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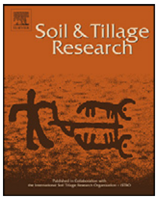

Non-invasive field measurements of soil water content using a pulsed 14 MeV neutron generator

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ABSTRACT

Current techniques of soil water content measurement are invasive and labor-intensive. Here, we demonstrate that an in situ soil carbon (C) analyzer with a multi-elemental analysis capability, developed for studies of terrestrial C sequestration, can be used concurrently to non-invasively measure the water content of large-volume ($\sim$0.3 m^3) soil samples. Our objectives were to investigate the correlations of the hydrogen (H) and oxygen (O) signals with water to the changes in the soil water content in laboratory experiments, and in an agricultural field. Implementing prompt gamma neutron activation analyses we showed that in the field, the signal from the H nucleus better indicates the soil water content than does that from the O nucleus. Using a field calibration, we were able to use the H signal to estimate a minimum detectable change of $\sim$2% volumetric water in a 0–30 cm depth of soil.

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1. Introduction

Knowledge of soil water content is critical to agricultural, hydrological and meteorological researches. Soil moisture–climate interactions are increasingly of interest in a changing climate, as recently reviewed by (Seneviratne et al., 2010). For example such data are vital for understanding the soil's hydraulic properties that are essential input to most hydrologic and climate models (Ines and Mohanty, 2008), because soil moisture is linked to evaporation and thus to the distribution of heat fluxes from the land to the atmosphere. Soil water sensors routinely are used in applications such as research on crop production, water budgeting in water sheds, precision agriculture and irrigation scheduling. Earlier, Schmugge et al. (1980) surveyed methods used to determine soil moisture content which included gravimetric, nuclear, electromagnetic and remote sensing techniques. Their study also included tensiometric techniques for measuring soil water potential that describes the energy status of the soil water and is an important parameter for water transport analyses, water storage estimates and soil–plant–water relationships. A recent review by Robinson et al. (2008) highlights the need for bridging the gap between point scale measurements (<1 m^2) and obtaining areal averages (10–100 m^2) that are necessary for spatial data describing watershed patterns. They discussed several emerging methods and technologies from geophysics such as ground penetrating radar and electromagnetic induction, together with some approaches for obtaining better spatial coverage that use time domain reflectometers (TDRs) fitted on mobile platforms like tractors and all-terrain vehicles (ATVs). However, these sensors are invasive and do not possess on-the-go sensing capabilities.

Here, we discuss the feasibility of extending the functionality of a surface nuclear probe that primarily was designed for non-invasive, in situ measurements for monitoring and verifying the soil's carbon stocks resulting from carbon-sequestration programs (Wielopolski et al., 2008, 2011). In this technique, fast neutrons produced by an electrically switchable pulsed 14 MeV neutron generator (NG) impinge on the soil and interact with its various elements. During the neutron burst (the ON state of the NG) they undergo inelastic neutron scattering (INS) with C and O nuclei; between the bursts (the OFF state of the NG), the neutrons previously released during the ON state, slow down via elastic scattering with the soil's matrix elements, particularly H, so that eventually some are captured in a thermal neutron capture (TNC) process. It is expected that the density of the resultant cloud of slow neutrons and the intensity of the characteristic 2.22 MeV prompt capture gamma-rays from H will be a function of the soils' water-content. To the best of our knowledge, there are no earlier reports of measuring neutron-induced prompt gamma-ray signals

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from H and O as a direct method to determine soil water under field conditions. The proposed method is quite distinct from the commercial neutron probe that measures soil moisture indirectly by detecting the thermalized neutrons escaping the soils' matrix.

Our objectives were the following:

- Demonstrate, in laboratory experiments, the response of the H and O signals from the surface nuclear probe to linear changes in the soil's moisture content.
- Compare the response of our instrument to changes in the water content of an agricultural field with that of the conventional theta-probe technique and to volumetric determination from soil cores.

2. Materials and methods

The instrument was assembled and mounted on a cart at Brookhaven National Laboratory (BNL), New York (Fig. 1). Static measurements can be acquired at a fixed spot, or the cart can be towed across a field in the scan mode to integrate the data across a field. The system consists of a pulsed 14 MeV NG and three 12.7 cm × 12.7 cm × 15.2 cm NaI(Tl) gamma-ray detectors whose signal outputs are summed and processed on board by a digital multi-channel analyzer (MCA) that concurrently records an INS- and TNC-spectrum in real time (Mitra et al., 2007). The NG and gamma-ray detectors are positioned 25 cm above the soil's surface. All instrumental-runs take an hour. Net elemental yields (net peak-area counts), were obtained by subtracting a background area from the total area in a region of interest of the gamma-ray spectrum, using the trapezoidal method (Wielopolski et al., 2008).

2.1. Laboratory and field experiments

Laboratory experiments were conducted at the Soil Analysis Facility at BNL, using topsoil collected from a nearby forest within the BNL campus. The soil was well drained Riverhead sandy loam (coarse-loamy, mixed, active, mesic Typic Dystrudepts), with 0–3 percent slopes. The soil was spread out in a barn with adequate ventilation and allowed to air-dry for about 3 weeks before being used for determining selected soil characteristics. The dried forest soil was screened through a 2 mm mesh to remove roots and other undesired debris before being used for laboratory measurements; thus all laboratory experiments were performed using disturbed topsoil. Similarly, prior to commencement of the experiments, the amount of the dry and sieved topsoil that was needed to fill the experimental pit (dimension 1.52 m × 1.52 m × 0.5 m deep) was determined to be ~1.0 Mg (1000 kg).

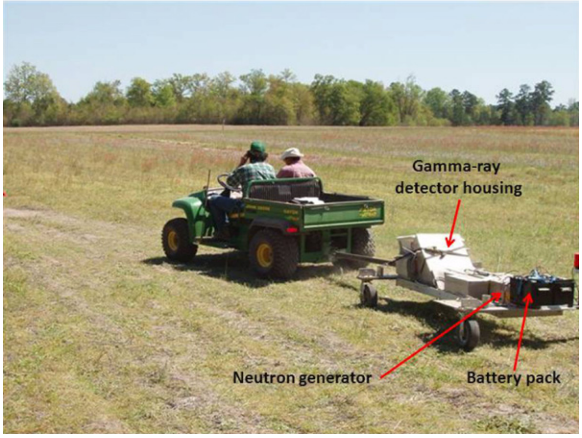

Fig. 1. The mobile nuclear probe built at Brookhaven National Laboratory comprises a 14 MeV pulsed neutron generator and three NaI(Tl) gamma-ray detectors that detect the Hydrogen and Oxygen signals. All on-board instruments are powered by a 12 V battery.

Triplicate subsamples of the sieved soil were collected and used to estimate the water holding and bulk density characteristics. Maximum soil-moisture holding capacity was estimated by tightly packing the air-dried soil into column (Teflon-stopcock and fritted disc columns; inner diameter = 22 and length = 300 mm) and a known quantity of water was gradually added from the top of the column until the soil was fully saturated (when the first few drops of water seeped out of the column). Although we are aware of the hysteresis effect, adding water to the soil column was more convenient to accurately determine the amount of water being added to the soil columns. In the absence of pressure plates, we estimated the soil's field water holding capacity (FC) by allowing the soil to drain for 24–48 h after adding the water to achieve maximum soil capacity; we assumed that this time frame was adequate for the soil macro pores to drain. Thereafter, the amount of water needed to bring the soil up to 25, 50, and 75% of the FC was calculated. Bulk density values also were determined in triplicates by filling aluminum cans of known volume (diameter, 7.6 cm and depth, 5.4 cm) with the soil, weighed, oven dried and re-weighed after drying to a constant weight at 105 °C for 24–48 h.

The relationship between the different soil water contents and the H and O signals were determined at 0, 25, 50 and 75% of the FC by adding the pre-determined amounts of water needed to bring the 1.0 Mg of soil to these desired soil water contents. Briefly, after recording the H and O signals in triplicate by centering the instrument on the pit, the soil was evacuated from the pit into a mechanical mixer and the desired amount of water was added to bring its soil water content to the next higher FC. After thorough mixing, the soil immediately was transferred back into the pit, and the H and O signals were recorded again. This cycle was repeated to cover the range of soil water up to 75% FC. At each soil water holding capacity level (0, 25, 50 and 75% FC), soil samples were collected in triplicate at random locations in the pit before and after the instrumental runs and gravimetrically estimated for the true water content levels. Unfortunately, the H and O measurement was not performed at maximum water holding capacity due to an apparent breakdown of the soil after repeated mixing.

Field experiments were carried out at the Clemson University Pee Dee Research and Education Center, Darlington, South Carolina. The INS and TNC spectra were recorded at seven fixed locations within a field along an approximately 100 m long transect situated up-slope to down-slope that corresponded with the soil mapping units shown in Fig. 2. This field is comprised of well-drained soils in up-slope positions with poorly drained soils located in depression areas. The latter soils areas are depicted as circular patterns referred to as Carolina Bays (Daniels et al., 1999). Field locations progressively up-slope consisted of grid points labeled V12, W11, Y11 and AB10 respectively. These up-slope soil series are well drained soils and had topsoil dominated by sand. Field locations progressively down-slope were labeled T12, S12 and S13, respectively. Soils in these locations are poorly drained and frequently received eroded silt and clay causing the top soil to have lower sand contents (Novak et al., 2009). The field has been under cultivation with row crops (corn, soy bean and cotton) for the past 20 years. Table 1 summarizes selected soil characteristics of the field.

At each location, and within the nuclear probe's footprint of ~150 cm diameter, we measured (a) volumetric content of soil moisture to a depth of 6.5 cm with a factory calibrated, Dynamax, TH_2O portable soil moisture theta probe at three spots before and after the INS measurements, and, (b) gravimetrically analyzed soil water from five cores collected within a 1 m^2 area centered on the instrument's footprint, using a soil probe with inner diameter of 3.12 cm. Each core was subsequently subdivided into 0–5, 5–10, 10–20, 20–30 and 30–40 cm depth intervals, bagged and taken to