Joint ICTP-IAEA Workshop on the Use of Cosmic Ray Neutron Sensor for Soil Moisture Management and Validation of Remote Sensing Soil Moisture Maps

10 May 2021 - 19 May 2021, virtual meeting

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

Lecture 3

Added value of combining CRNS and point scale soil moisture

Ass.Prof. Gabriele Baroni

Department of Agricultural and Food Sciences (DISTAL)

Alma Mater Studiorum – University of Bologna

Outline

1. CRNS horizontal and vertical sensitivity
2. Correct for vertical sensitivity
3. Identify additional hydrogen pools
4. Concluding remarks

Do we have to abound point-scale soil moisture?

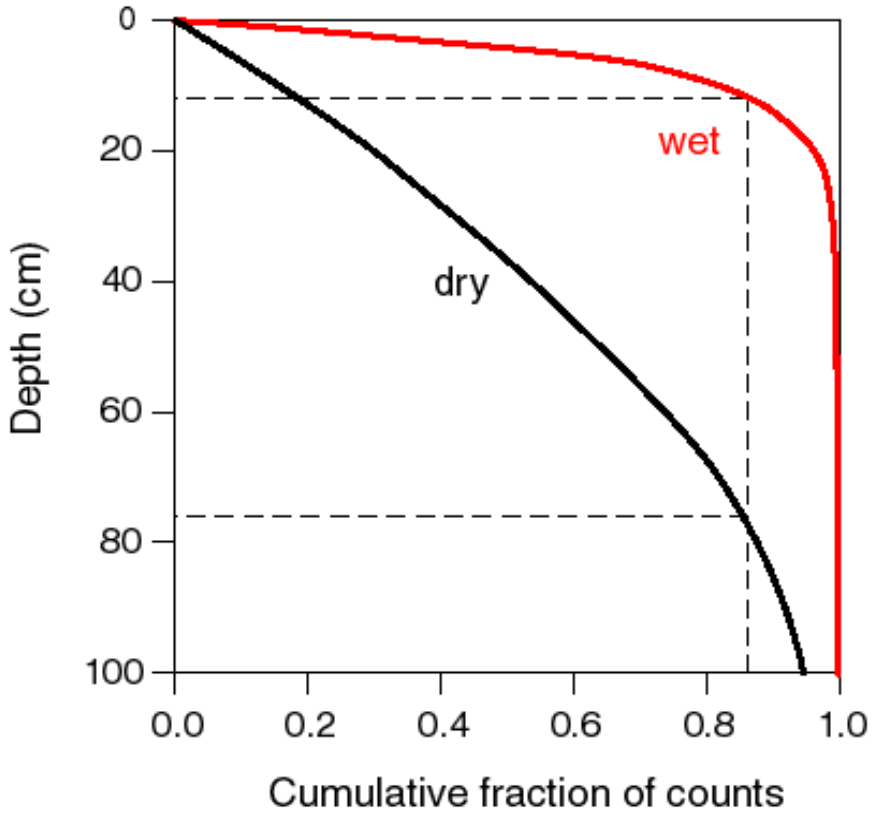
I have started my first lecture explaining my motivation to move from point scale soil moisture to CRNS method

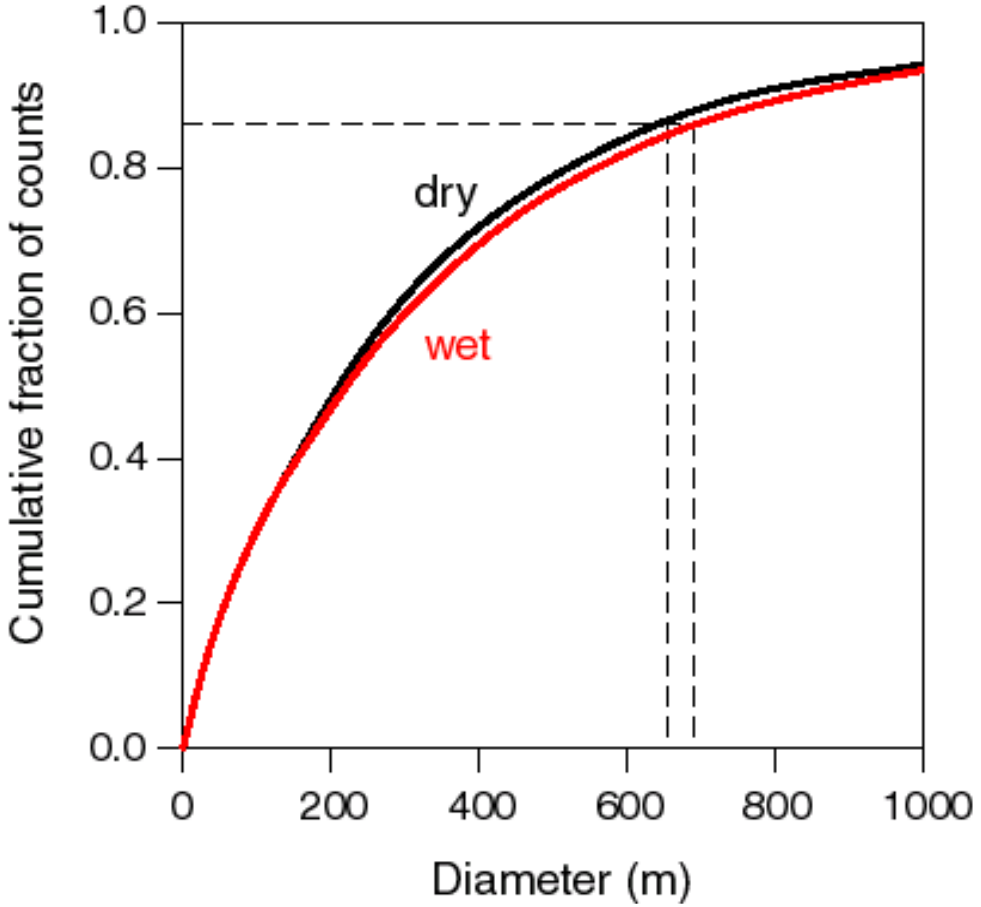
I'm my self still skeptical on using single (or few) point scale soil moisture sensors for practical applications, model and remote sensing comparison due to the inherent spatial variability of the soil-plant systems but also as affected by agricultural practices

But what about combining?

CRNS horizontal and vertical sensitivity

Presentation from T.Franz



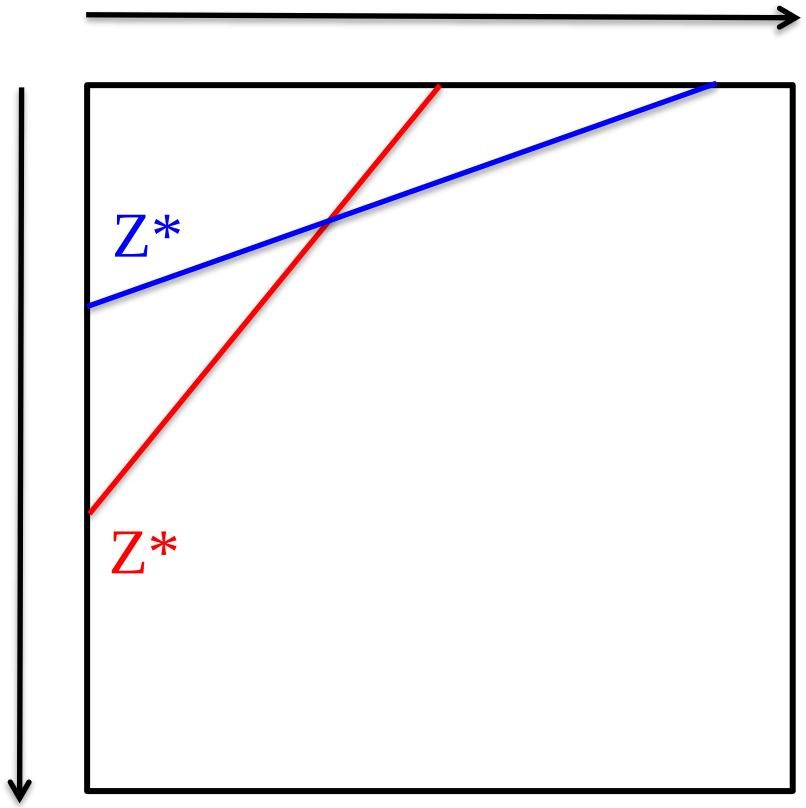


Zreda et al., 2008

CRNS horizontal and vertical sensitivity

$$z^* = \frac{5.8}{\frac{r_{bd}}{r_w}(t + SOC) + q + 0.0829}$$

Presentation from T.Franz



r_{bd} = dry bulk density of soil (g/cm^3)

t = gravimetric weight fraction of lattice water (g/g)

SOC = gravimetric weight fraction of soil organic carbon (g/g)

θ = volumetric water content (cm^3/cm^3)

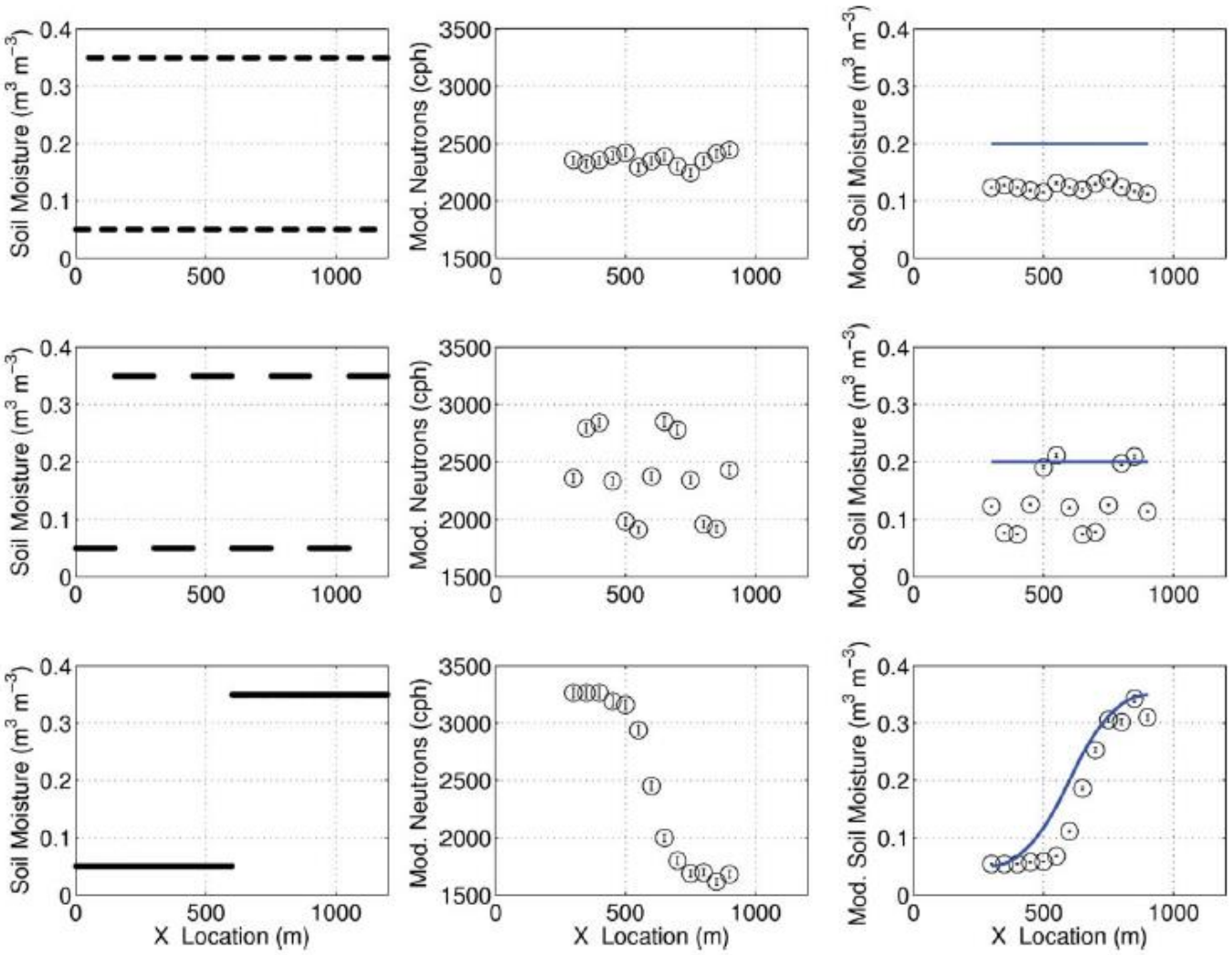
z* = effective sensor depth (cm)

Note: Coefficients 5.8 and 0.0829 derived using MCNPx*

Franz et al. (2012a)

$$wt(z) = \theta\left(1 - \frac{z}{z^*}\right) \quad 0 \le wt \le z^*$$

CRNS horizontal and vertical sensitivity

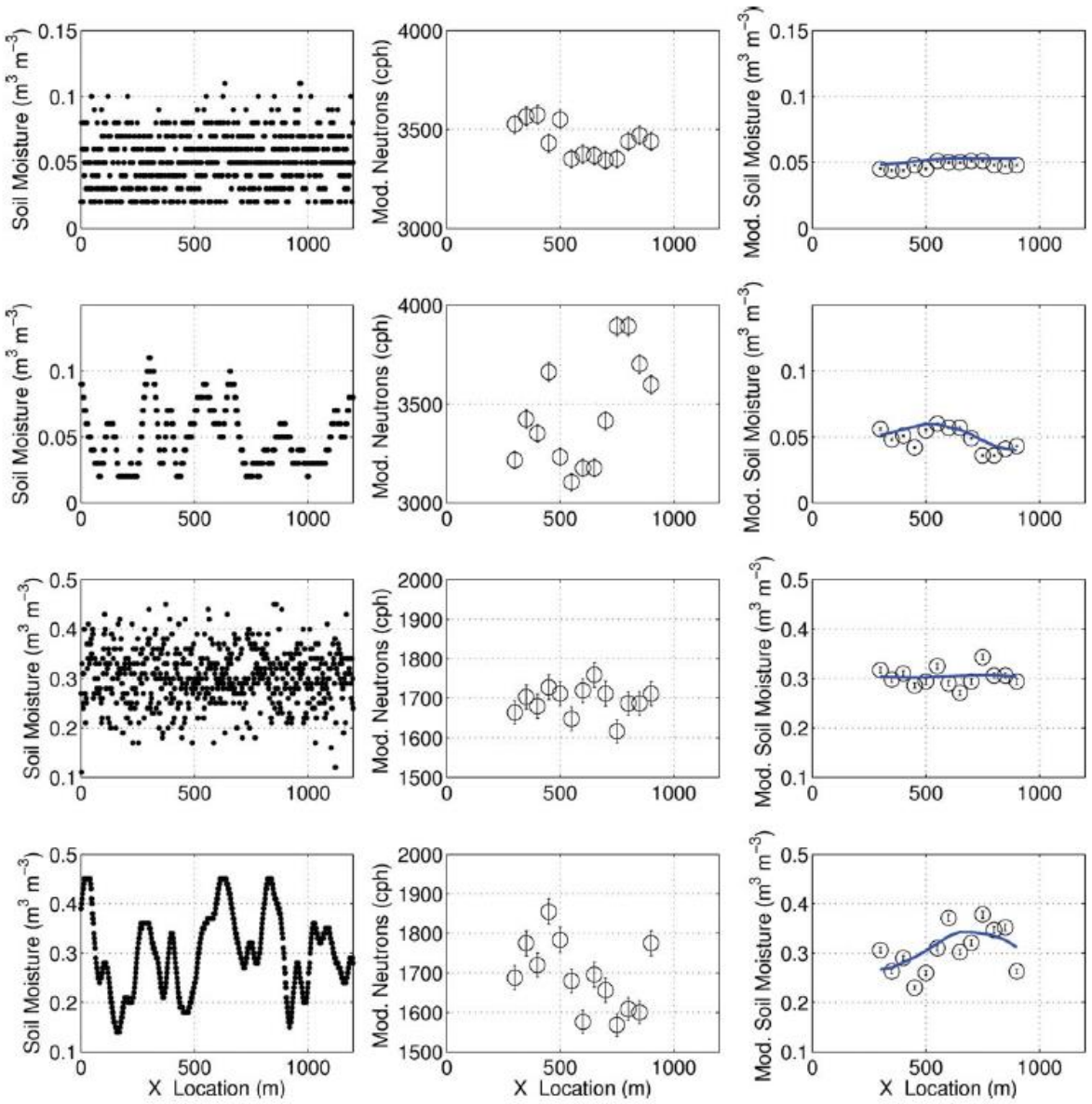


Franz, T. E., M. Zreda, T. P. A. Ferre, and R. Rosolem. "An Assessment of the Effect of Horizontal Soil Moisture Heterogeneity on the Area-Average Measurement of Cosmic-Ray Neutrons." *Water Resources Research* 49, no. 10 (October 2013): 6450–58. https://doi.org/10.1002/wrcr.20530.

- Hypothetical cases of binary wet and dry stripes of varying length (left)
- Modelled neutrons (center)
- Estimated soil moisture (right)

Mostly sensitive to relatively large spatial patterns within the footprint: Lakes, Roads, stripes

CRNS horizontal and vertical sensitivity



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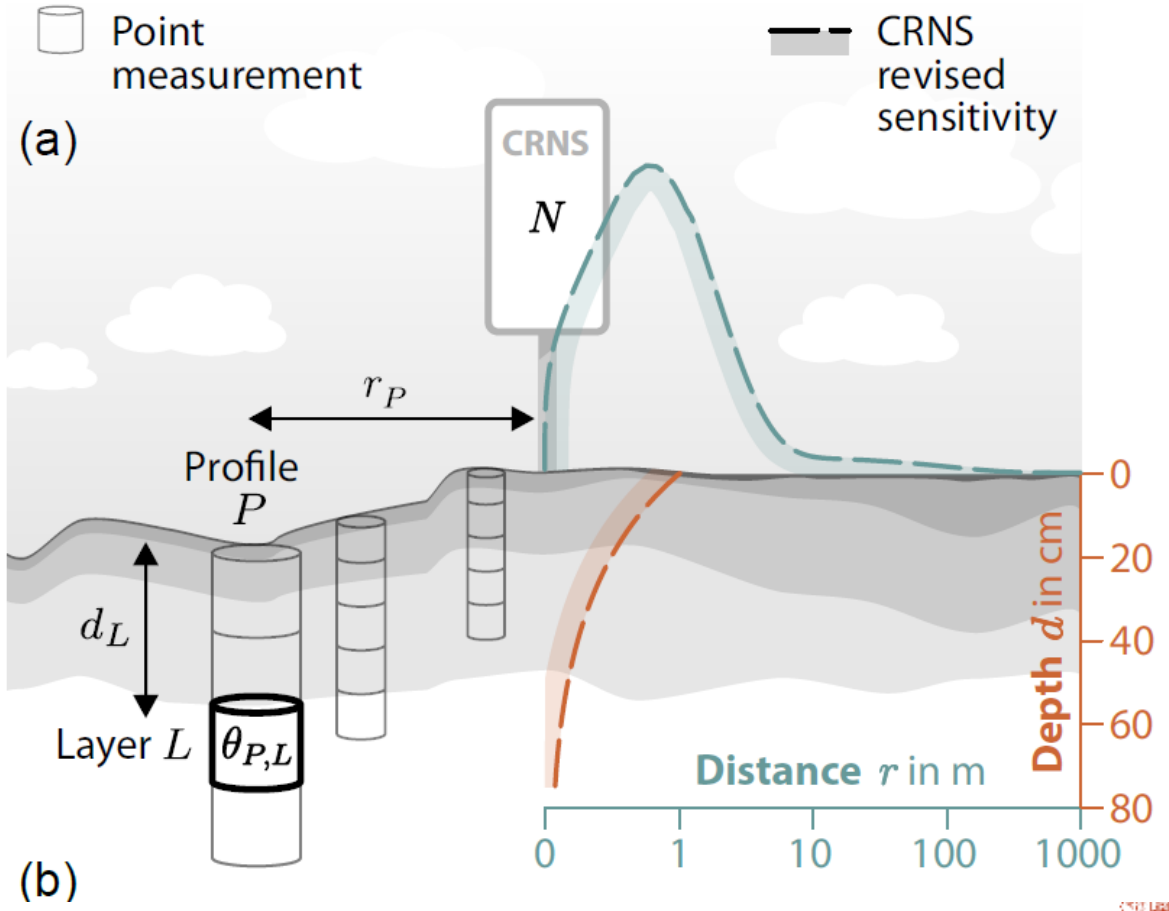
- Hypothetical cases of binary wet and dry stripes of varying length (left)
- Modelled neutrons (center)
- Estimated soil moisture (right)

Mostly sensitive to relatively large spatial patterns within the footprint: Lakes, Roads, stripes

CRNS horizontal and vertical sensitivity

It has been shown that detected neutrons are much more affected by upper soil layer and short distance from the detector

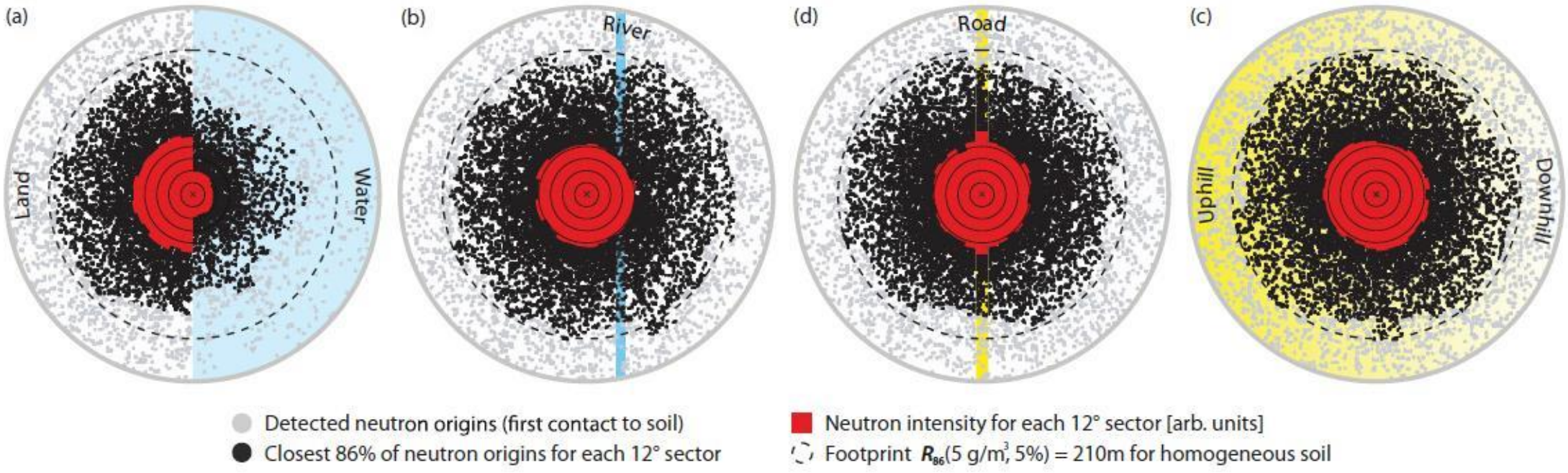
updated by Köhli et al. 2015 and by By Schrön et al 2017



Sensitivity analysis to understand its importance

Spatial sensitivity: mostly sensitive to relatively large spatial patterns within the footprint: Lakes, Roads, stripes

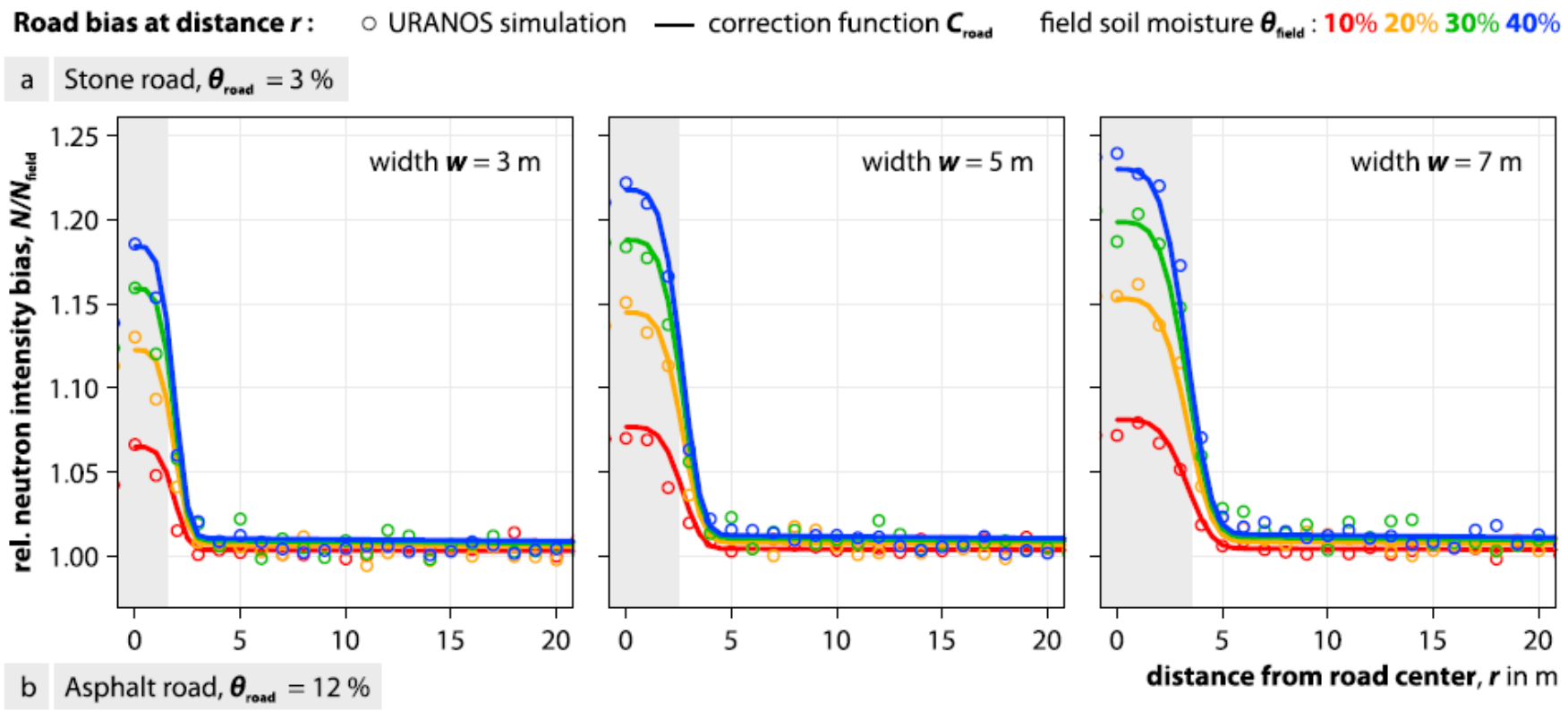
From Köhli et al. (2015)



Sensitivity analysis to understand its importance

Spatial sensitivity: mostly sensitive to relatively large spatial patterns within the footprint: Lakes, Roads, stripes

From Schrön et al., 2018



Sensitivity analysis to understand its importance

Spatial sensitivity: not simple to correct this effect **(bias)** but to some extend can be handle:

- by defining the location where to install
- Or to calculate the contributions of the different spatial patterns

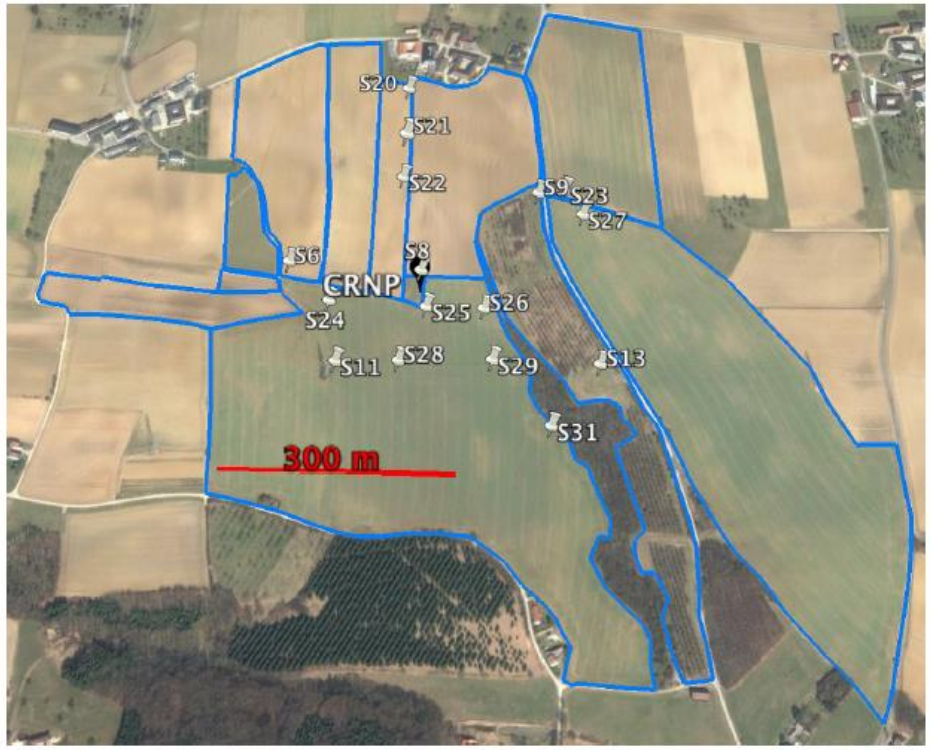


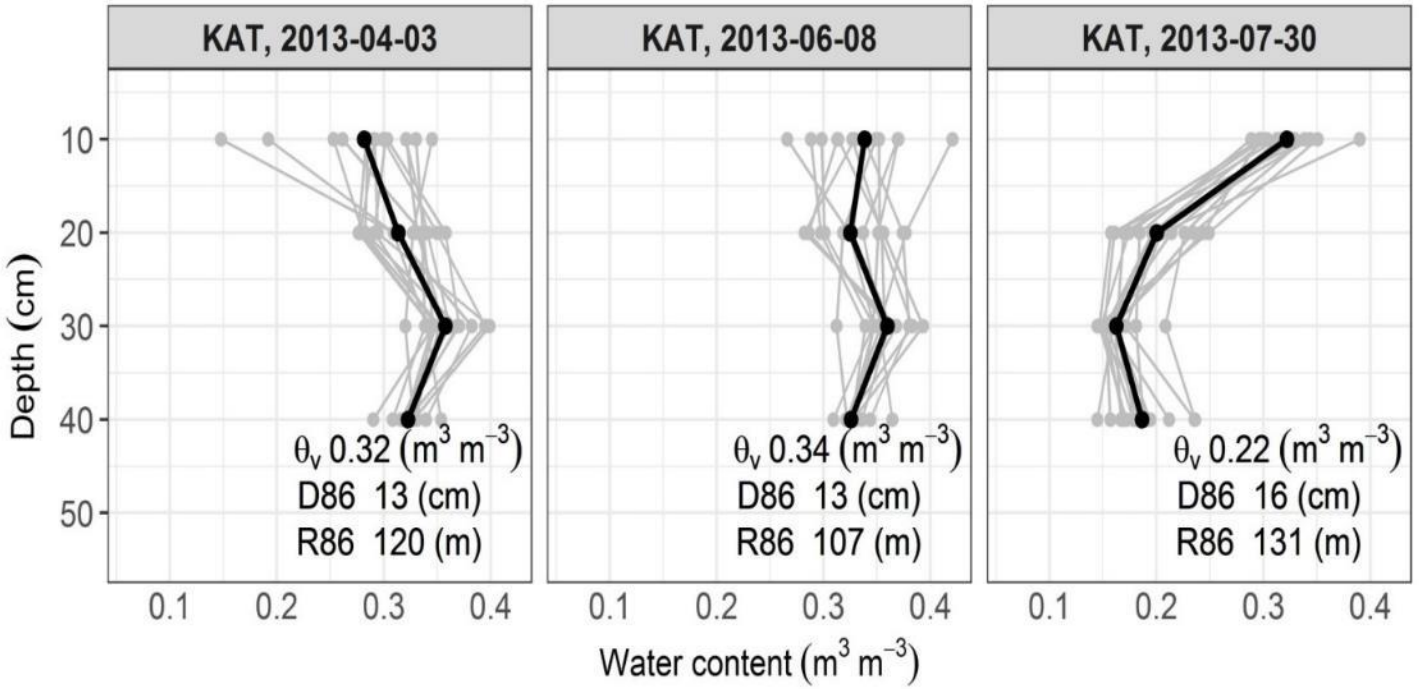
Fig.3.1. Location of 16 sites for soil moisture profiles (sensor measurement depths at 0-5 cm, 5-10 cm, 15-20 cm, and 45-50 cm) within the radial CRNS footprint[1].

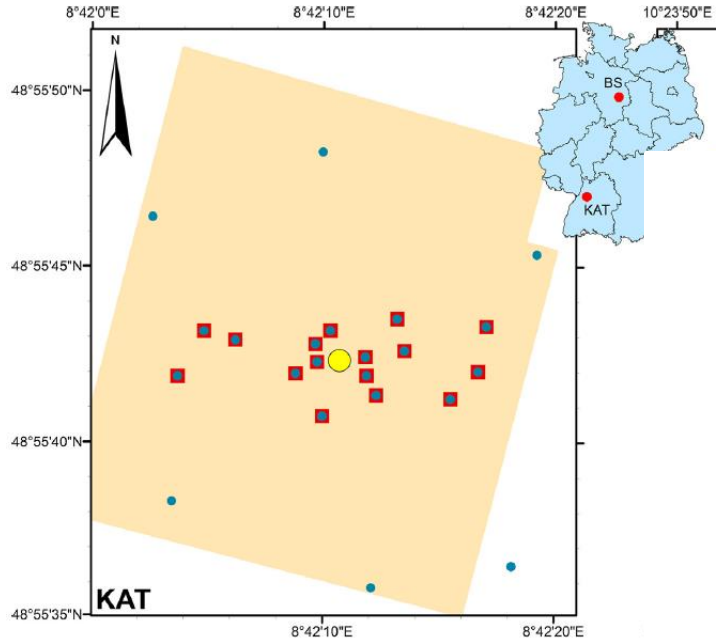
IAEA. *Cosmic Ray Neutron Sensing: Use, Calibration and Validation for Soil Moisture Estimation*. TECDOC Series 1809. Vienna: INTERNATIONAL ATOMIC ENERGY AGENCY, 2017. https://www.iaea.org/publications/11097/cosmic-ray-neutron-sensing-use-calibration-and-validation-for-soil-moisture-estimation.

Sensitivity analysis to understand its importance

Vertical sensitivity

In each date, soil moisture based on CRNS = 34%





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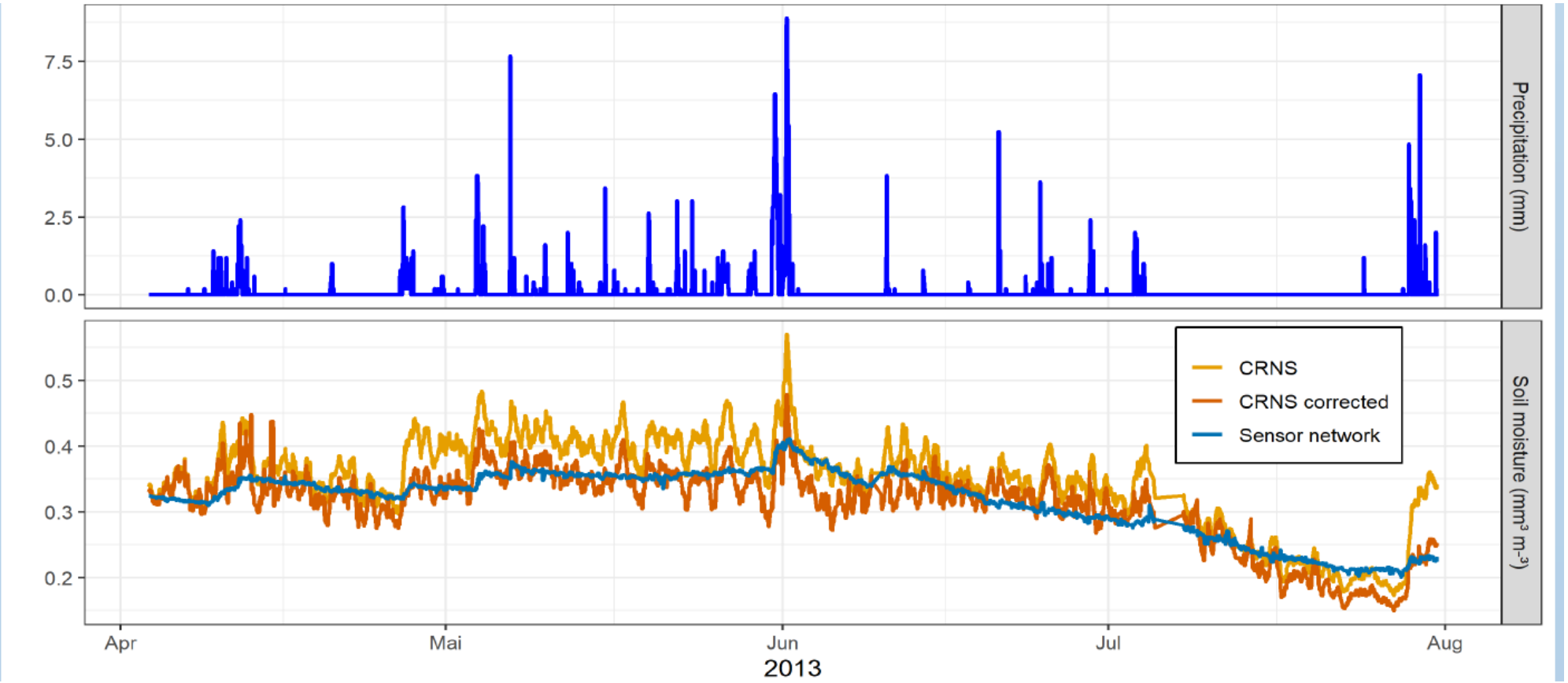
Correction to account for vertical sensitivity

Baroni, G., L. M. Scheiffele, M. Schrön, J. Ingwersen, and S. E. Oswald. "Uncertainty, Sensitivity and Improvements in Soil Moisture Estimation with Cosmic-Ray Neutron Sensing." *Journal of Hydrology* 564 (September 1, 2018): 873–87. https://doi.org/10.1016/j.jhydrol.2018.07.053.

1. average θ_p and weighted-average $\theta_{p(wt)}$ soil moisture in one point location p is calculated
2. the weighting correction factor f_{wt} is calculated as: $f_{wt} = \theta_p/\theta_{p(wt)}$
3. this factor is used to correct CRNS soil moisture as: $\theta_{CRNS(non\text{-}wt)} = \theta_{CRNS} f_{wt}$
4. finally, average LW and W_{SOC} are subtracted to obtain the corrected volumetric soil moisture estimated by CRNS as $\theta_{CRNS(v)} = \theta_{CRNS(non\text{-}wt)} - (LW + W_{SOC})$

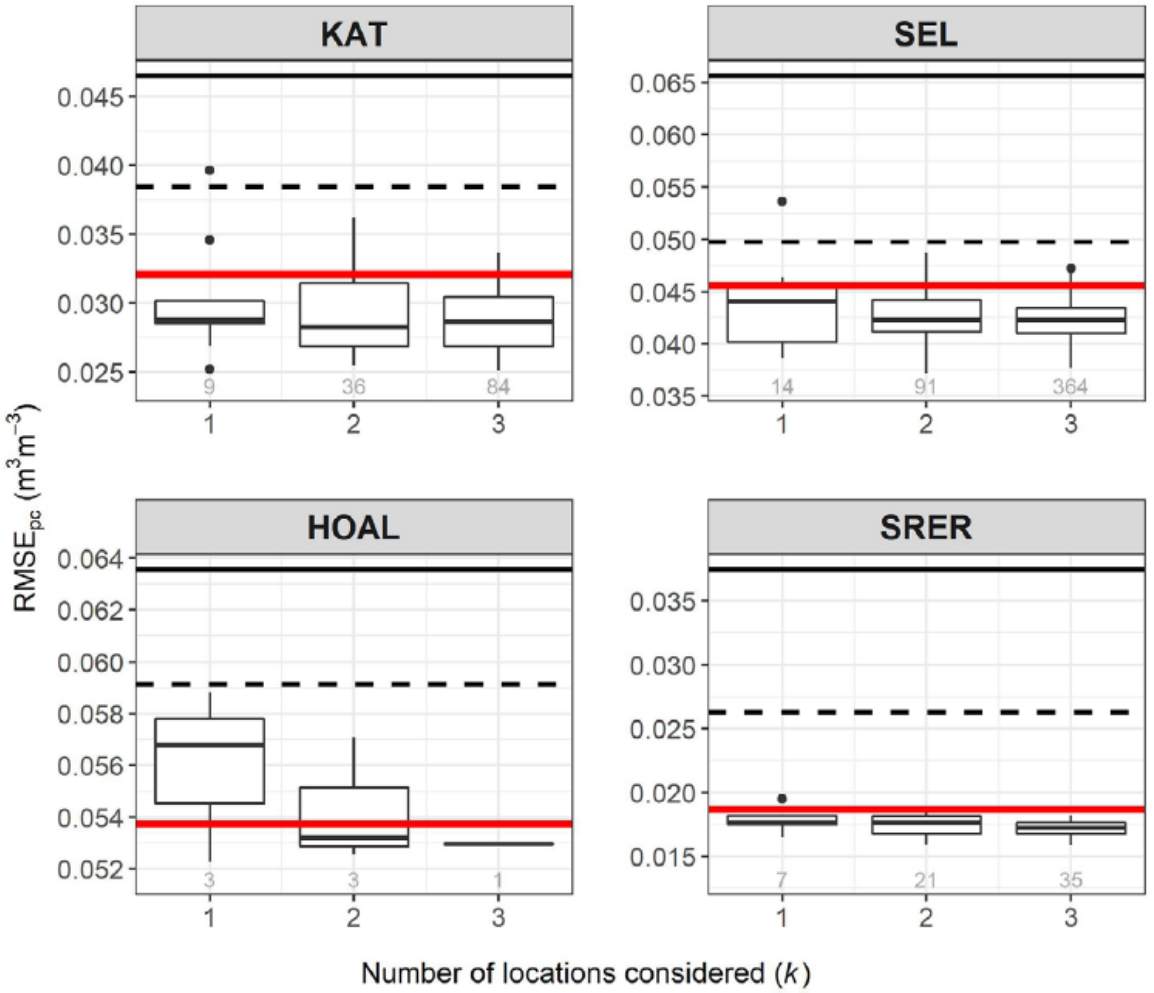
Correction to account for vertical sensitivity

Baroni, G., L. M. Scheiffele, M. Schrön, J. Ingwersen, and S. E. Oswald. "Uncertainty, Sensitivity and Improvements in Soil Moisture Estimation with Cosmic-Ray Neutron Sensing." *Journal of Hydrology* 564 (September 1, 2018): 873–87. https://doi.org/10.1016/j.jhydrol.2018.07.053.



How many point scale sensors?

FIGURE 6 Results in $RMSE_{pc}$ (profile shape correction performance using the root mean square error [RMSE]) for using one to three locations (k) for the profile shape correction for all field sites (depth $d \leq 50$ cm, radial distance $r < 75$ m for Katharinentaler Hof [KAT], Santa Rita Experimental Range [SRER], and Selhausen [SEL] and $r \leq 100$ m for Hydrological Open Air Laboratory [HOAL]). The black line marks the $RMSE_{base}$ (baseline performance), the dashed line marks the $RMSE_{bias}$ (bias performance), and the red line marks the $RMSE_{ref}$ (reference performance). Numbers below the boxes show the amount of location combinations contained in the boxes



Scheiffele, Lena M., Gabriele Baroni, Trenton E. Franz, Jannis Jakobi, and Sascha E. Oswald. "A Profile Shape Correction to Reduce the Vertical Sensitivity of Cosmic-Ray Neutron Sensing of Soil Moisture." *Vadose Zone Journal* 19, no. 1 (2020): e20083. https://doi.org/10.1002/vzj2.20083.

On the use of combining point-scale and CRNS

Journal of Hydrology 571 (2019) 679–696

Contents lists available at ScienceDirect

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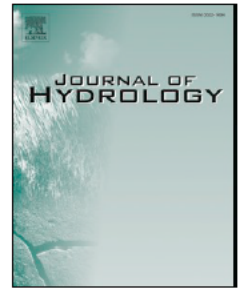


Research papers

Extension of cosmic-ray neutron probe measurement depth for improving field scale root-zone soil moisture estimation by coupling with representative in-situ sensors

Hoang Hai Nguyen, Jaehwan Jeong, Minha Choi*

Environment and Remote Sensing Laboratory, Department of Water Resources, Graduate School of Water Resources, Sungkyunkwan University, Suwon 440-746, Republic of Korea

Combining for disentangling additional hydrogen pools

$$\theta_{CRNS} = f(N, p)$$

Field soil moisture

$$= \theta_{field}$$

N = neutron counts

f = non-linear function

p = parameters

θ_{CRNS} = soil moisture by CRNS

Combining for disentangling additional hydrogen pools

$$\theta_{CRNS} = f(N, p)$$

Field soil moisture

$$= \theta_{field}$$

Second Hydrogen Pools

$$= \theta_{field} \pm \theta_{SHP}$$

N = neutron counts

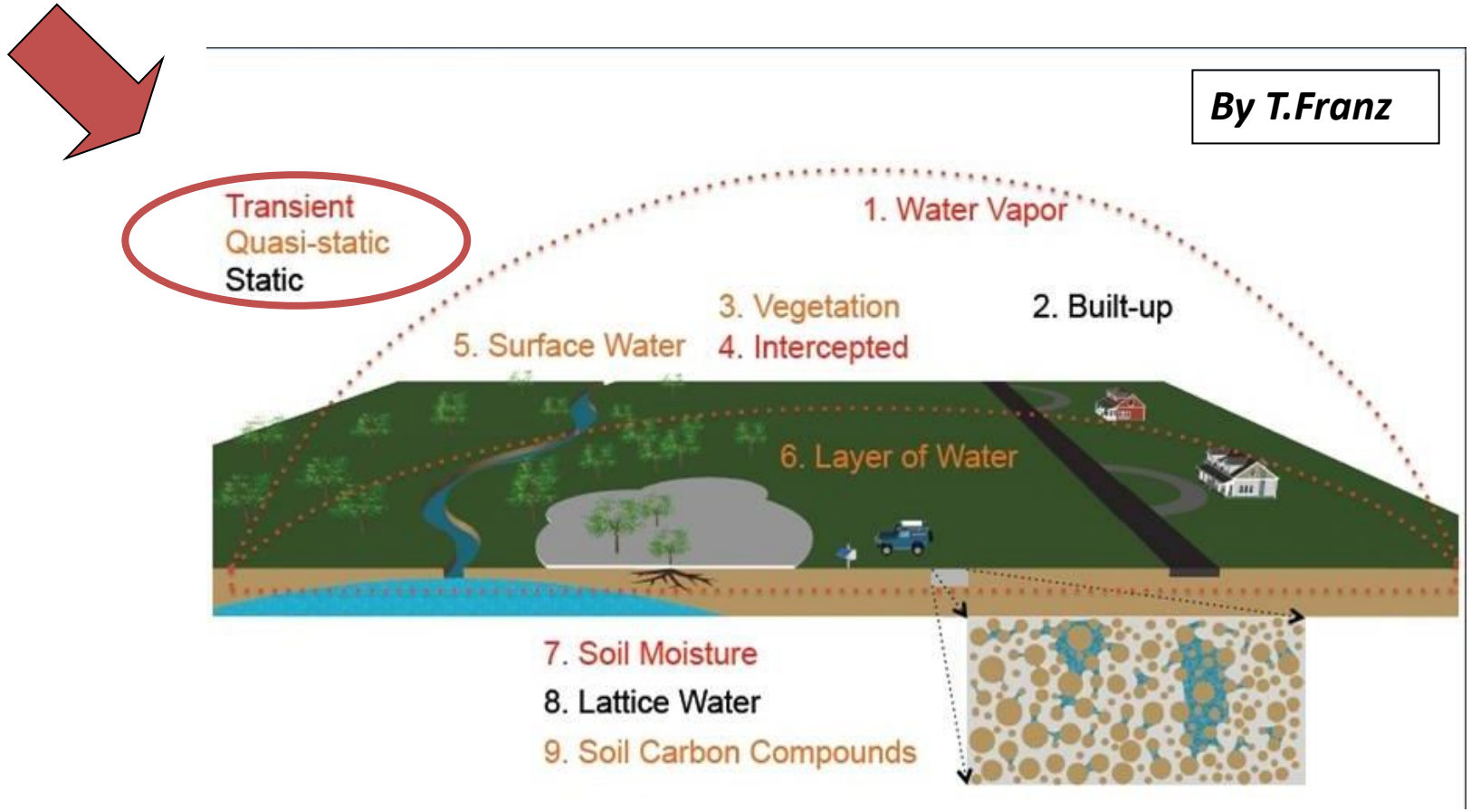
f = non-linear function

p = parameters

θ_{CRNS} = soil moisture by CRNS

θ_{SHP} = soil moisture from secondary hydrogen pool (e.g., biomass)

Secondary hydrogen pools (SHP)



What to do?

Lattice water (LW) and soil organic carbon (SOC) relatively **constant in time**

- to be estimated within the footprint
- but can be simply added or removed

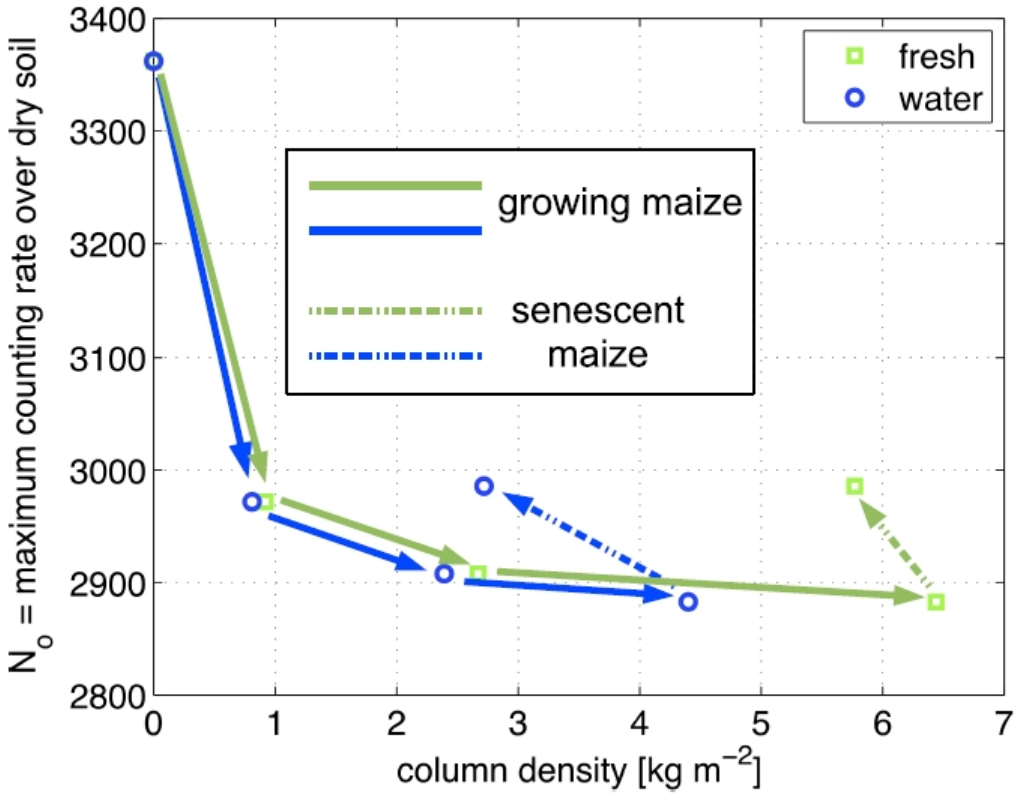
$$\theta_{tot(wt)} = \theta_{v(wt)} + \left(LW_{(wt)} + SOC_{(wt)}\right) \cdot \frac{\rho_b}{\rho_w}$$

But if time varying secondary hydrogen pools (biomass)?

Hornbuckle et al. (2012)

$$\theta_{CRNS} = f(N, p)$$

Correct the parameters N0 by means of biomass measurements



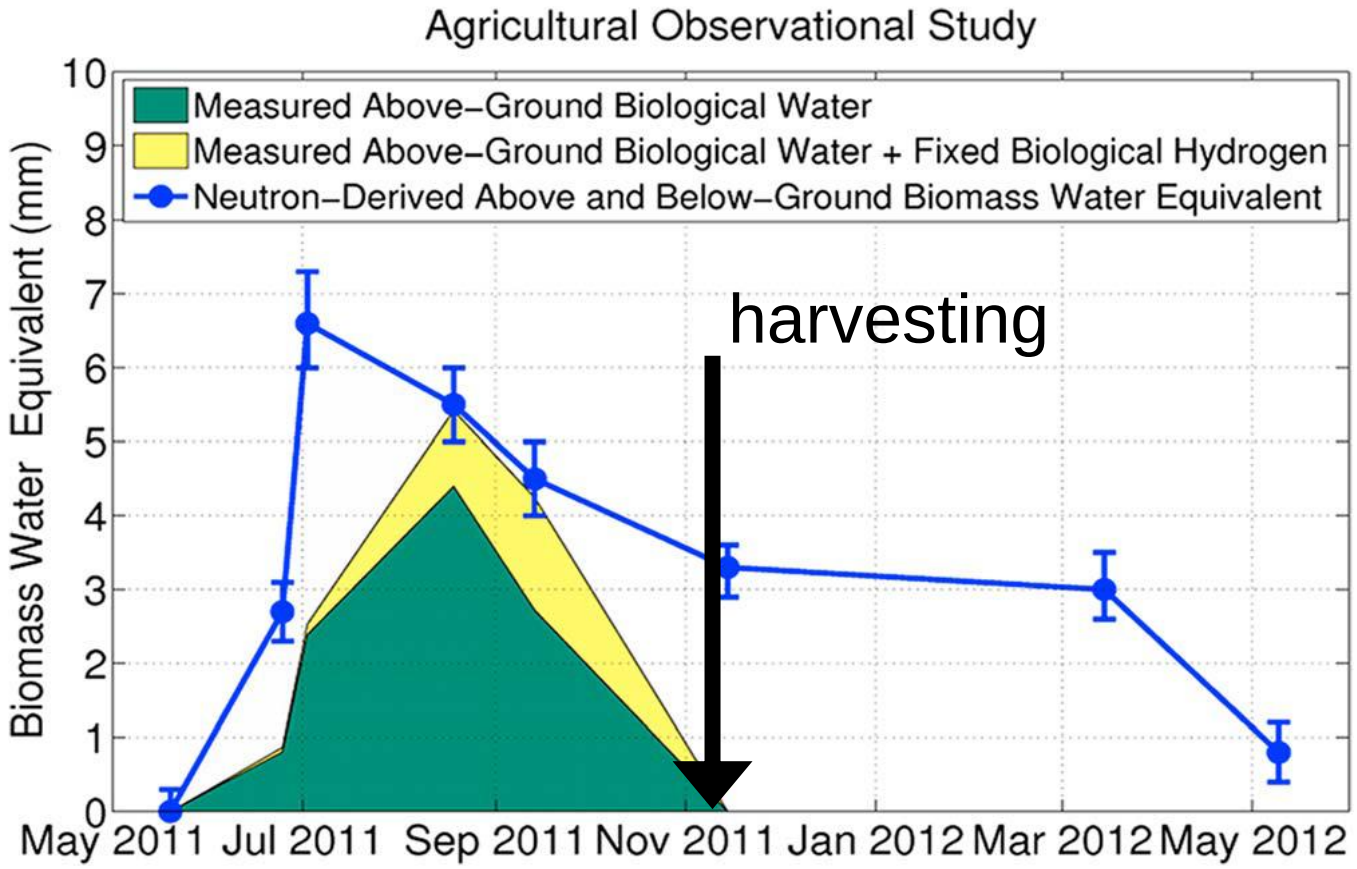
How to measure biomass?

Direct measurements require hard work….

Estimation from proxy data

remote sensing or drones

But what about estimate biomass based on CRNS?



Franz, T. E., M. Zreda, R. Rosolem, and T. P. A. Ferre. "A Universal Calibration Function for Determination of Soil Moisture with Cosmic-Ray Neutrons." *Hydrology and Earth System Sciences* 17, no. 2 (February 1, 2013): 453–60. https://doi.org/10.5194/hess-17-453-2013.

$$\theta_{SHP} = \theta_{CRNS} - \theta_{field}$$

Which limitations?

$$\theta_{CRNS} = \theta_{CRNS_C} \pm \theta_{bio}$$

sampling campaign θ_{sam}	network $\theta_{SoilNet}$
$\theta_{CRNSc} = \theta_{sam}$	$\theta_{CRNSc} = \theta_{SoilNet}$
snapshot in time	Installation??

What else can we do?

A scaling approach based on point-scale observation

Baroni, G., and S. E. Oswald. "A Scaling Approach for the Assessment of Biomass Changes and Rainfall Interception Using Cosmic-Ray Neutron Sensing." *Journal of Hydrology* 525 (June 2015): 264–76. https://doi.org/10.1016/j.jhydrol.2015.03.053.

$$\theta_{CRNSc} = m_i \cdot \theta_i + c_i$$

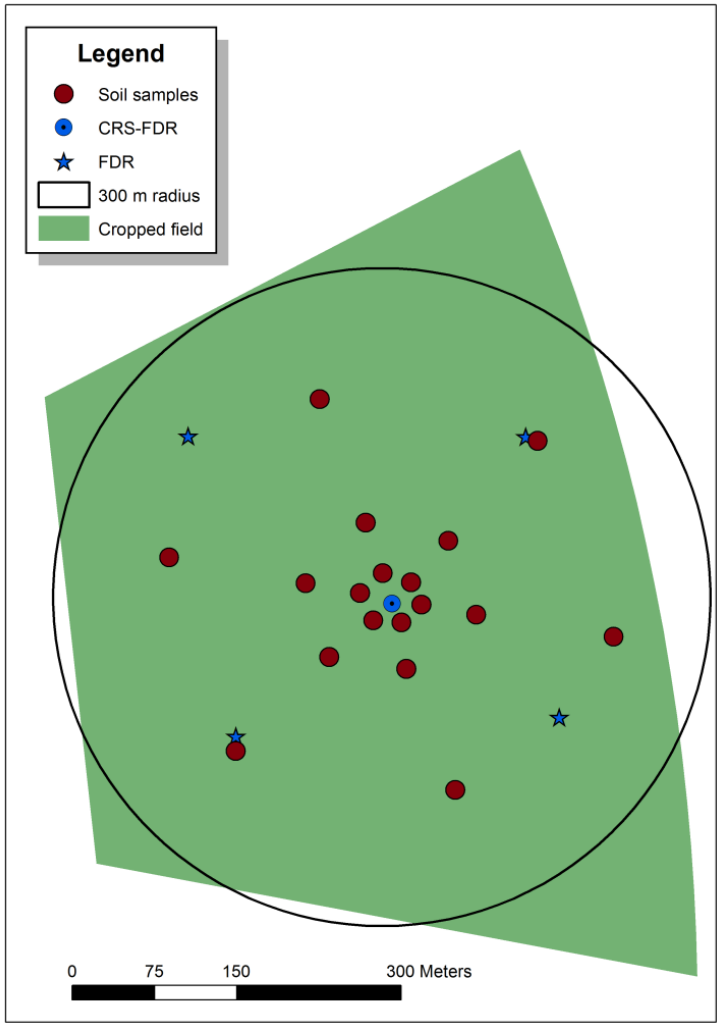
Soil moisture in one position within the field

2013 Maize

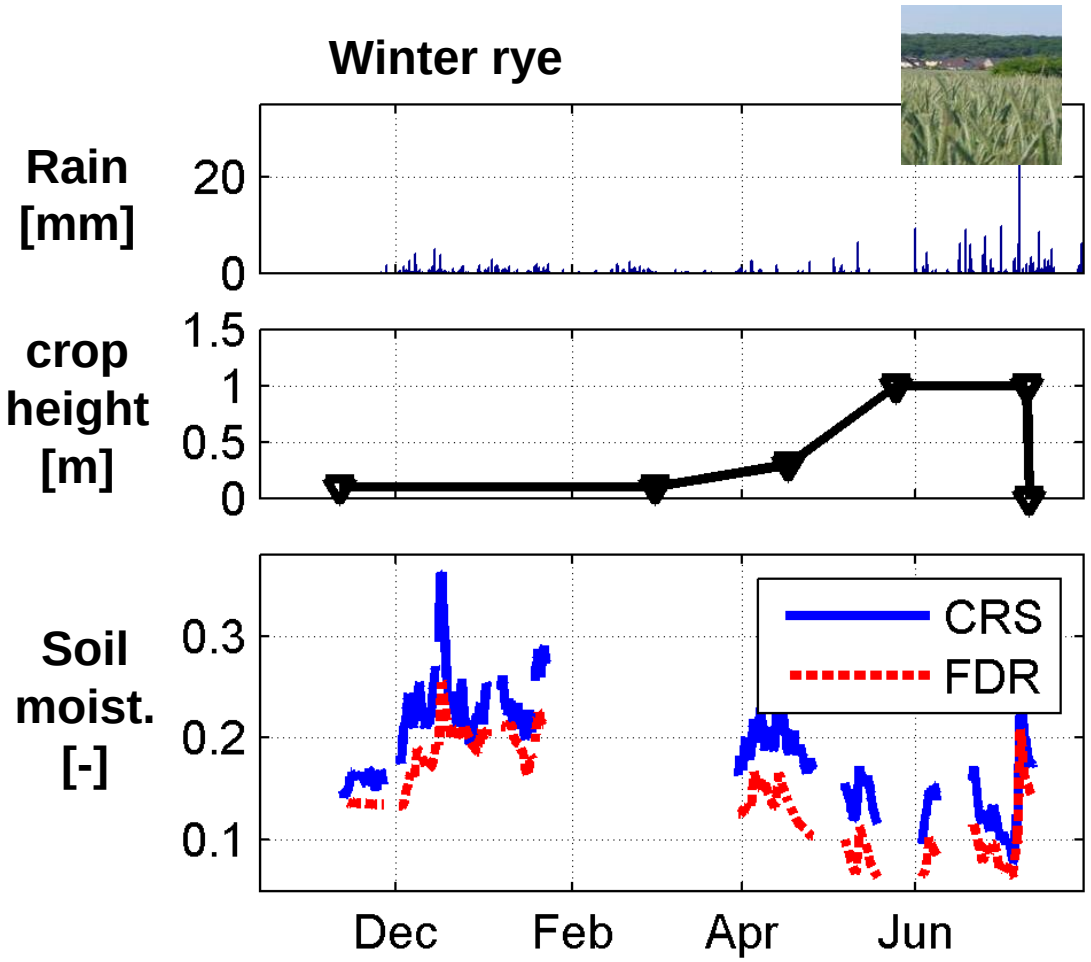
Cosmic-Ray probe

FDR probes

4 soil sampling campaigns

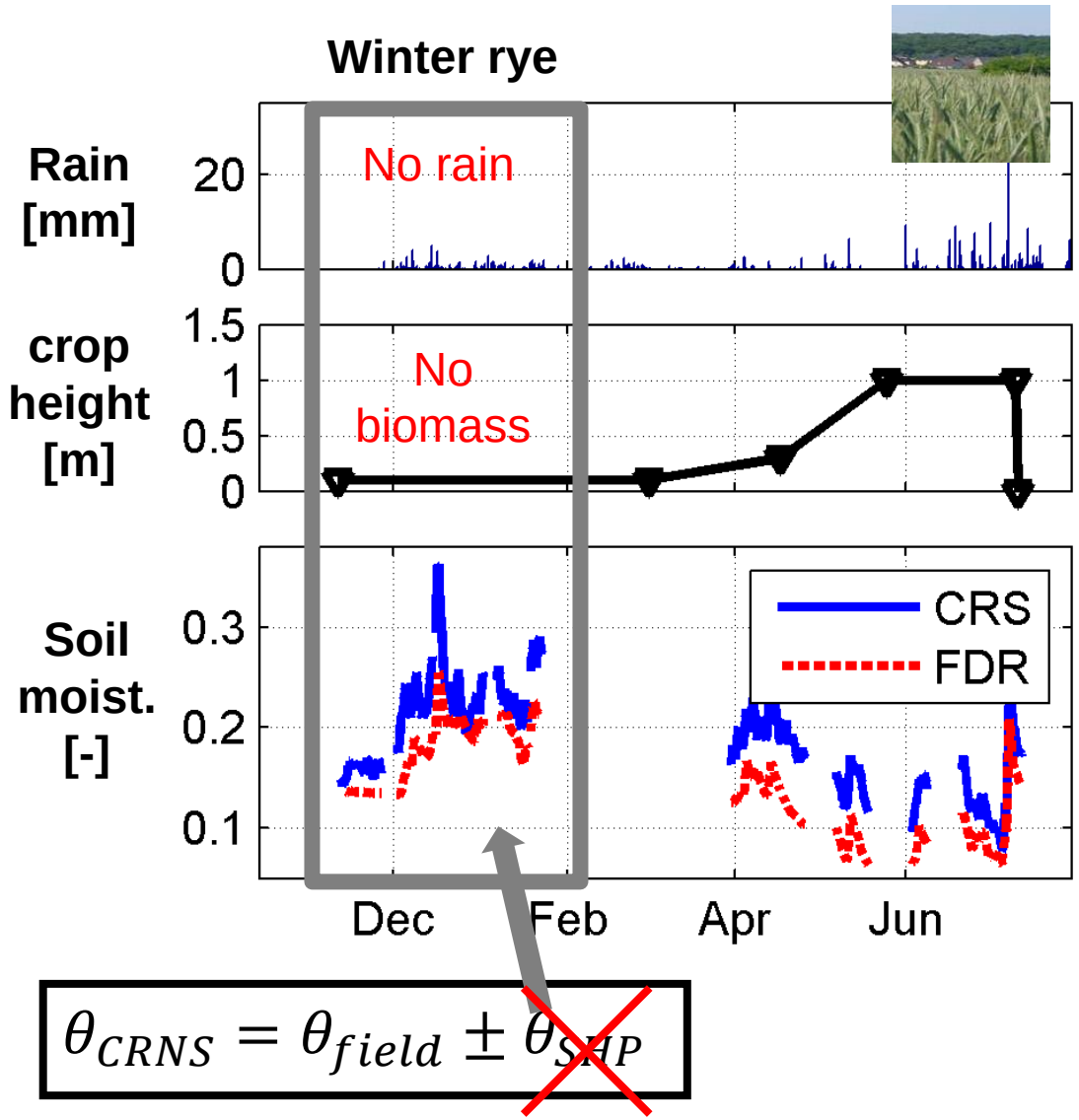


A scaling approach based on point-scale observation



$$\theta_{CRNS} = \theta_{field} \pm \theta_{SHP}$$

A scaling approach based on point-scale observation



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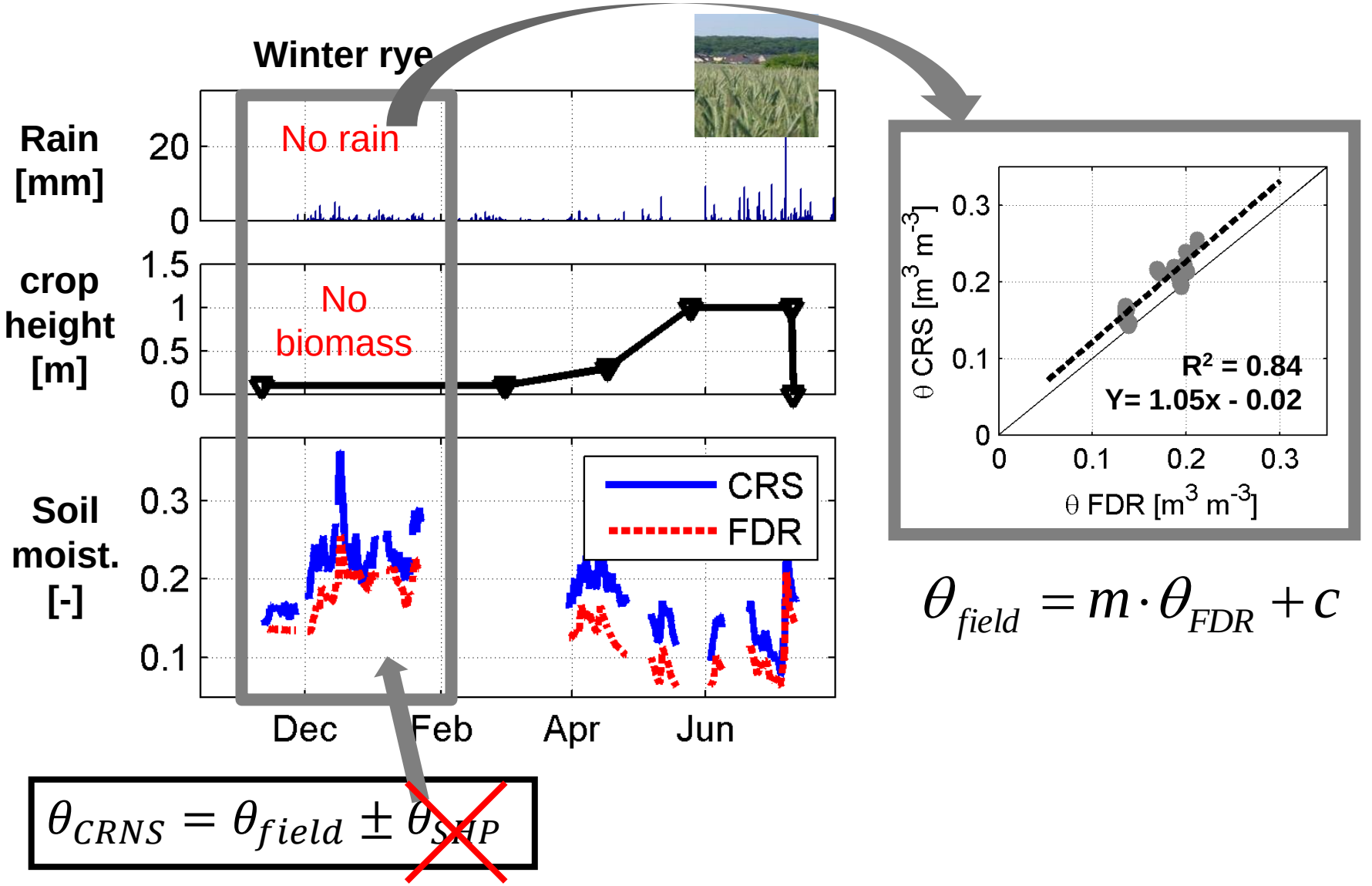
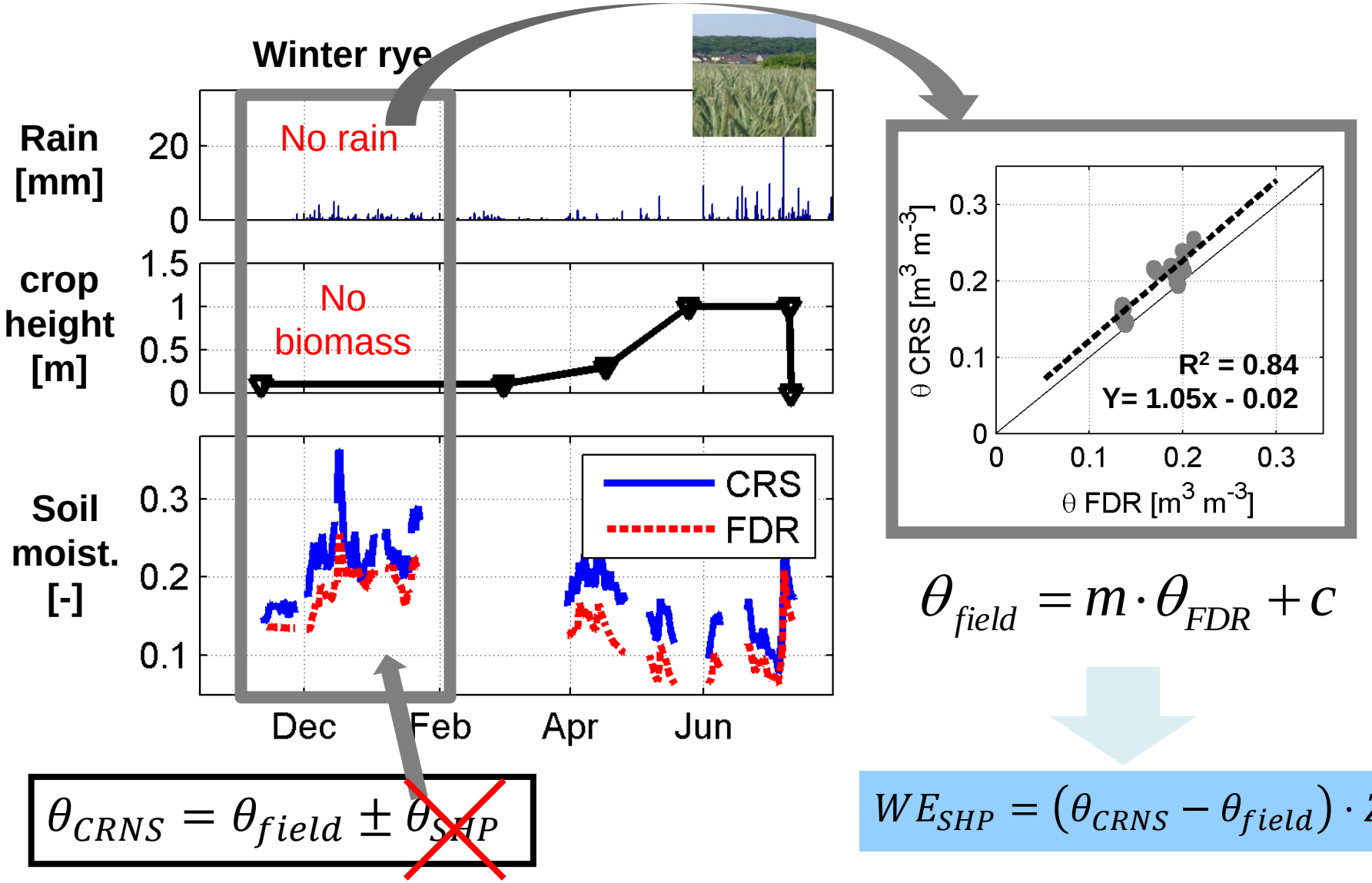


$$\theta_{field} = m \cdot \theta_{FDR} + c$$

$$\theta_{CRNS} = \theta_{field} \pm \theta_{SWP}$$

A scaling approach based on point-scale observation



$$\theta_{field} = m \cdot \theta_{FDR} + c$$

$$\theta_{CRNS} = \theta_{field} \pm \theta_{SHP}$$

$$WE_{SHP} = (\theta_{CRNS} - \theta_{field}) \cdot Z$$

Results (1): sub-daily dynamics WE_{SHP} [mm]

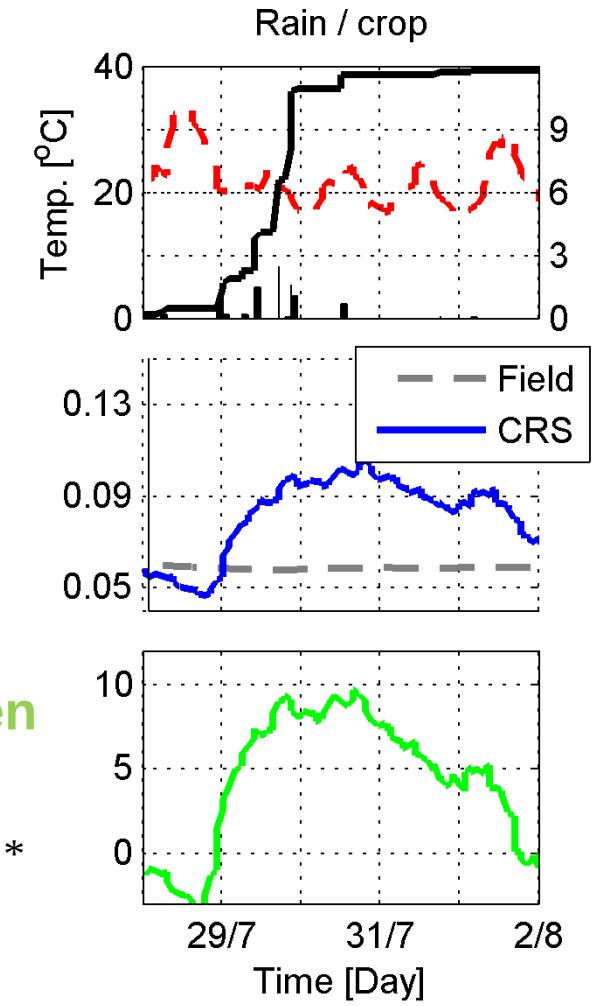
Temperature
Rainfall

Water content [-]

θ_{CRS} θ_{field}

Second hydrogen pool [mm]

$$WE_{SHP} = \left(\theta_{CRS} - \theta_{field}\right) \cdot z^*$$



CRNS = Canopy interception

Results (1): sub-daily dynamics WE_{SHP} [mm]

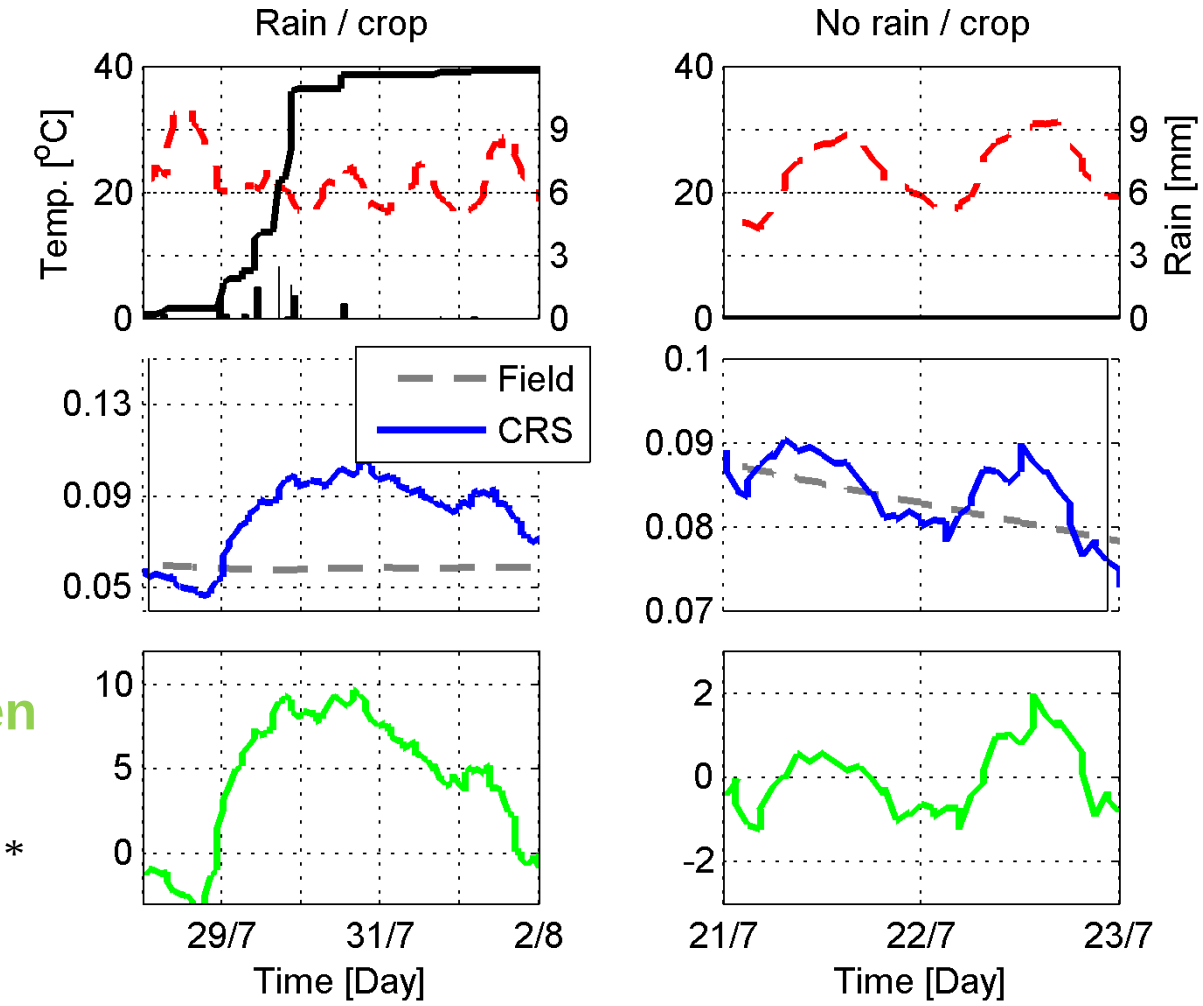
Temperature
Rainfall

Water content [-]

θ_{CRS} θ_{field}

Second hydrogen pool [mm]

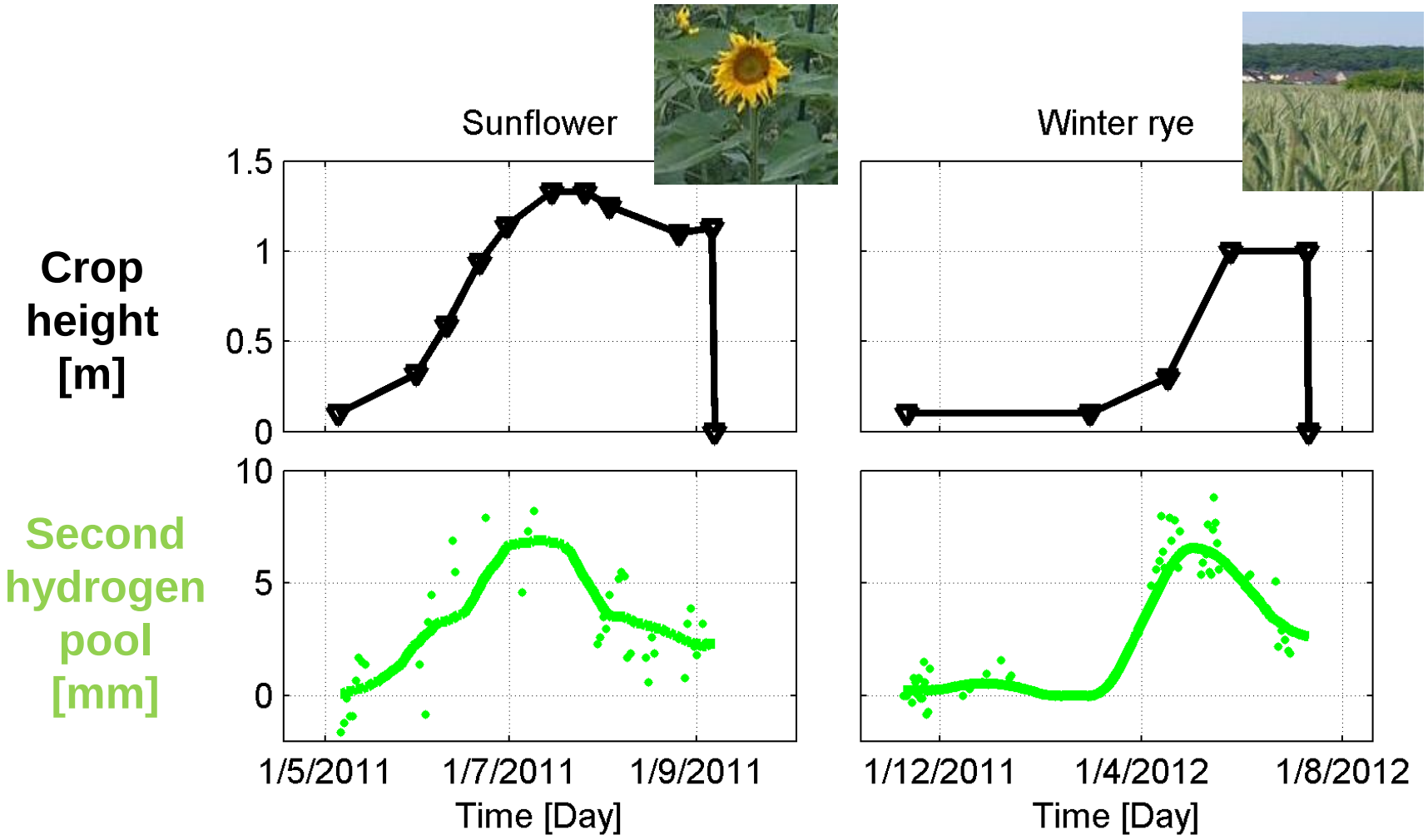
$$WE_{SHP} = \left(\theta_{CRS} - \theta_{field}\right) \cdot z^*$$



CRNS = Canopy interception

CRS = Daily cycle

Results (2): seasonal dynamics WE_{SHP} [mm]



CRS = Biomass water equivalent [mm]

Concluding remarks

- CRNS is an innovative **non-invasive** method to estimate **soil moisture** over large area (**5-10 ha**) and depth down to **50 cm**.

- CRNS shows capability to estimate **snow** in alpine terrain: e.g., Schattan, Paul, Gabriele Baroni, Sascha E. Oswald, Johannes Schöber, Christine Fey, Christoph Kormann, Matthias Huttenlau, and Stefan Achleitner. "Continuous Monitoring of Snowpack Dynamics in Alpine Terrain by Aboveground Neutron Sensing." *Water Resources Research* 53, no. 5 (May 1, 2017): 3615–34. https://doi.org/10.1002/2016WR020234.

- The use for estimating others secondary time varying hydrogen pools (**biomass**) under research

Concluding remarks

In agriculture several opportunities, most of them **underexplored**

- Irrigation scheduling
- Trafficability
- Sowing and harvesting
- Leaching and pollutant controls
- Drought monitoring

New CRNS technologies and **simpler data-processing** are emerging that will help applicability of the method

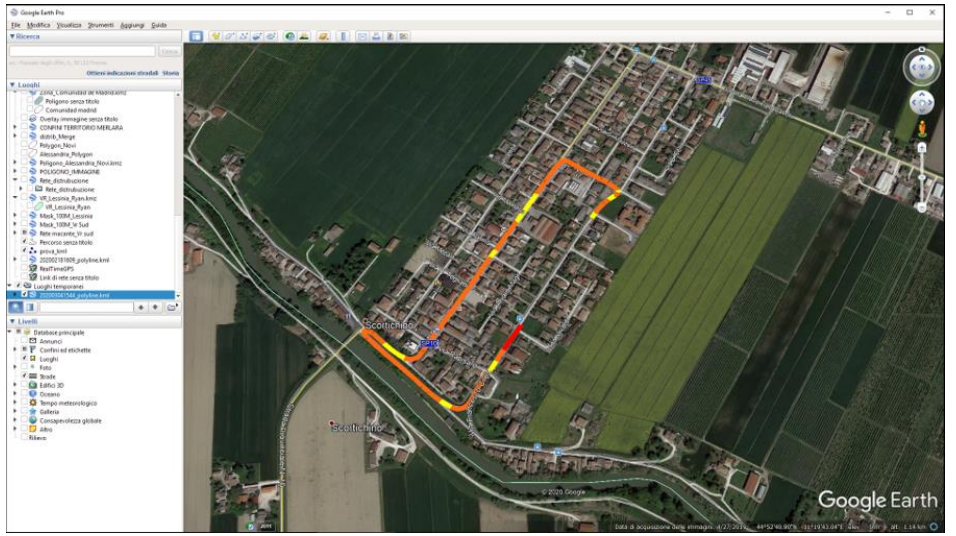
Additional further research of CRNS method are relevant (thermal-epithermal, footprint control etc.)

New opportunities and applications…

Concluding remarks

Water Leaks Detection and CRNS: https://cosmicwaterleaks.space/

- Current methods for detecting water leaks slow and expensive



- CRNS a very good alternative
- working on neutrons counts: high drop of the signal with pipe leakage. **No need to convert to soil moisture, no need to know footprint details**
- Equipped public transportation

Thank you for the attention!

For any further questions or interest in collaboration feel free to contact me

Hope to see you in Bologna!

Gabriele Baroni, PhD
Associate Professor
Agricultural Engineering Division / Soil Hydrology
Department of Agricultural and Food Sciences (DISTAL)
Alma Mater Studiorum – University of Bologna
Viale Giuseppe Fanini 50, 40127 Bologna (Italy)
Tel. +39 051 20 9 3622
Email: g.baroni@unibo.it
web: https://www.unibo.it/sitoweb/g.baroni/en

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

Ass.Prof. Gabriele Baroni

Department of Agricultural and Food Sciences (DISTAL)

g.baroni@unibo.it