Factors affecting the accuracy of cosmic-ray neutron counts and estimated soil moisture

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Structure for the day

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

- Factors do influence the signal from the cosmic-ray sensors
- Important to account for those factors to reduce uncertainty in estimated soil moisture

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

- Despite important, there are currently no standard way that individual national-scale networks correct such factors and process the data globally
- There are ongoing efforts to produce a global harmonized database

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

- Examples of applications of cosmic-ray neutron sensors combined with different environmental models with a wide range of complexity

At the end of this lecture you should…

- Be familiar with the way the cosmic-ray sensor works in translating neutron counting rates to soil moisture estimates
- Be able to understand the required corrections and to identify additional factors affecting the sensor signal
- Be aware of way the sensor operates in dry versus humid site conditions
- Have a basic understanding of which factors may impact, more or less, both the neutron signal as well as the derived soil moisture product

Brief introduction

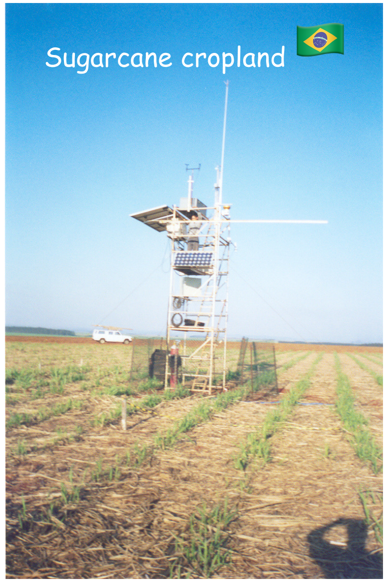
Who am I?

Born in Piracicaba, Brazil
1999 – 2002 BSc Meteorology (University of São Paulo 🇧🇷)
2003 – 2005 MSc Agricultural Systems Ecology (University of São Paulo 🇧🇷)
2006 – 2010 PhD Hydrology (University of Arizona 🇺🇸)
2009 – 2012 NASA Earth and Space Science Fellow (University of Arizona 🇺🇸)
2013 – Senior Lecturer Hydrometeorology (University of Bristol 🇬🇧)

Additional (current) appointments :
Co-leader for the ‘Water’ theme of the Cabot Institute of the Environment
Co-leader for the ‘Impact and risk-based predictions’ theme of the MetOffice Academic Partnership
Board Member for the GW4 Water Security Alliance
Associate Editor for the American Geophysical Union’s Water Resources Research Journal
Associate Editor for the American Meteorological Society’s Journal of Hydrometeorology

Experience in the field


Amazon Rainforest


Sugarcane cropland


Cerrado (Woody Savanna)


Biosphere2 Tropical Rainforest mesocosm


Harvard Forest

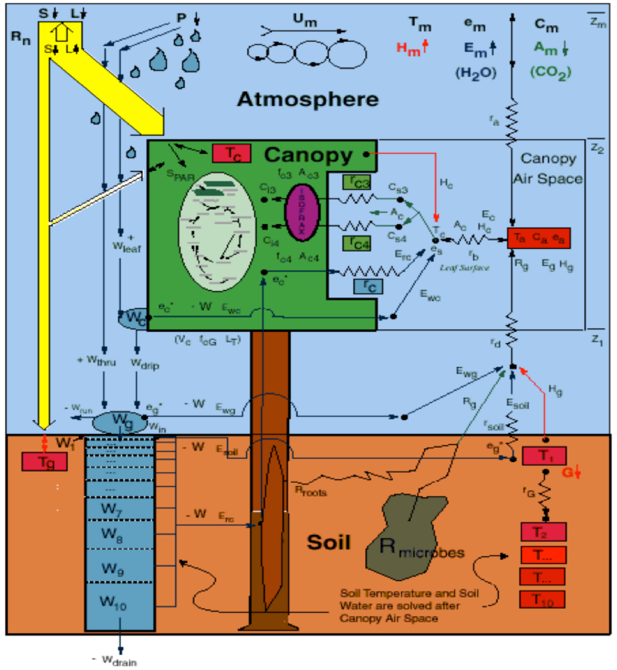

Grassland/pasture


Cerrado (Woody Savanna)

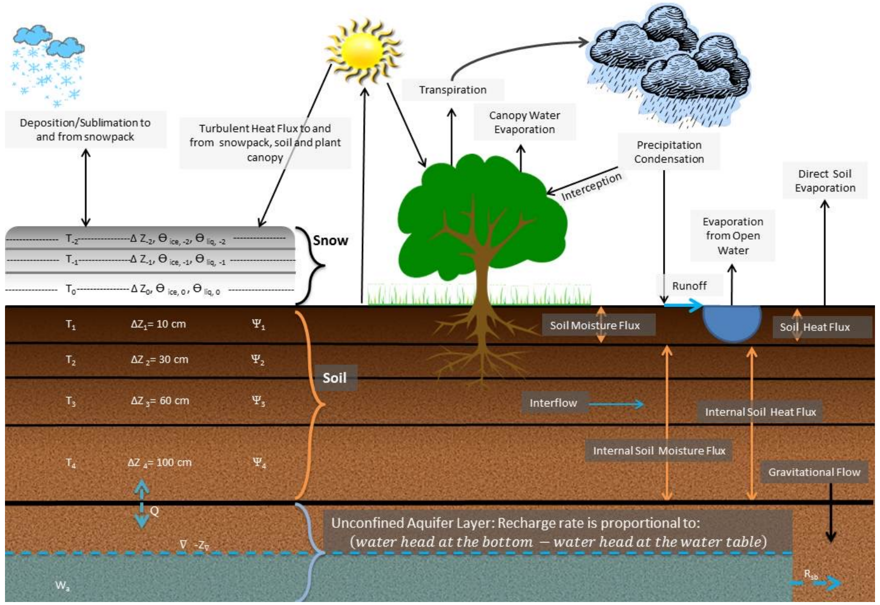

Farmland/grassland

Experience with modeling

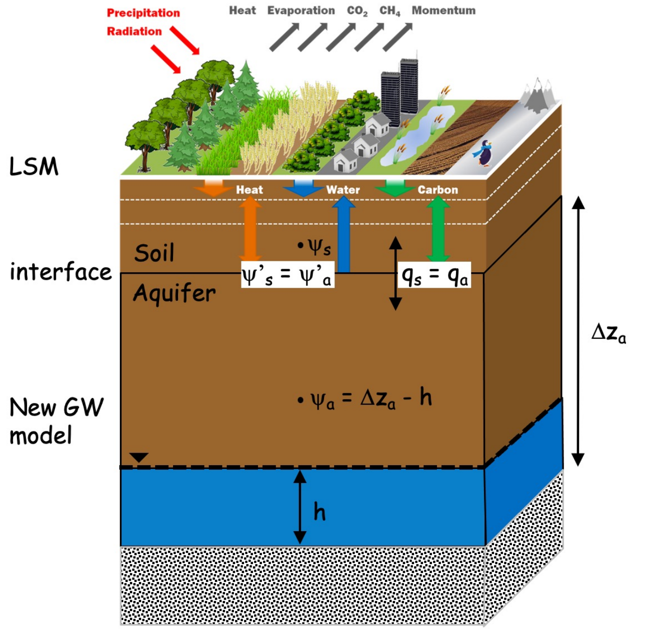
Simple Biosphere Model



NOAH model



Joint UK Land Environment Model



Research projects

- Team member ‘Large-scale Biosphere Atmosphere Experiment in Amazonia’ – LBA (NASA/INPE)
- Principal Investigator ‘A MUlti-scale Soil moisture- Evapotranspiration Dynamics study’ – AMUSED (NERC)
- Co-Principal Investigator ‘MOSAIC Digital Environment Feasibility Study’ (NERC)
- Principal Investigator ‘Brazilian Experimental datasets for MUlti- Scale interactions in the critical zone under Extreme Drought’ – BEMUSED (NERC/FAPESP)*
- Co-Investigator ‘Drought Resilience In East African dryland Regions’ - DRIER (Royal Society)*
- Co-Investigator ‘Mobile phone App Development for Drought Adaptation in Drylands - MAD DAD’ (EPSRC)*
- Co-Investigator ‘DOWN2EARTH: Translation of climate information into multilevel decision support for social adaptation, policy development, and resilience to water scarcity in the Horn of Africa Drylands’ (ERC)*

* Ongoing projects

Understanding the factors

Our understanding of the sensor was limited at the beginning

$$\theta_{GRAV} = \frac{a_0}{\frac{N_{pi}}{N_0} - a_1} - a_2$$

where

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

θ_{GRAV} = gravimetric water content (g g^{-1})
N_{pi} = corrected measured neutron counting rate (counts per hour)
N_{raw} = raw measured neutron counting rate (counts per hour)
N_0 = site-specific calibration parameter
f_p = atmospheric pressure correction factor (-)
f_i = solar intensity correction factor (-)
a_0, a_1, a_2 = fixed coefficients (-)

Based on Zreda et al. (2008) and Desilets et al. (2010)

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 (-)

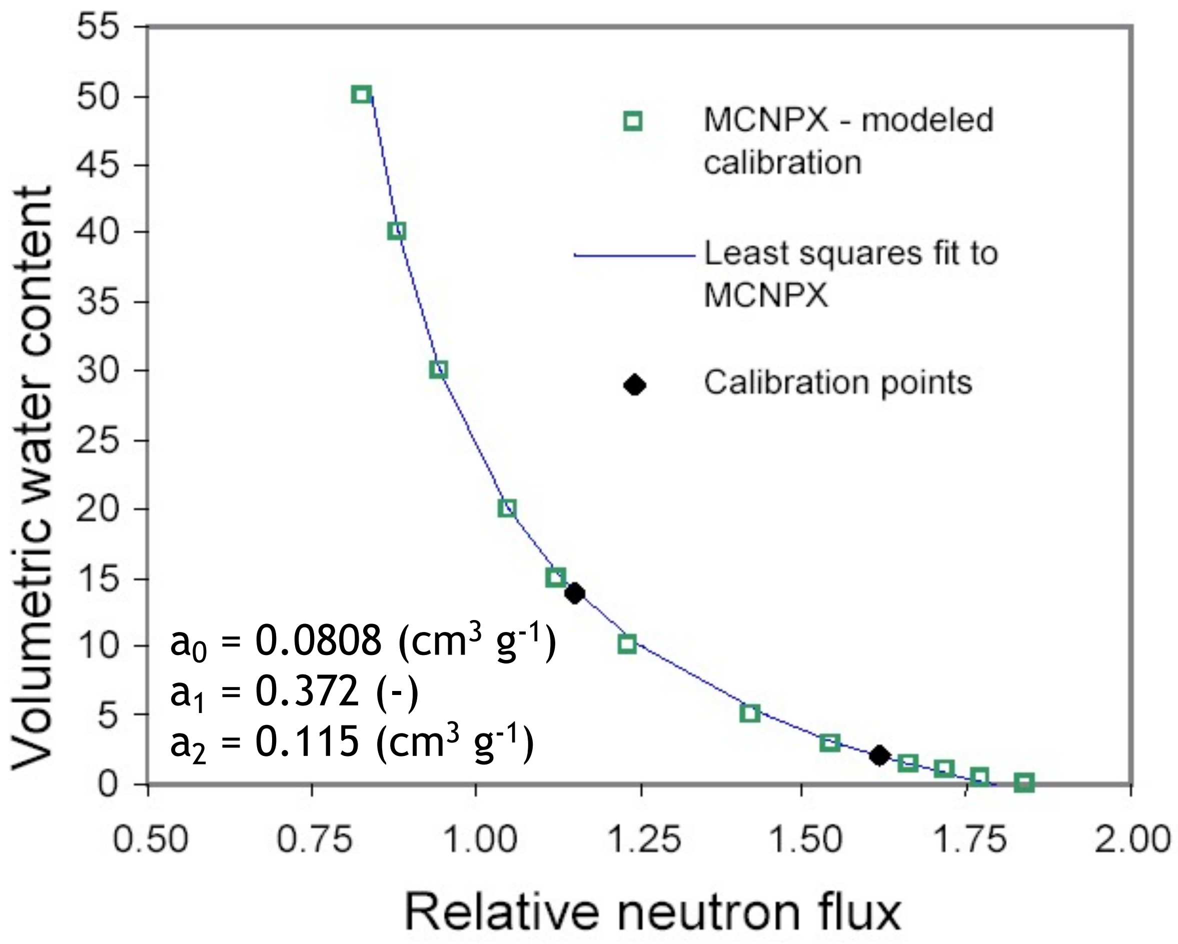
f_i = solar intensity correction factor (-)

f_h = atmospheric water vapor correction factor (-)

f_v = aboveground biomass correction factor (-)

a_0, a_1, a_2 = fixed coefficients (-)

a_0, a_1, a_2 are fixed coefficients originally obtained from neutron particle transport modeling



a_0 = 0.0808 ($cm^3\ g^{-1}$)
a_1 = 0.372 (-)
a_2 = 0.115 ($cm^3\ g^{-1}$)

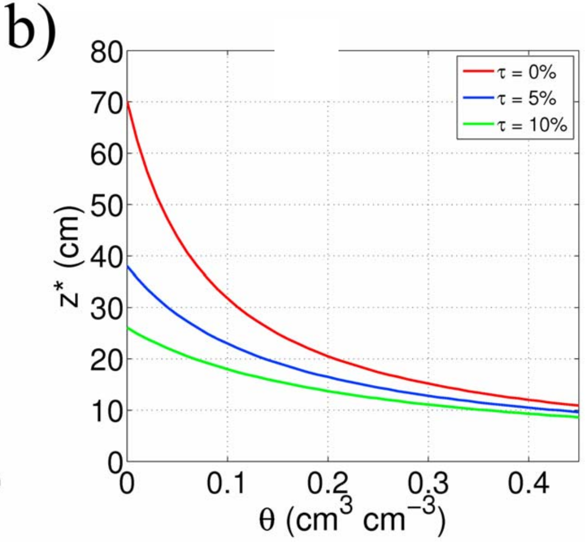
Unpublished work by Marek Zreda and Darin Desilets

However, there have been attempts to ‘adjust’ these coefficients to site-specific conditions through empirical methods!

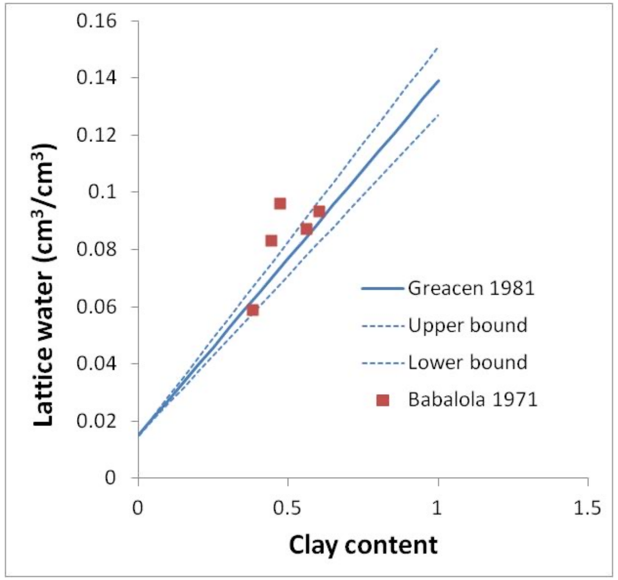
See for example:
Rivera Villarreyes et al., 2011
Iwema et al., 2015
Heidbüchel et al., 2016

What are the advantages and disadvantages of such approaches?

Chemically-bound "lattice" water is not exchanged with the atmosphere but affects the signal

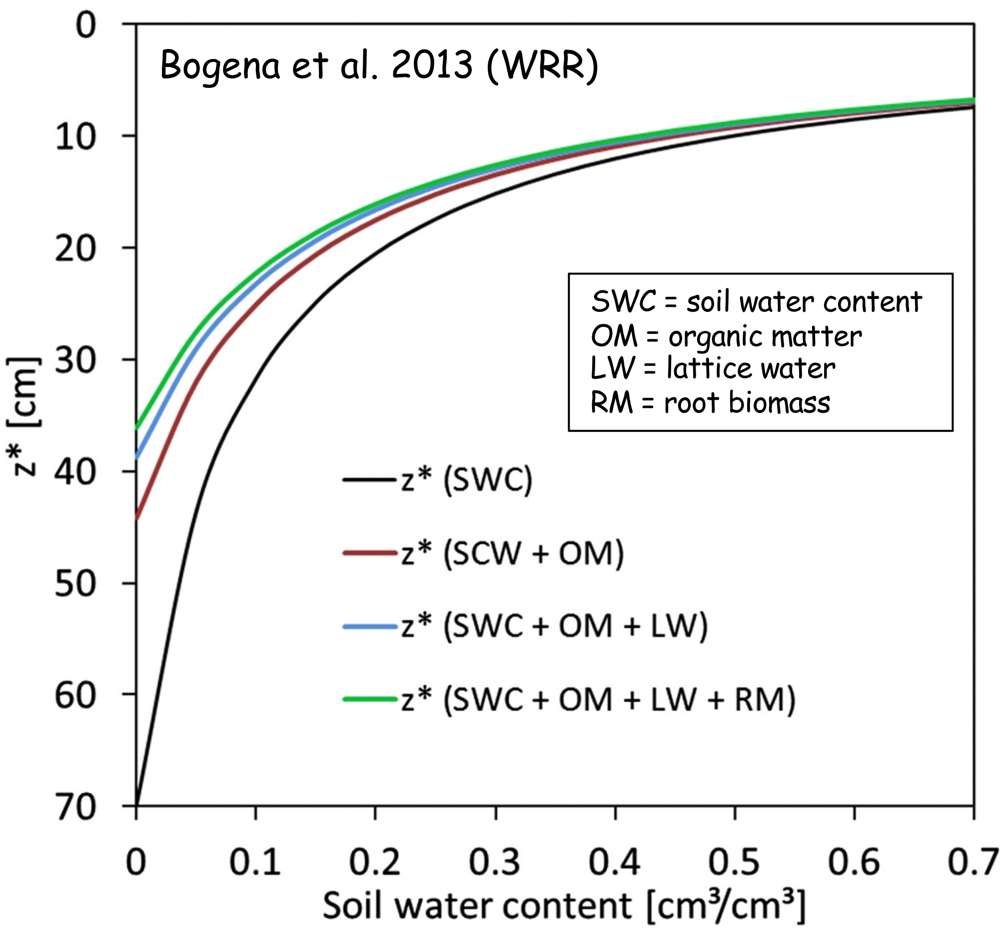


Franz et al. (2012; WRR)



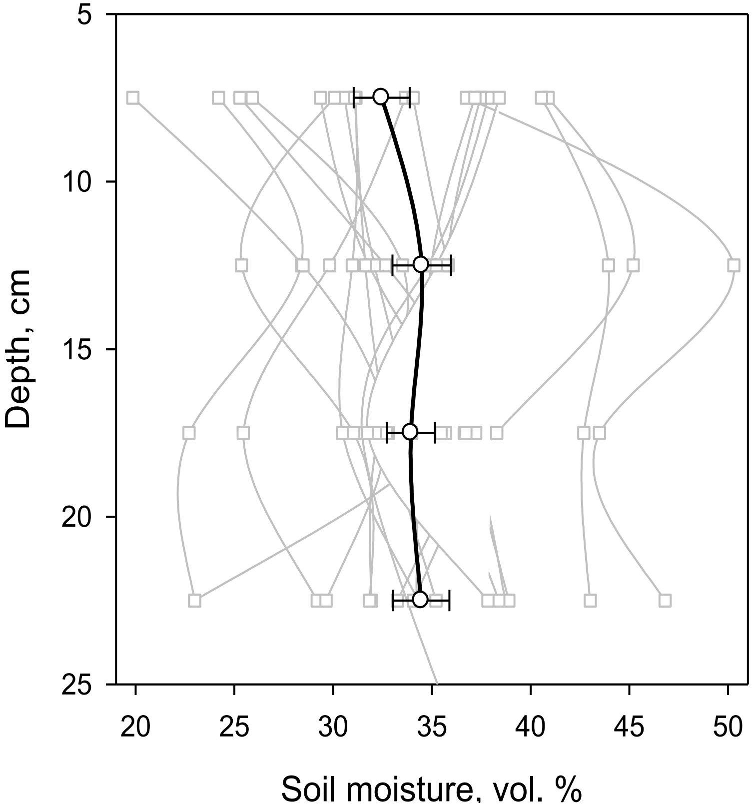
McJannet (3rd COSMOS Workshop 2012)

Soil Organic Carbon acts in a similar way to lattice water (usually assumed time-invariant)



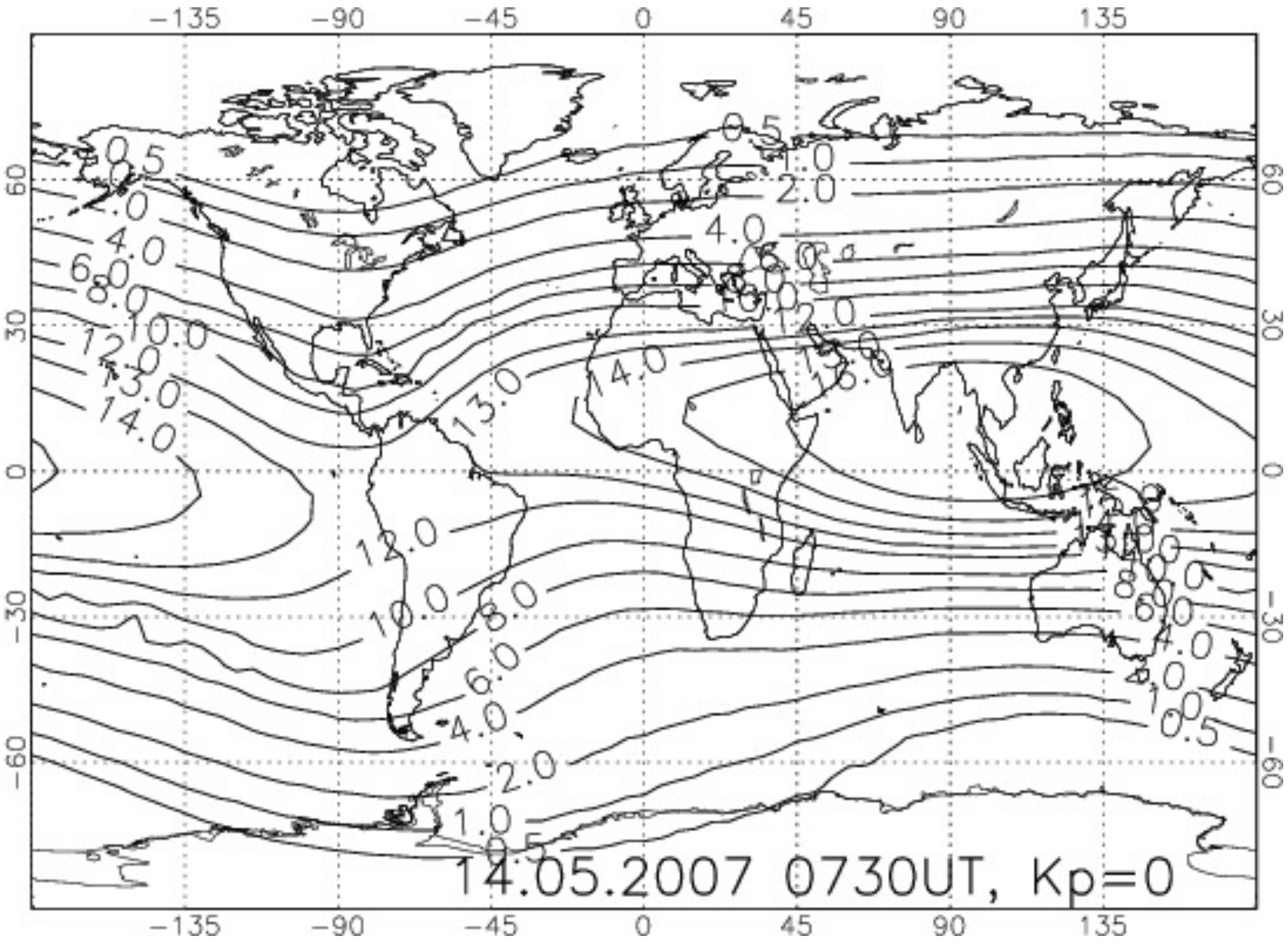
Dry soil bulk density is important if estimating volumetric water content but hard to sample

Source: COSMOS (Trenton Franz)



Iowa
September 2010

Cosmic-ray intensity



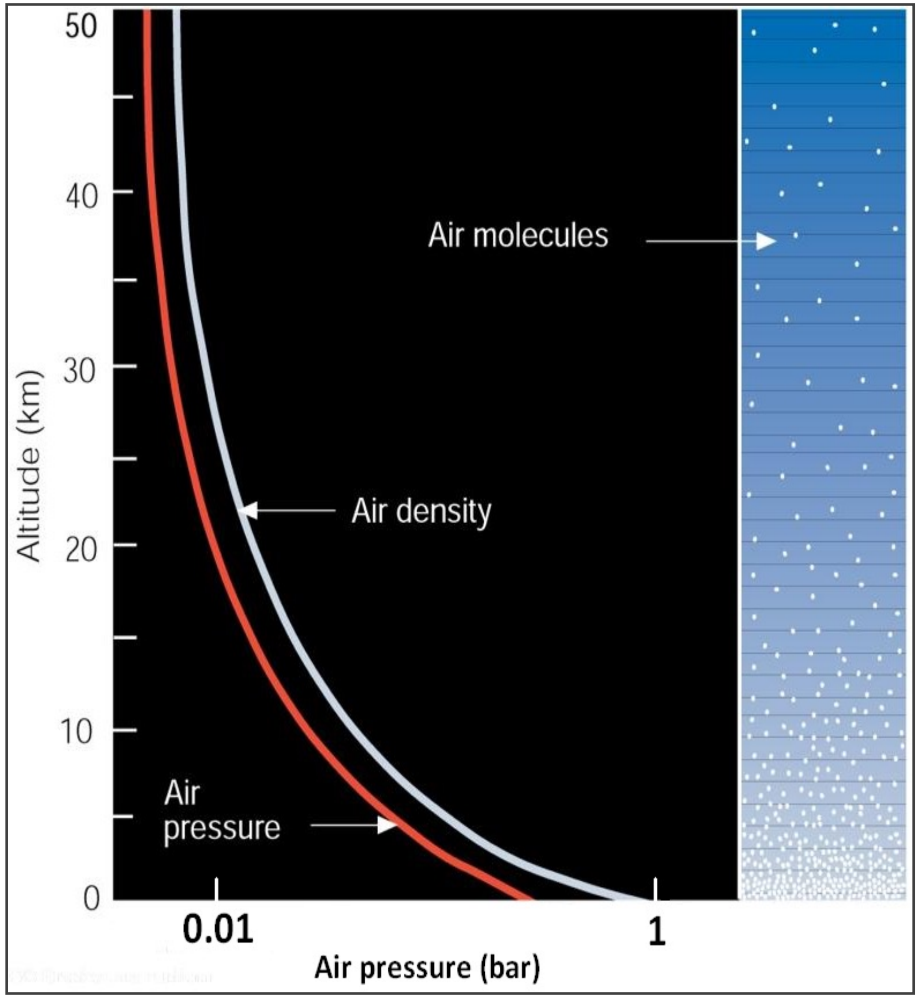
Cut-off rigidity map!

Higher values show regions with stronger magnetic field (i.e., near the equator)

Stronger magnetic fields result in less cosmic-rays reaching the Earth's atmosphere

Luckily, this correction is easily applied in the cosmic-ray sensor measurements

Atmospheric pressure



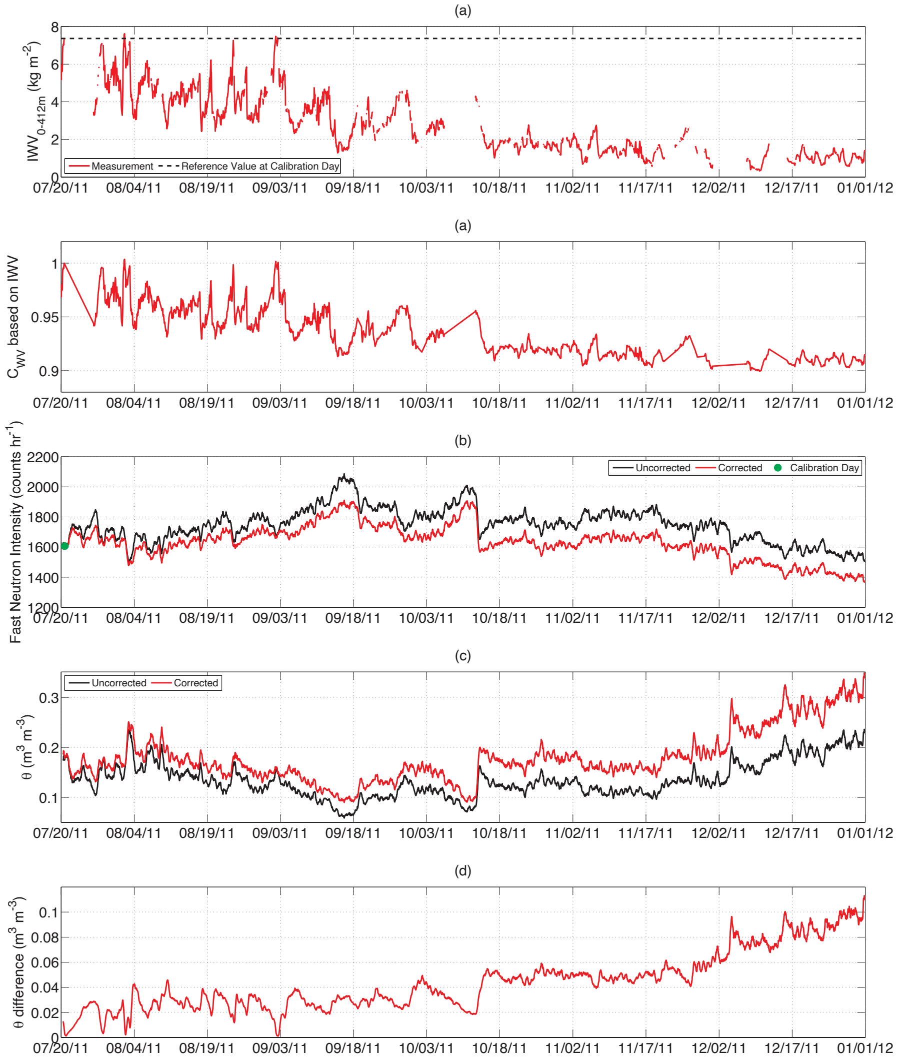
Compare the number of molecules at 10 km of altitude versus surface level! What do you notice?

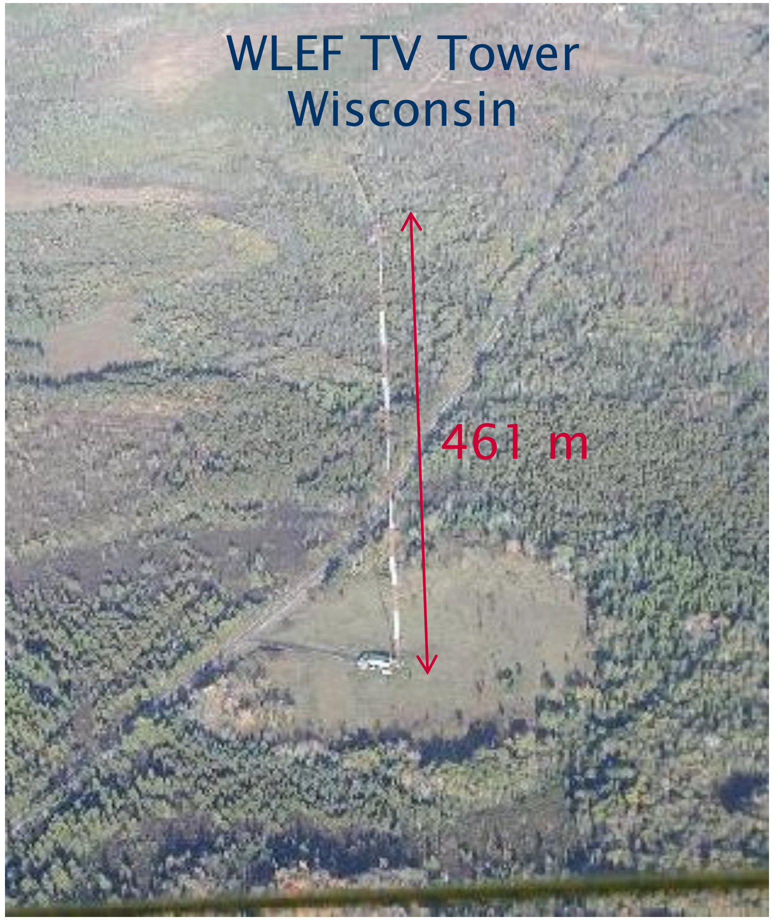
More particles were in the cosmic-ray neutron's downward pathway in a thicker atmosphere

Also remember that pressure is continuously changing due to weather patterns

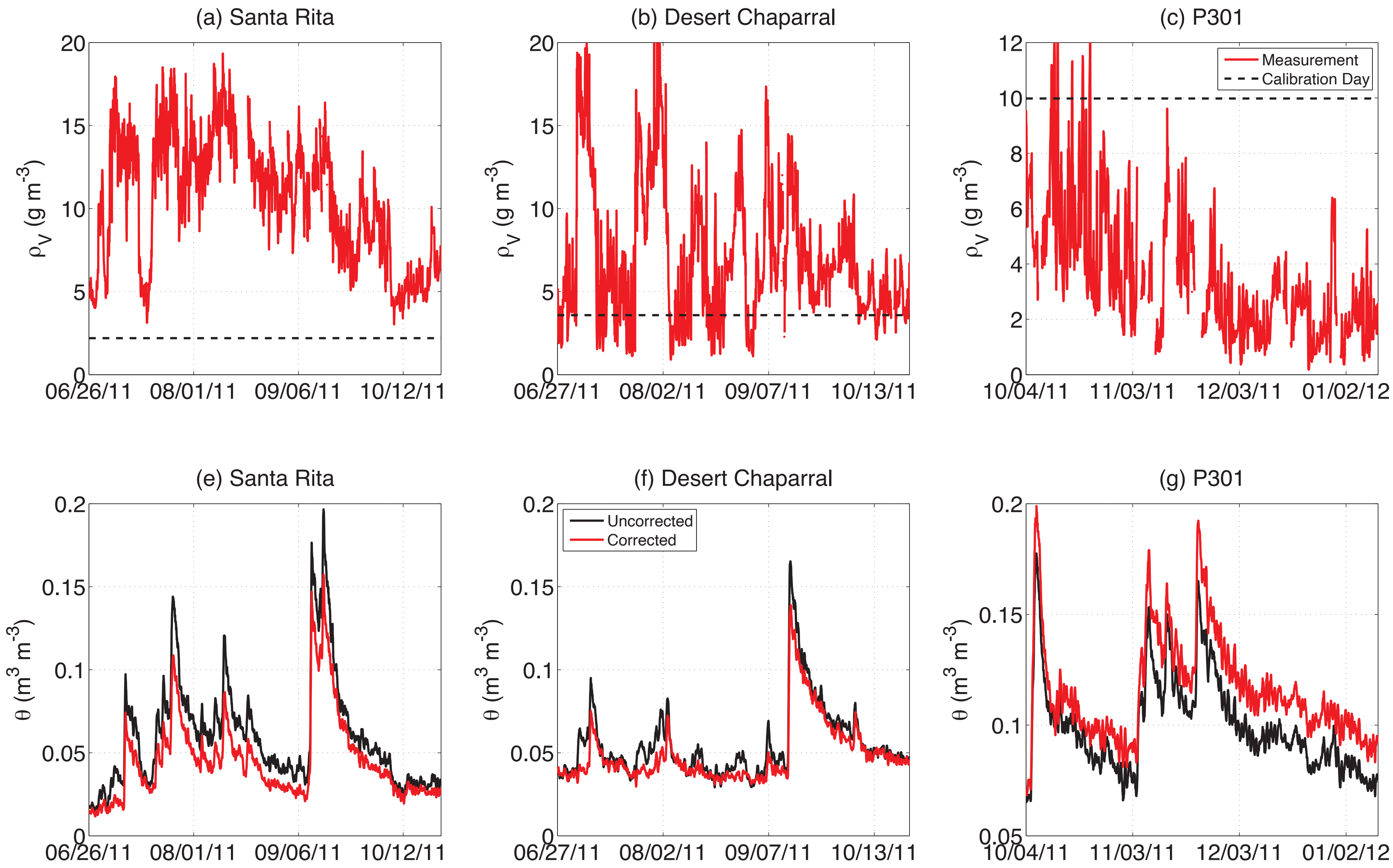
Luckily, this correction is also easily applied to the cosmic-ray sensor

Atmospheric water vapor





Rosolem et al. 2013 (J. Hydromet)

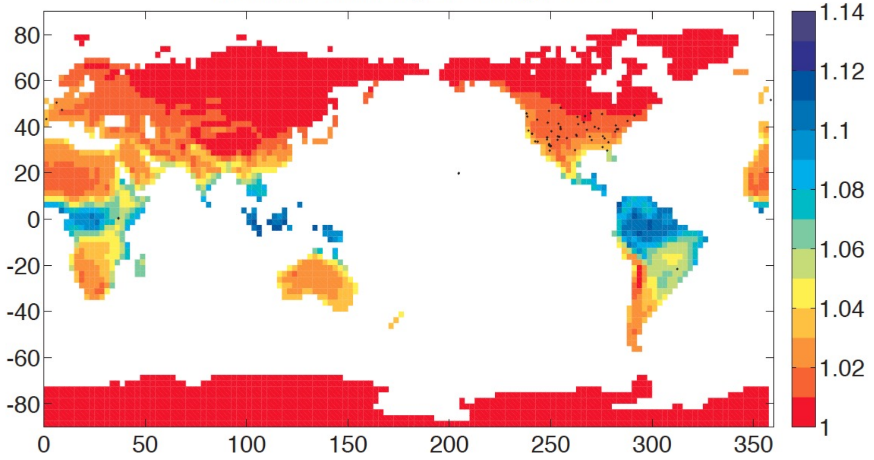


Rosolem et al. 2013 (J. Hydromet)

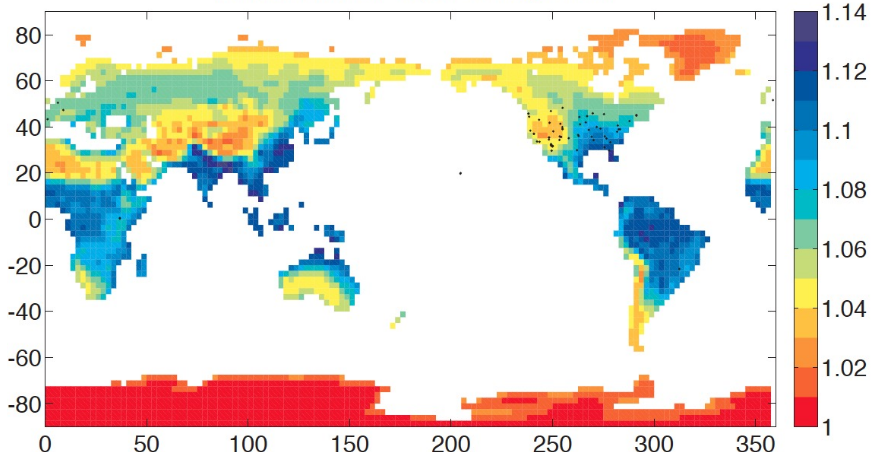
Additional temperature and humidity sensors allows for calculation of water vapor correction with surface meteorological measurements

Water vapor correction factor relative to fully dry atmosphere

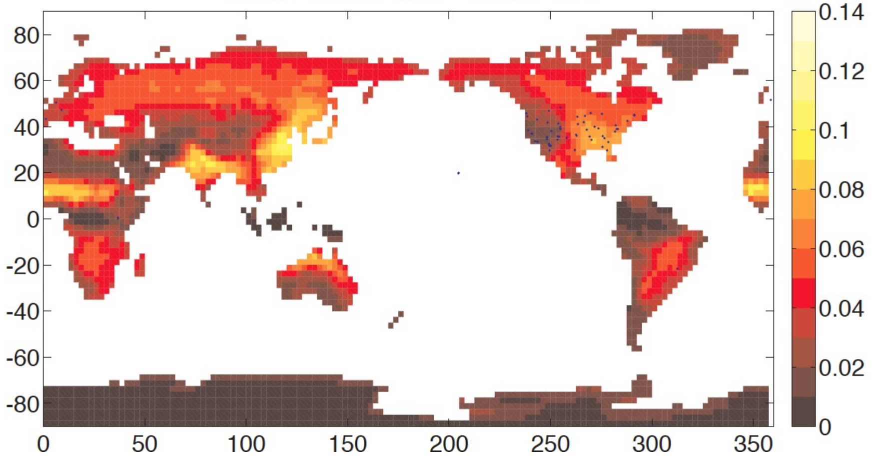
Minimum Water Vapor Scaling Factor



Maximum Water Vapor Scaling Factor

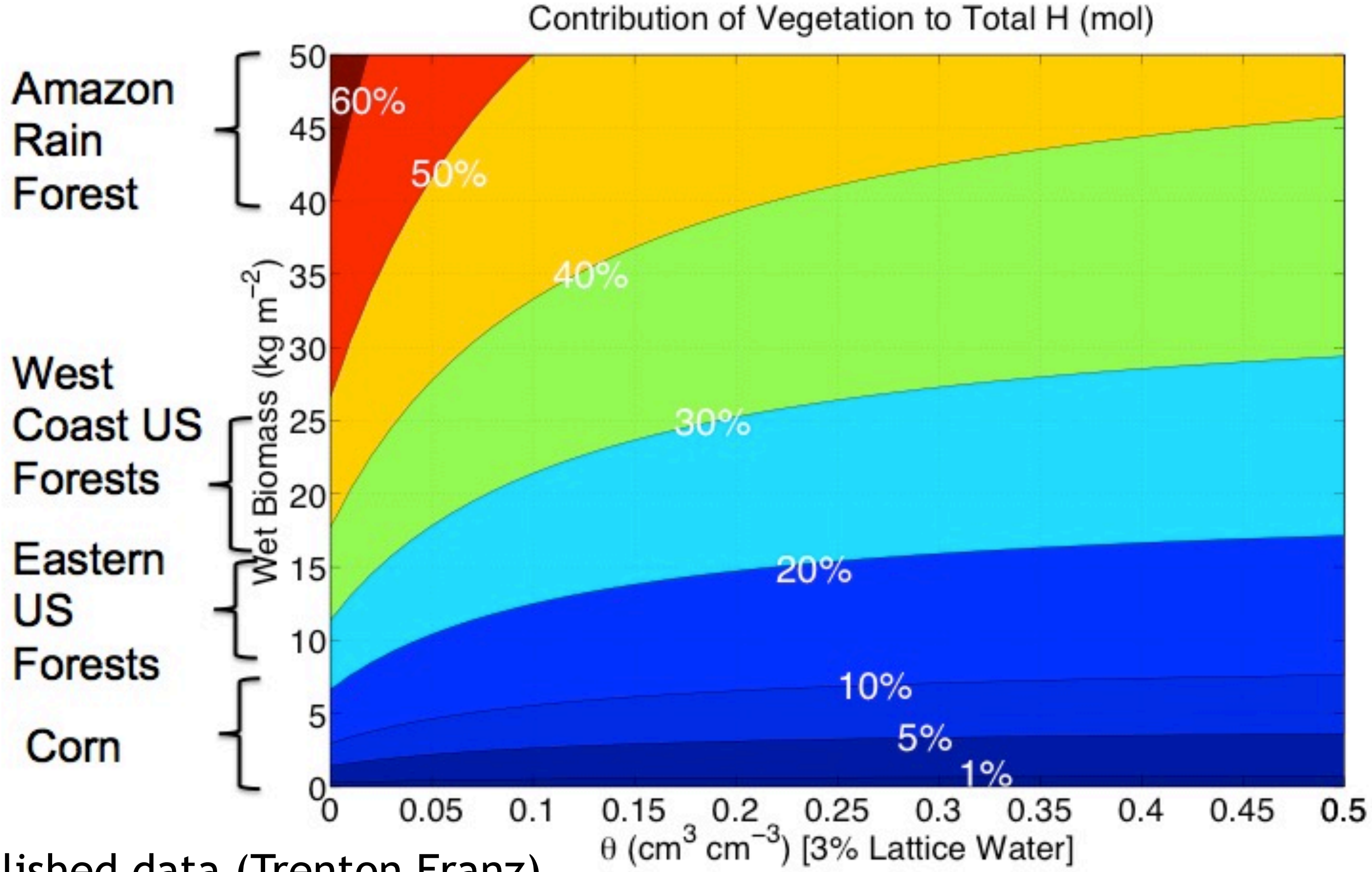


Range Water Vapor Scaling Factor



Data from NCEP Reanalysis:
Monthly climatology (1948-2011)

Aboveground biomass



Unpublished data (Trenton Franz)

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

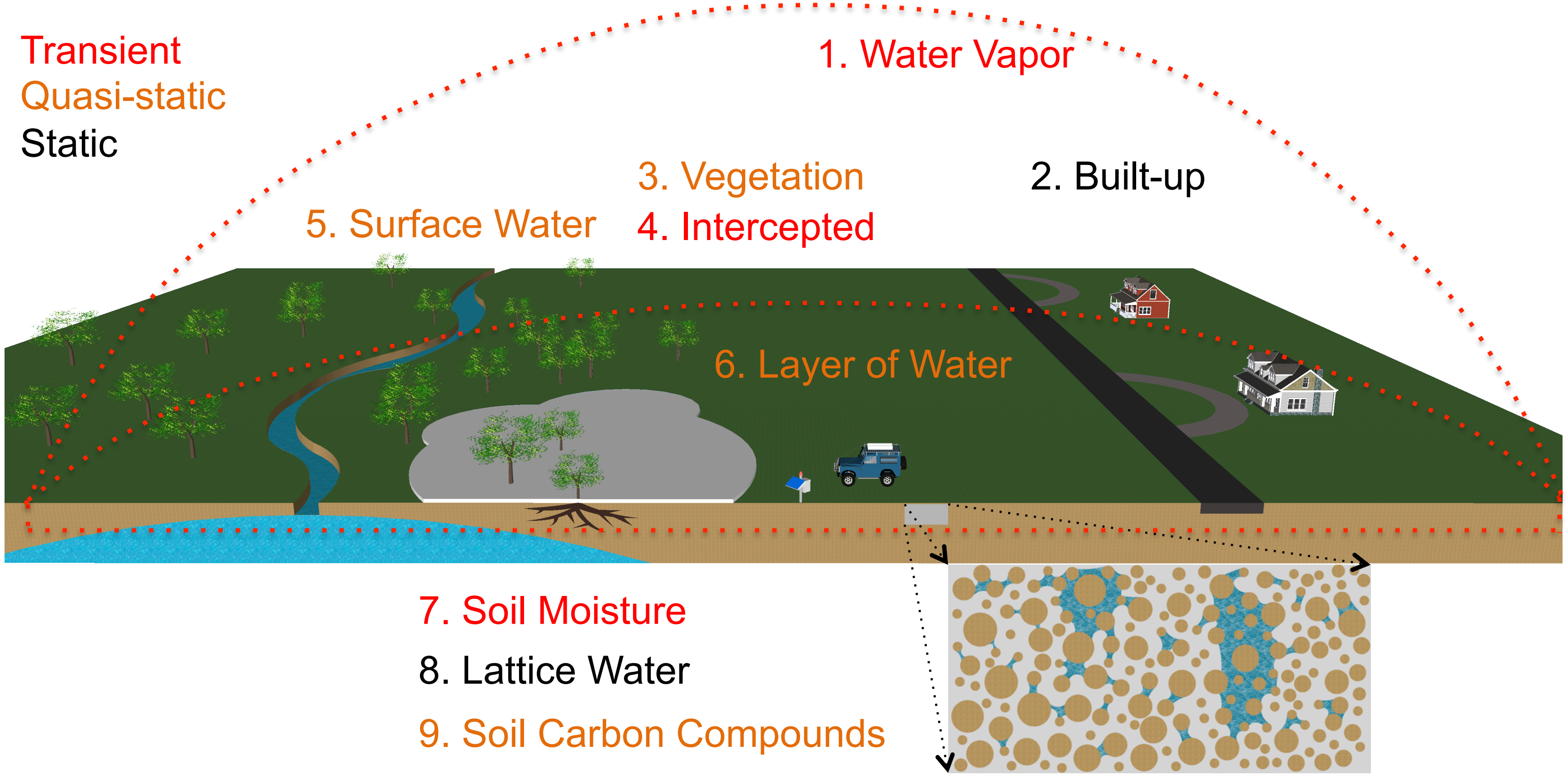
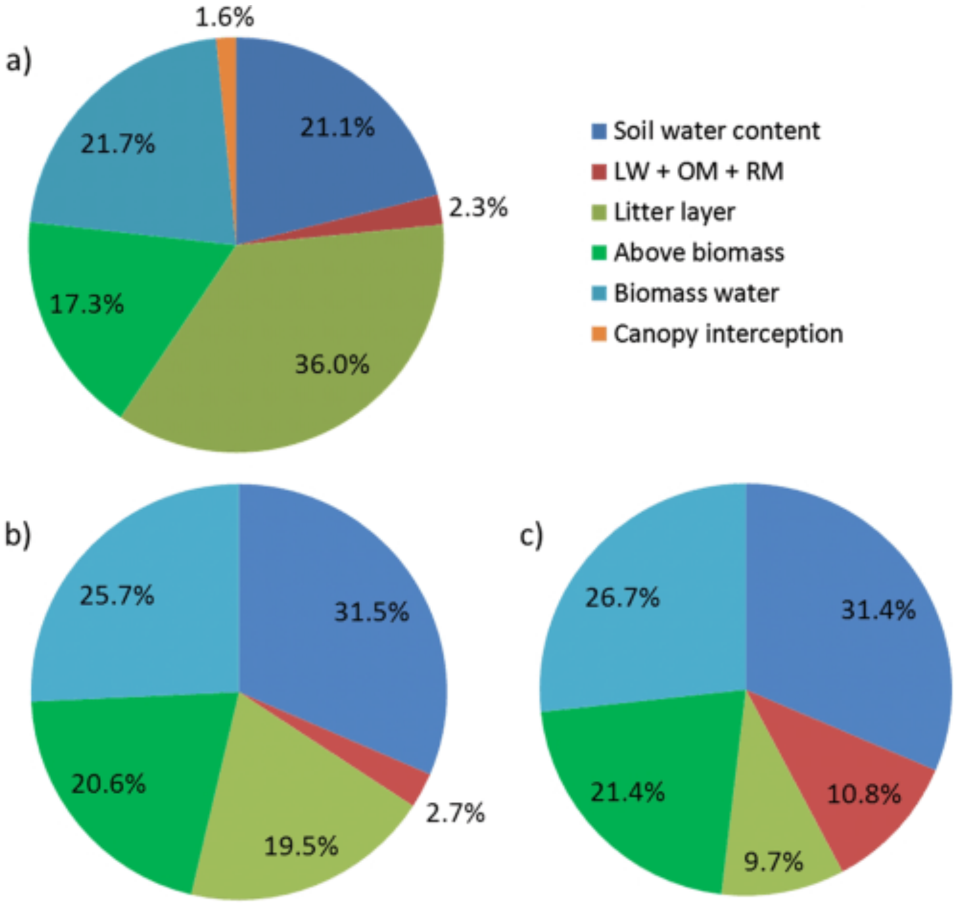


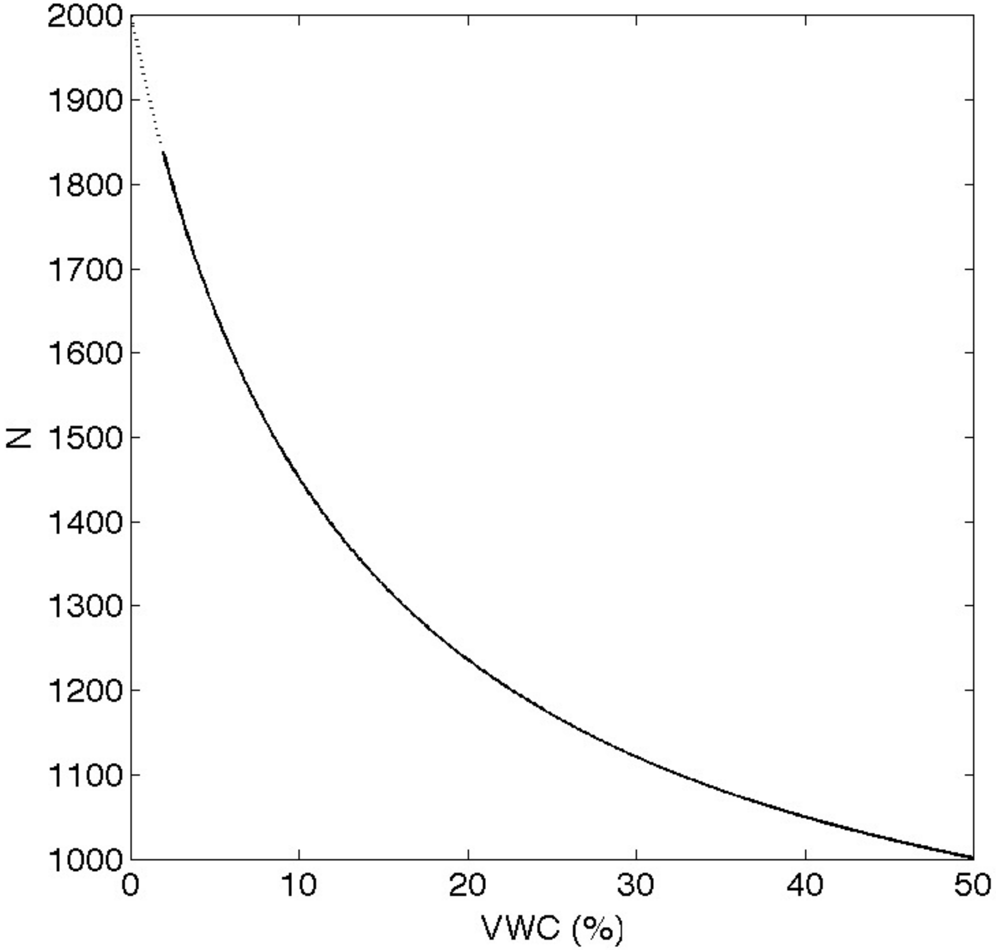
Image kindly provided by Trenton Franz (Nebraska-Lincoln)

Example of relative contribution from different hydrogen pools in a humid region



Bogena et al. (2013)

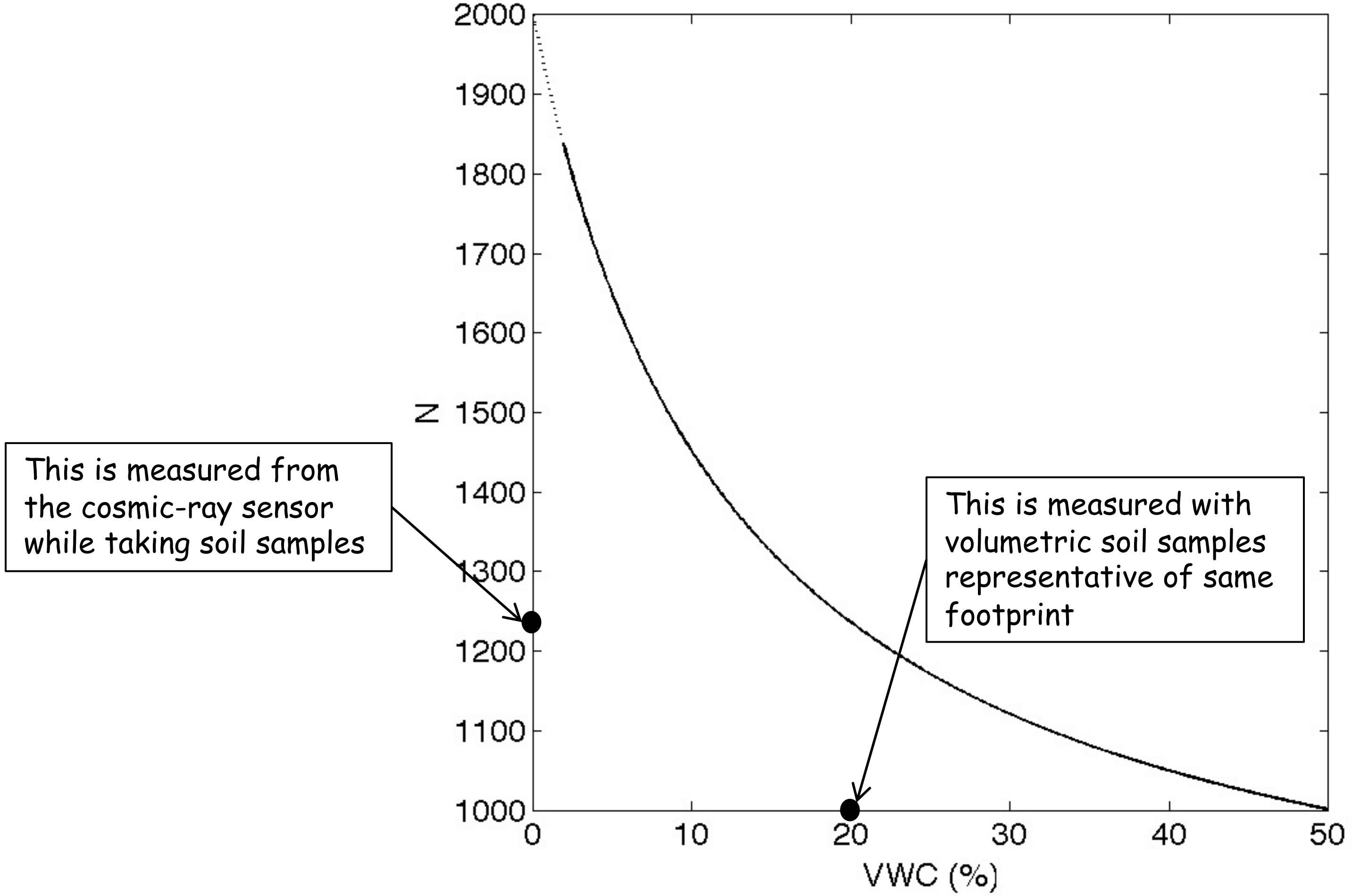
N0 is a parameter obtained through site calibration



Requires an independent estimation of soil moisture with similar footprint

N0 is the theoretical maximum amount of neutron counts under fully dry conditions

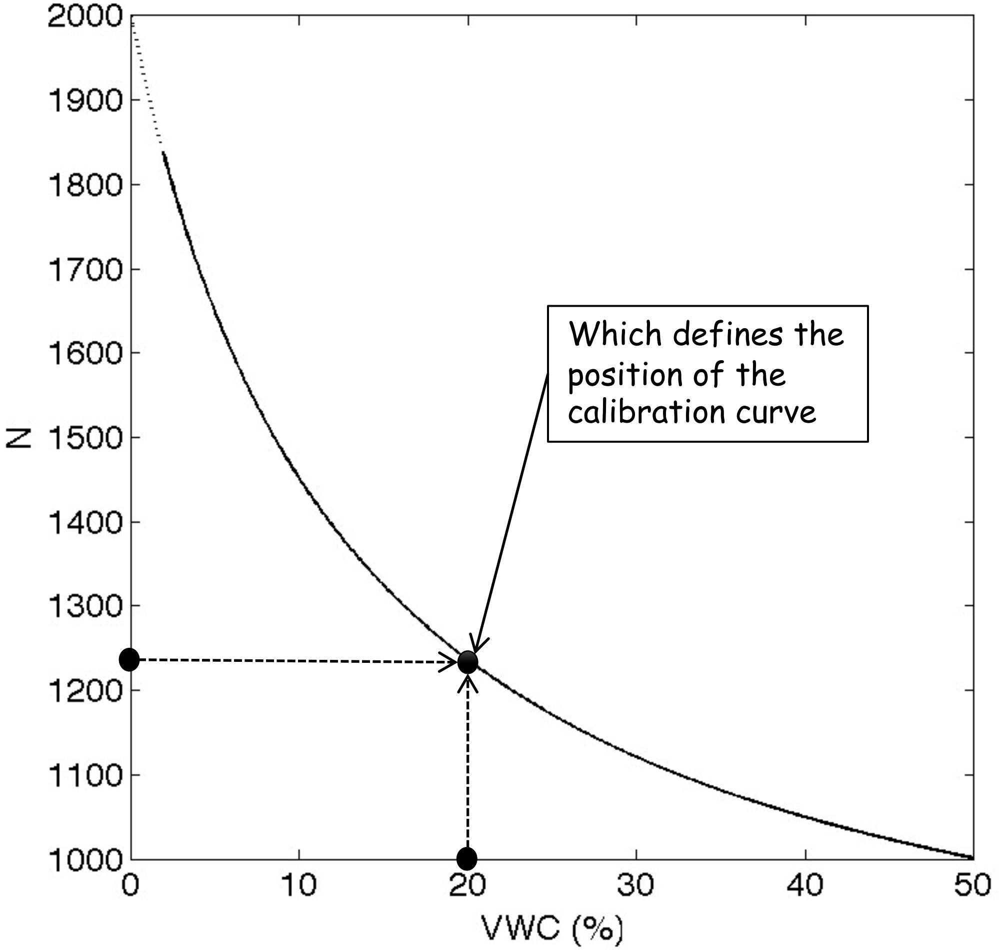
N0 is a parameter obtained through site calibration



This is measured from the cosmic-ray sensor while taking soil samples

This is measured with volumetric soil samples representative of same footprint

N0 is a parameter obtained through site calibration

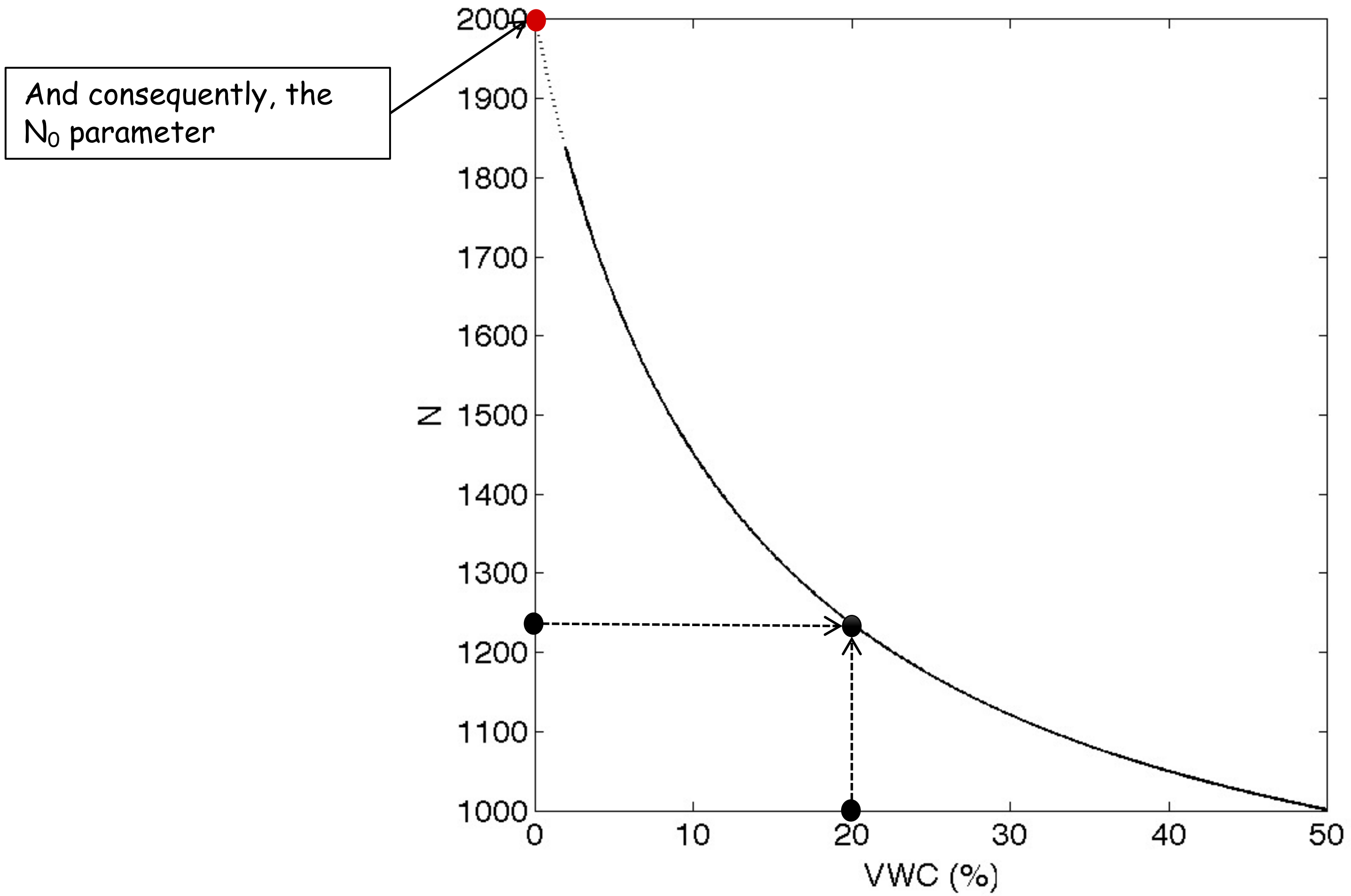


Which defines the position of the calibration curve

Requires an independent estimation of soil moisture with similar footprint

N0 is the theoretical maximum amount of neutron counts under fully dry conditions

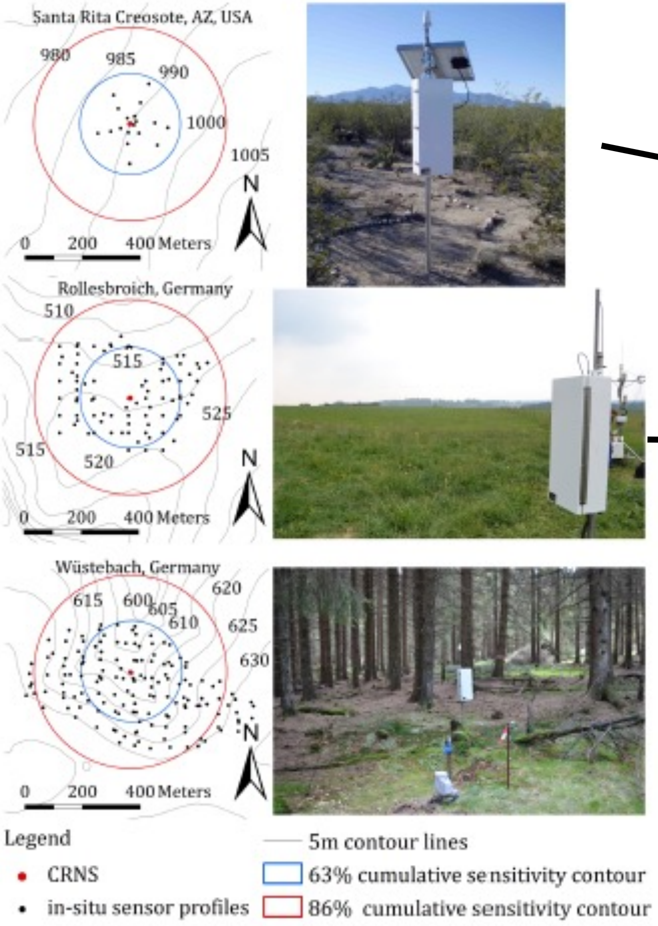
N0 is a parameter obtained through site calibration

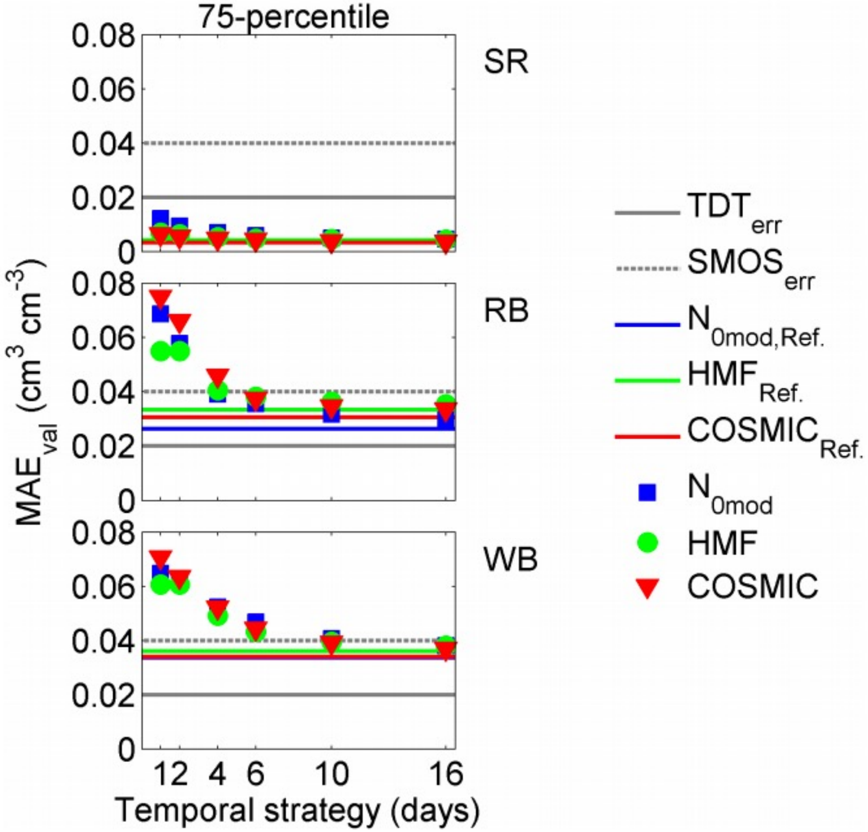


Can you think of potential issues with these calibration steps?

Think of extreme dry or wet regions?

We found that CRS needs to be calibrated for multiple days for better performance

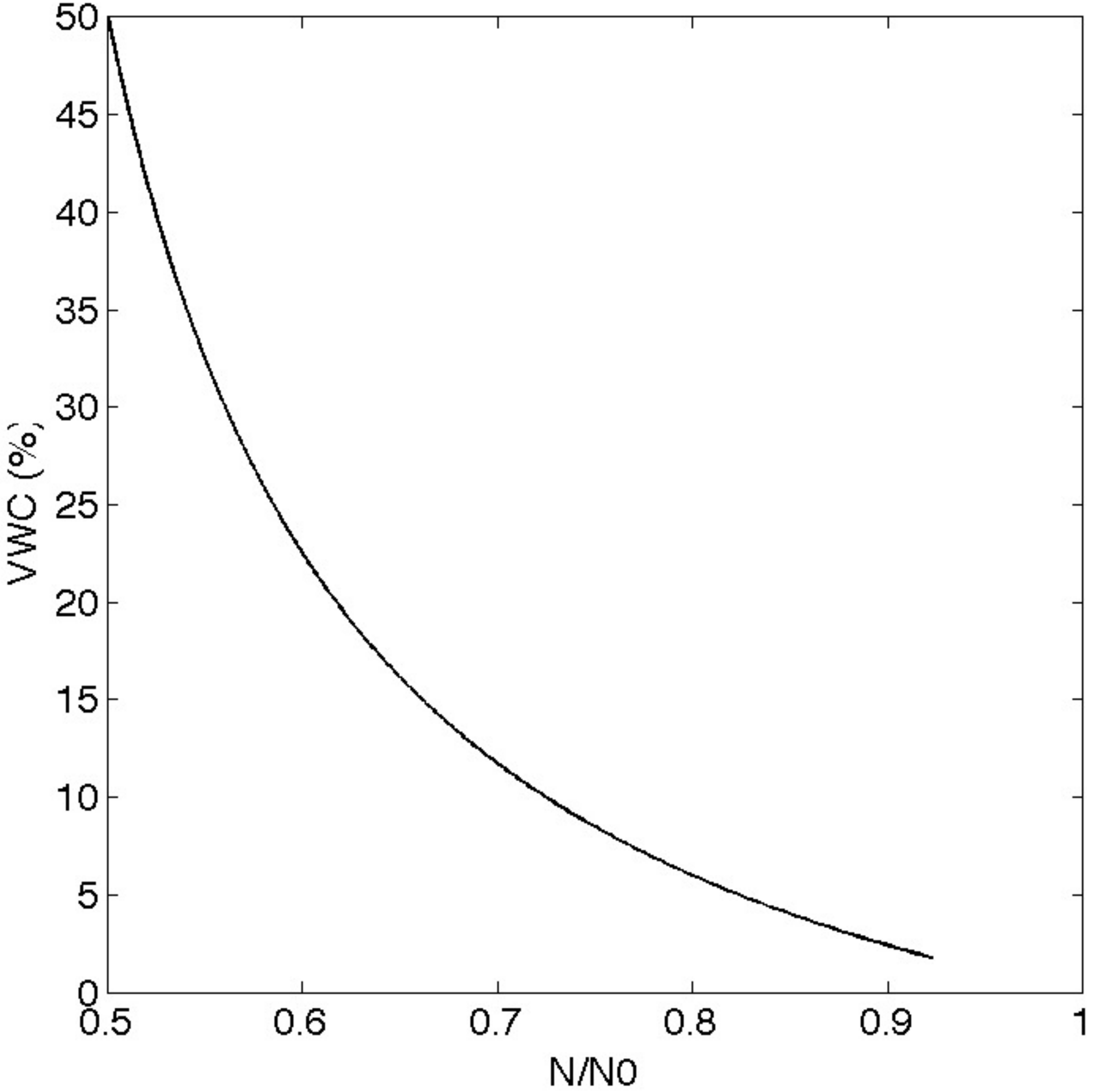




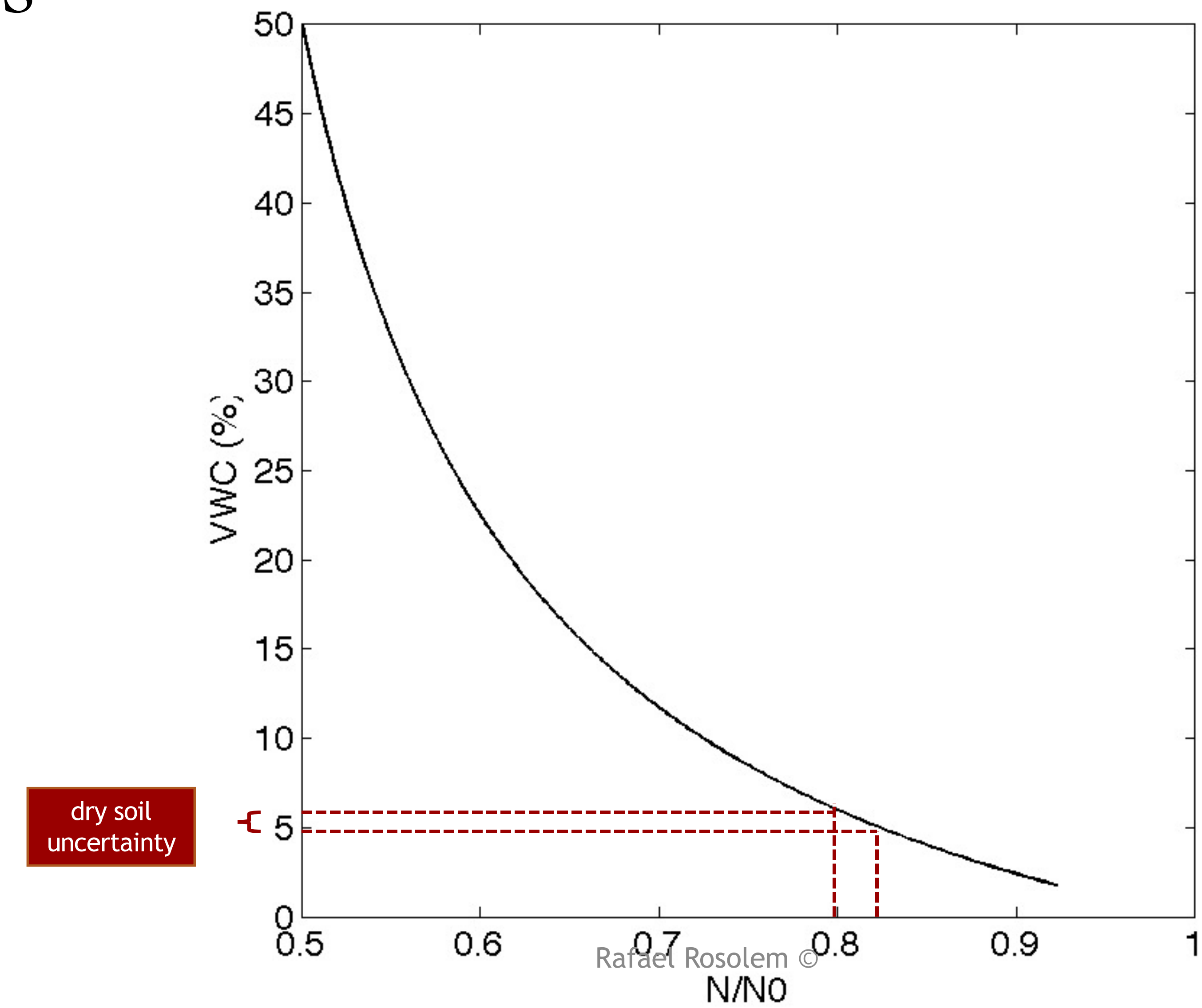
Iwema et al. 2015 (HESS)

Propagation of uncertainties

Propagation of uncertainty: dry versus humid regions



Propagation of uncertainty: dry versus humid regions



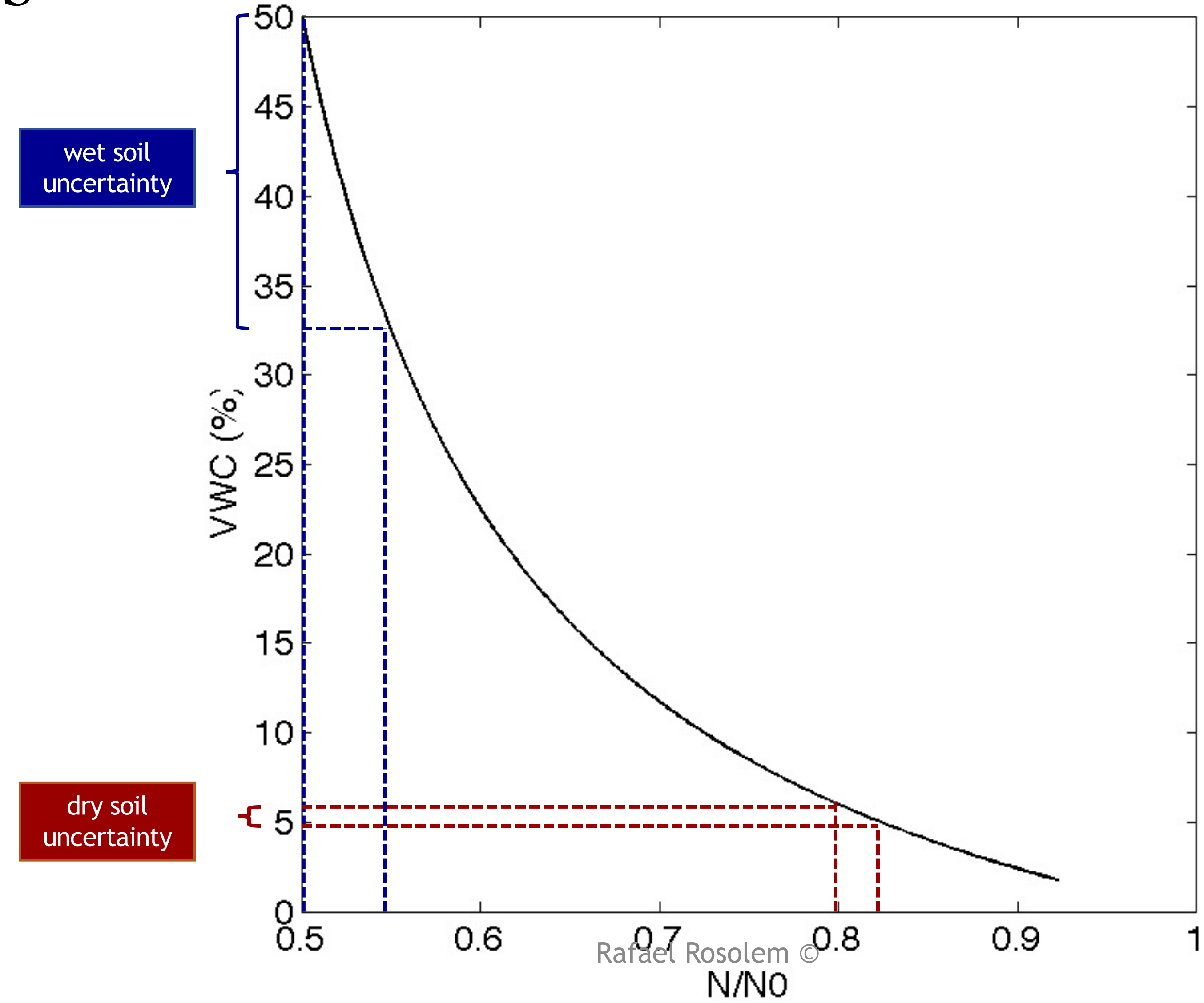
In a dry region:

Uncertainty of neutron counts on the order of 2%

Propagated uncertainty of soil moisture on the order of 1.5% vol.

What do you expect to happen for humid regions?

Propagation of uncertainty: dry versus humid regions



In a humid region:

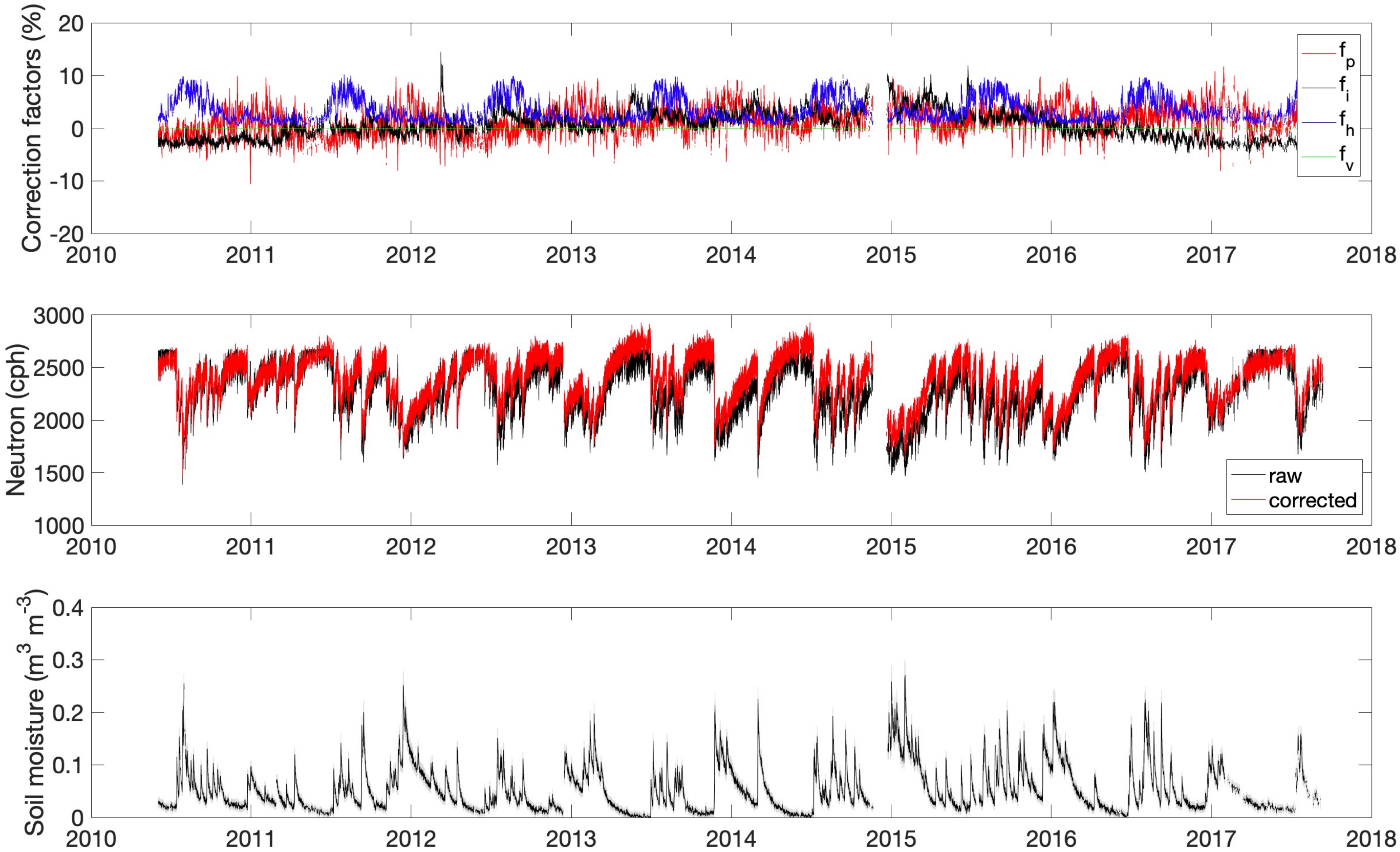
Uncertainty of neutron counts on the order of 5%

Do you know why?

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

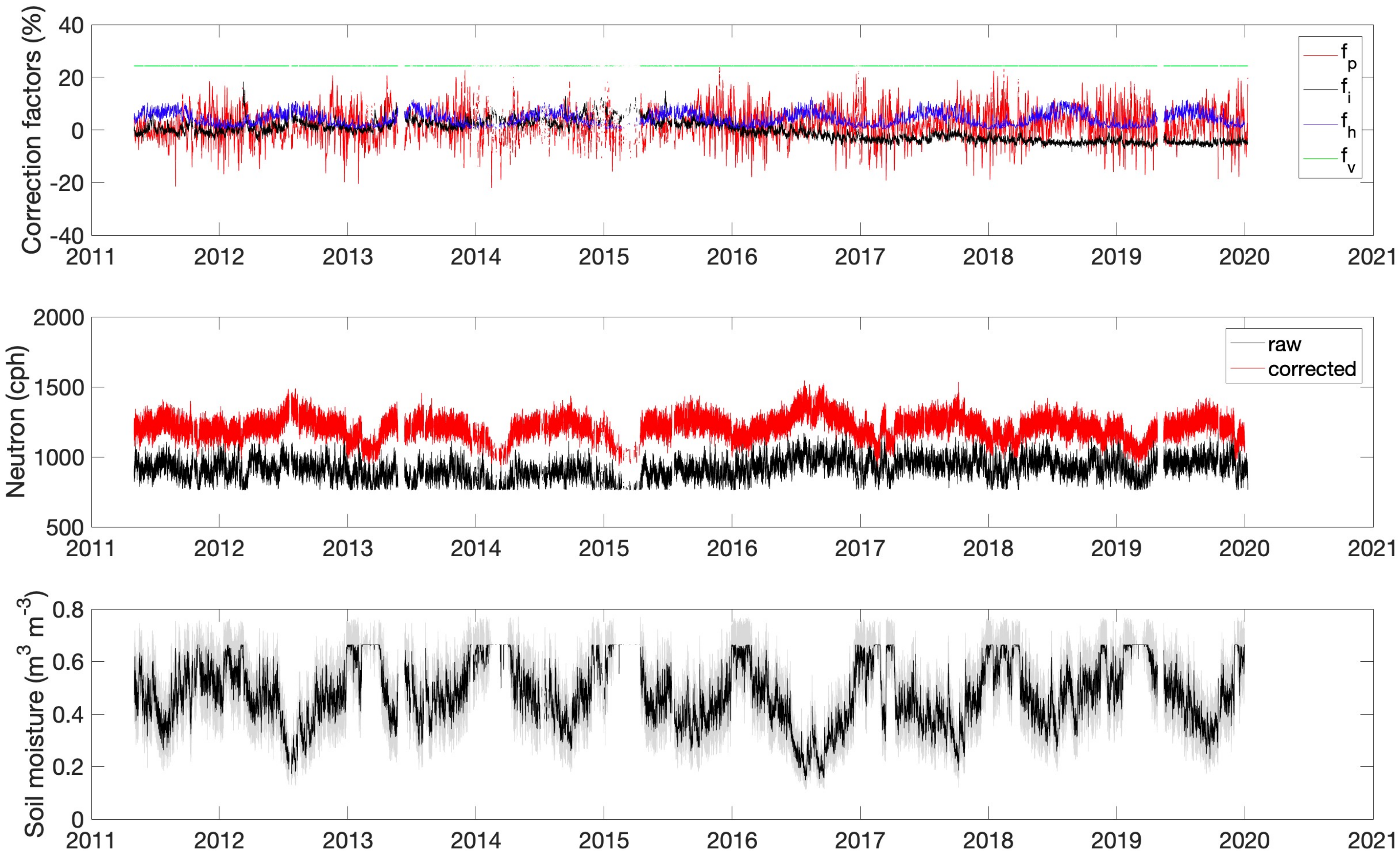
Can you understand why?

Let’s have a look at a dry site: Santa Rita (AZ, USA)



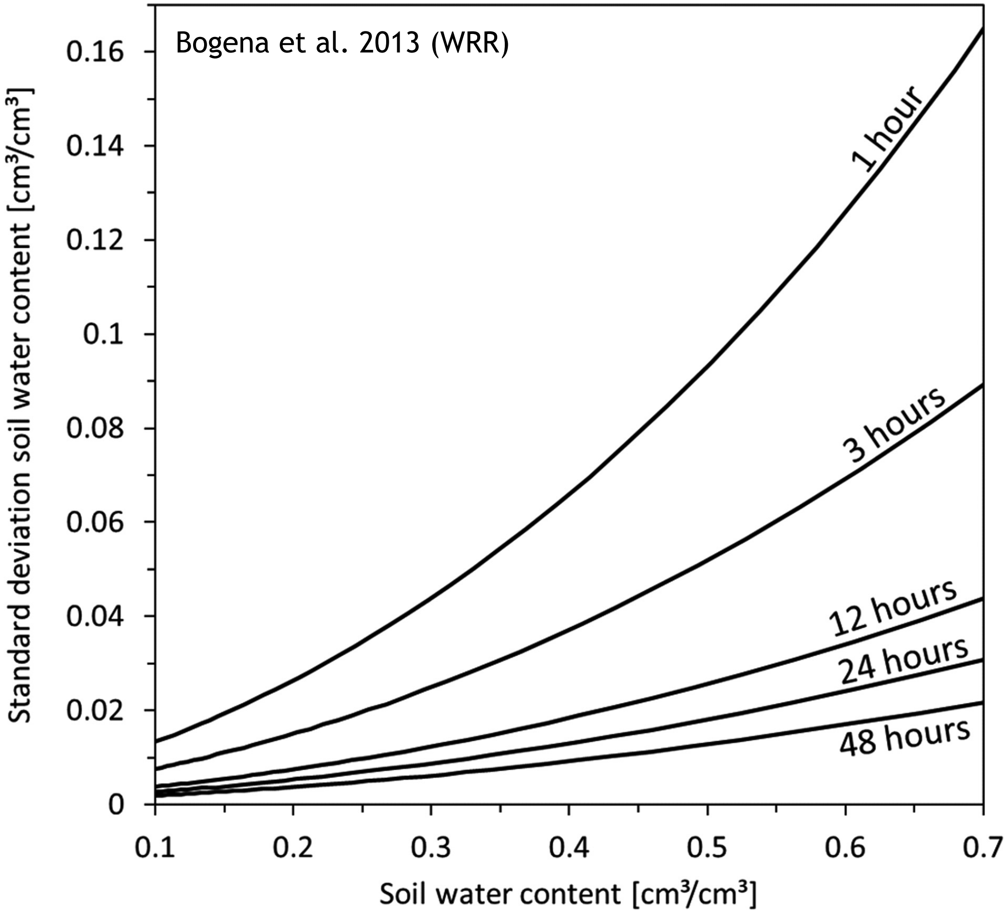
“Hot semi-arid”
Annual Temp = 18.7 ^{o}C
Annual Prec = 335 mm

Now, let’s have a look at a humid site: Harvard Forest (MA, USA)



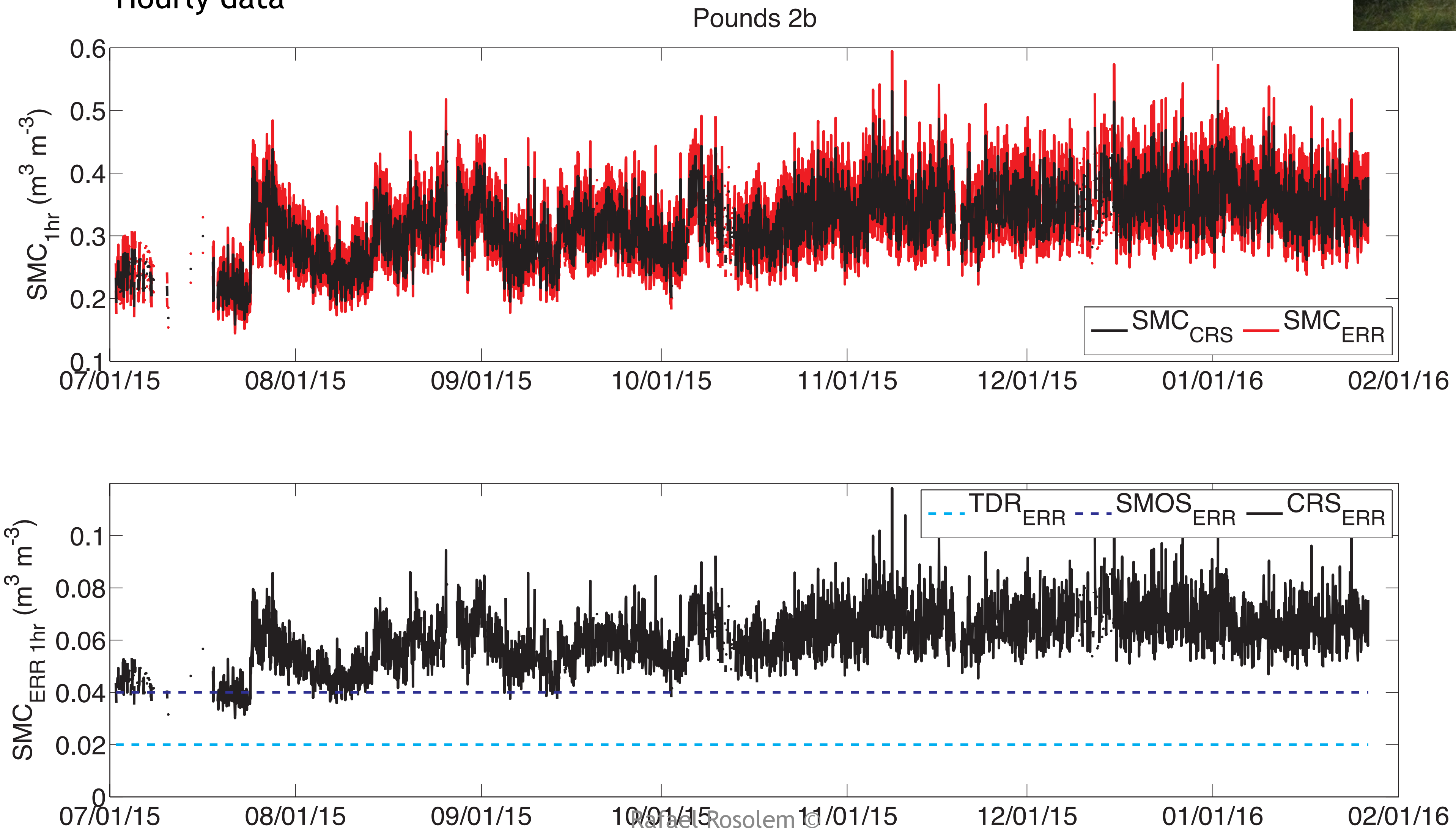
“Humid continental”
Annual Temp = 9.0 °C
Annual Prec = 1,131 mm

Longer integration time can reduce uncertainty at the cost of lower temporal resolution



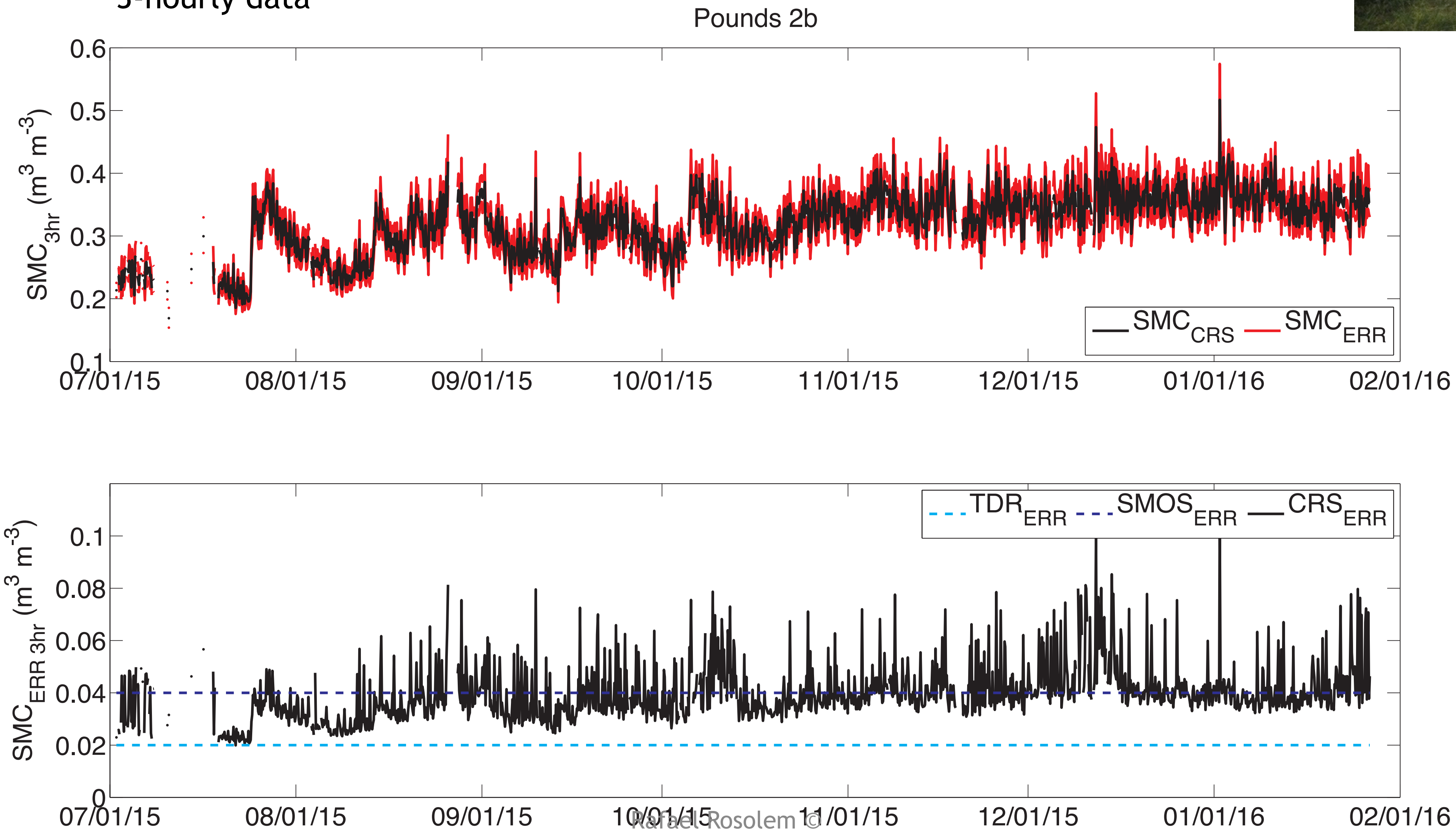
Example: Sheepdrove Farm (UK)

Hourly data



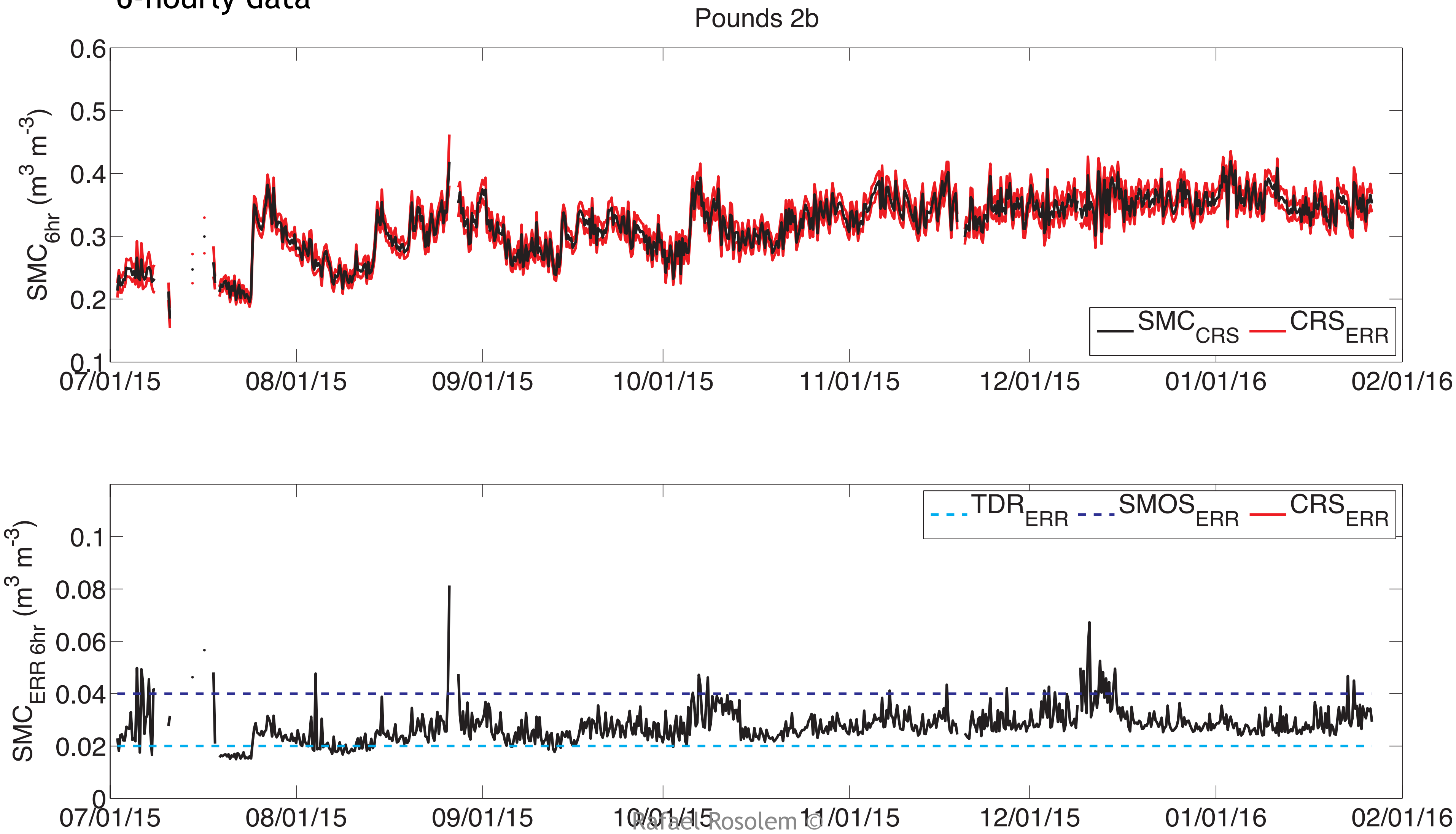
Example: Sheepdrove Farm (UK)

3-hourly data



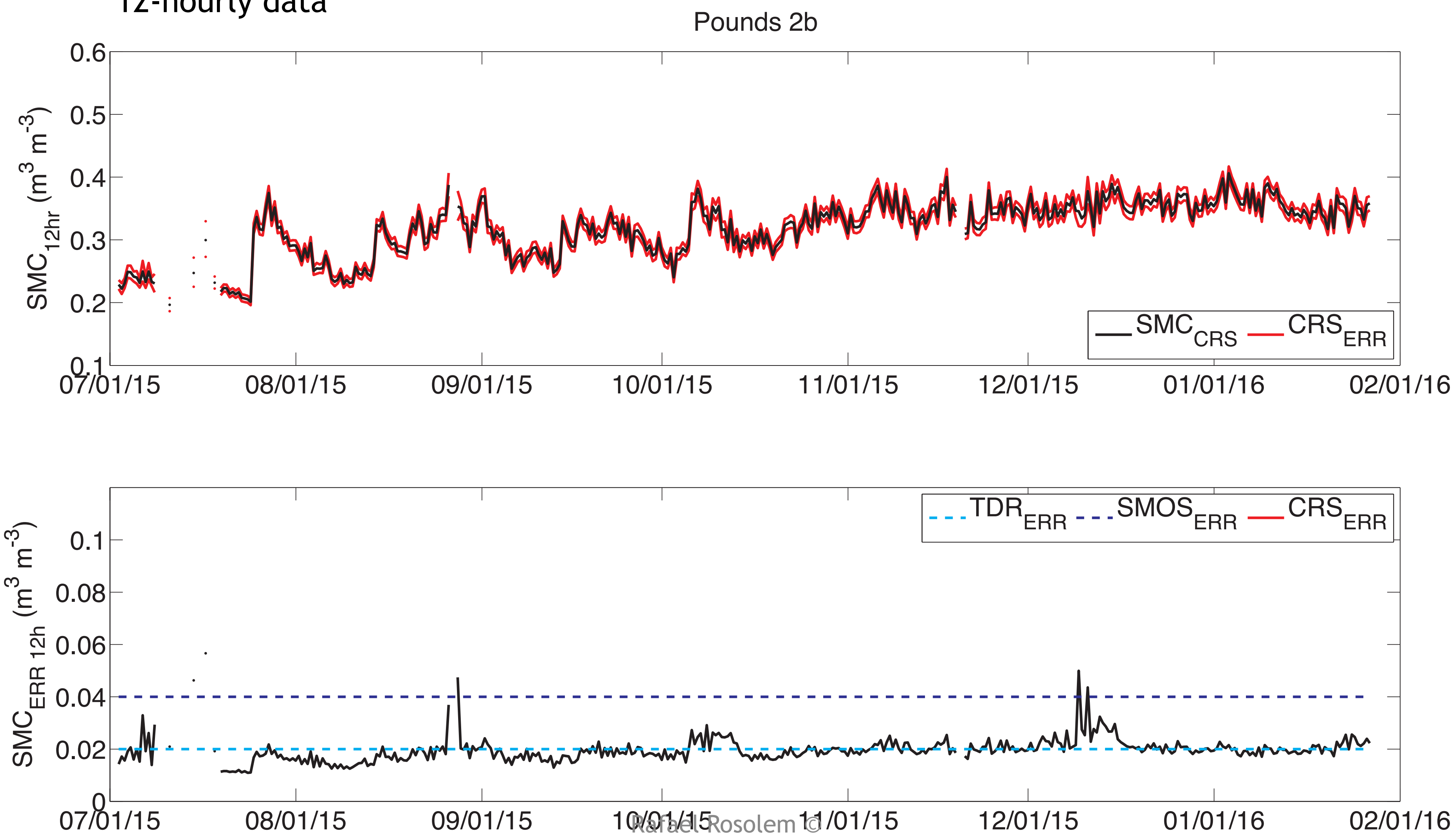
Example: Sheepdrove Farm (UK)

6-hourly data



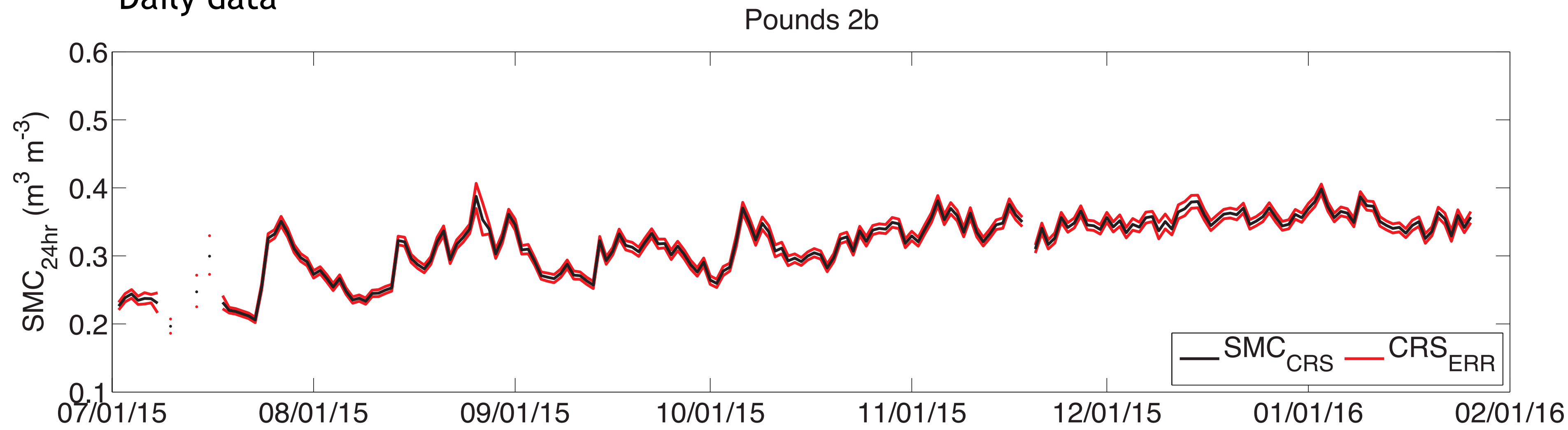
Example: Sheepdrove Farm (UK)

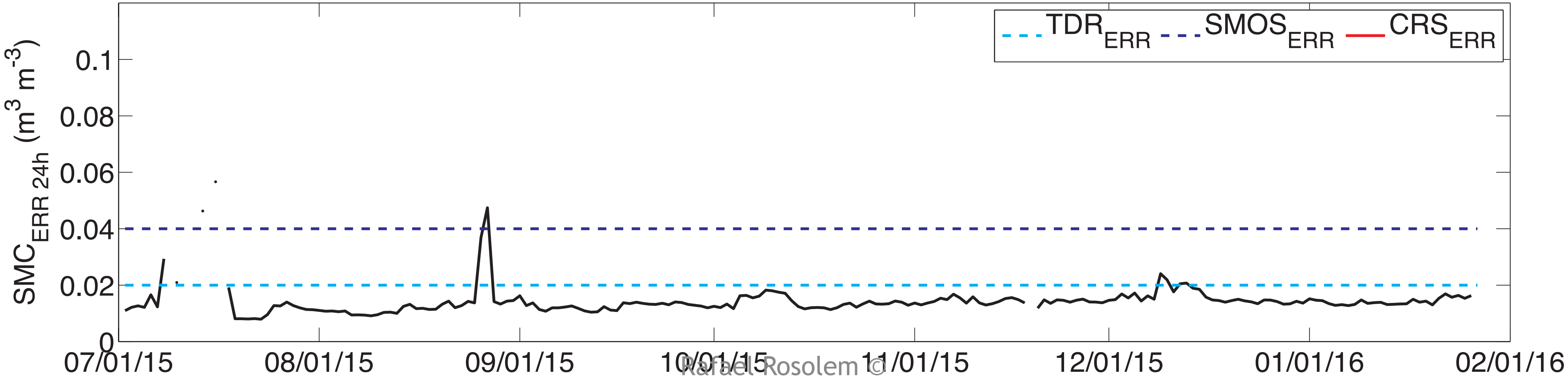
12-hourly data



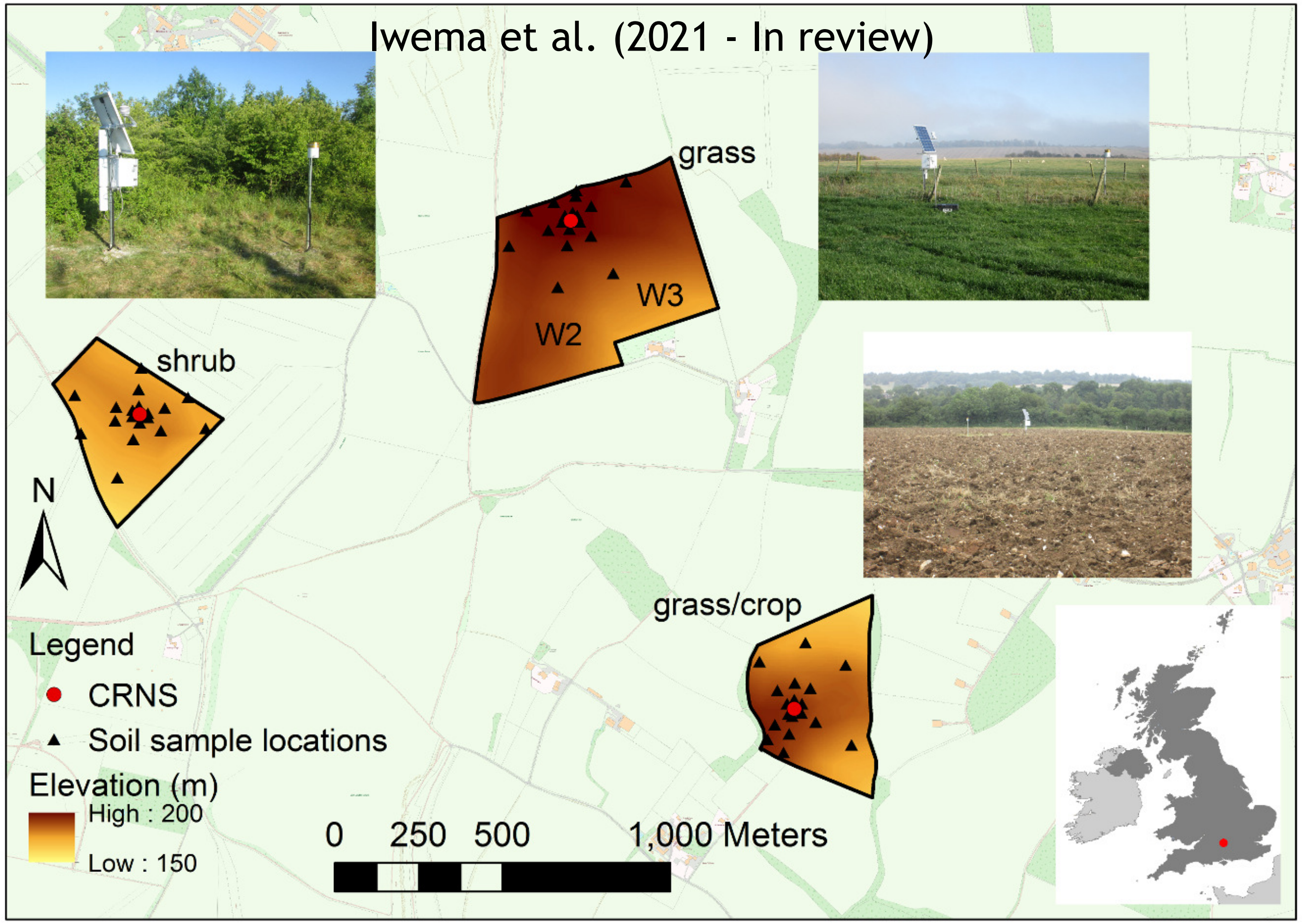
Example: Sheepdrove Farm (UK)

Daily data

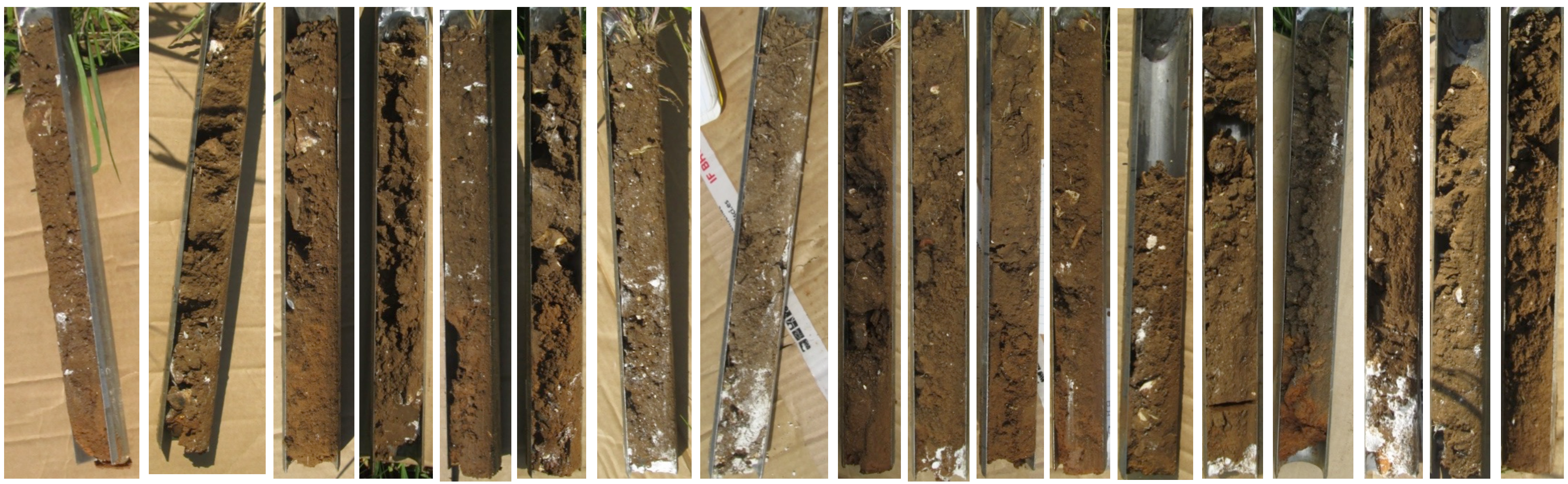




Applying proper sensitivity analysis in a humid region



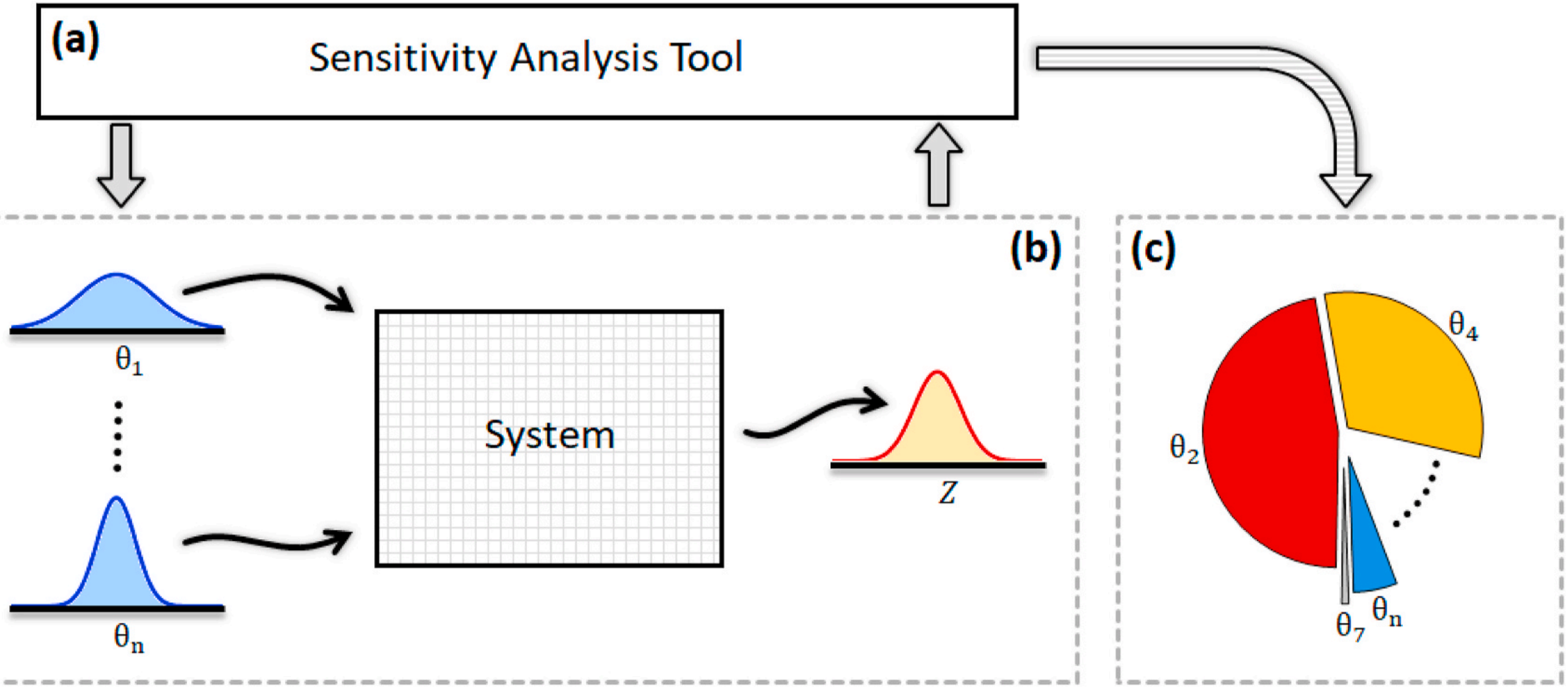
Grass/crop site: Pounds 2b



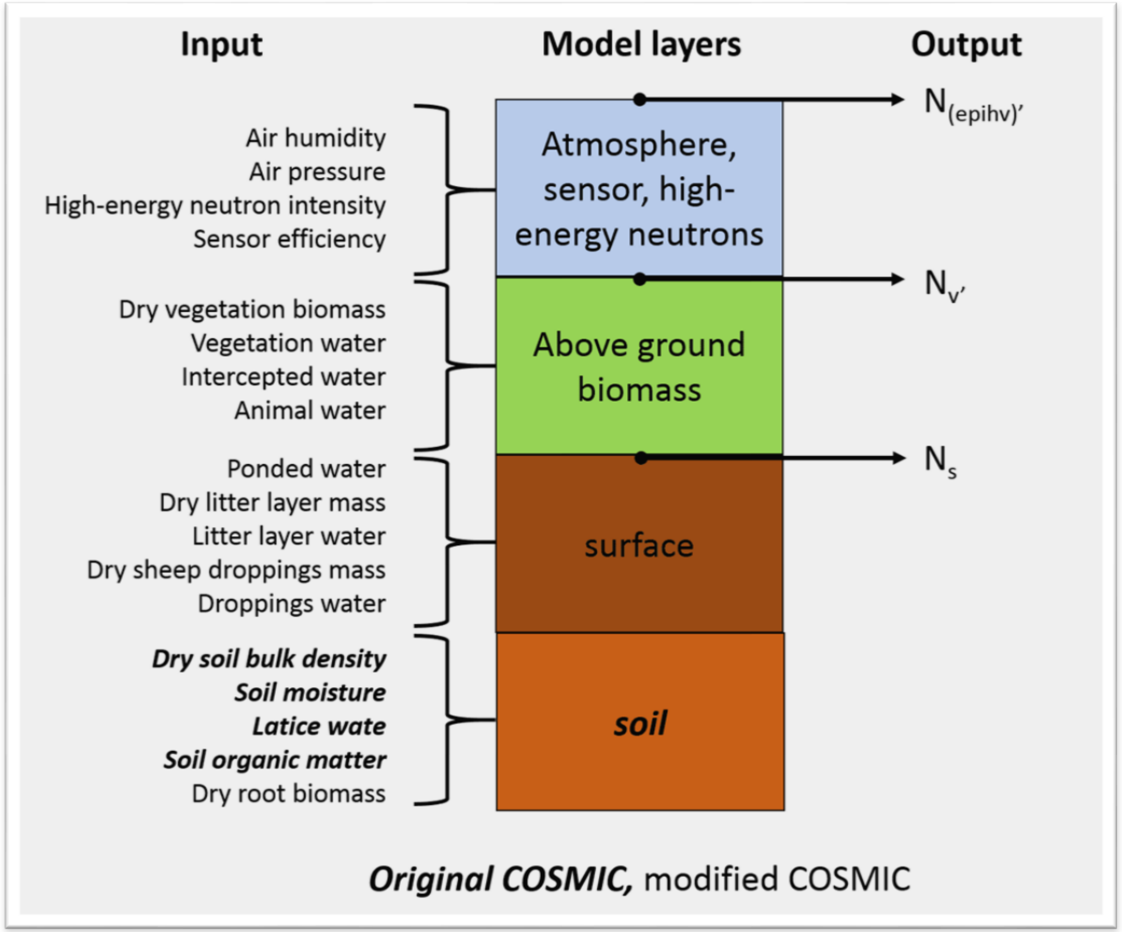
Grass site: W2/W3

Shrub site: Melville Woods

Sensitivity analysis can help identify which factors contribute most/least to the process of interest



We use a simple analytical model to account for all possible factors affecting the neutron signal and soil moisture estimates



Input | **Model layers** | **Output**

Air humidity
Air pressure
High-energy neutron intensity
Sensor efficiency

Atmosphere, sensor, high-energy neutrons → $N_{(epihv)'}$

Dry vegetation biomass
Vegetation water
Intercepted water
Animal water

Above ground biomass → $N_{v'}$

Ponded water
Dry litter layer mass
Litter layer water
Dry sheep droppings mass
Droppings water

surface → N_s

Dry soil bulk density
Soil moisture
Latice wate
Soil organic matter
Dry root biomass

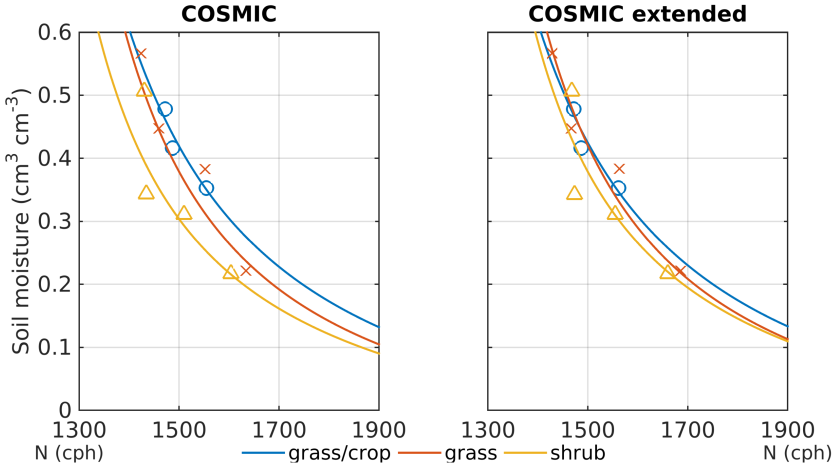
soil

Original COSMIC, modified COSMIC

Modified version of the COSmic-ray Interaction Code (COSMIC) to include additional factors

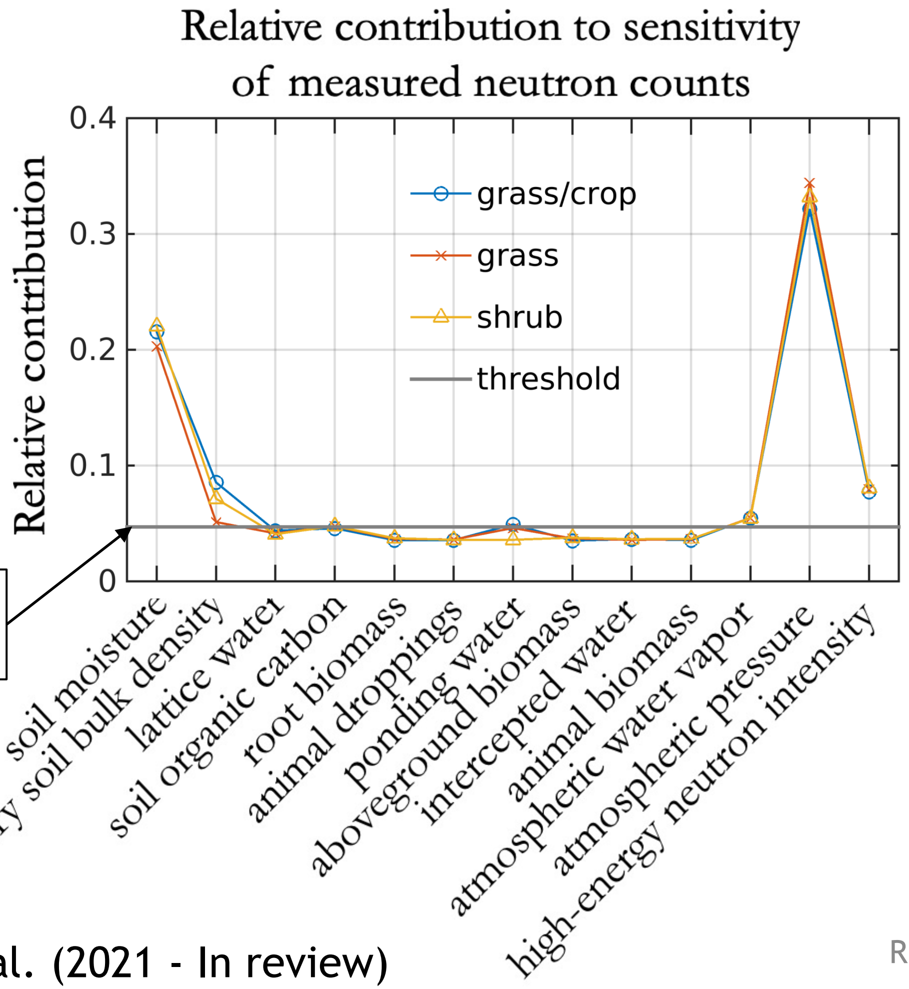
Limited number of factors in the original COSMIC model (highlighted in bold)

Note: COSMIC will be introduced properly in our last lecture

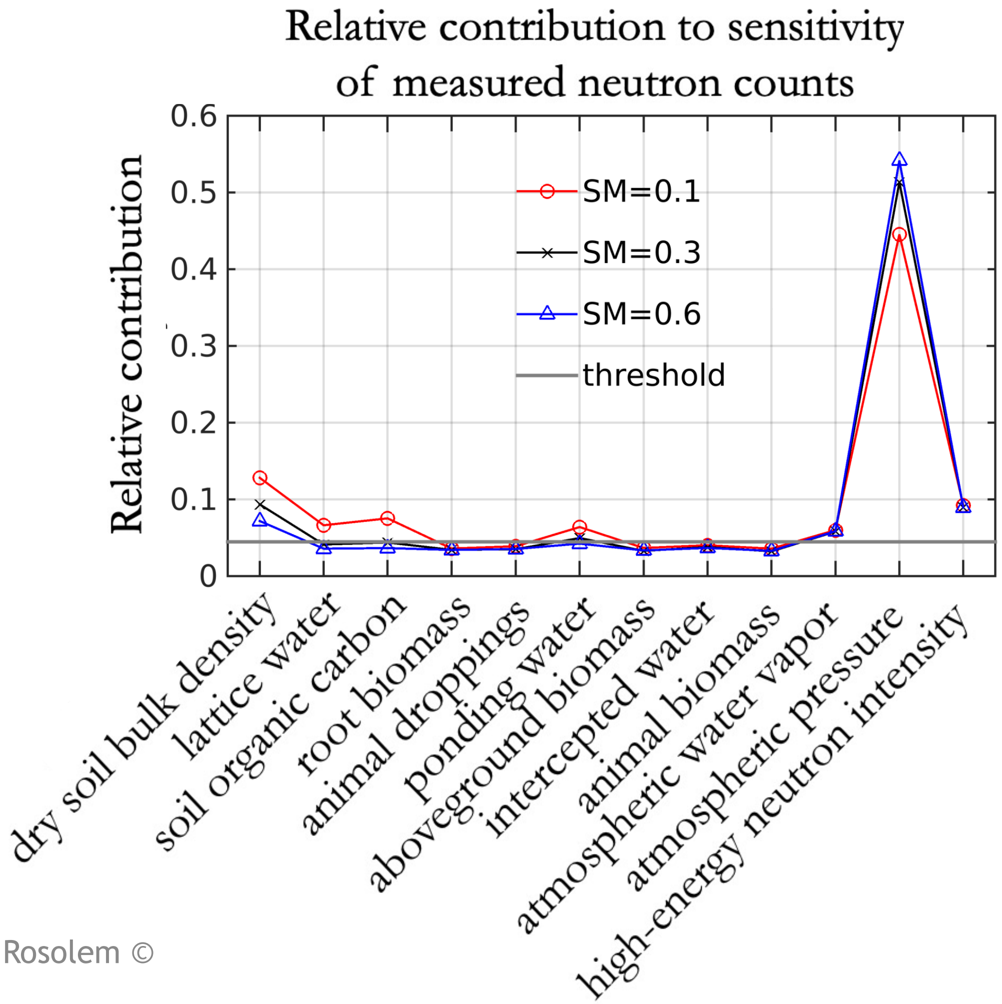


Iwema et al. (2021 - In review)

How does each factor influence the neutron signal?

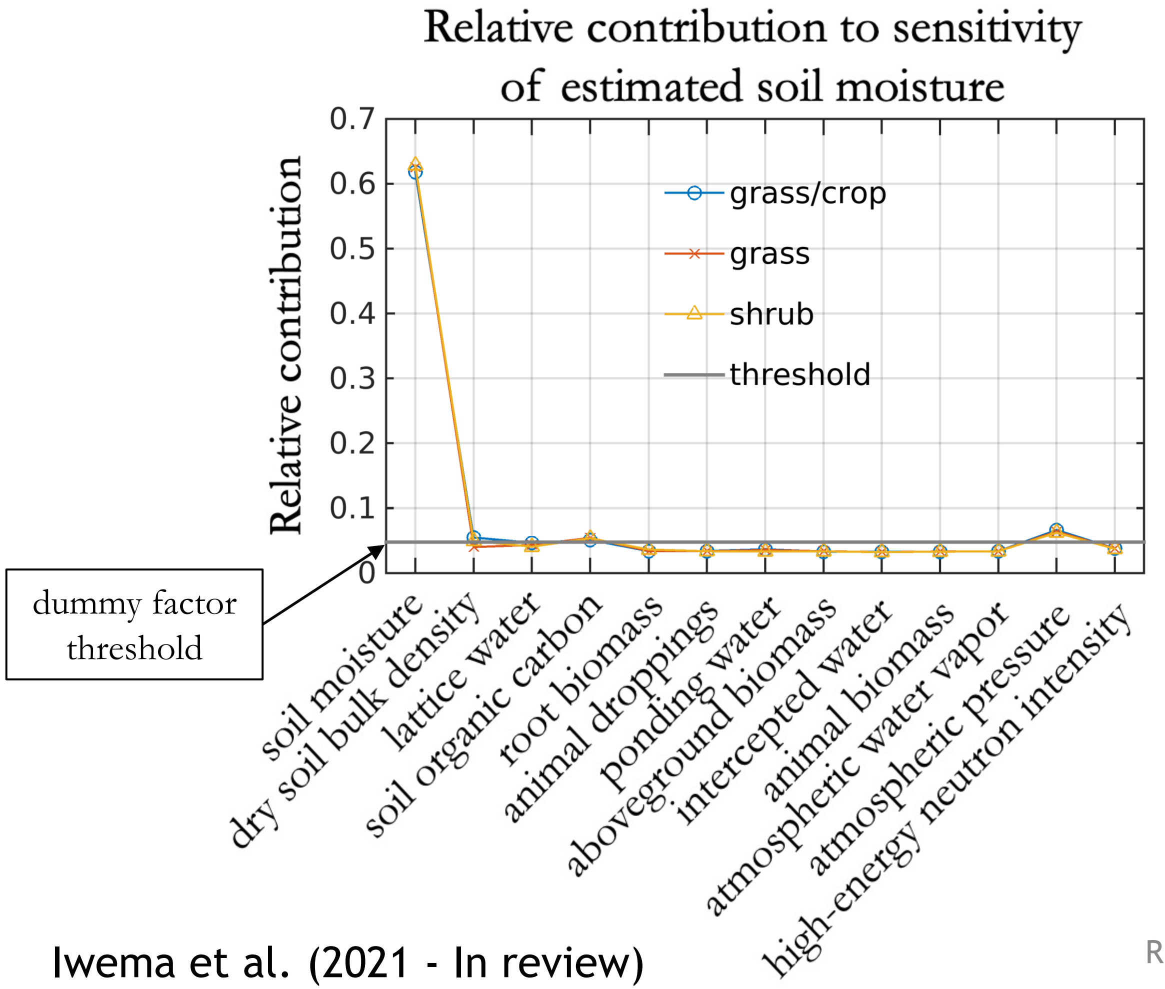


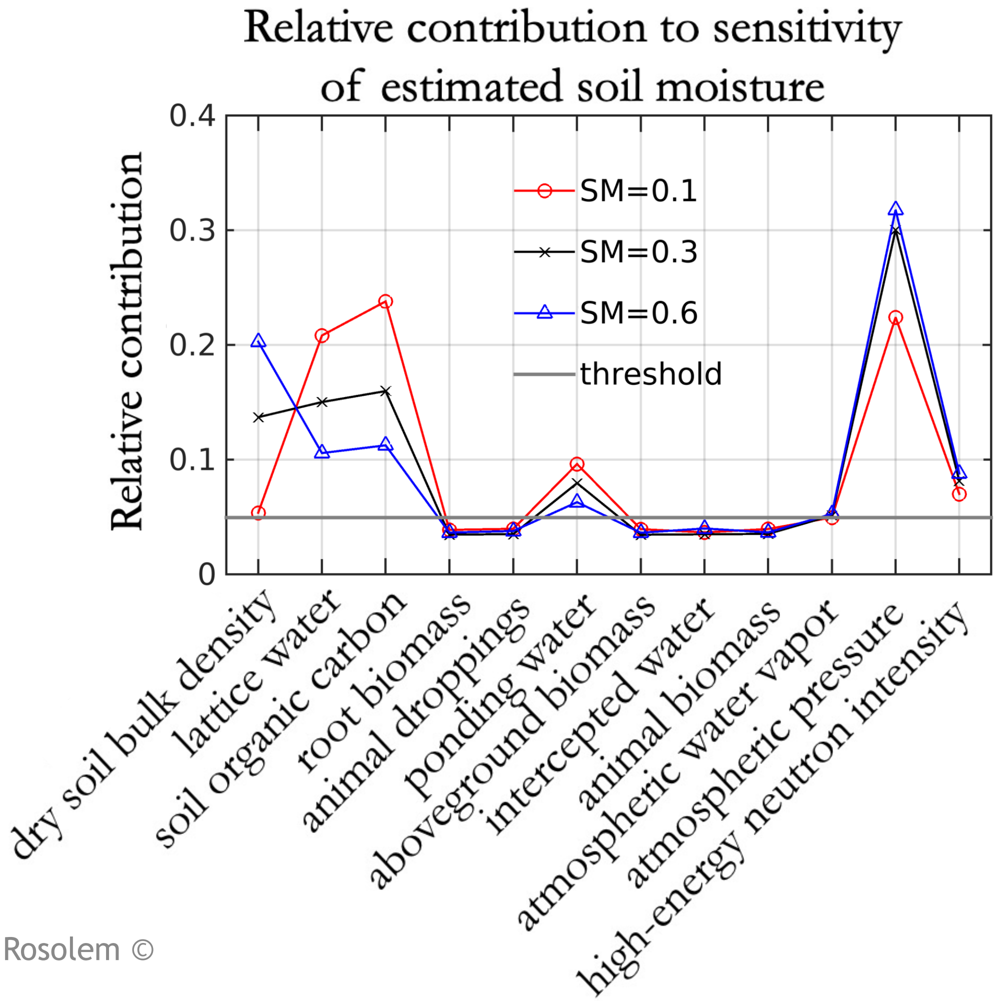
dummy factor threshold



Iwema et al. (2021 - In review)

How is that propagated to the derived soil moisture estimation?





Iwema et al. (2021 - In review)

Final recommendations

- Whenever possible… measure/sample everything → residual uncertainty
- Consider multi-day calibration especially if site has strong seasonality (if unable, consider sampling on a day with average conditions)
- Uncertainty can be further reduced with longer integration time at the cost of temporal resolution (e.g., daily versus hourly)
- Neutron signal overwhelmingly responds to changes in pressure, but luckily this can be easily corrected for (with some impacts from in situ soil moisture and dry soil bulk density)
- Derived product is by far a result of soil moisture variations (as a result of effectiveness of corrections) but dry soil bulk density, lattice water, and soil organic carbon are likely to affect the estimates

References

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Also, please have a look of Chapter 2 from Iwema (2017; PhD Thesis), provided with the lecture, for a comprehensive review on the measurement steps related to the cosmic-ray neutron sensing technology.