Simultaneous monitoring of soil water content and vegetation with cosmic-ray neutron sensors: novel findings and future opportunities

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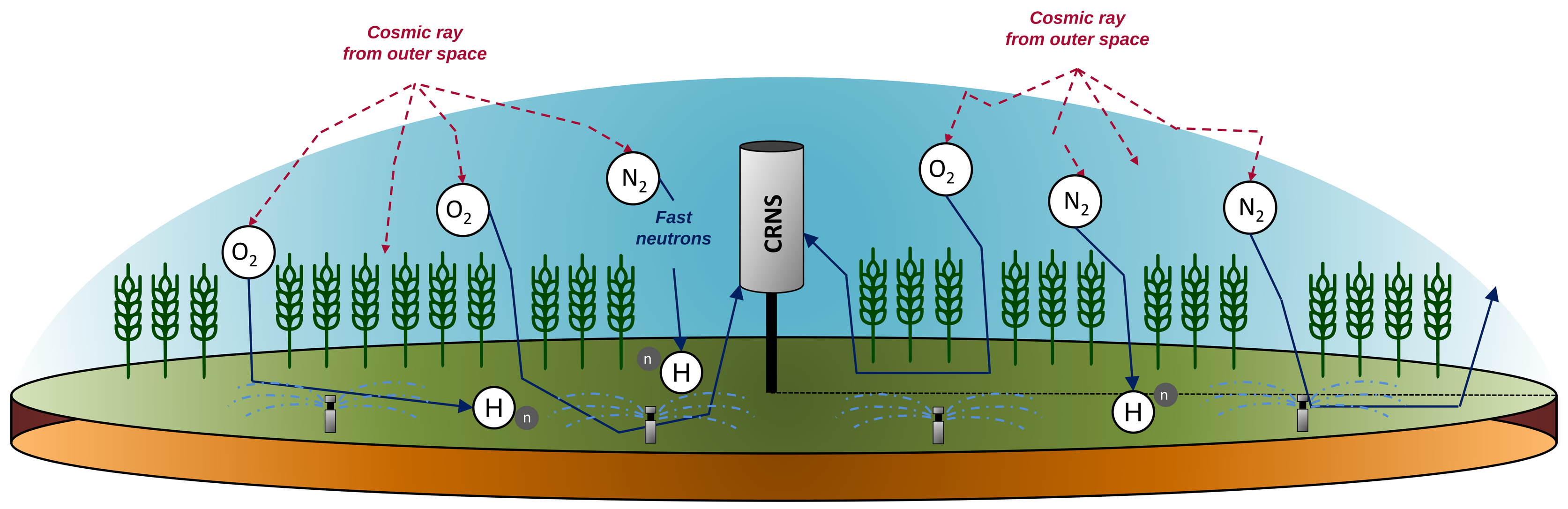
Introduction

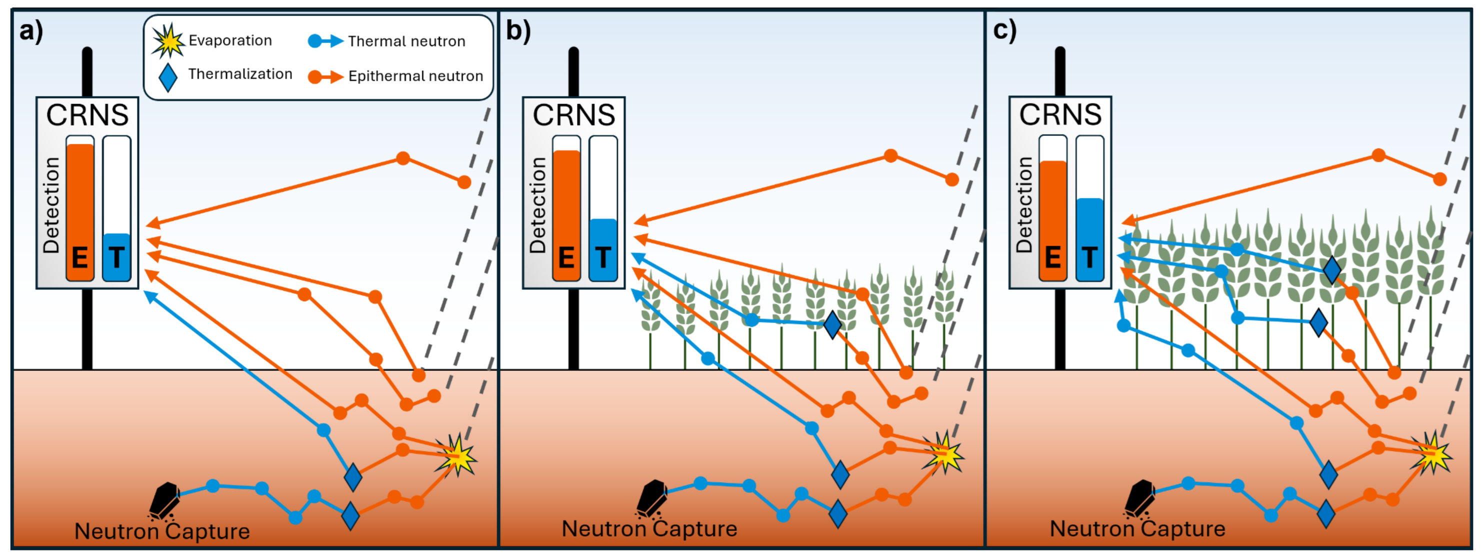
Cosmic ray neutron sensors (CRNS) estimate Soil Water Content (SWC) by measuring environmental neutron intensities:

- Moderated detector measuring **Epithermal Neutron intensity (E_n)**:
  - Inversely related to SWC in 150-250 m radius
- Bare detector measuring **Thermal Neutron Intensities (T_n)**:
  - Lower energy neutrons that are not strongly affected by SWC



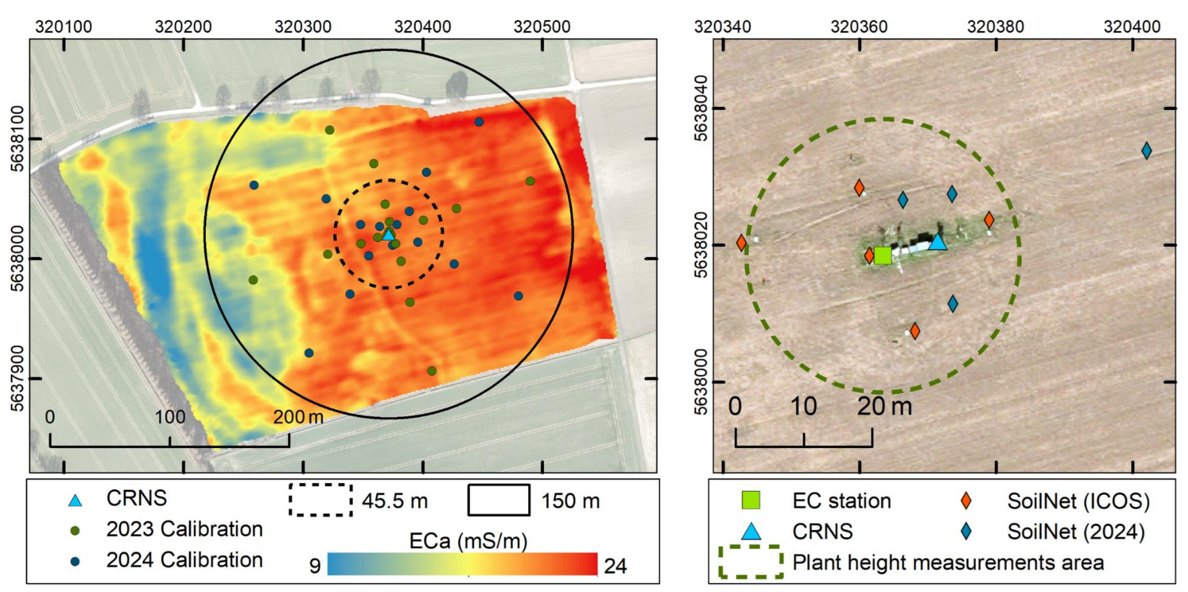
After multiple interactions with the environment, neutrons can reach the CRNS where, depending on their energy, they can be detected

It was recently suggested that T_n can be used to monitor vegetation at the field scale (e.g., Jakobi *et al.* 2022).



Effects of bare soil and vegetation on measured epithermal (E_n, orange) and thermal (T_n, blue) neutron intensities. Vegetation acts as an additional moderator and further slows down epithermal neutrons. With vegetation, E_n decreases slightly while T_n increases.

Selhausen Jülich ICOS station (DE-RuS)

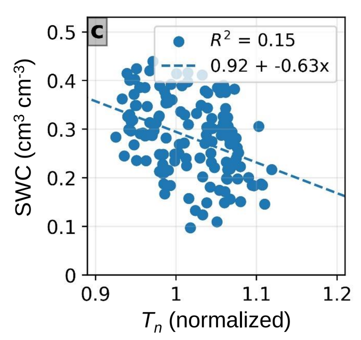


Study area with soil heterogeneity (apparent Electrical Conductivity, ECa), instruments and measurements positions, and CRNS footprints.

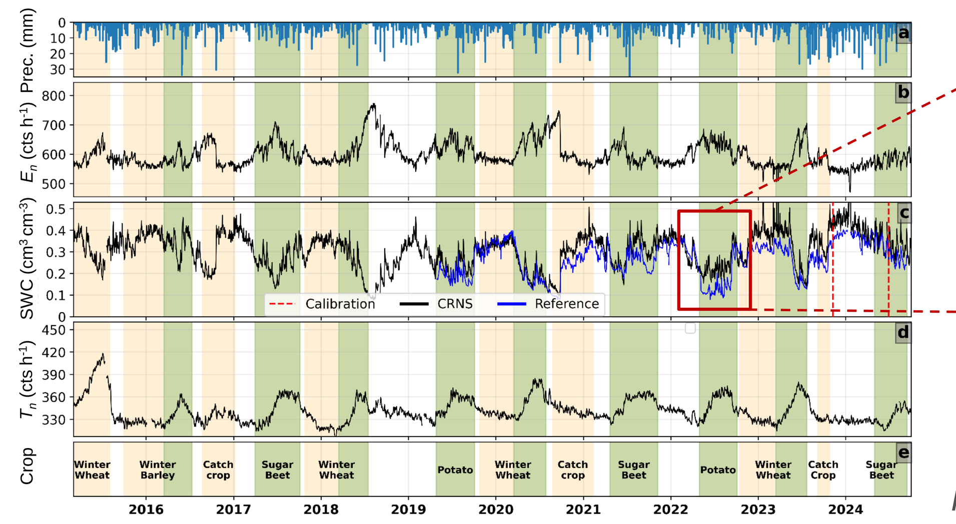
- 10-year CRNS and eddy covariance measurements
- Point-scale SWC
- Manual measurements
  - ✓ Plant Height (PH)
  - ✓ Leaf Area Index (LAI)
  - ✓ Dry Above Ground Biomass ($_{dry}$AGB)

CRNS estimates of SWC

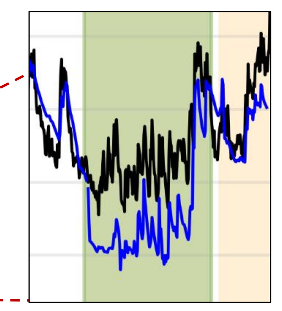
- E_n provides consistent estimates of SWC at relevant scale
- Point-scale sensors are affected by frequent dismantling and reinstallation and by loss of soil contact



Low correlation between T_n and SWC estimations



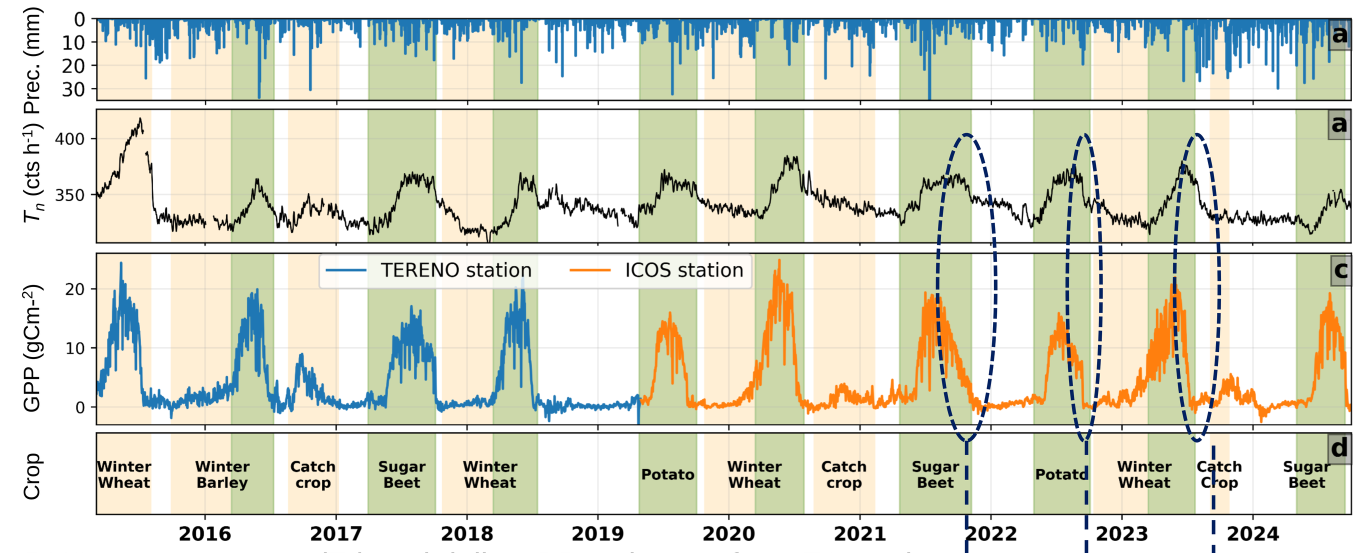
10-year CRNS measurements (E_n and T_n) and SWC estimates



Pronounced underestimation of SWC by the point-scale sensors. Possible loss of soil contact or challenging reinstallation.

- T_n is not correlated to SWC changes
- T_n dynamics well match cropping periods (green areas in plots)

Thermal neutron intensities and GPP



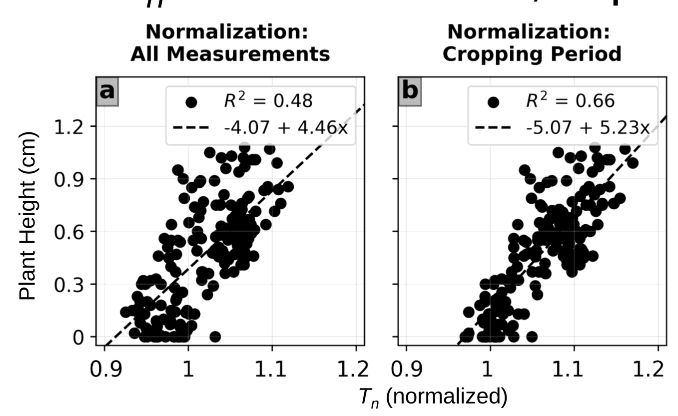
10-year CRNS measurements (T_n) and daily GPP estimates from EC station

- *Similar* T_n and GPP dynamics during cropping periods
- T_n and GPP differ at late growing stages
- Probable influence of crop structure, composition, or below-ground biomass

- Less favorable growing conditions
- Desiccation
- Senescence

CRNS-based predictions of Vegetation Traits

- Good T_n - PH correlation, especially during cropping periods

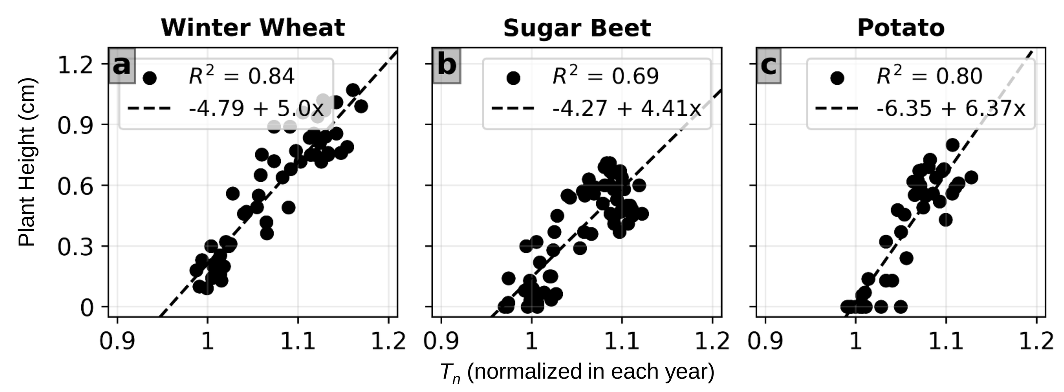


Two T_n normalization strategies:

Plot a) T_n normalized using the average value of the investigated period.

Plot b) in each year, T_n normalized using the average value at 15th-17th March, which precedes crop emergence or significant crop growth. Exception: in 2024, 26th-28th April was used.

- Crop-specific models provide improved correlations

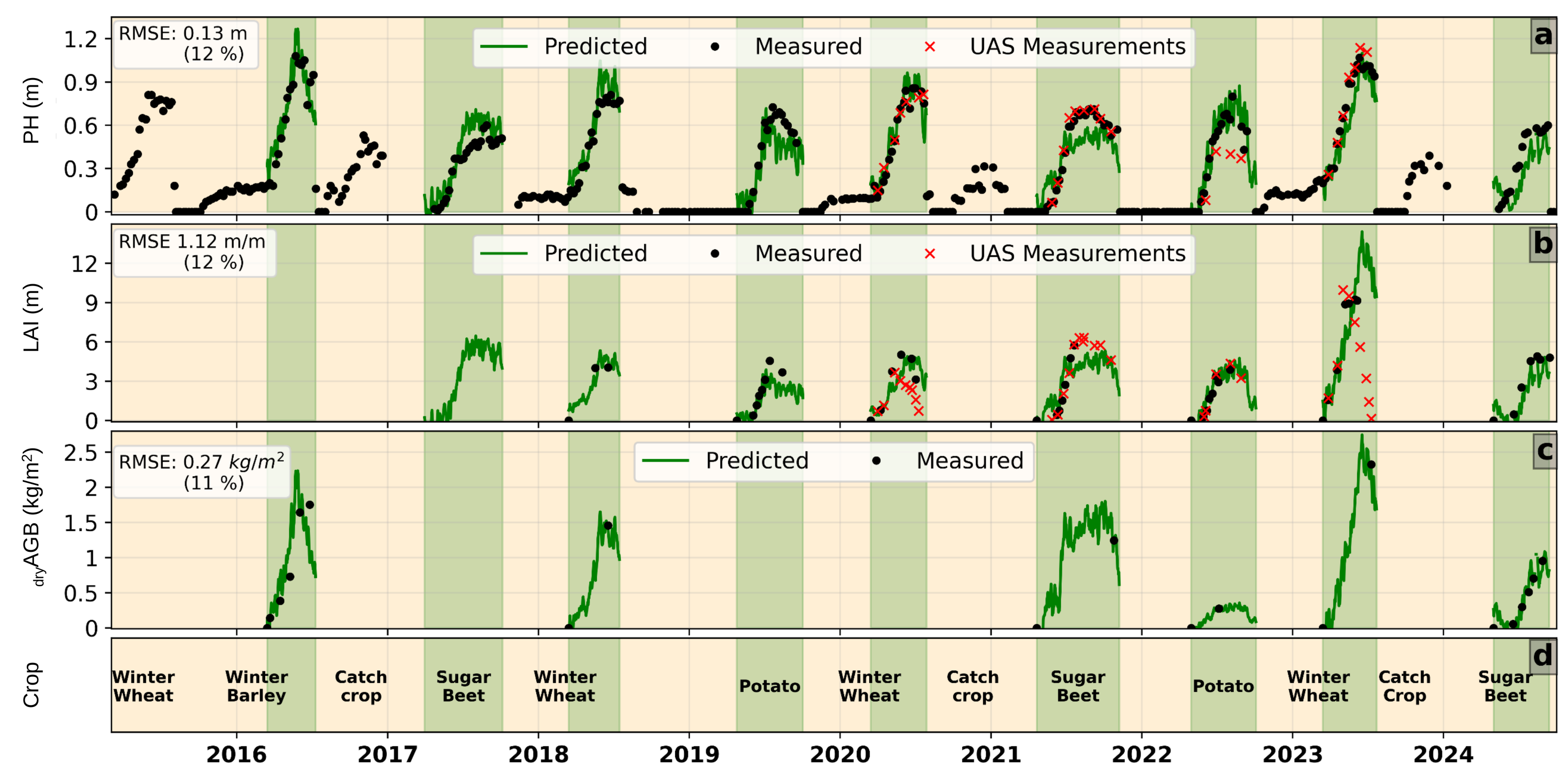


- Annual model may provide some benefits, but crop-specific models are more promising

Year	2016	2017	2018	2019	2020	2021	2022	2023	2024
Crop	Barley	Beet	Wheat	Potato	Wheat	Beet	Potato	Wheat	Beet
R^2	0.72	0.85	0.89	0.87	0.89	0.84	0.89	0.90	0.75
RMSE (m)	0.15	0.07	0.08	0.10	0.09	0.11	0.09	0.10	0.11

Annual T_n – PH models with R^2, and RMSE (T_n normalized in each year).

- Continuous T_n-based predictions of PH, LAI, and $_{dry}$AGB



T_n-based crop-specific predictions of PH and LAI, annual predictions of $_{dry}$AGB

	Plant Height				Leaf Area Index				$_{dry}$AGB	
	Barley	Wheat	Beet	Potato	Wheat 2018+2020	Wheat 2023	Beet	Potato	Barley 2016	Beet 2024
N. Obs.	17	54	67	43	7	6	14	9	5	5
RMSE	0.16	0.12	0.13	0.13	1.08	1.37	0.86	1.31	0.438	0.092
LOOCV RMSE	0.18	0.12	0.14	0.13	1.70	1.86	0.97	1.63	0.555	0.133

RMSE and leave-one-out cross validation (LOOCV) RMSE analysis of T_n – predictions of PH, LAI, and $_{dry}$AGB.

Conclusions and perspectives

- CRNS can offer simultaneous estimates of SWC and vegetation traits
- CRNS estimates are less accurate than manual measurements, but have the key advantage of being continuous and non-laborious
- Potential for long-term monitoring platforms, development and validation of environmental models, and agricultural applications

Acknowledgments and References

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Cosmic-ray neutron sensors provide scale-appropriate soil water content and vegetation observations for eddy covariance stations – Brogi C., Jakobi J., Huisman J. A., Schmidt M., Montzka C., Bates J., Akter S., and Bogena H. R., Under review in Agricultural and Forest Meteorology

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