Improved monitoring of soil water resources to benefit crop management decisions

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Abstract
Rainfall variability remains the dominant influence in dryland agriculture leading to increased awareness by farmers of the importance of soil water availability impacting on crop management decisions. Site-specific estimates of soil water can be difficult for farmers to quantify, with timely measurement requiring intensive and expensive soil sampling. Gravimetric soil sampling has served as the baseline measurement by which all other methods for determining soil water are normally compared. However, the temporal variability and dynamic nature of available soil water can be difficult to capture with infrequent gravimetric sampling. Whilst non-destructive technologies for monitoring change in soil water have been used by researchers and irrigators for many years it is only in recent times that their use has expanded to dryland agriculture.

To evaluate the potential for broader application in dryland agriculture, soil water, calculated from field measurements of commercially available sensors using; neutron scattering; electro-magnetic induction; capacitance; resistivity and time-domain reflectometry (TDR) are compared with volumetric measurements from a black cracking clay soil. The shrink swell nature of clay soils influenced reliability and accuracy of all sensors and the traditional gravimetric sampling. In situ placements of electronic sensors captures temporal change at those locations but are unable to account for spatial variability which is only captured using gravimetric sampling or mobile sensors such as an EM38. On the other hand, electronic sensors are able to continuously monitor soil water status over time, something that is not possible with gravimetric or EMI methodologies. Whilst a range of sensor technologies were evaluated, this paper describes the results from continuous, real time monitoring of soil water using TDR, with results showing that once calibrated, these non-destructive tools can provide useful and timely information for farmers in dry land agricultural systems.

Key Words
TDR, Volumetric Soil Water Content.

Introduction
For decades gravimetric sampling for determining soil water has served as the baseline measurement by which all other present methods such as tensiometers, resistance blocks, and neutron probes have been compared (Gardner 1986; Leib, *et al.* 2003). More recent technological additions using, capacitance, time-domain reflectometry (TDR), electromagnetic induction (EMI), gamma ray and optical attenuation all apply gravimetric sampling in sensor calibration. Use of these technologies in determining soil moisture is well documented (Zazueta and Xin 1994) but characterising soil water can be difficult for farmers, their advisers and researchers without access to expertise and soil sampling equipment (Peake *et al*. 2010). Local calibration requires intensive soil sampling (Long *et al.* 2002), therefore how useful are non-destructive monitoring technologies in providing relevant and timely information to farm managers. A study of 5 commercially available electronic methods for measuring volumetric water content (VWC), in addition to traditional gravimetric sampling was evaluated on a black vertosol soil in north-east Australia during 2010-2012. The broader aim of this study was to highlight the potential benefits on crop decisions from improved understanding of soil water through comparison of a number of monitoring tools. This paper focuses on the calibration and use of TDR as an indirect method for measuring volumetric water. TDR uses the propagation of electromagnetic waves to measure change in the dielectric constant of a soil due to changes in soil water content (www.campbellsci.com) and is an established and reliable means to measure volumetric water content in many soil types (Topp *et al.* 1980). Here we have investigated its use in heavy clay soils. High spatial variability in gravimetrically measured soil water observed during the sensor calibration phase and over the experimental period is also discussed.

Methodology
Five non-destructive devices for determining volumetric soil moisture were compared at a farm site near Norwin, Queensland (151.19.13E 27.34.44S) sown to a wheat – maize – wheat rotation between January 2010 and December 2011. The soil is described as a Norillee Black Vertosol with a clay content of ~ 70%

(Radjagukguk *et al.* 1980) and having a Drained Upper Limit (DUL) of > 0.52 mm/mm volumetric, potentially holding 300-350 mm Plant Available Water Capacity (PAWC) when planted to cotton (Dalgliesh and Foale 1998). Campbell Scientific CS616 water content reflectometers (TDRs) were installed horizontally at 4 depths of 7.5, 22.5, 45 and 75 cm from the surface using a soil pit dug to 90 cm in each of 4 replicated plots of 40 m^2. Campbell Scientific 107 temperature probes were also installed at the above depths in one of the replicates while the pit was open. Black plastic lining along the pit walls sealed the sensors from potential lateral flows of water before the pit was refilled. Electronic data was collected using Campbell Scientific data loggers with gravimetric sampling conducted at intervals of less than 30 days. Manufacturers' specifications for the CS616 indicate an accuracy of $\pm$ 2.5% VWC over a measurement range of 0% VWC to 50.0% VWC. However, in compacted or high clay soils the signal response time of CS616 sensors can be significantly affected resulting in observed measurement error of > 40% VWC when using Campbell Scientific's recommended measurement process. Alternatively, using a method of period averaging accounts for increased signal response time enabling CS616 sensors to operate effectively in high clay soils with a DUL of above 50% VWC.

Calibration

The heterogeneity of a soil type can significantly influence the extent of spatial variability as soil moisture contents change between field capacity (30 kPa) and wilting point (1500 kPa). Calibration of electronic sensors in this environment requires gravimetric sampling of the soil at the point measured by the instrument. To achieve this, pits between the plots were excavated to expose buried CS616 probes and horizontal cores to 30 cm collected at each sensor installation point. Soil temperature for each sample was recorded using an infrared thermometer and applied with 107 temperature probe data in temperature correction of sensors. Samples were processed gravimetrically and converted to volumetric water content using measured bulk density values obtained from a soil characterisation site adjacent to the experimental plots. Sensor calibration for TDR (Rüdiger *et al.* 2010; Herkelrath, *et al.* 1991) are well documented however, soil specific calibration of electronically measured data with gravimetric soil moisture values is required to achieve significant levels of accuracy.

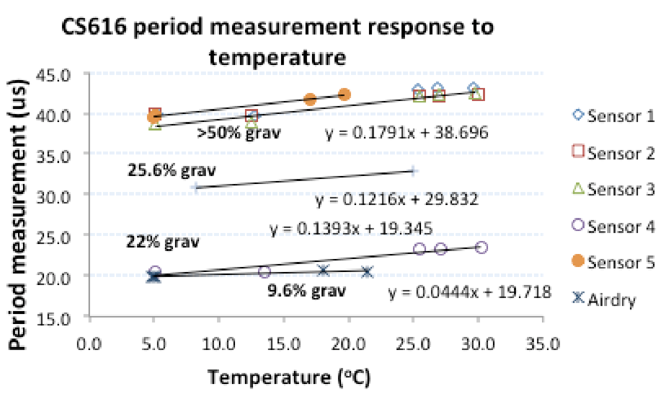

Figure 1. Temperature effect on measurement period response time (µs) for CS616 TDR sensors at 4 soil moisture levels of 9.6% to >50% gravimetric taken in close proximity to the sensors.

Changes in soil temperature affect the dielectric properties of a soil as shown by the increased measurement period of CS616 sensors (Figure 1) in response to temperature and soil moisture. A brief description of the temperature correction and calibration process for the CS616 probe is described with further analysis and calibration ongoing for the other sensors (data not presented). Temperature correction is applied to half hourly data with results expressed as daily mean measurement periods (P_{25}) using a simplified equation (1) developed by Rüdiger, *et al.* 2010 and reproduced here.

$$P_{25} = \frac{P_{obs} - (sP_{0.0})(T - 25)}{1 + s(T - 25)} \tag{1}$$

The CS616 measurement period (μs) is corrected for temperature to 25 ºC in each soil layer using soil profile temperatures (T) obtained from temperature probes installed with CS616 sensors and infrared temperature measurements (where $P_{0.0}$ is 16.81μs for oven dry soils and soil type-specific calibration factor for slope (s) defined as 0.00757 for clay soils). P_{25} values are normalised to between 0 and 1 for $P_{0.0}$ and $P_{4.0}$ using locally optimised values (Table 1). θ is then calculated using a modified equation (Rüdiger, et al. 2010) and locally optimised parameters for a high clay content soil (Table 1).

Results and discussion

Evett, *et al.* 2006 states that a more accurate sensor is one whose reading is closer to the true value of a property being sensed. Precision of electronic moisture sensors in determining VWC currently relies on the accuracy of gravimetric measurement in the calibration process. Analysis of gravimetric and sensor data collected during a final calibration phase of this experiment found poor correlation at a number of measurement points. High variability within the plots and between replicates for the gravimetric samples was high, with differences of up to 14% VWC between replicated points. This variability between samples taken in close proximity highlights the difficulty of collecting a representative sample from even a relatively small and visually uniform site in these high clay soils. Calculated mean daily values for VWC from both CS616 measurement and gravimetric data collected during the experimental period are presented in Figure 2.

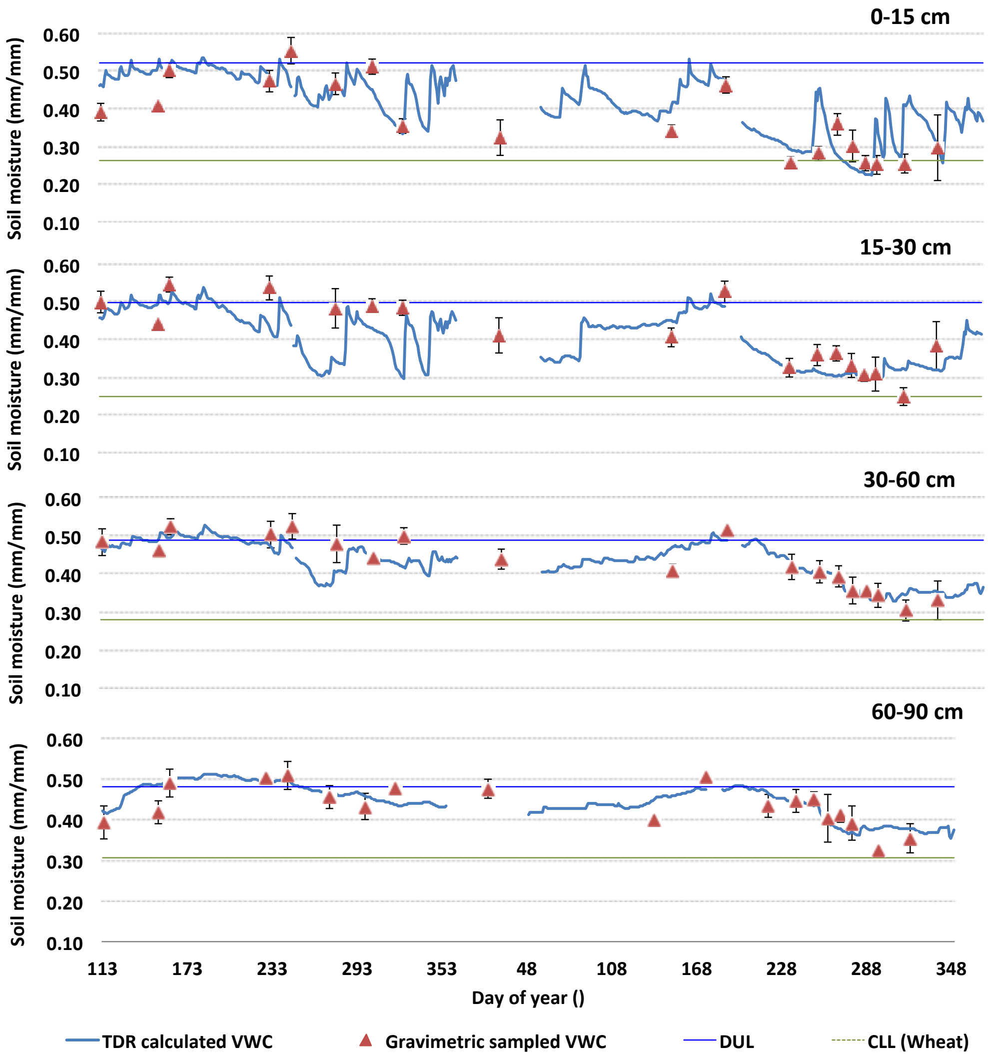

Figure 2. Daily volumetric soil water (mm/mm) calculated from CS616 TDR measurements and gravimetric sampling for 4 depths to 90 cm taken from nearby samples. Error bars represent standard deviation from the sample mean.

Drained upper limit (DUL) and crop lower limit for wheat (CLL) are provided as indicators of the range of water extraction by the wheat and maize crops, particularly during the second season wheat crop. Gaps over the summer period are results of lost data due to extensive flooding. Rainfall during 2010 was above average, which contributed to the non-uniform water extraction observed in both the wheat and maize sowings. TDR data captures temporal changes in water extraction particularly between the 15-60 cm layers not observed by the less frequent gravimetric sampling. In 2012 water extraction by the wheat crop was captured and demonstrates good correlation between TDR and gravimetric methods. The high clay content of the local soil influenced reliability and accuracy of all sensors including traditional gravimetric sampling.

Table 1. Parameters reproduced from Rüdiger, *et al.* 2010 used for normalising P_{25} values and used in calculation of θ with local soil-specific optimised parameters (in red) for $P_{4.0}$, A and β for 4 depths.

Depth (cm)	$P_{0.0}$	$P_{4.0}$	A	γ	β
0-15	16.81	**38.5**	**0.48**	0.407	1.478
15-30	16.81	**42.0**	**0.48**	0.407	**2.8**
30-60	16.81	**43.5**	0.283	0.407	**2.8**
60-90	16.81	**44.1**	0.283	0.407	**2.8**

Conclusion

The deep cracking nature of the soil at this site typifies the high osmotic binding of clay soils and is problematic for electronic sensors operating in this environment with in-situ sensors relying on good contact with the material being measured. The CS616 TDR sensors have been demonstrated to operate effectively between 20% VWC and 50% VWC in these high clay soils but with reduced accuracy as soil water contents approach or exceed DUL. Although gravimetric sampling remains the baseline measurement for comparison of all other monitoring methods it is well acknowledged in irrigated systems that continuous real time monitoring captures short-term soil water dynamics occurring in the root zone of a crop. TDR installation, monitoring and calibration requires a certain level of expenditure and expertise but, once calibrated, these non-destructive tools for monitoring available soil water could provide additional and timely information over traditional gravimetric measurement for farmers in dryland agricultural systems.

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