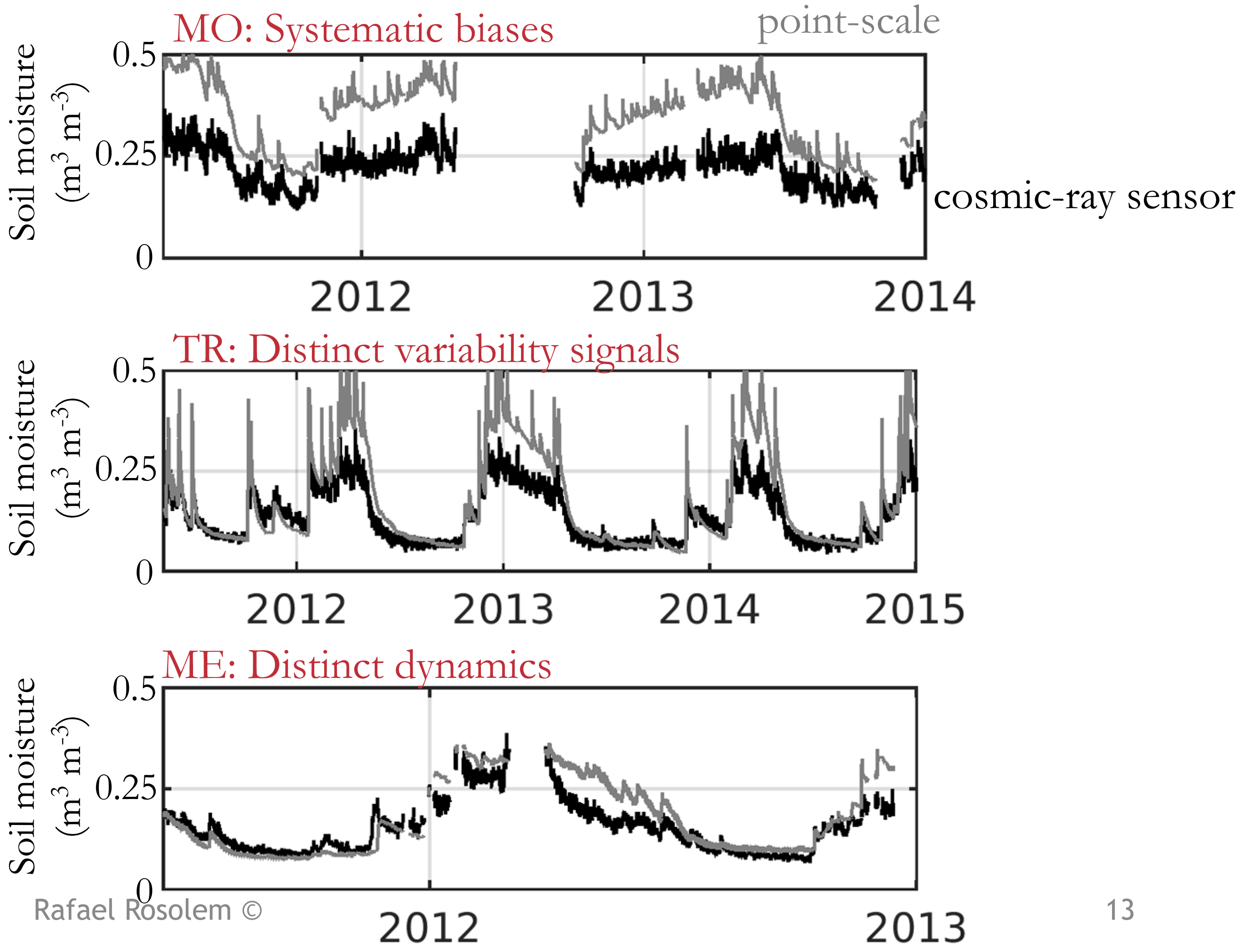
This new technology is relevant to environmental modeling and remote sensing communities

Rancho Mirage in southern California

http://www.theguardian.com/environment/2015/apr/12/californian-drought-water-restrictions

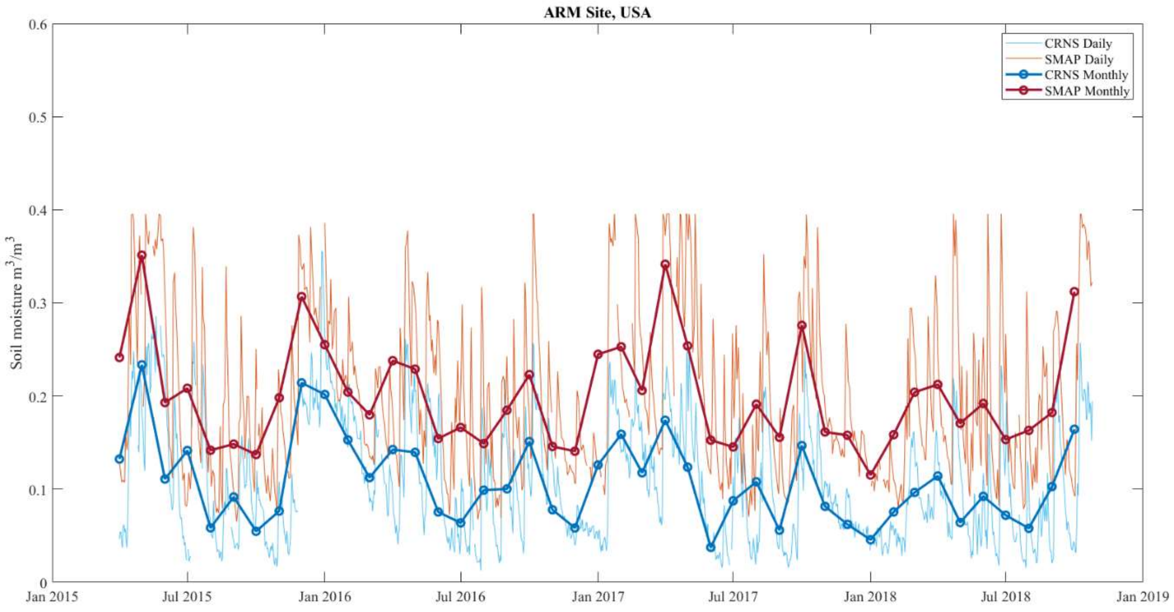
Soil moisture from cosmic-ray sensors have unique information at sub-kilometer scales

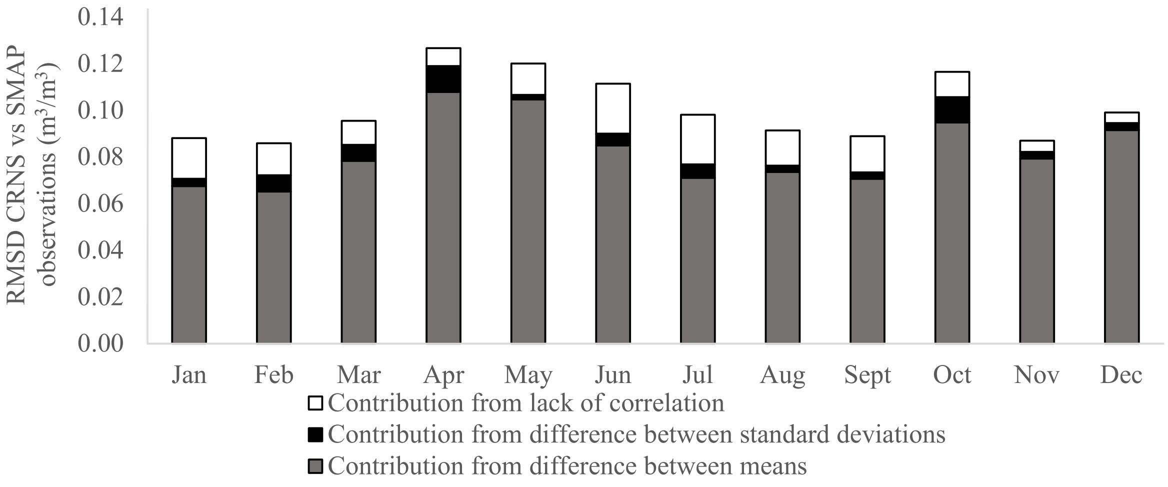




Iwema et al. 2017 (HESS)

Soil moisture from cosmic-ray sensors have unique information at sub-kilometer scales



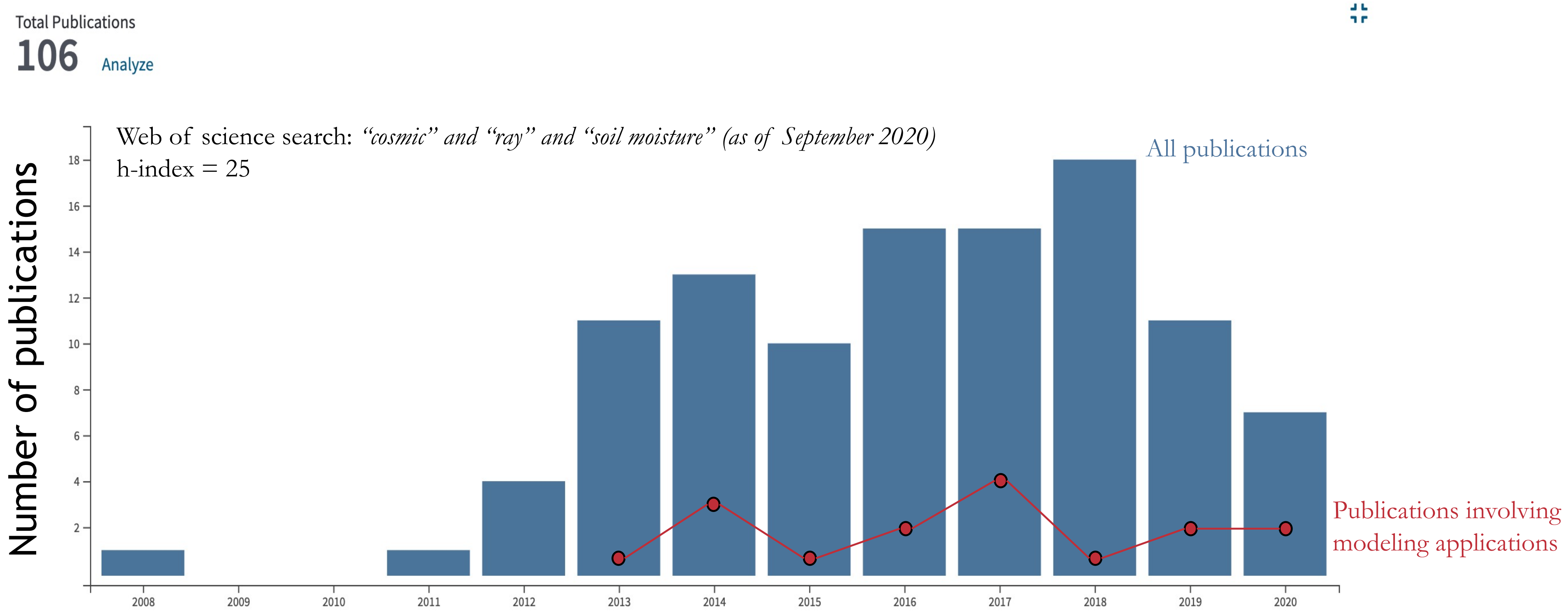


Source: Isobel Roberts undergraduate project

The importance of in situ soil moisture has led to global international efforts

Challenges ahead

However, the combined use of cosmic-ray neutron sensors with environmental models is still lacking



Partially processed cosmic-ray sensor measurements hinders more comprehensive comparisons with hydrological and land surface models

Error metric on soil moisture memory

Network	*Network Mean*	GLDAS	CFSR	CFS	20CR	MERRAland	MERRA	GEOS5	ERA-I land	ERA-Interim	IFS	CLM	CCSM	Average Bias	*SD*
Ameriflux	7.6	-0.7	-0.8	-0.5	14.1	11.0	5.0	7.4	7.7	-1.7	-0.3	-2.0	-5.6	2.8	*5.8*
ARM	9.7	-3.8	-2.6	-3.5	2.9	-2.5	-2.0	-2.3	8.3	-4.2	-4.1	-3.9	-4.3	-1.8	*3.6*
AWDN	3.7	2.8	5.5	2.9	10.1	9.8	9.5	10.7	13.7	2.0	1.7	2.5	-0.7	5.9	*4.4*
CHILI	4.1	5.4	7.4	4.9	14.7	9.9	9.6	12.9	19.4	0.4	0.3	4.6	1.0	7.5	*5.7*
COSMOS	8.8	-2.0	1.2	-1.9	5.3	7.1	6.6	9.4	8.4	-1.6	-2.0	-0.5	-5.1	2.1	*4.8*
DEOS	15.9	-7.3	-2.3	-6.1	3.0	-0.4	6.3	11.5	14.4	-8.1	-10.7	-8.9	-11.7	-1.7	*8.4*
ECONET	7.2	4.3	1.0	3.7	18.4	20.2	19.3	22.2	25.9	1.2	0.8	4.4	-3.7	9.8	*10.0*
MAWN	8.7	-2.5	0.7	-2.4	3.9	6.4	5.3	6.9	9.3	-1.9	-2.2	-0.9	-4.9	1.5	*4.4*
MAW-MO	7.3	-1.1	3.4	1.0	9.0	9.6	6.0	9.9	11.2	-2.2	-3.1	-0.7	-4.8	3.2	*5.5*
NOAAHMT	7.9	-1.1	-0.6	0.1	14.2	10.9	4.8	7.6	7.4	-1.7	-0.4	-2.5	-5.9	2.7	*5.9*
OK-Meso	9.0	-3.6	-2.6	-2.1	7.1	-1.2	-1.8	0.7	4.6	-4.8	-4.1	-4.1	-6.7	-1.6	*3.8*
PBO-H2O	8.9	-1.2	0.1	-3.8	-1.4	16.3	6.2	20.1	4.0	-3.5	-1.4	-0.7	-6.1	2.4	*7.8*
SCAN	17.6	-7.3	-0.5	-6.5	6.7	5.1	6.0	4.3	11.7	-8.8	-11.0	-9.7	-13.6	-1.9	*8.1*
SDAWN	7.8	-1.6	0.7	-2.2	5.8	7.9	6.2	6.8	10.4	-1.3	-1.4	-1.0	-4.9	2.1	*4.8*
SNOTEL	14.0	-9.3	-3.3	-7.9	0.2	23.3	30.9	18.3	0.1	-7.9	-8.3	-5.1	-12.4	1.5	*13.8*
SOILSCAPE	9.6	-3.9	-2.0	-5.0	0.0	7.5	7.3	8.7	5.9	-1.5	-1.7	-3.0	-5.1	0.6	*5.0*
USCRN	14.3	-8.2	-6.8	-6.6	-2.3	-2.8	-5.4	-5.1	6.9	-7.5	-7.6	-7.9	-11.0	-5.4	*4.3*
USDA-ARS	6.7	3.8	5.1	1.7	14.6	28.5	31.0	19.4	9.0	0.8	0.7	1.6	-4.8	9.3	*11.1*
WTX-Meso	3.7	0.7	7.4	1.2	5.5	30.2	32.2	13.1	0.0	0.0	0.0	12.0	-0.7	8.5	*11.1*
Average	7.9	-1.9	0.6	-1.7	6.9	10.4	9.6	9.6	9.4	-2.7	-2.9	-1.4	-5.8	2.5	
SD	*3.8*	*4.1*	*3.7*	*3.6*	*5.9*	*9.4*	*10.6*	*7.1*	*6.0*	*3.2*	*3.8*	*5.0*	*3.8*		

-10 -6 -4 -2 2 4 6 10 16

Dirmeyer et al. 2016 (JHM)

Data processing steps **included**

- ✓ conventional/uniform calibration weighting
- ✓ atmospheric pressure correction
- ✓ high-energy neutron intensity correction

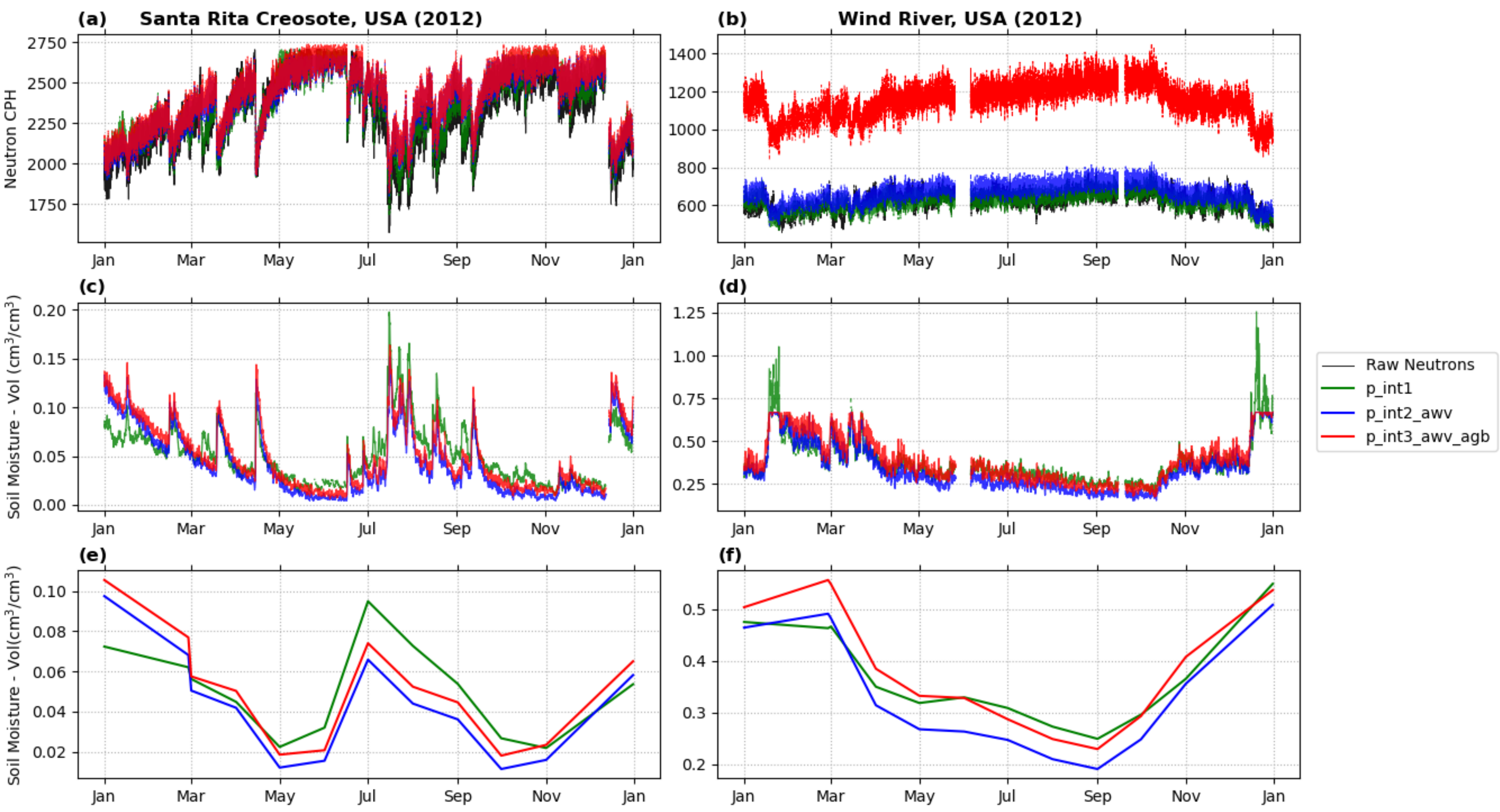
Missing processing steps

- X lattice water and soil organic carbon correction (Franz et al. 2012; WRR)
- X atmospheric water vapor correction (Rosolem et al. 2013; JHM)
- X aboveground biomass correction (Baatz et al., 2015; WRR)
- X revised calibration weighting (Schrön et al. 2017; HESS)

Worldwide evaluation for modeling applications is limited due to lack of harmonized datasets

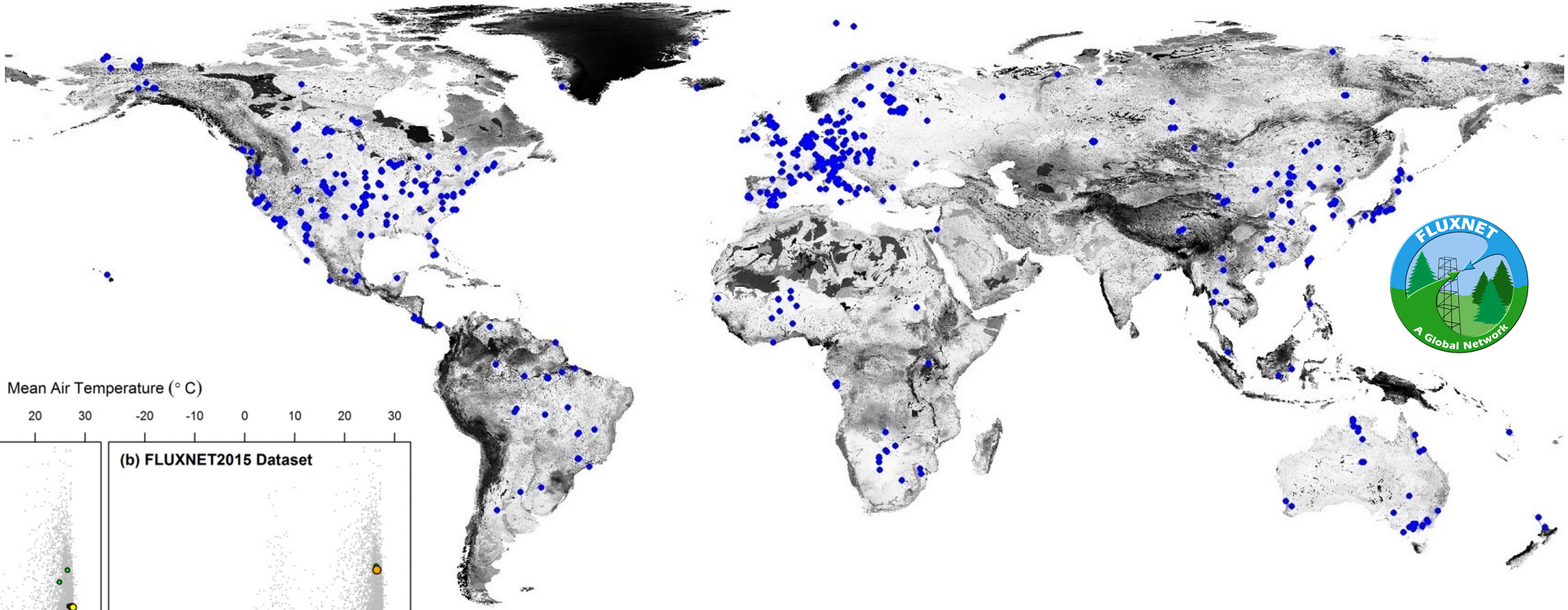
Data processing steps	COSMOS (Cosmic-ray Soil Moisture Observing System)	CosmOz	COSMOS-UK (UK Soil Moisture Monitoring Network)
Atmospheric pressure correction	Yes	Yes	Yes
High-energy neutron intensity correction	**Jungfraujoch reference site with no local correction**	**Neutron monitor site with closest cutoff rigidity value to site**	**Jungfraujoch reference site with local correction (Hawdon et al. 2014; WRR)**
Atmospheric water vapor correction	**No**	**Yes**	**Yes**
Aboveground biomass correction	No	No	No
Lattice water and soil organic carbon correction	**No**	**Yes**	**Yes**

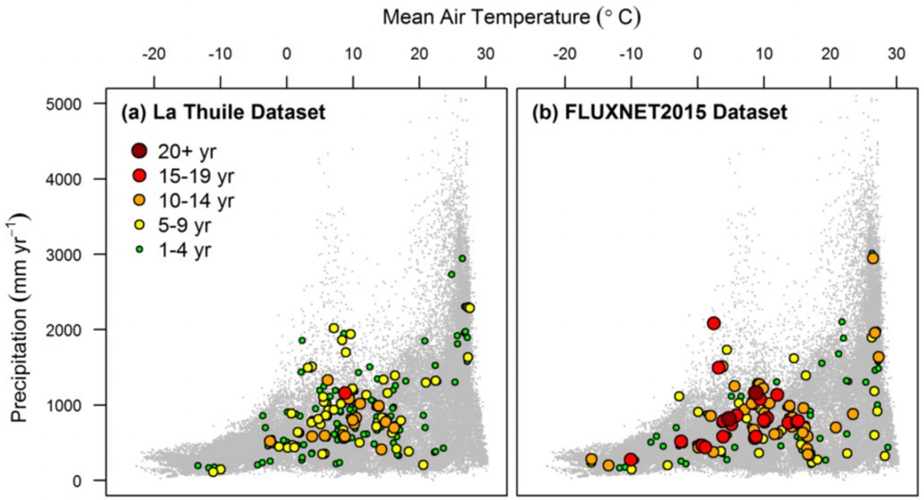
Different data processing procedures can lead to different estimates of soil moisture



Power et al. 2021 (GMDD)

Good practices from other networks





Towards a 'Global COSMOS' initiative?

Voluntary participation; PI-driven research; bottom-up organizational structure

Strengths	Weaknesses	Can we solve the issue?
✓ Interdisciplinarity ✓ Strong sense of community ✓ Good representation hydroclimates and biomes	X Insecurity of funding for many sites X Underrepresentation of some biomes or geographical location X Lack of incentives for data sharing	! National to multi-national consortia ('network of networks') ! Availability of subset of data ! Publication of datasets with DOI numbers

Rosolem et al. (In prep.)

Towards a 'Global COSMOS' initiative?

Lack of standardization/harmonization of instrumentation and quality-control processing

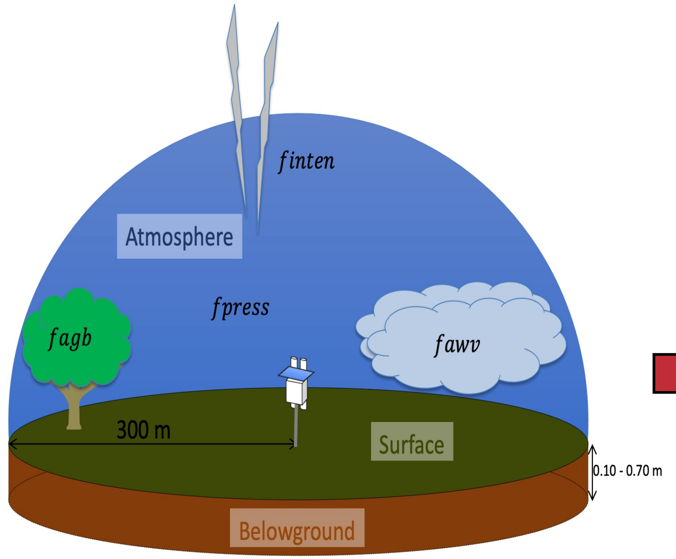
Strengths	Weaknesses	Can we solve the issue?
✓ Open and flexible methodology to advance the technology ✓ Incentive for PIs to submit data with 'in-house' data processing	X Undesired biases and data inconsistencies for continental/global comparison X Limited adoption by wide modeling community X Unclear about publication strategies and authorship	! Hybrid approach: flexible processing of data while sharing a subset of data for harmonization ! Open-source software for modeling and data processing are becoming widely available (COSMIC, URANOS, Cornish Pasdy, crspy)

Rosolem et al. (In prep.)

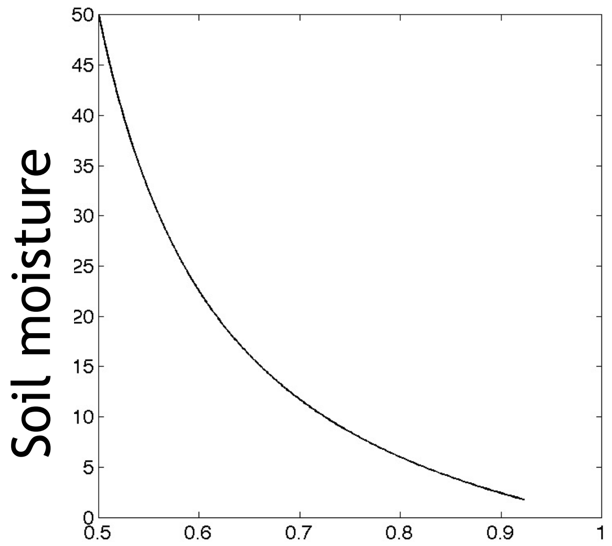
Towards a 'Global COSMOS' initiative?

Lack of a common platform for data quality control and processing for multiple sites globally

Raw neutron counts



Data quality control
Signal corrections



Corrected neutron counts


network B
individual data processing procedures
network C
network A
limited understanding and application
Before

Opportunities for a Global COSMOS network

We have developed 'crspy': a comprehensive data processing tool for cosmic-ray sensor

https://github.com/danpower101/crspy

master · 1 branch · 1 tag · Go to file · Add file · Code

danpower101 Added refs · a223362 2 days ago · 87 commits

crspy	Added refs	2 days ago
data	Added alternative intensity correction.	5 months ago
example	delete duplicate file to avoid confusion	last month
.gitignore	adding gitignore	3 months ago
LICENSE	Create LICENSE	4 months ago
README.md	Update README.md	2 months ago
name_list.py	change to name_list default	last month
run_crspy_workthrough.ipynb	Added notebook workthrough (mk2)	2 months ago
setup.py	Changes to n0 calib	26 days ago

README.md

Cosmic-Ray Sensor PYthon tool (crspy)

This tool can process Cosmic Ray Sensor data into soil moisture estimates. It is based on research conducted by many individuals and groups (see references).

Please note: this is a work in progress that is being updated regularly, so bugs or issues may be found. If you have any issues with crspy please do get in touch daniel.power@bristol.ac.uk

python v3.7+ · contributions welcome · license LGPL-3.0

https://doi.org/10.5194/gmd-2021-77

Abstract · Discussion · Metrics

Submitted as: model description paper · 07 May 2021

Review status: this preprint is currently under review for the journal GMD.

Cosmic-Ray neutron Sensor PYthon tool (crspy): An open-source tool for the processing of cosmic-ray neutron and soil moisture data

Daniel Power[1], Miguel Angel Rico-Ramirez[1], Sharon Desilets[2], Darin Desilets[2], and Rafael Rosolem[1,3]
[1]Faculty of Engineering, University of Bristol, Bristol, UK
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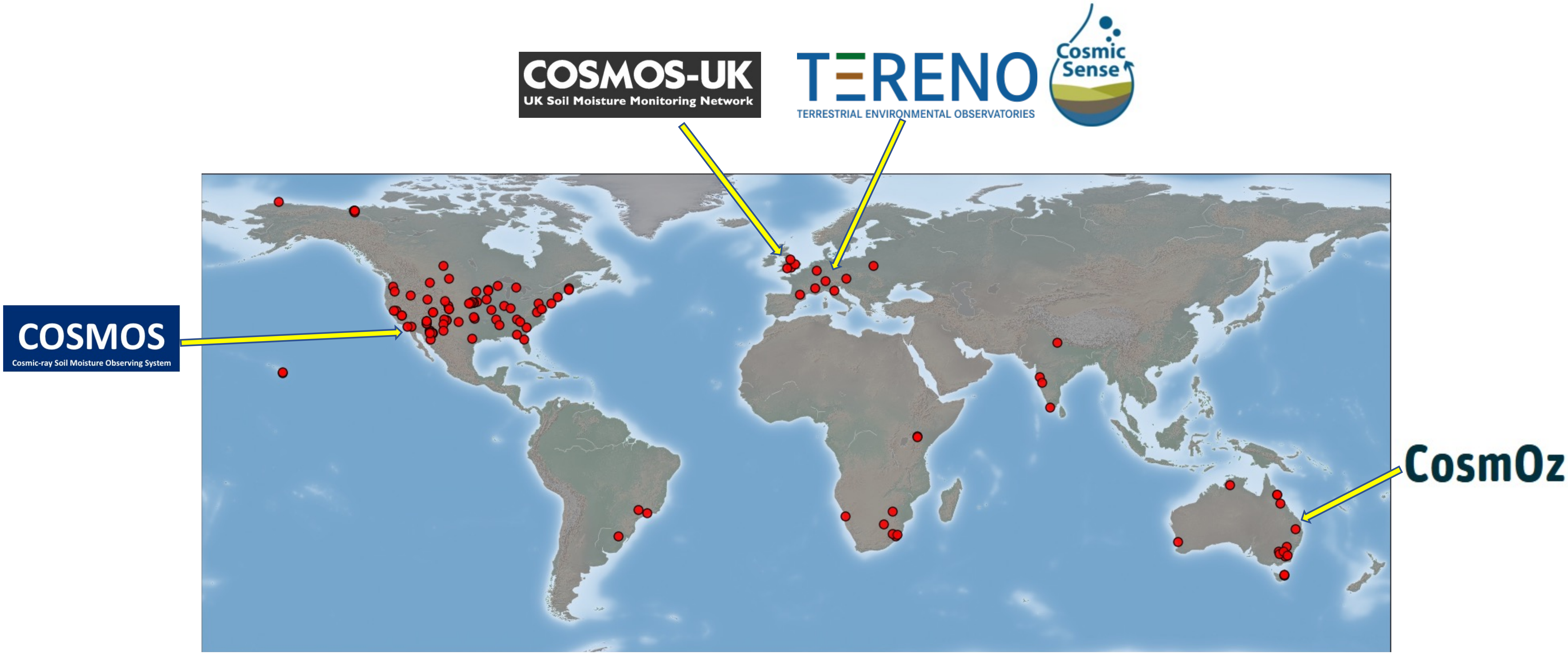
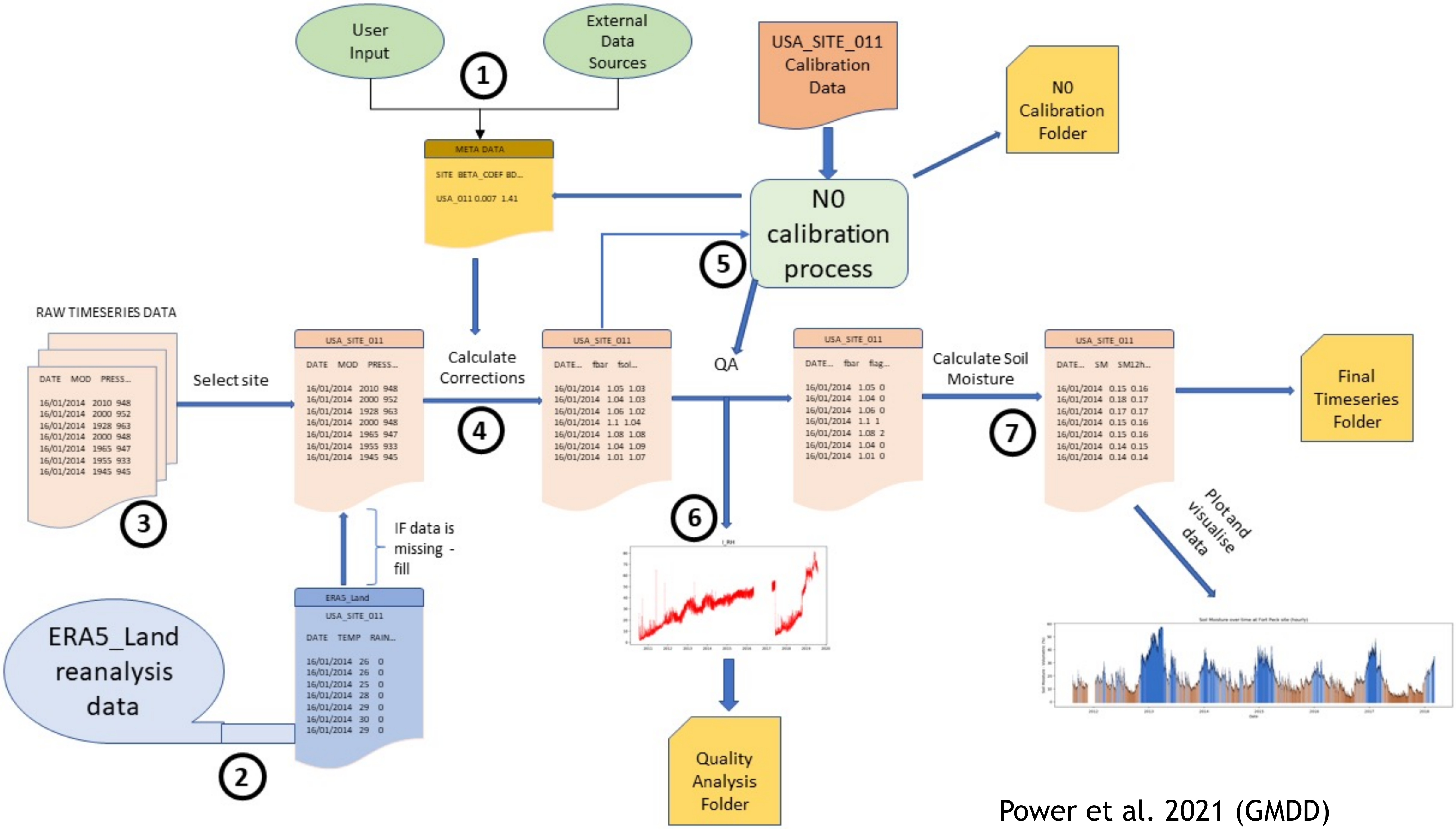
[3]Cabot Institute for the Environment, University of Bristol, Bristol, UK

Received: 12 Mar 2021 – Accepted for review: 05 May 2021 – Discussion started: 07 May 2021

Power et al. 2020 (GMDD)


COSMOS-UK
UK Soil Moisture Monitoring Network
TERENO
TERRESTRIAL ENVIRONMENTAL OBSERVATORIES
Cosmic Sense
COSMOS
Cosmic-ray Soil Moisture Observing System
CosmOz



Power et al. 2021 (GMDD)

crspy contains functions to help with working directory set up for each processing step

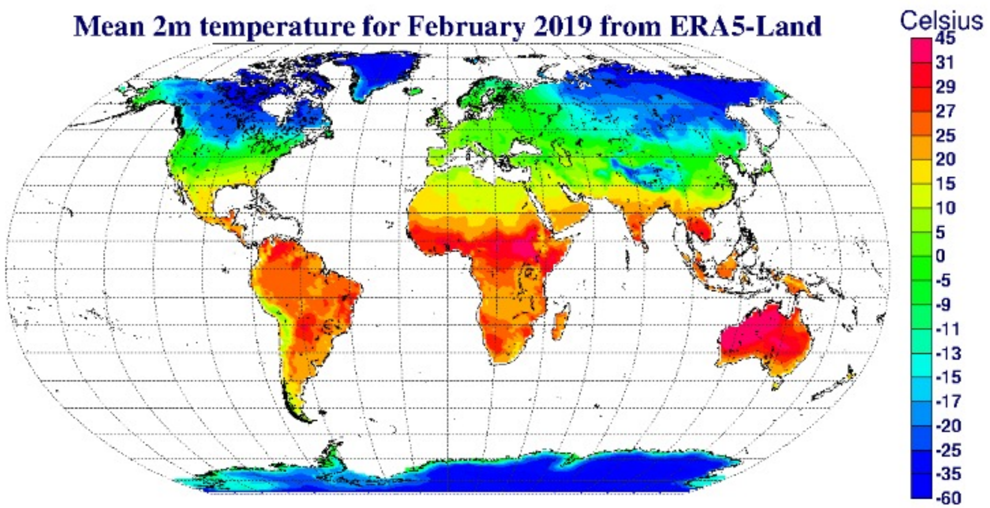
```
import crspy
```

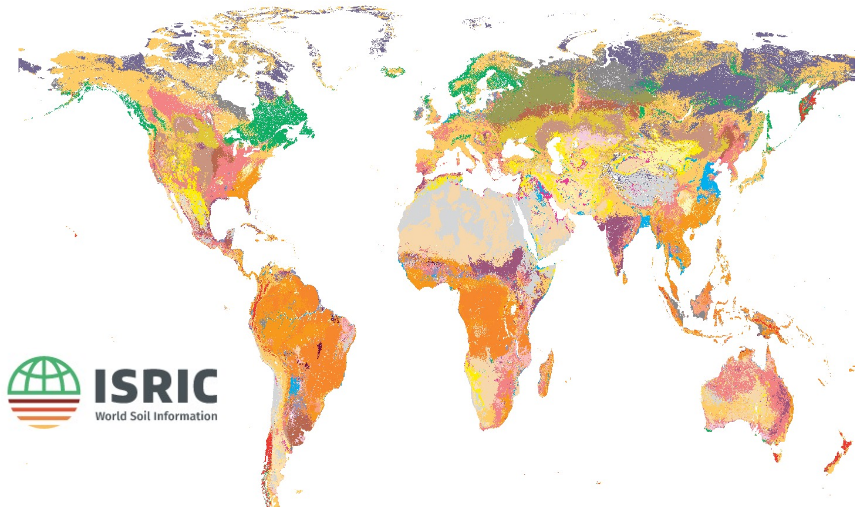
→

```
crspy.initial(wd)
```

Name	Status	Date modified	Type	Size
calibration_data	✓	24/09/2020 12:19	File folder	
crns_data	✓	22/09/2020 12:09	File folder	
era5land	✓	11/09/2020 10:37	File folder	
figures	✓	01/10/2020 14:10	File folder	
global_biomass_netcdf	✓	24/06/2020 12:27	File folder	
land_cover_data	✓	03/06/2020 11:02	File folder	
n0_calibration	✓	01/10/2020 14:24	File folder	
nmdb	✓	18/06/2020 14:56	File folder	
qa	✓	01/10/2020 14:09	File folder	
metadata - Copy	⟳	17/06/2020 16:08	Microsoft Excel C...	33 KB
metadata	✓	01/10/2020 14:25	Microsoft Excel C...	35 KB

Pre-processing steps integrate global products for use in processing and analysis of sites





User can calibrate the sensor using crspy

Hydrol. Earth Syst. Sci., 21, 5009–5030, 2017
https://doi.org/10.5194/hess-21-5009-2017

Hydrology and Earth System Sciences
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EGU

Improving calibration and validation of cosmic-ray neutron sensors in the light of spatial sensitivity

Martin Schrön[1,2], Markus Köhli[1,3,4], Lena Scheiffele[5], Joost Iwema[6], Heye R. Bogena[7], Ling Lv[8], Edoardo Martini[1], Gabriele Baroni[2,5], Rafael Rosolem[6,9], Jannis Weimar[3], Juliane Mai[2,10], Matthias Cuntz[2,11], Corinna Rebmann[2], Sascha E. Oswald[5], Peter Dietrich[1], Ulrich Schmidt[3], and Steffen Zacharias[1]

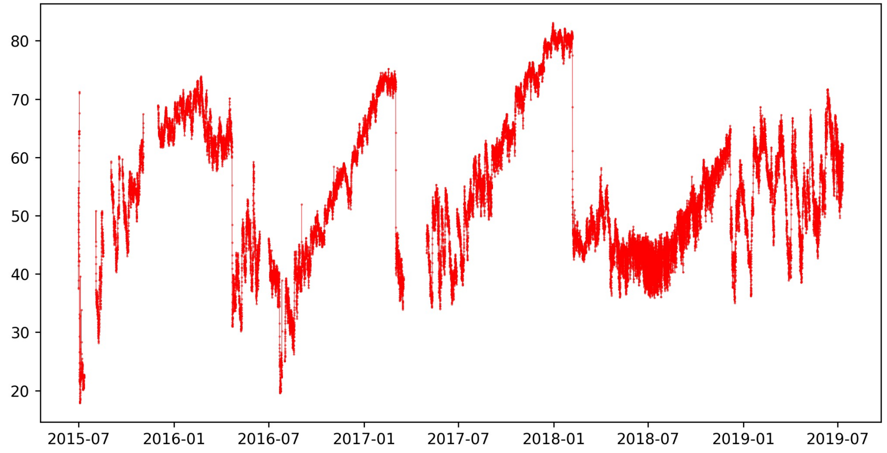
Revised weighting approach for soil samples that takes into dependencies on air pressure, air humidity, soil moisture and vegetation

```
The optimised N0 is calculated as:
N0   |  Total Relative Error
        RelErr    N0
3476  0.618526  3476

The site calibrated was site number 102 in  UK and the name is W2-W3
The bulk density was 1.166
The user defined accuracy was 0.01
The soil organic carbon was 0.046 g/m^3
The lattice water content was 0.031


Unique calibration dates where on:
[datetime.date(2015, 11, 2) datetime.date(2016, 2, 8)
 datetime.date(2016, 11, 1) datetime.date(2015, 7, 4)]

Average neutron counts for each calib day where {0: 1800.0, 1: 1759.0, 2: 1901.0, 3: 1977.0}

The weighted field scale average of theta (from soil samples) was {0: 48.01, 1: 61.86, 2: 31.40, 3: 20.02}

Please see the additional tables which hold calculations for each calibration date
```

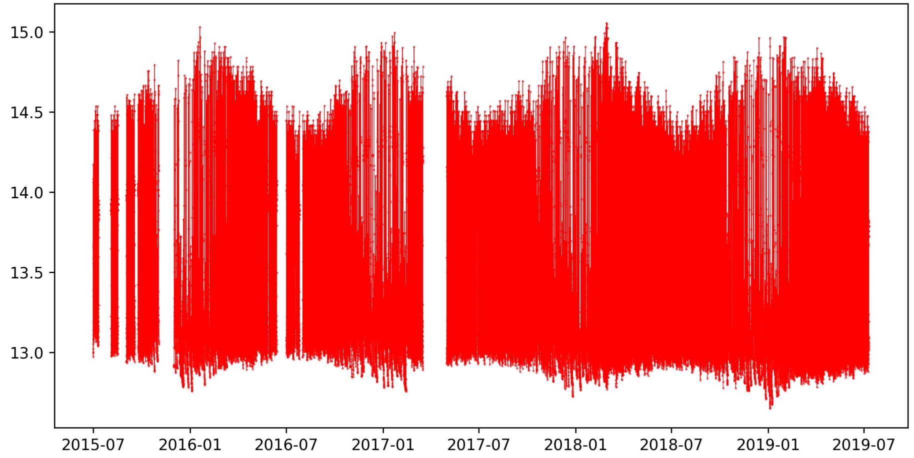
Outputs a mini-report along with any tables written during the calibration process. This can be useful to check for any issues in the calibration process.

Data quality assessment with visual outputs

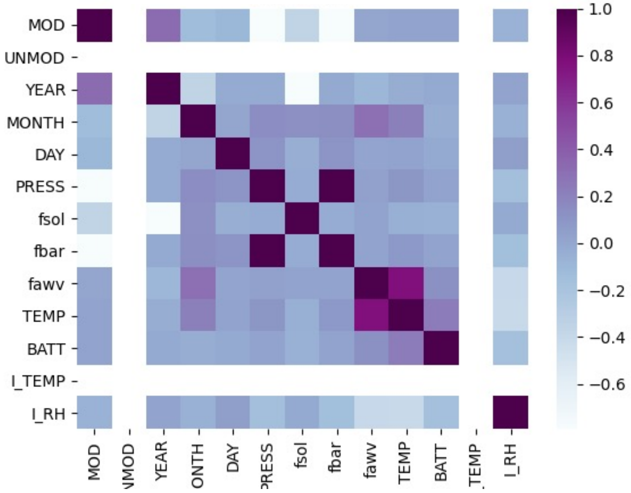
Internal relative humidity



Battery Voltage



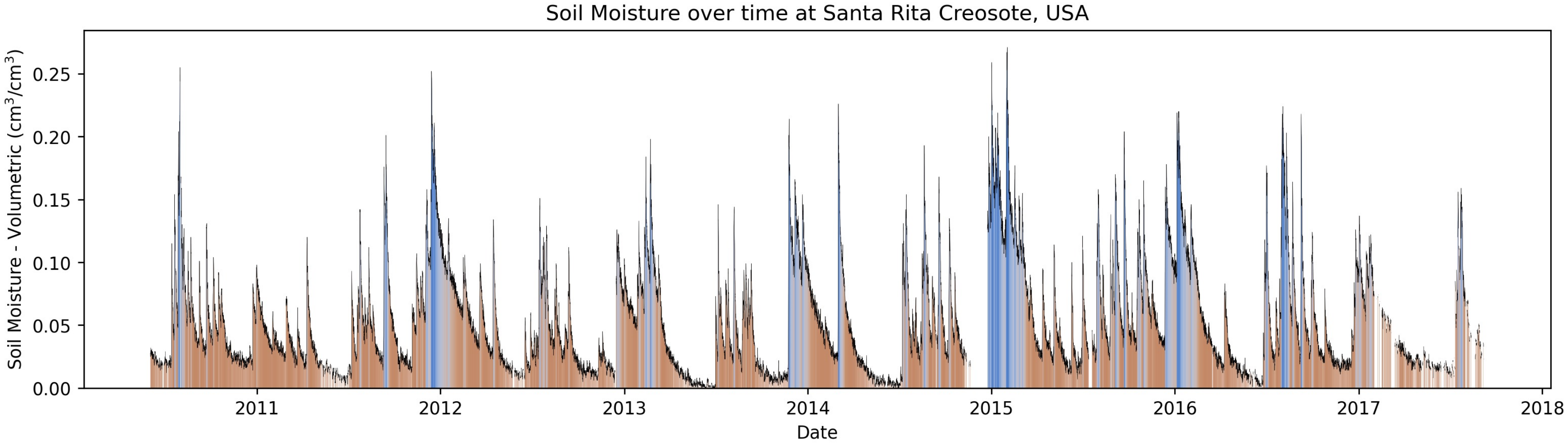
Correlation Plot

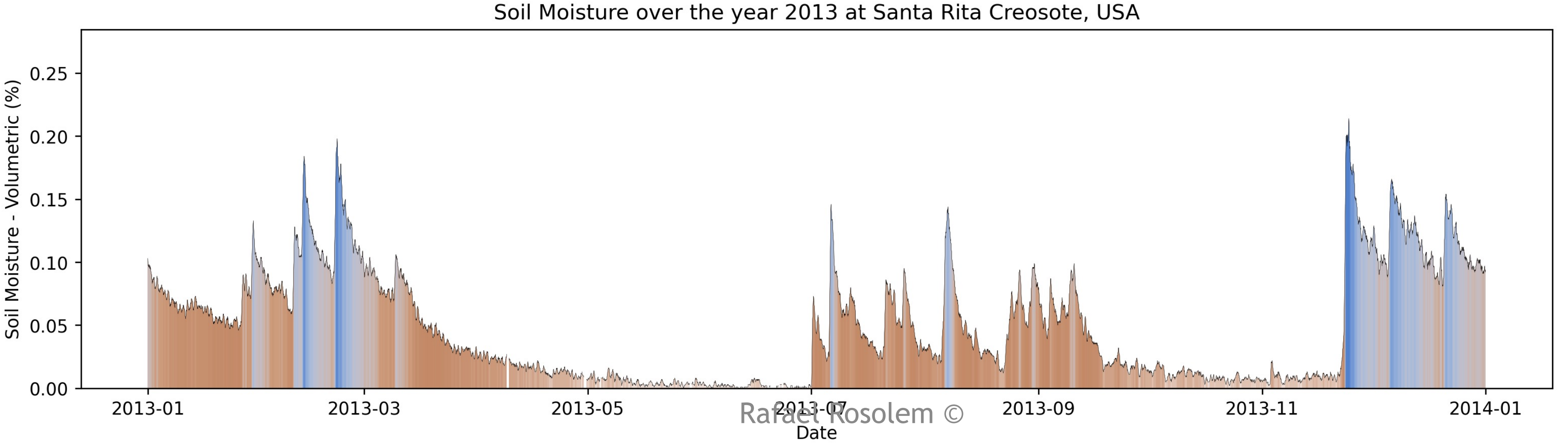


Data quality flags

```
Flags:
    1 = fast neutron counts more than 20% difference to previous count
    2 = fast neutron counts less than the minimum count rate (default == 30%)
    3 = fast neutron counts more than n0
    4 = battery below 10v
```

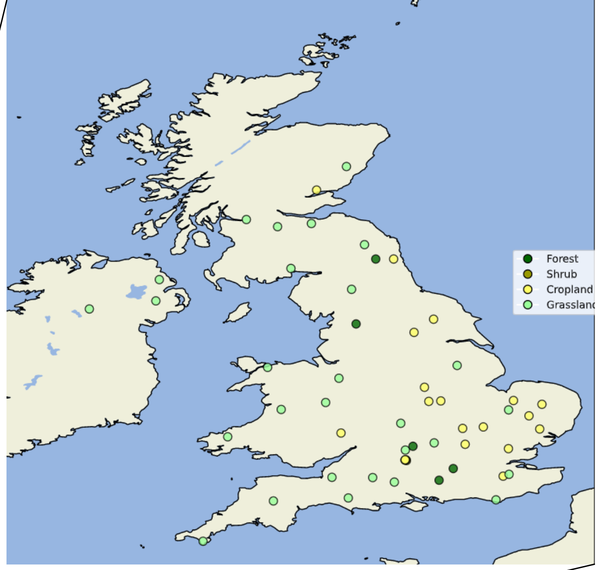
crspy generates soil moisture analysis for easy checks





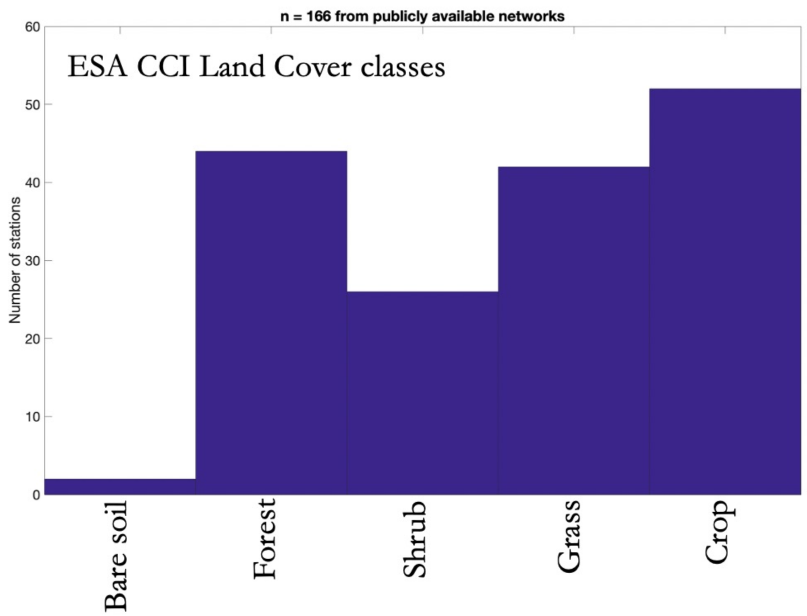
Metadata file is generated for single- or –ulti-site processing

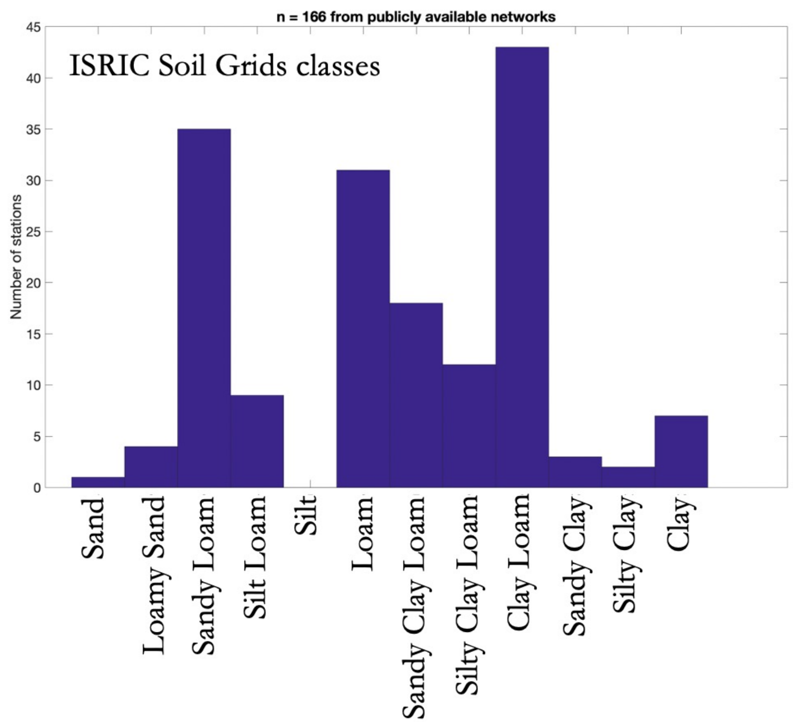
COUNTRY	SITENUM	SITE_NAME	INSTALL_DATE	LATITUDE	LONGITUDE	ELEV	TIMEZONE	GV	LW	SOC	BD
USA	001	Mount Lemmon	27/10/2007	32.4418	-110.782	2747	-7	5.08	0.04	0.016	nan
USA	003	Biosphere 2	28/04/2008	32.5795	-110.851	1180	-7	5.02	0.04	0.016	nan
USA	004	Manitou Forest Tower	24/10/2009	39.101	-105.102	2411	-6	2.93	0.028	0.005	1.4
USA	005	Santa Fe Watershed-SF2	24/10/2009	35.683	-105.823	2427	-7	3.72	0.04	0.016	nan
USA	006	Marshall Colorado	24/10/2009	39.9495	-105.195	1756	-6	2.74	0.04	0.016	nan
USA	007	Manitou Forest Ground	24/10/2009	39.1006	-105.103	2391	-6	2.93	0.028	0.005	1.4
USA	008	Santa Fe Watershed-SF1	23/12/2009	35.6792	-105.827	2482	-7	3.68	0.04	0.016	nan
USA	009	Rancho No Tengo	02/06/2010	31.7438	-110.022	1401	-7	5.08	0.0317	0.016	1.4
USA	010	Kendall	02/06/2010	31.7368	-109.942	1548	-7	5.26	0.024	0.008	1.23
USA	011	Santa Rita Creosote	02/06/2010	31.9085	-110.839	989	-7	5.21	0.01	0.003	1.43
USA	012	Silver Sword	15/06/2010	19.765	-155.423	2868	-10	12.87	0.0957	0.0181	0.78
USA	013	Island Dairy	16/06/2010	19.998	-155.286	381	-10	12.82	0.2093	0.0325	1.01
USA	014	SMAP-OK	21/07/2010	36.0635	-97.217	326	-6	3.27	0.0517	0.0065	1.42
USA	015	ARM-1	21/07/2010	36.6054	-97.4878	322	-6	3.14	0.0537	0.0059	1.4
USA	016	Iowa Validation …	05/09/2010	41.9832	-93.6837	316	-6	1.93	0.045	0.0159	1.43
USA	017	Sterling	10/09/2010	38.9739	-77.4852	95	-4	2.49	0.0637	0.0045	1.32
AUT	018	Rietholzbach	16/12/2010	47.3805	8.9934	755	1	4.34	0.0518	0.0308	0.97
USA	019	VCNP CZO	15/12/2010	35.8896	-106.533	3037	-6	3.79	0.04	0.016	nan
USA	020	San Pedro 2	19/01/2011	31.5615	-110.14	1233	-7	5.3	0.016	0.005	1.42

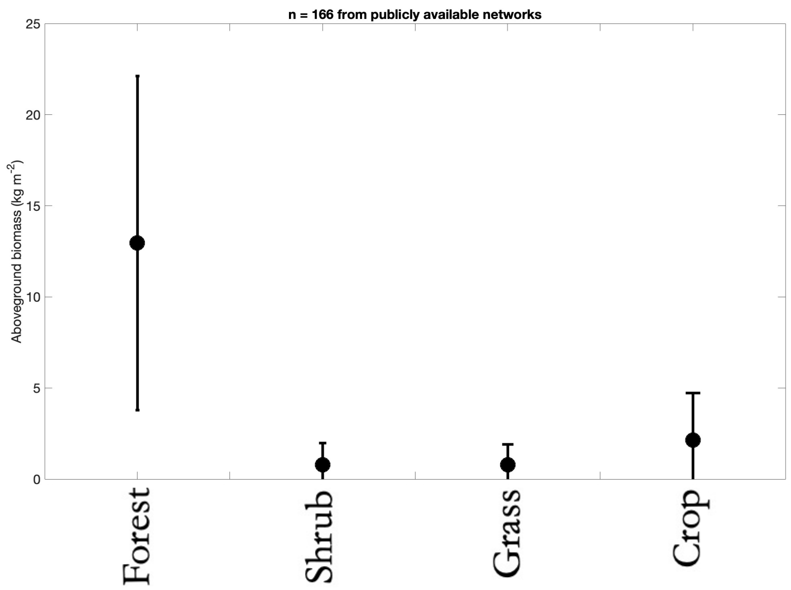

Forest
Shrub
Cropland
Grassland


Forest
Shrub
Cropland
Grassland

How are cosmic-ray stations characterized worldwide

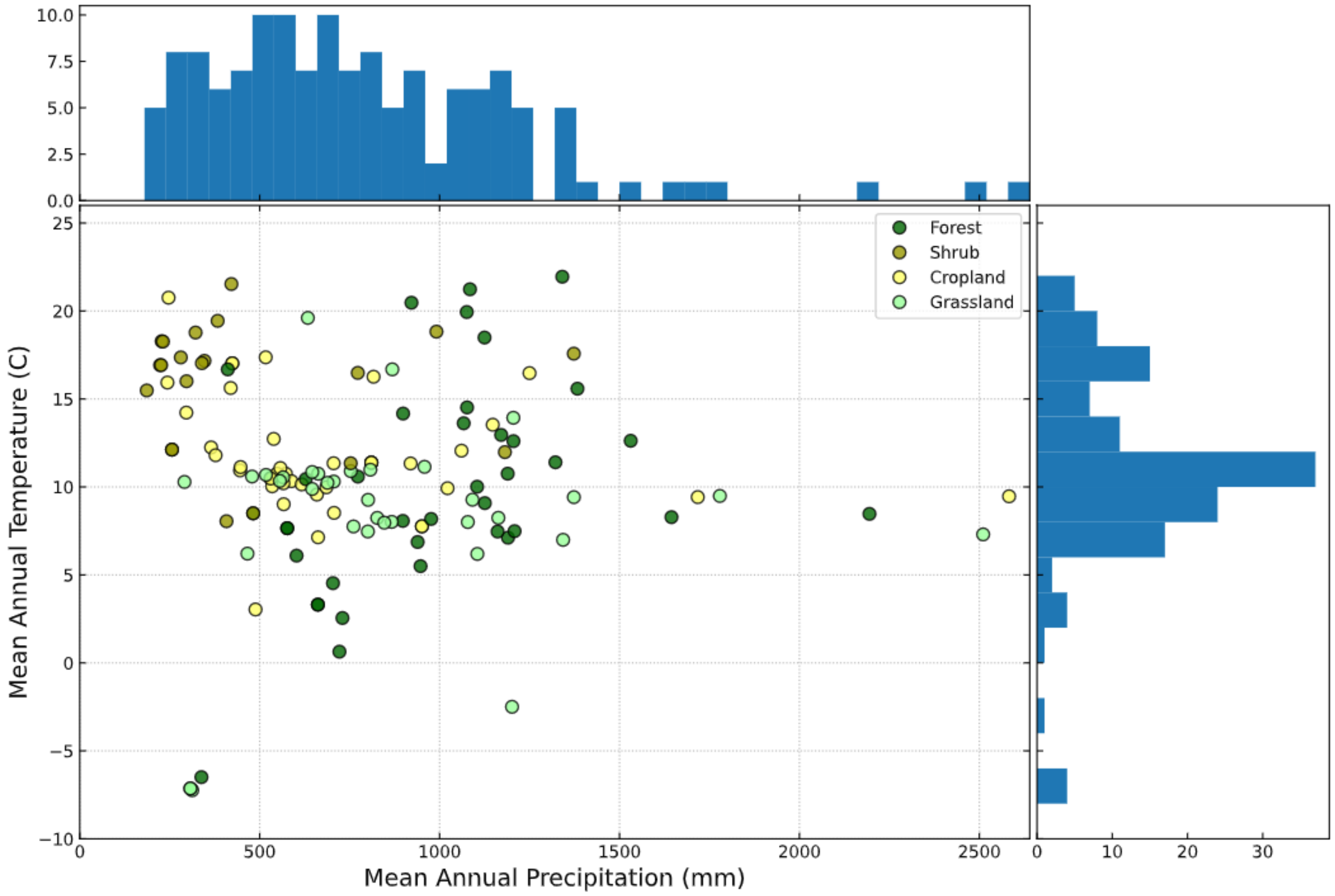


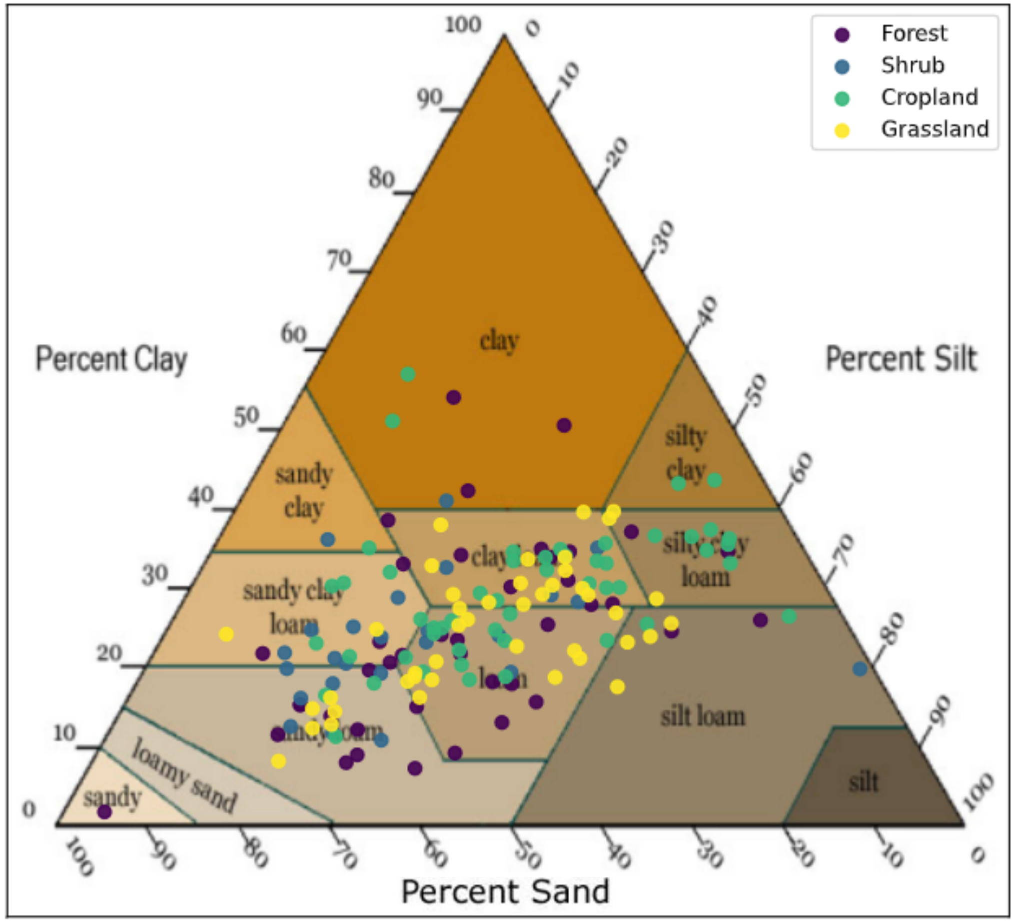


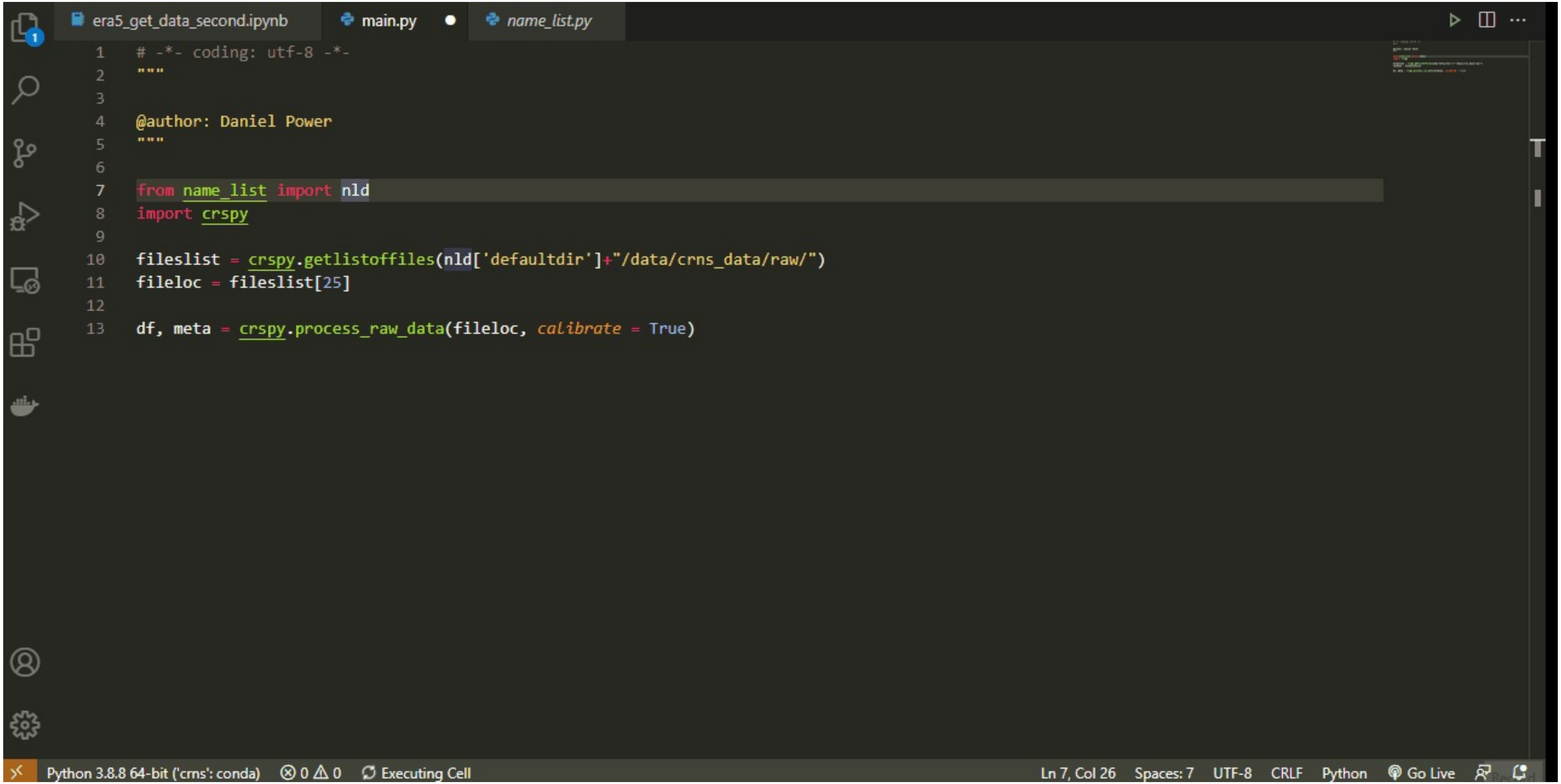


Rosolem et al. (In prep.)

New harmonization tool crspy






era5_get_data_second.ipynb
main.py
name_list.py
-*- coding: utf-8 -*-
"""

@author: Daniel Power
"""

from name_list import nld
import crspy

fileslist = crspy.getlistoffiles(nld['defaultdir']+"/data/crns_data/raw/")
fileloc = fileslist[25]

df, meta = crspy.process_raw_data(fileloc, calibrate = True)
Python 3.8.8 64-bit ('crns': conda)
⊗ 0 ⚠ 0
Executing Cell
Ln 7, Col 26
Spaces: 7
UTF-8
CRLF
Python
Go Live


network B
individual data processing procedures
network C
network A
limited understanding and application
Before
Rafael Rosblem ©


harmonized data processing procedures
network C
network A
network B
enhanced understanding and application
After

Final remarks

- There has been a steady adoption of cosmic-ray neutron sensing technology recently
- Combined used with environmental models currently at slower pace
- Efforts to harmonized global data from cosmic-ray neutron sensors can facilitate further adoption
- Initial steps taken with the development of crspy as a common platform for data quality control and analysis

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