Discriminating irrigation and rainfall with proximal gamma-ray spectroscopy

Andrea Serafini
Dept. of Physics and Earth Sciences, University of Ferrara, Ferrara, Italy
INFN, Ferrara Section, Ferrara, Italy
serafini@fe.infn.it
0000-0001-9191-661X

Matteo Albéri
Dept. of Physics and Earth Sciences, University of Ferrara, Ferrara, Italy
INFN, Legnaro National Laboratories, Legnaro, Padua, Italy
alberi@fe.infn.it
0000-0001-9150-8798

Enrico Chiarelli
Dept. of Physics and Earth Sciences, University of Ferrara, Ferrara, Italy
INFN, Ferrara Section, Ferrara, Italy
chrnrc@unife.it
0000-0002-0104-3614

Michele Montuschi
Dept. of Physics and Earth Sciences, University of Ferrara, Ferrara, Italy
INFN, Ferrara Section, Ferrara, Italy
montuschi@fe.infn.it
0000-0002-2930-5030

Kassandra Giulia Cristina Raptis
Dept. of Physics and Earth Sciences, University of Ferrara, Ferrara, Italy
INFN, Ferrara Section, Ferrara, Italy
rptksn@unife.it
0000-0002-0232-9120

Virginia Strati
Dept. of Physics and Earth Sciences, University of Ferrara, Ferrara, Italy
INFN, Ferrara Section, Ferrara, Italy
strati@fe.infn.it
0000-0001-7271-5353

Fabio Mantovani
Dept. of Physics and Earth Sciences, University of Ferrara, Ferrara, Italy
INFN, Ferrara Section, Ferrara, Italy
mantovani@fe.infn.it
0000-0003-1200-0174

***Abstract*—We present a study of the performances of a proximal gamma-ray ground station based on a 7 months continuous acquisition, including 42 rain episodes and 16 irrigations. In particular, we demonstrate the reliability of the station in discriminating irrigations and rains through their peculiar gamma signals fingerprint. This proof of concept experiment shows that proximal gamma-ray spectroscopy can potentially fill the spatial gap between punctual and satellite soil water content measurements, as well as provide an unbiased approach for producing comprehensive irrigations maps.**

Keywords—Irrigation, soil water content, proximal gamma-ray spectroscopy, rain induced gamma activity, real-time soil water content monitoring.

I. Introduction

A global and updated dataset of amount of water for irrigation is still an unattained goal. Most of the existing comprehensive maps of irrigation are based on statistical surveys or can identify just the areas equipped for irrigation rather than the truly irrigated areas [1]. Those maps are patchy and incomplete since illegal pumping is not included, there are self-reporting relevant biases, and temporal/spatial coverage is not homogenous. Some vegetation indexes based on optical and visible remote sensing techniques are tentatively used as proxies for irrigation monitoring, since irrigated and non-irrigated lands show different spectral responses [2]. Sometimes these methods fail because climate conditions, natural vegetation regimes and agricultural practices are often unpredictable variables. Recent attempts to integrate these approaches seems to give promising results [3], although temporal and spatial heterogeneity of the information remains a persistent Achilles' heel. The Cosmic-Ray Neutron method, based on back diffusion of neutrons produced from secondary cosmic rays, demonstrated its effectiveness in probing soil water content [4]. Unfortunately, time variations of atmospheric pressure, primary cosmic rays flux, canopy cover and snow between different areas represent sources of noise impractical to assess if not through ancillary sensors and tailored Monte Carlo simulations [5].

In the last five years an alternative approach has been developed. The increase of Soil Water Content (SWC) due to irrigation can be obtained by comparing the measurements from microwave remote sensing to the modelled values calculated with numerical forecasts [6]. In a subsequent refinement [7], the irrigation water is inferred subtracting the rainfall measured with rain gauges from the total amount of water entering into the soil (rain + irrigation), calculated with an adapted version of the SM2RAIN algorithm [8]. This approach has been recently tested using data from Proximal Gamma-Ray (PGR) ground station [9].

In this paper we show how PGR spectroscopy represents a novel technique able not only to measure the SWC on a field scale (~10^3 m^3) and at a high temporal resolution (1 h), but also to undoubtedly and independently distinguish irrigations from rainfalls.

II. Rationale

PGR spectroscopy is a method for a non-stop tracing of SWC at an intermediate spatial scale, between punctual and satellite fields of view. Thanks to the installation of remotely controlled stations on field, SWC can be measured in real time on the basis of temporal variations of the gamma signal, produced by the decay of ^{40}K naturally and homogenously (in space and time) distributed in cultivated soils. The gamma signal measured with a spectrometer installed at a few meters above the ground is basically insensitive to temporal variations of cosmic radiation and to soil chemical composition and is inversely correlated with SWC. Indeed, having water 1.11 times as many electrons per gram compared to soils, it is 1.11 times as effective in attenuating gamma radiation [10]. By tuning the height of the detector above the ground, it is possible to adapt the footprint to the typical spatial resolution of satellite images (Fig. 1).

During a precipitation event, the transient increase of gamma activity of ^{214}Pb and ^{214}Bi (atmospheric ^{222}Rn daughters) generates an impulsive signal recorded by the permanent gamma ray station, which is clearly distinguishable from the typical morning/evening fluctuations [11, 12]. A drop of the ^{40}K signal and a significant increase of ^{214}Pb gamma rate are hence expected.

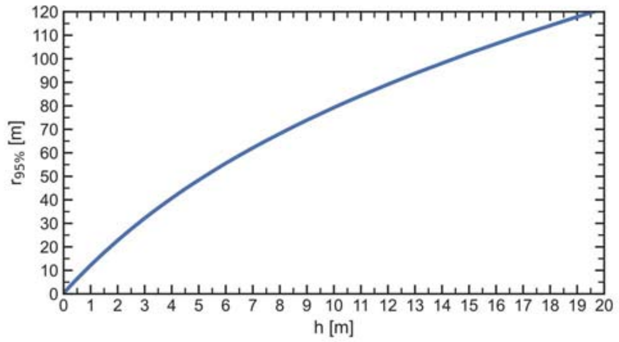

Fig. 1. The footprint radius $r_{95\%}$ is reported as a function of height h of the spectrometer with respect to the ground. The function $r_{95\%} = 16.2 \cdot h^{0.68}$ is calculated assuming that 95% of the unscattered gamma photon flux is produced in a circular area with radius $r_{95\%}$.

Since the irrigation water (e.g. underground water, freshwater) has a negligible content of ^{214}Pb, during an irrigation a drop of the ^{40}K and ^{214}Pb signal are instead concurrently expected.

III. Experimental Setup

In the period 4 April–2 November 2017 a PGR sensing experiment was conducted in a 40 m × 108 m tomato test field of the Acqua Campus (44.57° N, 11.53° E; 16 m above sea level), a research Centre of the CER irrigation district close to Bologna (Emilia-Romagna, Italy) [13].

An agro-meteorological station (MeteoSense 2.0, Netsens) and a custom PGR station collected data with a 94.8% duty cycle (Fig. 2). Air temperature, relative air humidity, precipitation, wind direction and speed, and short-wave incoming radiation were continuously measured by the agro-meteorological station. The gamma spectrum in the energy range [0.3 – 3.0 MeV] was continuously logged by a 1 dm^3 sodium iodide detector (NaI) coupled to a photomultiplier tube base and a digital multichannel analyzer. This gamma spectrometer is characterized by an energy resolution high enough to simultaneously measure the photopeaks of ^{214}Pb and ^{40}K at 352 keV and 1461 keV, respectively. This equipment was placed in a PGR station at a height of 2.25 m. Both stations were self-powered and web connected. The meteorological and radiometric data have been synchronized and processed in a unique time-referenced dataset having a 15 minutes temporal resolution.

Fig. 2. The agro-meteorological station (in the foreground) and the PGR station (in the background).

Tomato plants were transplanted on the 23rd of May in coupled rows, with an overall average planting density of 3.5 plants/m^2. The crop irrigation was performed by sprinklers following the schedule provided by the IRRINET soil-crop system model [14]. The minimum and maximum irrigation water amounts have been 7 mm and 35 mm respectively. The berries' maturity occurred on the 30th of August and their harvesting on the 14th of September [13].

IV. Results

The SWC and the rain induced gamma activity was determined by measuring simultaneously the gamma count rate (count per second, cps) in the ^{40}K and ^{214}Pb energy windows.

The Gravimetric Soil Water Content $SWC_G(t)$ at a specific time t was measured hourly using the following equation:

$$SWC_G(t) = S^C/S(t) \cdot (\Omega + SWC^C_G) - \Omega \quad (1)$$

where $SWC^C_G = 0.163 \pm 0.008$ [kg/kg] is the gravimetric water content at calibration time (18 September 2017) and $S^C = 11.7 \pm 0.2$ [cps] and $S(t)$ are the net ^{40}K gamma rate at calibration time and at time t respectively. The dimensionless coefficient $\Omega = 0.895$ is calculated based on the ratio between the mass attenuation coefficients in water and soil matrix [15].

Four sets of validation measurements were carried out with sampling campaigns devoted to estimate the SWC via gravimetric method [16]. Although the tests were performed in different weather and soil coverage conditions, the discrepancies among SWC values measured with gamma and gravimetric methods are compatible within 1 standard deviation of the measurements. Moreover, the absolute discrepancy among the SWCs obtained with the two methods is always less than 8.3%.

The ^{40}K gamma signal is measured simultaneously to atmospheric ^{222}Rn gamma daughters. Some of them (e.g. ^{218}Po and ^{214}Pb) are chemically active and adhere to water molecules forming "radioactive aerosol" in time scales of 1-100 s. This well-known rainout phenomenon (i.e. in-cloud scavenging) is the main process responsible for the radioactive enrichment of rain droplets.

During the 42 rains occurred in 7 months of data taking, we always observed the typical impulsive increases of ^{214}Pb count rates ΔC [cps]. Using a subset of these rain episodes, we found that ΔC is clearly related to the rain rate R [mm/h] by a power law dependence:

$$\Delta C = A \cdot R^{0.50 \pm 0.03} \quad (2)$$

where $A = 2.15 \pm 0.15$ [cps $mm^{-0.50}$ $h^{-0.50}$] is an equipment dependent parameter [17]. The sensitivity of this measurement is very high. A weak rainfall rate of 5 mm/h produces an increase of ^{214}Pb count rates $\Delta C \sim 4.8$ cps, to be compared with a typical background rate of ~ 1 cps.

On the contrary, the ^{214}Pb count rate is totally insensitive to water irrigation. In particular, no ^{214}Pb count rate spike has been observed during the 16 irrigations.

This evidence is particularly clear on 11 July 2017, when 30 mm of irrigation water (with a rate of 12 mm/h) were followed by a subsequent rainfall of 23.5 mm (Fig. 3). During the 2.5 hours of irrigation, the volumetric SWC measured by the PGR station increased from ~0.13 m^3/m^3 to ~0.28 m^3/m^3, reaching the maximum of 0.33 m^3/m^3 5 h after the end of the

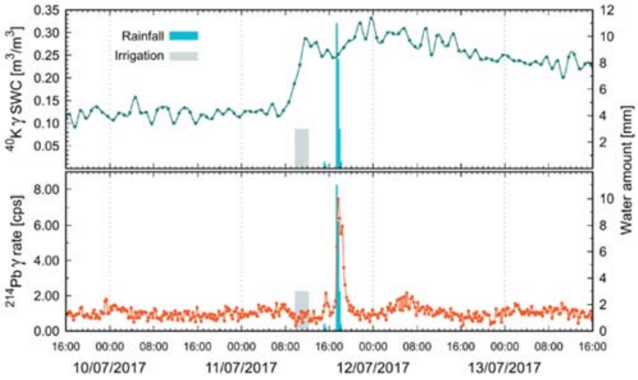

Fig. 3. In the upper panel, the volumetric SWC measured hourly by PGR is reported together with irrigation water (in grey) and rainfall (in blue). Since the variation of ^{214}Pb gamma signal changes rapidly, we report in the lower panel the ^{214}Pb count rate sampled every 15 minutes. The ^{214}Pb signal is totally insensitive to irrigation.

rain. On the opposite, during the irrigation the ^{214}Pb count rate remains constant (~ 1 cps), while it suddenly increases up to ~ 7.5 cps after 11 mm of rain fallen in 15 minutes.

This behavior is reaffirmed in all the observed rains and irrigations of the 7 months data taking period. Hereafter, we present 3 episodes of rain and 3 of irrigation with different quantities of total deposited water where it can be seen that the evidence shown for the previous episode still holds (Fig. 4 and Table I). Taking into account the percentage variations between the mean of the 4 hours before the start of the rain episodes and the 4 hours after, it can be seen that PGR measured SWC goes up as does the ^{214}Pb count rate. Applying the same criteria to the irrigations, the SWC still increases whereas the ^{214}Pb count rate decreases, attenuated by the deposited layer of water.

This evidence appears clear from Table 1, where the percentage variations of ^{214}Pb count rate and SWC are reported: whilst the latter increases in all 6 cases (by 28% to

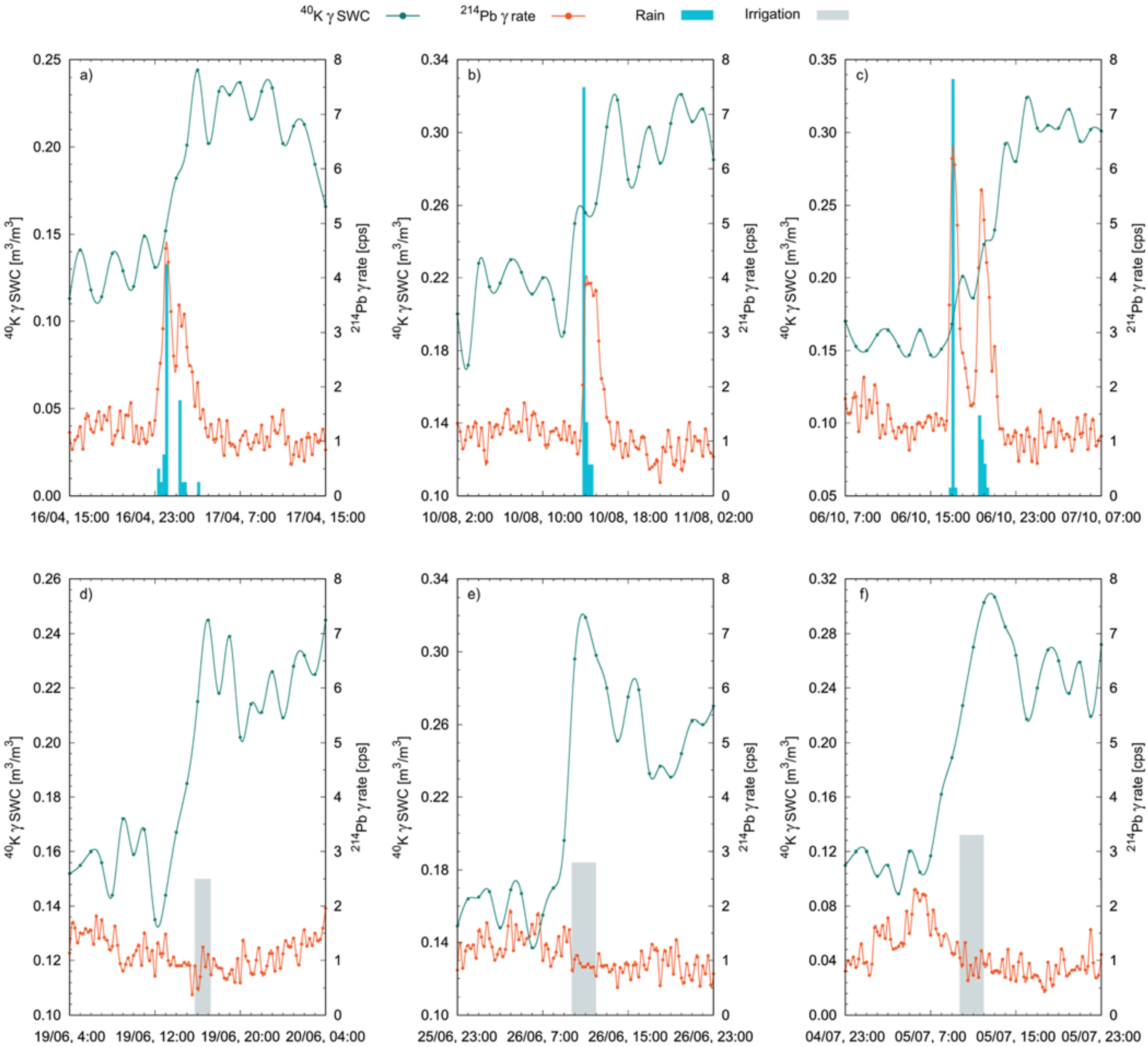

Fig. 4. Hourly volumetric PGR measured SWC (in green) and ^{214}Pb count rate sampled every 15 minutes (in orange) of 3 rains, panels a), b) and c), and of 3 irrigations, panels d), e) and f). The total water of rains (in blue) and irrigations (in grey) are reported in Table 1.

93%), the former decreases in case of irrigations (by -45% to -16%) and rises in the case of rains (by 103% to 187%).

TABLE I. START, DURATION, TOTAL WATER AND RELATIVE VARIATIONS IN PERCENTAGE OF ^{214}Pb COUNT RATE AND ^{40}K SWC FOR THE RAIN AND IRRIGATION EPISODES SHOWN IN FIG. 4

	Start date and time	**Duration [h]**	**Total water [mm]**	**Δ^{214}Pb count rate [%]**	**Δ^{40}K SWC [%]**
Rains	16/04/2017, 23:15	4.00	8.3	+ 130	+ 47
	10/08/2017, 13:45	1.00	13.0	+ 103	+ 31
	06/10/2017, 16:45	3.75	19.0	+ 187	+ 28
Irrigations	19/06/2017, 15:45	1.50	15.0	- 16	+ 45
	26/06/2017, 09:45	2.25	25.0	- 33	+ 81
	05/07/2017, 09:45	2.25	30.0	- 45	+ 93

While the PGR measured SWC increases linearly with the total water deposited with constant rate by irrigations, the same relation deviates from linearity for rains because of their erratic nature. Instead, the ^{214}Pb count rate increase during rains is not related to the total water deposited but rather to the rain rate, as in (2) and extensively discussed in [17]. During irrigations the ^{214}Pb count rate decreases for the shielding effect induced by the water in soil.

As shown in Fig. 4, the measured ^{214}Pb count rate readily responds to the deposition of rainwater while PGR measured SWC slowly increases, reaching the maximum moisture level more than 1.5 h after the first deposition.

V. CONCLUSIONS

In this study we show how a PGR station specifically tailored for continuous and autonomous in-situ measurements can gather reliable and unbiased measure of SWC, distinguishing at the same time the gamma signal produced by irrigations and rainfalls. PGR spectroscopy is one of the best space-time trade-off methods which can provide not only a continuous tracing of SWC at an intermediate spatial scale between punctual and satellite fields of view, but also steady estimations of the rain intensity.

ACKNOWLEDGMENTS

This work was partially founded by the National Institute of Nuclear Physics (INFN) through the ITALian RADioactivity project (ITALRAD). The authors would like to acknowledge the support of the Project “Protocolli Operativi Scalabili per l’agricoltura di precisione - POSITIVE”- CUP: D41F18000080009 and of the University of Ferrara (FAR 2018-2019). The authors thank the staff of GeoExplorer Impresa Sociale s.r.l. for its support and Stefano Anconelli, Gabriele Baroni, Marco Bittelli, Luca Brocca, Enrico Bucchi, Stefano Caselli, Barbara Fabbri, Giovanni Fiorentini, Salvatore Gentile, Vincenzo Guidi, Tommaso Letterio, Martina Natali, Domenico Solimando for their collaboration which made possible the realization of this study.

REFERENCES

[1] S. Siebert, M. Kummu, M. Porkka, P. Döll, N. Ramankutty, and B. R. Scanlon, "A global data set of the extent of irrigated land from 1900 to 2005," *Hydrology and Earth System Sciences,* vol. 19, pp. 1521-1545, 2015.

[2] M. Ozdogan, Y. Yang, G. Allez, and C. Cervantes, "Remote Sensing of Irrigated Agriculture: Opportunities and Challenges," *Remote Sensing,* vol. 2, pp. 2274-2304, 2010.

[3] J. M. Salmon, M. A. Friedl, S. Frolking, D. Wisser, and E. M. Douglas, "Global rain-fed, irrigated, and paddy croplands: A new high resolution map derived from remote sensing, crop inventories and climate data," *International Journal of Applied Earth Observation and Geoinformation,* vol. 38, pp. 321-334, 2015.

[4] Zreda, D. Desilets, T. Ferré, and R. L. Scott, "Measuring soil moisture content non - invasively at intermediate spatial scale using cosmic - ray neutrons," *Geophysical Research Letters,* vol. 35, 2008.

[5] Zreda, W. Shuttleworth, X. Zeng, C. Zweck, D. Desilets, T. Franz*, et al.*, "COSMOS: the cosmic-ray soil moisture observing system," *Hydrology and Earth System Sciences,* vol. 16, pp. 4079-4099, 2012.

[6] S. V. Kumar, C. D. Peters-Lidard, J. A. Santanello, R. H. Reichle, C. S. Draper, R. D. Koster*, et al.*, "Evaluating the utility of satellite soil moisture retrievals over irrigated areas and the ability of land data assimilation methods to correct for unmodeled processes," *Hydrology and Earth System Sciences,* vol. 19, pp. 4463-4478, 2015.

[7] L. Brocca, A. Tarpanelli, P. Filippucci, W. Dorigo, F. Zaussinger, A. Gruber*, et al.*, "How much water is used for irrigation? A new approach exploiting coarse resolution satellite soil moisture products," *International Journal of Applied Earth Observation and Geoinformation,* vol. 73, pp. 752-766, 2018.

[8] L. Brocca, L. Ciabatta, C. Massari, T. Moramarco, S. Hahn, S. Hasenauer*, et al.*, "Soil as a natural rain gauge: estimating global rainfall from satellite soil moisture data," *Journal of Geophysical Research: Atmospheres,* vol. 119, pp. 5128-5141, 2014.

[9] P. Filippucci, A. Tarpanelli, C. Massari, A. Serafini, V. Strati, M. Alberi*, et al.*, "Soil moisture as a potential variable for tracking and quantifying irrigation: A case study with proximal gamma-ray spectroscopy data," *Advances in Water Resources,* vol. 136, 2020.

[10] R. L. Grasty, "Radon emanation and soil moisture effects on airborne gamma-ray measurements," *Geophysics,* vol. 62, pp. 1379-1385, 1997.

[11] M. Greenfield, A. Domondon, N. Okamoto, and I. J. J. o. a. p. Watanabe, "Variation in γ-ray count rates as a monitor of precipitation rates, radon concentrations, and tectonic activity," vol. 91, pp. 1628-1633, 2002.

[12] P. Sturrock, G. Steinitz, and E. J. A. P. Fischbach, "Analysis of gamma radiation from a radon source. II: Indications of influences of both solar and cosmic neutrinos on beta decays," vol. 100, pp. 1-12, 2018.

[13] V. Strati, M. Albéri, S. Anconelli, M. Baldoncini, M. Bittelli, C. Bottardi*, et al.*, "Modelling Soil Water Content in a Tomato Field: Proximal Gamma Ray Spectroscopy and Soil–Crop System Models," *Agriculture,* vol. 8, p. 60, 2018.
[14] P. Mannini, R. Genovesi, and T. Letterio, "IRRINET: Large Scale DSS Application for On-farm Irrigation Scheduling," *Procedia Environmental Sciences,* vol. 19, pp. 823-829, 2013.
[15] M. Baldoncini, M. Albéri, C. Bottardi, E. Chiarelli, K. G. C. Raptis, V. Strati*, et al.*, "Investigating the potentialities of Monte Carlo simulation for assessing soil water content via proximal gamma-ray spectroscopy," *Journal of Environmental Radioactivity,* vol. 192, pp. 105-116, 2018.
[16] M. Baldoncini, M. Albéri, C. Bottardi, E. Chiarelli, K. G. C. Raptis, V. Strati*, et al.*, "Biomass water content effect on soil moisture assessment via proximal gamma-ray spectroscopy," vol. 335, pp. 69-77, 2019.
[17] C. Bottardi, M. Albéri, M. Baldoncini, E. Chiarelli, M. Montuschi, K. G. C. Raptis*, et al.*, "Rain rate and radon daughters' activity," *Atmospheric Environment,* vol. 238, 2020.