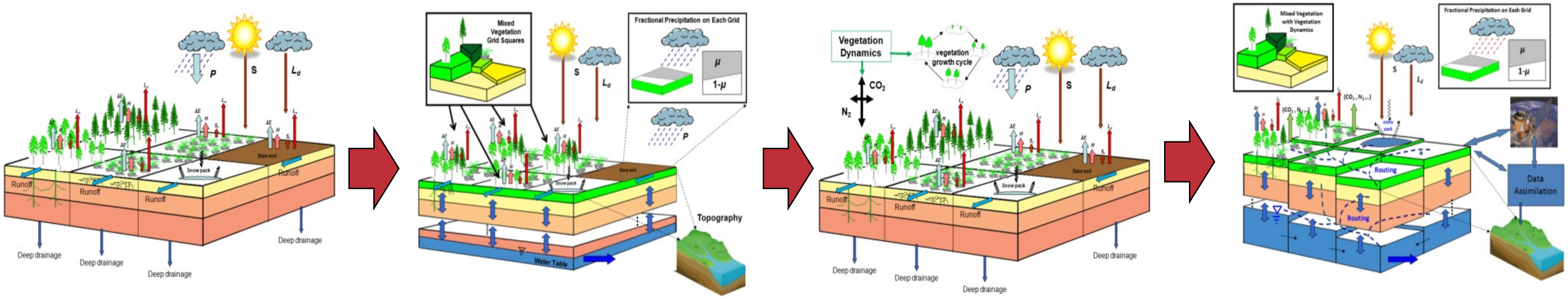
The use of cosmic-ray neutron sensors in hydrometeorology



Rafael Rosolem

University of BRISTOL

At the end of this lecture, you should…

- Understand the broader context and motivation of environmental modeling and the links to soil moisture process
- Be familiar with land surface and hydrological models
- Identify potential uses of cosmic-ray neutron sensing observations in combination with models

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

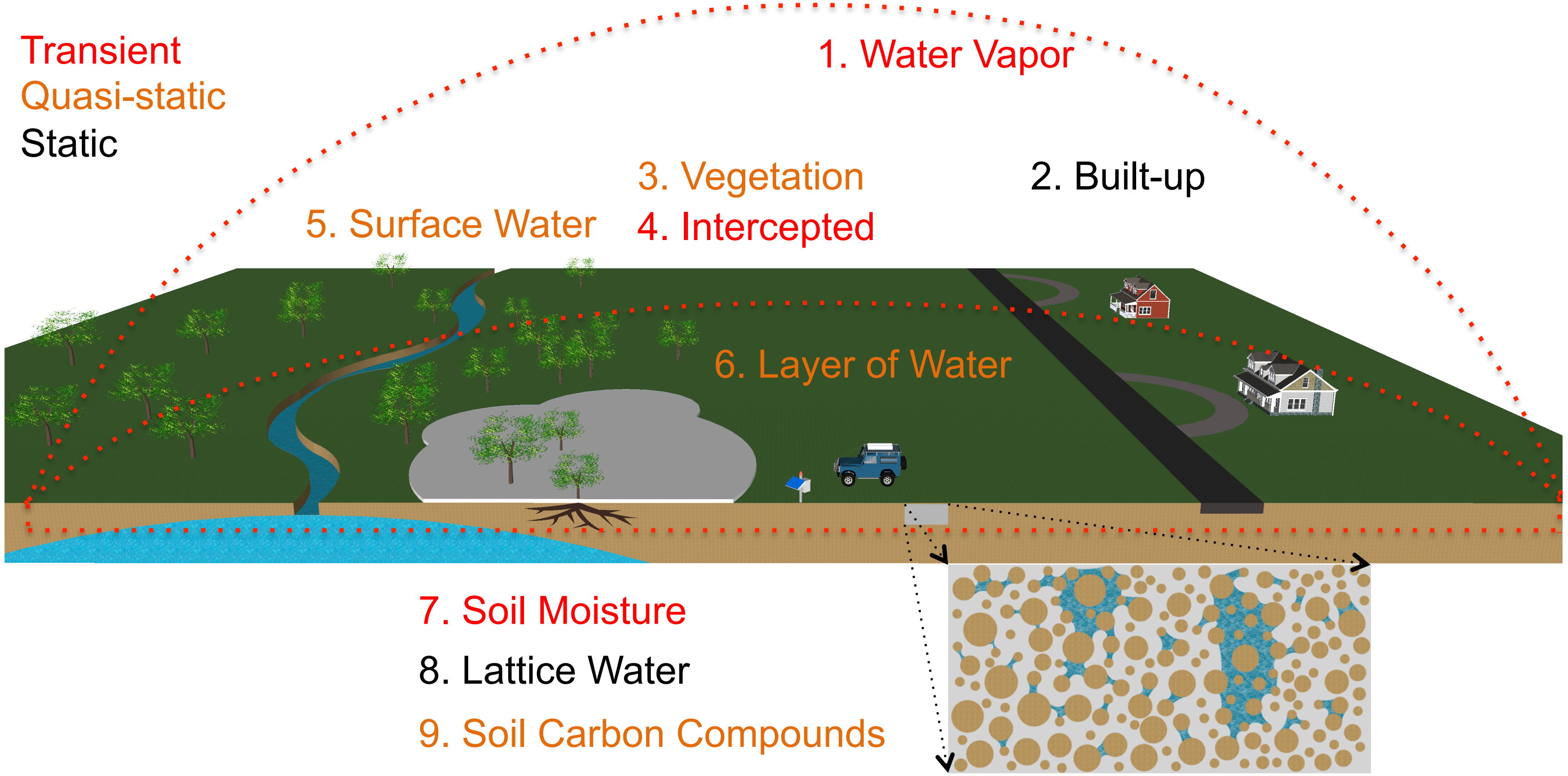
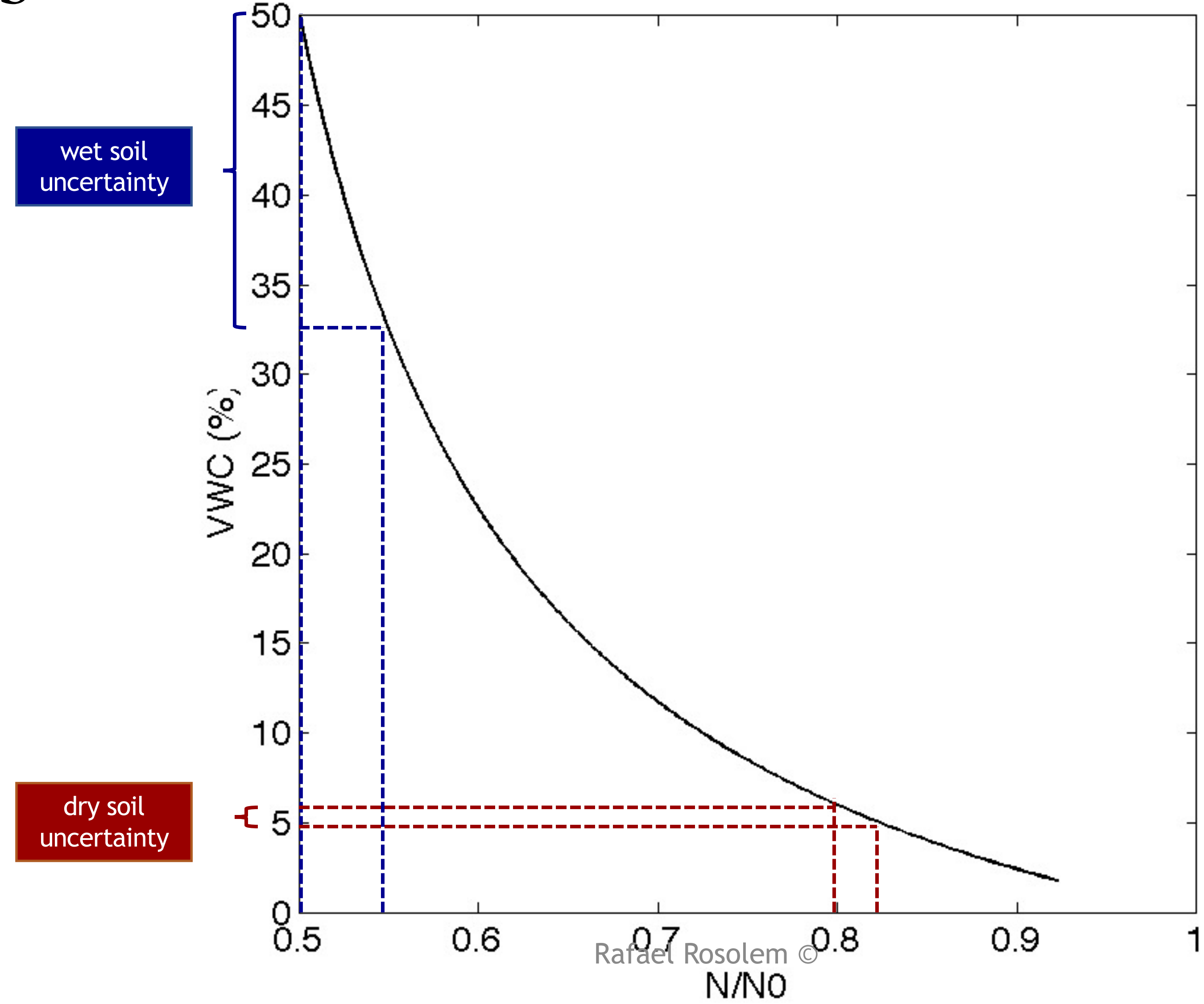


Image kindly provided by Trenton Franz (Nebraska-Lincoln)

Propagation of uncertainty: dry versus humid regions



In a humid region:

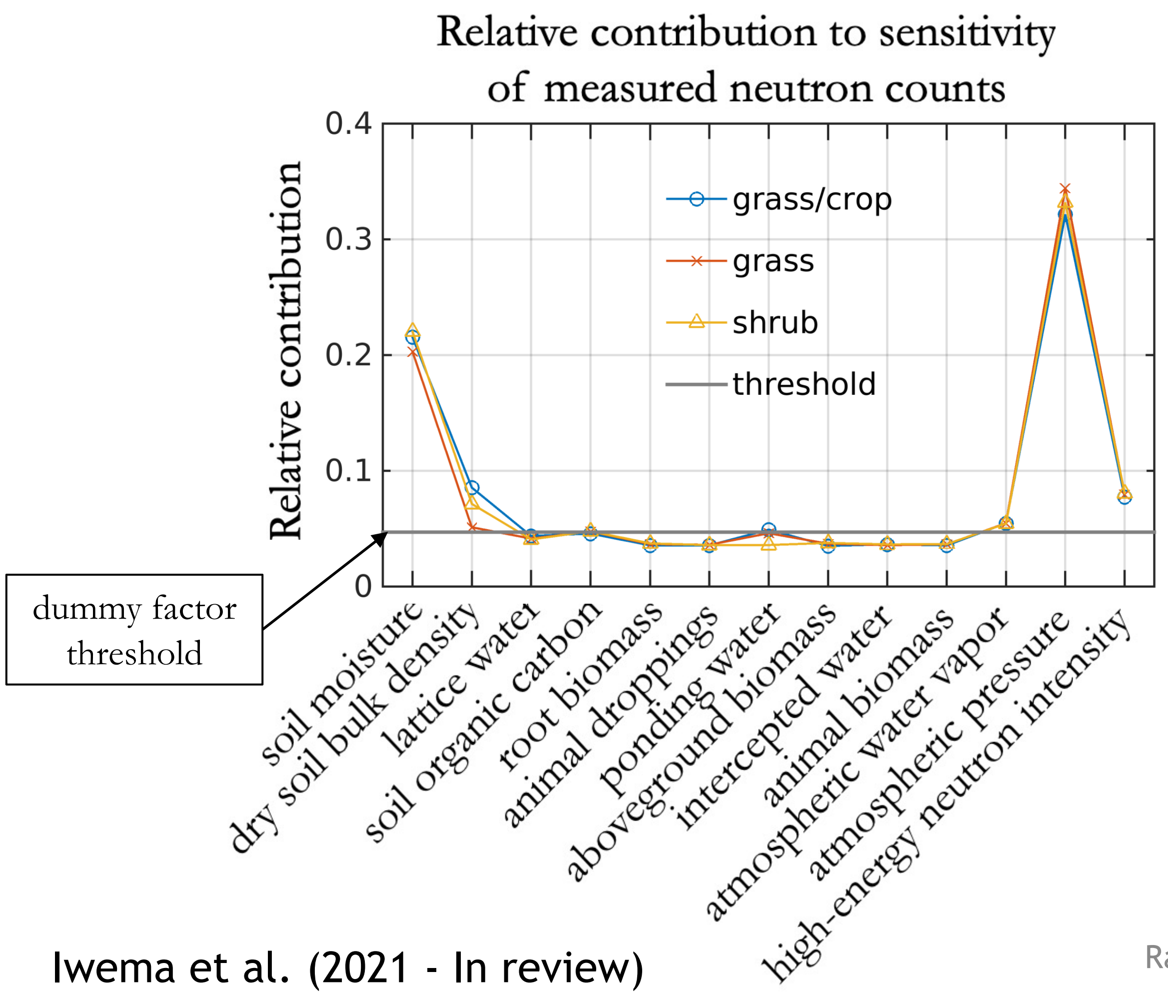
Uncertainty of neutron counts on the order of 5%

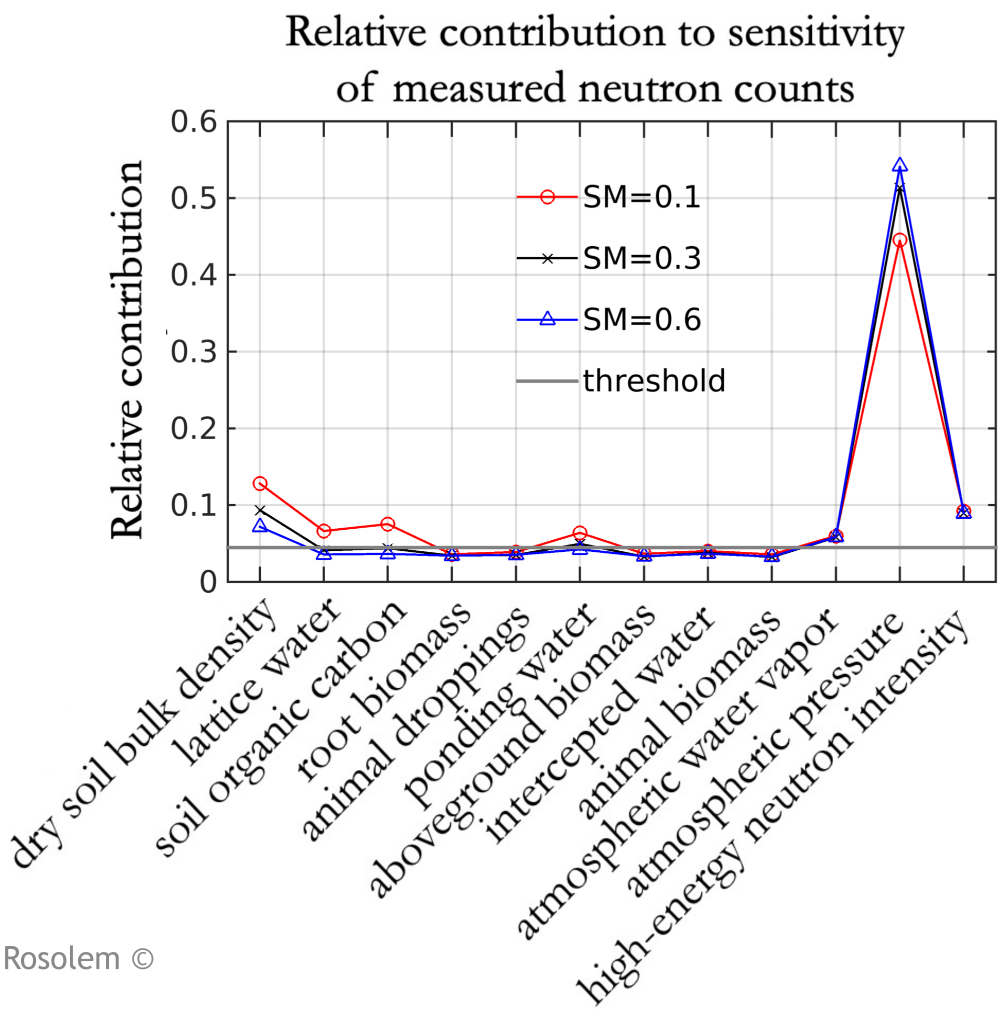
Do you know why?

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

Can you understand why?

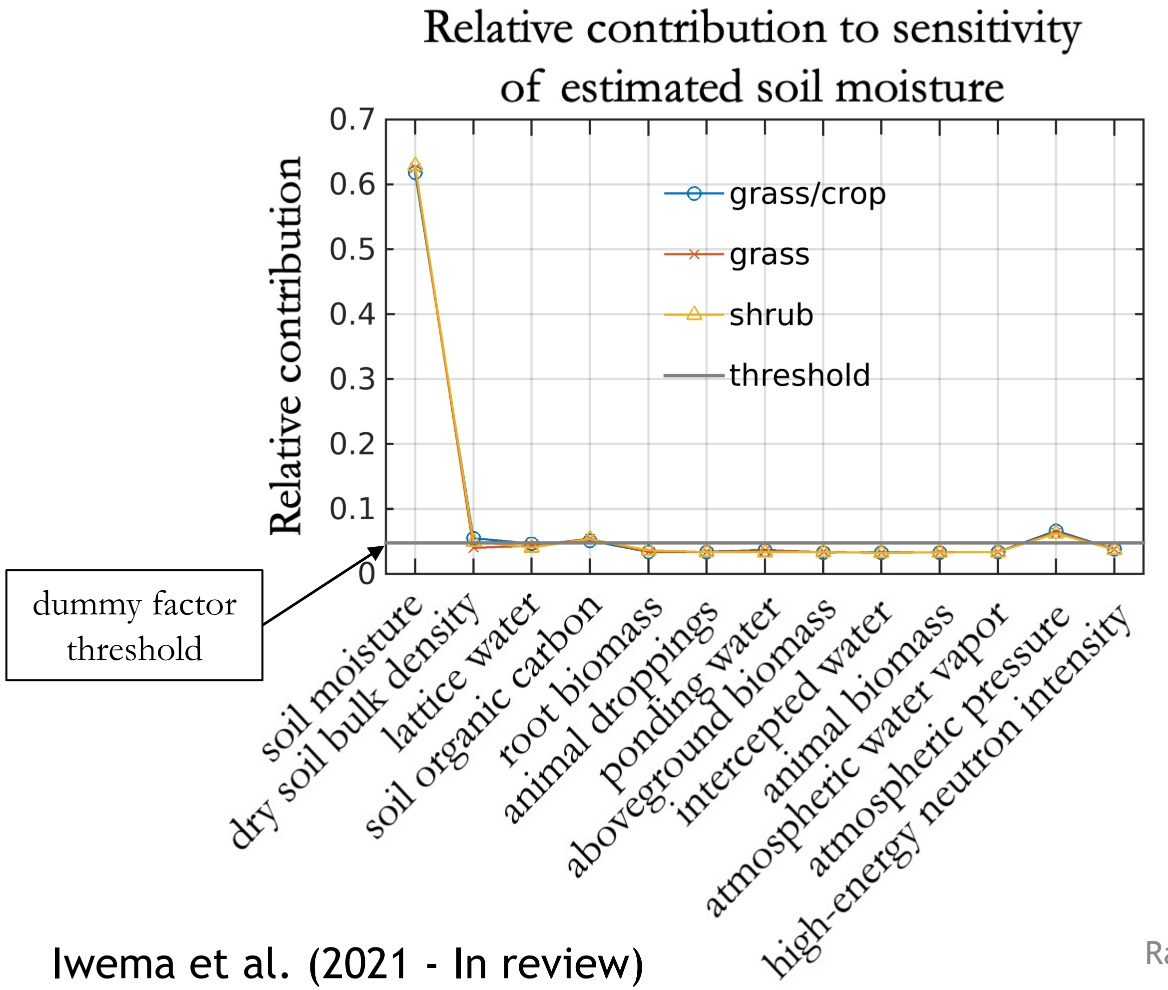
How does each factor influence the neutron signal?

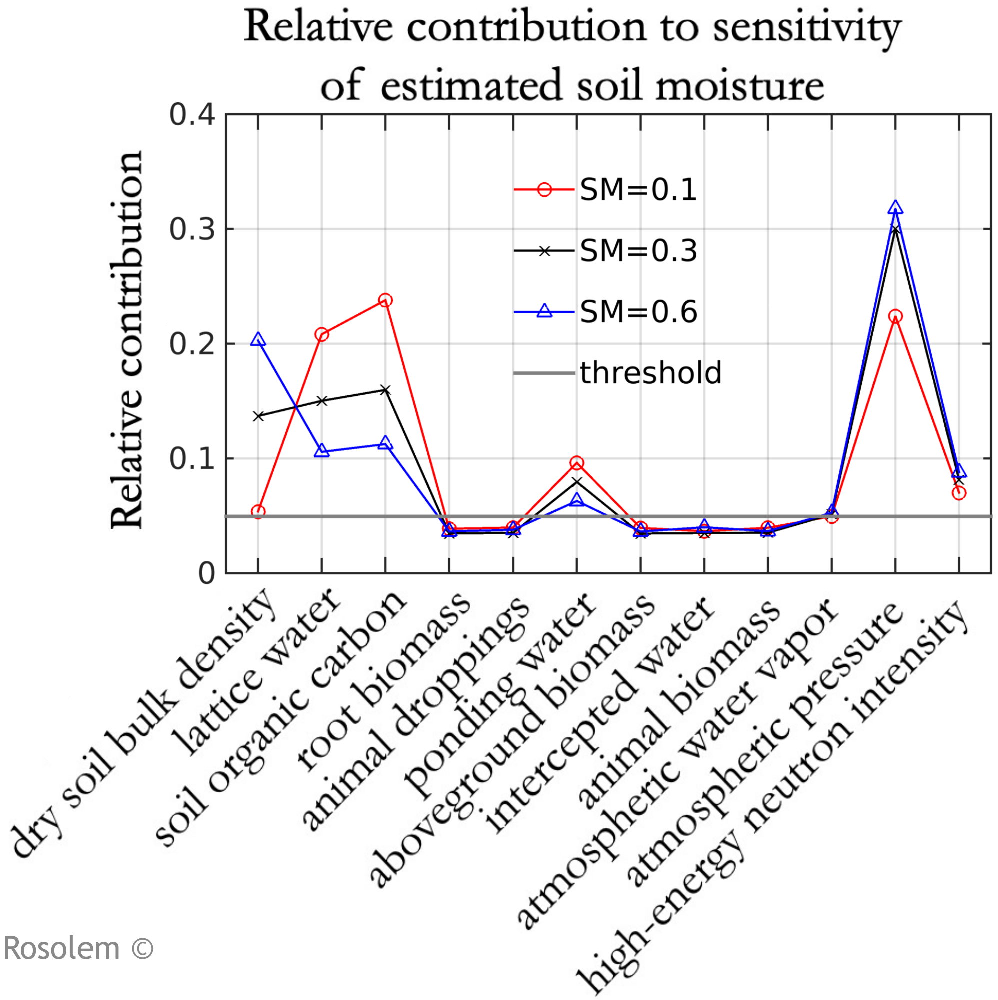




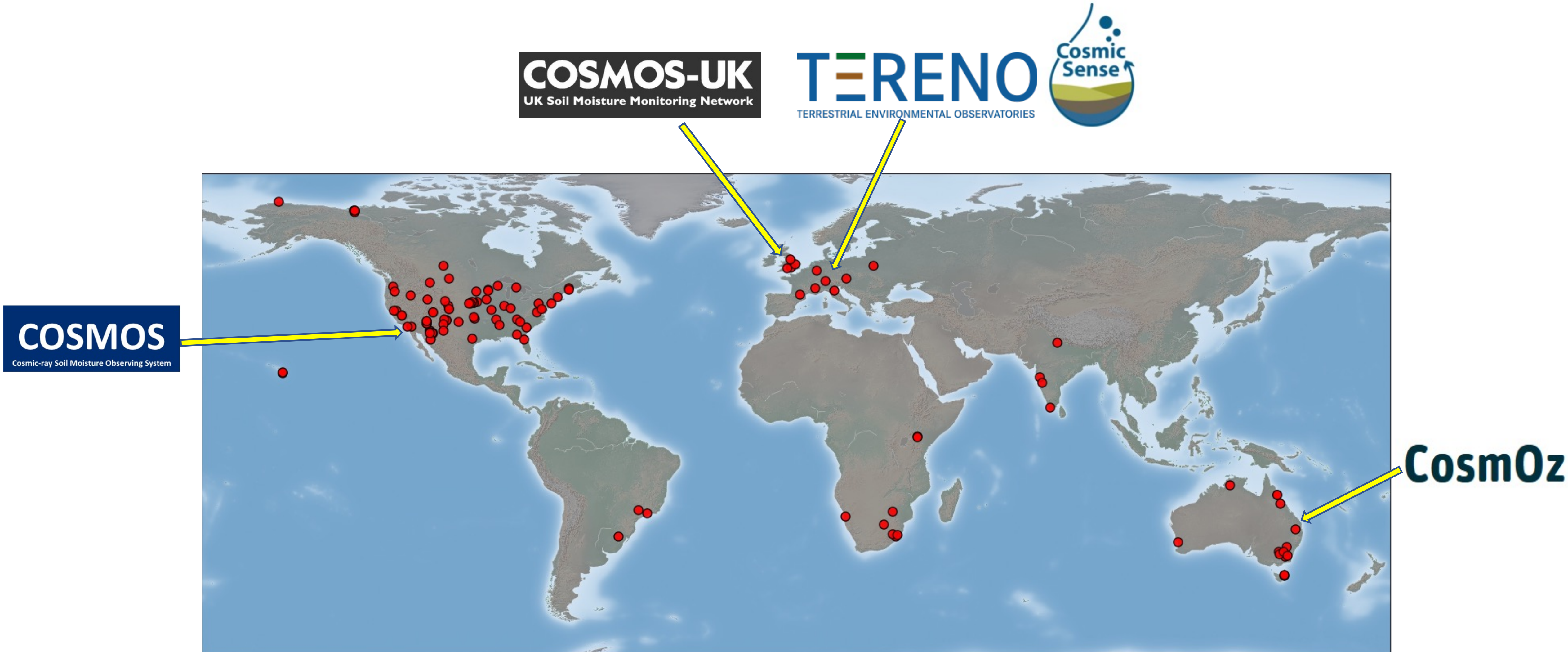
Iwema et al. (2021 - In review)

How is that propagated to the derived soil moisture estimation?

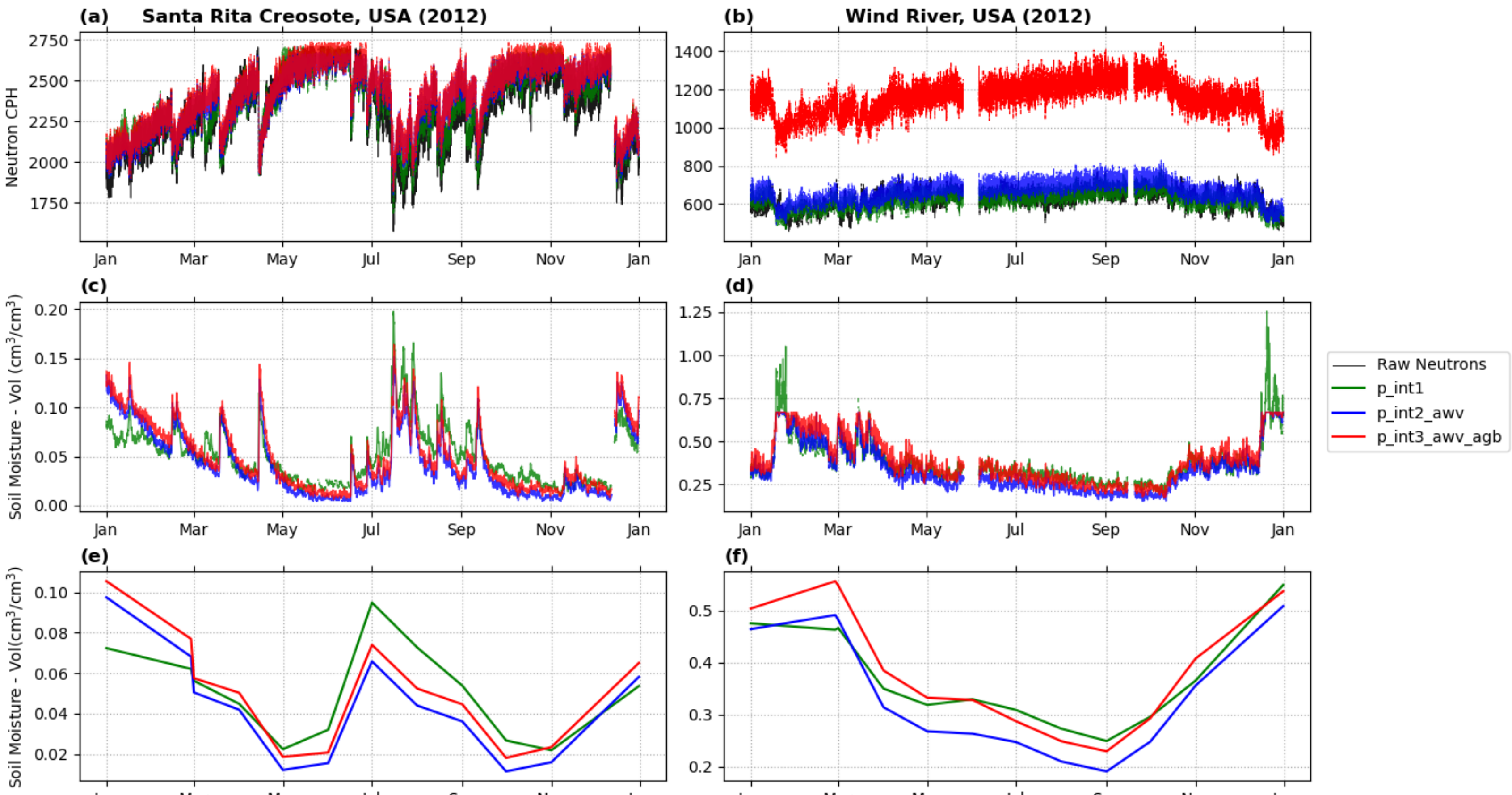




Iwema et al. (2021 - In review)


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

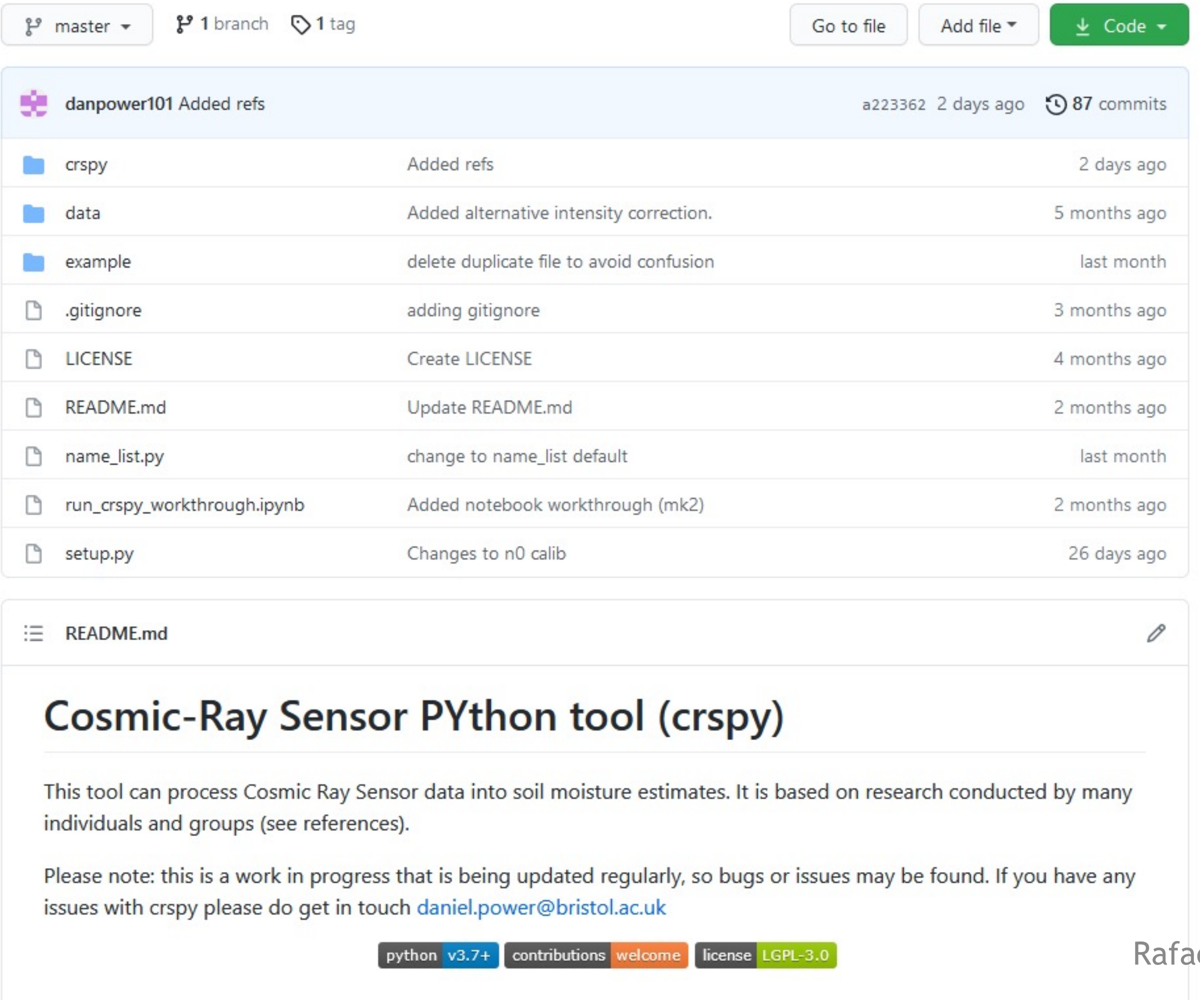
Different data processing procedures can lead to different estimates of soil moisture



Power et al. 2021 (GMDD)

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.

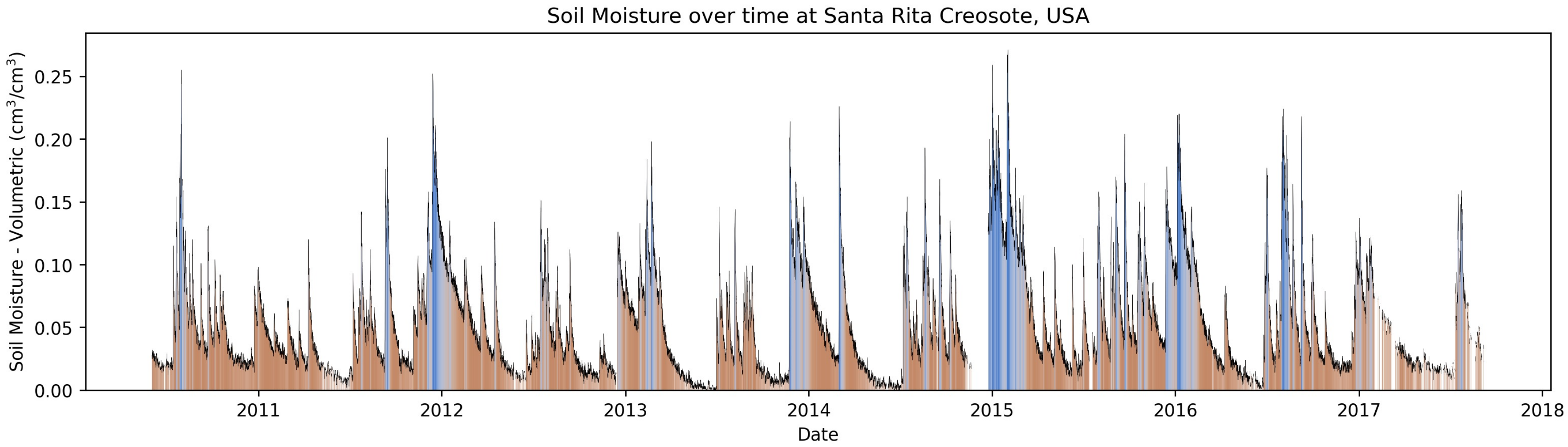
Cosmic-Ray neutron Sensor PYthon tool (crspy): An open-source tool for the processing of cosmic-ray neutron and soil moisture data

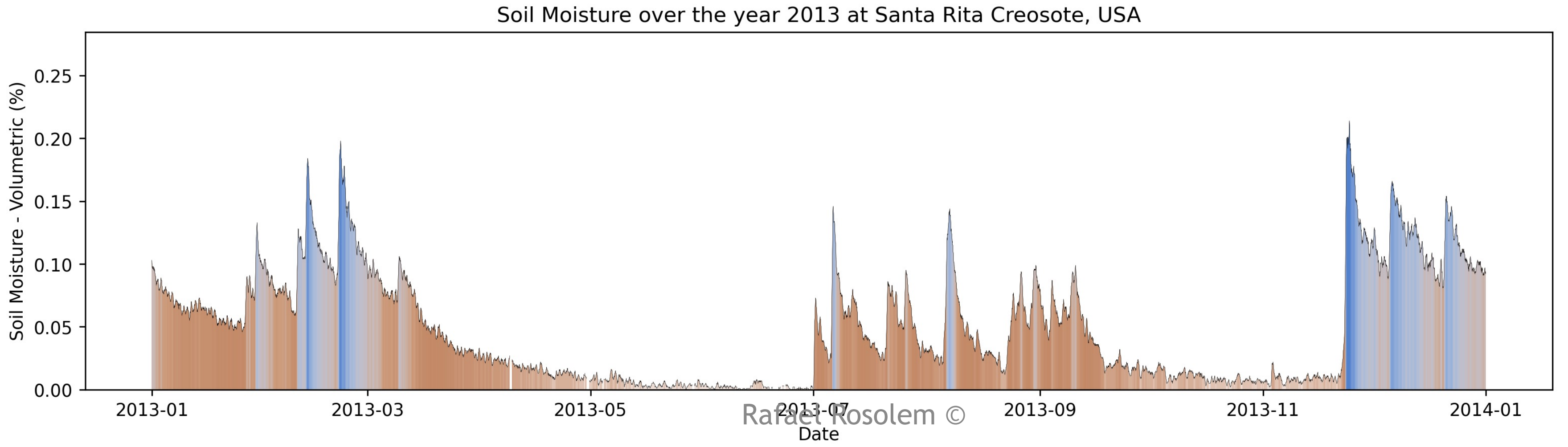
Daniel Power[1], Miguel Angel Rico-Ramirez[1], Sharon Desilets[2], Darin Desilets[2], and Rafael Rosolem[1,3]
[1]Faculty of Engineering, University of Bristol, Bristol, UK
[2]Hydroinnova, Albuquerque, New Mexico, USA
[3]Cabot Institute for the Environment, University of Bristol, Bristol, UK

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

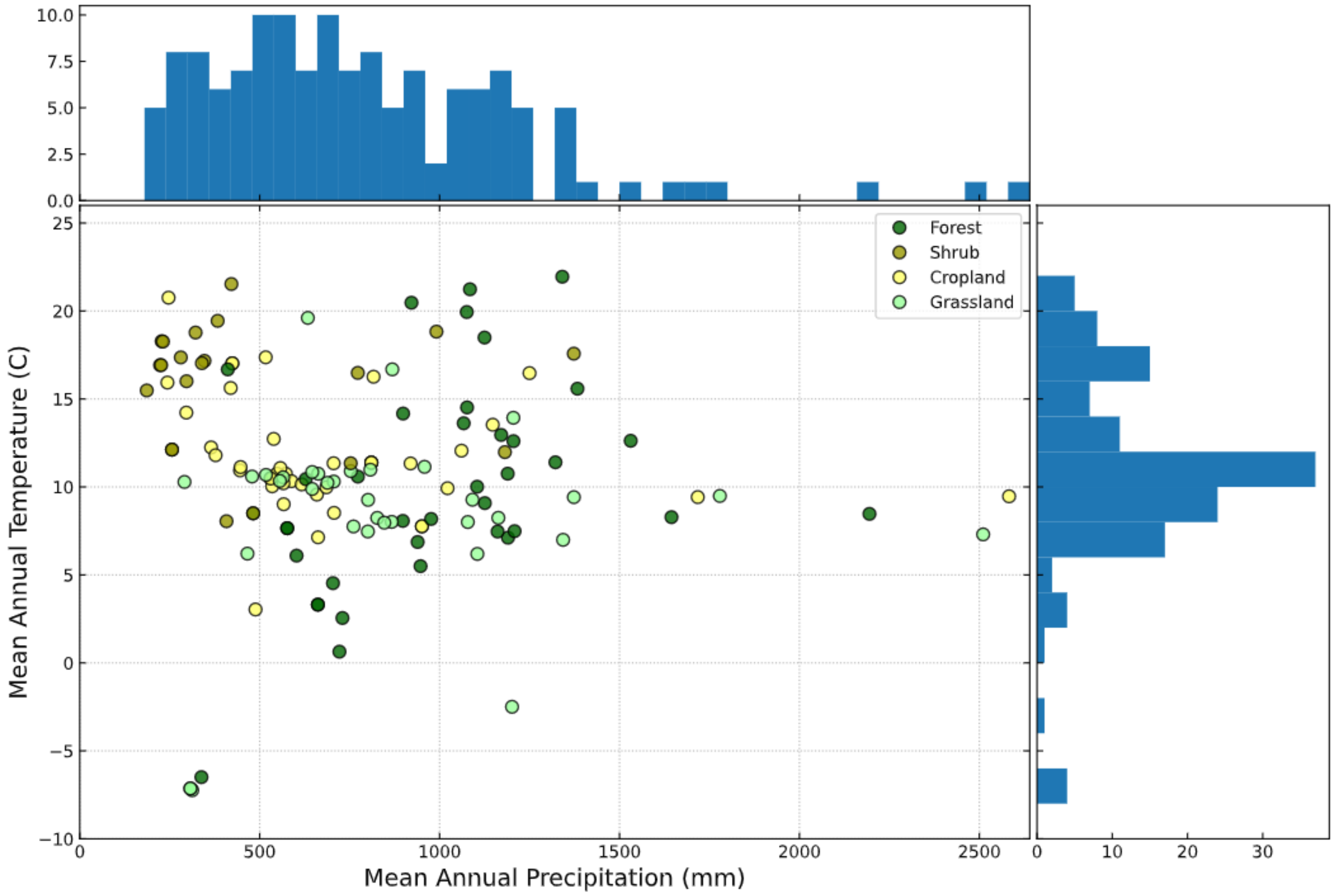
Power et al. 2020 (GMDD)

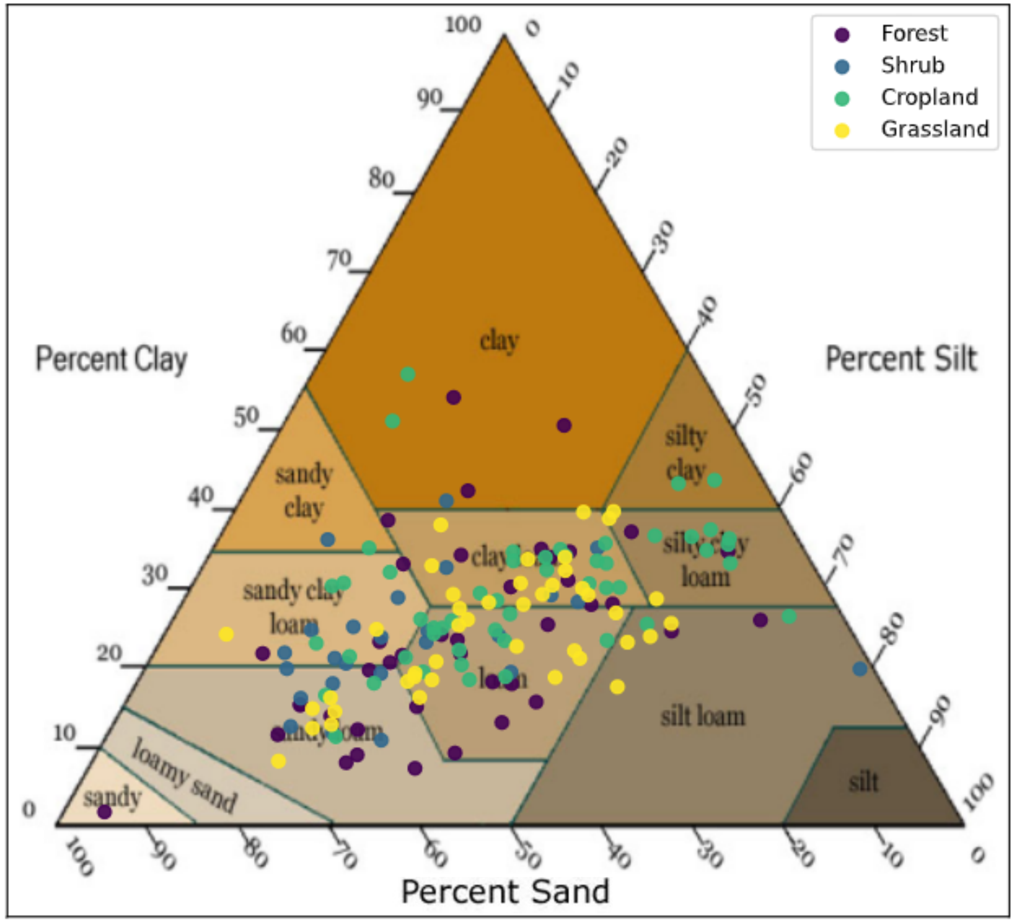
crspy generates soil moisture analysis for easy checks





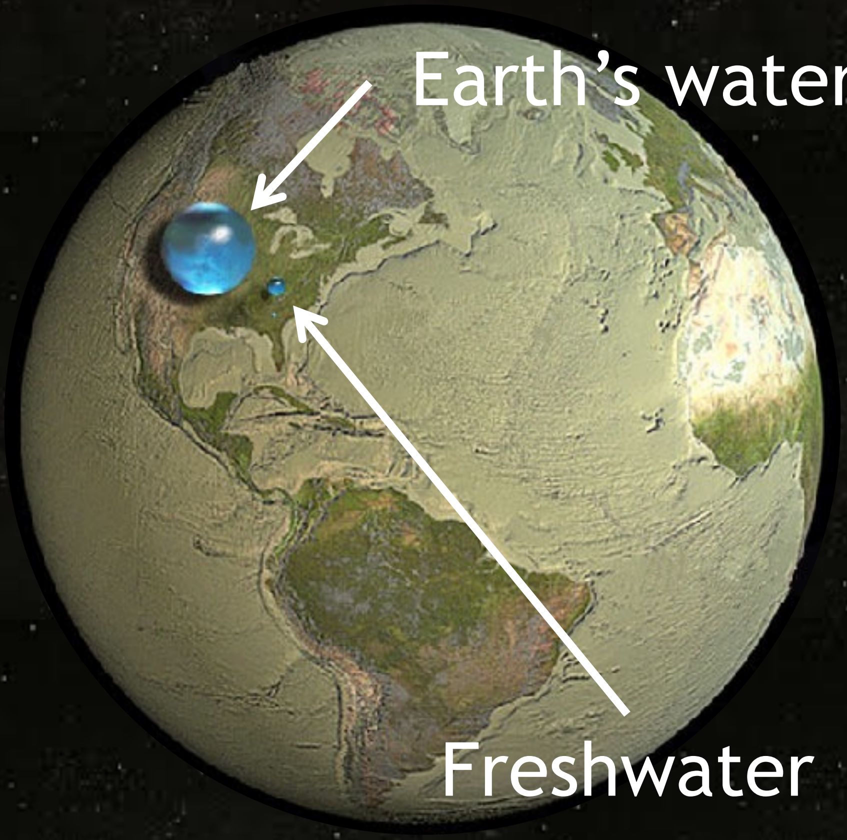
New harmonization tool crspy

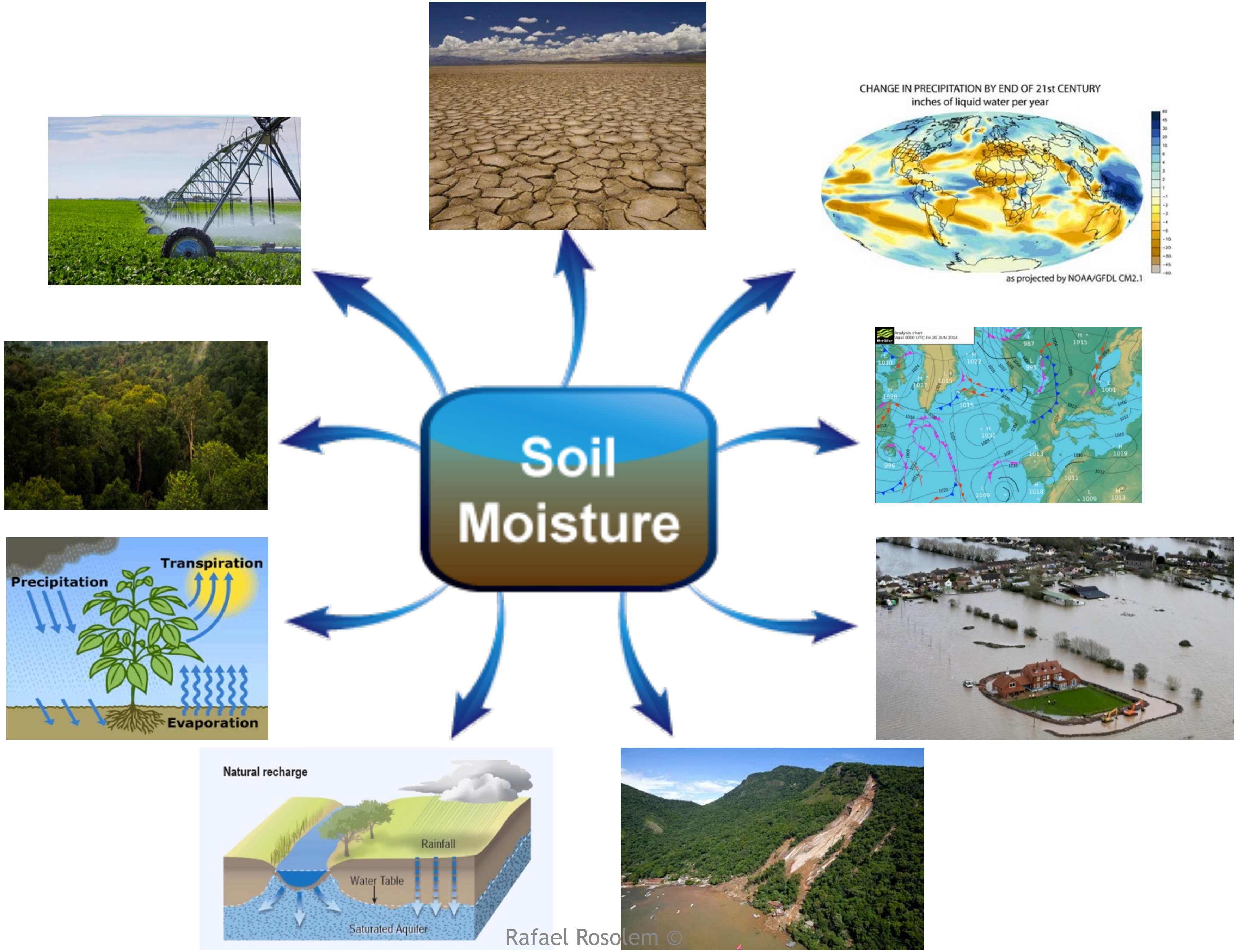




Hydrology context for environmental models

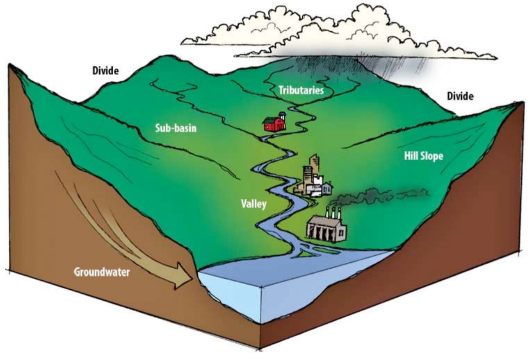
Soil moisture represents only a tiny fraction of the available freshwater on Earth (about 3.5%)

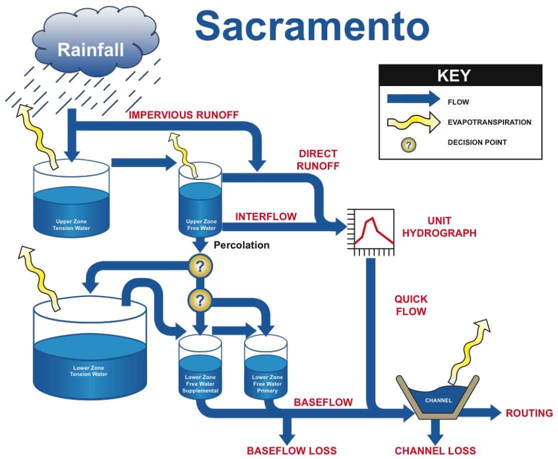



Soil Moisture
CHANGE IN PRECIPITATION BY END OF 21st CENTURY
inches of liquid water per year
as projected by NOAA/GFDL CM2.1
Precipitation
Transpiration
Evaporation
Natural recharge
Rainfall
Water Table
Saturated Aquifer

In the past, hydrological and land surface models had focused on different spatial scales

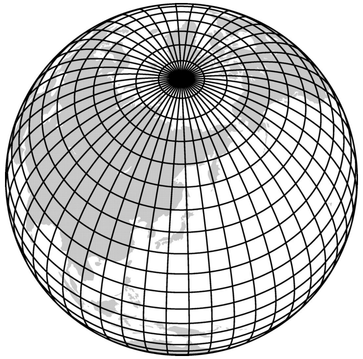
Hydrological Model

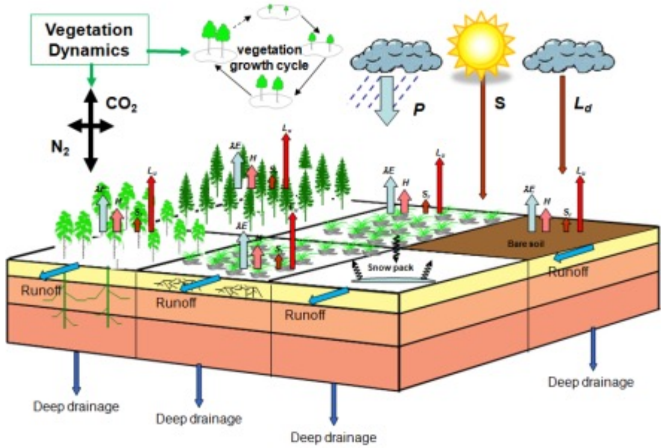




Conceptual lumped response
Dependent on calibration
Catchment scale

Land Surface Model

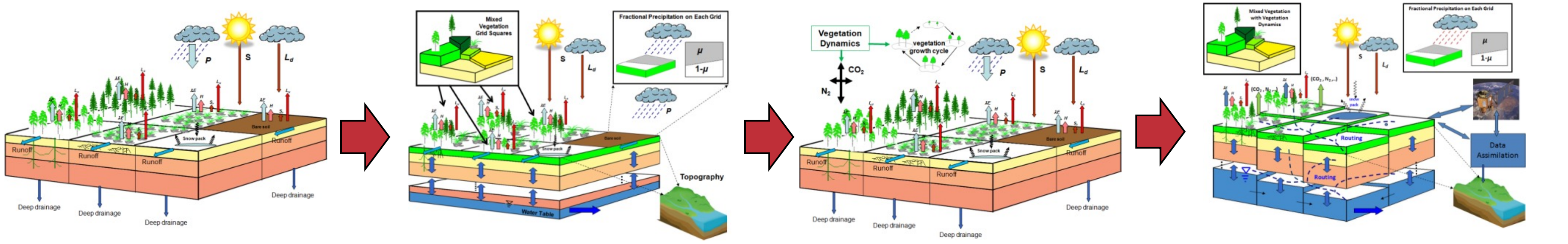




Physics-based
Look up tables vs. calibration
Larger grid domain

Hydrological and land surface models have converged to "hyper-resolution" at sub-kilometer scales supported by new datasets

Further <u>improvement</u> in the <u>realism</u> of hydrometeorological models



1. Plot-scale, 1-d models
BATS, SiB, Noah

2. Improved hydrology
VIC

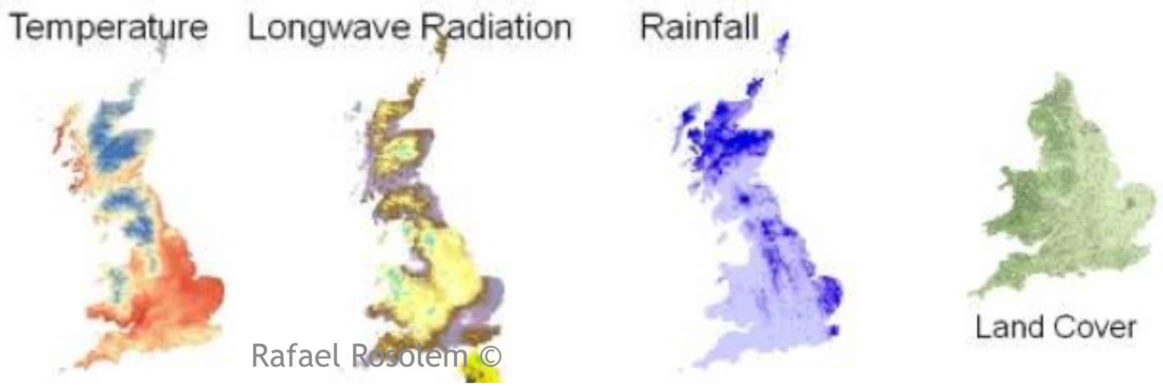
3. Improved CO_2 exchange
BATS2, SiB2/3, CLM, Noah-MP, JULES

4. Ongoing (groundwater, hydraulic redistribution, …)

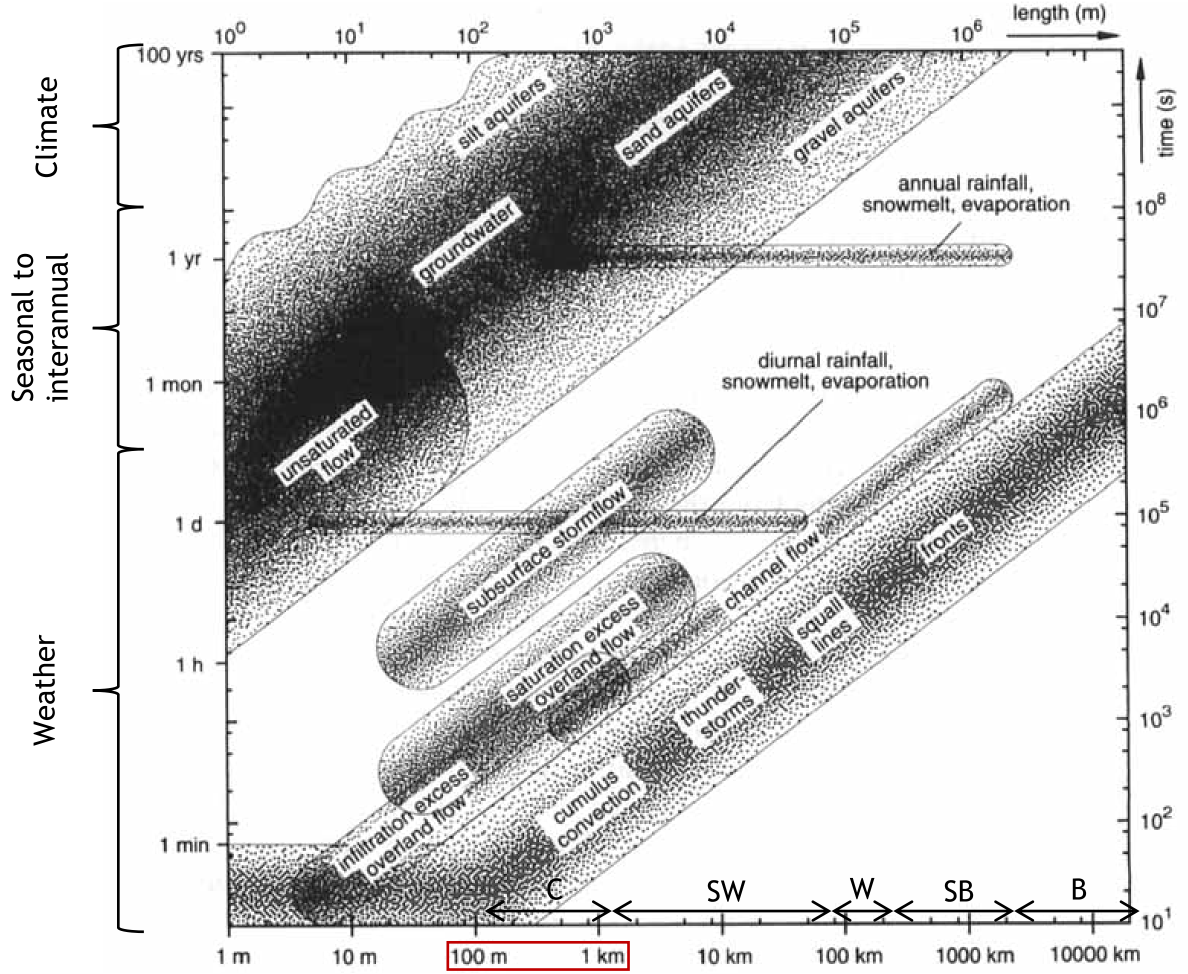
Model grid <u>resolution</u> of regional and global models has <u>increased</u> hugely

Climate Hydrology Ecology Support System (CHESS)

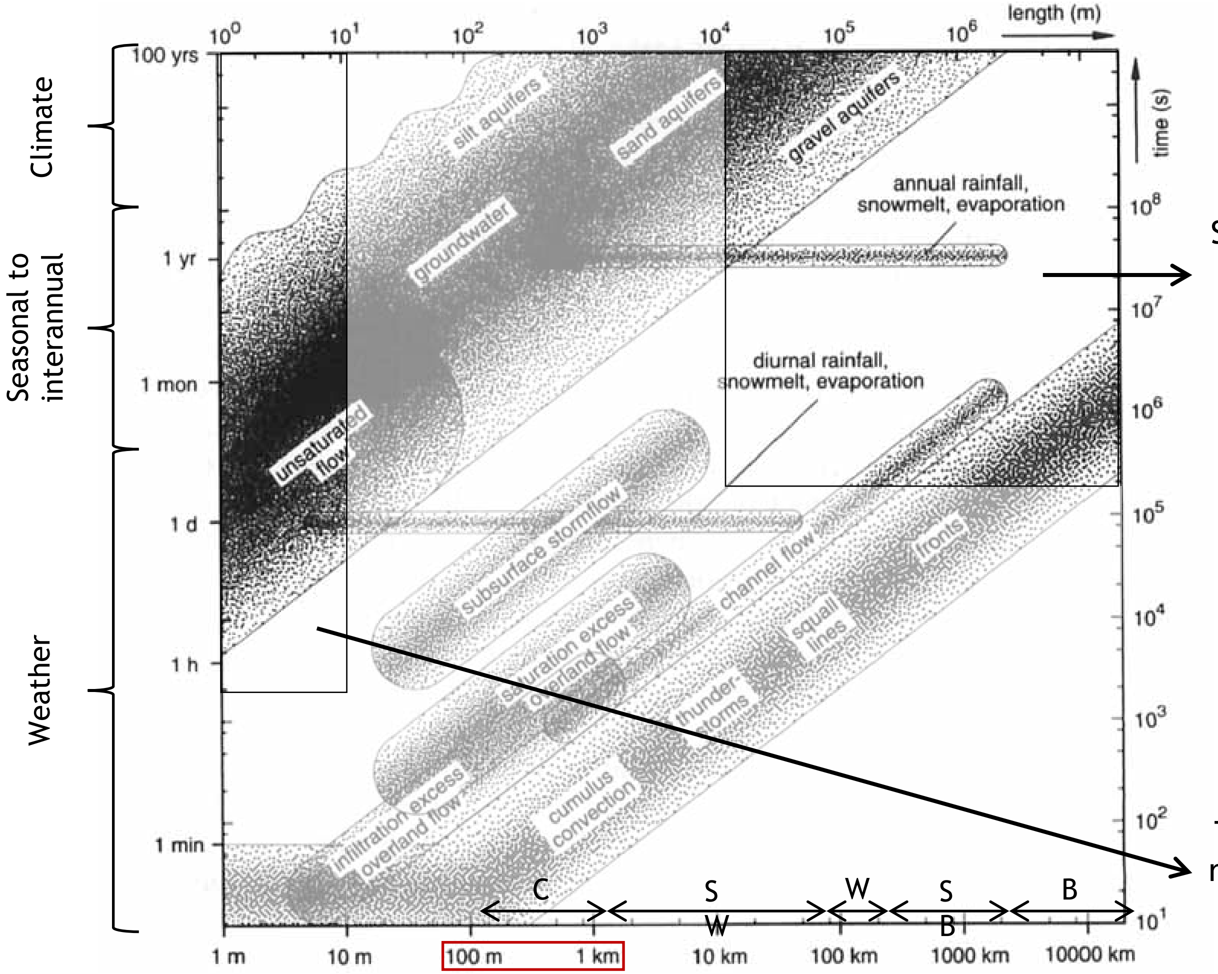
Centre for Ecology & Hydrology
NATURAL ENVIRONMENT RESEARCH COUNCIL



Soil moisture across spatiotemporal scales

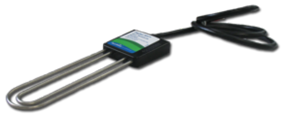


Soil moisture across spatiotemporal scales

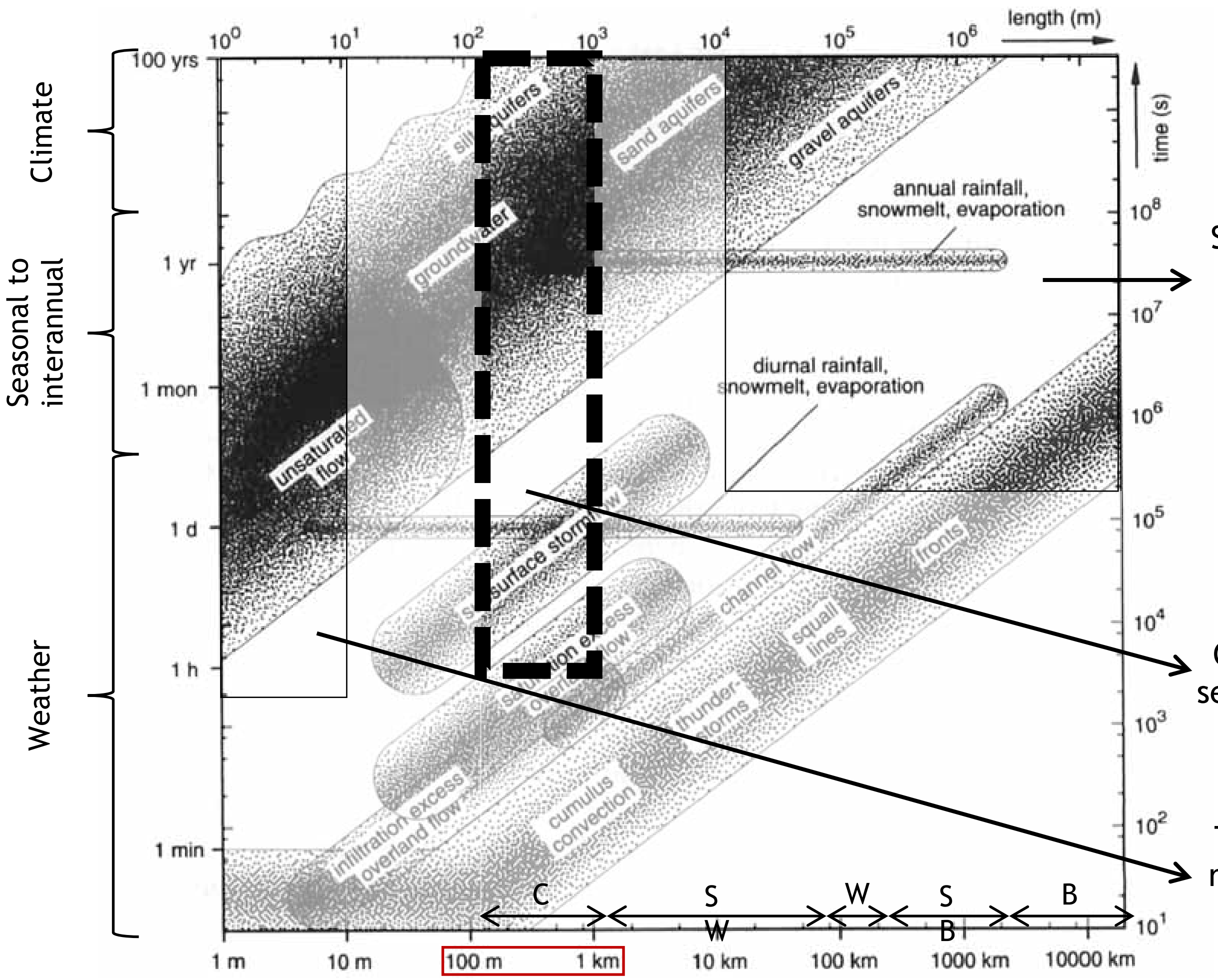


Satellite remote sensing

Time-domain reflectometry (TDR)



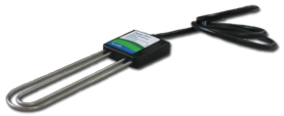
Cosmic-ray sensors fills the gap between traditional methods



Satellite remote sensing

Cosmic-ray sensors (CRS)

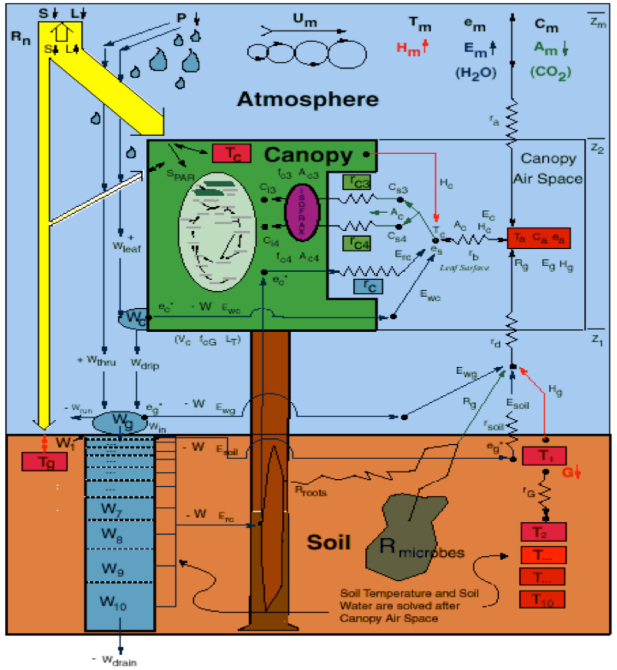
Time-domain reflectometry (TDR)



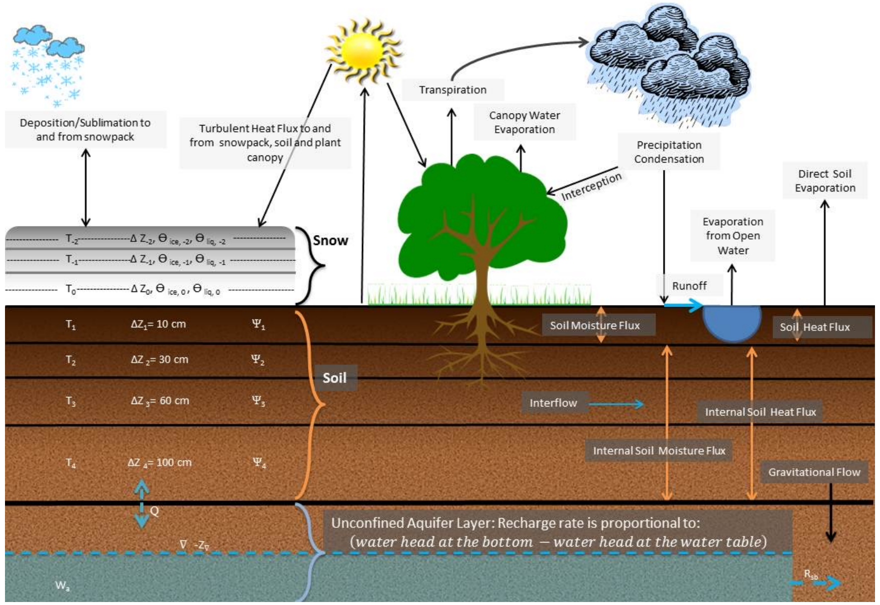
Example of applications using land surface models

Example applications with land surface models

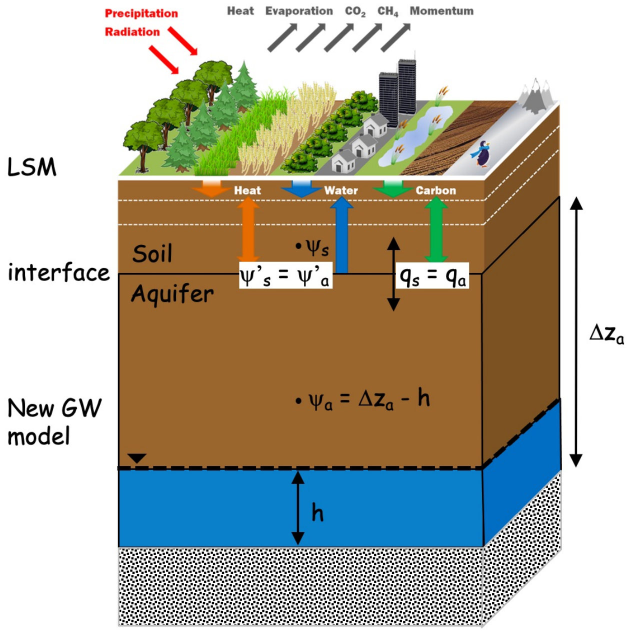
Simple Biosphere Model



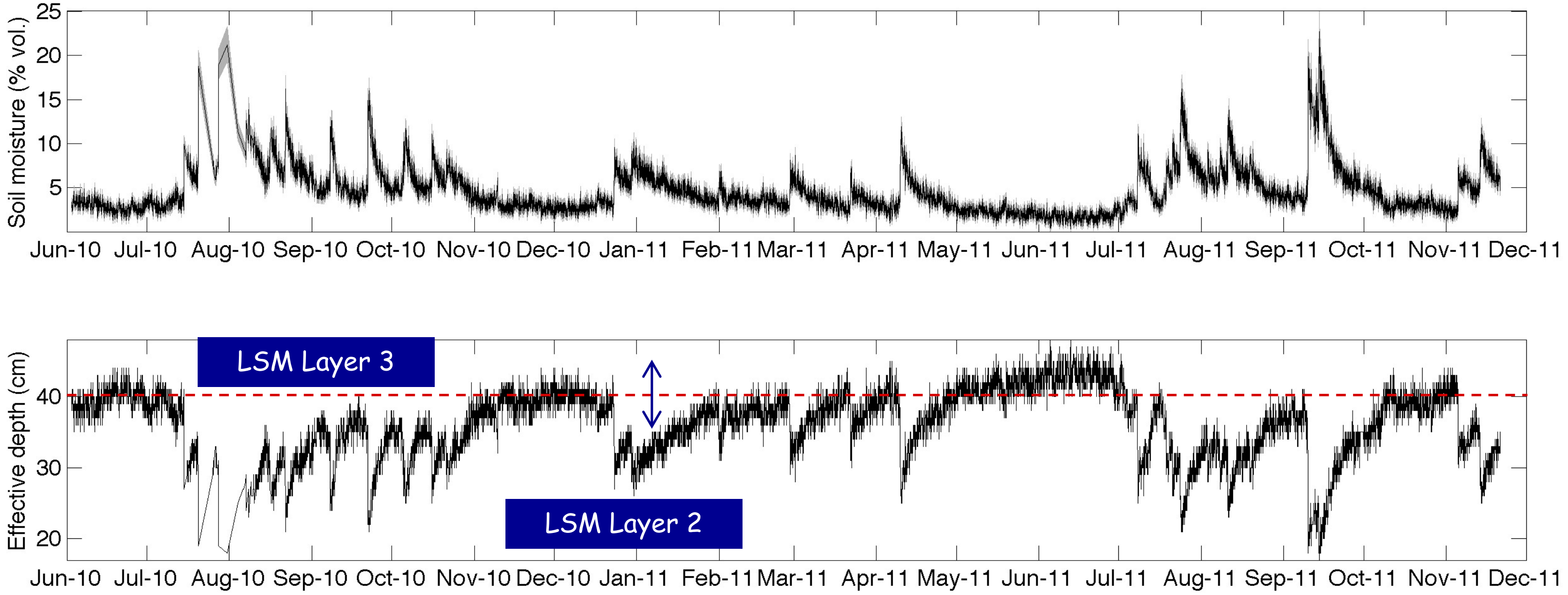
NOAH model



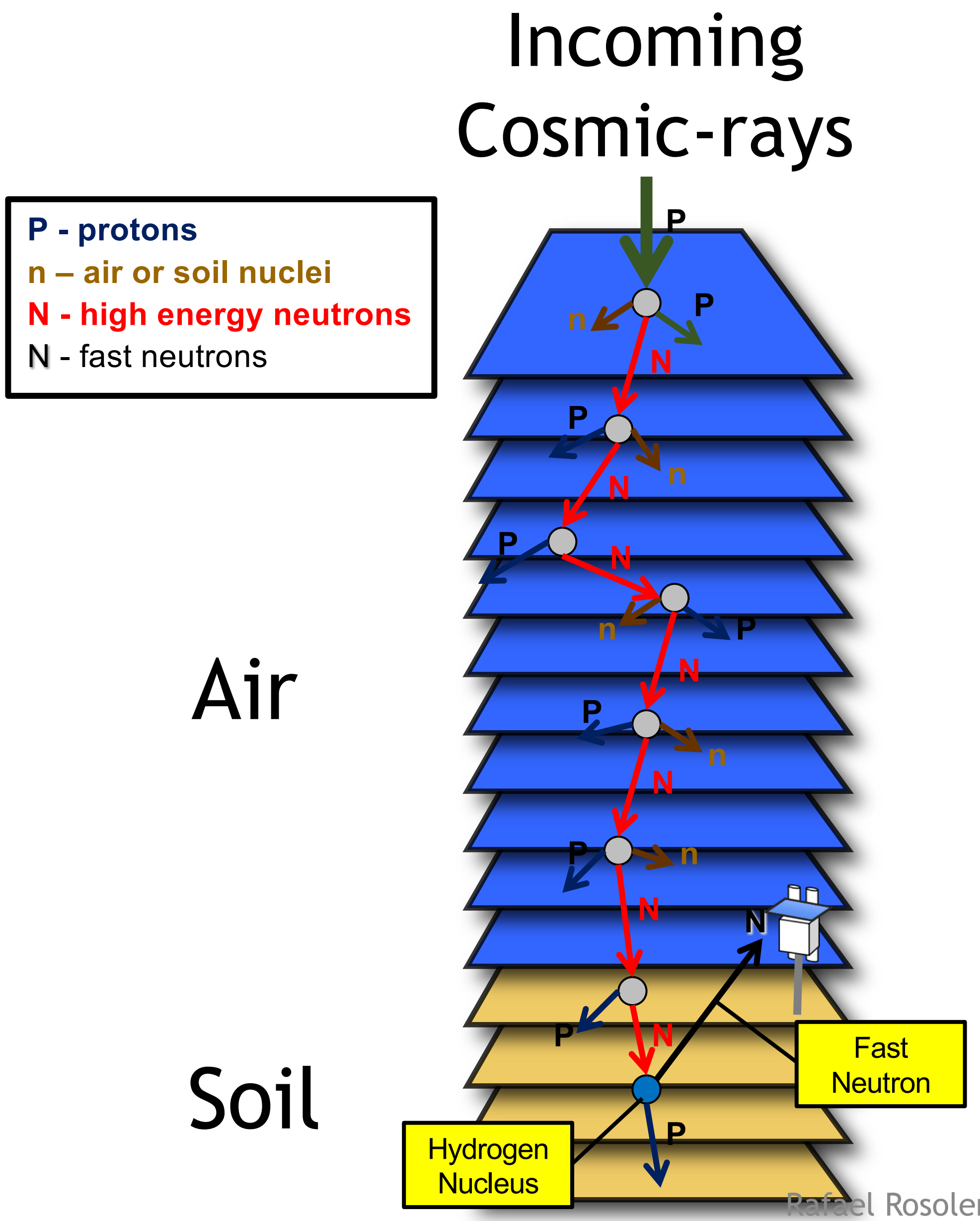
Joint UK Land Environment Model



Soil layers in models poses challenges when combining with cosmic-ray neutron sensors



Integrated soil moisture from cosmic-ray sensors can reach multiple soil layers in land models!!!

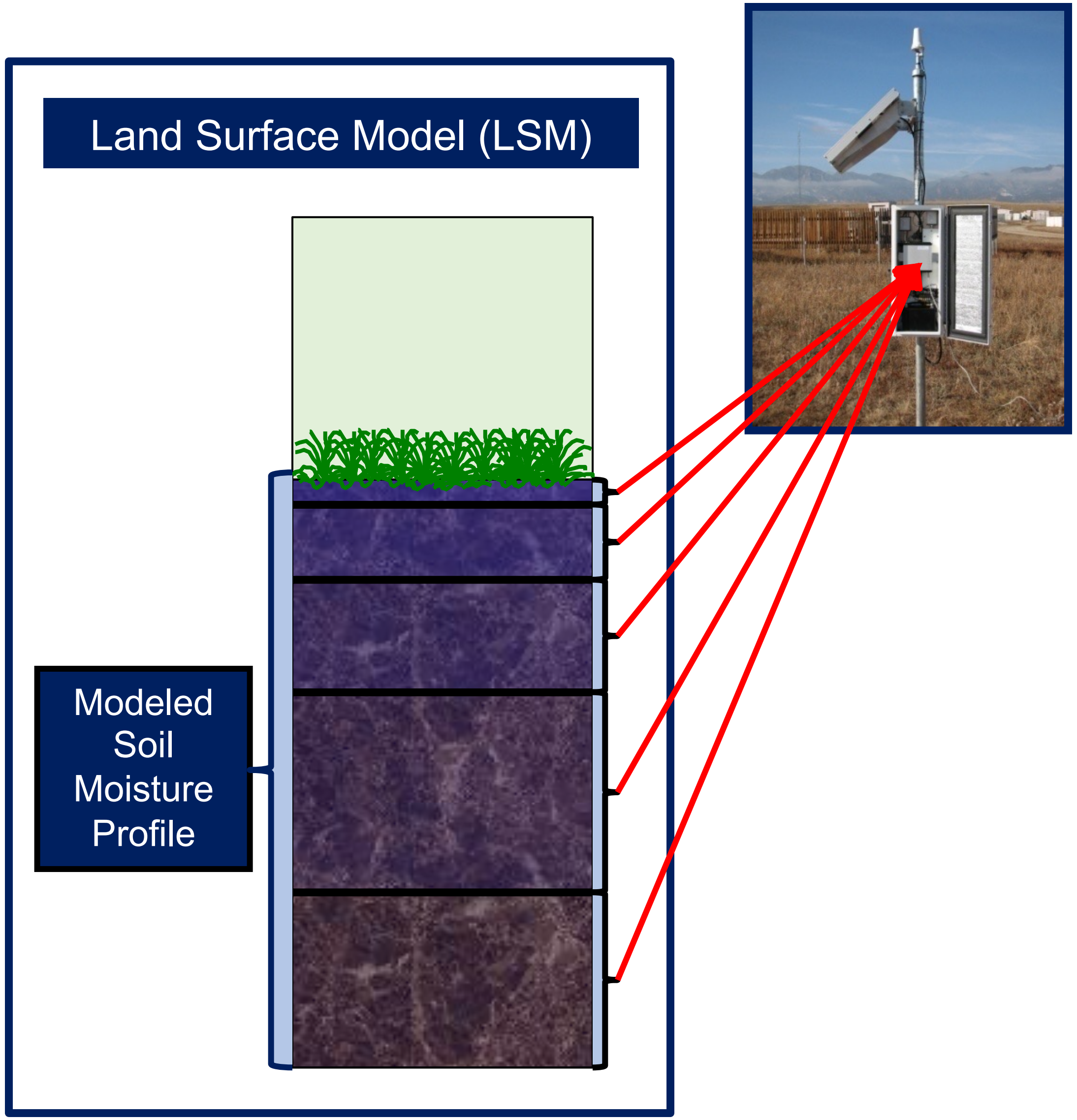


The *Monte Carlo N-Particle eXtended* (MCNPX) model

(created to design nuclear bombs!)

- requires specified chemistry for the atmosphere and soil, including hydrogen.
- uses measured nuclear collision cross sections for all constituents
- tracks the life history of randomly selected, individual cosmic rays and their collision products
- counts the "fast neutrons" (~1 MeV) that pass through the detector volume of the COSMOS probe

But it is too computationally demanding

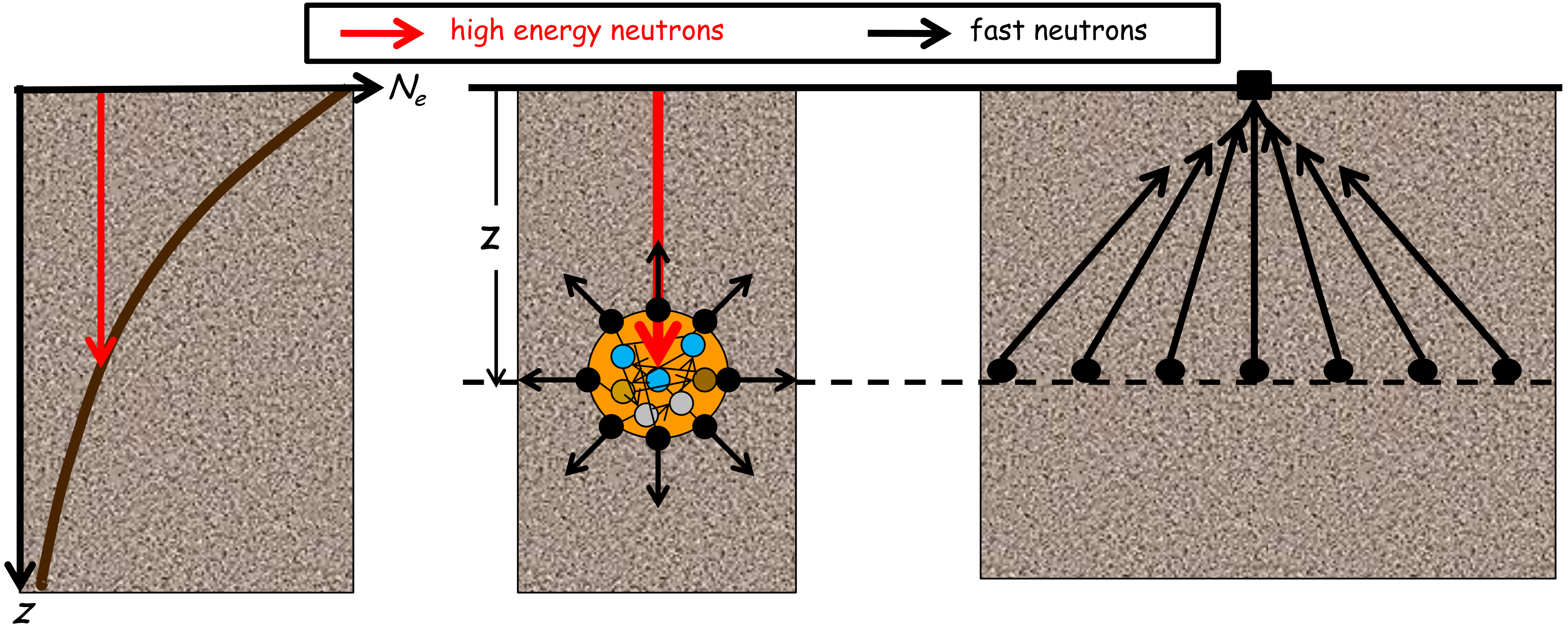


We developed the COsmic-ray Soil Moisture Interaction Code (COSMIC) to resolve the issues with multi-layers in land surface models

COSMIC translates model-derived soil moisture profiles into an equivalent neutron count which can be compared directly with the measurement from cosmic-ray sensors

This reduces the uncertainty in the process and eventual propagation of errors

COSMIC captures essential below-ground physics in parametric form



Exponential reduction in the number of high energy neutrons with depth

Isotropic creation of fast neutrons from high energy neutrons at level "z"

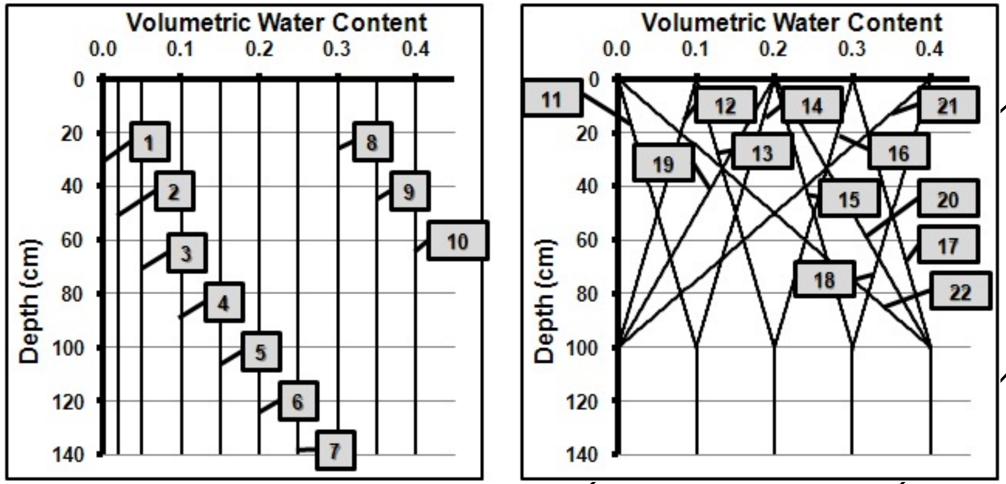
Exponential reduction in the number of the fast neutrons created at level "z" before their surface measurement

$$N_{COSMOS} = N\int_0^{\infty}\left[\exp\left(-\left[\frac{m_s(z)}{L_1}+\frac{m_w(z)}{L_2}\right]\right) . \left[\alpha\ \rho_s(z)+\rho_w(z)\right] . \left(\frac{2}{\pi}\right)\int_0^{\pi/2}\exp\left(\frac{-1}{\cos(\theta)}\left[\frac{m_s(z)}{L_3}+\frac{m_w(z)}{L_4}\right]\right).d\theta\right].dz$$

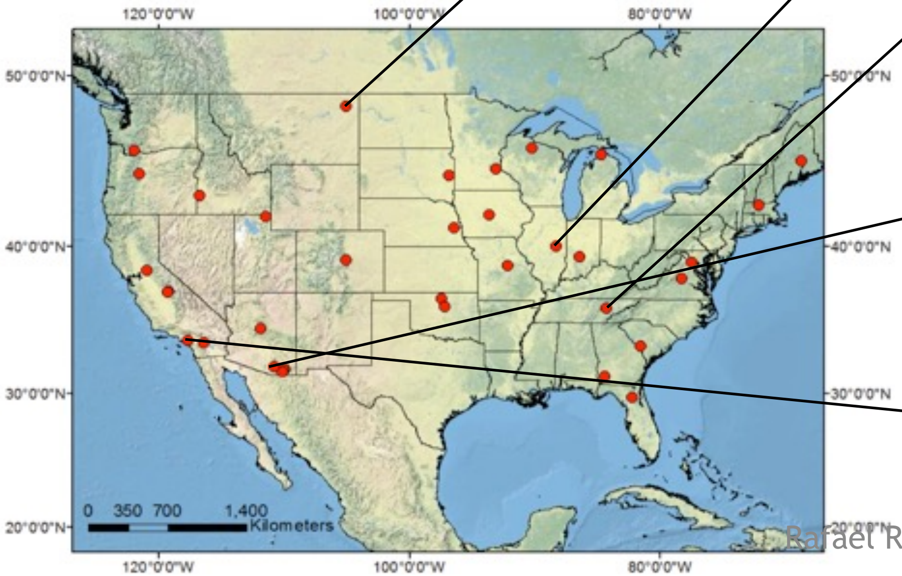
Shuttleworth et al. (2013)

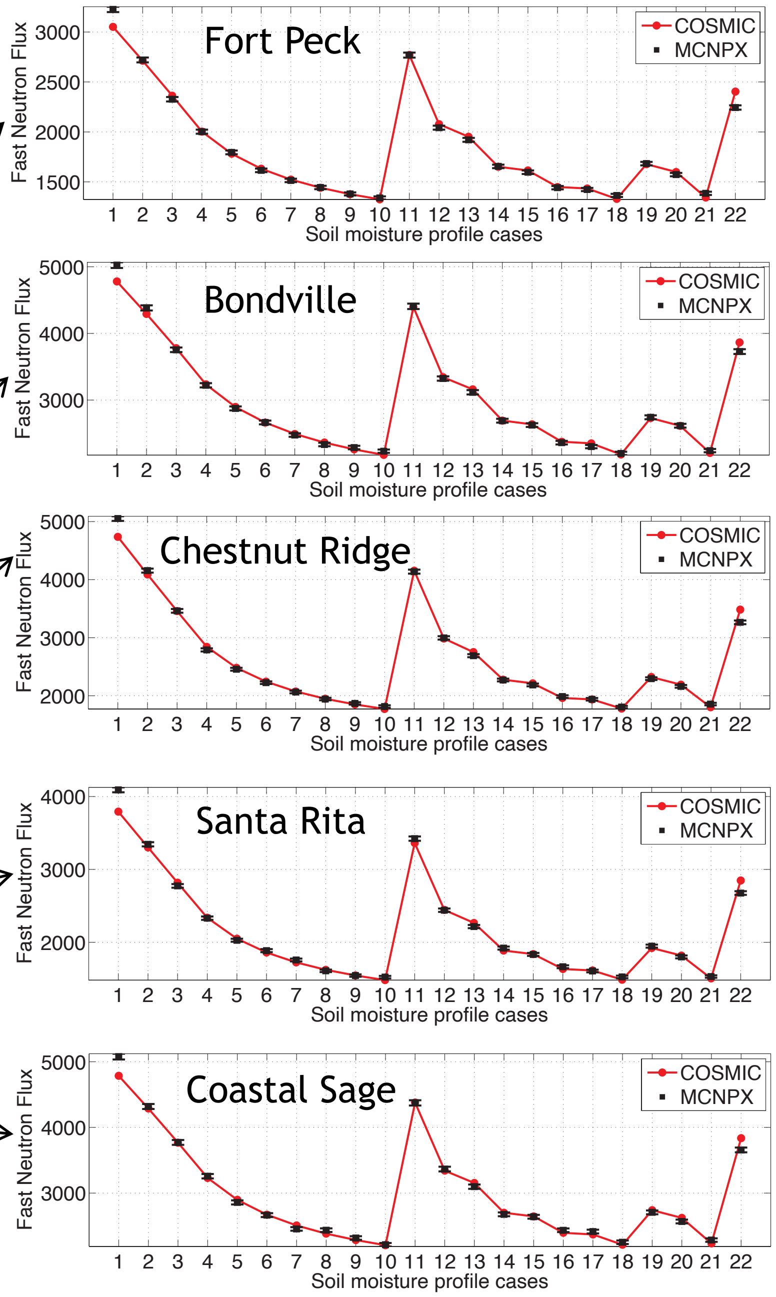
Initial COSMIC calibration against MCNPx at 42 sites using synthetic soil moisture profiles

Hypothetical soil water profiles

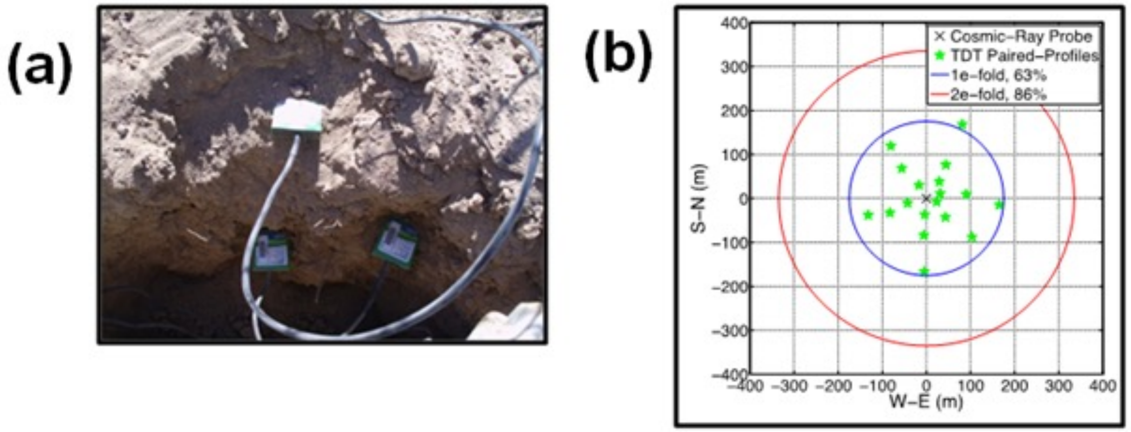


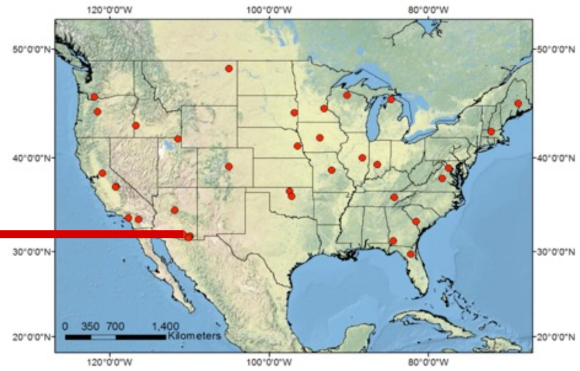
Shuttleworth et al. 2013

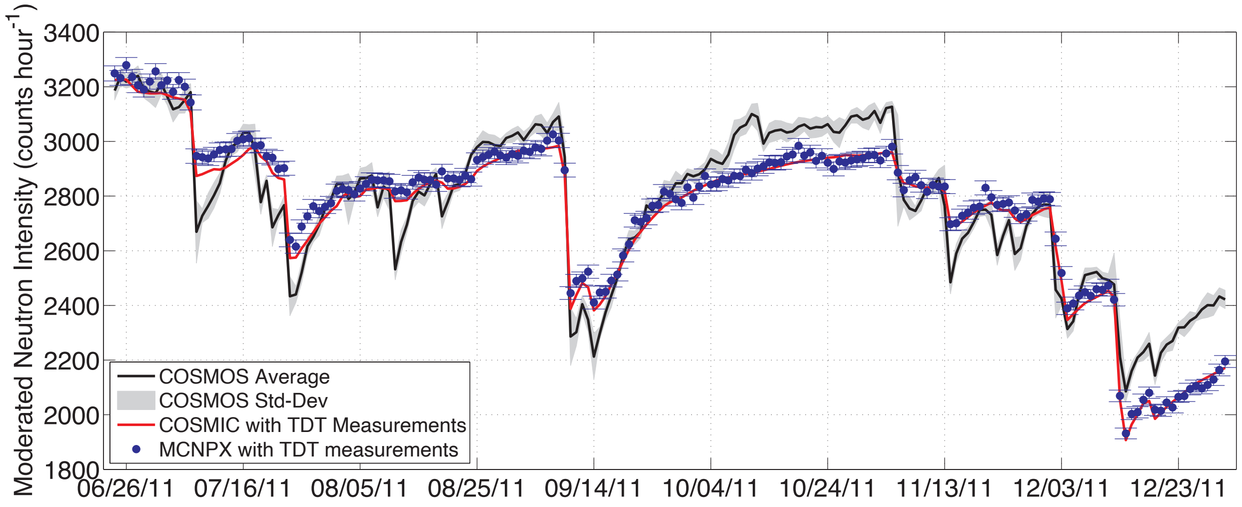




COSMIC comparison against independent network of soil moisture sensors



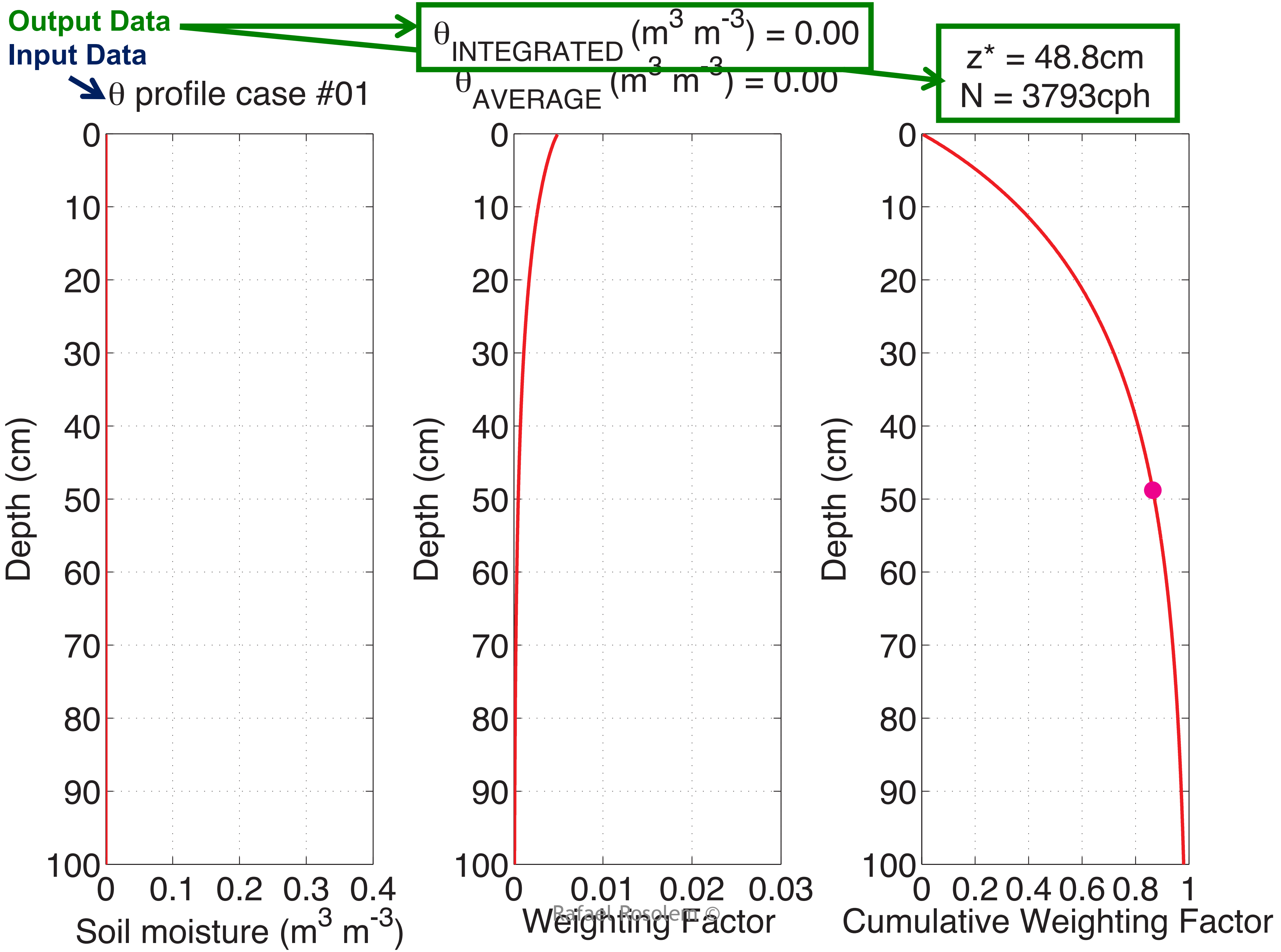


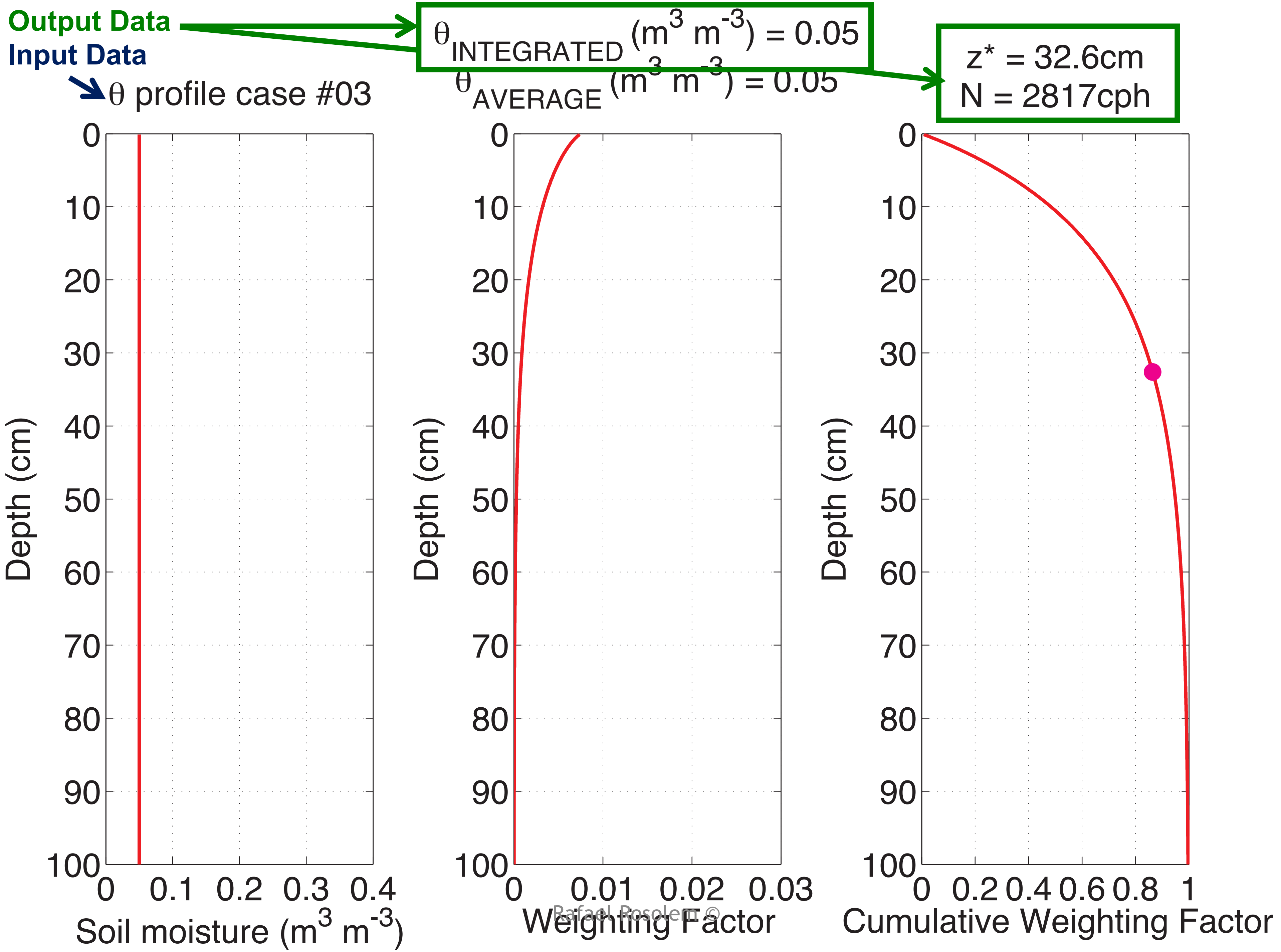


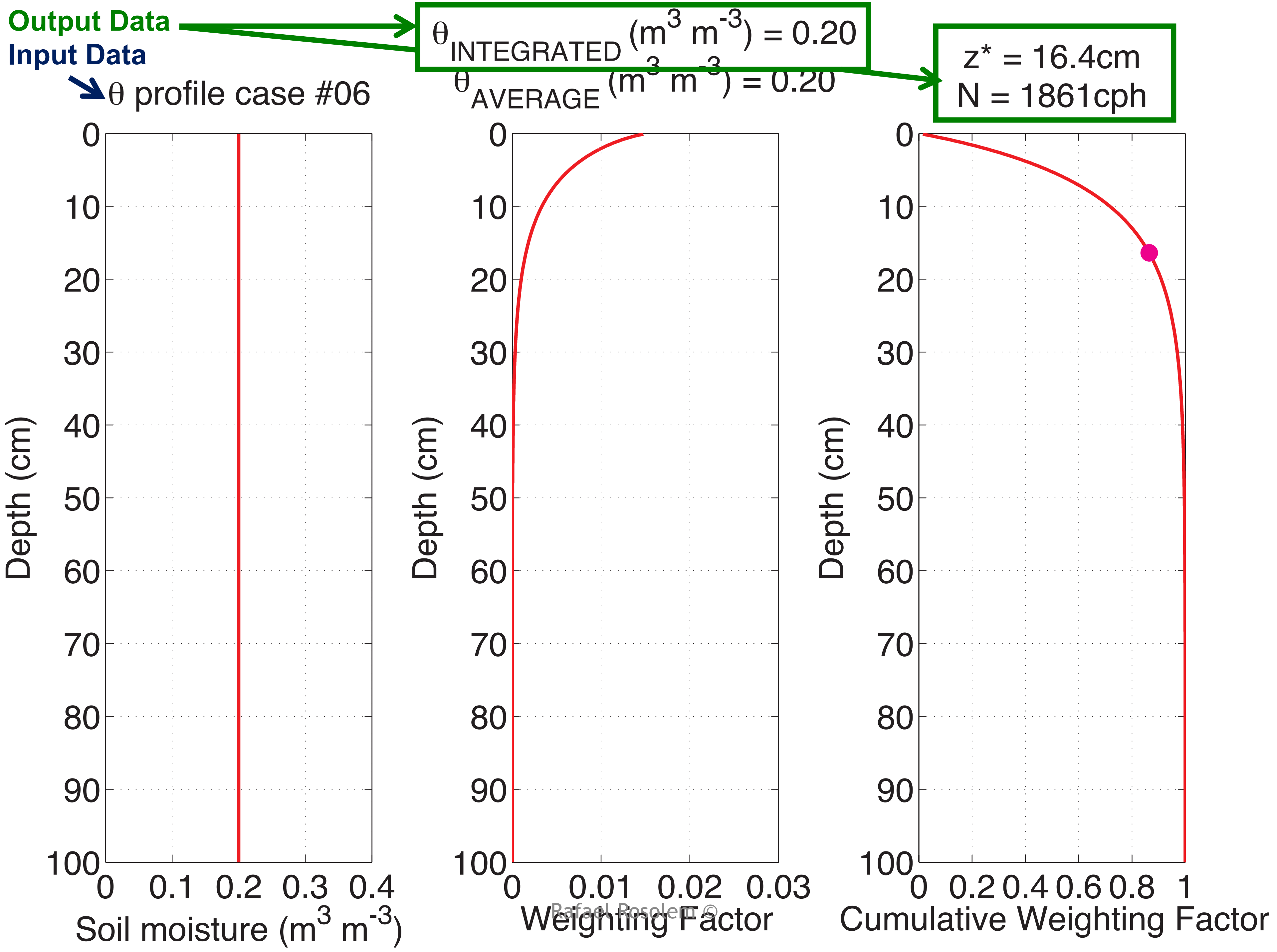
Running time for a single soil moisture profile

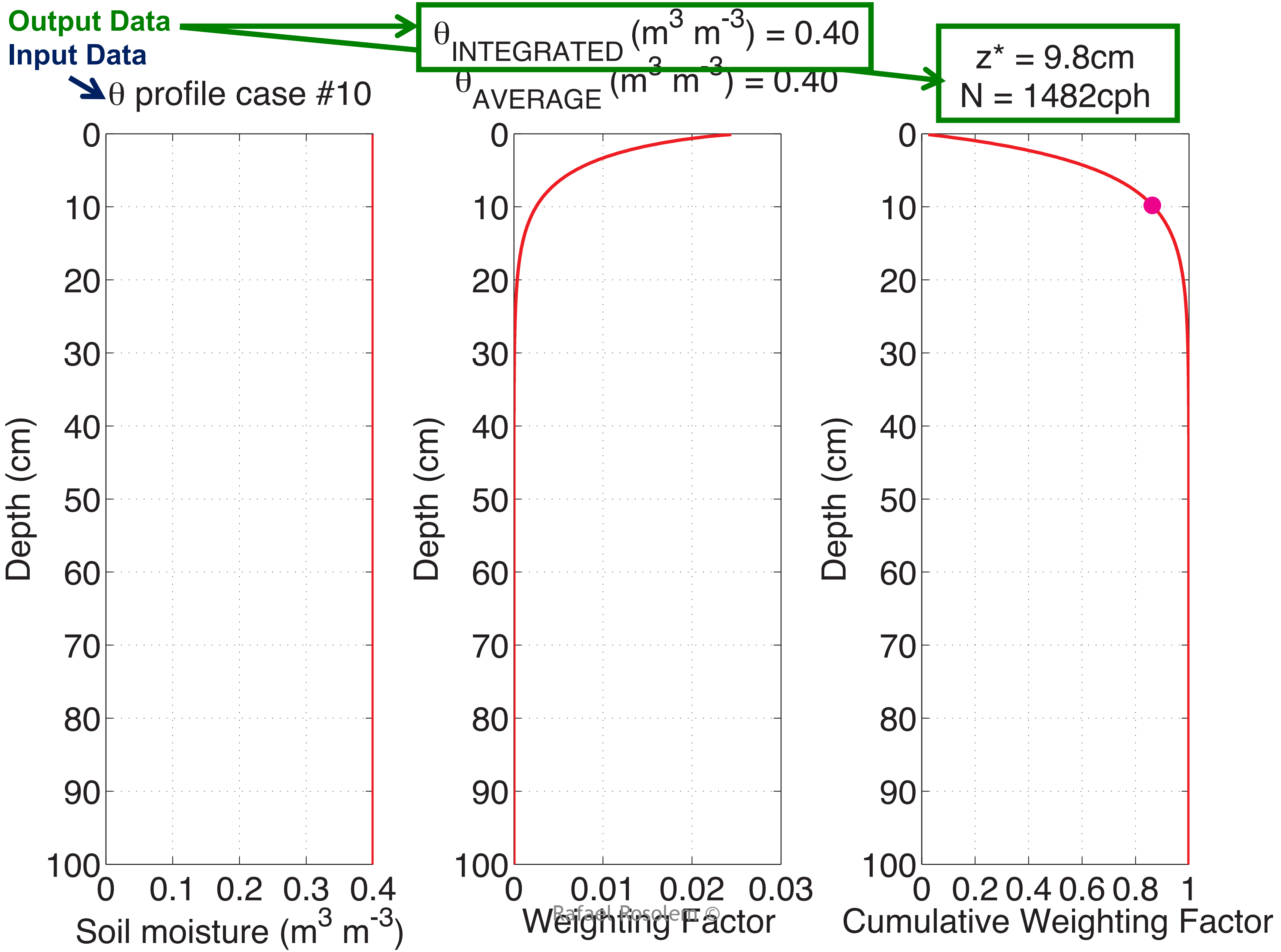
MCNPx ~ 30-60 minutes

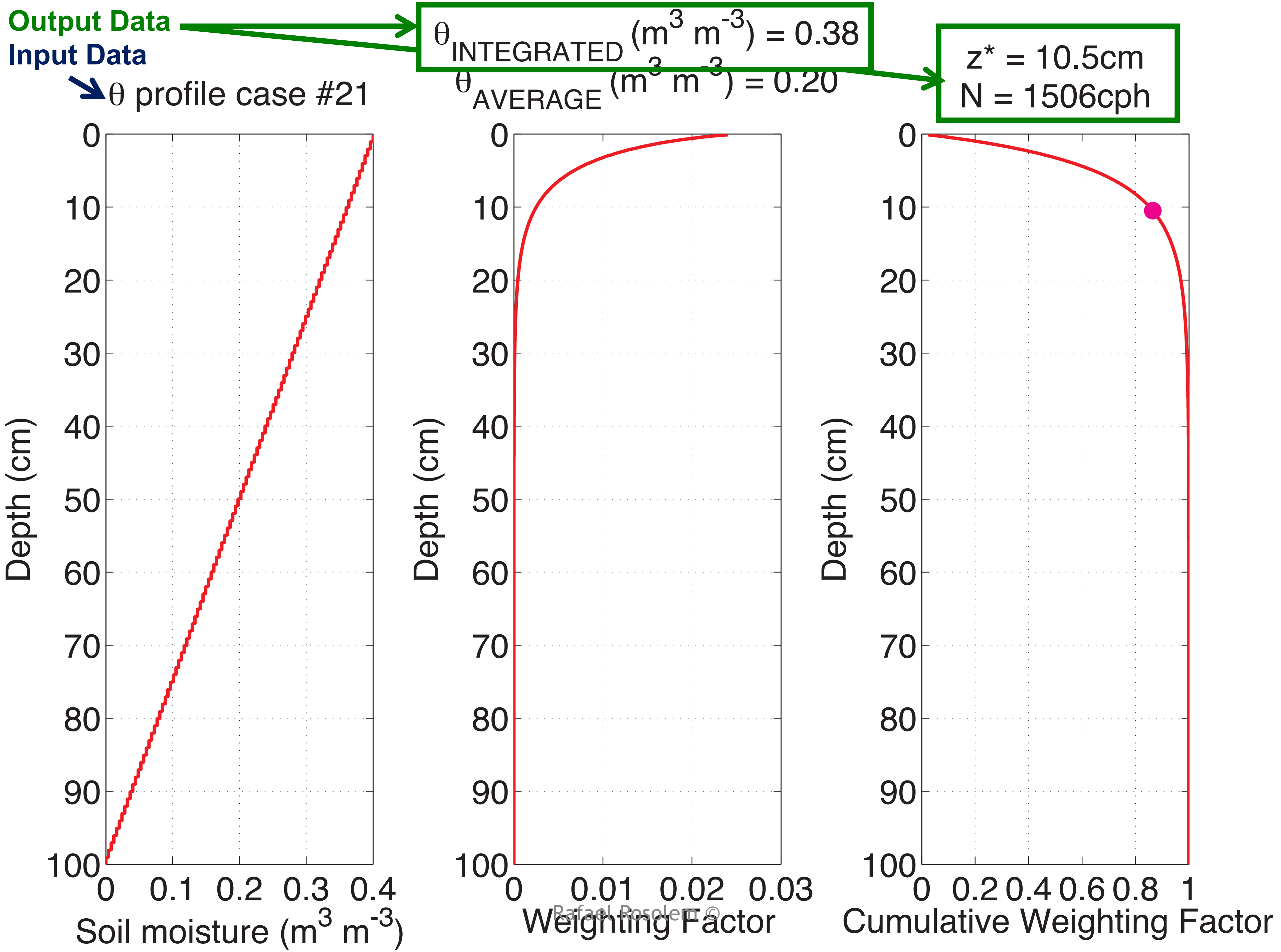
COSMIC ~ 0.5 seconds

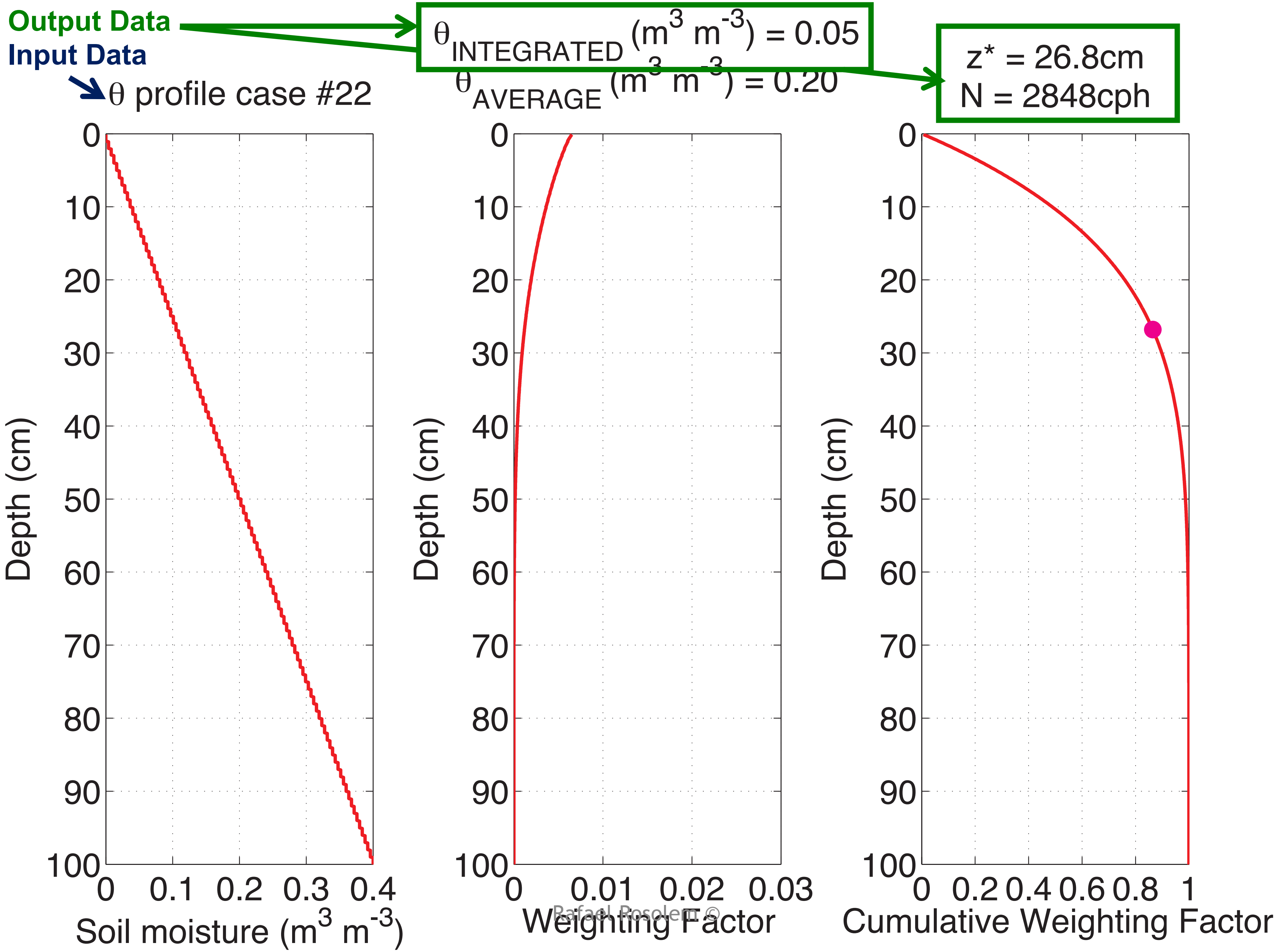

Output Data
Input Data
θ profile case #01
$\theta_{INTEGRATED}$ (m³ m⁻³) = 0.00
$\theta_{AVERAGE}$ (m³ m⁻³) = 0.00
z* = 48.8cm
N = 3793cph
Depth (cm)
Soil moisture (m³ m⁻³)
Weighting Factor
Cumulative Weighting Factor
0
10
20
30
40
50
60
70
80
90
100
0 0.1 0.2 0.3 0.4
0 0.01 0.02 0.03
0 0.2 0.4 0.6 0.8 1


Output Data
Input Data
θ profile case #03
θ_INTEGRATED (m^3 m^-3) = 0.05
θ_AVERAGE (m^3 m^-3) = 0.05
z* = 32.6cm
N = 2817cph
Depth (cm)
Soil moisture (m^3 m^-3)
Weighting Factor
Cumulative Weighting Factor
Rafael Rosolem ©


Output Data
Input Data
θ profile case #06
$\theta_{INTEGRATED}$ (m^3 m^{-3}) = 0.20
$\theta_{AVERAGE}$ (m^3 m^{-3}) = 0.20
z* = 16.4cm
N = 1861cph
Depth (cm)
Soil moisture (m^3 m^{-3})
Weighting Factor
Cumulative Weighting Factor
Rafael Rosolem ©

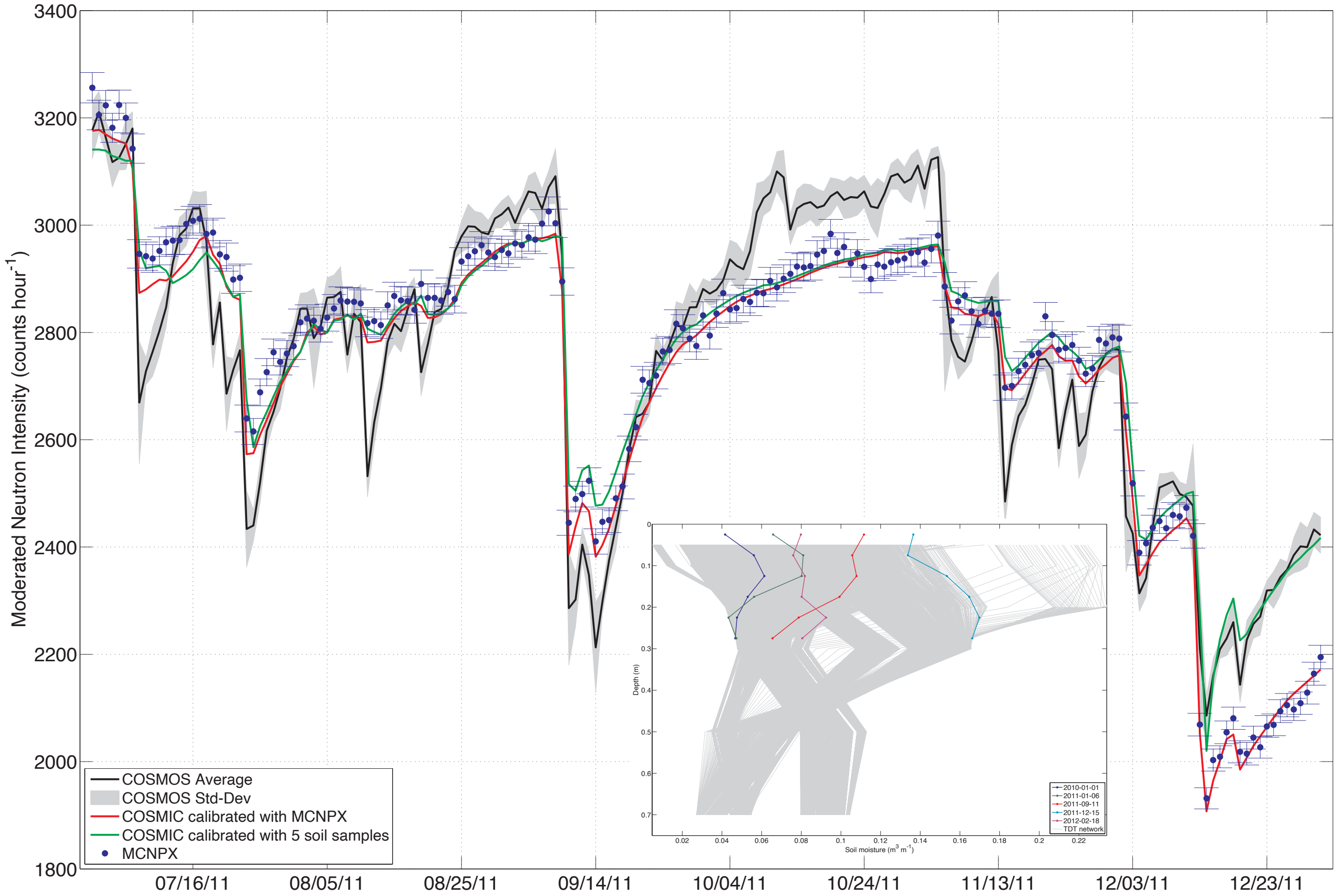

Output Data
Input Data
θ profile case #10
θ_INTEGRATED (m^3 m^-3) = 0.40
θ_AVERAGE (m^3 m^-3) = 0.40
z* = 9.8cm
N = 1482cph
Depth (cm)
Soil moisture (m^3 m^-3)
Weighting Factor
Cumulative Weighting Factor
0
10
20
30
40
50
60
70
80
90
100
0 0.1 0.2 0.3 0.4
0 0.01 0.02 0.03
0 0.2 0.4 0.6 0.8 1


Output Data
Input Data
θ profile case #21
θINTEGRATED (m3 m-3) = 0.38
θAVERAGE (m3 m-3) = 0.20
z* = 10.5cm
N = 1506cph
Depth (cm)
Soil moisture (m3 m-3)
Weighting Factor
Cumulative Weighting Factor
0
10
20
30
40
50
60
70
80
90
100
0.1
0.2
0.3
0.4
0.01
0.02
0.03
0.4
0.6
0.8
1

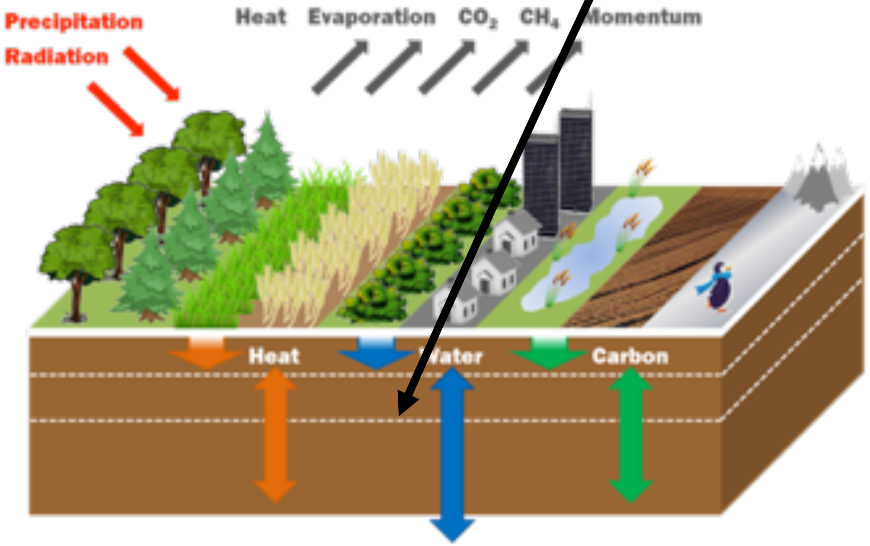


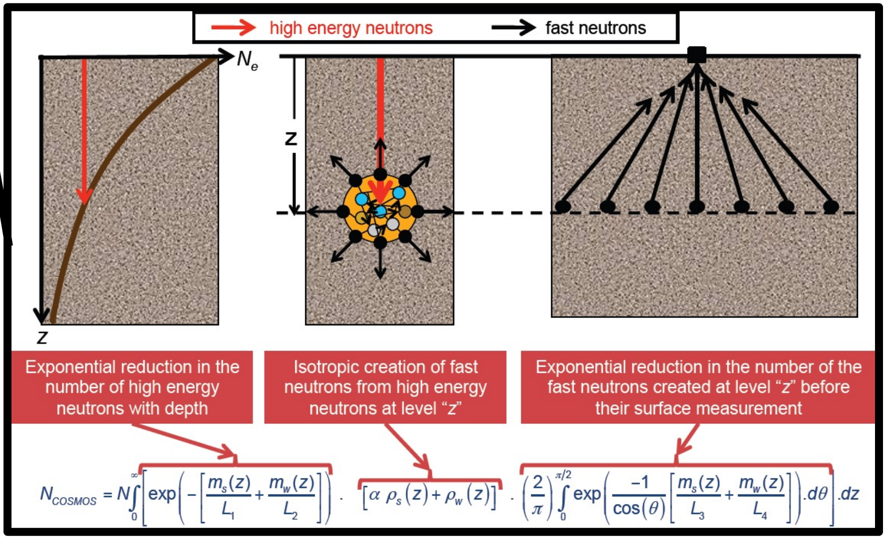
Output Data
Input Data
θ profile case #22
θ INTEGRATED (m3 m-3) = 0.05
θ AVERAGE (m3 m-3) = 0.20
z* = 26.8cm
N = 2848cph
Depth (cm)
Soil moisture (m3 m-3)
Weighting Factor
Cumulative Weighting Factor
0
10
20
30
40
50
60
70
80
90
100
0 0.1 0.2 0.3 0.4
0 0.01 0.02 0.03
0 0.2 0.4 0.6 0.8 1

COSMIC can also be calibrated with in-situ soil samples - the more campaigns, the better!



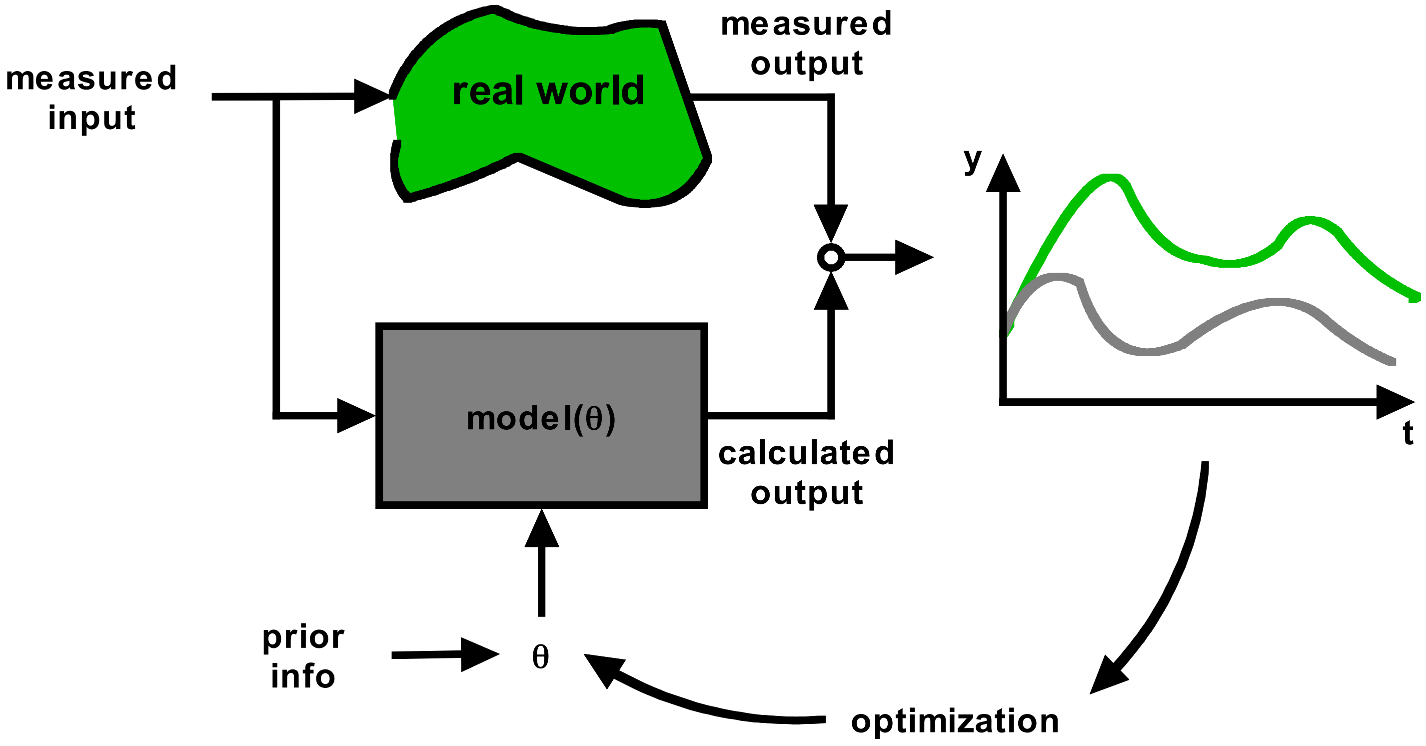
We have incorporated COSMIC into land surface models





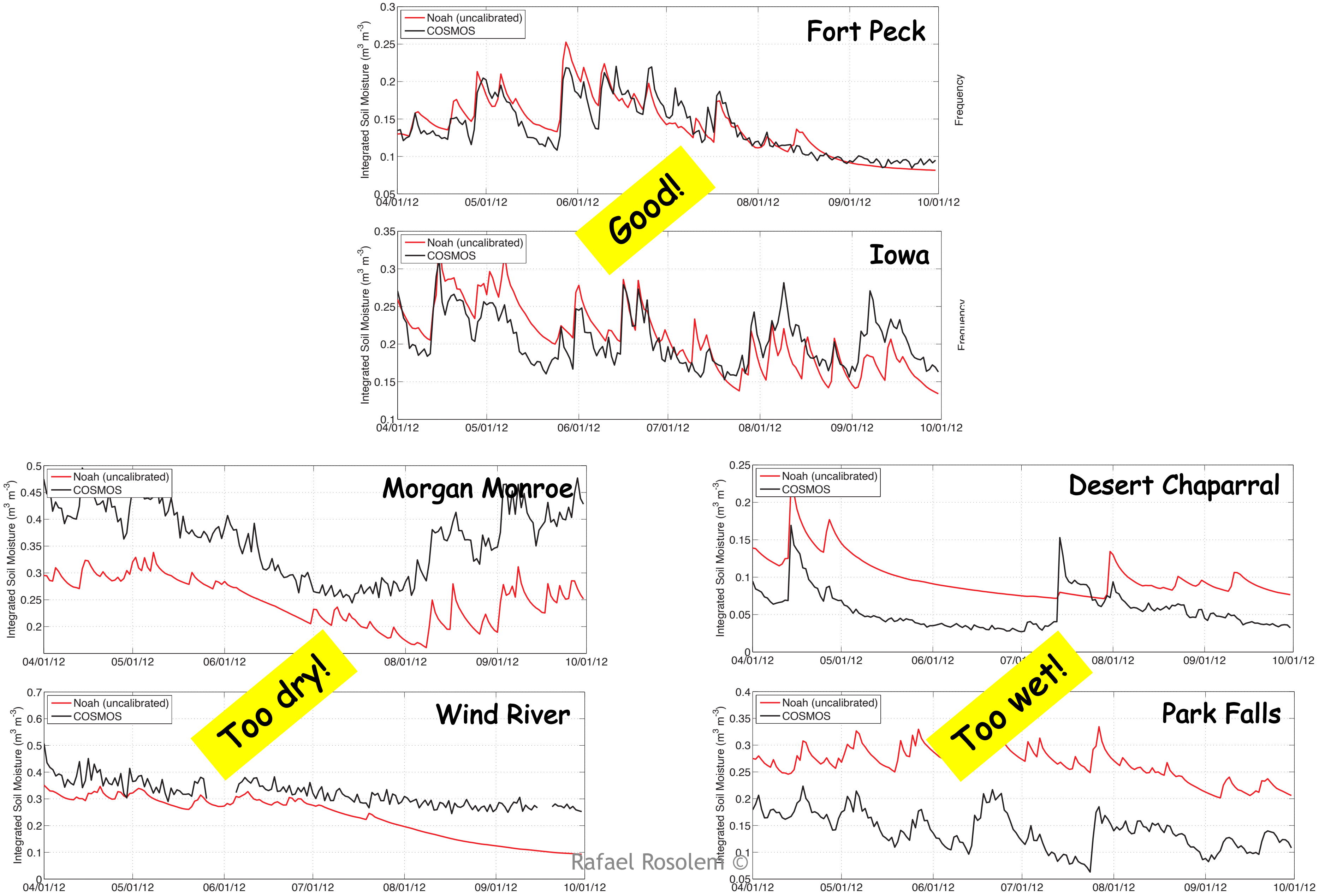
Shuttleworth et al. 2013 (HESS)
Rosolem et al. 2014 (HESS)

Model optimization (or calibration) refers to tunning model parameters to reduce as much as possible the error against a reference measured quantity

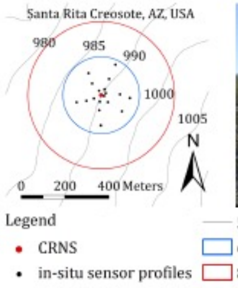


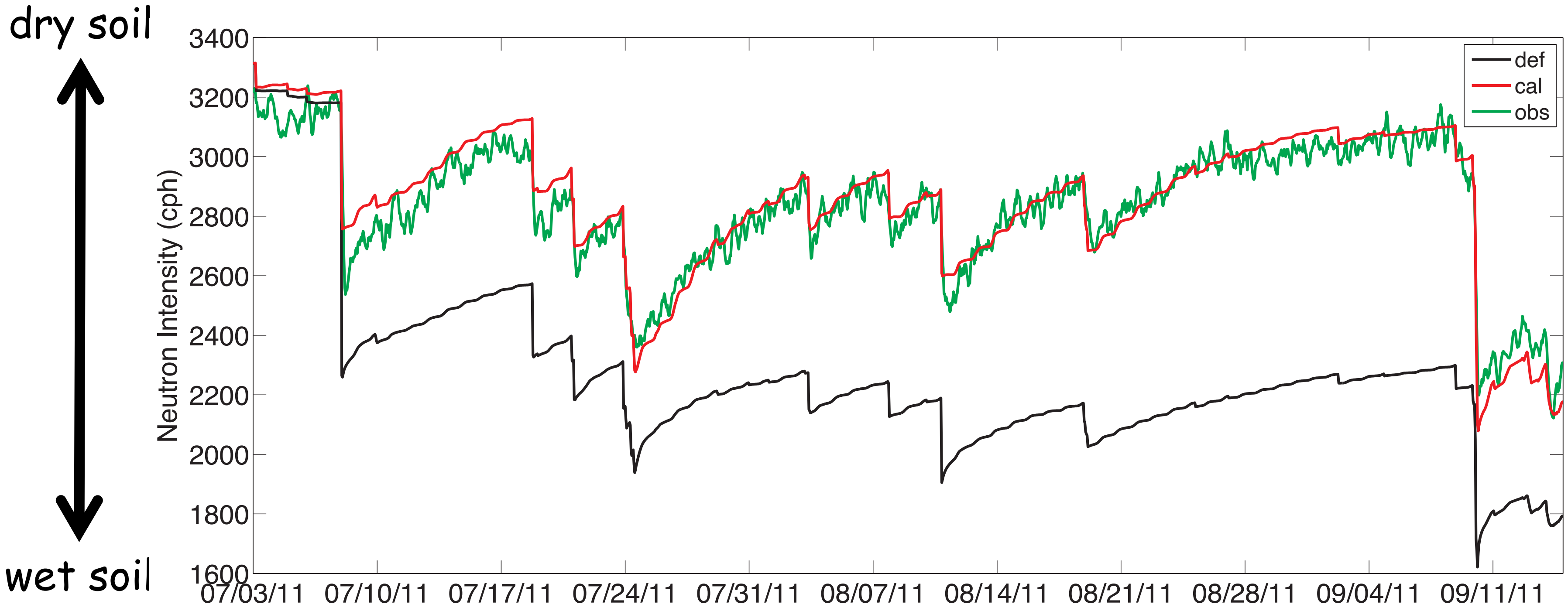
Adapted from Hoshin Gupta slides (Univ. of Arizona)

Land surface models don’t always represent soil moisture accurately

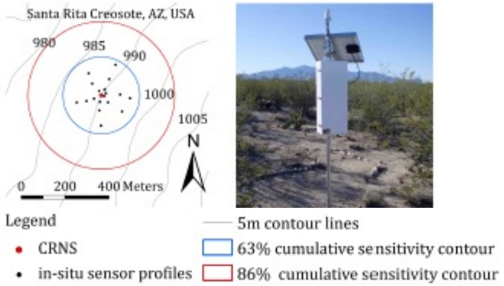


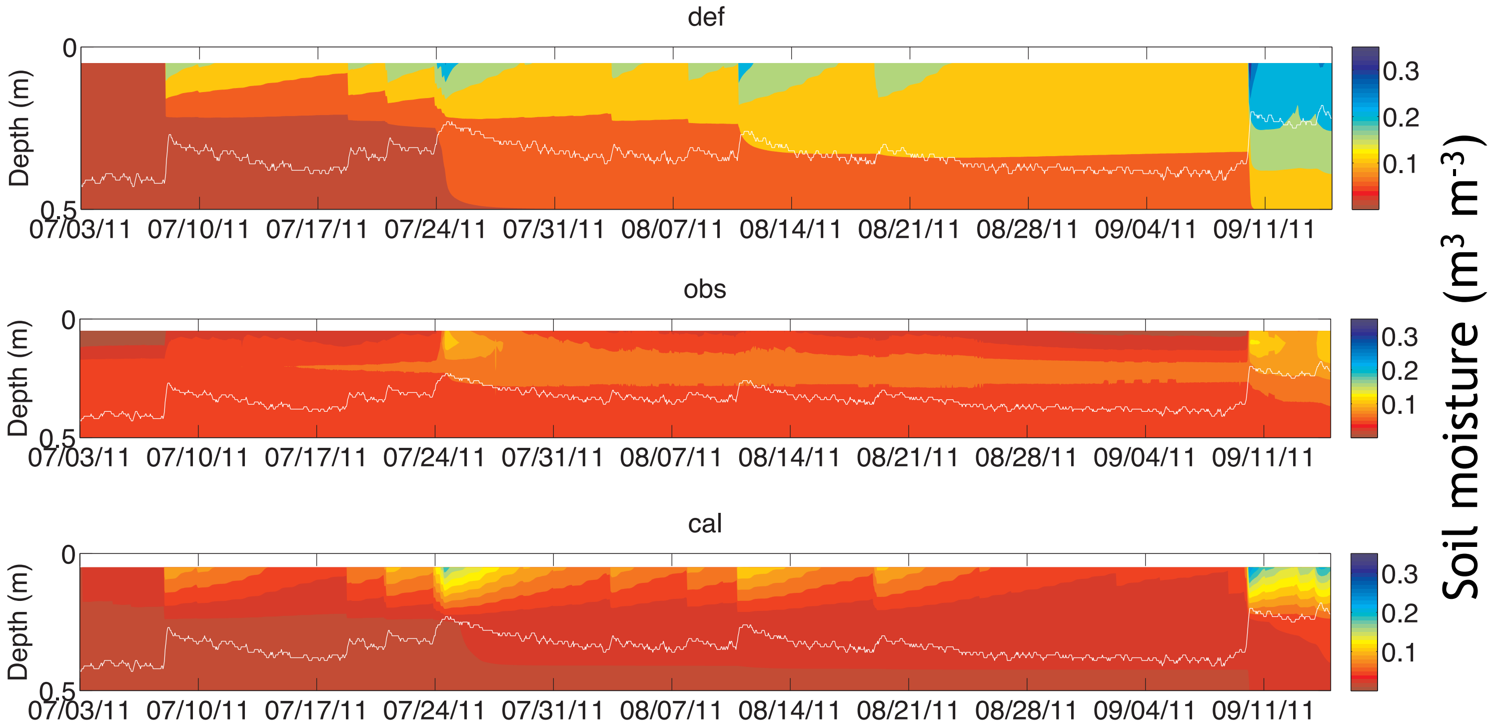
We calibrated the soil properties in the model using only measured neutron counts



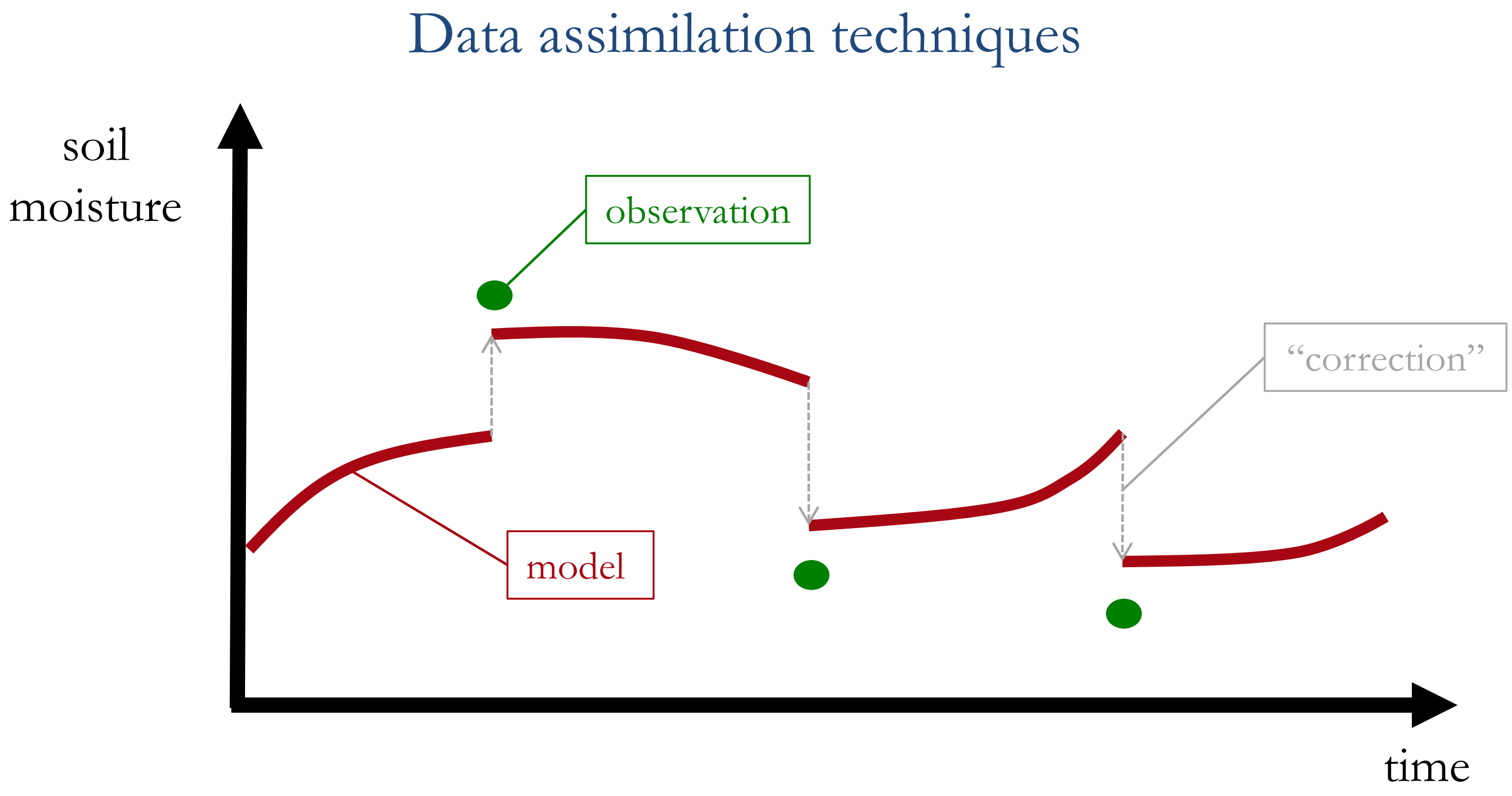


Calibrated model reproduces well the soil moisture profile from independent measurements





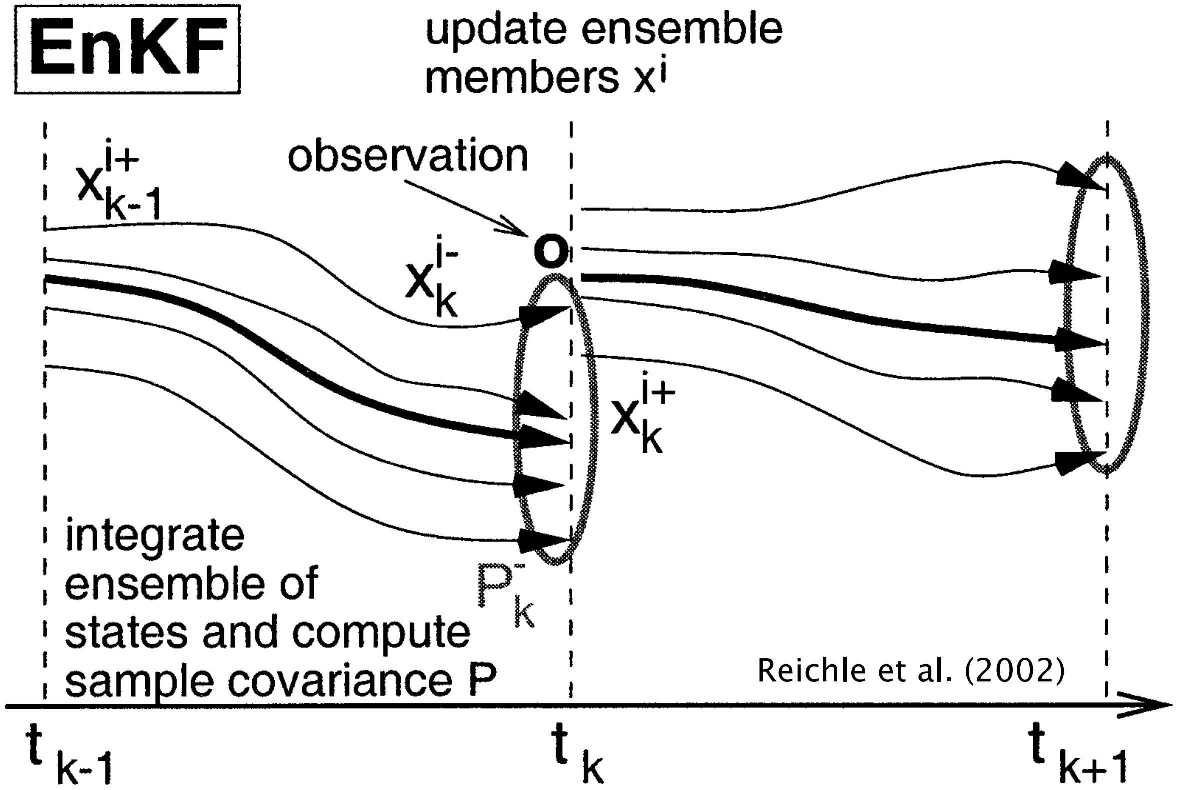
Data assimilation attempts to correct model states (and sometimes parameters) continuously as independent observations become available



All done with the use of probability distributions!

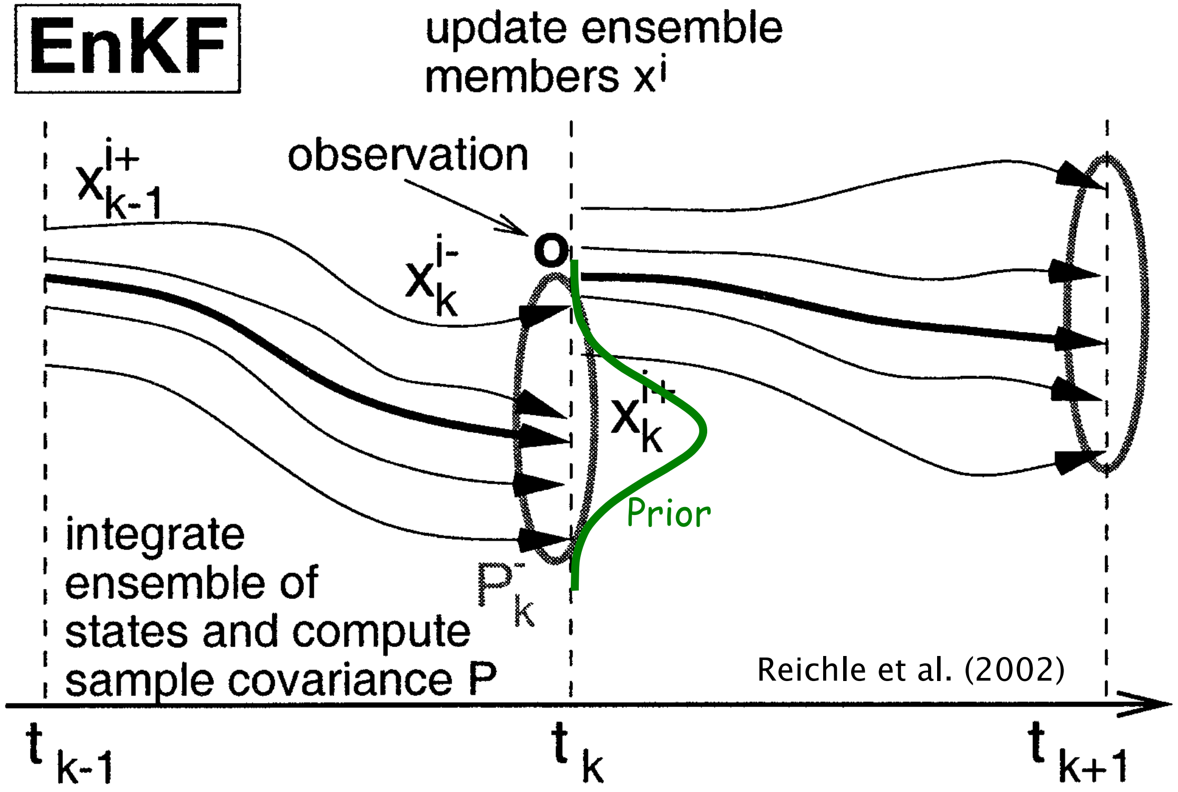
Bayes Theorem:

$$P(x_k \mid y_k) = \frac{P(y_k \mid x) P(x_k \mid y_{k-1})}{normalization \quad factor}$$



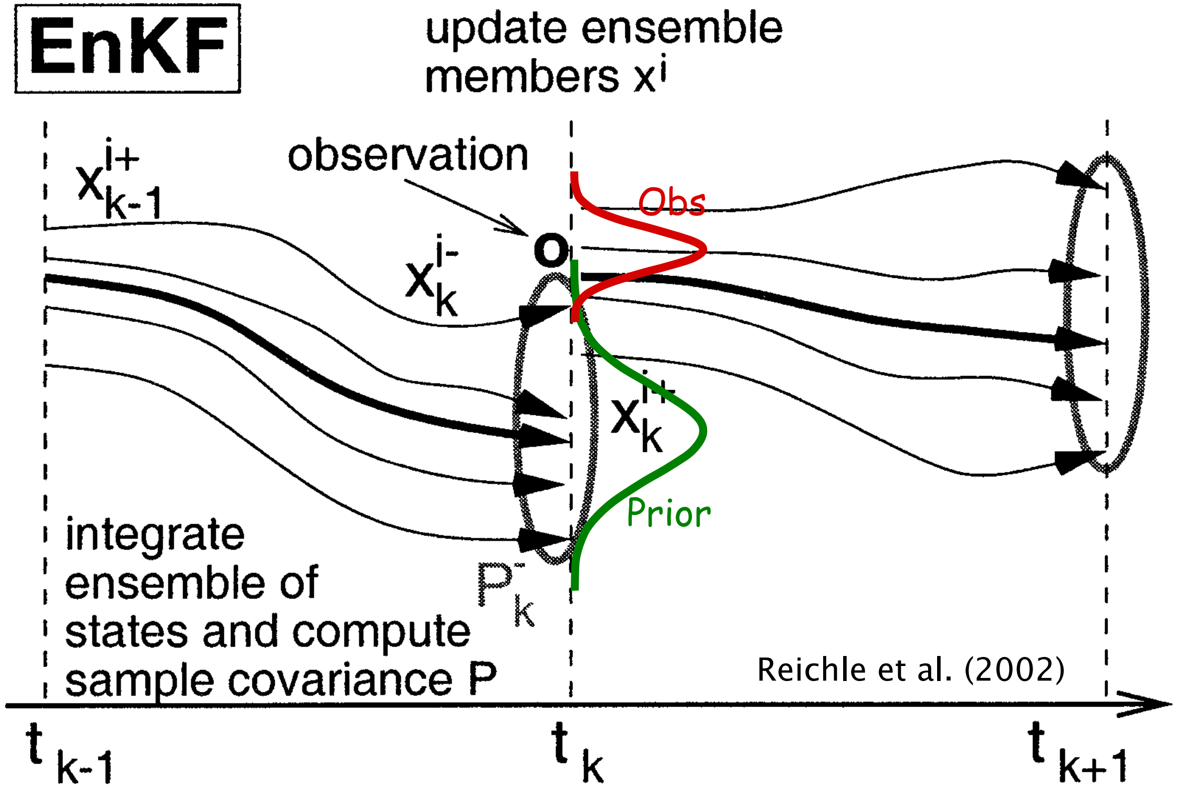
Bayes Theorem:

$$P(x_k \mid y_k) = \frac{P(y_k \mid x)\,\boxed{P(x_k \mid y_{k-1})}}{normalization \quad factor}$$



Bayes Theorem:

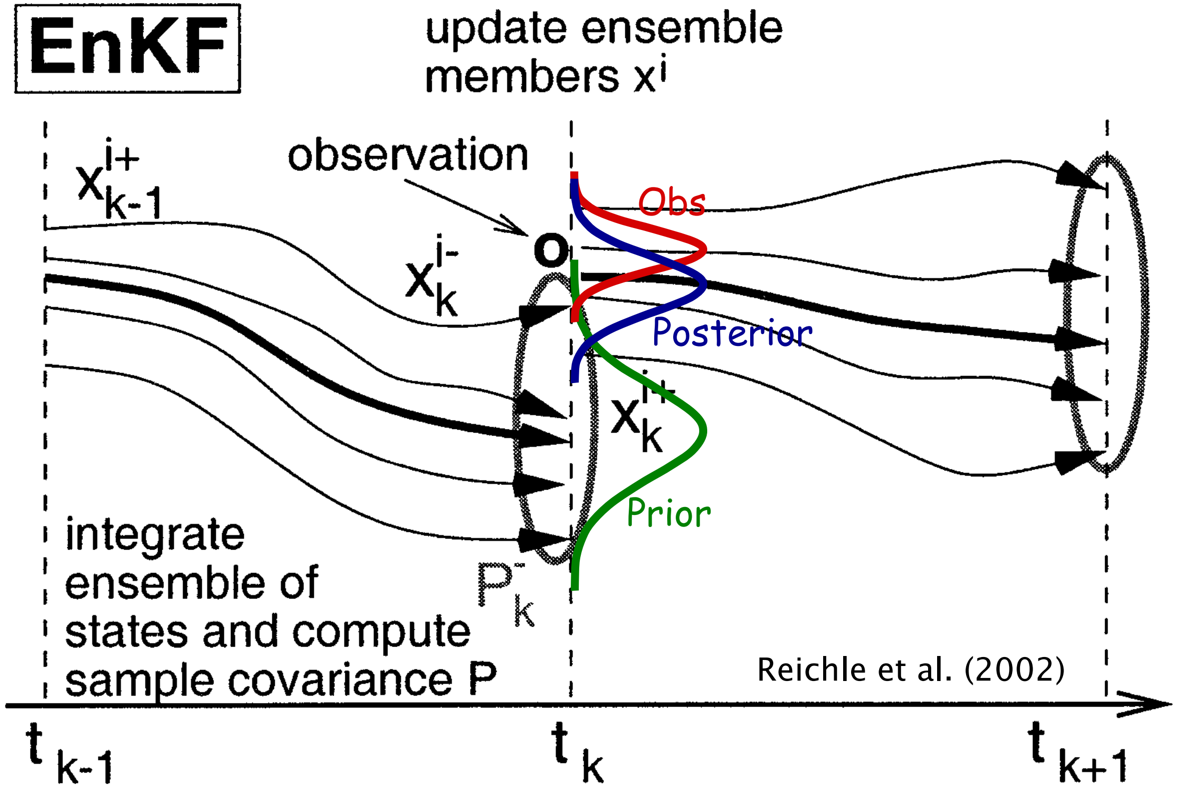
$$P(x_k \mid y_k) = \frac{P(y_k \mid x)\,P(x_k \mid y_{k-1})}{normalization \quad factor}$$



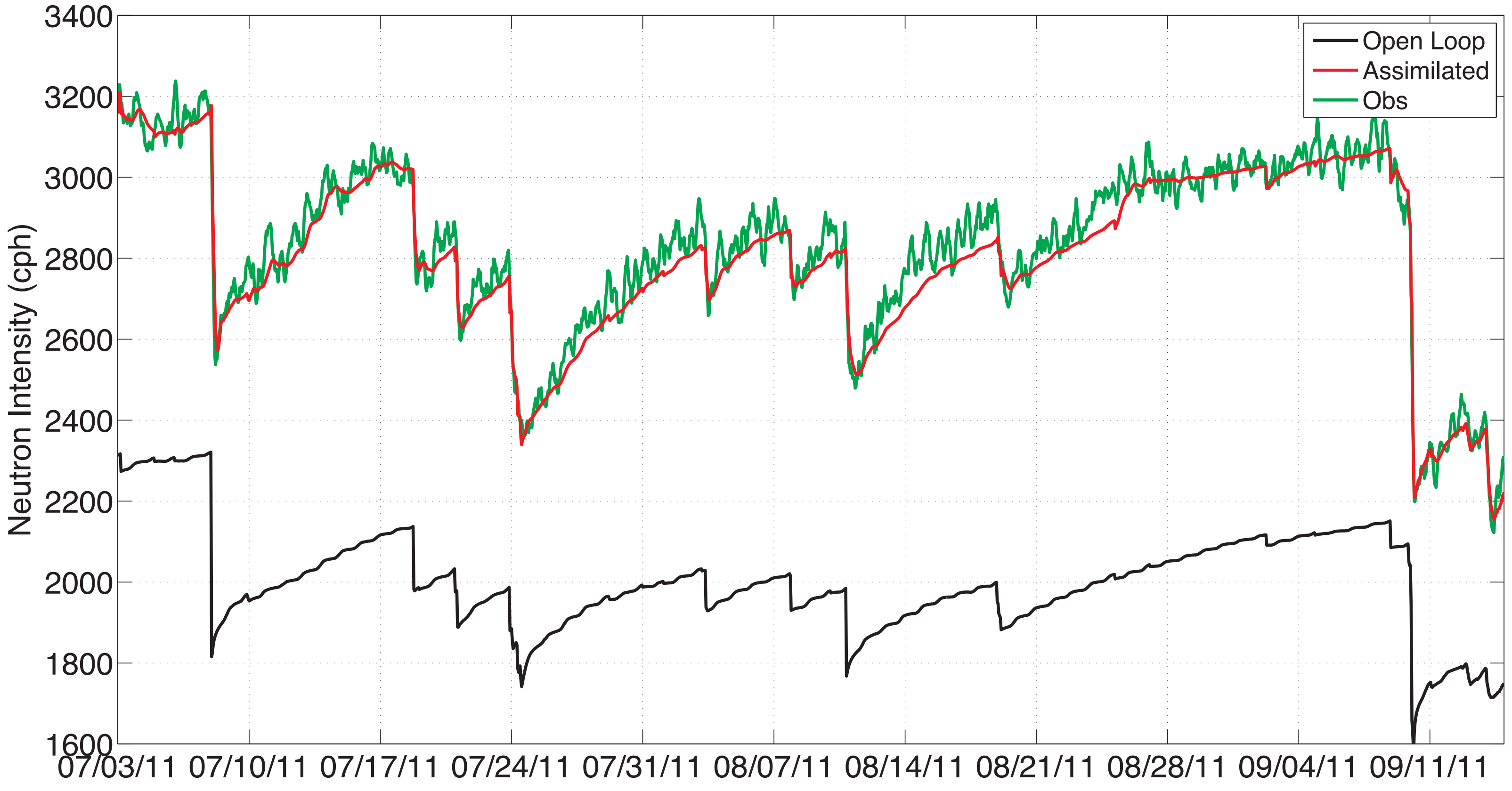
The ensemble data assimilation method is an approximation to a general filtering algorithm developed using Bayes Theorem

Bayes Theorem:

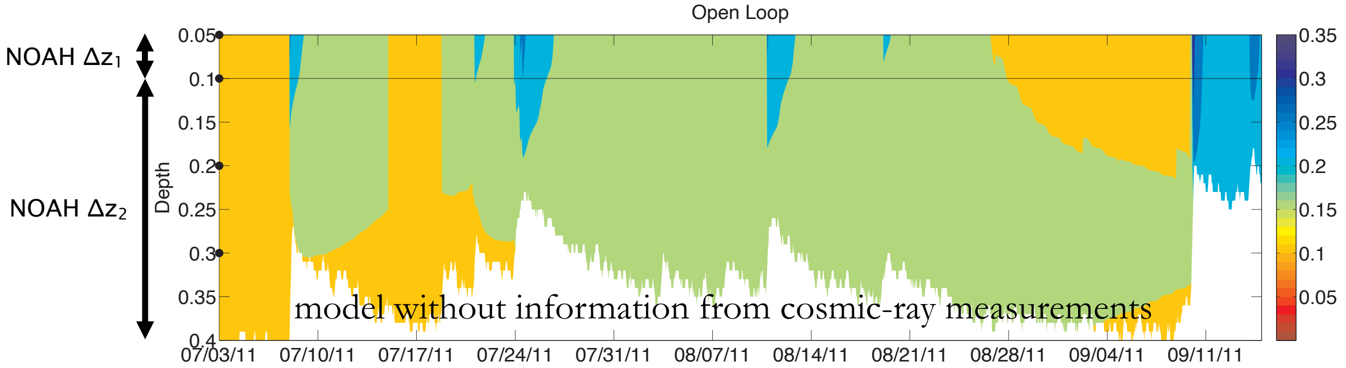
$$P(x_k \mid y_k) = \frac{P(y_k \mid x)\, P(x_k \mid y_{k-1})}{normalization \quad factor}$$

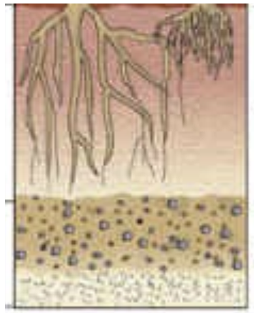


Data assimilation of neutron counts

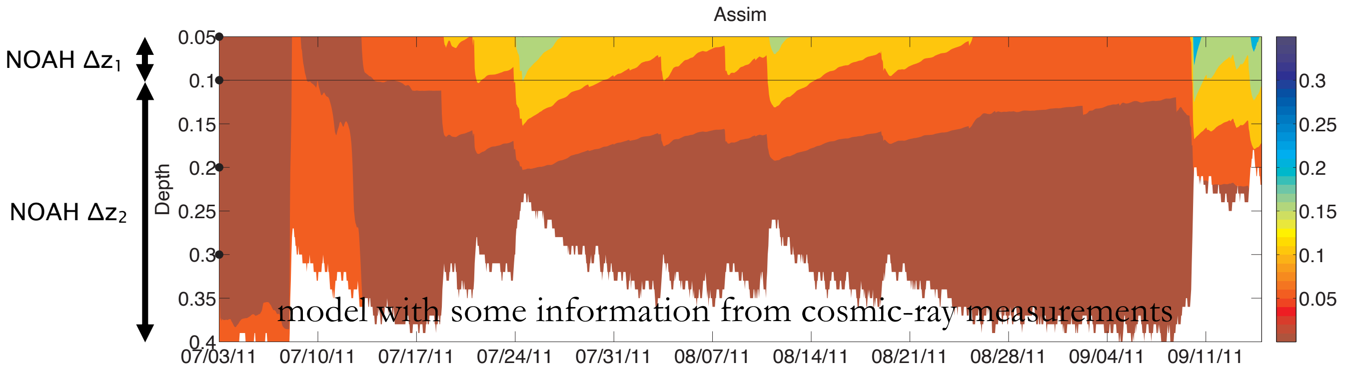


Soil moisture estimates are improved!

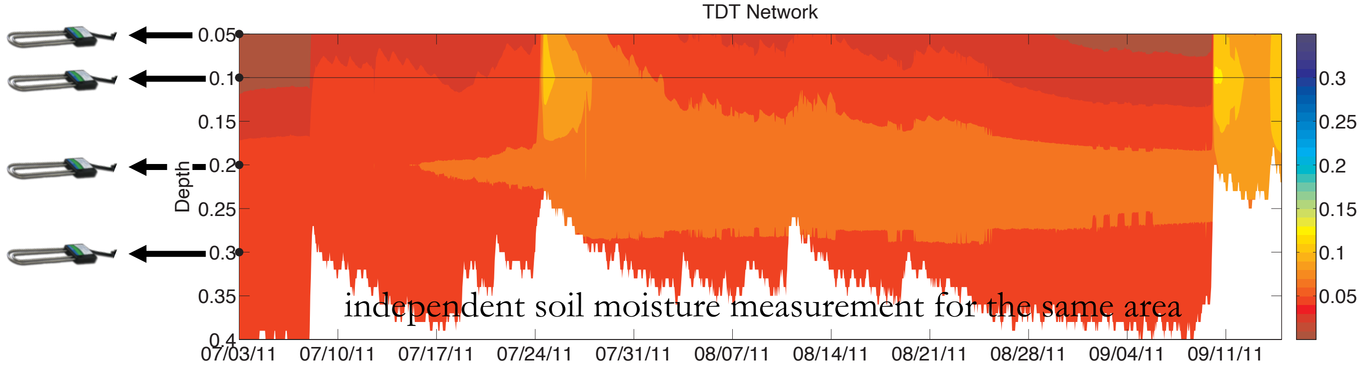




model thinks is wet…

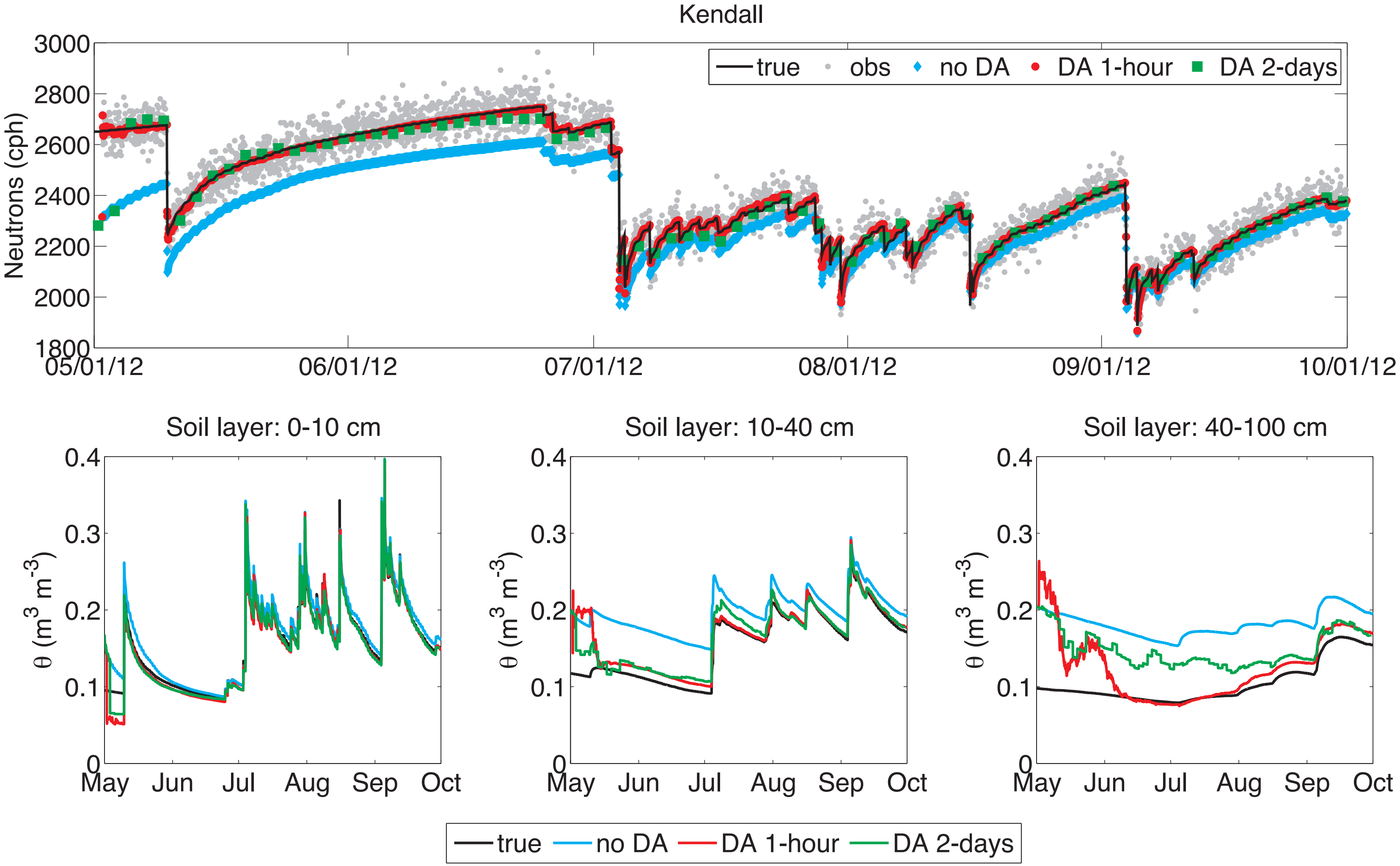


but information from measurements tells otherwise



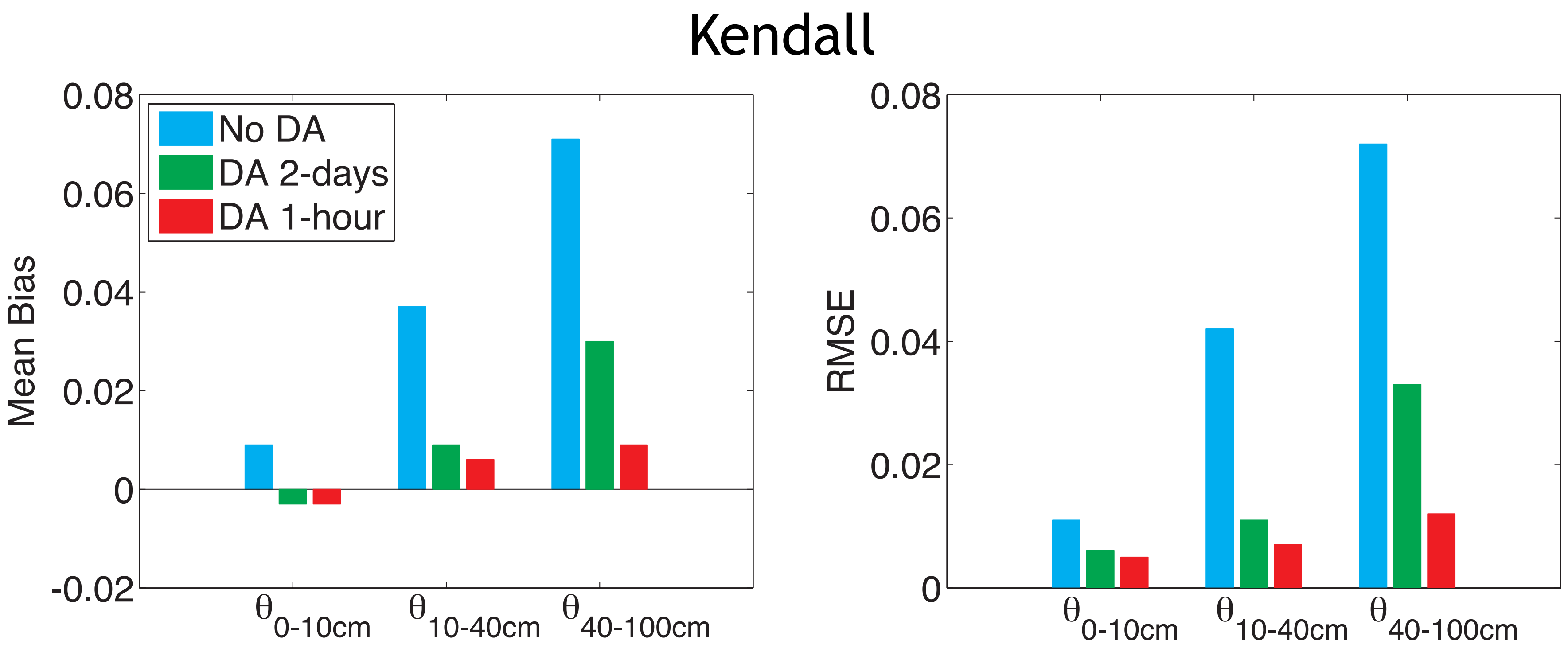
model simulation in combination with measurements agree with independent observations

Another example of data assimilation of neutron counts using a synthetic experiment



Rosolem et al., 2014 (HESS)

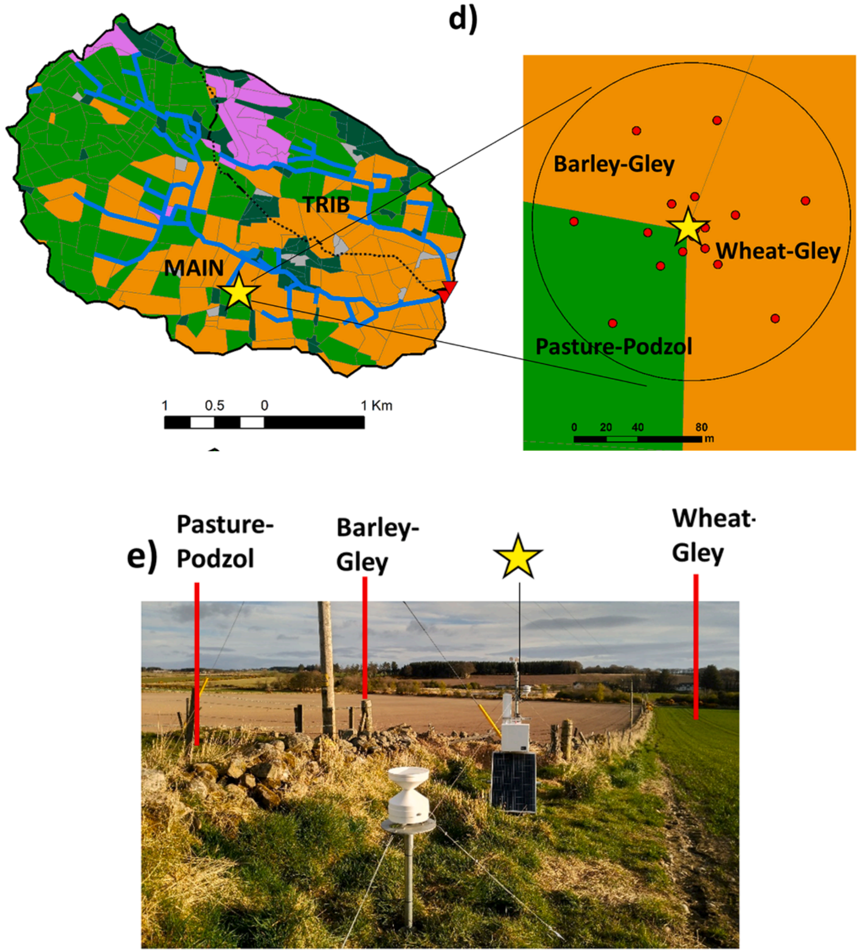
High frequency of cosmic-ray neutron sensing data positively impacts the assimilation

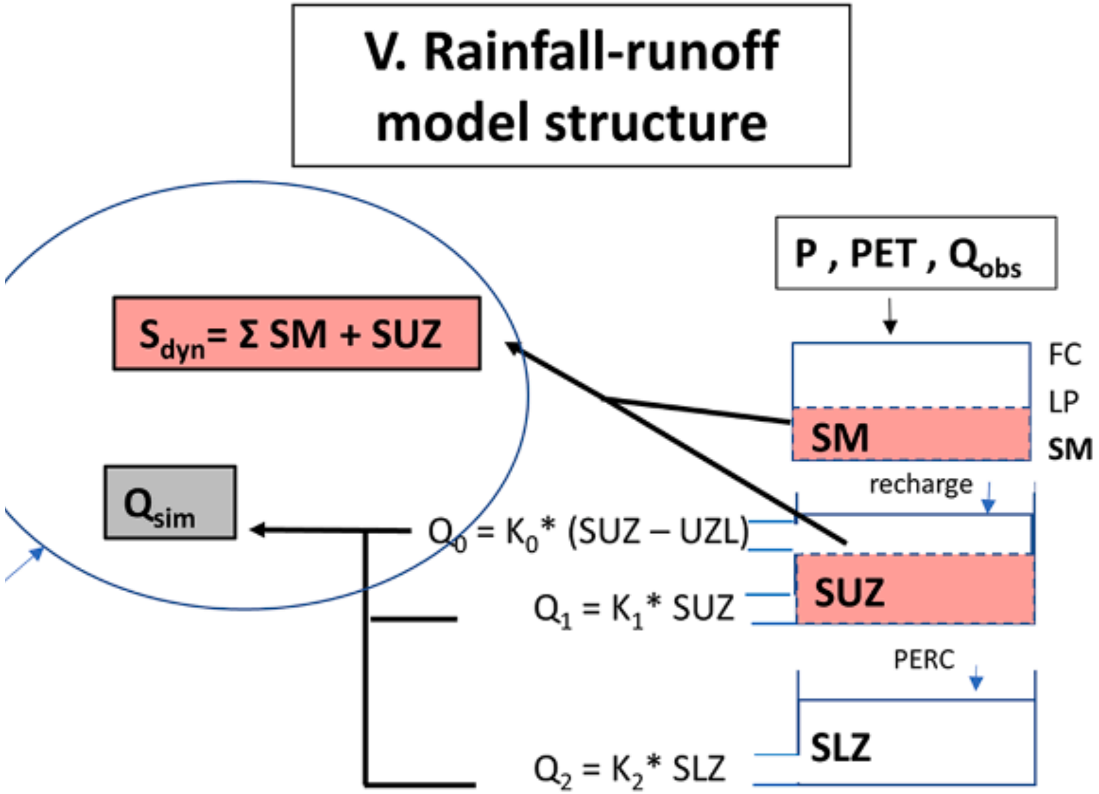


Adapted from Rosolem et al. 2014 (HESS)

Example of applications using hydrological models

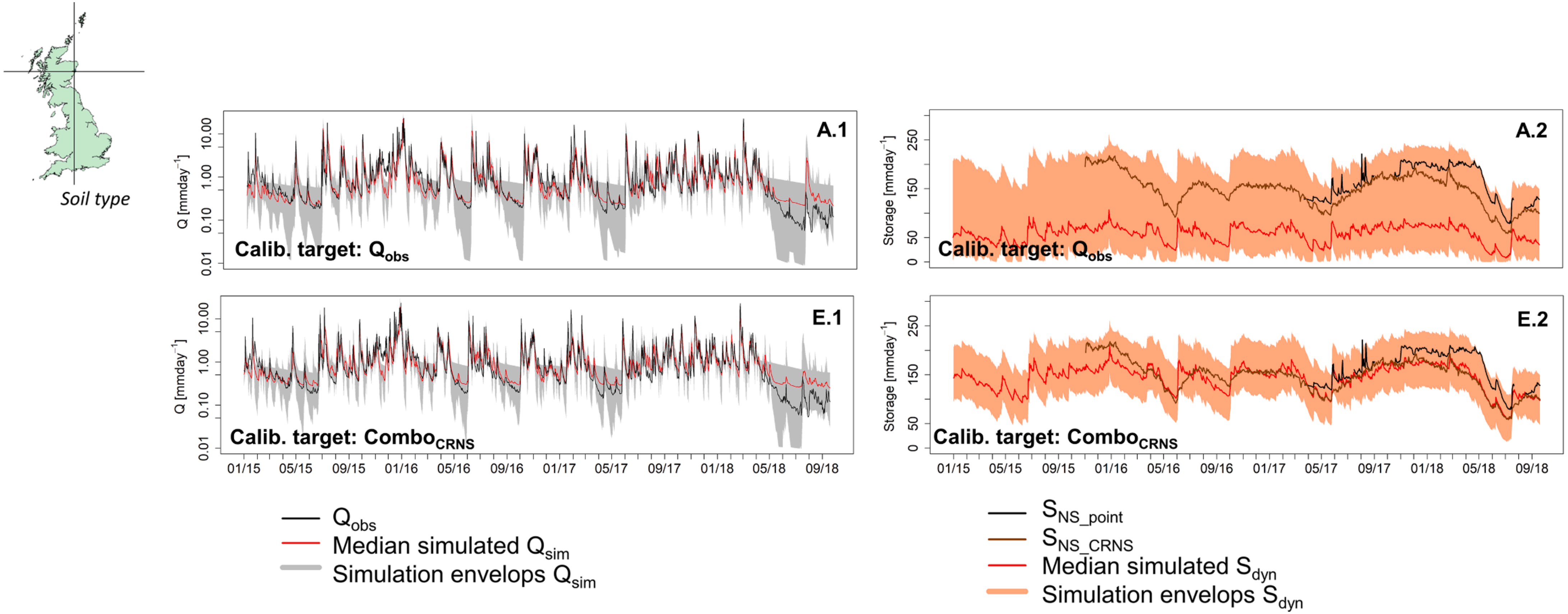
Example of calibration of conceptual lumped hydrological model





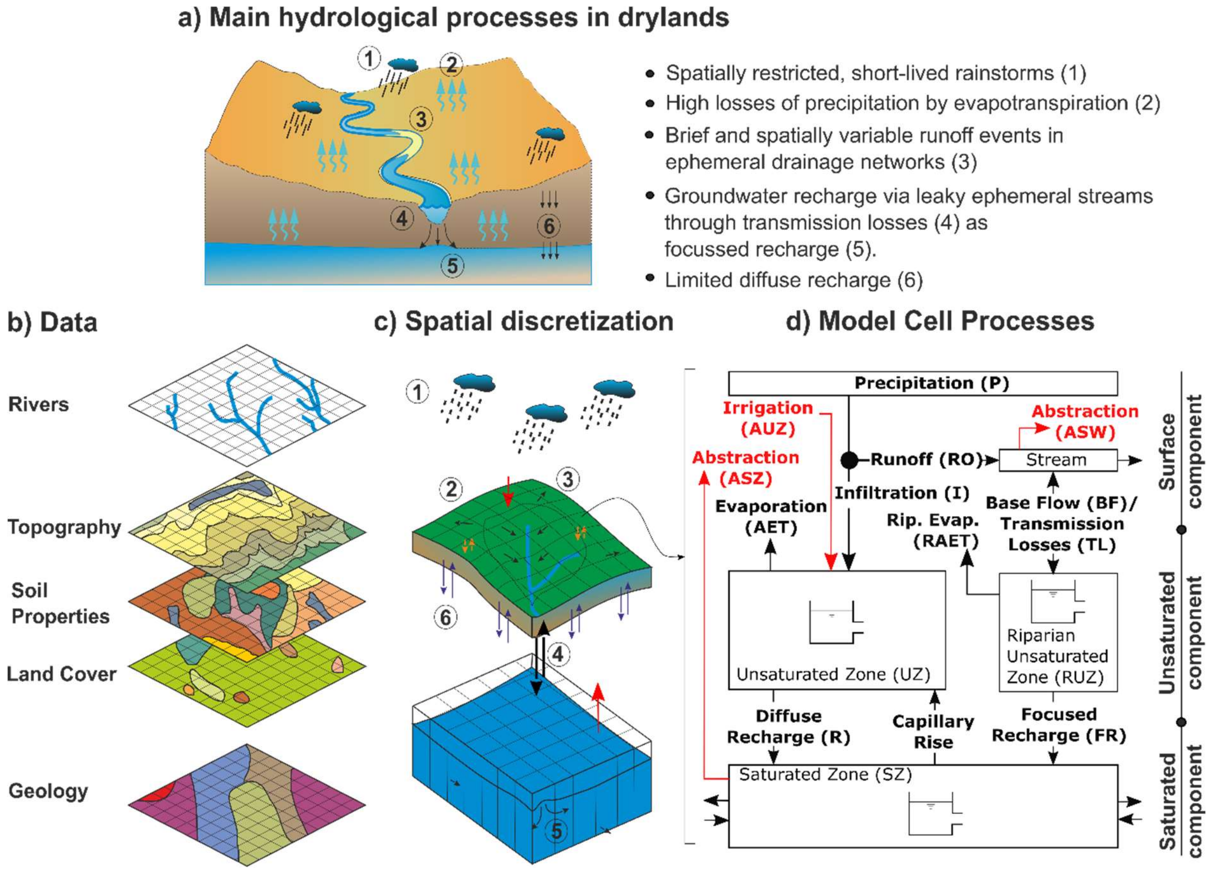
Dimitrova-Petrova et al. 2020 (J. Hydrol.)

More realistic representation of hydrological processes achieved when streamflow and storage information are available



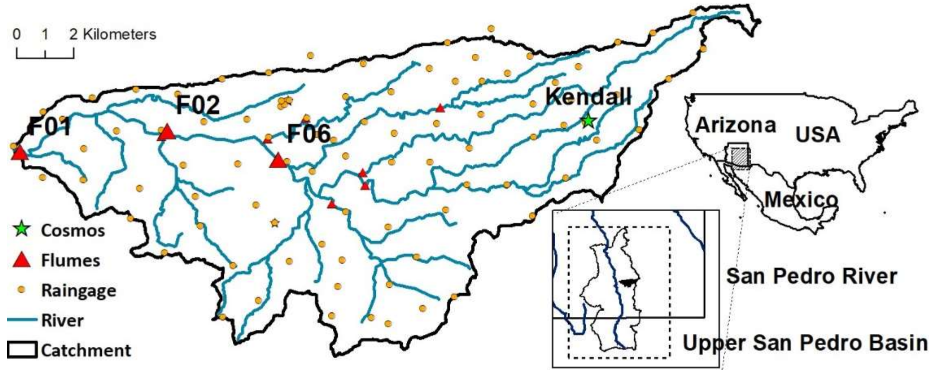
Dimitrova-Petrova et al. 2020 (J. Hydrol.)

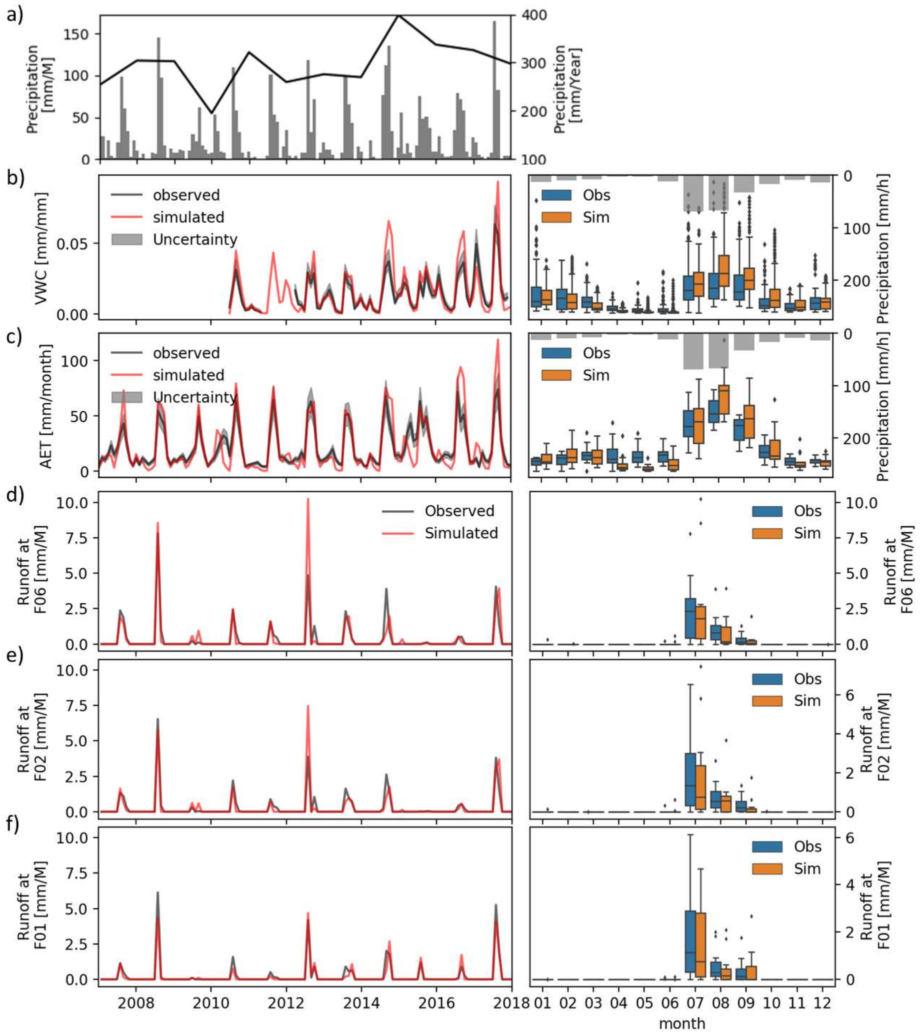
Checking consistency of internal structure in newly-developed hydrological model for drylands using cosmic-ray neutron sensors



Quichimbo et al. 2021 (GMDD)

Model results for the Walnut Gulch Experimental Watershed

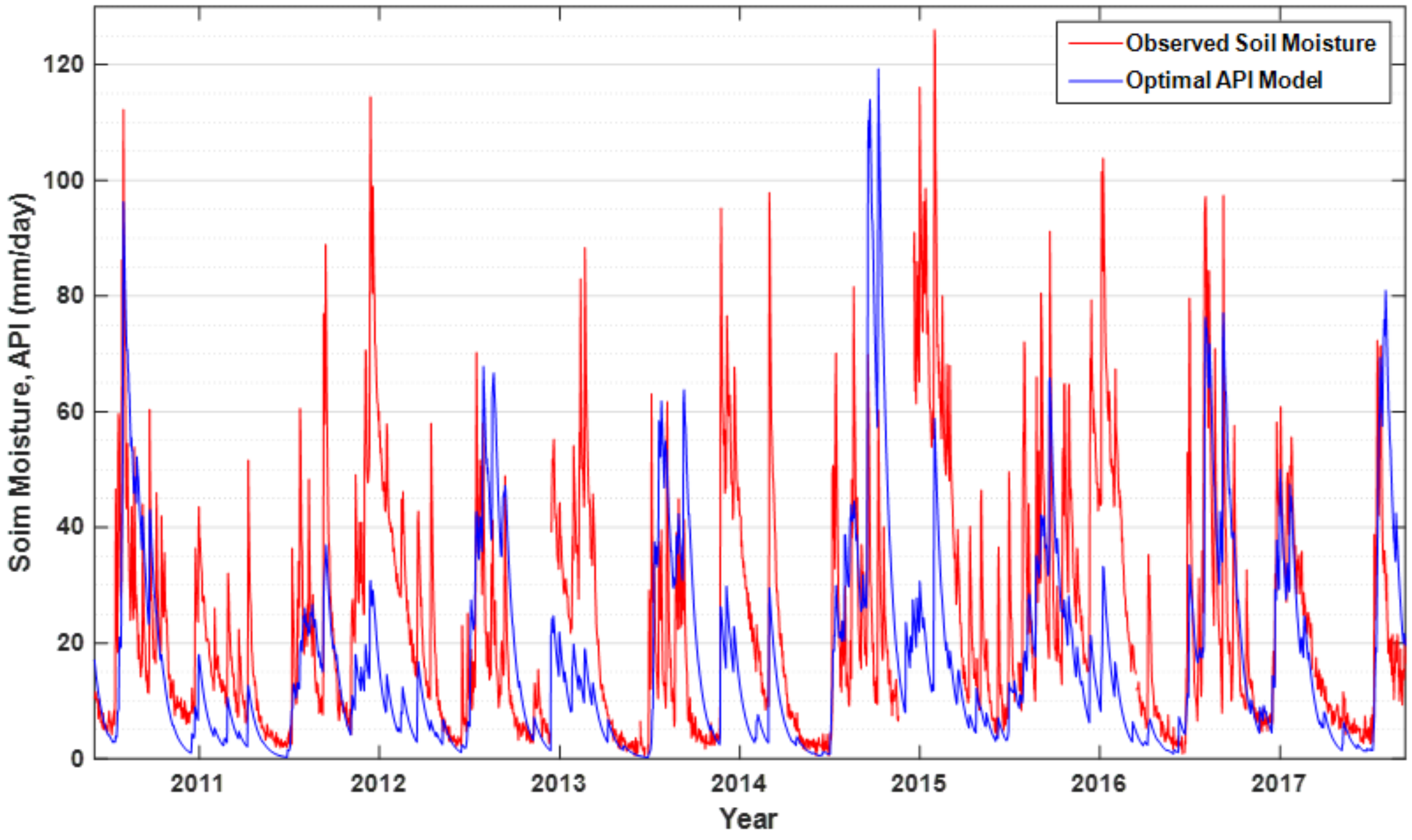




Quichimbo et al. 2021 (GMDD)

Example of applications using simple hydrologic engineering methods

Cosmic-ray neutron sensors can also be used for simpler hydrologic and agricultural engineering applications



$API(t) = P(t) + k.P(t-1) + k^2.P(t-2) + \ldots$

or

$\mathbf{API(t) = k.API(t-1) + P(t)}$

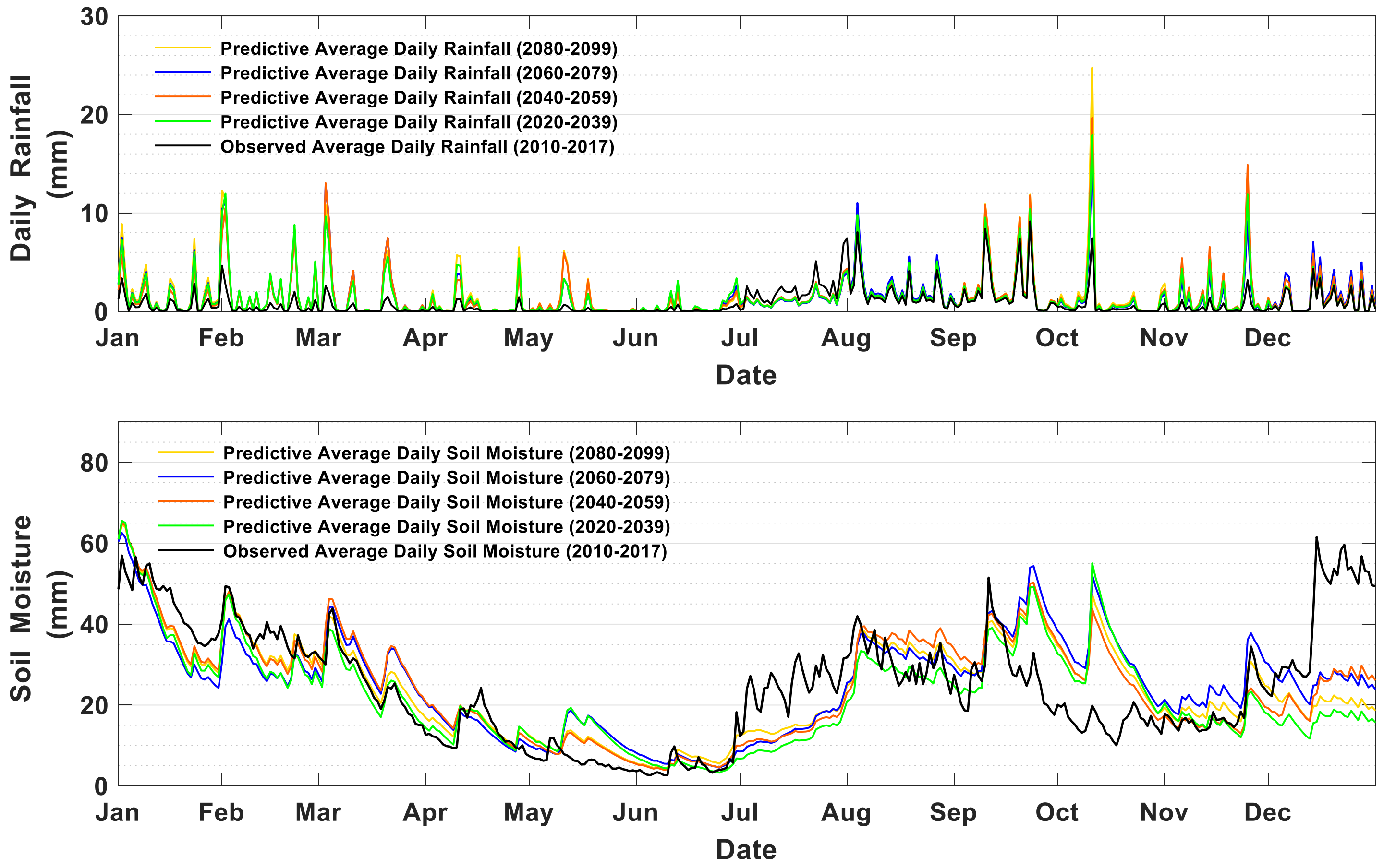
where

API(t) = is the Antecedent Precipitation Index for day *t*

k is an empirical decay factor (k < 1)

P(t) is precipitation for day *t*

Simple API model allows for easy scenario analysis for wetness conditions of the region



Final remarks

- Environmental modeling applications are interested in predicting many hydrological processes
- The spatial and temporal scales of cosmic-ray neutron sensors fills the gap between point-scale and satellite remote sensing methods, and are strongly related to establishment of hyper-resolution hydrological models
- Cosmic-ray neutron sensing observations can be used with models for calibration, data assimilation, or independent structural checks

Structure for the day

Lecture 1: *Factors affecting the accuracy of cosmic-ray neutron counts and estimated soil moisture*

- You learned how individual factors may impact the measured cosmic-ray neutron signals and ultimately can be propagated to the derived soil moisture estimation

Lecture 2: *Efforts to a harmonized data processing approach for cosmic-ray neutron sensors*

- You learned that because individual networks apply different quality control and data processing protocols, adoption of global use of cosmic-ray neutron sensing technology has been limited, but recent efforts to provide harmonized datasets can mitigate some of the issues

Lecture 3: *The use of cosmic-ray neutron sensors in hydrometeorology*

- You learned a few examples of applications using cosmic-ray neutron sensing technology in combination with land surface and hydrological models as well as from simple hydrologic and agricultural engineering approaches

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