Geoderma 335 (2019) 69–77

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

Biomass water content effect on soil moisture assessment via proximal gamma-ray spectroscopy

Marica Baldoncini[a,b,*], Matteo Albéri[a,b], Carlo Bottardi[b,c], Enrico Chiarelli[a,b], Kassandra Giulia Cristina Raptis[a,b], Virginia Strati[b,c], Fabio Mantovani[b,c]

[a] INFN, Legnaro National Laboratories, Viale dell'Università, 2, 35020 Legnaro, Padua, Italy
[b] Department of Physics and Earth Sciences, University of Ferrara, Via Saragat 1, 44121 Ferrara, Italy
[c] INFN, Ferrara Section, Via Saragat 1, 44121 Ferrara, Italy

ARTICLE INFO

Handling Editor: A.B. McBratney

Keywords:
Real-time continuous soil water content monitoring
Precision agriculture
NaI gamma-ray spectra
Vegetation shielding effect
Monte Carlo simulation method
Biomass equivalent water layer

ABSTRACT

Proximal gamma-ray spectroscopy supported by adequate calibration and correction for growing biomass is an effective field scale technique for a continuous monitoring of top soil water content dynamics to be potentially employed as a decision support tool for automatic irrigation scheduling. This study demonstrates that this approach has the potential to be one of the best space–time trade-off methods, representing a joining link between punctual and satellite fields of view. The inverse proportionality between soil moisture and gamma signal is theoretically derived taking into account a non-constant correction due to the presence of growing vegetation beneath the detector position. The gamma signal attenuation due to biomass is modelled with a Monte Carlo-based approach in terms of an equivalent water layer which thickness varies in time as the crop evolves during its life-cycle. The reliability and effectiveness of this approach is proved through a 7 months continuous acquisition of terrestrial gamma radiation in a 0.4 ha tomato (*Solanum lycopersicum*) test field. We demonstrate that a permanent gamma station installed at an agricultural field can reliably probe the water content of the top soil only if systematic effects due to the biomass shielding are properly accounted for. Biomass corrected experimental values of soil water content inferred from radiometric measurements are compared with gravimetric data acquired under different soil moisture levels, resulting in an average percentage relative discrepancy of about 3% in bare soil condition and of 4% during the vegetated period. The temporal evolution of corrected soil water content values exhibits a dynamic range coherent with the soil hydraulic properties in terms of wilting point, field capacity and saturation.

1. Introduction

Soil water content (SWC) is a relevant state variable tracking the exchange of water at the land surface and is a key to understand and predict soil hydrological processes over a broad range of scales (Vereecken et al., 2015). Tracing its dynamics provides essential information for a deeper understanding of the major hydrological, biogeochemical, and energy exchange processes (Brocca et al., 2017), as well as for improving water use efficiency in agriculture, which is definitely the main competitor in the worldwide race to water resources (Levidow et al., 2014; Ozbahce and Tari, 2010). Therefore, technological and methodological advancements are highly desired for accurate measurements of the spatial and temporal SWC variability (Michot et al., 2003; Robinet et al., 2018; Sultana et al., 2017).

Recently, proximal and on-the-go soil sensors are being widely adopted for understanding soil properties and hydrogeological processes in precision agriculture (Heggemann et al., 2017; Piikki et al., 2015; Viscarra Rossel et al., 2007). From one side they have a relatively wider spatial coverage compared to point scale sensors, and from the other side they are less subject to interfering factors (e.g. atmospheric effects or observation conditions in terms of intensity and direction of illumination) in comparison to traditional remote sensing methods based on satellite spectral images (Barnes et al., 2003; McBratney et al., 2003). In this scenario, permanently installed measurement stations for proximal gamma-ray spectroscopy match the current requirements for SWC sensing methods as they (i) keep the soil structure undisturbed during the data taking, (ii) operate continuously allowing for a characterization of the SWC temporal dynamics and (iii) integrate measurements at the field scale over areas of 1 to about 10 km^2 (Bogena et al., 2015; Strati et al., 2018).

* Corresponding author at: INFN, Legnaro National Laboratories, Viale dell'Università, 2, 35020 Legnaro, Padua, Italy.
E-mail address: baldoncini@fe.infn.it (M. Baldoncini).

https://doi.org/10.1016/j.geoderma.2018.08.012
Received 26 April 2018; Received in revised form 20 July 2018; Accepted 7 August 2018

Gamma-rays are high-energy photons continuously produced in soils due to the presence of ^{40}K and daughter products of the ^{238}U and ^{232}Th decay chains. As the signal recorded by a spectrometer provides clues on the propagation of gamma-rays from the emission to the detection point, environmental gamma spectra probe at the same time the activity of the radioactive source and the physical-chemical properties of the traversed materials in terms of different attenuation effects, the latter essentially dominated by material density and consequently by SWC (Minty, 1997).

Environmental gamma-ray spectroscopy measurements are influenced by plenty of experimental boundary conditions which knowledge help in interpreting radiometric data at different levels according also to the spatial scale of the surveys. Airborne gamma-ray spectroscopy already raised the attention on the attenuating effects on the gamma signal due to the presence of vegetation (Dierke and Werban, 2013; Norwine et al., 1979; Sanderson et al., 2004; Wilford et al., 1997). However, the presence of biomass in terms of plants, leaves and fruits is expected to play a much more critical role in proximal gamma-ray surveys, which implies that an accurate estimate of the signal reduction is needed.

The physical-chemical properties and the radioactive content of agricultural soils can be considered almost stationary, or at least sufficiently under control. The same does not apply to the crop system which is subject to a highly dynamic development generally affected by variable climatic conditions and irrigation management practices. Indeed, the presence of growing vegetation introduces a sizable extra attenuation due to the Biomass Water Content (BWC). The BWC varies in time during the crop life-cycle and causes a gamma-ray attenuation which is in principle undistinguishable from that generated by an increase in SWC. In this perspective, a reliable correction for the BWC shielding is mandatory in order to avoid a systematic overestimation of SWC.

The goal of this paper is evaluating the BWC attenuation effect in the framework of a proximal gamma-ray spectroscopy experiment performed at a tomato test field. The experiment was conducted by installing a permanent gamma station constituted by a 1 L sodium iodide (NaI) detector placed at a height of 2.25 m, which collected gamma-rays emitted within an area of about 25 m radial distance and within a depth of approximately 30 cm. An ad-hoc gravimetric calibration campaign was performed by collecting soil and biomass samples. Experimental daily values of the SWC were estimated over a data taking period that lasted for 7 months and were evaluated by taking into account the shielding effect due to the presence of growing BWC during the tomato crop season.

2. Material and methods

In the following section we briefly present a geographical and climatic setting of the experimental site and a characterization of the main physical and hydraulic properties of the soil. The gamma and agro-meteorological stations are described together with the data acquisition methods. The gravimetric sampling campaign performed on soil and biomass samples is described along with the obtained results.

2.1. Experimental site

The experiment was conducted in the period 4th of April–2nd of November 2017 at a tomato field of the Acqua Campus, a research center of the Emiliano-Romagnolo Canal (CER) irrigation district in the Emilia Romagna region in Italy (44.57° N, 11.53° E; 16 m above sea level) (Fig. 1). According to the Köppen-Geiger climate classification (Peel et al., 2007), this geographical area is classified as Cfa (i.e. temperate, without dry season and with hot summer); its average annual temperature is 14 °C and rainfall is 700 mm.

About 24% of the agricultural territory in Emilia Romagna, one of the richest regions of Italy and Europe, is devoted to irrigated agriculture, which plays a major role in the regional economy (Munaretto and Battilani, 2014). In particular, Emilia Romagna is the Italian region having the largest surface of land cultivated with tomatoes, one of the most water-demanding crops among vegetables, and contributes for about one third of the tomato national production (ISTAT, 2017).

The main physical and hydraulic parameters of the soil, characterized by a loamy texture and a 1.26% organic matter content, are listed in Table 1 (after (Strati et al., 2018)).

Tomato plants were transplanted on the 23rd of May with a row and plant spacing as shown in Fig. 1, which corresponds to a 3.5 plants/m^2 density, and harvested on the 14th of September. The crop phenological growth stages of anthesis and maturity, together with the planting and harvesting dates, are indicated in panel (a) of Fig. 3. Irrigation water was delivered by a sprinkler system, following a schedule based on the criteria provided by the decision support tool of IRRINET (Munaretto and Battilani, 2014).

2.2. Experimental setup

The experimental setup is composed of a gamma spectroscopy station and a commercial agro-meteorological station (MeteoSense 2.0, Netsens) both powered by solar panels and provided with an internet connection (Fig. 2).

The gamma station was specifically designed and built for the purpose of this experiment: its external structure is made up of steel and comprises a steel box welded on top of a 2.25 m high pole which hosts a 1 L sodium iodide (NaI(Tl)) gamma-ray spectrometer (Baldoncini et al., 2018). The crystal is coupled to a photo-multiplier tube base which output is processed by a digital Multi-Channel Analyzer (MCA, CAEN γstream) having 2048 acquisition channels. At a height of 2.25 m about 95% of the detected gamma signal is produced within a cone having base radius of approximately 25 m (Feng et al., 2009) (Fig. 2).

The MCA is complemented with a small integrated computer which provides the necessary hardware interface to the detector and runs the software required for managing the acquisition parameters, namely the start time, the acquisition dynamics in terms of spectral gain [keV/ch], and the operating high voltage. Additional software was developed to make the data-taking continuous and more resilient to some hardware related failures like accidental restarts or power shortages.

Measured weather data include air temperature, relative air humidity, wind direction and speed, precipitation and Short Wave Incoming Radiation (SWIR). Fig. 3 shows the daily values of Minimum and Maximum Temperatures (T_{min} and T_{max}), ranging in the T_{min} = [1.3–22.7] °C and T_{max} = [13.5–39.3] °C intervals (panel a), the SWIR (ranging from 34.7 to 257.3 W/m^2) (panel b), the daily rainfall amount (up to a maximum of 56.2 mm) and irrigation water (up to a maximum of 35 mm) (panel c). The evapotranspiration (ET0, panel b) is calculated with the Hargreaves method (Hargreaves and Samani, 1985) using weather data recorded by the agro-meteorological station. During the last ten years (2008–2017) local meteorological archives (Arpae) recorded a mean total rainfall in the same period of 384.3 mm, a mean daily minimum temperature of 13.2 °C and a mean daily maximum temperature of 26.3 °C.

2.3. Data acquisitions

2.3.1. Gravimetric measurements

Gravimetric measurements were carried out on bulk soil samples as means to both calibrate and validate the soil water content estimation based on proximal gamma-ray spectroscopy. Five sets of samples to be characterized via gravimetric measurements were collected: (i) a calibration set collected in bare soil condition on the 18th of September one day before a rainfall event, (ii) a validation set collected in bare soil condition on the 21st of September two days after a rainfall event, (iii) three validation sets collected in presence of the tomato crop and one