Automated measurement of crop water balances under a mobile rain-exclusion facility

A.J. Michel, H.E. Brown, R.N. Gillespie, M.J. George and E.D. Meenken
The New Zealand Institute for Plant & Food Research Limited, Private Bag 4704, Christchurch Mail Centre, Christchurch 8140, New Zealand

Abstract

For the past 20 years crop water balances have been manually monitored in The New Zealand Institute for Plant & Food Research Limited rain-shelter facility located at Lincoln (Canterbury) using weekly neutron probe and time domain reflectometry (TDR) measurements. While this method is robust and has provided much useful information, automated instrumentation systems have advantages over manual data collection. Such an automatic system has been set up in using CS650 Water Content Reflectometers (Campbell Scientific, Inc.) on a deep Templeton silt loam soil with 250-300 mm of soil water-holding capacity in the rain-shelter facility. Sensors were installed vertically from 0-15, 15-30, 30-60, 60-90, 90-120, 120-150 and 150-180 cm depths and soil water contents were recorded at 15-minute intervals. Weekly measurements of soil water content were also taken using a neutron probe (CPN, Model 503DR Hydroprobe). Those soil water content measurements were carried out as part of an experiment assessing the effects of different timing of water stress on two barley cultivars (Dash and Omaka). The installation and operation of the new soil water monitoring system is described, the results from this system against those from the neutron probe compared, and the need for a precise calibration of the CS650's to achieve satisfactory estimations of volumetric water content in deeper layers demonstrated.

***Additional keywords**:* neutron probe, time domain reflectometry, frequency domain reflectometry, soil water content, *Hordeum vulgare*

Introduction

Crop water balance is a key component influencing crop yield and the environmental impact of agricultural production. The accurate measurement of soil volumetric water content (VWC) is necessary to calculate how much water a crop is using, the extent of water stress it is experiencing, and how these influence crop growth and development. The rain-shelter facility at The New Zealand Institute for Plant & Food Research Limited in Lincoln, Canterbury, is designed to investigate such effects. The facility allows for the exclusion of rainfall by covering the experimental area with a mobile shelter when a rainfall event occurs. To calculate the crop water balance it is necessary to measure the variation in VWC through the profile while the crop is growing. Historically, VWC at the rain-shelter has been recorded using neutron probe (NP) measurements down the profile to 1.5 m and time domain reflectometry (TDR) on the top soil (0-30 cm depth). NP is a widely implemented and accepted method of measuring VWC, and is even used as a reference method (Gardner *et al.*, 1991). However, NP has some disadvantages. Firstly, it uses radioactivity. This requires precautions (health hazard) and its use is tightly controlled by legislation (Lekshmi *et al.*, 2014). It is also sensitive to bulk soil density, and so requires calibration for each soil type and each soil horizon (Gardner *et al.*, 1991). Measuring VWC using NP is time consuming when done across a replicated trial, so the frequency of measurement is limited by labour availability.

Reflectometry uses the dielectric properties of the soil for estimating VWC. This method has become widely accepted for measuring VWC (Lekshmi *et al.*, 2014). The major disadvantages of reflectometers are their loss of accuracy in highly saline soil and their sensitivity to soil disturbances, stones and air gaps. However, VWC measurements using reflectometry are faster than using NP, allowing for more measurements more frequently (Lekshmi *et al.*, 2014). Reflectometry is also an easier technique to automate using data logging equipment.

The results obtained from the automated reflectometer system and NP measurements which were carried out at the rain-shelter facility as part of a trial assessing the effects of different irrigation treatments on two cultivars of barley (*Hordeum vulgare* L.) are compared and discussed.

Materials and Methods

The experiment was located at the Plant & Food Research rain-shelter facility at Lincoln, Canterbury, New Zealand (43° 38'S, 172° 30'E). The facility allows the exclusion of rainfall from the experimental site, thus enabling soil water availability to be controlled by different irrigation regimes (Martin *et al.*, 1990). The soil at the site is a Templeton silt loam over sand and has been described by Martin *et al.* (1992). It is stone-free and therefore provided a suitable area for the experimentation of the automated soil moisture monitoring system using reflectometers.

The experiment was set up as a randomised block design with four replicates and six factorial treatments, giving a total of 24 plots. The treatments consisted of two cultivars of barley, Omaka and Dash, and three irrigation treatments. Irrigation was applied using a drip-line system. The treatments were: a 'high' treatment, irrigated weekly to replace measured crop water use; a 'med' treatment, irrigated twice (early December and end of December) applying half of the total water that had been applied to the 'high' treatment prior to each irrigation; and a 'low' treatment, irrigated only once (early December) at flag leaf appearance (Tottman and Makepeace, 1979), to replace a week of measured crop water use by the 'high' treatment. After the final biomass assessment was complete, all plots were re-wetted to field capacity.

A NP access tube was installed in each plot following seedling emergence, and weekly measurements of VWC using NP (Model 503DR Hydroprobe, Instro Tek Inc.) were carried out in 300-mm increments from 300 mm to 1500 mm depth. A TDR wave guide (TRASE Systems, Soilmoisture Equipment Corp.) was installed alongside the NP access tube to measure VWC in the 0-300 mm increment weekly.

Automated reflectometers (Model CS650 Water Content Reflectometers, Campbell Scientific Inc., Utah, USA) were installed in each plot (approximately 2 m away from the NP access tube) measuring VWC at the following depths: 0-150 mm (two reflectometers installed at that depth, within and between drill rows); 150-300 mm; and then in 300 mm increments from 300 mm to 1800 mm depth (total of eight sensors per plot). The shallow sensors were inserted at a 45° angle to sample at 0-150 and 150-300 mm depths. The sensors in deeper layers were installed at the bottom of an auger hole. Both the hole and the sensors were positioned at a 15° angle from the vertical so that the sensors were not directly below the installation access hole. The reflectometers were connected to a data logger (Model CR1000, Campbell Scientific Inc., Utah, USA) and recorded VWC at 15-min intervals. The reflectometers had two 30 cm length rods (7800 cm^3 sampling volume) (Campbell Scientific Inc, 2012). These sensors also have an in-built measurement of and correction for the effects of soil temperature and electrical conductivity on the soil dielectric permittivity and subsequent VWC estimations. The Topp equation (Topp *et al.*, 1980) was applied by the sensor's on-board electronics to estimate VWC. The manufacturer stated an accuracy of ±3% VWC at 5-50% VWC and in mineral soils where solution EC ≤ 3 dS/m (Campbell Scientific Inc, 2011-2012).

Data Analysis

Data were analysed, for each depth increment of 300 mm separately (starting from the surface), by graphical presentation of the relationships between NP and reflectometer VWC measurements, and by fitting linear regression models. Treatment effects and plot differences were tested by Analysis of Variance (ANOVA). All analyses were carried out using GenStat (14th Edition, VSN International Ltd, UK).

Results

Profile water content measured with NP and reflectometer data was closely correlated for all treatments (Figure 1). However there was a consistent offset between NP and reflectometers measurements of VWC: VWC (CS650) = VWC (NP) +100. The differences in VWC measurements by NP and reflectometers were significant and influenced by the irrigation treatment ($P<0.001$).

When analysed by depth increment, the correlation in VWC measurements between TDR waveguide and reflectometers was good at the top depth (0-300 mm) (Figure 2). However, the correlation became inconsistent between NP and reflectometers as the depth increased (Figure 2). This is obvious from a depth of 600 mm onwards, where the data points get further away from the y=x line.

At depths of 900-1200 mm and below, there was also a differentiation in VWC measured by NP and reflectometers between the two cultivars ($P<0.001$).

There was also a significant differentiation between plots (both in slopes and intercepts) at each depth ($P<0.001$), including those receiving the same irrigation treatment and growing the same cultivar.

Discussion

The correlation in VWC measurements between NP and reflectometers was consistent when averaged across the soil profile (0-1800 mm depth). This means that, for the purpose of calculating crop water use during the season, the data from the reflectometers can be used. Even though the absolute values of VWC measured by the reflectometers were different from those measured by NP, their trends were similar. However, when VWC data is analysed separately for each depth increment, the correlation is inconsistent at depths below 600 mm. In the top depth (0-300 mm), the correlation between VWC measured by NP and reflectometers is consistent so no further calibration of the reflectometers is needed.

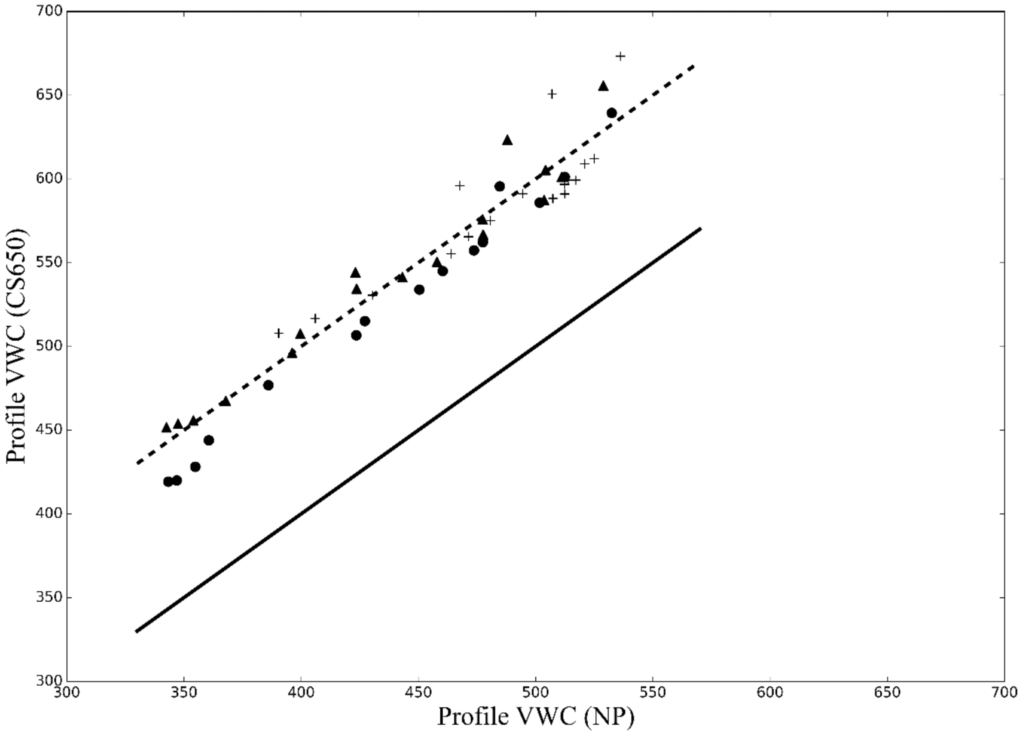

Figure 1: Seasonal volumetric soil water content (VWC) measured by neutron probe versus CS650 Water Content Reflectometers, averaged across the soil profile (0-1800 mm depth) and for both cultivars of barley under three irrigation treatments. 'Low' irrigation (●), 'Med' irrigation (▲) and 'High' irrigation (+). Black line represents y=x. Black dash line represents y=x+100.

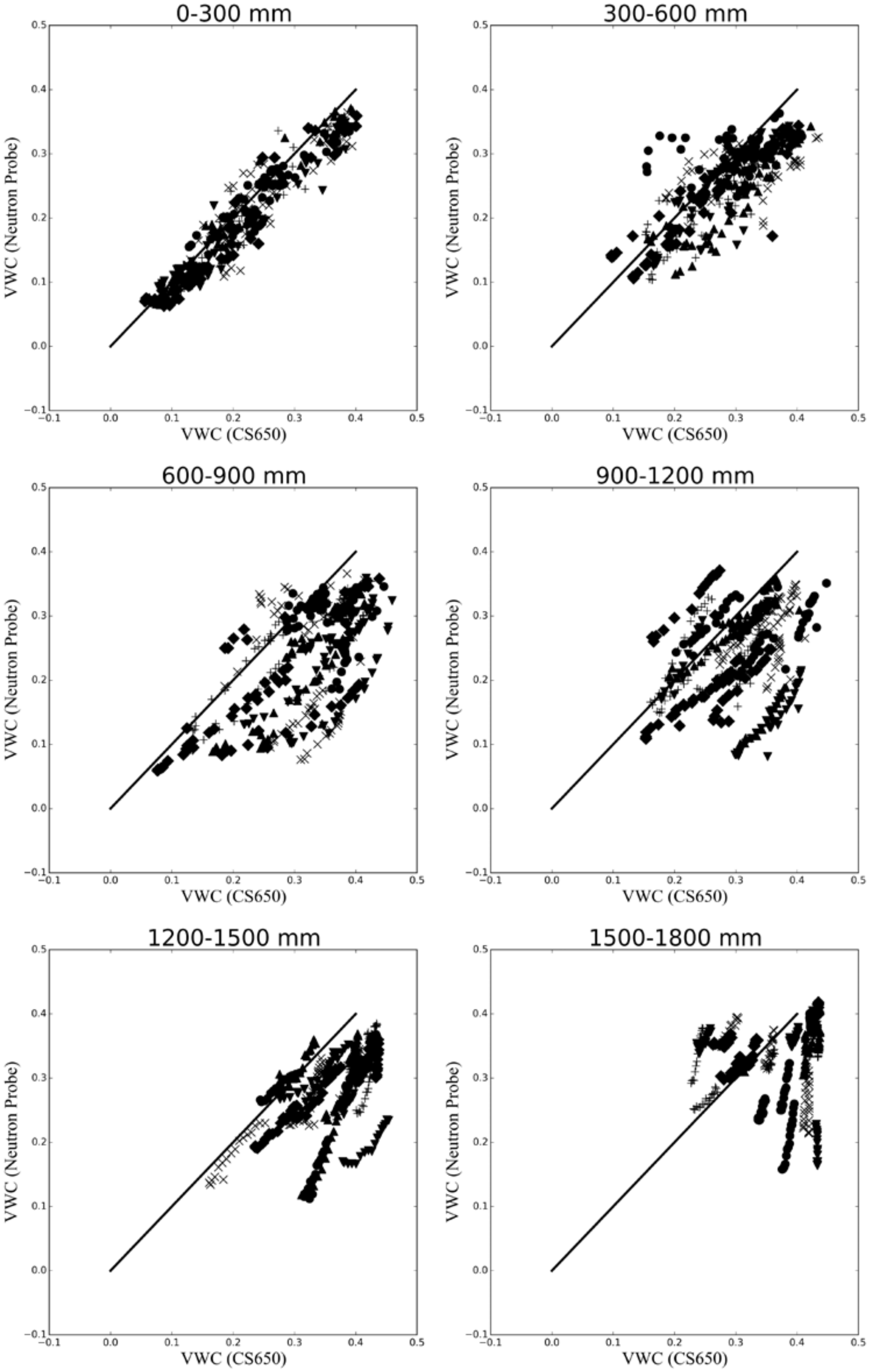

Figure 2: Volumetric soil water content (VWC) measured by neutron probe (or Trase TDR) versus CS650 Water Content Reflectometers, at six different depths across the soil profile for two cultivars of barley under three irrigation treatments. Dash high (●), Dash med (▼), Dash low (▲), Omaka high (×), Omaka med (+) and Omaka low (♦). Black line represents y=x.

At 300-600 mm depth, under the 'high' irrigation treatment for the Dash cultivar (and to a lesser extent for the Omaka cultivar as well), NP consistently measured higher VWC values than the reflectometers did. This suggests a calibration is required to give accurate VWC estimates at this depth. A separate, precise calibration of CS650 sensors in Canterbury alluvial soils (Brown, unpublished data) has shown separate calibrations are required for top soil and sub soil.

Below 600 mm depth, the correlation in VWC measurements between the two instrumentation techniques was weak but there was a significant plot effect. This was exacerbated as soil depth increased. In general the CS650's gave a higher estimate of VWC and showed smaller variations in VWC throughout the season. It has been previously reported in the literature that reflectometers can experience a loss of accuracy in soils with a high VWC (Lekshmi *et al.*, 2014) and the overestimates and lack of sensitivity in the CS650's is probably due to this. This could also be explained by differences in soil texture between the physical location of NP access tube and reflectometers. At the bottom depth (1500-1800 mm), for individual plots there is a good correlation between the two measurements but the relationship varies considerably from plot to plot (Figure 2). The variation in this relationship at these depths is most likely due to the spatial separation of the two measurements and the high degree of textural variation in these soils (Karageorgis *et al.*, 1984). Soil texture was recorded during the installation of the reflectometers: some plots presented soil with a sandy texture, while others presented soil with a clay texture. Reflectometers have also been reported to be sensitive to any soil disturbance, air gap and/or stones in the direct surrounding area (Evett *et al.*, 2012; Lekshmi *et al.*, 2014). There could have been disturbances to the profile during the reflectometer installation process, which occurred two months before the start of the experiment, but it is unlikely since great care was taken to minimise such effects. The data obtained shows that a more precise calibration for CS650's is required to account for soil textural variability before the data from the CS650's can be used to give absolute estimates of VWC.

A study comparing TDR with different models of reflectometers (Mittelbach *et al.*, 2012), including one from the same manufacturer as the current study, showed that the calibration equation provided by manufacturers was not appropriate, thus requiring a calibration for each site where the reflectometers were used. Another study (Vaz *et al.*, 2013) showed that calibration supplied for reflectometers by manufacturers can present some inconsistency. For the reflectometers installed at the top depths (0-600 mm), the manufacturer calibration using the Topp equation provided acceptable results and applying a linear calibration coefficient would allow correction of VWC measurements from the reflectometers. However, another approach is needed to calibrate the reflectometers at depths below 600 mm: VWC should be measured directly (e.g. weighing a known volume of soil wet and dry) near the area where the reflectometer is sampling or in a soil with similar texture and properties, and then comparing this with VWC measured by the reflectometer. This would provide a correction coefficient for each depth and soil texture (sand or clay) that could be applied to VWC measurements in each plot depending on the soil properties of that plot at each depth. That correction coefficient would be valid through time since the reflectometers at those depths have been permanently installed and will not be moved. Any possible soil disturbance should also settle through time: there are four experimental sites within the rain-shelter facility, allowing for a rotation of cropping sites, and the soil resting fallow for three years.

Conclusions

The use of reflectometers to replace NP measurements in the rain-shelter facility is valid for the purpose of crop water use calculations, but depending on measurement depth different approaches are needed to correct the VWC measurements. However, the benefits of using automated reflectometers include more frequent measurements of VWC (compared with NP). Furthermore, once installed, the system is completely automated, thus requiring very little labour to maintain it (compared with the cost of labour required to use NP).

Acknowledgements

The experiment was funded by the Ministry of Business, Innovation and Employment (MBIE) – formally The Foundation for Research Science and Technology – through the Land Use Change and Intensification (C02X0812) programme and the MBIE Irrigation programme. The cost of the reflectometers and equipment required to automate the system was covered by The New Zealand Institute for Plant & Food Research Ltd. The authors would like to thank the Plant & Food Research staff involved in the installation of the reflectometers.

References

Campbell Scientific Inc. 2012. CS650 and CS655 Water Content Reflectometers, Instruction Manual, Revision: 10/12, 2011-2012, Campbell Scientific Inc. 56 pp.

Evett, S.R., Schwartz, R.C., Casanova, J.J. and Heng, L.K. 2012. Soil water sensing for water balance, ET and WUE. *Agricultural Water Management* 104: 1-9.

Gardner, C.M.K., Bell, J.P., Cooper, J.D., Dean, T.J., Gardner, N. and Hodnett, M.G. 1991. Soil water content. *In*: Soil analysis - physical methods. 1-73 pp.

Karageorgis, D., Tonkin, P.J. and Adams, J.A. 1984. Medium and short-range variability in textural layering in an ochrept developed on an alluvial floodplain. *Australian Journal of Soil Research* 22: 471-474.

Lekshmi, S.U.S., Singh, D.N. and Baghini, M.S. 2014. A critical review of soil moisture measurement. *Measurement* 54: 92-105.

Martin, R.J., Jamieson, P.D., Wilson, D.R. and Francis, G.S. 1990. The use of a rainshelter to determine yield responses of Russet Burbank potatoes to soil water deficit. *Proceedings of the Agronomy Society of New Zealand* 20: 99-101.

Martin, R.J., Jamieson, P.D., Wilson, D.R. and Francis, G.S. 1992. Effects of soil-moisture deficits on yield and quality of russet burbank potatoes. *New Zealand Journal of Crop and Horticultural Science* 20: 1-9.

Mittelbach, H., Lehner, I. and Seneviratne, S.I. 2012. Comparison of four soil moisture sensor types under field conditions in Switzerland. *Journal of Hydrology* 430: 39-49.

Topp, G.C., Davis, J.L. and Annan, A.P. 1980. Electromagnetic determination of soil-water content - measurements in coaxial transmission-lines. *Water Resources Research* 16: 574-582.

Tottman, D.R. and Makepeace, R.J. 1979. An explanation of the decimal code for the growth stages of cereals, with illustrations. *Annals of Applied Biology* 93: 221-234.

Vaz, C.M.P., Jones, S., Meding, M. and Tuller, M. 2013. Evaluation of standard calibration functions for eight electromagnetic soil moisture sensors. *Vadose Zone Journal* 12: 1-16.