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Assessing soil water content variability through active heat distributed fiber optic temperature sensing

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ABSTRACT

Soil spatial variability is a key point for the sustainable water management in agriculture. Fractal techniques provide proper tools to analyze soil spatial variability searching for statistical self-similarity patterns among different scales. Although they have been extensively applied to study the soil properties variability, its applicability for the soil water content (SWC) distribution is complicated because requires many data difficult to obtain with the typical point soil water sensors. Recently, a fiber optic distributed temperature sensor has been used to measure soil thermal properties which relate to SWC. These sensors provide large amount of data with high spatial and temporal resolution, thus filling the gap of point soil water sensors. In the present work, soil temperature was measured with a Distributed Temperature Sensing (DTS) and SWC was estimated by different fitting functions which have been studied with focus on spatial variability.

Temperature was measured in a 133 m fiber optic cable laid in a sandy soil field plot. A The Active Heat Fiber Optic (AHFO) method was used, with 12 cm sampling resolution, and heat pulses (19,4 W/m during 2 min) were applied. The temperature data were correlated to SWC, considering the integration of temperature during the heat pulse T_{cum}, and then the datasets Tcum-SWC were fitted to the best fit statistical function (exponential, potential and polynomial). The results showed that the T_{cum} distribution presented a non-Gaussian pattern. Additionally, highly anti-persistent patterns have been detected for the larger spatial scaling lags. The function`s performance was different thus, the exponential function reproduced better the absolute moments of the temperature profile but it failed reproducing the non-Gaussian behavior.

1. Introduction

Agriculture is the largest water user with approximately 70% of the global consumption (Fischer et al., 2007). Soil water content (SWC) represents a small percentage (≈0.05%) of the global freshwater resources (Dingman, 2002) but it is a key factor that conditions the agricultural yields. Good agricultural performance, especially in irrigated areas, is limited by the SWC and its availability for the plants. SWC measurements for irrigation management are commonly obtained from point sensors. Although some works have dealt with the proper sensor placement (Dabach et al., 2015), they have not consider soil water spatial variability whose impact on SWC distribution has been widely assessed (Burrough et al., 1994).

Soil spatial variability has been studied using different theoretical frameworks. Thus, geostatistics have been used for quantifying the spatial pattern of soil properties, and Kriging techniques have been proved sufficiently robust for estimating values at non sampled locations in most of the cases (Nielsen and Wendroth, 2003; Webster and Oliver, 2001).

Multifractal analysis (MFA) was initiated with the seminal work by Mandelbrot (1982) and can provide insight into spatial variability of crop or soil parameters (Vereecken et al., 2007). This technique has been used to characterize the scaling property of a variable measured along a transect as a mass distribution of a statistical measure on a spatial domain of the studied field (Zeleke and Si, 2004; Lopez de Herrera et al., 2016 among others). Based on rescaled range analysis

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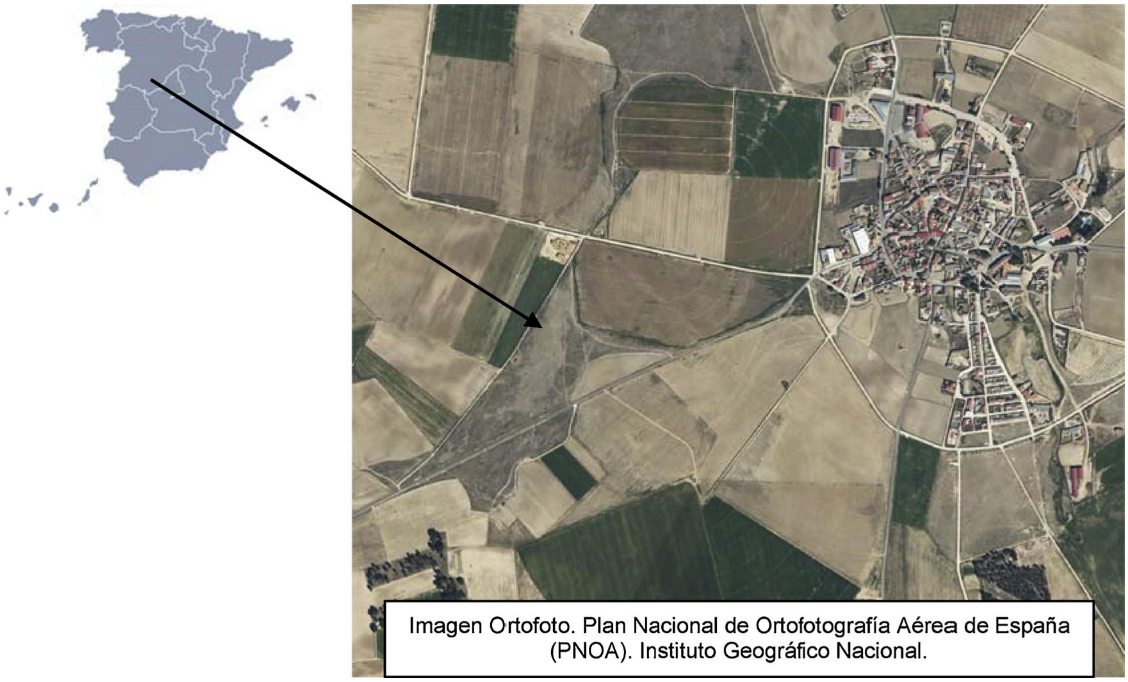

Fig. 1. Location of the experimental plot (Image © 2018 Google, Data from map © 2018 Google, Instituto Geográfico Nacional).

(Hurst, 1951), several MFA can be used to study the fluctuation in signals (Davis et al., 1994; Schmitt et al., 1995; Taqqu et al., 1995).

Some authors have applied these techniques to soil science to look for statistical self-similar series (Pozdnyakova et al., 2005; Kravchenko et al., 2002; Garcia Moreno et al., 2010; Morató et al., 2017). Likewise, other works (Tarquis et al., 2008; Morató et al., 2017) have studied wider scaling behaviors which cannot be captured in a consistent way by the MFA. These analyses include linear relations between log structure functions, and frequency distributions of the variables' increments tending to be symmetric with increasing kurtosis as the lags between pairs of values decreases (Guadagnini et al., 2015; Molinari et al., 2015).

Despite of the many studies focused on the MFA of soil properties, only few have centered on applying these techniques to study SWC spatial variability. Their application is limited by the use of discrete measurements by point sensors, and consequently the high cost of collecting enough data.

However in this century, the development of approaches to estimate SWC by distributed temperature techniques (DTS) can help to fill this gap. They estimate SWC from a distributed temperature measurement along a fiber optic (FO) cable. Its resolution depends on the cable´s properties and the DTS unit, limiting the cable's length that can be deployed up to several kilometers (Selker et al., 2006). Soil temperature and therefore SWC, can be obtained every second and every 12 cm.

Among these approaches, both passive and active methods (AHFO) have been proposed to estimate SWC from the temperature measurement of the FO cable. While passive techniques only require the simple temperature measurement, AHFO requires heating the FO cable to study the heat transfer pattern from the cable to the surrounding soil to be correlated with the SWC. The procedure determines the best fitting curve between the heat transfer indicator and the SWC and then, each value of the heat transfer indicator measured in the field will be easily transformed into SWC.

Several indicators for heat pattern transfer are available. For example, Sayde et al (2010) or Striegel and Loheide (2012) proposed the T_{cum} or ΔT_8, respectively. In addition, some fitting curves have also been defined to correlate them with SWC (Serna et al., 2017; Gil Rodríguez et al., 2013; Benitez-Buelga et al., 2016). However, there are some uncertainties that must be taken into account not only when calculating the fitting curve but also in the SWC estimation. For example, some authors determine the fitting curve trough measurements in soil disturbed samples in the laboratory that later will be used to estimate the SWC in field experiments. Alternatively, other authors determine it in the field without disturbing the soil structure. The fitting functions obtained in the lab usually cover the whole range of possible SWC, from the residual to the saturated levels. Conversely, their determination in the field often only covers a narrower SWC range.

Otherwise, the authors do not reach an agreement on the functional form of the estimation fitting curve. Potential, polynomial end exponential have majorly been proposed. The differences among them are evident and their selection will affect the accuracy of SWC estimation.

So that, there is a scope for further analysis related to the SWC spatial variability and to the procedures to estimate the SWC from the DTS measurements.

Within this framework, this paper focuses on the study of SWC spatial variation, using DTS, and on the SWC estimation from the DTS as well. The main objectives are (1) to study the spatial variability of the SWC using the data collected from the DTS and (2) to discuss the SWC estimation procedures from the indicators obtained with the DTS technique.

2. Materials and methods

2.1. Experimental sites

The study site was a field plot of 300 m^2 of sandy soil located in the Irrigation District "Río Adaja", Nava de Arévalo (Ávila, Spain), (Fig. 1).

The experimental installation comprised a buried FO cable, a DTS and an electrical installation to heat the FO cable (Fig. 2).

The FO cable, 300 m long, was buried at 0.2 and 0.4 m depths laid in 6 parallel with symmetric spacing between successive pairs of parallel cables (Fig. 3).

The cable's deployment was conducted during the first week of August 2010. FO cable was buried helped by a custom plow with two blades held at 45-degrees from vertical that simultaneously buried cables at 0.2 m and 0.4 m depths. These depths were chosen to monitor SWC within the root's zone for most crops at the location. The cable's diameter was $3.8{\cdot}10^{-3}$ m comprising 3 layers of sheathing, a stainless