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Soil Moisture Mapping with a Portable Cosmic Ray Neutron Sensor

Joint FAO/IAEA Programme
Nuclear Techniques in Food and Agriculture

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International Atomic Energy Agency

SOIL MOISTURE MAPPING WITH A PORTABLE COSMIC RAY NEUTRON SENSOR

The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

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SOIL MOISTURE MAPPING WITH A PORTABLE COSMIC RAY NEUTRON SENSOR

PREPARED BY THE
JOINT FAO/IAEA DIVISION OF NUCLEAR TECHNIQUES IN FOOD AND AGRICULTURE

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FOREWORD

The IAEA and the Food and Agriculture Organization of the United Nations (FAO), through the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture, assist scientists, policy makers and farmers worldwide to ensure food security and to promote sustainable agricultural practices. The Joint Division's programme and activities are demand driven and focus on developing and transferring technologies in response to real and practical needs. This programme provides assistance to Member States in the implementation of suitable nuclear and related techniques to enhance agricultural production.

This publication provides information on the proper use of the mobile 'backpack' cosmic ray neutron sensor. This technology senses soil moisture on a field scale for use in many applications, most notably in the management of water resources in agricultural landscapes. This publication describes how Member States can calibrate, validate and deploy this device effectively.

The IAEA is grateful to all the contributors to the preparation of this publication, in particular the University of Nebraska–Lincoln (United States of America) and the Federal Agency of Water Management (Austria). The IAEA officers responsible for this publication were A. Wahbi, G. Dercon and L. Heng of the Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture.

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SUMMARY

To meet the food security demand of the 21st century, global agricultural output must be increased. This will put pressure on the already strained surface and groundwater resources. The incorporation of new techniques and technologies into agricultural water resource management has the potential to improve the ability of farmers, scientists and policy makers in assuring food security. The Soil and Water Management & Crop Nutrition Subprogramme of the Joint FAO/IAEA Division, focuses on the development of improved soil, water, and crop management technologies and practices for sustainable agricultural intensification through the use of nuclear and conventional techniques.

Nuclear and related techniques can help develop climate-smart agricultural practices by optimizing water use efficiency. The measurement of soil water content is essential to improve the use of this resource in agriculture. However, most sensors monitor small areas (less than 10 cm in radius), hence a large number of sensors are needed to obtain an area averaged representation of soil water content, which can be both costly and labor intensive.

Wider scale measuring devices are needed as an alternative to the traditional, point approach. The cosmic-ray neutron sensor (CRNS) is such a device that monitors soil water content in a non-invasive, non-hazardous and continuous way. This recently developed device is used to measure water content in the topsoil over wide areas, covering approximately 20 hectares. It fills the gap in measuring soil moisture over large areas for better agricultural water management. In addition, stationary, backpack, and vehicle mounted CRNS are available to meet a variety of challenges across a wide range of scales.

A CRNS can be used to monitor soil water content over a footprint (the area covered by the sensor) diameter of 500 m (approximately 20 hectares in area) and to an integrated depth varying from 0.1 to 0.4 m, depending on soil water content. The cosmic ray technique is a fairly recent advance soil moisture monitoring technology, having developed out of research performed mainly over the past decade. The technique is applicable to a number of disciplines, including ecology, agronomy, atmospheric science and remote sensing which require a robust, readily deployable field instrument for automatic monitoring of near surface and area wide moisture conditions.

This publication was developed as a partial output of the Coordinated Research Projects titled: "Landscape Salinity and Water Management for Improving Water Productivity" and "Nuclear Techniques for a Better Understanding of the Impact of Climate Change on Soil Erosion in Upland Agro-ecosystems" managed by the Soil and Water Management & Crop Nutrition Subprogramme of the Joint FAO/IAEA Division. This publication is intended to serve as a guideline for scientists, technicians and students and provides a description of the key characteristics of the technique, a review of recent literature related to its use and field validation, and procedures for installation, calibration, and validation and use in backpack and vehicle mounted roving operations. The data processing procedure is also described and includes corrections based on ancillary measurements.

This publication is divided into three Chapters. Chapter one introduces the technique and overview and the mobile sensors highlighting their advantages, disadvantages and recommended use; Chapter two details data processing, calibration of the mobile CRNS and

overview of geostatistical principles; Chapter three includes four examples of the CRNS using the stationary sensor, a backpack sensor for 1-Dimensional surveys, and vehicle mounted detector for 2-Dimensional surveys.

Future research and publications will include CRNS training materials, and descriptions of processing software and custom web services.

The IAEA does not endorse the product mentioned in the publication. D. Desilets, co-author of this publication, is co-owner of HydroInnova LLC which manufactures the CRNS used in this study as a test case. His contributions are provided as an expert in this field of study and the remaining authors declare that there is no conflict of interest regarding the publication of this manuscript. The information provided is relevant for any CRNS device

CHAPTER 1. OVERVIEW OF COSMIC-RAY NEUTRON SENSOR

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1.1. INTRODUCTION

To meet the increasing demand for agricultural products brought about by global population growth and diet changes, agricultural output must be increased around the world. Changing land use patterns, urbanization, climate change and precipitation extremes are placing great strain on agricultural systems. This is particularly true in arid nations and regions where the management of water resources is crucial to the success of agricultural activity. The application of technology to address this problem carries great potential for providing stakeholders with valuable knowledge of field conditions for a more effective decision-making process. With the ultimate goal of assuring food security, The Soil and Water Management & Crop Nutrition Subprogramme of the Joint FAO/IAEA Division, is devoted to the advancement of soil, water, and crop management practices and technologies for sustainable agricultural development through the incorporation of both nuclear and conventional activities.

The optimization of irrigation water uses as well as the preservation of soil water holding capacity can be improved through the use of active and passive nuclear technology. The cosmic-ray neutron sensor (CRNS) is one such passive technology that applies principles of nuclear physics. The CRNS is capable of estimating soil moisture on a large scale (approx. 30 ha), via the detection of moderated neutrons, the intensity of which is inversely correlated with the abundance of hydrogen atoms (mostly contained in water molecules) in the soil matrix. There is a need for spatial soil moisture information across a wide range of agricultural settings and levels of agricultural development. Many readily available soil moisture sensors rely on a point-based approach that fails to provide exhaustive spatial data capable of encompassing entire cultivated areas. Representative soil moisture data are critical as they can directly or indirectly influence a variety of management decisions including: irrigation timing, irrigation depth, planting density, crop variety, fertilizer application and much more.

This publication details the use of a portable version of the CRNS technology designed into the form of a backpack for an individual to carry in addition to a vehicle mounted option. Specifically, this publication discusses the theory behind the CRNS technique, differences between the mobile and stationary versions of the technology, advantages and disadvantages of a mobile device, and protocols for the use of a mobile device with step by step data reduction procedures. This work concludes with example applications of a mobile CRNS within an agricultural and mountainous setting, including three examples of the stationary and mobile CRNS backpack in use are provided with analyses and data comparisons for context. This publication is divided into three Chapters the first detailing the background and fundamentals of the technique and the calculations, the second detailing data processing steps and the third providing three examples from the field.

1.2. REVIEW OF HISTORICAL SOIL MOISTURE MAPPING

Given our need to understand soil moisture patterns over landscapes, a multitude of technologies and methods have been used to map soil moisture [1]. Direct sampling efforts [2] using thermo gravimetric methods throughout the 20^{th} century required great human effort and time with limited spatial coverage in depth and area. After the advent of the active neutron probe in the mid-20^{th} century, mobile versions were used primarily in research settings. The active neutron probe requires dedicated access tubes, site specific calibration, and government/state regulation and training. While recent mobile versions using other electromagnetic spectrum properties (i.e. capacitance, resistance, time domain reflectometry, electromagnetic conductance, visible, near-infrared, thermal etc.) have removed some of the regulation barriers, the active neutron probe remains the gold standard of volumetric water content observations. Never-the-less each method requires laborious insertion of probes or dedicated access tube sites with limited spatial coverage and flexibility.

With respect to airborne and satellite observations passive and active microwave sensors can cover wide areas with variable spatial resolutions but with limited vertical penetration in the top few centimeters [1]. A variety of satellites orbiting the earth offer global coverage the past few decades but at the spatial resolution of tens of kilometers. Airborne platforms can provide higher spatial resolutions but are largely limited to research settings given their high operational costs. Future work using unmanned aircraft and sensors covering the visible, near-infrared to thermal wavelengths may provide more flexibility and lower costs. However, observations will be limited to the very near surface and collected only during periods with minimal vegetation cover. Alternatively, hyperspectral sensors mounted to mobile specially designed heavy machinery may provide rapid surface and downhole data collection opportunities.

A fundamental challenge remains in soil moisture mapping to rapidly collect high quality data across space and time at low costs with minimal effort. The CRNS method can help meet this challenge. Details of the advantages, disadvantages and proper use in agricultural applications will be discussed in the remainder of this publication.

1.3. SUMMARY OF COSMIC-RAY NEUTRON SENSORS AND BASIC PRINCIPLES

Cosmic rays are a natural source of radiation on Earth. The term “cosmic ray” ultimately refers to charged particles produced outside of our solar system in super novae. Some of these particles penetrate solar and terrestrial magnetic fields, eventually reaching Earth itself. These highly energetic particles collide with the nuclei of atmospheric gases, producing showers of sub-atomic particles that are directed towards the soil surface. Along this path the newly accelerated particles continue to impact additional atmospheric nuclei causing further reactions as they travel. Over time the energy contained in the cosmic ray shower is dispersed among these numerous atmospheric collisions. This process gives rise to a measurable flux of fast neutrons near the Earth’s surface. These neutrons scatter isotopically and are slowed down mainly through collisions with hydrogen atoms in the environment. Once slowed by hydrogen collisions they are absorbed by various elements in the soil and air [3, 4].

Because hydrogen has a much greater capacity than other elements to slow fast neutrons to the point of absorption, the presence of hydrogen on the surface and the atmosphere is the primary means of fast neutron “removal” from any terrestrial system. Additionally, the main form of hydrogen in any terrestrial system is in the form of soil water molecules. As such, a relationship can be formed between counts of neutrons and the amount of water in a given area. This means that the CRNS technology is fundamentally a hydrogen detector. The CRNS technique employs a calibration process designed to account for the presence of hydrogen other than that within soil water molecules. Once calibrated, a CRNS device can provide accurate soil moisture information wherever it is deployed around the world.

1.4. STATIONARY AND MOBILE COSMIC-RAY NEUTRON SENSORS

Most CRNSs exist in a stationary setting [Fig. 1.1], and by design lack the capacity to be easily moved from field to field. As of October 2017, approximately 200 stationary probes have been deployed on 6 continents for long term monitoring of landscape scale soil moisture. The affiliation of CRNS networks include various subgroups of sensors from country level research to individual research projects to commercial agricultural applications. The largest subgroup of CRNS are part of the USA based COsmic ray Soil Moisture Observing System (COSMOS) network [4]. In addition to the stationary devices, mobile CRNS have recently been used for applications in agricultural environments due to the added value of collecting soil moisture across the landscape [5, 6 and 7]. Much of the work with mobile CRNS has been conducted with sensors incorporated into a ‘rover’, which is a larger version of the sensor that is mounted on a motor vehicle [5 and 6]. Fast moving vehicles such as the CRNS rover [Fig. 1.2] can gather soil moisture data over multiple fields in relatively short succession. However, mobile applications such as this cannot be readily executed in difficult terrain such as those found in mountainous environments or certain agricultural systems.

FIG. 1.1. Example of a stationary CRNS device, taken near Petzenkirchen, Austria, courtesy of the IAEA/FAO. The detectors typically accumulate neutron counts over an hour-long period.

FIG. 1.2. Example of a mobile "roving" CRNS device in Nebraska USA. The boxes containing the CRNS detectors are mounted in the back of the vehicle. The larger detectors accumulate enough neutron counts over 1-minute periods to allow for mobile surveys over large areas like commercial agricultural fields typical of Nebraska.

To compliment the roving CRNS, a smaller version of the technology has been developed (Hydroinnova, limited liability company (LLC)). The “backpack” CRNS [Fig. 1.3] contains many of the same characteristics and components of its larger counterparts miniaturized into a highly mobile battery powered device capable of being carried by a single individual (~ 15 kg) [7]. This backpack CRNS technology can be carried into otherwise inaccessible terrain to explore soil moisture mapping potential. The rover and backpack CRNS detects a sufficient number of neutrons over a faster time interval compared to the stationary CRNS device (~1 and 10 minutes as opposed to 1 hr). The optimal neutron collection interval time depends on-site latitude, elevation, detector gas type, detector gas volume and pressure, and statistical information gain due to spatial autocorrelation between points. A rule of thumb is that at least 1000 counts per time interval should be collected for stationary applications and 400 counts per time interval for mobile applications is recommended as best practice (the minimum rate is usually lower for mobile applications because of the tendency for interpolations from other points, sometimes overlapping, to effectively improve the counting statistics). Noted that higher count rates will lead to lower soil moisture uncertainty as the standard deviation of counts is equal to the square root of total counts. Meaning that either larger detectors or longer integration times are needed to obtain higher total counts. Fig. 1.4 provides the expected soil moisture uncertainty for a stationary CRNS as a function of soil moisture and detector specifics (i.e. the N_0 theoretical dry counting rate parameter). Note that a target level uncertainty of less than 0.04 m^3 m^{-3} is best suited for remote sensing products. See [8] for additional details on error analysis.

FIG. 1.3. Example of a mobile “backpack” CRNS device in Rauris Austria. The CRNS detectors are located inside the metal box and can be hand carried by a single individual. The lighter weight medium sized detectors allow for accumulated neutron counts over a period of ten to twenty minutes.

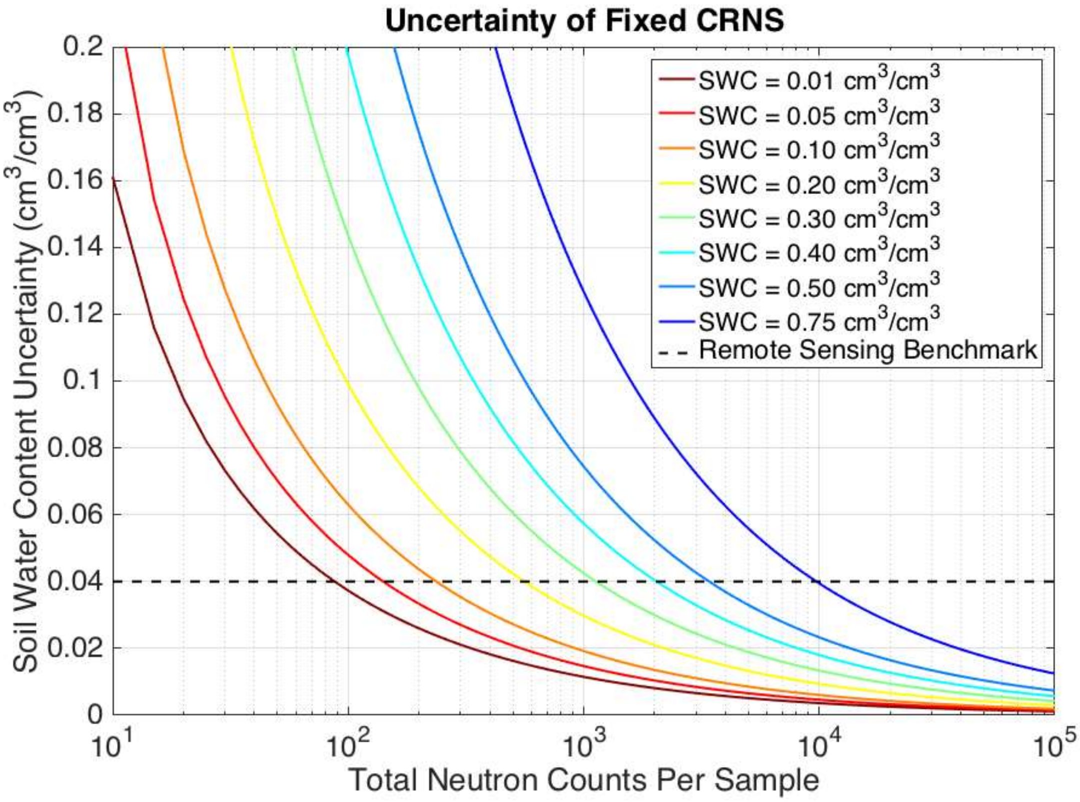

FIG. 1.4. Uncertainty in soil volumetric water content as a function of total neutron counts, and for different soil water contents. A benchmark of less than 0.04 cm^3/cm^3 is recommended for remote sensing products. See chapter 1.5 and [8] for details.

1.5. ADVANTAGES, DISADVANTAGES, AND GUIDELINES FOR MOBILE CRNS

A summary of advantages, limitations and best uses of the three CRNS device types are provided in TABLE 1.1. The primary advantage of the CRNS backpack is its mobility and lightweight. However, this comes at the expense of longer integration times to collect data. While roving versions of the CRNS technology have been in research settings with vehicles in recent years, the backpack CRNS may be better suited for commercial use in global agricultural settings due to pragmatic considerations of land use, labor and maintenance costs of vehicles. Due to the fact that the backpack can be carried by a single individual, it can be taken to remote, rugged or fragile locations that are not accessible by motor vehicle. For example, mountainous terrain like the conditions encountered in [Fig. 1.3] offer a prime example of challenging site conditions. The backpack CRNS is also capable of being taken from field to field without the need for costly and time-consuming transportation making it ideal for use in developing countries and remote locations where infrastructure is limited and the landscape is challenging. For example, the backpack could be used to simultaneously collect soil moisture information relatively quickly in a heterogeneous landscape with a concentration of densely located small holder farms with plot sizes > 1 ha. Biweekly or weekly surveys could be made to help manage dozens of small holder farms with a single backpack unit, making it both time and cost effective.

The most appropriate use of the CRNS backpack is the estimation of soil moisture in either a single location for short periods (days), multiple locations or in a 1-Dimensional transect. Note that 2-Dimensional surveys are possible but may be limited by the length survey time. See Fig. 1.4 for survey criteria design. Long term monitoring of soil moisture is less feasible with this device and better suited to a stationary sensor. For example, a backpack CRNS should be deployed when the landscape is best suited to a single individual hiking in rather than a difficult installation process or limited by vehicle access.

TABLE 1.1 SUMMARY OF ADVANTAGES, DISADVANTAGES AND BEST USES OF THE THREE TYPES OF CRNS DEVICES

	Stationary	**Backpack**	**Roving**
Approx. minimal data collection interval (min)*	60	10	1
Weight (kg)	30	15	>50
Main advantages	Minimal maintenance, long term deployment	Lightweight, mobile with 1 person, use in harsh environments	Mobile, 2-Dimensional surveys
Main disadvantages	Longer set-up time, not mobile	Limited to 1-Dimensional surveys due to longer integration time	Need vehicle and access, higher cost
Best use cases	Long term minimal maintenance deployment at 1 location (weeks to years)	Short term deployment at temporary location (hours to days)	2-Dimensional surveys (hundreds of locations)
		1-Dimensional transect survey (dozens of locations)	Time repeat surveys of field or watershed (biweekly, weekly, monthly)
		Time repeat 1-Dimensional transect surveys (biweekly, weekly, monthly)	
		Time repeat surveys of small holder land units (dozens of locations)	

* Based on conditions in Nebraska USA, elevation 800 m. Note this time will be reduced at higher elevations as raw counts approximately scale with the ratio of sea level pressure to local pressure where the survey is being conducted [4]

1.6. SUMMARY OF CALCULATIONS – SOIL MOISTURE AND CALIBRATION FUNCTION

For most soils, a calibration function is employed to convert the counting rates of neutrons detected by the CRNS device into soil moisture. A calibration curve for soil moisture has been developed that has yielded the following equation [9]:

$$\theta_T = \theta_V + \theta_{LW} + \theta_{SOC} + \theta_B = \left(\frac{a_0}{F(t)\frac{N}{N_0} - a_1} - a_2 \right) \rho_b \tag{1.1}$$

Where a_0, a_1, and a_2 are constants and stand for $a_0 = 0.0869$, $a_1 = 0.3720$, $a_2 = 0.1236$. θ_T (m^3 m^{-3}) is the total water content in units of volume per volume. Total water can be further defined as the sum of soil moisture θ_V, clay lattice water (LW) θ_{LW}, soil organic carbon water (SOC) equivalent θ_{SOC}, and the biomass water equivalent θ_B . These variables are all expressed in units of volume per volume (m^3 m^{-3} or cm^3 cm^{-3}). Note that each unit can be converted to a mass per unit if divided by dry soil bulk density (ρ_b, g cm^{-3}). Ultimately, these terms serve to quantify and account for all sources of hydrogen within the instrument footprint.

N stands for the raw counts of detected neutrons (counts/time interval), N_0 is the counting rate in a theoretical environment of completely dry soils. N_0 serves as the central calibration variable and is used to compare and reference counting rates determined in the field with counting rates in an environment devoid of hydrogen. N_0 is instrument specific and once determined need not be determined again for a particular device. Typically, a minimum of 3 calibrations are recommended to estimate N_0 for each device. *F(t)* is a correction factor and helps to account for changes in atmospheric pressure, solar intensity and air humidity. These variables change in time, as such it is helpful for local meteorological data to be acquired when field experiments involving the CRNS are ongoing. A step by step summary of *F(t)* and remaining calculations is provided in [8].

1.7. SUMMARY

The most effective use of the CRNS technique involves an understanding of the particular needs of a scientist, grower, policy maker, natural resources manager or anyone who would benefit from in situ soil moisture information. Specifically, the application of a CRNS device in either a stationary or mobile setting will greatly affect the utility of the final data depending on its intended use (TABLE 1.1). The calibration process along with data processing are the same for both a stationary and backpack version of the CRNS technology. The mobile backpack CRNS carries many inherent advantages due to its mobile nature, allowing for soil moisture estimation across landscapes with only one instrument. This publication details the proper use and application of this particular version of the CRNS technique and provides additional examples for context.

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CHAPTER 2. DATA PROCESSING OF SURVEY DATA

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2.1. INTRODUCTION

The use of the backpack CRNS for soil moisture estimation is best suited for remote field sites with difficult to reach terrain, large study areas or both. The mobile nature of the device lends itself towards applications in 1 and 2-Dimensional surveys in which the CRNS device is moved from location to location over time or carried by an individual or vehicle along a transect or bisecting a watershed. This chapter details the calibration process associated with the backpack CRNS in a guided fashion.

2.2. BACKPACK CALIBRATION PROCESS

This section details the proper field calibration procedure for a mobile backpack CRNS. It is worth noting that this calibration process is conducted in precisely the same fashion as a calibration of any other CRNS device, stationary or otherwise. A detailed guideline for the physical principles of the CRNS technique and the mathematics behind the calibration function see IAEA TECDOC # 1809 [1], Desilets et al., (2010) [2], Franz et al., (2015) [3], Avery et al., (2016) [4], and Franz et al., (2016) [5].

Proper calibration of a CRNS device requires the quantification of significant sources of hydrogen within the instrument footprint (circle of radius ~ 250 m). This entails mainly in situ soil sampling as well as biomass if significant plant material is present within the study area. Once a study site has been selected the following tools are required:

1) CRNS “backpack” [Fig. 2.1];

2) Shovel (preferably a spade);

3) Plastic or wooden mallet;

4) Notebook with pen;

5) 108 soil sampling cans, these are usually tin or aluminium cans about 5 cm deep and 10 cm in diameter;

6) Standard bulk density sampling rings and associated attachment [Fig. 2.2].

FIG. 2.1. Example of the backpack CRNS device deployed in a mountainous environment in Austria.

FIG. 2.2. Example of an in-situ soil sampler to determine volumetric water content and soil bulk density.

The sampling pattern for any CRNS device is designed around adequately representing the footprint of the sensor. A sampling pattern consisting of six transects spaced equally in a radial pattern extending from a central point (where the CRNS backpack is placed) every 60°. Each transect has three locations where soil sampling must take place. The first location along the transect is 25 m away from the central point, the next is 75 m from the central point, and the final location is 200 m away from the central point. This pattern is continued along each of the six transects for a total of 18 sampling locations [Fig. 2.3]. Note that the sampling protocol best strategy continues to evolve. [6] Discuss in detail a reweighting scheme of calibration samples that has been shown to improve CRNS performance by taking into account more accurate descriptions of the horizontal and vertical footprint and variability of soil water content (SWC) within the footprint.

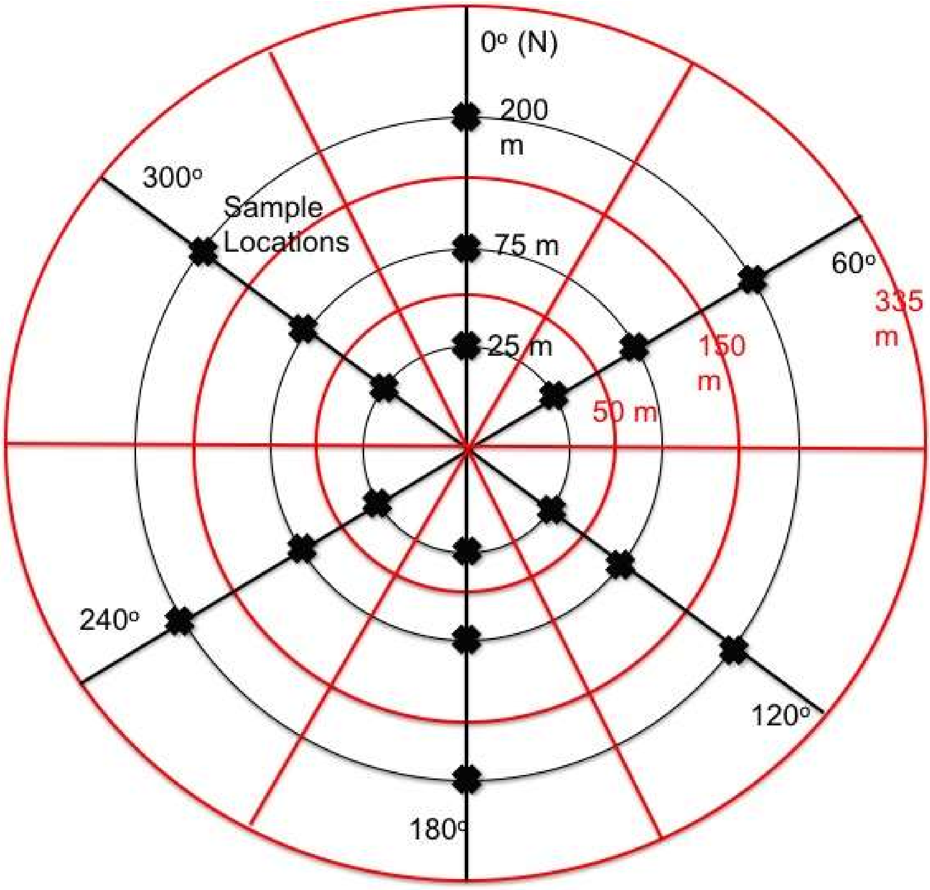

FIG. 2.3. Layout of 18 sampling locations around a CRNS to calibrate the sensor. Gravimetric samples are taken at 6 depths (0-30 cm) at each of the 18 locations for a total of 108 samples. Bulk density is estimated at approximately 6 sites and 6 depths. One composite soil sample is taken for chemical analysis and estimation of soil organic carbon and lattice water.

Each of the 18 sampling locations must have six soil samples taken at the following depths: 5 cm, 10 cm, 15 cm, 20 cm, 25 cm and 30 cm. If the soil is too shallow, or excessive rocks are encountered than as many samples that can be taken without extreme difficulty is sufficient. These samples will serve to determine gravimetric (mass based) water content. Each of the 18 sampling locations should also have a ~1 gram (a pinch) of soil from each of the six samples be placed into a separate sealed container. This composite sample of the entire area will serve as a source of material for the analysis of soil organic compounds and soil lattice water (water contained within the lattice structure and trapped around soil particles that plants cannot access).

The CRNS technology ultimately provides soil moisture data in the form of volumetric water content. Converting from mass based water content (gravimetric) requires knowledge of the study sites average soil bulk density. As such, comparisons of in situ samples with the CRNS must have bulk density information to convert sample gravimetric to volumetric water content. Bulk density samples (taken with the device mentioned earlier) are typically performed once per transect (at the same six depths) alternating from the 25-m location at transect one to the 75-m location at transect two and finally the 200-m location at transect three. Then the samples are to be alternated back with sampling at the 200-m location at transect four the 75-m location at transect five and lastly the 25-m location at transect six. This sampling pattern intends to balance the sampling effort needed to establish an average footprint bulk density.

If significant biomass (such as growing maize or similar crop) is present within the instrument footprint to a large extent, then biomass samples can be taken as well as soil samples in the same pattern as soil bulk density mentioned in the previous paragraph. As a rule of thumb moderated neutron counts have been shown to decrease by about 1% for every 1 kg/m^2 of above ground biomass for the same soil moisture condition [3]. At each of these locations one to three individual plants (one if fully grown or large biomass, three if small biomass) should be harvested from the field within the immediate area in which the soil samples are taken (~ 1 m^2). Note: Detailed descriptions of the quantification of agricultural crop biomass for use in the CRNS calibration process are given by IAEA TECDOC #1809 [1]. Ultimately these plant samples will be weighed, dried, and weighed again to determine the water percentage by mass and eventually the biomass water equivalent (BWE). The BWE is then used to modify the instrument N_0 value.

The following images depict the field calibration of the backpack CRNS in a high-altitude environment. Each step in the process is shown and described.

Step One: Place the backpack CRNS in a central location to the particular study site. Turn on the device with care given to ensure the battery is secured, the datalogger is running, the neutrons are being counted (tiny red-light flashing), the relative humidity and temperature probe is attached, and the GPS is attached.

Step Two: With the tools mentioned previously in hand, walk approximately 25 m north along the first transect to the first sampling location. Once there, dig a hole approximately 40 cm deep and 60 cm wide [Fig. 2.4]. Take the spade and remove a profile of soil from the approximately 30 cm in length. Remove soil samples at each of the six depths (every 5 cm) and place the soil into the tins. Place the lid on the tins tight enough so no moisture can escape. Remember to remove a pinch (~ 1 gram) from each sample and place in a separate container for chemistry analysis of organic material and lattice water.

FIG. 2.4. Example of in situ soil hole dug for CRNS calibration soil sampling.

Step Three: To sample for soil bulk density (which should be done according to the pattern mentioned previously), the six soil samples should be taken differently. The soil rings (standard tool for soil bulk density measurement) should be placed flush with the side of the hole at the appropriate depth (5 cm, 10 cm, 15 cm, 20 cm, 25 cm and 30 cm) and the attachment should be placed on its rim. Using the mallet, hammer the ring into the side of the hole until it is fully hammered into the soil [Fig. 2.5 and 2.6]. Then using a soil knife, carefully remove the soil core so that the soil within the cylinder is not disturbed. Use the soil knife to cut any excess soil from the ends of the ring and either place the soil (exactly flush in the ring so as to only occupy the cylinder volume) into a new container specially marked as a bulk density soil sample, or place metal lids on the ring itself for it to serve as its own storage vessel. Note: If biomass is to be taken follow the procedures for destructive sampling outlined in IAEA TECDOC # 1809.

FIG. 2.5. Example of the proper placement of an in situ soil bulk density sampling ring.

FIG. 2.6. Example of the proper technique for soil bulk density sampling.

Step Four: Once the soil samples have been taken for the first location, move to the second along the first transect (75 m from the central point) and repeat the process (except for bulk density, only conduct these samples once per transect). This pattern is to repeat for all six transects in order for the field calibration sampling process for a backpack CRNS to be complete.

2.3. DATA FORMAT

Raw data should typically be reported in the backpack in the following format (Table 2.1):

TABLE 2.1. TYPICAL DATA OUTPUT FROM A CRNS WITH GPS RECEIVER

Columns: 1 2 3 4 5 6 7 8							
YY-MM-DD HH:MM,	Mod,	Pressure,	Temperature,	RH,	Batt,	Latitude,	Longitude
UTC	cts h-1	hPa	°C	%	V	WGS84	WGS84
2010-06-08 00:02	828	923.0	28	37	12.5	48.1547	15.1484
2010-06-08 01:02	869	923.3	27	37	12.4	48.1547	15.1484
2010-06-08 02:02	810	923.1	28	38	12.4	48.1547	15.1484
2010-06-08 02:38	866	932.6	25	46	12.4	48.1547	15.1484

Note: Column numbers represent:
1: Date and time at end of record period in Universal Time;
2: Counting rate from the moderated neutron channel in counts per interval; Note that depending on system specifics each instrument could be composed of multiple detectors. The moderated counts from each detector should be summed together for each time interval effectively making 1 large detector.
3: Barometric pressure;
4: Air temperature;
5: Relative humidity;
6: Battery voltage.
7: Latitude in WGS84 from GPS receiver
8: Longitude in WGS84 from GPS receiver
Additional sensors, including other neutron counting channels, may also be present depending on the configuration of the sensor. Other data recorded by the logger, but not telemetered unless needed, include pulse height histograms from the detector tubes. These histograms provide diagnostic information that can help troubleshoot problems with the sensor. This information is generally used only by the manufacturer. Note data from a stationary CRNS will be nearly identical but without the GPS locations (see [1]). Detailed calculations and worked spreadsheet are provided in [1].

2.4. SUMMARY OF GEOSTATSTICAL METHODS

Depending on the CRNS application, geostatiscal methods may be used to reduce the error between points in space or interpolate a smooth transect (1-Dimensional) or surface (2-Dimensional). See [7] for an overview of geostatiscal methods. The basic principle is that points closer together will be more correlated than points further apart. Formally, this is represented by a semi-variogram, which plots the lag distance between groups of points of their variance. From this diagram the distance at which points are no longer correlated can be estimated, the correlation length. In addition, the shape of the correlation vs. lag distance can be preserved when interpolating data collection points to a line or surface. A variety of software packages exist to perform different interpolation techniques from linear, quadratic, spline, inverse-distance-weighted, ordinary kriging and co-kriging. The specific algorithm needs to be matched with the underlying data available and inherent spatial heterogeneities that exist and that should be preserved with the interpolation technique.

2.5. DATA PROCESSING OF 1-DIMENSIONAL SURVEYS

With the data summarized in TABLE 2.1 equation 1.1 and details in [1] can be used to compute the series of correction factors needed to convert raw neutron counts into corrected neutron counts and then soil moisture. TECDOC-1809 provides a sample spreadsheet and step by step procedure. For use with the backpack the additional piece of information is the GPS location. The GPS data is collected with the projected coordinate system WGS84 and is in units of latitude and longitude. For ease of distance calculations latitude and longitude are transformed into a coordinate system. For example, the Universal Transverse Mercator (UTM) is a conformal projection that uses a 2-dimensional Cartesian coordinate system to give locations on the surface of the Earth. Each Universal Transverse Mercator grid is broken into 6 degrees' latitude and longitude. Following the projection to Universal Transverse Mercator (UTM), distance calculations and geostatistics can be more easily computed. Following spatial interpolation, the coordinates can be projected back into latitude and longitude and displayed properly on the Earth's surface. A variety of open source and commercial software are available to perform the projections and transformations for proper display. For 1-Dimensional surveys data points that are within a few meters are grouped together and averaged to obtain a greater count rate. For backpack applications here this required leaving the system in place for 10-20 minutes. Fig. 1.4 can be used as a guideline to design a survey which depends on-site conditions, size of instrument (i.e. count rate), and desired level of soil moisture uncertainty versus survey collection time. Note that Fig. 1.4 is an upper bound as the uncertainty in soil moisture will be further reduced by spatial autocorrelation for survey points located close together.

2.6. DATA PROCESSING of 2-DIMENSIONAL SURVEYS

Given the higher count rates the roving CRNS can be mounted to a vehicle. The same basic processing steps listed in chapter 2.5 will be used here with 1 additional step for interpolation. For ease of explanation let's assume a survey with a 20-m spatial resolution over an 800 by 800 m area is desired. For this size of survey, the vehicle can be driven at the speeds of 8-15 km hr^{-1} at ~15-20 m spacing, taking about 90 minutes to complete. The CRNS backpack theoretically can also provide spatial maps if a minimum of 40 spatial locations are included with 15 minutes per location. This is time prohibitive and inefficient, as such 2-dimensional mapping is better suited to mobile vehicles equipped with larger CRNS devices.

In order to provide a soil moisture map, a spatial map of neutron intensity must first be estimated, and then the calibration function applied following chapter 1. The neutron intensity map is created in two steps. First, a drop-in-the-bucket preprocessing step is applied, where a dense grid is generated (here 20 by 20 m) and all raw data points are found within a certain radius (here 50 m). Then, the average of all raw data found within the search radius is assigned to the grid center. This oversampling approach is necessary for sharpening the image quality and is a common strategy used in remote sensing analyses [8] when overlapping area-average observations are collected, like the CRNS. Next, an inverse-distance-weighted approach is used on the resampled 20 m grid to produce a neutron intensity estimate. The gridded neutron intensity estimate is then converted to soil moisture following chapter 1. Note that the survey size and desired spatial resolution should be specified ahead of time depending on need and instrument limitations [see Fig. 1.4].

2.7. SUMMARY

The mobile CRNS is calibrated and data processed in nearly the same manner as the stationary CRNS. Specific details are summarized here and a worked spreadsheet are provided in IAEA TECDOC – 1809 [1]. The main difference is that a GPS location is also recorded. The CRNS device records the latitude and longitude for every data collection period with the common projection of WGS84 (World Geodetic System). In order to perform distance calculations needed for spatial interpolation using geostatistical methods, the latitude and longitude is transformed into a 2-Dimensional surface (e.g Universal Transverse Mercator). Following coordinate transformation, a variety of commercial and free software can perform the geostatisical interpolation of the neutron counts. Given the spatial autocorrelation the neutron data is smoothed and random counting error reduced allowing for shorter observation times compared to a stationary CRNS. Lastly, the neutron data can be converted into soil moisture using the standard calibration procedure.

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CHAPTER 3. DESCRIPTION OF SOFTWARE AND FIELD EXAMPLES OF CRNS SURVEYS

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3.1. INTRODUCTION

Data analysis and map generation of the mobile CRNS involves a set of standardized steps that can be performed by the local interested party using this TECDOC and 1809 [1]. To aid with data analysis a series of web pages have been developed with automated data processing for both stationary and mobile CRNS (will be publicities by the end of 2018). A description of the software will be provided in this chapter. In addition, four examples of a stationary CRNS, backpack CRNS site comparison, backpack CRNS 1-Dimensional survey and vehicle CRNS 2-Dimensional survey will be presented.

3.2. SUMMARY OF SOFTWARE

Custom webpages for processing project specific stationary, backpack and vehicle mounted rover data are available through Hydroinnova LLC. The general guidelines summarized here and [1] provide details and example data processing algorithms.

3.3. EXAMPLES OF STATIONARY, BACKPACK, AND VEICHLE CRNS

3.3.1. Stationary CRNS example

To give context to the use of the mobile CRNS backpack device, an example of a typical CRNS device existing in a stationary setting should be given. Stationary CRNS devices collect data at a fixed interval for extended periods of time in a semi-permanent fashion. These data are often monitored for months or years at an hourly time interval that can be used to examine long term soil moisture trends, schedule irrigation and determine ideal planting schedules among other uses. Often these stationary instruments are co-located with meteorological stations that provide additional data and perspective on the total environmental conditions of any particular field in which they are placed. An example of how these sensors are deployed in the field is given in Section 1 [Fig. 1.1].

The monitoring of soil moisture changes over time and integrated across a heterogeneous landscape is the primary application of a stationary CRNS device. An example of this application in an agricultural setting exists near the Austrian town of Petzenkirchen, where the IAEA owns and operates a stationary CRNS device since December 2013. The resulting soil moisture information has been used to provide data to compliment a nearby weather station to provide valuable field level data for use by local farmers in a variety of their decision-making processes. Year to year patterns of soil moisture can be observed from such data as well as comparisons of more traditional point sensors soil sampling methods of soil moisture measurement for the purpose of validation of the CRNS signal [Fig. 3.1]. Fig. 3.1 illustrates a near continuous CRNS times series, 8 gravimetric calibration datasets to estimate N_0, and 5 cross-validation datasets using the backpack CRNS. The time series shows good correspondence with the backpack and gravimetric calibrations, albeit with some uncertainty. Because of this uncertainty a minimum of 3 gravimetric calibrations is recommended to estimate N_0 for each CRNS. The changes in the stationary CRNS show the dynamic range of soil moisture with each season and response to individual rain events. For future irrigation applications this time series can be provided in real time via a webpage (will be available by the end of 2018). In addition, soil moisture management thresholds like irrigation triggering point, plant water stress and potential for nutrient loss due to deep percolation can be set to help guide decisions.

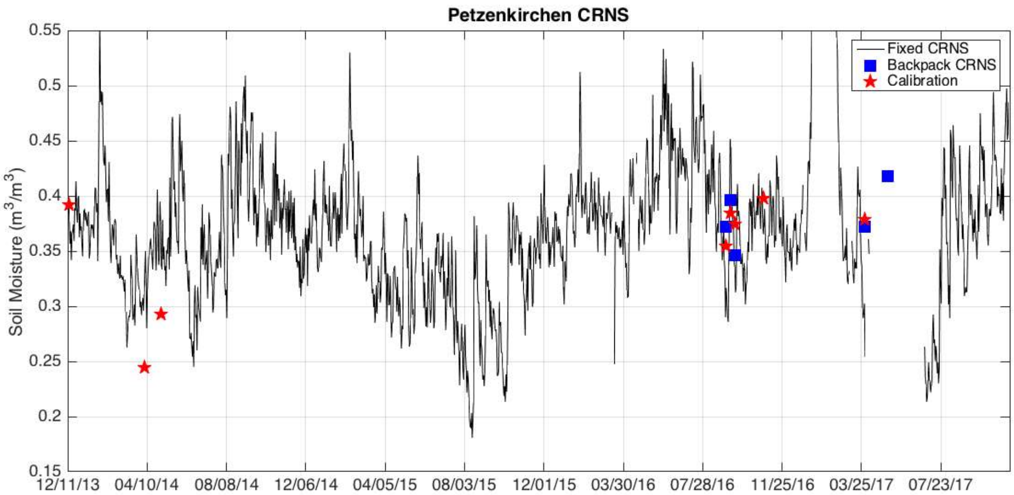

FIG. 3.1. Example of a stationary CRNS device located near Petzenkirchen, Austria, operated by the IAEA Soil Water Management and Crop Nutrition Laboratory. The backpack CRNS and in situ soil sampling are compared to the stationary CRNS signal that has operated since December 2013.

3.3.2. Comparison of backpack CRNS across Austria

As a way to investigate the site to site variation of a backpack CRNS survey we present a total of 16 calibration datasets from 5 sites across Austria. Fig. 3.2 illustrates the locations of 2 agricultural study sites at Petzenkirchen and Grabenegg and 3 mountainous sites near Rauris at different elevations, low, medium and high. Table 3.1 provides a site summary of location, neutron correction factors and soil properties needed to convert raw counts into soil moisture. Table 3.2 presents a summary of each calibration dataset including neutron counts and error over the 2-4-hour calibration period, gravimetric soil moisture, bulk density, total soil moisture and calculations of N_0. In addition, the prediction of soil moisture using the neutron counts and average N_0 is presented. To illustrate the challenge of providing average soil moisture over a complex landscape, Fig 3.3 illustrates the 108 gravimetric samples plotted as spatial average by depth. It is evident that a large degree of natural variation in spatial and vertical soil moisture exists at any given time and study site. Furthermore, Fig 3.4 illustrates the same type of plot but for bulk density, again showing a large amount of natural variation that exists in the sampling. Practically speaking this indicates that the ground truth datasets of gravimetric soil moisture and bulk density have a wide range of uncertainty, thus neutron predictions of average soil moisture contain this underlying uncertainty plus neutron count uncertainty and processing errors.

FIG. 3.2. Location of 5 backpack calibration sites across Austria.

TABLE 3.1. SUMMARY OF 5 BACKPACK CRNS AUSTRIAN CALIBRATION SITE LOCATIONS, NEUTRON CORRECTION FACTORS AND SOIL INFORMATION NEEDED TO CONVERT NEUTRON COUNTS INTO SOIL MOISTURE

	Grabenegg	**Petzenkirchen**	**Rauris Low**	**Rauris Medium**	**Rauris High**
Latitude	48.1378	48.1547	47.2134	47.2328	47.2468
Longitude	15.2420	15.1484	12.9883	13.0280	13.0085
Elevation (m)	253.0	278.0	941.0	1460.0	1713.0
Reference air temperature (°C)	25.0	25.0	25.0	25.0	25.0
Reference air pressure (hPa)	983.1	980.2	905.1	849.6	823.6
Scaling factor =	1.149	1.174	2.028	3.086	3.760
Lattice water (g/g)	0.046	0.039	0.047	0.052	0.041
Soil organic carbon water equivalent (g/g)	0.0035	0.0044	0.0064	0.0079	0.0089
Avg. Soil bulk density (g/cm^3)	1.58	1.41	1.29	1.20	0.97
Standard Deviation of soil bulk density (g/cm^3)	0.091	0.130	0.257	0.061	0.219

TABLE 3.2. SUMMARY OF 16 CALIBRATION DATASETS AT 5 BACKPACK CRNS SITES IN AUSTRIA. THE TABLE INCLUDES CALCULATION OF N_0 AND THE PREDICTION OF SOIL MOISTURE (CM^3/CM^3) FROM THE AVERAGE OBSERVED N_0

Site	**Date**	**Corrected Moderated Counts (cpm)**	**Standard Deviation (cpm)**	**Depth Weighted Bulk Density (G/cm^3)**	**Depth Weighted Soil Moisture (Cm^3/cm^3)**	**Depth Weighted Soil Moisture (g/g)**	**Standard Deviation of Soil Moisture (g/g)**	**Total Water (g/g)**	**Computed N_0 (cph)**	**Predicted Soil Moisture from avg. N_0 (cm_3/cm_3)**
Grabenegg	9/1/16	23.59	0.312	1.49	0.360	0.242	0.033	0.2911	41.3	0.272
Grabenegg	3/28/17	21.88	0.382	1.48	0.413	0.279	0.048	0.3286	39.5	0.391
Grabenegg	4/12/17	22.34	0.457	1.48	0.386	0.261	0.035	0.3104	39.8	0.353
Grabenegg	5/3/17	23.10	0.524	1.48	0.399	0.269	0.048	0.3187	41.4	0.301
Grabenegg	7/4/17	23.25	0.342	1.48	0.353	0.238	0.058	0.2879	40.6	0.291
Petzenkirchen	8/31/16	21.62	0.501	1.30	0.319	0.245	0.035	0.2881	37.8	0.372
Petzenkirchen	9/8/16	21.31	0.376	1.29	0.363	0.281	0.030	0.3242	38.3	0.396
Petzenkirchen	9/15/16	21.95	0.409	1.30	0.326	0.250	0.034	0.2934	38.5	0.346
Petzenkirchen	3/29/17	21.62	0.501	1.30	0.327	0.251	0.046	0.2947	38.0	0.372
Petzenkirchen	5/3/17	21.10	0.517	1.30	0.314	0.241	0.037	0.2843	36.7	0.418
Rauris Low	9/12/16	18.33	0.269	1.22	0.641	0.525	0.158	0.5782	37.5	0.804
Rauris Low	5/24/17	17.97	0.360	1.22	0.625	0.512	0.132	0.5652	36.6	0.910
Rauris Medium	9/11/16	18.76	0.267	1.18	0.643	0.543	0.145	0.6029	38.7	0.673
Rauris Medium	5/23/17	18.61	0.343	1.18	0.722	0.610	0.149	0.6701	39.2	0.705
Rauris High	9/10/16	18.82	0.257	0.74	0.549	0.741	0.395	0.7911	40.8	0.421
Rauris High	5/22/17	18.71	0.296	0.76	0.494	0.649	0.223	0.6990	39.7	0.447

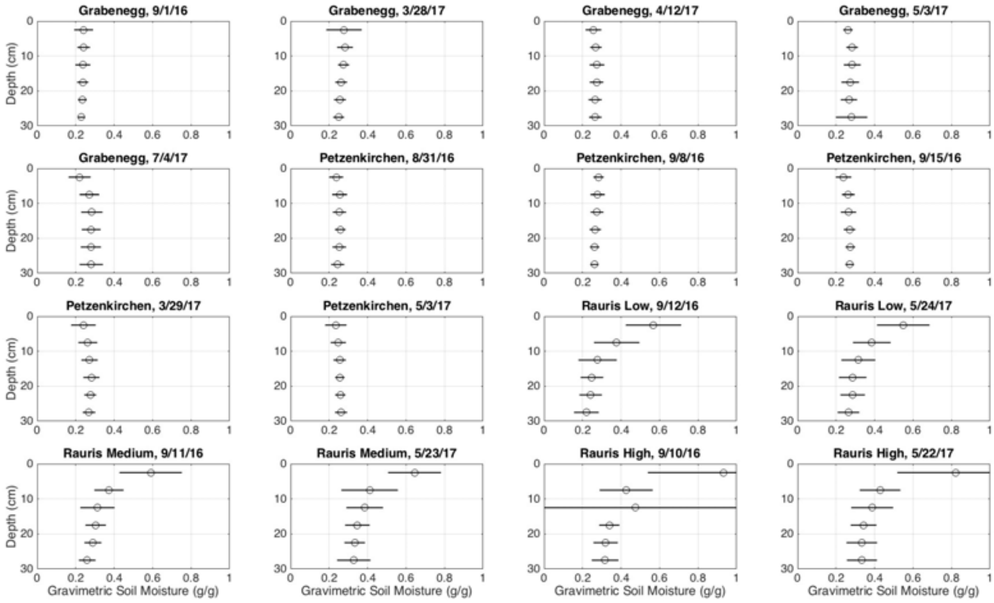

FIG. 3.3. Depth vs. gravimetric soil moisture for the 16 calibration datasets. The open circle is the mean of the 18 samples and the bars are +/- 1 standard deviation.

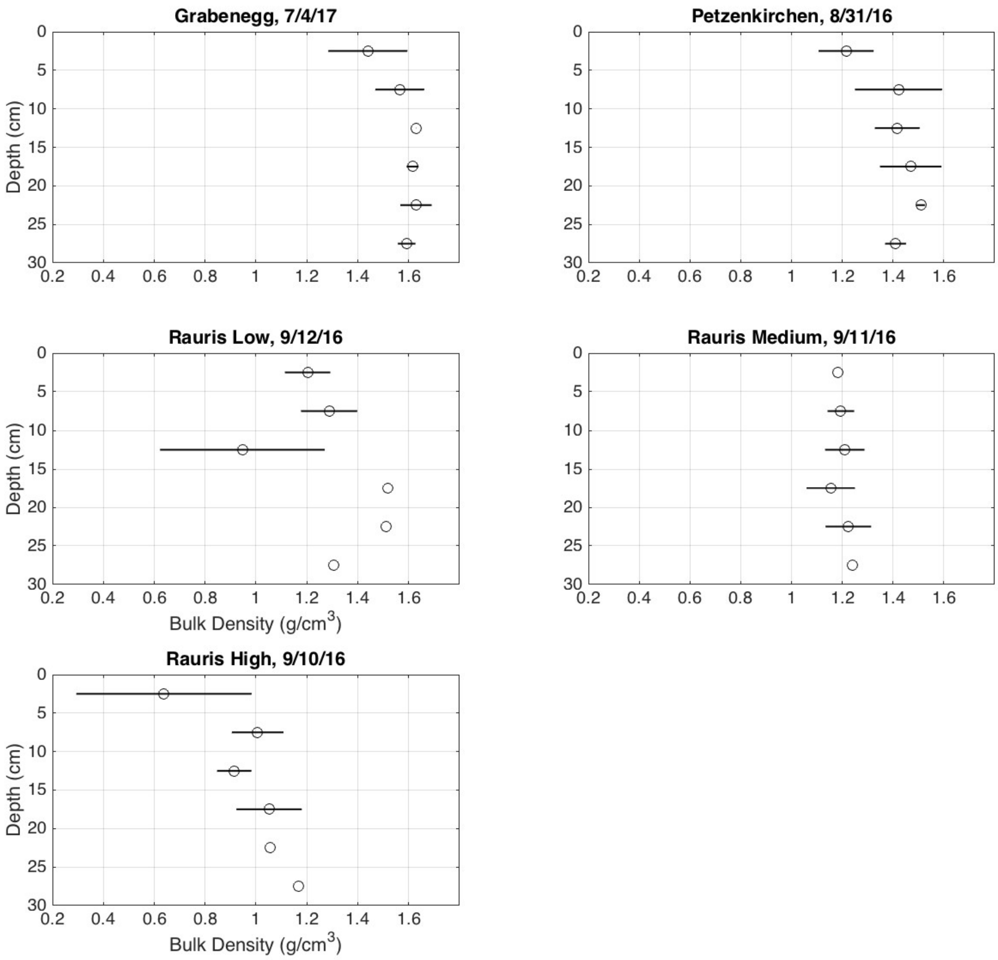

FIG. 3.4. Depth vs. soil bulk density for the 5 site calibration datasets. The open circle is the mean of 3 samples and the bars are +/- 1 standard deviation. Note some locations are missing information due to challenging sampling conditions due to large aggregate or shallow mineral soils.

Fig 3.5 illustrates a plot of corrected neutron counts vs. total water for all 5 sites and 16 calibration datasets. The calibration function using the average N_0 and +/- 1 standard deviation of N_0 are also plotted. In general, the total soil moisture decreases nonlinearly vs the corrected neutron counts across each site. It is also clear that site specific N_0 would help improve local estimates of soil moisture. Of course, a local estimate of N_0 would undermine the main purpose of a backpack CRNS and use of a single calibration function. Note the perception of different site N_0's are due to uncertainty and natural spatial variation in the calibration dataset estimates of bulk density, gravimetric soil moisture, soil organic carbon and lattice water. In addition, a small amount of uncertainty will be introduced by imperfect neutron scaling factors and high energy neutron intensity corrections. Most importantly Fig. 3.6 illustrates the observed soil moisture vs. calibration function predicted soil moisture. Note that for soil moisture values less than ~0.45 cm^3 cm^{-3} the CRNS shows errors less than the 0.04 cm^3 cm^{-3} remote sensing benchmark. For the wetter alpine sites this error grows considerably, which is a product of the large variations in the calibration gravimetric soil moisture and challenges of working in mountain alpine soils. It is recommended that future studies with repeat backpack visits that a site specific N_0 could be used to reduce local soil moisture error vs. a more global N_0 value. Lastly, collection of a minimum of 3 local calibration datasets is recommended to ensure the highest quality estimates of soil moisture using the CRNS.

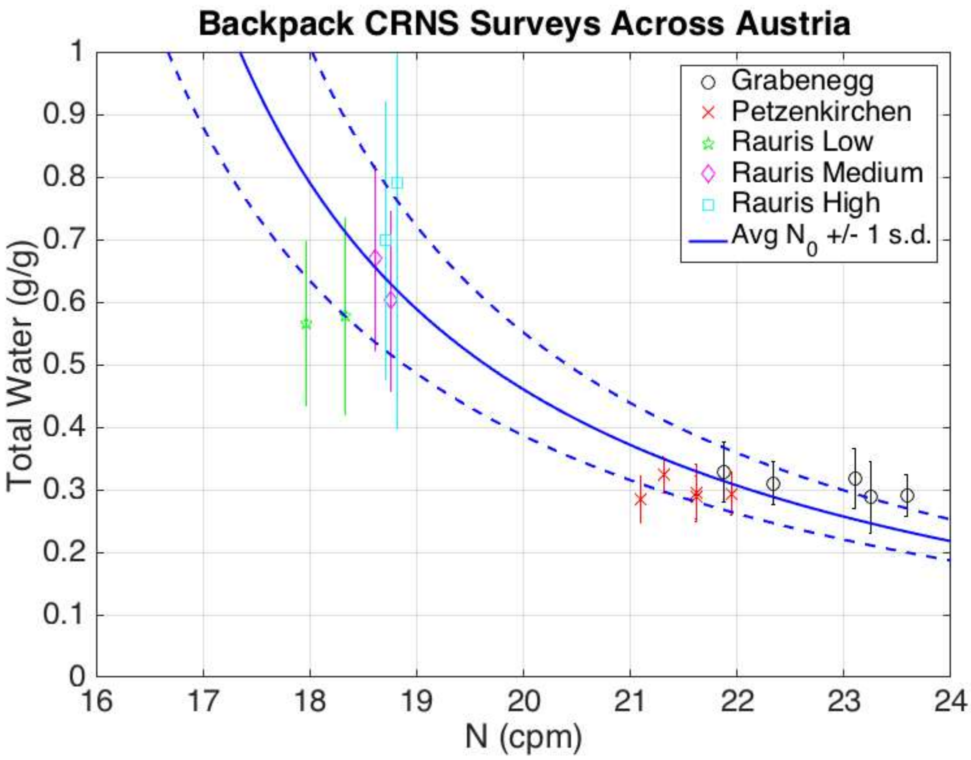

FIG. 3.5. Comparison of corrected neutron counts vs. total water observed from 16 calibration datasets across 5 sites in Austria. The vertical error bars are +/- 1 standard deviation of gravimetric soil moisture.

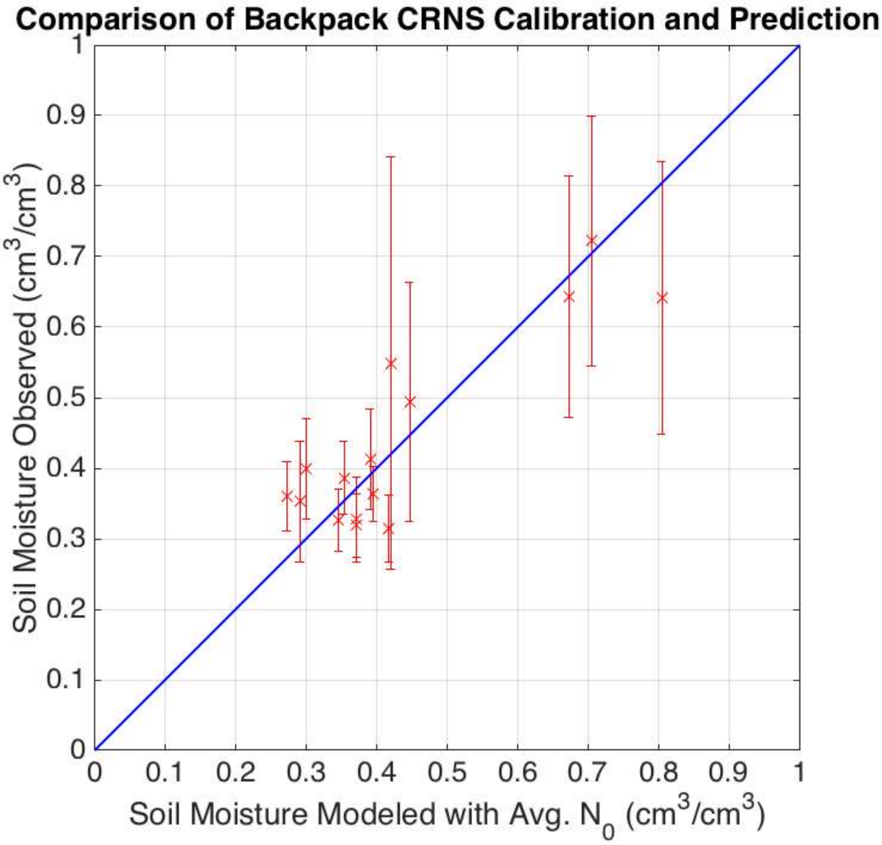

FIG. 3.6. Comparison of observed soil moisture (cm^3/cm^3) vs. modelled soil moisture with average observed N_0 value. The vertical error bars are +/- 1 standard deviation of gravimetric soil moisture.

3.3.3. 1 – Dimensional backpack CRNS survey from Austria

A 1-Dimensional backpack survey was conducted at Grabenegg Austria on 6 July 2017 (Fig. 3.7). The site is a hilly undulating landscape with moderate to severe slopes. The survey consisted of 2 linear transects of 6 locations in maize and 5 locations in grassland. Fig. 3.8 shows the location of each of the 11 backpack points. At each location the backpack was set on the ground and left running for a minimum of 15 minutes. For the first 6 locations a handheld time domain reflectometry (TDR) sensor was used to measure soil moisture at 10 spatial locations around the backpack. Note the TDR sensor had rod lengths of 15 cm which is shallower than the 30 cm the CRNS backpack will see. As such one would expect similar spatial trends but a different absolute soil moisture value. It was also found that the soils in the grassland area where too hard to insert the rods without damage thus precluding us from sampling all 11 sites as intended. This underscores the main advantage of the CRNS backpack non-invasive observations and rapid use in all study sites.

FIG. 3.7. Photograph of 1-Dimensional backpack survey collection on 6th of July 2017 in Grabenegg Austria.

FIG. 3.8. Location of 11 backpack survey points collected on 6th of July 2017 in Grabenegg Austria. The backpack was left at each location for ~15 minutes. In addition, a mobile TDR sensor (0-15 cm) was used at 10 locations around each backpack survey point. The TDR system was only used on the first 6 survey points due to challenging soil conditions.

Using the average N_0 value from the calibration procedure the neutron counts were grouped by location in order to estimate soil moisture. Fig. 3.9 illustrates the estimate of CRNS average soil moisture and uncertainty due to counting statistics. Fig. 3.9 also shows the average TDR and uncertainty from 10 repeat samples around the backpack. As expected the soil moisture values follow the same general pattern with TDR having lower values due to its shallower sensing depth of 15 cm vs. 30 cm. In addition, the soil moisture transects values follow the general contours of the landscape. In particular site 2 was in a topographic low area that receives large amounts of surface drainage. Sites 5 and 6 were on hill tops and the surrounding vegetation was noticeably smaller due to gravellier soils and likely greater water stress conditions. Lastly, the second transect in the grassland (sites 7-11) were in general drier than the maize survey points (1-6). This is likely due to its higher topographic location and reduced benefits from shading of the maize canopy on the surface.

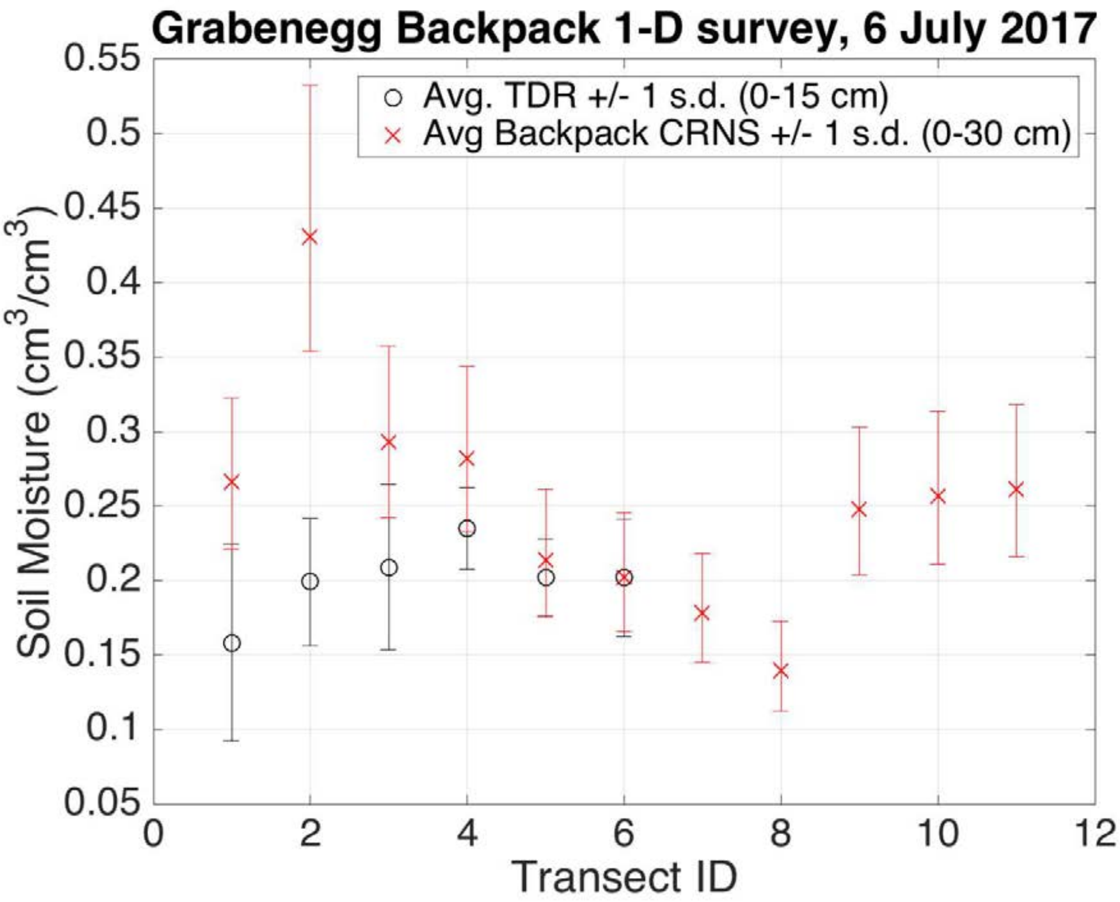

FIG. 3.9. Results of backpack CRNS and TDR sampling at 11 and 6 survey points. Note the TDR rods were only 15 cm long and thus resulted in drier observations compared to the backpack which sees down to ~30 cm. Location 2 is a topographic low area with significant surface drainage.

3.3.4. 2 – Dimensional rover CRNS survey from Nebraska, USA

Using the larger CRNS detector [Fig 1.2] a survey over a 64-ha agricultural field can be collected in approximately 90 minutes by continuously driving across the field at speeds of 10-15 kph. Fig 3.10 illustrates the average vehicle location during the 1-minute collection periods and corresponding neutron counts. Driving in a serpentine pattern allows us to see the spatial pattern of soil moisture and underlying features larger than approximately 10 meters. Fig. 3.11 illustrates the average vehicle location (black dots) and resampled 20 m grid (red X's). The resampled grid allows us to smooth out the neutron counts due to the uneven sample locations and spatial autocorrelation between points. Using the resampled grid and an inverse distance weighting scheme a spatially interpolated surface is provided that minimizes sampling noise and retains the underlying soil moisture features in space. Fig. 3.12 shows the resulting soil moisture field for the circular area that is under center-pivot irrigation. The field shows large variations in soil moisture reflective of the underlying soil texture and properties. The study site is located near an old stream channel where the alluvial materials are a mixture of gravels, sands, silts and clays. Understanding the underlying spatial distribution of soil types and drainage properties is critical for future optimal irrigation management.

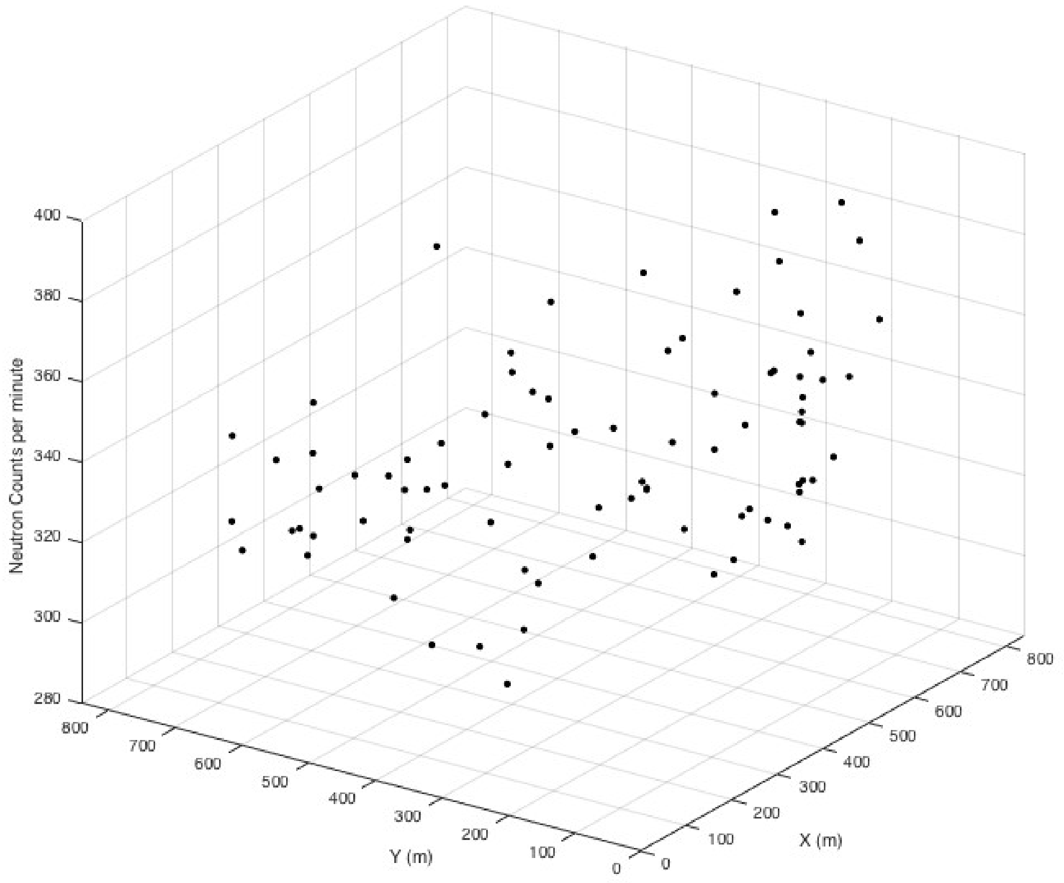

FIG. 3.10. Neutron counts collected at 86 locations over an 800 by 800 m field in Western Nebraska USA with a rover CRNS on 3 May 2017. The rover was driven back and forth at a speed of 10-15 kph.

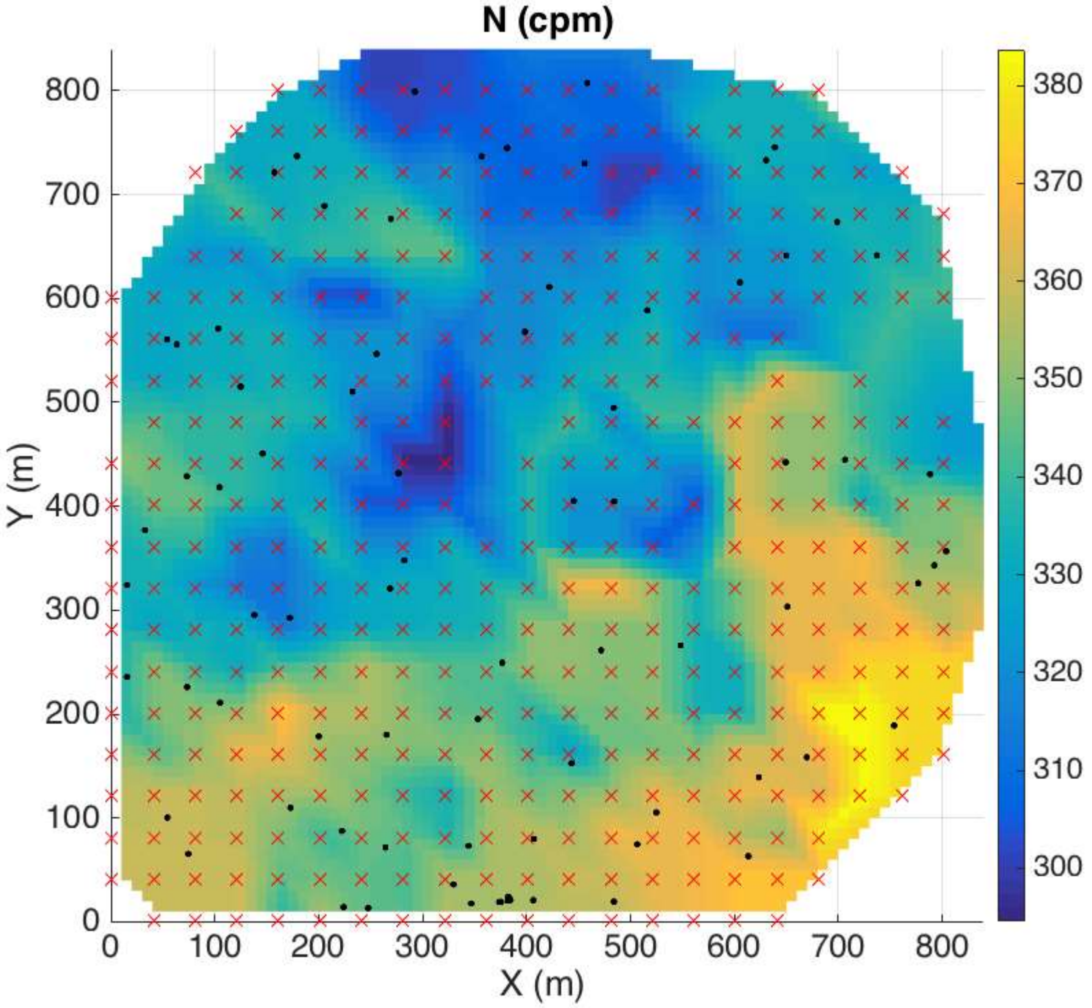

FIG. 3.11. Interpolated neutron counts from rover CRNS survey in Western Nebraska, USA. The black dots show the average rover location during the 1-minute collection period. The red x's show a resampling grid to smooth the uneven collection points and sharpen the neutron surface following standard processing algorithms of remote sensing products.

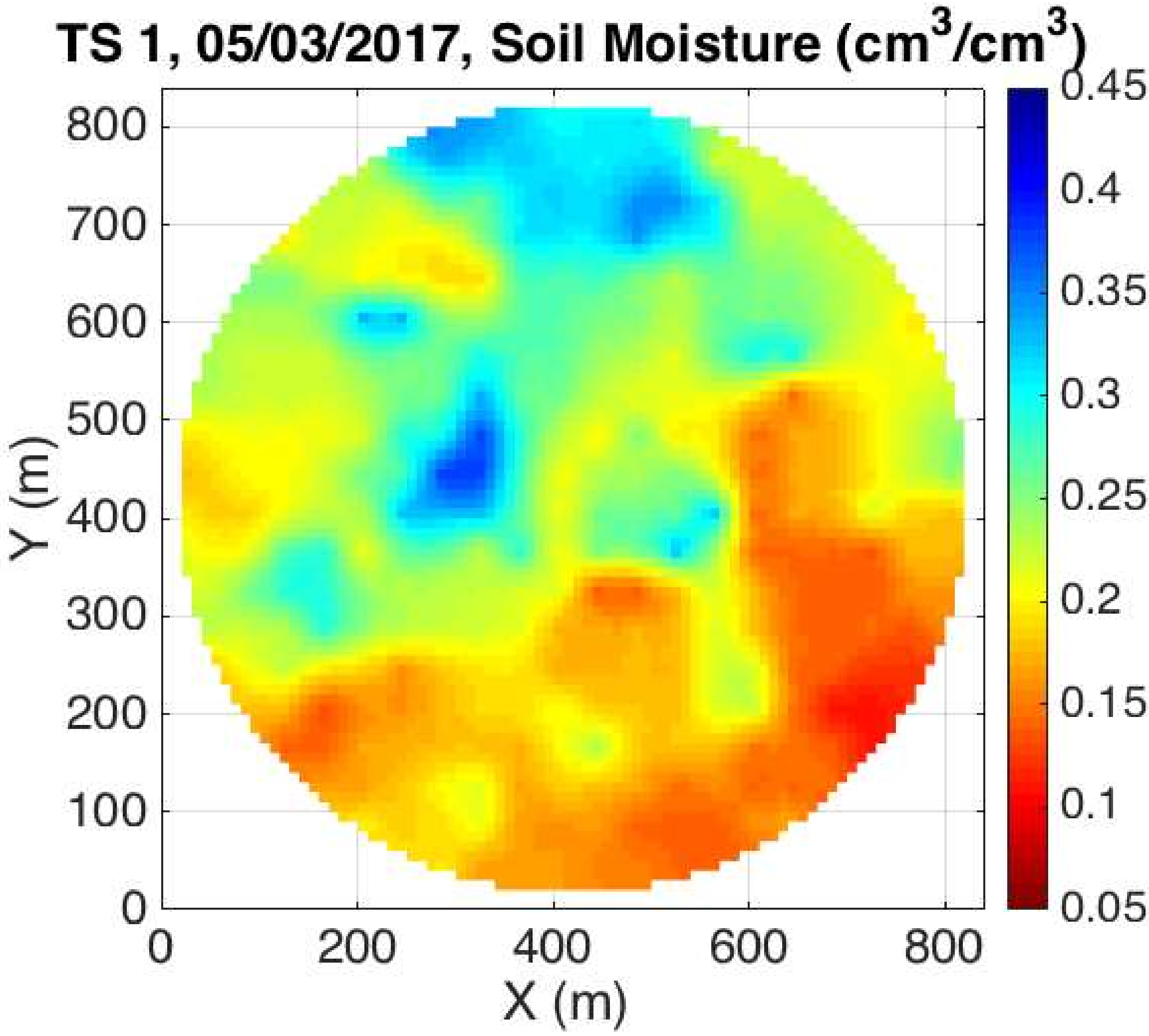

FIG. 3.12. Interpolated soil moisture map from rover CRNS survey at an agricultural field in Western Nebraska, USA. The neutron surface from FIG 3.11 is converted to soil moisture. The survey was conducted over a 55-ha circular field with center-pivot irrigation.

3.4. SUMMARY

The processing of stationary and mobile CRNS has been standardized but remains burdensome, particularly for mobile surveys. In this chapter spreadsheet resources and web based software to aid in the data analysis were described. In addition, 4 CRNS examples were presented consisting of a stationary CRNS and cross-validation with a backpack, an inter-site comparison of the backpack CRNS at 5 sites in Austria, a 1-Dimensional backpack survey in Austria, and a 2-Dimensional rover survey from Nebraska, USA. The stationary vs. backpack comparison illustrated high correspondence between the sensors through time. The stationary CRNS showed the dynamic range of soil moisture with future software allowing for real time observations and aid in management decisions. The comparison of 16 calibration datasets from 5 sites across Austria indicated similar CRNS response with more accurate soil moisture estimates below 0.45 cm^3 cm^{-3}. Soil moisture estimation in alpine soil environments is challenging with conventional methods. The CRNS provided reasonable soil moisture estimates given the large natural variation that exists. The 1-Dimensional backpack survey in Austria showed high correspondence with a mobile handheld soil moisture probe and agreement with general topographic and edaphic site conditions. The 2-Dimensional CRNS rover example illustrated that data can be rapidly collected over a 64-ha field. The survey identified underlying spatial patterns believe to be representative of soil texture and properties that will be useful for future optimal precision irrigation management.

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