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Cosmic Rays Neutron Sensing for soil moisture monitoring in vineyard with variable soil conditions

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With collaboration of:

1. Background

Cosmic Rays Neutron Sensing (CRNS) is a well-known method in Hydrology that allows to measure soil water content on a large scale and in depth (1). It is based on the detection of cosmogenic neutrons, particles generated by the interaction of cosmic rays with the atmosphere, after their interaction with the soil where they can be effectively absorbed by water molecules (Fig.1). The signal collected by a single CRNS probe in terms of neutron count rate is sensitive to soil moisture within a volume spanning up to a dozen hectares and up to 50 cm depth, in real-time, positioning itself in a horizontal spatial scale in between point measurements and satellites.

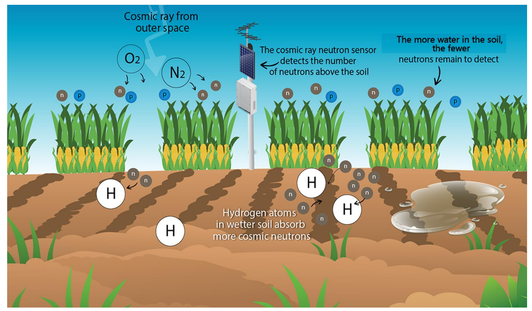


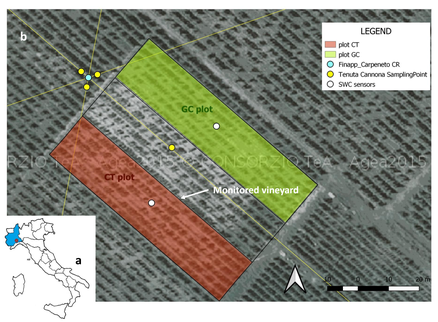
Fig 1: skecth of the functioning of a Cosmic Ray Neutron Sensing probe (Source infographic: R. Kenn/IAEA, https://www.iaea.org/newscenter/news/using-cosmic-rays-to-measure-moisture-levels-in-soil)

The objective of this work is to retrieve information about soil moisture in a complex agricultural system: vineyard with inter-rows with different soil management.

2. Study site and soil moisture measurements

The study is carried out in the Alto Monferrato vine-growing area (Piedmont, NW Italy), considering two vineyard-field-scale plots with inter-rows managed with conventional tillage (CT) and grass cover (GC), respectively, belonging to the Experimental Centre of Agrion Foundation in Carpeneto (AL) (Fig.2a,b).

Precipitation, temperature, humidity and wind measurements are available from an agro-meteorological station, placed at the border of the plots. Soil moisture capacitance sensors are located in different positions and depths (from 10 to 50 cm) in the vineyard (Fig.2c), including the STEMS network that is part of the International Soil Moisture Network (2). The site was equipped with a Finapp CRNS probe since August 2023 (Fig.2d).



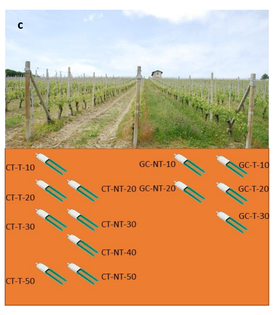


Fig. 2. The study site: a) localization of the study site in Italy; b) view of the monitored vineyard and landscape from the radar side and c) sketch of the positioning of the SWC sensors in the vine rows; d) the Finapp CRNS probe in the vineyard.

3. Data analysis

Precipitation measurements during the study period are compared with records over more than 20 years, show that 2023 was very dry, with Standardized Precipitation Index (SPI) lower than -1 for most of the year, whereas 2024 was increasingly wet, with exception of first two months of the year (Fig.3).

Available soil moisture data from CRNS and sensors have been compared until autumn 2024 (Fig.4), using statistical indexes such as the efficiency coefficient of Nash and Sutcliffe (NSE), root mean square error of residuals (RMSE) and the coefficient of determination of the linear regression (R^2). The analysis was carried out separately for the two years, which were considered respectively dry and wet.

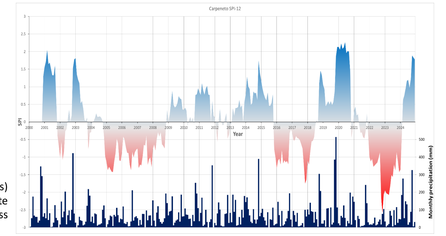
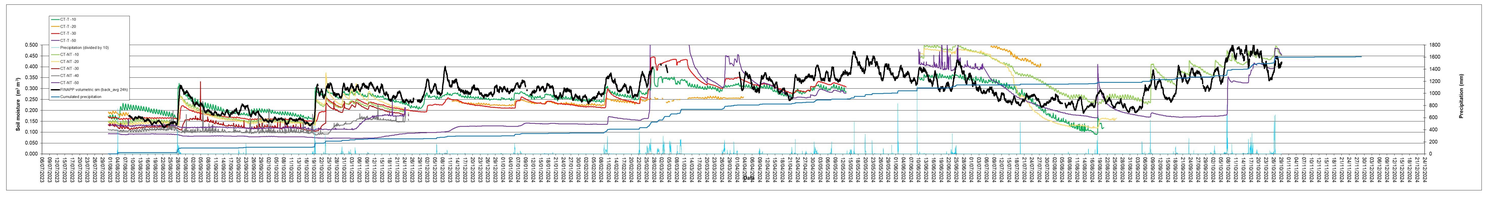


Figure 3: The 12-month SPI index calculated using monthly rainfall values (blue histograms) recorded at CA site over the 25 years from 2000 to 2024. Positive values greater than 1 indicate wet periods (light blue), or extremely wet periods if greater than 2 (blue). Negative values less than -1 indicate dry periods (pink) or extreme drought if less than -2 (red).

Figure 4: Precipitation (daily and cumulated), hourly SWC measured by CRNS and superficial (depth 10 cm) sensors in the CT vineyard plot during the observation period.



4. Results

Statistics showed that in the last 5 months of 2023 (dry period) there was a good agreement of soil moisture values measured by sensors between 10 and 20 cm of depth with both soil management, with different results according to the position, the best reported in the middle of the GC inter-row at depth of 20 cm (R^2=0.913, NSE=0.756, RMSE=0.25). The results for 2024, which was a wetter year, showed great variability, such as the values recorded by the sensors, with unsatisfactory statistics, since best values for indexes were obtained for the sensor placed in the middle of CT inter-row (R^2=0.598, NSE=0.485, RMSE=0.118) (Table 1).

Thus, in the dry period the CRNS probe gave good information on soil moisture conditions in the most superficial layer disregarding the soil management of the vineyard. On the contrary, the difficulty in having good agreement in wet conditions can be due to the high spatial variability of soil moisture both in the horizontal and in-depth directions, soil saturation and ponding, in addition to variable conditions of soil conditions (i.e. soil density) depending to soil management and tractor traffic during the growing season (Fig.5).

	CT-T				CT-NT				GC				
2023													
Statistical parameters	*CT-T-10*	*CT-T-20*	*CT-T-30*	*CT-T-50*	*CT-NT-20*	*CT-NT-30*	*CT-NT-40*	*CT-NT-50*	*GC-T-10*	*GC-T-20*	*GC-T-30*	*GC-NT-10*	*GC-NT-20*
R2	*0.909*	0.861	0.654	*0.916*	0.783	0.574	0.322	n.a	*0.911*	0.888	n.a	0.670	*0.913*
NSE	*0.696*	-0.143	-0.835	*0.748*	0.357	-1.341	-1.538	n.a	*0.704*	-0.118	n.a	-0.816	*0.756*
RMSE	*0.029*	0.049	0.057	*0.025*	0.041	0.076	0.110	n.a	*0.029*	0.049	n.a	0.057	*0.025*
PBIAS	*-7.543*	-14.780	-15.166	*-5.296*	15.623	42.908	82.876	n.a	*-7.643*	-14.886	n.a	-15.257	*-5.420*
2024													
Statistical parameters	*CT-T-10*	*CT-T-20*	*CT-T-30*	*CT-T-50*	*CT-NT-20*	*CT-NT-30*	*CT-NT-40*	*CT-NT-50*	*GC-T-10*	*GC-T-20*	*GC-T-30*	*GC-NT-10*	*GC-NT-20*
R2	0.532	0.481	0.523	0.337	*0.598*	n.a	n.a	*0.279*	0.534	0.518	0.548	0.309	0.594
NSE	-2.779	-1.845	-1.325	-1.334	*0.485*	n.a	n.a	*0.546*	-2.845	-1.810	-1.267	-1.343	-1.516
RMSE	0.040	0.041	0.041	0.055	*0.118*	n.a	n.a	*0.098*	0.040	0.040	0.041	0.056	0.062
PBIAS	5.558	-0.834	-1.984	12.820	*-9.623*	n.a	n.a	*16.182*	5.569	-0.848	-1.980	13.030	17.140

Table 1: Statistical indexes obtained comparing the daily SWC values obtained from CRNS and capacitive sensors in different positions and depths. The values highlighted in blue are the best for each year according to different indexes.

The preliminary results show that the estimation of moisture in vineyard varies in relation to the soil management, and is difficult especially when soil moisture is highly variable due to frequent rainfall and water dynamics are more complex.
Results are encouraging especially in critical conditions during dry seasons.

Figure 5: Comparison of the daily average of SWC obtained from point capacitive sensors and CRNS (best performing sensors).

Link to the abstract

5. Aknowledgments

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6. References

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