Discriminating biomass and soil water content with proximal gamma-ray spectroscopy

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Terrestrial radioactivity: the potassium

Terrestrial radioactivity is due to naturally occurring radioactive elements with half-lives comparable to the Earth’s age. Among them, potassium and some radioisotopes in the uranium and thorium decay chains emit $\gamma$-rays having energy of the order of MeV and can be easily detected via $\gamma$-rays spectroscopy.

<table>
<thead>
<tr>
<th>Element</th>
<th>Radioisotope</th>
<th>Isotopic abundance</th>
<th>Half life</th>
<th>Typical abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potassium</td>
<td>$^{40}$K</td>
<td>0.012%</td>
<td>$1.3 \times 10^9$ years</td>
<td>0.02 g/g</td>
</tr>
<tr>
<td>Uranium</td>
<td>$^{238}$U</td>
<td>99.3 %</td>
<td>$4.5 \times 10^9$ years</td>
<td>3 µg/g</td>
</tr>
<tr>
<td>Thorium</td>
<td>$^{232}$Th</td>
<td>100 %</td>
<td>$14.1 \times 10^9$ years</td>
<td>10 µg/g</td>
</tr>
</tbody>
</table>

- K makes up about 2.6% of the weight of the Earth’s crust and is the 7th most abundant element in the crust.
- K is one of the main building blocks of the most widespread minerals forming rocks and soils.
Different $\gamma$-rays measurements techniques

... in laboratory

~ 0.1 m

HPGe

... in situ

~ 10 m

NaI

... airborne

~ 100 m

NaI
GOAL: study the soil water content measuring the attenuation effects on gamma rays emitted by $^{40}\text{K}$ during a tomato crop season.
Cumulative contribution of ground radioactivity in percentage as function of the source radius reaches ~95% at ~25 m of radius.

In a typical soil ~95% of the gamma radiation is emitted from the top 25 cm of the soil.
The rationale: a simple idea

- The water mass attenuation coefficient is significantly higher than those of minerals
- $^{40}$K is everywhere and **homogenously** distributed in agricultural soils

The soil water content $w \left( \frac{M_{\text{water}}}{M_{\text{soil}}} \right)$ is **inversely proportional** to the signal $S(K)$ produced by the $^{40}$K decay measured by the gamma spectrometer:

$$w(t) = \frac{A}{S_K(t)} - B$$

Crucial information for irrigation scheduling and efficient use of water
[4th April – 2nd November 2017]

- **15 minutes** acquired spectrum
- Total counts $\sim 180 \times 10^3$
- Net counts in $^{40}$K window $\sim 10^4$
- Typical statistical uncertainty $\sim 1.3\%$ for 15 min acquisition
- We acquired 20502 spectra in 7 months (260 GB)
- 97.5 % of duty cycle
Calibration procedure: gravimetric measurements

$w_{\text{CAL}}$ : mean value obtained from 48 samples in the 0 – 30 cm depth range at 16 planar sampling points homogeneously distributed within 15 m from the detector.

$CR_{\text{CAL}}$ : count rate in $^{40}\text{K}$ window.

\[
wt\left[\frac{kg}{kg}\right] = \frac{CR_{\text{CAL}}[cps]}{CR_i[cps]} \left(0.899 + w_{\text{CAL}}\right) - 0.899
\]

$M_{\text{Water}} = M_{\text{Wet}} - M_{\text{Dry}}$

BARE SOIL CONDITION
From the count rates to the water content in soil

The presence of growing biomass introduces an extra attenuation which gives a strong positive bias on $\theta_\gamma$ values.
Estimating plants shielding effect

- A tomato plant consists of about 90% of water: the vegetative cover produces a **shielding effect** and then an overestimation of water content.

**Monte Carlo method:** estimation of the effect of attenuation as a function of the Biomass Water Content (BWC).

- The plants can be approximated to a layer of water that corresponds to the **BWC** in kg/m² (numerically equal to the water height in mm).

- The **count rate attenuation** $\Lambda$ produced by the BWC is given by:

$$\Lambda = \frac{CR(BWC[mm])}{CR}$$

$$w_i = \frac{CR_{CAL}}{CR_i} \Lambda_i (0.899 + w_{CAL}^i) - 0.899$$

\[\Lambda = (-0.0120 \pm 0.0001) \cdot BWC + 1.0000\]

\[R^2 = 0.999\]
The water content in tomato plants was estimated from destructive above-ground biomass samples at different stages of plant growth. A straight line function was calculated for describing the growth of BWC in time:

$$BWC[mm] = 3.5 \times 10^{-3} \times t[h]$$
From the count rates to the **corrected** water content in soil.
Validations measurements: gamma vs gravimetric method

$\theta_g$: soil water content inferred from gamma measurements
$\theta_y$: measured with gravimetric measurements

<table>
<thead>
<tr>
<th>Date</th>
<th>$\theta_g$ [m$^3$/m$^3$]</th>
<th>$\theta_y$ [m$^3$/m$^3$]</th>
<th>$\Delta\theta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>21/09/17</td>
<td>23.7 ± 1.5</td>
<td>24.5 ± 1.1</td>
<td>3.4 %</td>
</tr>
<tr>
<td>24/07/17</td>
<td>16.7 ± 2.8</td>
<td>17.0 ± 1.9</td>
<td>1.8 %</td>
</tr>
<tr>
<td>26/07/17</td>
<td>26.5 ± 2.8</td>
<td>24.3 ± 1.3</td>
<td>-8.3 %</td>
</tr>
<tr>
<td>28/07/17</td>
<td>18.9 ± 1.5</td>
<td>17.9 ± 1.5</td>
<td>-5.7 %</td>
</tr>
</tbody>
</table>

$\Delta\theta \sim 2.1 \%$
Comparison with soil-crop system models

- **CRITeRIA** is a physically-based numerical model for simulating soil water balance.
- **AquaCrop** is the FAO tipping-bucket conceptual model for soil water transport based on soil hydraulic properties and crop water demand.
- **Irrinet** is a regional model for irrigation management implementing economic calculation of the crop-tailored irrigation profitability.

**CRITeRIA** show the best agreement with gamma data over the entire data-taking period while, **IRRINET** provides the best results in presence of the tomato crop.
Conclusions: what’s next?

✓ The attenuation of the $^{40}$K gamma signal coming from the ground is an unequivocal smoking gun for a soil water content increase after rainfalls and/or irrigation.

✓ Provided a (single) soil gravimetric calibration measurement and biomass samplings, soil water content can be assessed via proximal $\gamma$-ray spectroscopy at the level of 10%.

✓ Proximal $\gamma$-ray spectroscopy is an effective tool for estimating soil water content at field-scale makes it a promising technique in view of satellite data calibration.
For more information...

**Modelling Soil Water Content in a Tomato Field: Proximal Gamma Ray Spectroscopy and Soil–Crop System Models**


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


**Investigating the potentialities of Monte Carlo simulation for assessing soil water content via proximal gamma-ray spectroscopy**


**Soil moisture as a potential variable for tracking and quantifying irrigation: a case study with proximal gamma-ray spectroscopy data.**


**Rain rate and radon daughters’ activity.**

Bottardi, C., M., Baldoncini, M. Albéri, E. Chiarelli, M. Montuschi, K. G. C. Raptis, A. Serafini, V. Strati, and F. Mantovani Advances in Water Resources, In press