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Seasonal dynamics of topsoil water content in the Nucice experimental catchment (Czech Republic) studied with the CRNS (Cosmic Rays Neutron Sensing) technique

MASTER DEGREE THESIS IN
ENVIRONMENTAL ENGINEERING FOR SUSTAINABILITY

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Abstract

CRNS (Cosmic Rays Neutron Sensing) is a technology able to define soil moisture, mapping its presence at an intermediate scale, in the order of tens of hectares. This is due to its response to neutrons related to incident cosmic rays interacting with hydrogen, present in the water chemical composition.

The CRNS station efficacy to map the soil moisture comes from a proper footprint definition and samples weighting process. The footprint radius ranged between 100 and 150 meters and the acquisition depths between 25 and 50 centimeters, with an exponential decrease with the distance. Decrease of the soil samples relative weight relates to increasing distance from CRNS.

The experimental site was set in Nucice (Czech Republic) with the presence of a CRNS probe and probes in the soil. The aim of the thesis was to calibrate the CRNS performing three soil sampling acquisitions between February 2023 and June 2023. The station calibration is needed to rely on its soil moisture-neutron detection relation description. The neutron counts per hour detected by the CRNS, together with soil moisture considerations, were useful to define the Nucice field theoretical dry counting rate N0.

Laboratory analyses were performed by drying the soil samples to define the soil moisture presence or by investigating their organic carbon content. First person soil samples acquisitions were performed also to download environmental average conditions data that change the soil moisture predictions, taken into consideration by defining some correction factors.

After its calibration, CRNS turned out to be reliable in defining soil moisture patterns by plotting graphs throughout the seasons. This reliability can be a key to have better water use management in the agricultural field.

Key-words: Soil moisture, Cosmic Rays Neutron Sensing, CRNS calibration, theoretical dry counting rate N0.

Abstract in lingua italiana

La tecnologia CRNS (Cosmic Rays Neutron Sensing) è una tecnologia in grado di definire la presenza di umidità nel suolo, mappandone la presenza a una scala intermedia, nell'ordine delle decine di ettari. Questa capacità è collegata alla sua risposta ai neutroni legati ai raggi cosmici incidenti che interagiscono con l'idrogeno, presente nella composizione chimica dell'acqua.

L'efficacia della stazione CRNS nel mappare l'umidità del suolo deriva dalla definizione dell'impronta di influenza e dal processo di dare ai singoli campioni un loro peso relativo. Il raggio dell'impronta varia tra 100 e 150 metri e le profondità di acquisizione dei campioni tra 25 e 50 centimetri, che diminuisce esponenzialmente con la distanza. La diminuzione del peso relativo dei singoli campioni di suolo è legata all'aumento della loro distanza dal CRNS.

Il sito sperimentale era situato a Nucice (Repubblica Ceca) con la presenza di una stazione CRNS e di sonde nel terreno. Lo scopo della tesi era quello di calibrare la CRNS eseguendo tre acquisizioni di campioni di suolo tra febbraio 2023 e giugno 2023.

Calibrare la stazione CRNS era necessario per definire la relazione tra umidità del suolo e rilevamento di neutroni N. Il loro conteggio orario rilevato dal CRNS, insieme alle considerazioni sull'umidità del suolo, sono stati utili per definire il parametro N0 teorico relativo al campo di Nucice.

Le analisi di laboratorio sono state eseguite sia per essiccare i campioni di terreno per definire la presenza di umidità nel suolo o per indagare il loro contenuto di carbonio organico. Sono state effettuate acquisizioni di campioni di suolo in prima persona anche per scaricare i dati relativi alle condizioni medie ambientali che modificano le previsioni di umidità del suolo, prese in considerazione attraverso la definizione di alcuni fattori di correzione.

Dopo la calibrazione, il CRNS si è rivelato affidabile nel definire i modelli di umidità del suolo tracciando i grafici relativi durante le stagioni. Questa affidabilità può essere la chiave per una migliore gestione dell'uso dell'acqua in ambito agricolo.

Parole chiave: Umidità del suolo, Cosmic Rays Neutron Sensing, calibrazione del CRNS, parametro N0 teorico.

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1. Introduction

To perform a proper management of the natural resources in this and following decades, deep and complete research about how to sustainably manage water is being conducted in the past and recent decades. The world in which we are living is going more and more frequently against water scarcity challenges and other issues. The risk of droughts, for example, is becoming more and more relevant in these years affecting food security in the next decades, just to highlight one important sphere of intervention. (Schrön, 2017). The importance of efficient planning and management is key in the regions where water is scarce and very required.

Groundwater is a critical resource with is getting more and more scarce in some parts of the world. Agriculture, in general, is responsible for 70% of groundwater withdrawal worldwide reaching the 90% in some arid countries (1). With this considerable water consumption, a possible water shortage case can lead to an endangered food production. On the other hand, also advanced and correct management of catchments could avoid future problems related to floods and water damage that could directly affect food security.

Therefore, it's critical but key to understand the spatiotemporal water distribution in the agricultural landscape. For this reason, it's important to identify good data related to soil moisture quantities even if issues related to the different procedures chosen to be applied arise.

Unfortunately, it is difficult to measure the soil water content on the field scale. A useful property is to know that it's a very heterogeneous property, especially in the shallow soil profile (so the first 20 cm approximately called tilled layer) that will be the most investigated.

By now, the soil moisture quantity monitoring has been done with several measurement techniques from point-scale sensors to large-scale remote sensing approaches (Corradini, 2014; Robinson et al., 2008). Every technology adopted had its own issues, starting from the specificity of the point-scale measurements unable to be expanded and utilized in a general way. Common probes in the ground return the soil moisture value but related only to a specific place being a point measurement failing to give info spatially (Baroni et al., 2018). Another problem with the point sensors is the impossibility to install point-scale measurements due to their invasiveness in the field. This is translated into having an area of interest non-representative representation, as is also the case in the Nucice field. Indeed, to get an average soil moisture value many sensors are needed, leading to complications in maintaining and calibrating them singularly, often analyzing the data and being very expensive to be installed and maintained.

One the other hand, tackling to the larger soil moisture study generally done with remote sensing, apart from the high costs, low temporal resolution, interfering cloud coverage, and significant influence of surface conditions, the shallow penetration is the major disadvantage of this technology products (Entekhabi et al. 2004; Wagner et al. 2007; Chang and Hong 2012). Also, because it's a large-scale application, it would give poor results with respect to water content below the first 5 centimeters (Schrön, 2017).

This lack of spatial coverage in the point-scale measurements makes the interpretation of available data difficult (Vereecken et al., 2008) united with the unreliability of larger footprints studies. This led to the need to define a mid-range technology, with these issues being called the intermediate scale gap (Robinson et al., 2008).

For these reasons, another technology needs to be adopted and the choice fell on CRNS (Cosmic Rays Neutron Sensing) that closed the gap between the two, covering a hectometer scale and the root zone in depth. It's based on the inverse relationship between natural neutrons created by cosmic-ray fluxes and the presence of hydrogen, which is predominantly found as water in the soil. The method has shown to be accurate in several studies in a wide variety of environments (Baatz et al., 2014; Franz et al., 2012; Heidbüchel et al., 2016; Rivera Villarreyes et al., 2011).

It has been one important instrument to be used to detect water in catchments and helps to assess the water distribution. Indeed, stationary CRNS can be defined as particle detectors that measure the neutron intensity in the well-mixed pool of neutrons above the land surface (Zreda et al., 2012) (Schrön et al., 2017).

Other than a relation with the food security and agriculture sphere, the CRNS can be used also to droughts and floods predictions, following the previous months data and having the time to intervene in summer or spring (Findell and Eltahir 1997; Koster et al. 2004). Finally, it's important not to forget the fact that soil moisture state determines the efficiency of infiltration and percolation (e.g., groundwater recharge), evapotranspiration (i.e., feedback of water to the atmosphere), water availability for plants, and surface runoff (Schrön et al., 2017).

A single cosmic-ray neutron detector installed just 1–2 m above ground can sample the largely homogeneous neutron density at one location, thereby providing an area-average soil moisture signal of tens of hectares and tens of decimeters depth. Indeed, the spatial correlation lengths of soil moisture patterns, typically ranging between 30 and 60 m (Western et al., 2004) are enhanced with CRNS because it can precisely work with reported footprint radius up to 300 m (Desilets and Zreda, 2013) (Köhli et al., 2015).

These tens of hectares are averaged giving to this method the advantage of serving representative data for agriculture and hydrological models at the hectometer scale, having the ability to outperform some conventional in situ measurements in terms of representativeness for scales beyond several tens of meters (Köhli et al., 2015).

It's important not to forget how also the CRNS has some drawbacks that doesn't make it a perfect technology. The problematic side of calibration and the presence of water elsewhere other than soil water pools are the main ones.

To conclude this introduction, the thesis purpose was to acknowledge the importance of the Cosmic Rays Neutron Sensing technology giving more credits to its usage. The key objectives are the CRNS upfield calibration and the SWC (soil water content) calculation based on the detected neutron flux, for a better representation of the soil moisture quantity in the Nucice field catchment (Czech Republic). This data were meant to be used by the CVUT's department of Landscape and Water Conservation of the Civil Engineering faculty in Prague.

2. Theory and Literary Review

2.1 Cosmic Rays Neutrons

Cosmic radiation that is pounding the Earth originates mostly in our galaxy, for example, from acceleration in shock regions of supernova remnants (Blasi (2014), Köhli et al., 2015). The initiating cosmic ray particles, known as primary cosmic rays, consist mainly of highly energetic protons and helium nuclei which are related to the collapse of supernovas throughout the Milky Way, generating particles when they explode.

Once directed to the Earth, the planetary magnetosphere is speeding the particles. Fortunately, once overpassed, the incident cosmic rays directed to Earth have a lot of interactions during their path producing secondary neutrons, in a series of events called elementary particles precipitation. This causes their nuclei to explode into a shower of protons, neutrons and other subatomic particles (IAEA, 2017).

The neutrons continuous interactions with air particles in their path towards the Earth lead to a decrease of their energy. Neutrons start as very fast particles moving and hitting other atoms, causing their decay. In each of these collisions, approaching the Earth surface, the neutrons diminish their kinetic energy being converted into heat and ionization.

Protons are the main part of the particles flux after collision, accompanied by other charged nuclei. The energy spectrum of the primary cosmic rays peaks at around 1 GeV per nucleon as can be seen in Figure 1. Their arrival path and intensity towards the Earth is not linear as it's susceptible to different factors. One of these is the solar magnetosphere that leads to temporal variations with wide ranges of the cosmic-ray intensity based on the solar activity index.

In Figure 1 it's possible to understand the different correlation between energy and number of neutrons with the neutron energy spectrum above the ground that can be divided into three regimes:

- highly energetic neutrons around (GeV, generated in cascades in upper atmosphere and interacting with heavy atoms);
- evaporation neutrons around 1 MeV (after the interactions with heavy atoms in the air or ground evaporation, labeled also as fast neutrons);

- low-energy neutrons (slowed down by elastic scattering and elastic collisions with light atoms. Being sensitive to water until they are in thermal equilibrium with the environment (less than 0.5 eV)).

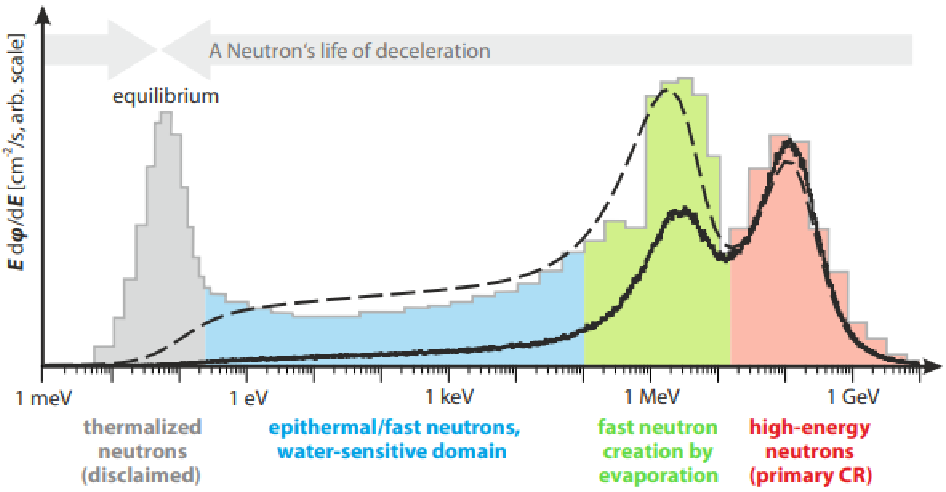

Figure 1 - *Neutron energy spectra at the surface: exemplary measurement by Goldhagen et al. [2002] in grey and simulated by Sato and Niita [2006] (dashed) (Köhli et al., 2015).*

As a first-order approach, one can expect neutrons to behave as a diffusive gas, as it was formulated by Glasstone and Edlund (1952) and applied to a footprint estimate by Desilets and Zreda (2013). But since every collision result in an energy loss for the neutrons, their mean free path between collisions changes and pure diffusion theory loses validity.

2.2 Neutrons-water interaction

Water vapor, oxygen, and nitrogen are particularly responsible for the neutron's deceleration in air. Therefore, the range a neutron can travel before thermalization is expected to increase with altitude (i.e., decreasing air density) and decrease with increasing air humidity. On the other hand, once arrived in contact with the Earth, the presence of dense soils, organic matter, or soil water content are expected to reduce the penetration depth (Köhli et al., 2015).

The most interesting interaction that happens to neutrons is however the one with hydrogen nuclei. They will keep on losing their energy through collisions with atmospheric nuclei and with a higher sensitivity related to hydrogen presence (2). This is because, when these neutrons hit hydrogen, they slow down considerably due to the presence of an equal mass causing a reciprocal elastic collision leading to being thermalized, having a lower energy. This elastic behavior is recognizable as related to hydrogen because it is the only element with molar mass equal to 1, as neutrons. With elastic collision it's meant having no deformation where all the energy is reciprocally transferred between balls (Köhli et al., 2015). With the other atoms only non-elastic collisions happen leading to the neutrons kinetic energy decrease.

The correlation between neutrons and hydrogen is interesting because of the hydrogen atom presence in water molecules (H_2O). They act as proxies for the water presence detection in the soil.

Now it's easier to understand the water-sensitive domain in Figure 1. Neutron interactions in the sub-MeV region (blue) are dominated by collisions with hydrogen. For this reason, this following energy band is most sensitive to water and organic molecules and thus most relevant for the method of cosmic ray neutron sensing. Finally, following its deceleration line and lower than 1 eV value, the neutrons have lost all their energy having done many interactions with the surroundings particles and are detected by the CRNS.

Highlighting another aspect in Figure 1, it's easy to notice that two black lines are also reported, one dashed and one continuous. It's important to remember that the hydrogen is present both in the air and the soil so, for this reason, after subtracting the ground reflected component over pure water, we obtain a pure incoming component (continuous black line), which is used as the source spectrum in this study. The more the ground reflected component is present, the greater the quantity of water in the soil, so it's possible to understand its general condition being dry, medium or wet.

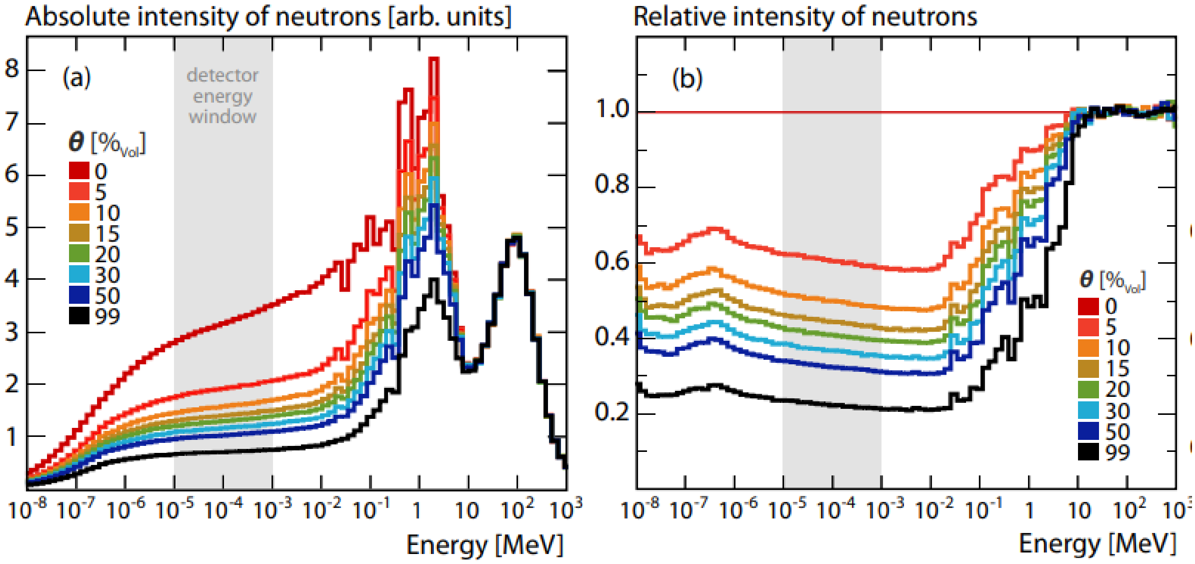

Figure 2 - *Calculated neutron spectra above ground with the highlighted energy window of the detector (grey) and the disclaimed thermal domain to its left, (a) for different soil moistures at an air humidity of 10 g/m3, (b) intensities of (a) scaled relative to 0% volumetric soil moisture (Köhli et al., 2015).*

Figures 2.a and 2.b confirm the efficient reduction of neutron intensity by soil moisture in the relevant energy range of the CRNS method (Köhli et al., 2015). The greater the soil moisture quantity, the less the intensity of neutrons detected.

2.3 Neutrons detection

Neutron detectors receive two components of neutron radiation: incoming neutrons from the atmosphere that have not had contact with the soil (N_{inc}) and reflected neutrons (N_{refl}) that scattered in soil and air before entering the detector almost isotropically (Schrön, 2017).

Due to the absence of electrical charge, neutrons can only be detected through nuclear reactions. Once these neutrons arrive in proximity to the Earth surface, the neutron detector constituted by PE shielding can be penetrated by the fast neutrons, the ones that hadn't a collision with hydrogen. This whole process defines how it's possible to count the neutrons which didn't interact with water.

Neutrons that hit hydrogen atoms before are too slow to penetrate the PE shield and cannot be counted. This is because the material polyethylene (PE) is a famous plastic and solid material which is sensitive to fast neutrons due to the chemical composition $(C_2H_4)_n$. PE is seen as a moderator material that surrounds the bare detector tubes and simultaneously shields thermal neutrons from entering the tube. This turns the moderated detector tube to be sensitive only to fast neutrons (Schrön, 2017).

This behavior causes an expected high number of neutrons detected related to the dry season while being detected less in the wet season, as more neutrons had contact with hydrogen atoms.

Once passed the PE shield, the neutron gets into the detector's pipe, ionizes the gas and it's counted by the CRNS. This was due to the equilibrium state reached by the neutrons which finally became thermalized and performed a random walk until they were detectable by the CRNS and absorbed (Köhli et al., 2021). Indeed, only thermalized neutrons have low enough energy to encounter a conversion reaction with high enough probability to be effectively detected.

It is further argued that the detection of the reflected component in air is indeed a promising strategy to infer water content of the soil, but special care should be taken about the influence of additional hydrogen sources in the environment. With measured humidity and air pressure it's possible to define the quantity of water in the air (Schrön, 2017). Also, vegetation presence plays its role in increasing the hydrogen content around the CRNS probe, with a higher amount in the spring and summer seasons.

Speaking about the interactions that generally could happen around the CRNS station, the density of the air is not high and so could happen to a neutron to not find another hydrogen atom in several meters. For this reason, whereas air is less, information about remote bodies can quickly propagate within hectometers. This huge spatiality, correlated with a homogeneous distribution of neutrons in the air, gives the possibility for the CRNS sensor to map the presence of humidity in the soil and water bodies up to several hectares.

However, the signal still may contain unidentified features of hydrological processes, and many calibration datasets are often required to find reliable relations between neutron intensity and water dynamics (Schrön et al., 2017).

3. METHODS

3.1 Description of the Nucice catchment, equipment and the CRNS detector

The Nucice field, subject to soil sampling and acquisitions throughout the whole duration of the thesis, is located 30 km east of Prague, as visible in Figure 3. Different experiments and studies are conducted there by the department of Landscape and Water Conservation of CVUT in Prague.

Figure 3 – *Visualization of Nucice field with respect to the whole Czech Republic.*

The catchment has an area of 0.531 km^2 and is in an agricultural landscape in the Central Bohemian Region, Czech Republic (catchment outlet location: 49°57'49.230''N, 14°52'13.242''E). The climate in the region is humid continental with mean annual temperatures equal to 7.9°C and annual precipitations equal to 630 mm. The soils are developed on Palaeozoic conglomerate and are classified as Haplic Luvisols and Cambisols. The soil texture is sandy loam, constituted by 9% clay, 58% silt, and 33% sand, on average (Zumr et al., 2019). Regarding the standard crop rotation, the field is dominated by winter wheat (Triticum aestivum L.), rapeseed (Brassica napus), summer oats (Avena sativa), and alfalfa (Medicago sativa) (Li, 2021).

The Nucice experimental catchment was established in 2011 and it was the object of multiple studies related to rainfall–runoff processes, soil erosion processes, and water balance of a cultivated landscape (Li, 2021). In this context, two CRNS stations are present. Anyway, for this study only the data from the CRNS_up are used, the one on the left in Figure 4.

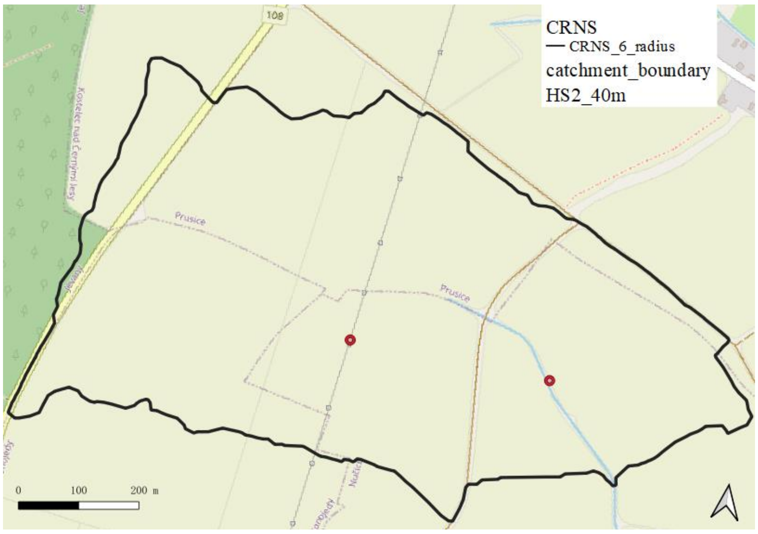

Figure 4 – *Position of the two CRNS stations (red dots) in the whole catchment.*

3.1.1 Nucice CRNS station

The CRNS station present in the Nucice field is provided by StyX Neutronica with a model called Black Pupper SP. The model series Black Puppet SP consists of the components (visible in Figure 5):

- a base unit with the neutron detector;
- amplifier and digitizer (nCatcher);
- a logger;
- additional sensors for environmental variables;
- a mounting pod;
- PV panel and battery for independent operation.

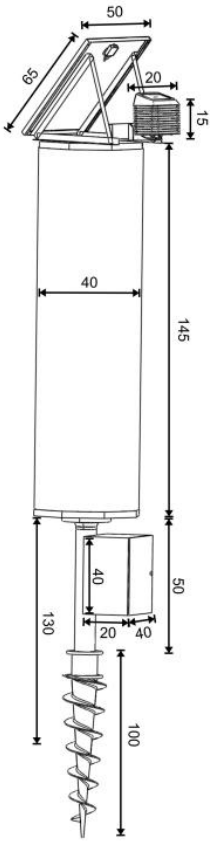

Figure 5 - *The full detector with its dimensions (StyX,, 2021).*

The main component of the Cosmic Ray Neutron Detector is the base unit. It consists of a HDPE casing with a thickness of 2.4 cm and the dimensions of 140 cm × Ø 40 cm. It contains up to five tubes with a length of 125 cm, which contain a coated copper foil as a converter and $ArCO_2$ as a counting gas.

In the specifics inside of the CRNS station, a potential of almost 1 kV is applied between the tube wall (the cathode) and a thin central wire (the anode). When a thermal neutron collides with an atom of the counting gas, the resulting ionization produces a cascade of electrons. These electrons are attracted to the anode producing a charge pulse. The potential is in this way measured between cathodes and anodes where there is electricity presence in the gas. Then count how many charges/events are present per certain time interval being the count rate.

The single-channel amplifier can be used to read out neutron pulses from up to five identical counting tubes. The logger acts as the central control unit of the sensor. It collects data from the neutron counters as well as several additional sensors for environmental variables (StyX, 2021).

A photo of the CRNS station in Nucice field can be seen in Figure 6.a. The Cosmic Rays Neutron Sensing station is usually mounted 1–2 meters above the ground surface, with the presence of a meteorological station near (Figure 6.b).

Figure 6 – *(a) CRNS station, (b) Meteorological station near CRNS.*

The cosmic-ray probes have been designed to be rugged, energy-efficient and independently powered using photovoltaic cells and they are equipped with a modem that sends data remotely on a server. Sometimes in the Nucice field catchment, during the autumn and winter months, there were difficulties with the CRNS station solar charging due to low amounts of sunny days. It was even possible to encounter situations in which the battery was able to work during the day, losing its energy in dark hours due to the low amount of daylight hours.

3.1.2 Laboratory equipment – Soil moisture analysis

The undisturbed soil samples were taken with the help of a defined shape cylinder with a volume equal to 250 cm^3. The soil moisture analysis were done in March, May and June after every soil samples acquisition.

Before the ovening, the samples were weighted to obtain the initial mass (m_{init}). Then the samples were oven dried at 105 °C for 72 hours until the steady mass was reached and the dry samples were weighted (m_{dry}). The soil moisture content was calculated as the difference between the two mass values before and after ovening. Later, the SWC in percentage was obtained by diving every sample value by the cylinder volume, obtaining a final average for every acquisition day.

3.1.3 Laboratory equipment – Organic carbon

After the samples to study have been dried in the oven to remove the soil water content, the chloric acid has been added to eliminate, in addition of another oven session, the non-organic carbon content.

This laboratory analysis was performed only in May after the second acquisition when soil samples for the organic carbon estimation were acquired. They were acquired directly from the tilt soil, the upper part situated in the first 12/15 centimeters.

Once the first drying procedure was performed, chloric acid was added the day after to eliminate the non-organic carbon quantity, drying again the soil sample for another two or three hours. Later, the samples were ready to be analyzed for their organic matter quantity being treated in the TOC analyzer at 950 °C for an amount of time that could arrive at maximum to six minutes.

The Total Organic Carbon (TOC) Analyzer, useful to track and measure the organic carbon content in the samples acquired in the field acquisition experiences. The machine burns the sample and measures the concentration of CO_2 and CO in the burnt gas. From the concentration it calculates the carbon mass.

Later every sample is processed inside the TOC Analyzer, where the measurements where there will be the integration of the concentration of carbon dioxide will take up to six minutes or even less. Finally, the mass of the organic carbon content measured is reported in mg for every sample. As with every laboratory procedure, also in this case some outliers in the results were spotted leading to mismatches in the final averages.

The resulting organic carbon content of the tested soil was equal to 0,755% and equal to 0,684% when the two outliers were canceled. In the two following Figure 7.a and Figure 7.b, the measured data are visualized, noticing how the R^2 is better in the second case.

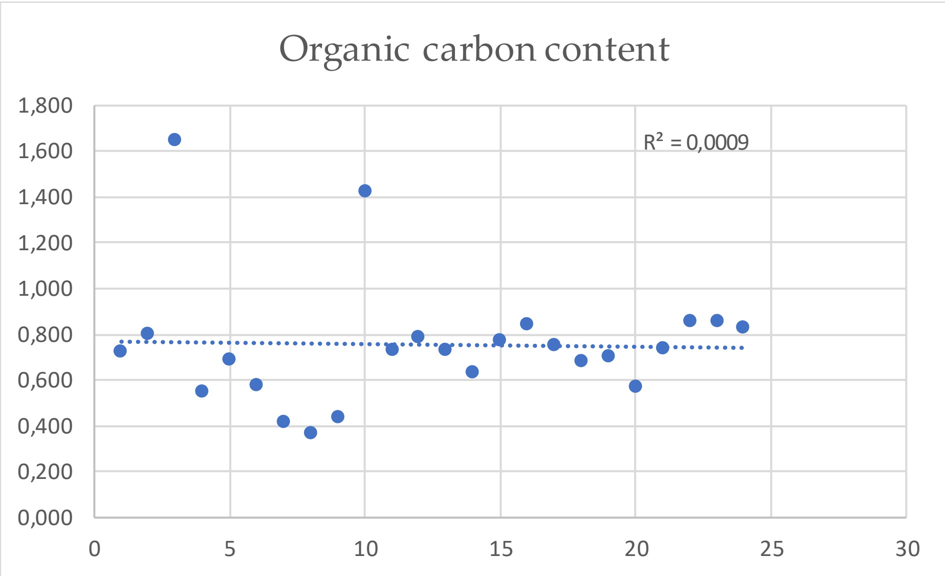

Figure 7.a – *Organic carbon content estimation with outliers.*

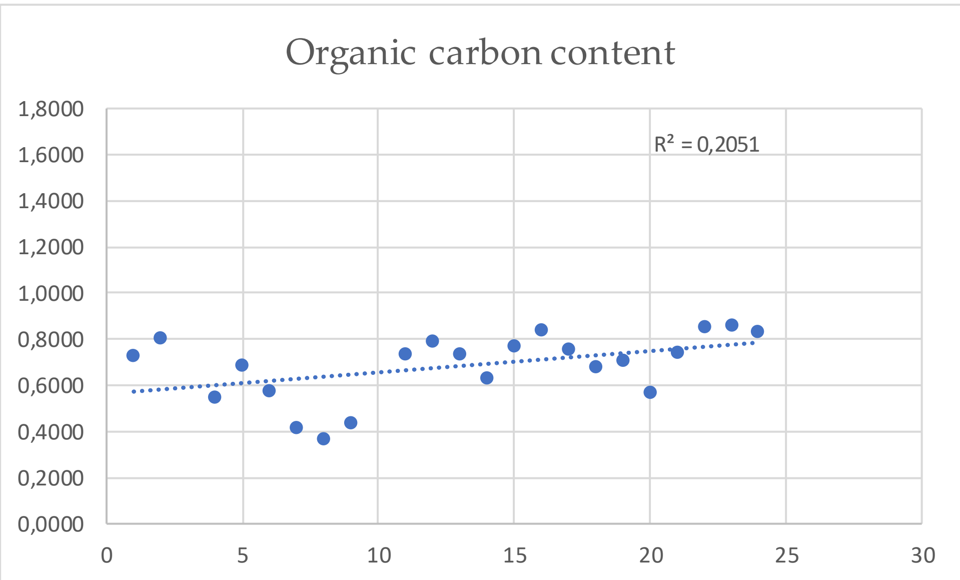

Figure 7.b – *Organic carbon content estimation without outliers.*

3.2 CRNS calibration

The relationship between the soil water content and the counted neutron by a neutron detector is specific for different locations and detectors. Therefore, each CRNS system needs to be calibrated and so it's the same for the upfield station in Nucice.

The term calibration defines the procedure of CRNS product calibration on datasets from calibration campaigns. The term typically refers to one or more days on which soil samples were taken in the field and then analyzed for soil water content in the lab (Schrön et al., 2017). This was performed three times in this thesis, in three different months (March 2023, May 2023 and June 2023) and acquiring different soil moisture values.

In the CRNS calibration procedure, the sensitivity of the probe decreases with distance and depth. Weighting procedures to calibrate the sensor and to compare independent point-scale measurements were introduced (Franz et al., 2012; Köhli et al., 2015; Schrön et al., 2017; Baroni et al., 2018). The distance-weighting procedures are connected to the CRNS calibration as it's necessary to obtain sufficient performance during calibration and validation with point data.

Simulations by Zreda et al. (2008), Franz et al. (2012b), and Köhli et al. (2015) have shown that the neutron signal integrated over a vertical soil column exhibits the highest sensitivity to the uppermost layers. For this reason, the following Figure 8 is key to show and understand the exponential relationship between the detector sensitivity and depth. Figure 8 helps to understand how the soil moisture data need to be evaluated considering the near the ground depths as more important rather than equally weighing all of them.

Both approaches follow an almost similar shape in Figure 8.a, but the conventional formulation is independent of distance r and soil bulk density so that's why it's chosen the revised formulation. It's clearer in Figure 8.b how conventional linear approach overestimates the relative contribution from shallow water when compared to the revised, exponential function, and neglects contributions from depths beyond $D^{conv} = z^{*}$.

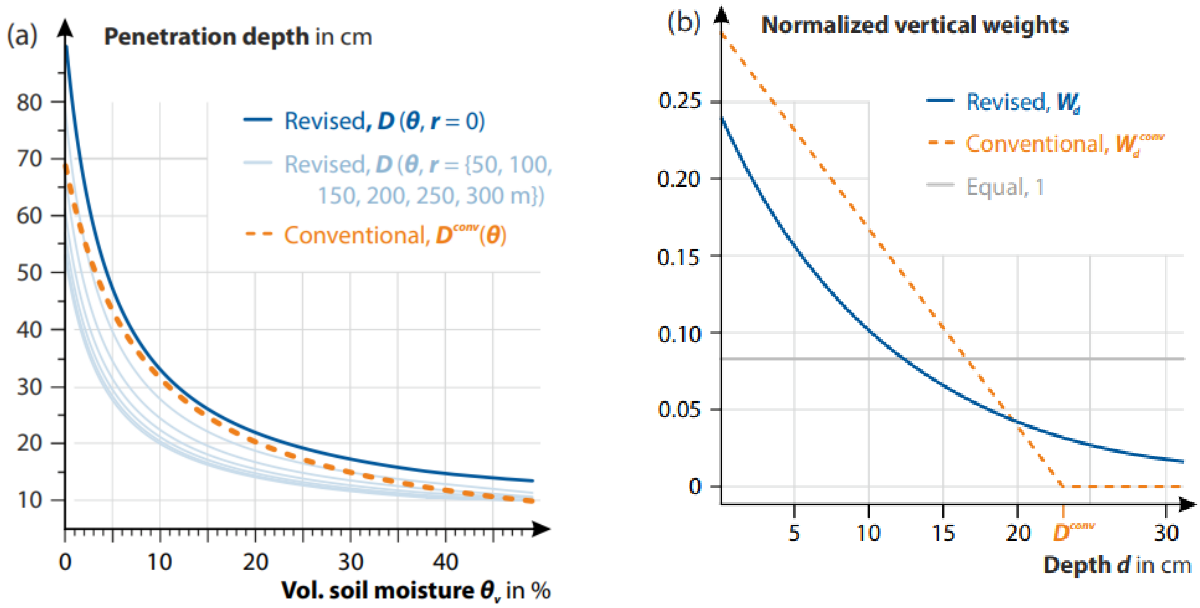

Figure 8 – *(a) A comparison between the revised and the conventional penetration depths. (b) Conventional linear approach compared to revised exponential approach (Schrön et al., 2017).*

$$W_d^{\text{conv}} = \begin{cases} 1 - d/D^{\text{conv}}, & d \leq D^{\text{conv}} \\ 0, & d > D^{\text{conv}} \end{cases}$$

$$\text{penetration depth}: D^{\text{conv}} \equiv z^*(\theta) = \frac{5.8}{\theta + 0.0829}, \text{ in cm;}$$

$$\text{see Franz et al. (2012b).} \tag{1}$$

The conventional vertical weighting, W_d^{conv}, is performed using a linear relation in Equation 1, which was based on Monte Carlo simulations from Zreda et al. (2008) and became widely accepted. Later the shortcomings described before led to the higher revised approach usage.

$$W_d\left(r, \theta, p, H_{\text{veg}}\right) = e^{-2d/D}, \tag{2}$$

In contrast, the revised vertical weighting function W_d, takes the full soil profile into account (as neutrons do) and considers the fact that the effective depth decreases with increasing distance r from the detector described in Equation 2. The variable D denotes the effective penetration depth, related to the radius r, the humidity value θ and the soil bulk density ρb.

This process can be defined as vertical weighting, where independent soil moisture measurements taken at different depths (d) need to be weighted differently to account for the soil moisture variations (Schrön et al., 2017).

Considerations about the depths where the soil samples need to be taken go on. To hypothesize in advance the percentage of humidity that could be found and the correlated depth that needs to be assumed before the acquisition, Figure 9 is taken as an example of how these parameters could change. It's clear the fact that in dryer seasons the soil samples need to be taken at higher depths due to the deeper presence of water in the soil. On the other hand, in wetter seasons there's a lower need to acquire soil samples in depths because the sufficient humidity presence could be right below the ground. Other than this, the more the distance from the CRNS increases, the more the parabola-shape will lead to less deep soil acquisitions. Results given by Zreda et al. (2008) imply that the sample depth ranges from 12 cm for saturated soil to 76 cm for dry soil. These values have been confirmed by the work of Köhli et al. (2015), who report a sample depth between 15 cm and 83 cm for their simulated soils at CRNS position (IAEA, 2017) in Figure 9.

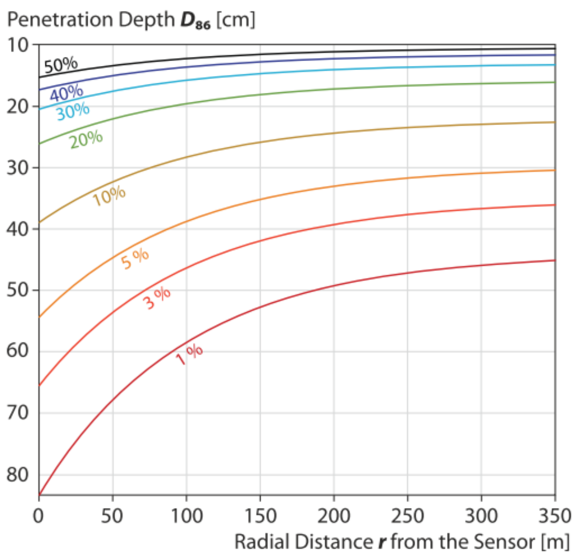

Figure 9 – *Dependency of the penetration depth with the distance radius from the CRNS station (Köhli et al., 2015).*

In the soil moisture data measured within the first 0 to 10 m radius and 0 to 20 cm depth around the sensor are most sensitive for calibration purposes. It is thus recommended to reduce the uncertainty of those measurements, for example, by increasing the number of samples in that area. And, in general, it can be recommended to select a significant portion of available sampling points within the nearest 25 m, since 30–50 % of detected neutrons typically originated in that area (Schrön et al., 2017).

Regarding the calibration, it's recommended to perform the acquisition only in periods when the site had not been exposed to rain events for few consecutive days so when there's no water ponding on the surface. Ideally, it can be done a few days after the last rainfall when the water is properly distributed in the soil profile.

Once defined the different considerations that depths need to face, a highlight is set on distances from CRNS. Starting from the footprint area width, that needs to be defined before every acquisition campaign, if soil is wet it detects the neutrons from a smaller area due to the attenuation of neutrons by water in the vicinity. The area size depends on the water content in the soil so, when the quantity of water in soil is higher, the related neutrons far away cannot reach the CRNS as they have a lot of interactions before the arrival onto detection.

In dryer seasons the footprint extension needs to be higher according to Köhli et al. (2015). A difference in the detected neutron intensity is clearly visible in the comparison between the two soil water contents in Figure 10.

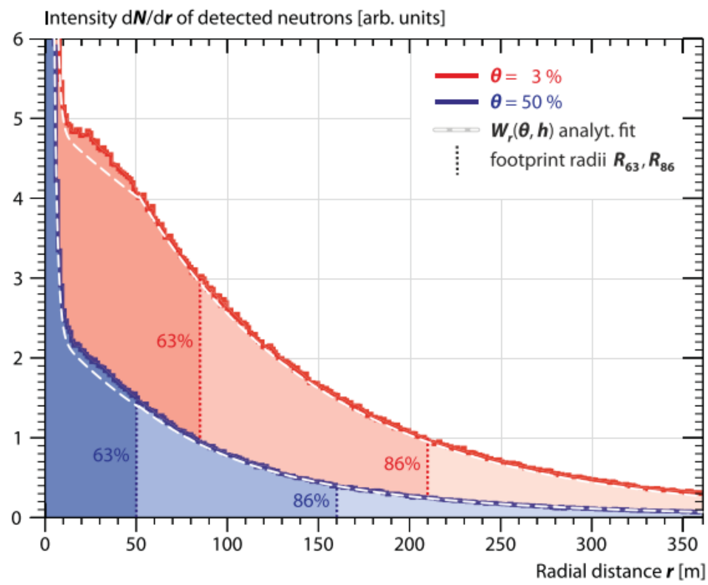

Figure 10 – *Dry condition (red curve, 3% soil moisture) and wet condition (blue curve, 50% soil moisture) for the neutron detection footprint. Definition of the exponential decay of detected neutrons over travel distance using the two e-folding lengths, the 86% quantile, in accordance with the radial decrease of the detected neutron intensity Wr (Köhli et al., 2015).*

Even if the CRNS detects neutrons symmetrically and the circular shape of the footprint remains isotropic for most field applications, it's important to remember the possible heterogenic water presence in the soil. For example, large water bodies or forests nearby can reduce range and intensity of detected neutrons from that direction or dry roads can contribute to an overestimation of neutron counts by a few percent. For this reason, the identification of soil and hydrologic transition zones within the field is important for understanding how variations in soil water content influenced CRNS readings in every acquisition done. This is not the case in Nucice field as the area around CRNS is quite homogeneous, without the presence of forests or roads.

The weighting procedure need is related to the fact that the more the footprint is spread, the more the value from far away samples needs to be less significantly considered in the soil water content estimation, because connected to probable overestimations due to high presence of soil moisture distant from the CRNS station (Flynn et al., 2021).

For this reason, after having understood the importance of a proper weighting, with different radius distances from the CRNS different weights have been assigned to each data point in the calculation of a so-called weighted average (Schrön et al., 2017).

Acquiring correct soil moisture values with the premises described, by taking an appropriate amount of soil samples, is key to have a correct final soil moisture value. At the same time measuring the neutron flux N at the CRNS is also important. The final averaged water equivalent $h_{\theta i}$ for the whole footprint is then combined with the neutron count rate N obtained by the CRNS station to derive the theoretical dry counting rate N0 for the studied field. The aim of calibration is, in essence, to find the value of N0.

A calibration curve for soil water content has been obtained by fitting simulated ground level neutron fluxes to the semi-empirical shape defining equation (Desilets et al, 2010), which can be written in a more generalized form as:

$$\theta_T = \theta_V + \theta_{LW} + \theta_{SOC} + \theta_B + \ldots + \theta_i = \left(\frac{a_0}{F(t)\frac{N}{N_0} - a_1} - a_2 \right) \rho_b \tag{3}$$

where

$a_0 = 0.0869$
$a_1 = 0.3720$
$a_2 = 0.1236$

where θ_T (cm^3/cm^3) is the total volumetric water content. This total consists of soil water content θ_V, clay lattice water content θ_{LW}, the soil organic carbon water equivalent θ_{SOC}, and the biomass water equivalent θ_B all in volumetric units (cm^3/cm^3). The term '+ … + θ_i' allows for the inclusion of other pools of hydrogen which might be present but generally assumed to be zero. As a matter of algebraic manipulation, these volumetric quantities can be expressed in gravimetric units by simply multiplying their values by the soil bulk density, ρb (g/cm^3).

Once the θ_T is obtained, the other humidity values calculated can be subtracted from it, to obtain the soil water content θ_V, the main variable of interest for the field studied.

The sum of these humidity contributions, as visible in the Equation 3, can be defined also with the contributions of other factors. The correction factor F(t) accounts for variations in barometric pressure, solar activity and absolute air humidity (weather parameters). These three variables have in common that they change in time, in accordance with changing meteorological and space weather conditions.

The constants a0, a1 and a2 define the shape of the calibration function. (IAEA, 2017).

About the theoretical dry counting rate N0, once acquired its value after the first acquisition, it's possible to spot the variation of humidity and neutron counts rate in the different months when the acquisitions were conducted. This is because the N0 of the same field needs to be constant and different constant values can be obtained, as visible in Figure 11, only related to the approach chosen (equal, conventional and revised).

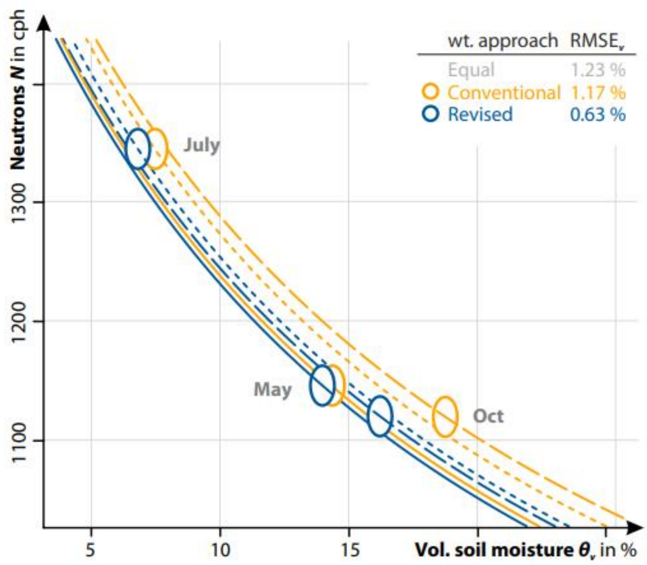

Figure 11 - *Sizes of the circles indicate the corresponding uncertainty range of the measurement, while every such measurement corresponds to a calibration curve θ (N, N0). The conventional weighting approach is not able to provide a unique theoretical line through the 3 calibration days. The revised approach converges the datasets to confirm the accepted neutron*

theory almost in a single calibration curve within uncertainties (size of ellipses). Example taken from Schrön et al. (2017) where May, July and October were the three months when the acquisitions of soil samples were performed.

In this thesis specific case, three campaigns/calibrations acquiring soil samples were conducted that led to obtain three different points in a (Vol. soil moisture, Neutrons N) graph. It was necessary to repeat calibrations three times to get a representative N0, being an average value.

The example reported in Figure 11 was chosen because there were values of soil moisture and corresponding neutron counts N that have been obtained in three different acquisitions. It's possible to appreciate the fact that the three different months acquisitions follow a satisfying path in the revised approach, confirming what was previously defined. This is even more confirmed by the RMSE value, the lowest between the three approaches.

In addition to the considerations about the representative domain, the arrangement of the soil samples can play a crucial role for the CRNS evaluation performance. If the locations of the soil samples (or in situ monitored soil profiles) do not cover the CRNS footprint representatively, the corresponding data would not be able to explain parts of the neutron signal (Schrön et al., 2017).

3.3 Correction factors

The parameters a0, a1 and a2 define the shape of the calibration function. The numerical values have been determined using neutron transport simulations and a best fit procedure, as reported by Desilets et al. (2010).

Unfortunately, the coefficients given were specific for that work. The limitation has been eliminated, with no loss of accuracy, by adjusting the coefficients originally reported by Desilets et al. (2010). This adjustment has the effect that now N0 is defined as the dry counting rate (whereas the previous coefficients implied a small amount of residual water in theoretical dry soil) and it's done recalculating the total correction factor F(t).

The total correction factor F(t) can be decomposed into the product of several specific correction factors calculated for every acquisition conducted.

In particular:

$$F(t) = f_{bar} \cdot f_{sol} \cdot f_{hum} \cdot \ldots \cdot f_i \quad (4)$$

The f_{bar} is the barometric pressure correction factor, calculated as:

$$f_{bar} = \exp[\beta(P(t) - P_0)] \quad (5)$$

where P(t) is the measured barometric pressure (in hPa), P_0 is a fixed reference pressure in hPa, usually taken to be an approximate long-term average for the site. β is the pressure coefficient, which at high to mid latitude can be assumed to be 0.0077 hPa^{-1}.

The second factor corrects for variations in solar activity, and is calculated as:

$$f_{sol} = \frac{M_0}{M(t)} \quad (6)$$

where M(t) is the counting rate of a neutron monitor at time t, and M_0 is the counting rate at an arbitrarily chosen reference time. The idea is to normalize all counting rates to a single reference solar activity level; the exact reference level chosen is not important if the user is consistent.

The, f_{hum}, adjusts the counting rate for changes in the absolute humidity of the atmosphere (H(t)). As absolute humidity rises the counting rate tends to drop. According to Rosolem et al. (2013), the neutron rate can be corrected with the formula calculated as:

$$f_{hum} = 1 + 0.0054 \cdot H(t) \quad (7)$$

where H(t) is in units of g/m^3. The absolute humidity of a well-mixed atmosphere can be calculated from a local measurement of air temperature (T) and relative humidity (U) by first calculating the saturation vapor pressure:

$$e_w = 6.112 \exp\left(\frac{17.62T}{243.12 + T}\right) \quad (8)$$

where ew (hPa) and T (°C) (WM0 Guide, 2008), and then calculating absolute humidity:

$$H = \frac{U}{100}\left(\frac{e_w k}{T + 273.16}\right) \quad (9)$$

where U is expressed as a percentage and k is a constant equal to 216.68 (g*k)/J.

An advantage of Equation 3 is that it's easy to invert, such that:

$$N_0 = \frac{N}{\left(F(t)\frac{a_0}{(\theta_T/\rho_b)+a_2}\right)^{-1} + a_1} \tag{10}$$

It's possible in this way to obtain the N0 value with the correction factors.

It's apparent that the value of N0 is strictly defined for given reference values of P_0 and M_0, and for the value H(t)=0. The choices for P_0 and M_0 are largely arbitrary, but it is important to remain consistent in using the same reference values for a given site. In the case where the reference conditions are assumed to be the same as the conditions at the time of the calibration, then F(t) = 1 (IAEA, 2017).

For the N0 calculation, after every acquisition, an online tool was used, a N0 calculator from the CRNSlab website (3).

The online tool is easier to use since the N0 value restitution already considers the total correction factor F(t) and the several specific correction factors that constitute it.

3.4 CORNY

CORNY is a Cosmic-Ray Neutron processing toolbox for Python and was used to calculate the soil water content data series. This is done by reading the original measurement files, performing basic quality control, correcting functions, and suggesting a first-order soil water conversion.

This project was initially developed by Martin Schrön et al. but it's open for contributions. It's been utilized for this thesis to develop the graphs defining the soil moisture changes throughout the seasons (4).

3.5 Acquisition of data for CRNS calibration and sampling techniques

To conclude the "Methods" chapter, a description about how the soil samples were acquired was key to be defined.

The sampling technique strategy was based on concentric rings, even if it can only be recommended for homogeneous terrain as this case study (where each sampling location is known to contribute equally to the signal) and should be adapted on the local site environmental conditions (air pressure, humidity, soil moisture, vegetation cover). The assumption was for this reason directed towards a circular footprint area with $A = \Pi r^2$ (Köhli et al., 2015).

3.5.1 March 2023

The first acquisition, performed on the 21st of March 2023, was the acquisition done in wet conditions in the Nucice field.

For this reason, to define an approximate depth and distances where to get the samples and construct the acquisition plan on QGIS, the humidity was assumed to be equal to 20%/30%. The GPS coordinates of each sample were pre-defined and possible to be seen in the field using the QField app.

The weather was sunny with an average air temperature equal to 10,6 °C. It was noticeable the absence of vegetation as it was still winter season.

About the QGIS acquisition plan, it was a priori defined to obtain a symmetrical scheme and a higher number of samples closer to the probe, due to little contribution of neutrons over long distances. These assumptions led to design an acquisition scheme as in Figure 12, with:

- At 2 meters from the probe → 4 samples (at 25 cm depth));
- At 10 meters from the probe → 8 samples (at 25 cm depth);
- At 25 meters from the probe → 12 samples (at 21 cm depth);
- At 60 meters from the probe → 12 samples (at 21 cm depth);
- At 100 meters from the probe → 4 samples (at 18 cm depth).

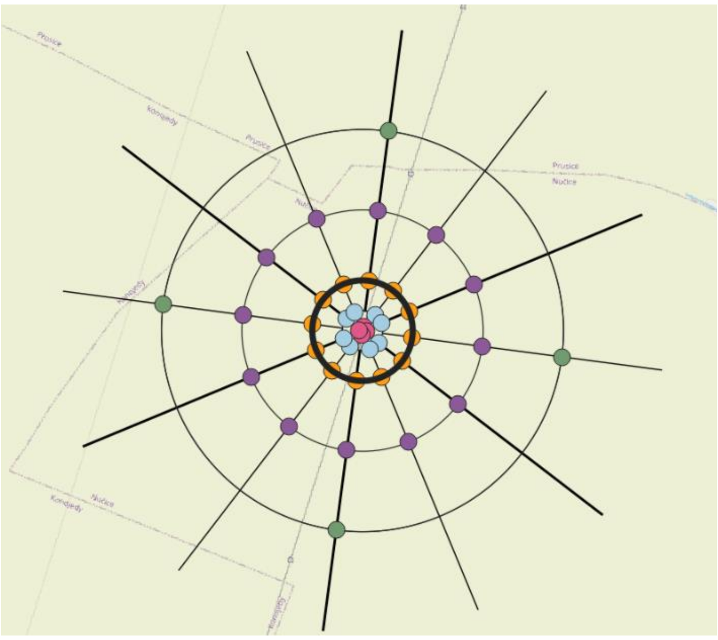

Figure 12 - *First acquisition map with dots at 2 meters (pink), 10 meters (light blue), 25 meters (orange), 60 meters (purple) and 100 meters (green) distance.*

As it's related to the wet measurement, the depths in the soil where the samples were taken were not changing much as the distance increased. This was since the distance from the probe wasn't much and the depths curves for higher values of soil humidity were less steep with respect to the dryer ones (Figure 9).

Other than the soil samples, in the same positions described in Figure 12, values about soil moisture were obtained using HydroSense II. These data were relevant for the upper 12 cm of the soil profile and were used to obtain more SWC measurements.

3.5.2 May 2023

After the first dry acquisition performed in March, this second was related to a medium dry condition, performed on the 11th of May.

The weather was cloudy with an average air temperature equal to 17,0 °C. Still there wasn't any presence of vegetation in the field.

About the QGIS acquisition plan, the acquisition scheme design was done, as in Figure 13, with:

- At 2 meters from the probe → 4x2 samples (at 20- and 45-cm depth) (as there could be instruments near the CRNS it's good to have the measurement right below the probe but not too much to avoid the risk of intercepting the instruments present);

- At 15 meters from the probe → 8x2 samples (at 20- and 45-cm depth);
- At 25 meters from the probe → 8 samples (at 30 cm depth);
- At 100 meters from the probe → 4 samples (at 30 cm depth);
- At 150 meters from the probe → 2 samples (at 25 cm depth).

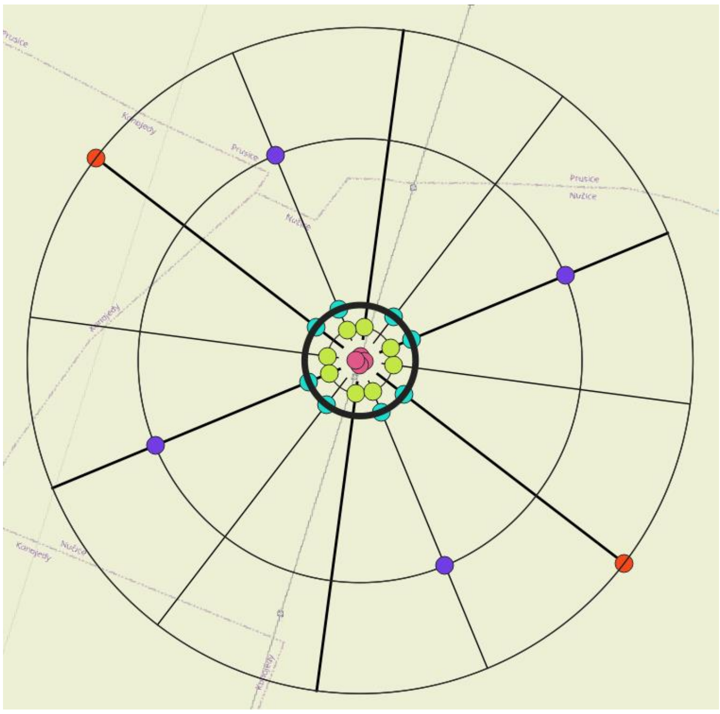

Figure 13 – *Second acquisition map with dots at 2 meters (pink), 15 meters (light green), 25 meters (light blue), 100 meters (purple) and 150 meters (red).*

In this acquisition, due to the increase of depths where to take samples, there was the need to have two soil samples at different depths in the same position, following Figure 9 scheme once again.

3.5.3 June 2023

The last acquisition, related to dry conditions, was performed on the 26th of June.

The weather was sunny with an average air temperature equal to 21,8 °C. For the last acquisition, the vegetation was present with its contribution to hydrogen presence.

Their water content and so their hydrogen pool, interact with the neutrons approaching leading to miscalculations. For this reason, their height is important to consider in the radial weighting function definition.

All the detailed average environmental conditions for the three acquisitions are reported in Table 1.

Their water content and so their hydrogen pool, interact with the neutrons approaching leading to miscalculations. For this reason, their height is important to consider in the radial weighting function definition.

About the QGIS acquisition plan, the acquisition scheme design was done, as in Figure 14, with:

- At 2 meters from the probe → 4x2 samples (at 25- and 50-cm depth);
- At 15 meters from the probe → 8x2 samples (at 25- and 50-cm depth);
- At 60 meters from the probe → 8 samples (at 30 cm depth);
- At 100 meters from the probe → 2 samples (at 30 cm depth);
- At 150 meters from the probe → 2 samples (at 25 cm depth).

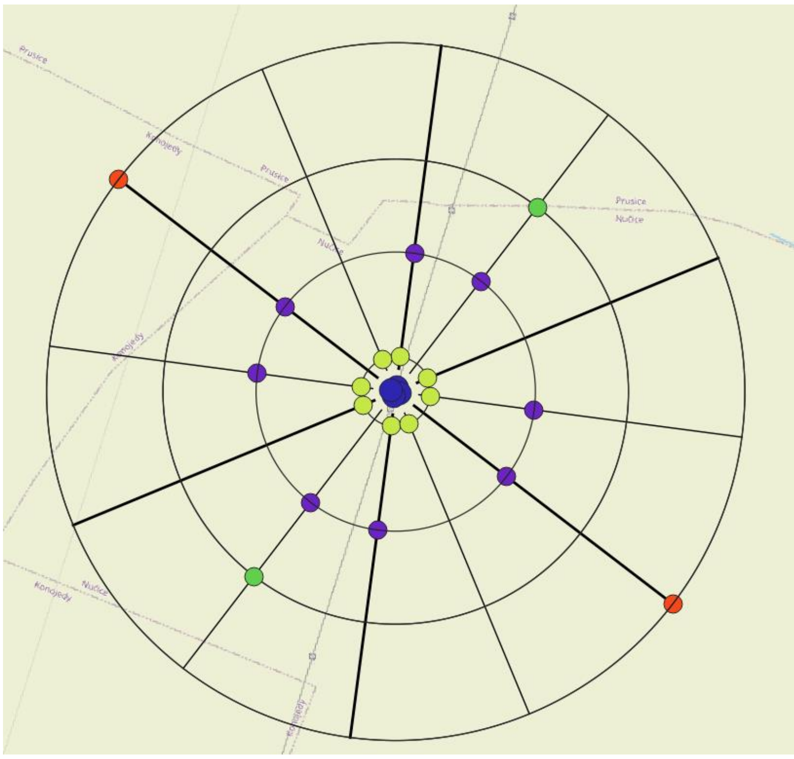

Figure 14 – *Third acquisition map with dots at 2 meters (blue), 15 meters (light green), 60 meters (purple), 100 meters (green) and 150 meters (red).*

4. Results

The final soil moisture value obtained for every acquisition is subjected to the utilization of a radial weighting function reported in Figure 15. All the three radial weighting functions related to the three acquisitions are merged.

As can be clearly seen, the radial weighting functions related to the three acquisitions have a very similar shape.

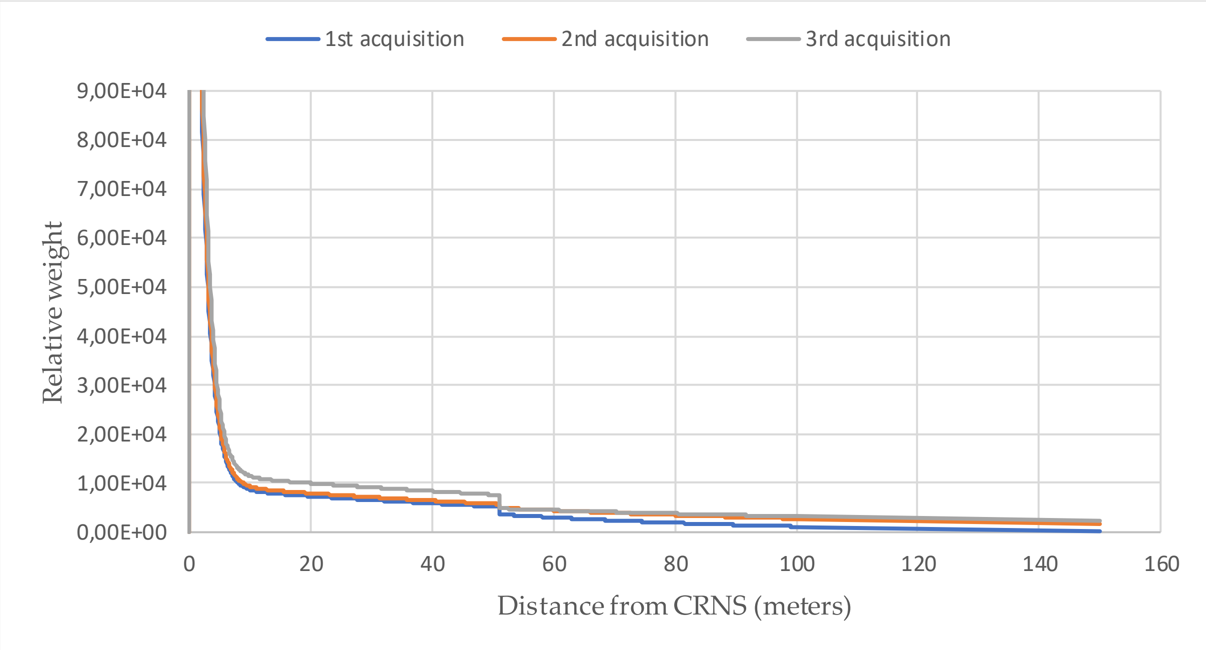

Figure 15 – *Radial weighting functions for horizontal averaging related to the three acquisitions in accordance with Equation 4 from Köhli et al. (2015).*

4.1 Calibration procedures

All the average environmental values for all the three acquisitions, used as inputs for the N0 calculation online tool (3) are summarized in Table 1.

Table 1 – *Average environmental conditions for all the three acquisitions.*

	1st acquisition (March)	2nd acquisition (May)	3rd acquisition (June)
Air temperature (°C)	10,9	17,0	21,8
General weather	Sunny	Cloudy	Sunny
Vegetation height (m)	/	/	0,3
t (time) (min)	1440 (1 day)	1440 (1 day)	1440 (1 day)
Soil bulk density (g/cm^3)	1,406 ± 0,148	1,065 ± 0,165	1,228 ± 0,105
Air humidity (g/m^3)	7,42	5,97	9,86
N (Neutron counted per hour) (cph)	1831	1862	2045
Air pressure (mbar)	971,8	972,4	967,1
P0 (air pressure at sea level) (mbar)	1013	1013	1013
RH (relative humidity) (%)	72,7	58,0	68,4
Fsol (solar activity factor)	1	1	1

SOC (soil organic content) (g/g)	0,007	0,007	0,007
LW (lattice water) (g/g)	0,04	0,04	0,04
N0 (cph)	2270	2309	2150

These values confirmed how the N0 values are very similar to each other describing how a general value valid for the CRNS location in Nucice can be defined.

Regarding the N0 general value for Nucice field, it's expected to be very similar in the three acquisitions. It's shown in Table 1 how it's never the same but in the range of values. The two values related to March and May are very close to each other, while the third value is a bit lower maybe due to errors in measuring soil moisture.

For this reason, the real N0 value to consider is in the middle between them, averaging it around a 2243 counts per hour value. New calibrations can be done in the future to get a more reliable value that describes the field.

Different soil moisture values for the three acquisitions, obtained by weighing the soil samples considering the radial weighting functions in Figure 15, are reported in Table 2.

Table 2 – *Soil samples weighted to obtain a final soil moisture for all the three acquisitions.*

	1st acquisition (March)	2nd acquisition (May)	3rd acquisition (June)
SM (soil moisture) (%)	29,4	19,4	16,5

Then, in Figure 16 is reported the final graphical representation of the three acquisitions done during the thesis. The three points have a similar N0 value but differ in the soil moisture and N values as reported.

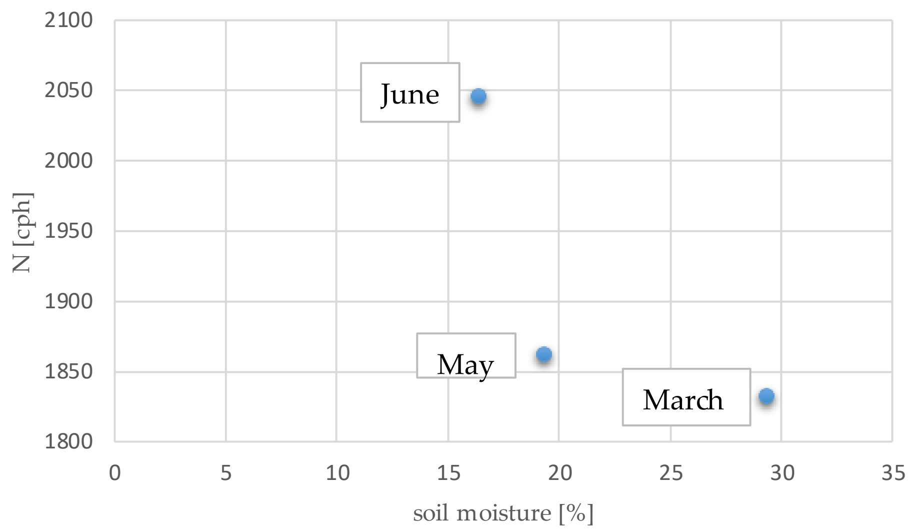

Figure 16 – *Soil moisture and N values in the three acquisitions.*

4.1.1 HydroSense II probe calibration

Hydrosense II calibration is a smaller and different step with respect to the CRNS calibration previously done. The calibration was done only in the first acquisition to define how valuable and reliable it would be to confirm the soil moisture data obtained with soil samples.

Generally, the points were able to follow a particularly good trend confirmed by the R^2 value equal to 0,9889 and visually by Figure 17 trend line, where the soil moisture values obtained by HydroSense II and soil samples are plotted together. This confirms the HydroSense II reliability as an instrument to verify soil moisture values where the soil samples were not taken.

This was obtained with the exclusion of only two soil samples that could be considered outliers as they were very far from the tendency line. The two outliers' zones are easily visible in Figure 18 because the highest soil moisture values, defined by dark blue colors, are in the exact positions where the uncommon values were found.

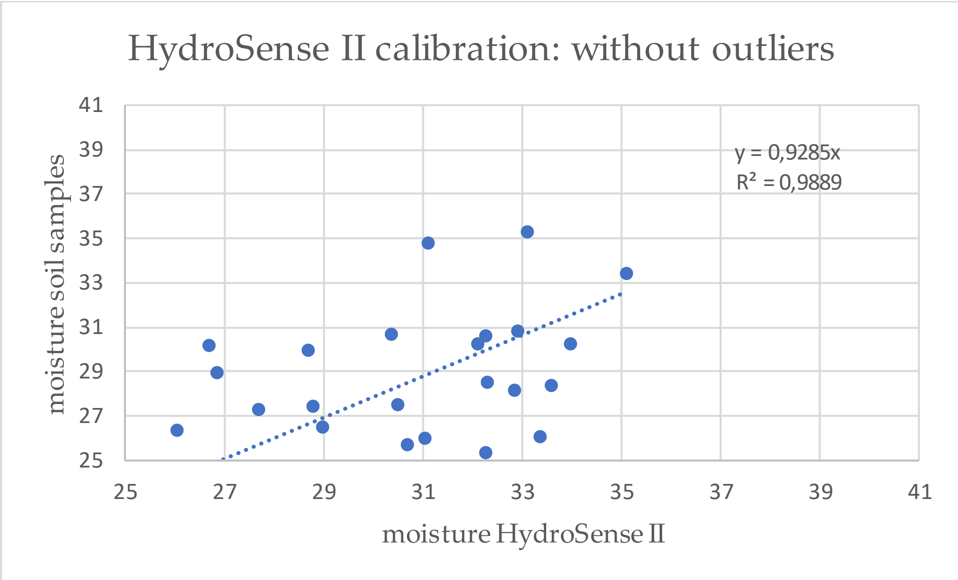

Figure 17 – *HydroSense II calibration.*

The HydroSense II value obtained at every acquisition are displayed in Figure 18, Figure 19 and Figure 20 with the kriging method deriving both the soil moisture values and the errors correlated.

The kriging method performed is the best way, by interpolation, to create soil moisture values map out of multiple points acquisition (black dots). This is necessary because a soil moisture value in every pixel can't be obtained.

In Figure 18/19/20, the interpolated spatial distribution of the topsoil water content in a vicinity of the CRNS system is shown. Kriging error estimation for every acquisition is also important to be shown as it defines how the error is very low in correspondence of a point and in its vicinity creating a reliable map.

The black circle radius of the circle is equal to 150 meters and the CRNS probe is situated in the center of the circle.

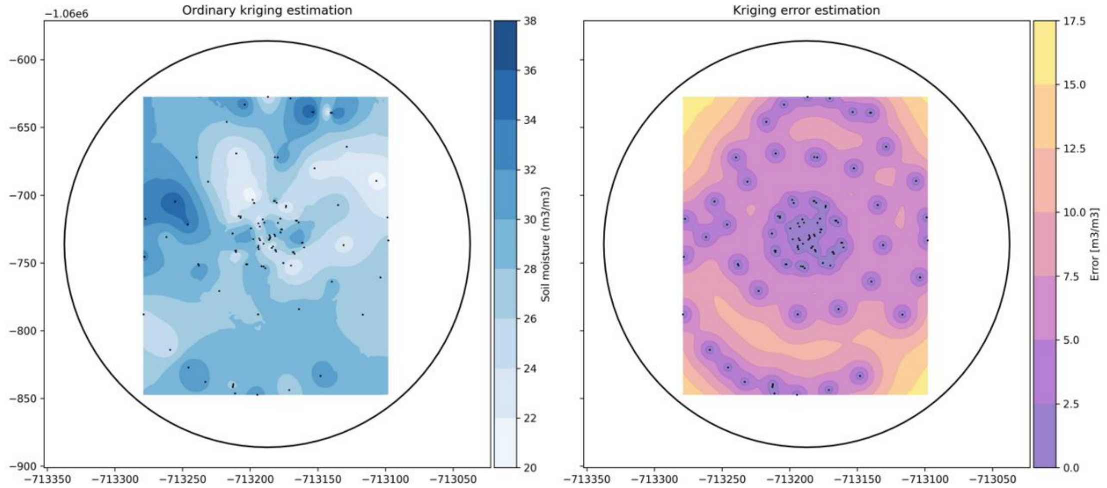

Figure 18 – *Interpolated spatial distribution of the topsoil water content in a vicinity of the CRNS system for the first acquisition.*

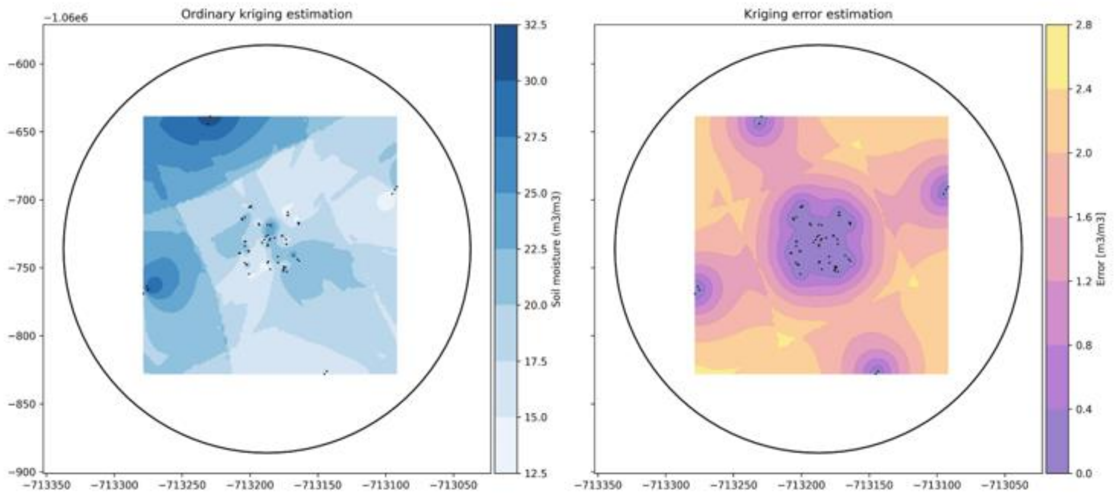

Figure 19 – *Interpolated spatial distribution of the topsoil water content in a vicinity of the CRNS system for the second acquisition.*

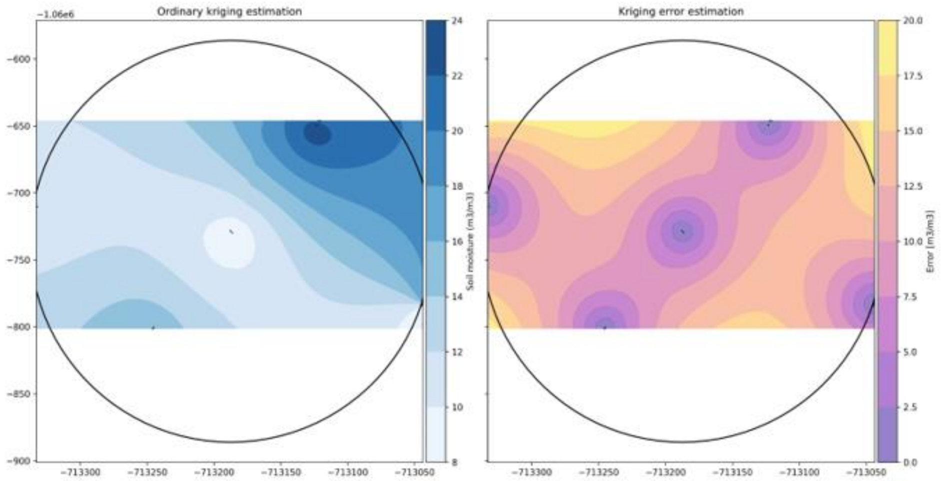

Figure 20 – *Interpolated spatial distribution of the topsoil water content in a vicinity of the CRNS system for the third acquisition.*

In Figure 18, the first calibration, the number of dots is way more because it was supposed to be the HydroSense II calibration acquisition also. In the other two acquisitions they were just used as a supplement and so the number of HydroSense acquisitions is lower.

4.2 Comparison between CRNS and probes soil water content

The following Figure 21 reports the data acquired during my staying in Czech Republic, from February 2023 to end of June 2023. It starts in April 2023, a few days after the first acquisition performed. The first, in order of appearance, is the timespan of precipitation throughout the months (Figure 21.a).

Figure 21.b reports the N obtained during the months (neutrons detected in counts per hour) from the CRNS station. The yellow curve refers to the value not processed while the red curve defines all the corrected values considering air humidity, temperature and pressure. In the thesis calculations the first curve values are the one measured by the CRNS station while the second curve is constructed considering the correction factors, visible in the N0 online calculator tool used (3).

In the third graph (Figure 21.c) is reported the soil water content estimated starting from the CRNS neutron counting rate, confirming a descending trend in spring.

Every single soil moisture value reported in Table 2 is confirmed visually by looking at Figure 21.c that shows the complete soil water pattern during the seasons for the interested field. This graph is reconstructed using the CORNY program, being a useful instrument to confirm the hypothesis about soil moisture (4).

Finally, in Figure 21.d and Figure 21.e it's possible to visualize how the soil moisture content data at PL143 (closest station to CRNS) and PL144 (station inside the field, distant from CRNS) confirm, in comparison with Figure 21.c, the whole soil moisture content during the seasons being a relying instrument to be used, obtained from the soil probes related to the stations.

The sensors are displayed at different depths in the soil but, for the considerations made above, only the curve related to the topsoil has to be considered, so in the 10-20 cm range. This is because there is a high seasonal dynamic, which is more pronounced in the space of the point sensors installed in 10 cm.

The higher depths are displayed the same as the CRNS is a technique capable of monitoring soil moisture even at the shallowest soil profile, being an important benefit.

Finally, there are clear peaks during the rainfall periods. When there is a rainfall or a short-term water ponding on the surface (during or after the rainfall) the SWC is overpredicted. The reason is that CRNS assumes the water to be in the soil, but it's on the surface, in the atmosphere or on the sensor, which are very sensitive areas. Therefore, the SWC content during rainfall periods and shortly after should not have been trusted.

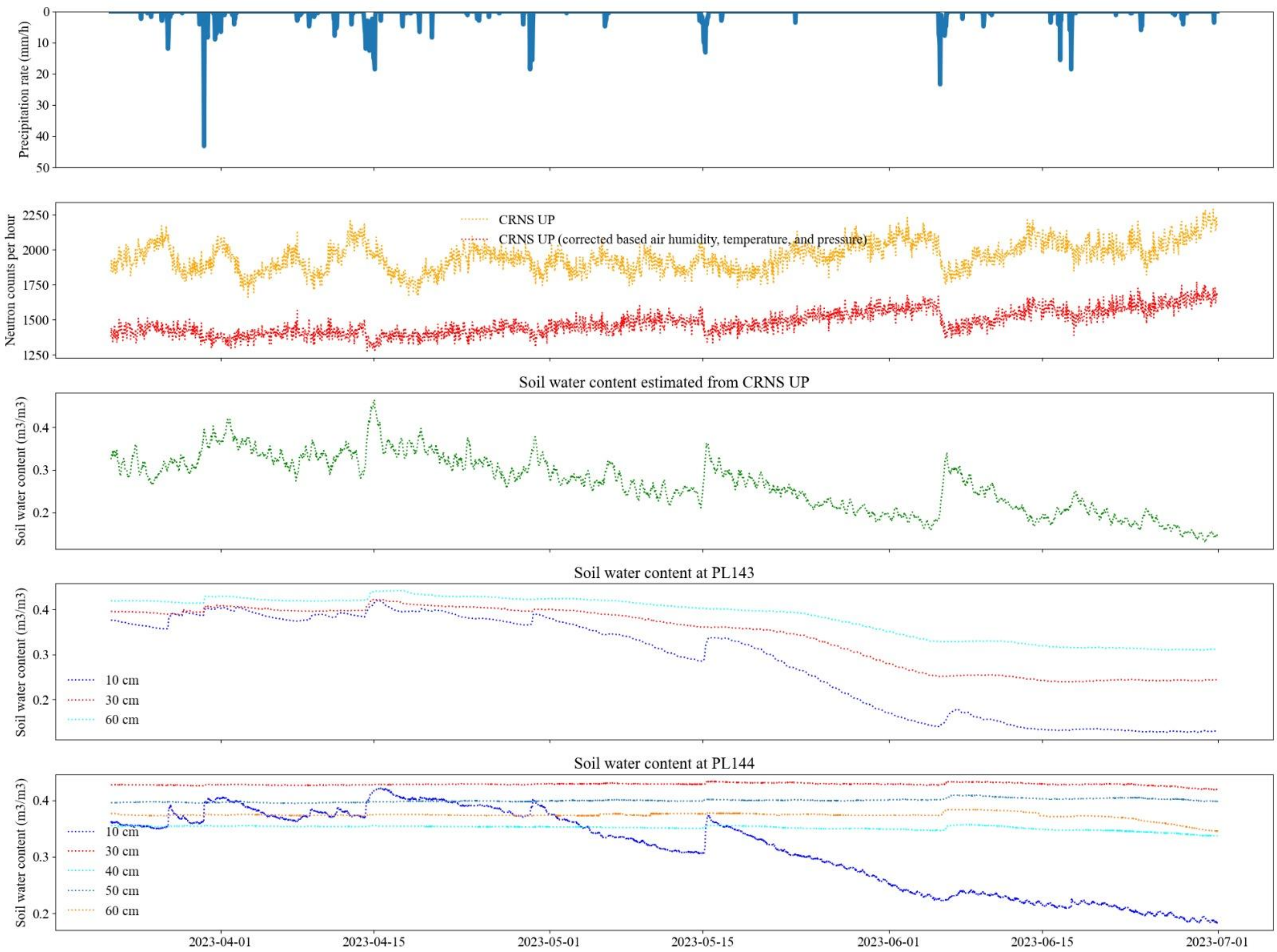

Figure 21 – *(a) Precipitations, (b) CRNS neutron count rate, (c) soil water content estimated from CRNS, (d) from PL 143 and (e) PL 144.*

5. Conclusions

The thesis conducted primarily concentrated on the CRNS station calibration in the Nucice field and the results obtained are satisfying. The resulting data have been demonstrated to show similar trends to point measurements and reliability. Up to that the CRNS also measures soil water content close to the surface and provides a representative N0 value for the given field. The CNRS device has been calibrated in three different soil moisture conditions throughout the months (wet, semi-wet and dry).

The environmental factors affecting the neutron signal have been evaluated and implemented and considered while results about CRNS footprint have been discovered. The footprint radius ranges between 100 and 150 meters based on the season when the acquisition was performed with also different depths ranging between 25 and 50 centimeters in the soil near the CRNS, already knowing its exponentially decreasing curve with the distance.

This makes it a potentially very useful technology for more sustainable water management in the landscape and for deeper applications in the agriculture field. The incorporation of new techniques and technologies into agricultural resource management has the potential to improve the ability of farmers, scientists, and policy makers in assuring food security (IAEA, 2017).

However, discovering each time something more about different technologies such as detector physics, particle physics and remote sensing can improve the efficacy of CRNS technology. By bridging the gaps between remote-sensing and point scale acquisitions, cosmic-ray neutron sensing has been established as a unique technique that is employable for a wide range of applications (Schrön, 2017). Indeed, results have proven that CRNS is a robust and valid proximal soil sensing method to estimate soil moisture at the field scale and a turning point in the agricultural, hydrological, climate-related and natural hazards studies field (Baroni et al., 2018).

An improvement to my thesis would be for sure present if the physical soil samples acquisition were performed, for the Nucice field, all over the year making a wider and complete expected neutron count rate description in different seasons. Indeed, data were related only to the timespan from early spring to early summer, missing completely the remaining summer, autumn and winter values (even if snow cover issues would be present). It can be interesting to observe the patterns throughout different years to understand the reliability of Nucice specific field soil moisture trend, with all the climatic uncertainties correlated.

Despite this, in the months when the acquisitions and experiments were conducted the main goal of finding a general N0 value for the whole Nucice field was accomplished. Indeed, the site-specific calibration done at every acquisition was useful to obtain a N0 value almost identical in time, able to describe generally the Nucice field.

Even in Bogena et al. (2022), a study about CRNS fields in the whole Europe, some sites share a N0 comparable range value (for example: Harzgerode, Jena, Bornheim, Noervenich (Deutschland), Bussoleno and Alento (Italy) and Leutasch (Austria)).

Assuming that the point scale measurements are not enough capable to depict the whole soil moisture presence in the field as already described, the CRNS hectares coverage can be interesting to be matched with remote sensing applications to obtain wider areas coverage without losing its precision. Indeed, the CRNS technology has the power to be useful both alone and as a support of a huge amount of engineering applications such as water resources management or climate studies.

In addition, trying to make previsions, future work around the CRNS technology can be related to covering larger part of Nucice with CRNS sensors and use the data for hydrological models calibration and validation.

To conclude, the journey of understanding the potentiality of the Cosmic Rays Neutron Sensing technology led to define for sure all these advantages reported before. For sure it's important to notify how this technology is not accessible to every project related to agriculture as the costs can be expensive to start its implementation in a field.

On the other hand, its ability to monitor soil moisture in the soil provides benefits as its non-invasiveness and its hydrological processes monitoring related to different environmental conditions. Finally, CRNS provides the representative SWC value for the topsoil on a field scale and has high effectiveness in water resource management, so important nowadays.

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