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Effects of heterogeneous soil moisture distributions in cosmic-ray neutron sensing - the case of irrigation monitoring

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Soil moisture (SM) sensors are widely used to monitor soil water dynamics and support irrigation management with the aim of achieving better yields while reducing water consumption. Unfortunately, due to the small measuring volume of point-scale sensors, their soil moisture readings are often not representative for heterogeneous agricultural fields. Therefore, in such cases, sensors with larger sensing volume are needed to address spatially variable SM. A suitable technique is the cosmic ray neutron sensor (CRNS) as it integrates SM over a large volume with a radius of ~130-210 m and a penetration depth of ~15-85 cm. The CRNS method is based on the inverse relationship between measured environmental neutron density and the presence of hydrogen pools (e.g., SM) in the instrument surroundings. However, the ability of CRNS to accurately monitor areas with complex SM heterogeneities (e.g., small irrigated fields) and the influence of detector design were not yet investigated. In this study, we used the neutron transport model URANOS to simulate the effect of SM variations on a CRNS placed in the centre of squared irrigated fields (0.5 to 8 ha dimensions). For this, SM in the irrigated field and in the surrounding was altered between 0.05 and 0.50 cm^3 cm^{-3} (500 simulations in total). In addition, we investigated the effect of employing high-density polyethylene (HDPE) moderators with different thickness (5 to 35 mm) as well as a 25 mm HDPE moderator with an additional gadolinium oxide thermal shielding. Results showed that, in heterogeneous SM scenarios, the 2 *e*-folding lengths footprint (R86) can become smaller or larger than what previous studies showed in homogeneous SM distributions. In addition, a thin HDPE moderator will result in relatively smaller R86 whereas thicker moderators and the addition of a thermal shielding will result in relatively larger R86. However, we found that a relatively small footprint is not directly related to a better monitoring of SM nearby the instrument. In fact, in all the investigated field dimensions, the 25mm HDPE moderator with gadolinium shielding showed the largest values of R86 but also the largest variations of detected neutrons with changing SM. In addition, such moderator showed the highest chances of detecting irrigation events that increase SM by 0.05 or 0.10 cm^3 cm^{-3} in the irrigated area. Generally, detection was uncertain only for SM variations of 0.05 cm^3 cm^{-3} in fields of 0.5 ha when initial SM was 0.02 cm^3 cm^{-3} or higher. Although the results of this study suggest the feasibility of monitoring and informing irrigation with CRNS, we found that SM variations outside the irrigated field have a considerable influence on CRNS measurements. Especially in fields of 0.5 and 1 ha dimension, it can be impossible to distinguish whether a relative change in detected neutrons is due to irrigation or to SM variations in the surroundings. These results are relevant for irrigation monitoring and the combination of neutron transport simulations and real-world installations has the potential to establish CRNS as a decision support system for irrigation management.