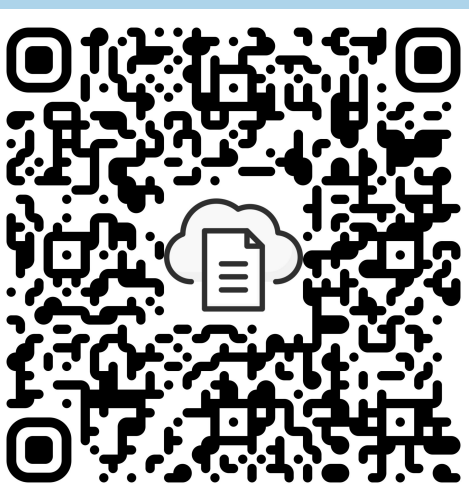


SYNERGIES OF COSMIC-RAY NEUTRON SENSORS & REMOTE SENSING PRODUCTS FOR SPATIAL MAPPING OF SOIL MOISTURE AND VEGETATION



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Abstract

Cosmic Ray Neutron Sensing (CRNS) offers field-scale soil moisture estimation [1], bridging the gap between point measurements and coarse satellite data. However, forest environments introduce significant biases due to hydrogen in above-ground biomass. Traditional CRNS correction methods rely on **literature estimates** of biomass, limiting accuracy in regionally varying forested environments. This project will leverage **high-resolution satellite-derived above-ground biomass density (AGBD)** and **seasonal remote sensing indices** to correct CRNS data. The goal is to improve soil moisture estimates and provide enhanced ground truth for satellite product validation. [4] A Python package for biomass-aware CRNS processing will be developed supporting open and reproducible research.

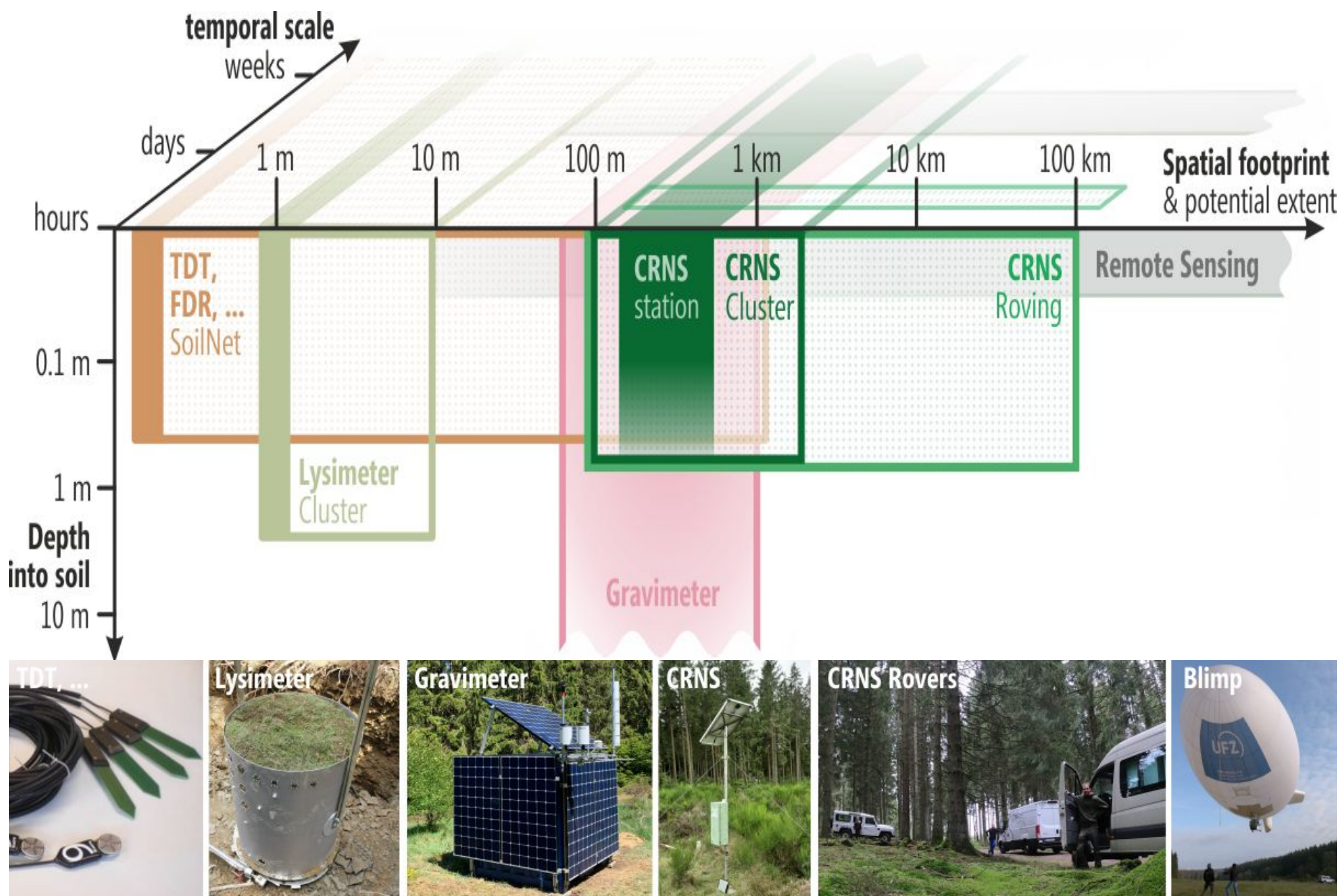


Figure 1: Scale of soil moisture observations [3]

Introduction

- **Soil moisture** is a key variable for hydrology, agriculture, and climate science.
- **Remote Sensing Soil Moisture Products** provide global coverage but at coarse resolution.
- **CRNS** fills intermediate scale (150–250 m radius), offering continuous, non-invasive soil moisture data [2]
- **Forest hydrogen pools** in vegetation cause **systematic signal attenuation**.
- **Remote sensing** provides high-resolution AGBD and potentially seasonal forest dynamics, enabling more accurate CRNS corrections.
- **DLR Above Ground Biomass Density (AGBD)** product offers high spatial but low temporal resolution for biomass correction in German forests

Objective

- **Develop a biomass-aware CRNS correction workflow** using satellite-derived AGBD and seasonal remote sensing indices.
- **Integrate correction methods into a new Python package** (cosmicbiomass)
- **Validate corrected CRNS soil moisture accuracy against in-situ soil moisture measurements**



Study Sites:

- **Hohes Holz:** Mixed beech forest
■ (52.09°N, 11.22°E)
- **Wüstenbach:** Norway spruce
■ (50.50°N, 6.33°E)

Figure 2: Study Sites Location

Data & Methods

Satellite-Based Biomass Correction

- **DLR Forest Structure:** Annual AGBD products (2017-2023, 10m resolution) [3]
- extract within CRNS footprint using distance-weighting [6]

Seasonal Dynamics Integration

- **Monitor forest phenology** using Sentinel-1 & Sentinel-2.
- **Machine Learning** for temporal upscaling of AGBD

Python Package Development

- Development of **cosmicbiomass** package for biomass-aware CRNS correction
- **Integrate with Neptoon** for processing and open science workflows [5]

Validation Plan

- Compare corrected CRNS soil moisture with **in-situ TDR & SoilNet measurements** [2]
- Compare with remote sensing soil moisture products (SMAP, SCATSAR-SWI)

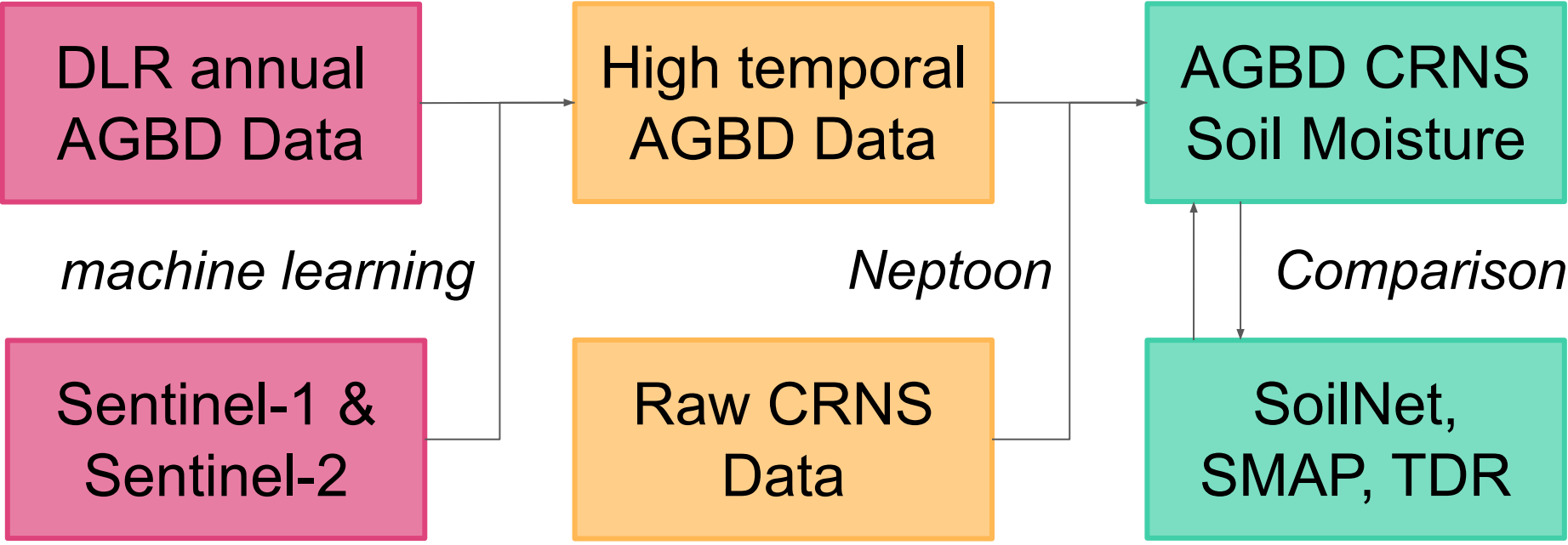


Figure 3: Workflow of CRNS AGBD Correction

Expected Outcomes

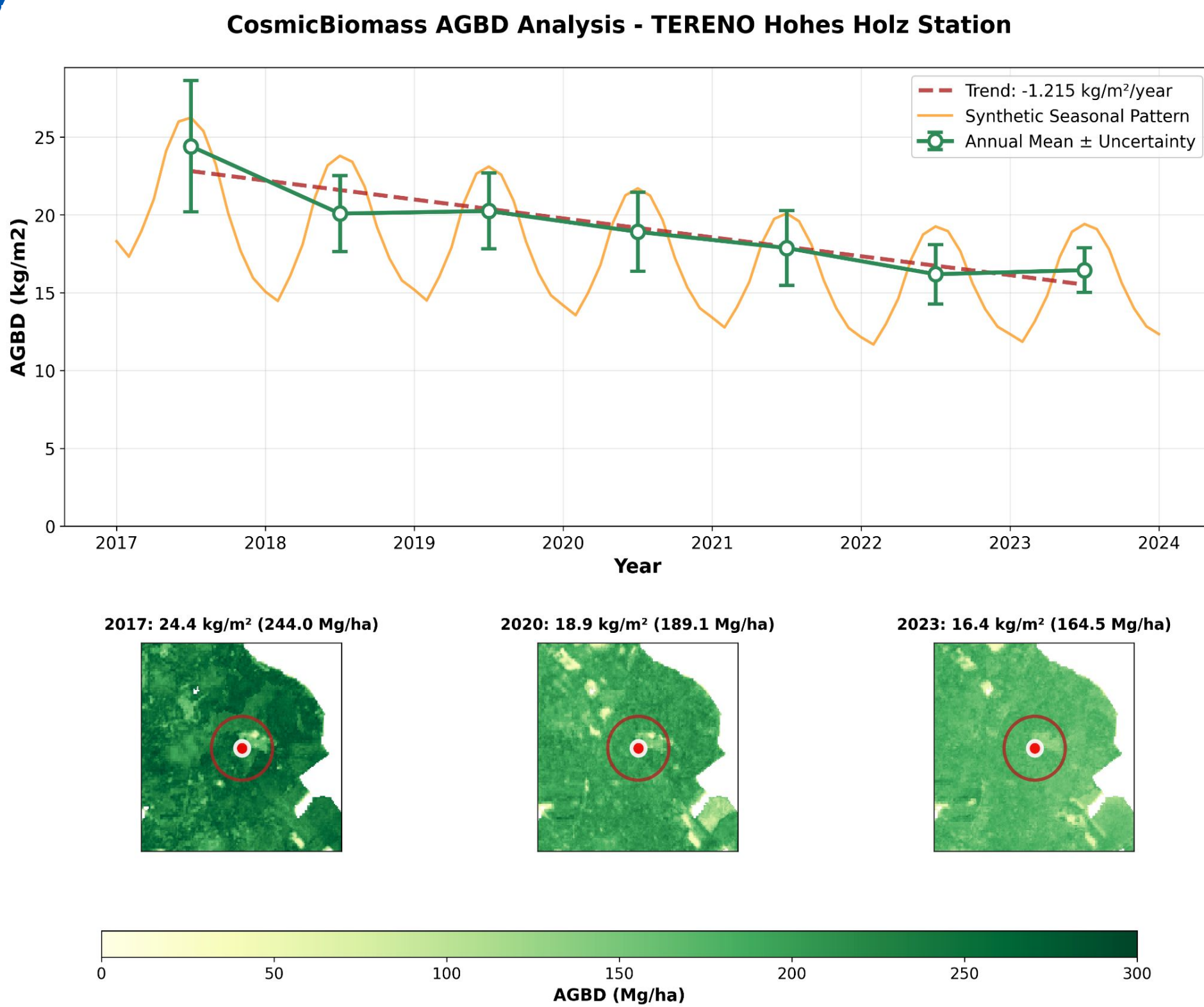


Figure 4: AGBD Extraction with cosmicbiomass

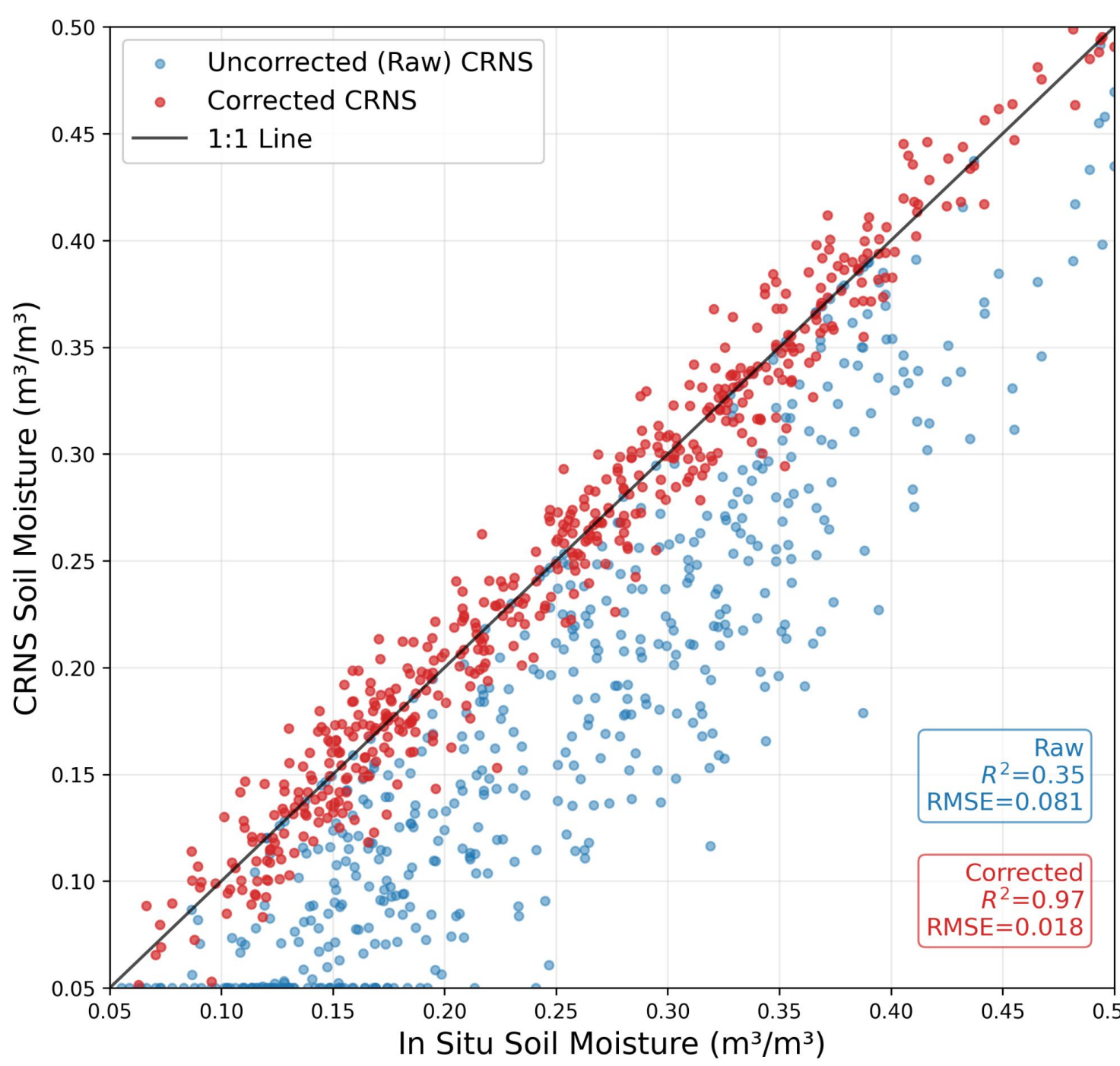


Figure 5: Hohes Holz In Situ vs. AGBD corrected CRNS Soil Moisture - Synthetic Data

cosmicbiomass

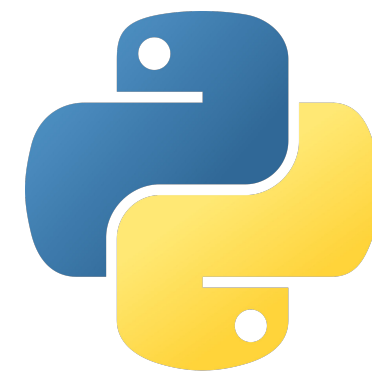
cosmicbiomass is a modern Python package designed to make above-ground biomass correction for CRNS soil moisture studies easy, reproducible, and robust.

- **Direct extraction of high-resolution biomass data** (2017–2023) from DLR and flexible integration of additional biomass datasets.
- **Flexible footprint-weighted statistics:** circular, Gaussian, and CRNS-specific weighting [6]
- **Uncertainty quantification** and outlier detection
- **Modular, open-source architecture**—easy to extend and integrate with other tools (e.g., Neptoon)
- **Simple API:** Analyze any site with just a few lines of code

Why it matters: cosmicbiomass enables precise, reproducible correction of CRNS data using state-of-the-art satellite biomass products, supporting better soil moisture estimates and improved satellite product validation.

Open science:

- Python 3.10+, type-hinted, >85% test coverage
- Will be free to use and contribute. Add me on GitHub:



Discussion & Conclusion

- **Novel Correction Approach:**
 - Satellite-derived above-ground biomass density (AGBD) replaces literature-based biomass estimates for CRNS soil moisture correction in forests
 - Could enable more accurate, spatially consistent soil moisture data, especially in forests.
- **Open-Source, Scalable Workflow:**
 - The new Python package (cosmicbiomass) allows reproducible, automated corrections at a national scale using DLR AGBD data.
- **Improved Validation & Applications:**
 - Biomass-corrected CRNS data provide higher-quality ground truth for validating remote sensing products (e.g., SMOS, SMAP, SCATSAR-SWI). [4, 5]
 - Enhanced soil moisture datasets support hydrological modeling and climate studies across Europe.
- **Broader Impact:**
 - The workflow bridges the gap between in-situ and remote sensing soil moisture, enabling better environmental monitoring and research.

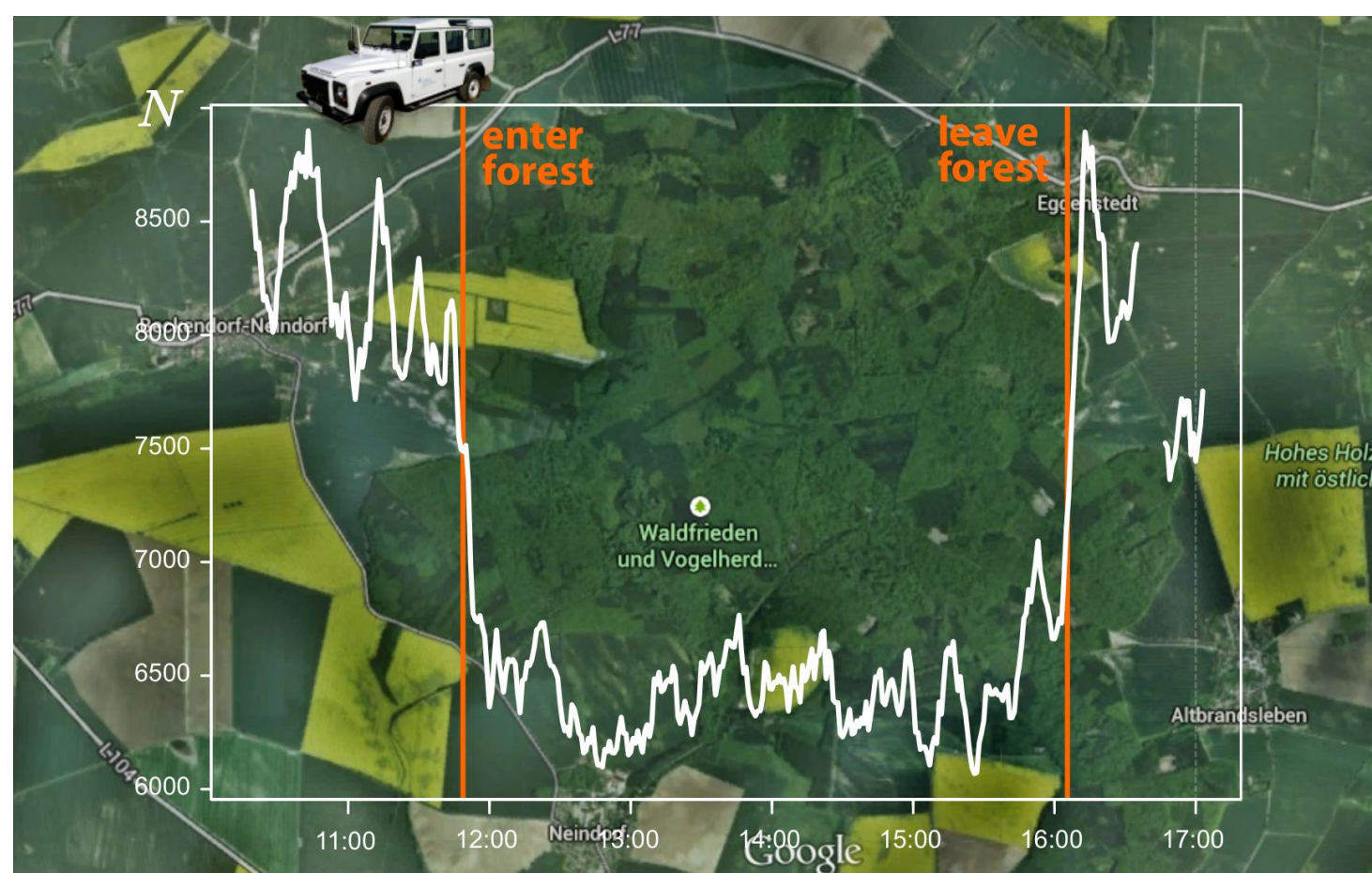


Figure 6: CRNS Measurement depends on vegetation in the footprint when moving through forests

References & Acknowledgements

- [1] Baatz, R., Hendricks Franssen, H. J., Han, X., Hoar, T., Bogena, H. R., & Vereecken, H. (2017). Evaluation of a cosmic-ray neutron sensor network for improved land surface model prediction. *Hydrology and Earth System Sciences*, 21(5), 2509-2530., <https://doi.org/10.5194/hess-21-2509-2017>
- [2] Heistermann, M., Bogena, H., Francke, T., Güntner, A., ... & Oswald, S. (2021). Soil moisture observation in a forested headwater catchment: Combining a dense cosmic-ray neutron sensor network with roving and hydrogravimetry at the TERENO site Wüstenbach. *Earth System Science Data Discussions*, 2021, 1-29., <https://doi.org/10.5194/essd-15-3243-2023>
- [3] Kacic, P., Thonfeld, F., Gessner, U., & Kuenzer, C. (2023). Forest structure characterization in Germany: novel products and analysis based on GEDI, Sentinel-1 and Sentinel-2 data. *Remote Sensing*, 15(8), 1969., <https://doi.org/10.3390/rs15081969>
- [4] Peng, J., Albergel, C., Balenzano, A., Brocca, L., Cartus, O., Cosh, M. H., ... & Loew, A. (2021). A roadmap for high-resolution satellite soil moisture applications—confronting product characteristics with user requirements. *Remote Sensing of Environment*, 252, 112162., <https://doi.org/10.1016/j.rse.2020.112162>
- [5] Power, D., & Schrön, M. (n.d.). Neptoon documentation [Software documentation]. <https://www.neptoon.org/en/latest/>
- [6] Schrön, M., Köhli, M., Scheffele, L., Iwema, J., Bogena, H. R., Lv, L., ... & Zacharias, S. (2017). Improving calibration and validation of cosmic-ray neutron sensors in the light of spatial sensitivity. *Hydrology and Earth System Sciences*, 21(10), 5009-5030., <https://doi.org/10.5194/hess-21-5009-2017>

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