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Research Paper

Performance assessment of factory and field calibrations for electromagnetic sensors in a loam soil

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ABSTRACT

Accurate continuous measurements of temperature (T), apparent electrical conductivity (EC_a), apparent dielectric permittivity (ε_{ra}), and volumetric water content (θ_v) are extremely valuable to irrigation management and other agronomic decisions. The performance of eight electromagnetic (EM) sensors (TDR315, CS655, HydraProbe2, 5TE, EC5, CS616, Field Connect, AquaCheck), were analyzed through a field study in a loam soil. T, EC_a, and ε_{ra} were compared in reference to overall average among all sensors, and θ_v in reference to a neutron moisture meter (NMM). The reported T and EC_a difference among the sensors were within 1 °C and 1 $dS\,m^{-1}$, respectively, at 0.15 and 0.76 m depths. Among the single-sensor probes, the range of depth-combined (0.15 and 0.76 m) RMSD for factory calibration varied from 0.039 $m^3\,m^{-3}$ (5TE) to 0.157 $m^3\,m^{-3}$ (CS616). In comparison to single-sensor probes, RMSD of Field Connect at combined depths (0.30 and 0.51 m) was moderate (0.083 $m^3\,m^{-3}$), and RMSD of AquaCheck at combined depths (0.30 and 0.61 m) was high (0.163 $m^3\,m^{-3}$). Regression calibrations improved θ_v accuracy substantially beyond factory calibrations, as RMSD of the evaluated sensors except Field Connect was below 0.025 $m^3\,m^{-3}$ using regression calibrations. The betterment in θ_v accuracy gained by using offset calibrations was smaller and less consistent than the improvements gained by using regression calibrations. The lower and upper bounds of the 95% confidence interval for mean RMSD of most sensors were below 0.02 and 0.04 $m^3\,m^{-3}$, respectively, when using depth-specific offset calibrations. The relative success of offset calibrations for certain sensors in this study is encouraging and may signal new opportunities. Because much of the uncertainty in sensor-reported θ_v for the sensors under evaluation was systematic, future work should aim to develop universal calibrations or facilitate site-specific calibrations.

1. Introduction

Accurate determination of soil water quantity and quality can better inform the timing and depth of irrigation applications and reduce the likelihood of excessively or insufficiently irrigating. Excessive irrigation increases fertilizer and irrigation pumping costs as well as generates additional nitrate leaching and greenhouse gas emissions. Furthermore, by subjecting soil and plant canopies to frequent and prolonged wet conditions, excessive irrigation can decrease harvestable yield due to greater occurrence and severity of disease, anaerobic soil conditions, nutrient deficiencies, and inability to operate farm machinery. On the opposite extreme, inadequate soil water, as a result of insufficient irrigation, limits transpiration and photosynthesis and, in turn, hinders crop growth and yield potential (Doorenbos and Kassam, 1979). Measurements of soil water quantity is arguably the most necessary geophysical estimate for implementing deficit irrigation, in which crop water status is carefully managed to maximize grain yield with a limited water supply (Geerts and Raes, 2009).

Although most attention in irrigation scheduling is focused on soil water quantity, soil water quality likewise deserves consideration. Measurements of soil salinity can guide the use of irrigation to leach salts out of the crop root zone to maintain soil salinity levels within a crop's tolerable range (U.S. Salinity Laboratory and Staff, 1954). Limited irrigation can be applied if rescue fertilizer applications are undesired or infeasible, based on the detection of nutrient stressed crops. Rudnick and Irmak (2014) observed a

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reduction in corn evapotranspiration (ET) when the crops were subjected to nitrogen stress. Irrigation exceeding a crop's ET rate can cause further reduction in nutrient availability through leaching, and consequently affect grain yield and the environment.

Repeated nondestructive measurement of soil water status is ideal because temporal trends can be determined without the potentially confounding influence of soil spatial variability. Neutron moisture meter (NMM) is the current standard to measure accurate, repeated, and non-destructive field volumetric water content (θ_v) (Chanasyk and Naeth, 1996) and, if calibrated with respect to thermogravimetric method, it can be used to compare other soil water monitoring devices (Leib et al., 2003). However, the NMM is not typically an option for on farm management or collecting high spatiotemporal dense data due to the radioactive source, which requires proper training, licensing, and safety measures when handling, storing, and transporting the instrument (Rudnick et al., 2015).

Since electromagnetic (EM) properties of soil vary with θ_v, various EM sensors that can be installed into the soil to provide continuous measurement of soil water quantity have been developed, tested, and adopted over the last several decades. Some of these EM sensors also measure apparent electrical conductivity (EC_a) and temperature (T). These extra capabilities undoubtedly broaden the applicability of EM sensors in both research and production scenarios. For example, measurement of EC_a can be used to monitor soil salinity (Rhoades et al., 1976) if calibrated using saturation extract electrical conductivity (EC_e), and to monitor nitrate-nitrogen (NO_3-N) concentrations in soil and water (Payero et al., 2006). Temperature is a key environmental variable for plants during the vegetative period as it affects time of emergence (Schneider and Gupta, 1985) and grain yield (Bollero et al., 1996).

However, merely deploying EM sensors and amassing a large dataset does not guarantee improvements in research and management. Predictive models, revealing findings, and better informed decisions require accuracy in soil water quantity and quality data. Despite commonalities among EM sensors, some studies have shown that the distinctions in measurement technology, design, installation method, internal adjustments, and factory calibration could culminate in substantial disparities in θ_v measurement accuracy across sensors (Varble and Chávez, 2011; Chavez and Evett, 2012; Mittelbach et al., 2012; Vaz et al., 2013). It is imperative that these disparities among sensors are recognized to identify appropriate sensors across regions and applications, and develop improved calibrations.

A field study was conducted to analyze the performance of eight EM sensors—TDR315, CS655, HydraProbe2, 5TE, EC5, CS616, Field Connect, and AquaCheck—in a loam soil of west central Nebraska. This field study was designed to generate new peer-reviewed information on EM sensors whose performance, to our knowledge, have scarcely been reported in the literature, e.g., CS655, TDR315, AquaCheck, and Field Connect (Kisekka et al., 2014; Rudnick et al., 2015; Zeelie, 2015; Schwartz et al., 2016) as well as supplement the body of knowledge on the performance of EM sensors that have been widely studied in the literature, e.g., HydraProbe2, 5TE, EC5, and CS616 (Ojo et al., 2014, 2015; Rüdiger et al., 2010; Udawatta et al., 2011; Varble and Chávez, 2011; Mittelbach et al., 2012) across diverse settings. Results of this field study may be somewhat directly transferable to similar environments, useful for meta-analyses in understanding sensor performance between divergent environments, and laying a foundation for future research.

The specific objectives of the research were to 1) evaluate factory calibrations of the EM sensors for T, EC_a, apparent dielectrical permittivity (ε_{ra}), and θ_v and 2) compare the factory calibration for θ_v against two custom calibration approaches, the first a conventional approach based on regression and the second an offset approach based on one known data point.

2. Material and methods

2.1. Site, soil, and experiment descriptions

A field experiment was conducted at the University of Nebraska-Lincoln West Central Research and Extension Center (WCREC) in North Platte, NE (41.1° N, 100.8° W, and 861 m above sea level) during the 2016 growing season. The research site is located in a semi-arid climate zone with average annual precipitation and standardized alfalfa reference ET (EWRI, 2005) of 514 and 1530 mm, respectively (HPRCC, 2016; NCDC, 2015). The research was performed with soybean at 0.76 m spacing planted on May 26, 2016. During the study period, which was 28 July to 5 September, 2016, three significant rain events occurred: 31 mm on 28 July, 17 mm on 11 August, and 9 mm on 26 August. Textural composition, organic matter content (OMC), and bulk density (ρ_b) were determined at soil depth intervals of 0.15 m from 0.08 to 0.84 m (Table 1).

A pit was dug between two rows of soybeans. Single-sensor probes were inserted into one of the pit walls so that the prongs were oriented horizontally and located directly underneath a single row of soybeans. Two replicates of the following sensors—5TE, EC5, HydraProbe2, CS616, CS655, and TDR315—were installed at a depth of 0.15 m, and two replicates of the same sensors were installed at a depth of 0.76 m. At each depth, the arrangement of the sensors along the soybean row was randomized, and the sensors were 0.15 m apart from each other. This spacing was chosen so that every sensor was outside the measurement volumes of the other sensors. The sensor outputs were recorded every hour. In addition, two replicates of the Field Connect and AquaCheck probes and four replicates of NMM aluminum access tubes were installed in the crop row neighboring the aforementioned sensors. All sensors were installed following manufacturer recommendations and allowed to equilibrate with the surrounding soil prior to the start of the study.

2.2. Description of sensors

2.2.1. TDR315

The Acclima TDR315 (Acclima, Inc., Meridian, ID) is a time domain reflectometer with three parallel rods serving as the waveguide. The sensor head has all necessary electronics and firmware to generate an EM pulse and construct a waveform to determine the propagation time of the EM wave, which is used to estimate ε_{ra}. The sensor is equipped with a thermistor to measure soil T. TDR315 measures EC_a based on Giese and Tiemann method (Giese and Tiemann, 1975) like conventional TDR equipment. A proprietary dielectric mixing model is used to estimate θ_v from ε_{ra}. However, Topp equation (Eq. (1); Topp et al., 1980) was considered for determination of θ_v from ε_{ra} reported by TDR315 as well.

$$\theta_v = 4.3\times10^{-6}(\varepsilon_{ra}{}^3) - 5.5\times10^{-4}(\varepsilon_{ra}{}^2) + 2.92\times10^{-2}(\varepsilon_{ra}) - 5.3\times10^{-2} \tag{1}$$

2.2.2. CS616 and CS655

The Campbell Scientific CS616 and CS655 (Campbell Scientific, Inc., Logan, UT) are water content reflectometers with two parallel rods forming an open-ended transmission line. The sensors measure the two-way travel time of an EM pulse to determine a period average. The CS616 uses a quadratic equation relating period average to calculate θ_v; whereas, the CS655 uses a factory calibrated empirical model involving voltage ratio and period average