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CRNPy: An Open-Source Python Library for Cosmic Ray Neutron Probe Data Processing

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DOI: 10.xxxxxx/draft

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Editor: Jayaram Hariharan

Reviewers:

- @jlarsen-usgs
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Submitted: 09 August 2023
Published: unpublished

Summary

CRNPy is a Python library that facilitates the processing, analysis, and conversion of raw cosmic-ray neutron counts obtained with stationary and roving cosmic-ray neutron probes (CRNP) into volumetric soil water content. The CRNPy library includes routines for atmospheric, biomass, and road corrections, along with one-dimensional and two-dimensional filtering. The library extends its utility by offering horizontal and vertical footprint determination, uncertainty estimation, depth extrapolation operators, and routines to assist users with field calibration. The design of the CRNPy library prioritizes reproducibility, ease of use, and compatibility across instruments, facilitating its adoption by manufacturers, end users, and researchers working to integrate non-invasive soil moisture sensing in agricultural and hydrological applications.

Statement of Need

Cosmic ray neutron probes (CRNP) are non-invasive soil moisture sensors that fill the niche between point-level and satellite sensors. However, the conversion of raw CRNP data into soil moisture requires multiple corrections and filtering steps that are described across various peer-reviewed articles. To circumvent this limitation and enhance reproducibility, the CRNPy library offers a simple, instrument-agnostic, and integrated solution with minimal dependencies. Compared to the existing `crspy`(Power et al., 2021) library, CRNPy avoids stringent data naming conventions and external data requirements. A flexible data naming convention enables a seamless integration with output files from different instrument manufacturers and the lack of external data requirements makes the library more compact (only ~65 KB) and straight forward to install. Compared to the `corny` (Schrön, Accessed: 2024) toolbox's GUI-based workflow, CRNPy's modular design based on Python functions promotes integration and reproducibility within data analysis pipelines and interactive development environments like Jupyter Lab notebooks. In addition, its straightforward installation using the Python Package Index, the minimal dependencies—most included with the Anaconda open-source ecosystem—and the comprehensive datasets with included examples in the form of Jupyter notebooks, provide an accessible start for CRNP data processing. The CRNPy library emphasizes easy maintenance and community-driven improvements since users can expand its capabilities by adding regular Python functions to the core module. The compact size and simple structure of the CRNPy library can also enable future integration into cloud-based services, IoT sensors, and system-on-chip technologies, broadening its use and customization potential.

Library features

The CRNPy library integrates standard routines for processing CRNP data, with features including:

- Utilization of core scientific Python libraries like Numpy (Harris et al., 2020), Pandas (McKinney & others, 2011), SciPy (Virtanen et al., 2020), and Matplotlib (Hunter & Dale, 2007), that are readily available within the Anaconda environment. All CRNPy functions are compatible with Numpy arrays or Pandas series for robust data science functionality.
- Utility functions for obtaining site-specific lattice water, geomagnetic cutoff rigidity (Smart & Shea, 2001), and neutron monitor references (Klein et al., 2009), which are required for pre-processing raw neutron counts.
- Flexible input data handling from delimited text files without stringent naming conventions for columns, which keeps scripts simpler, increases reproducibility, and minimizes human error. This aspect also enables a more versatile, modular, and customizable workflow (Figure 1 and Figure 2) that adapts to instrument outputs from different manufacturers.
- Detection of possible outliers using range detection based on user-provided lower and upper boundaries, interquartile range, z-scores, and a scaled mean absolute difference (Iglewicz & Hoaglin, 1993).
- Corrections for atmospheric pressure as described by Zreda et al. (2012), air humidity (Rosolem et al., 2013), and incoming neutron flux following the guidelines from Zreda et al. (2012); Hawdon et al. (2014); McJannet & Desilets (2023). The article by Andreasen et al. (2017) provides an overall description of these correction methods included in CRNPy (Figure 3a and Figure 3b).
- Corrections to account for additional hydrogen pools in above- and below-ground plant biomass (Baatz et al., 2015; Wahbi et al., 2018).
- Corrections to account for the impact of road soil moisture conditions during roving surveys (Schrön et al., 2018).
- Conversion of corrected counts into volumetric soil water content following the approach suggested by Desilets et al. (2010).
- Determination of neutron count uncertainty following the method detailed in Jakobi et al. (2020) (see Figure 3c).
- Estimation of sensing depth by determining the volume that accounts for 86% of the origin of the counted neutrons (Franz et al., 2012; Schrön et al., 2017).
- An exponential filter operator (Albergel et al., 2008) to extend near-surface soil moisture conditions to the rootzone (Franz et al., 2020; Rossini & Patrignani, 2021), see Figure 3d.
- Utility functions for spatial filtering and basic interpolation routines required to process CRNP rover surveys (see Figure 4)
- Additional functions for temporal interpolation and filtering required to process stationary CRNP observations (see Figure 3).

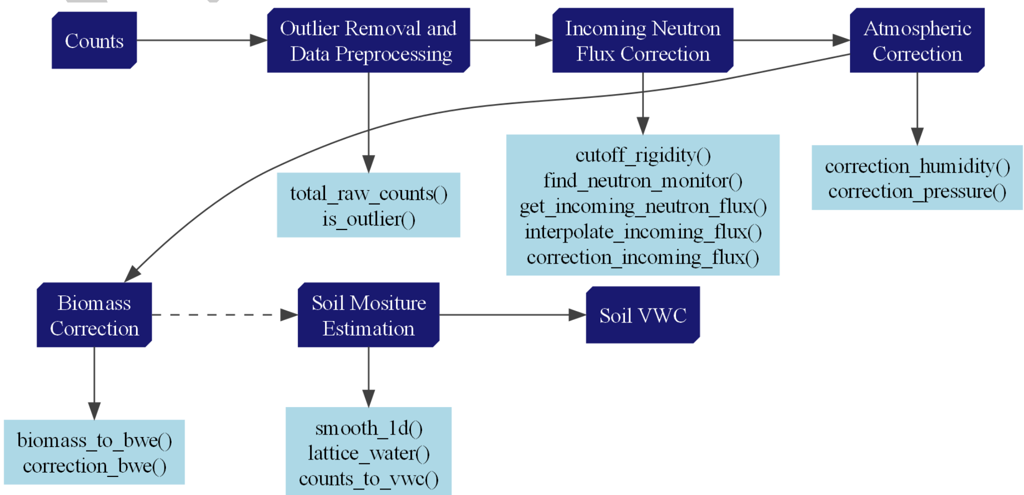

Figure 1: Example workflow for stationary CRNP, dashed lines represent optional steps.

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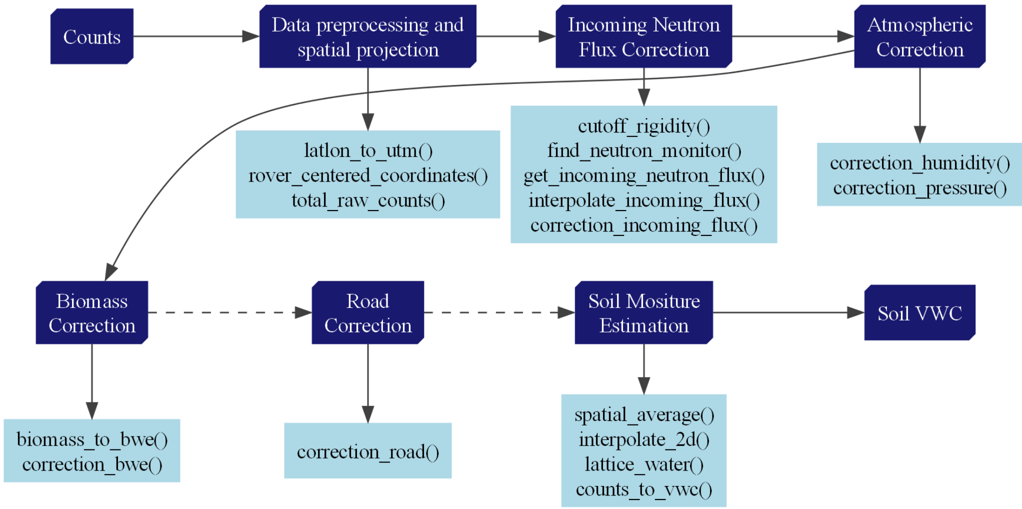

Figure 2: Example workflow for roving CRNP, dashed lines represent optional steps.

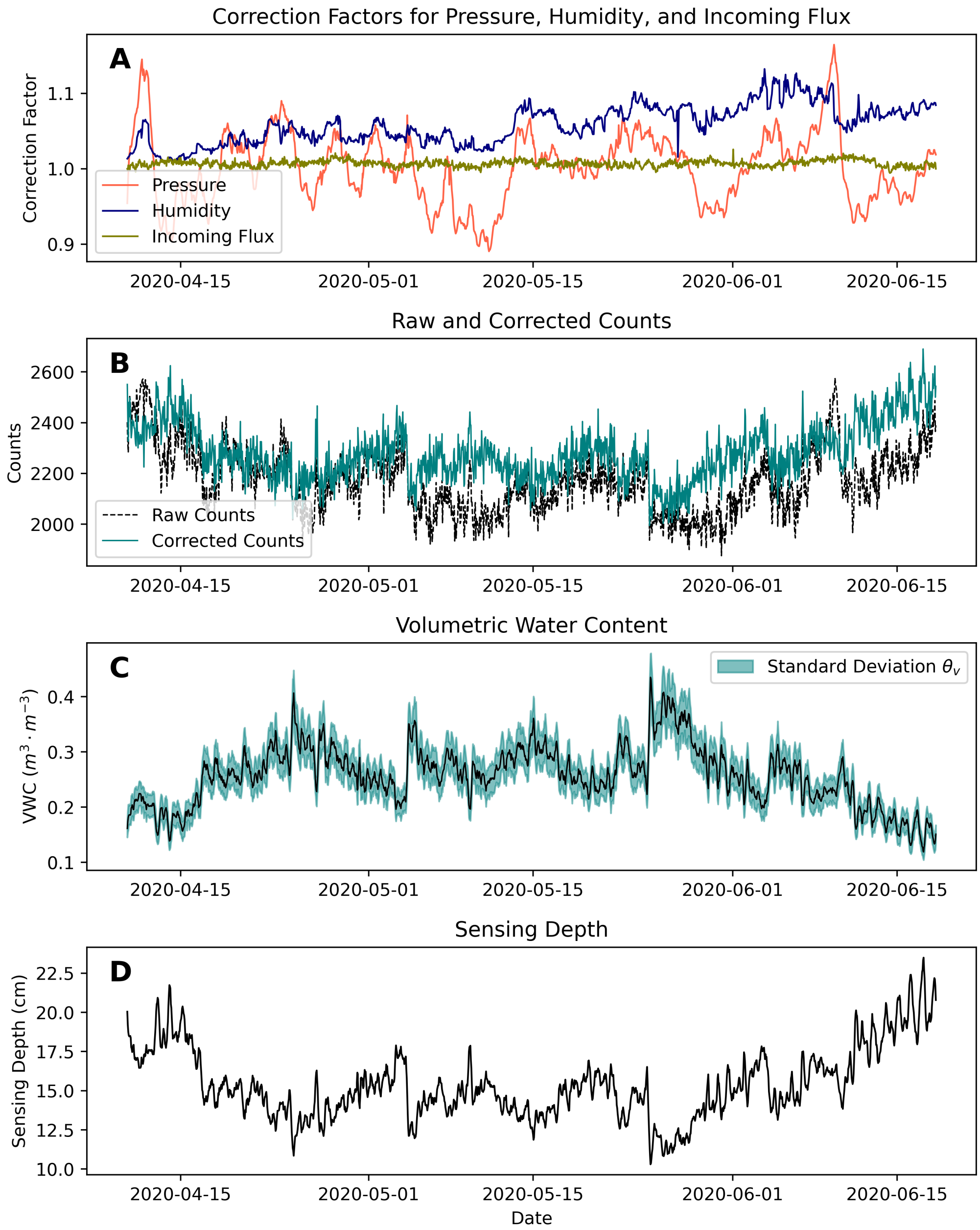

Figure 3: Outputs of a stationary device in each of the steps of the workflow, A) Impact of each factor in the correction process. B) Difference between raw and corrected counts. C) Resulting volumetric water content time series with the propageted neutron count uncertainity. D) Depth that accounts for the 86% of the observed counts.

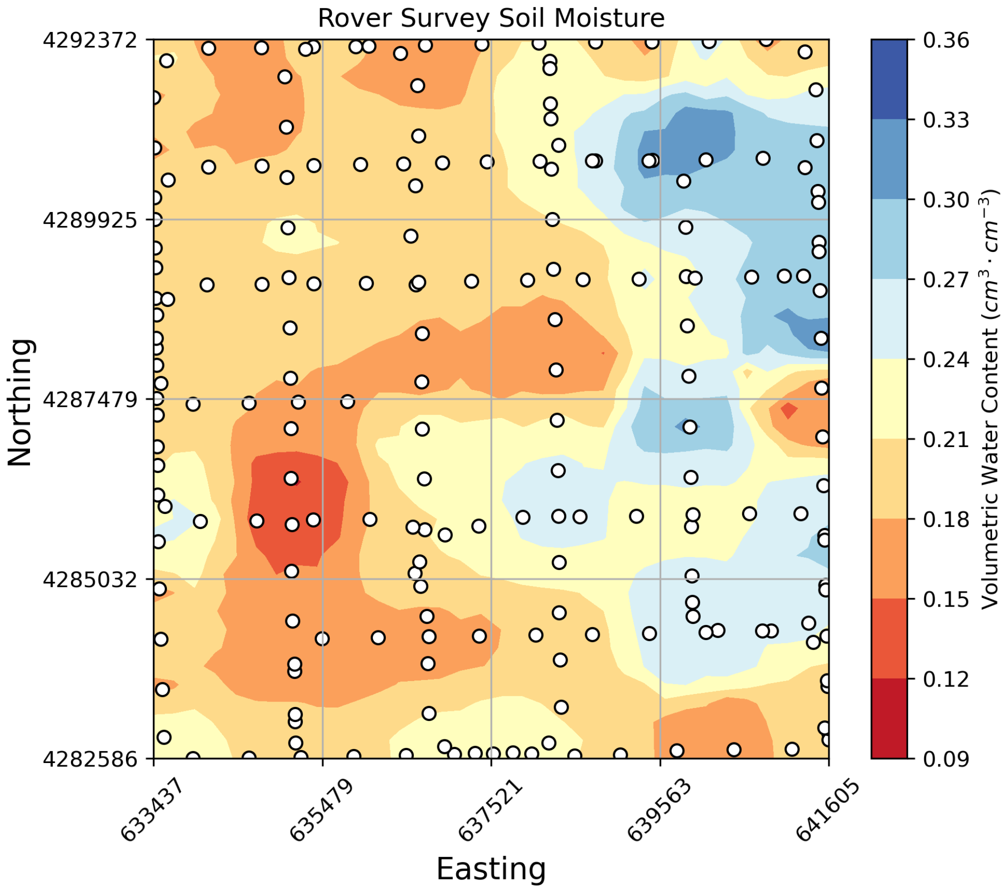

Figure 4: Contour plot of the roving transect spatial output. Each marker represents the estimated center of the observation.

Acknowledgements

This work was supported by the USDA National Institute of Food and Agriculture through the Agriculture and Food Research Initiative Competitive Grant no. 2019-68012-29888 and through Multistate project W4188. The authors declare no competing interests. This is contribution no. 24-179-J of the Kansas Agricultural Experiment Station.

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