# Soil Moisture Portable Probes: A Comparison of Different Devices

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**Abstract**

The measurement of soil moisture can be a time-consuming task that can be difficult to capture spatially and temporally. The accuracy of soil moisture measurements is essential to improve aspects of hydrology in a range of modelling situations. This paper compares soil moisture measurements from two un-calibrated in-situ measurement devices against gravimetric data. The devices used are a Delta T Theta Probe and a Campbell Scientific CS659 while the gravimetric readings are from soil cores (12 cm and 21 cm). The soil moisture readings were taken over two large semi-arid catchments (562 $km^2$ and 808 $km^2$) located in South East Australia in the Hunter Valley, NSW. Multiple field campaigns were conducted in 2014, 2015 and 2018, resulting in 308 gravimetric samples for analysis in predominately clay soils. The two core depths sampled showed a strong correlation coefficient (R value) of 0.89. The gravimetric and probe measurements returned R values of approximately 0.8 for 2014 and 2015. The 2018 results showed a decrease in correlation (to approximately 0.3 and 0.5) although this coincided with average gravimetric soil moisture values being much lower than previous data collection campaigns (approximately 13% opposed to 20-23%). The extreme dry period potentially the reason for the reduced correlation. The manufacturer calibrated probe measurements did not provide a 1:1 relationship with the lab based gravimetric soil moisture. Results show that either the Theta Probe or CS659 are comparable to the gravimetric results in most conditions. Both the Theta Probe and CS659 regressions produced root mean square errors that were within the quoted accuracy in the device manuals, ±5% and ±3% respectively. The instruments may be used in conditions showing soil moistures of ˜5% to ˜45%, although the best results will be obtained by using appropriate techniques and knowing the potential limitations of devices. The linear regression equations found in this study may also allow calibration of probes for future measurements.

## 1 Introduction

Whole profile soil moisture content is highly variable both spatially and temporally. However, near-surface soil moisture (i.e. top 5 – 10 cm of the soil profile) is particularly complex (Canton, Sole-Benet, & Domingo, 2004; Cosh, Willgoose, & Saco, 2004; Famiglietti, Rudnicki, & Rodell, 1998; Hébrard, Voltz, Andrieux, & Moussa, 2006; Qiu, Fu, Wang, & Chen, 2001; Svetlitchnyi, Plotnitskiy, & Stepovaya, 2003; Western, Grayson, Blöschl, Willgoose, & McMahon, 1999; Western et al., 2004; D. J. Wilson, Western, & Grayson, 2005). Most hydrological, vegetation growth and climate models require some form of soil moisture data as input, identifying its importance. Therefore, accurate and reliable soil moisture data, both near surface and whole profile is vital to understand and manage environmental processes. Our ability to quantify its spatial and temporal variability is a critical factor in improving our understanding of the hydrological cycle (Famiglietti et al., 1998; Starks, Heathman, Jackson, & Cosh, 2006; David. J. Wilson et al., 2003).

The spatial and temporal variability of soil moisture over large spatial domains provides great challenges for the soil and hydrological communities. While remote sensing has become a popular and ever improving tool, on ground measurement is still needed for both calibration, validation and evaluation of any remote sensing technology (Chen et al., 2017; Senanayake et al., 2019; Wu, Liu, Wang, & Deng, 2016; Zhang, Zhang, Zhou, Shao, & Gao, 2017). The most reliable method for the quantification of soil moisture is the gravimetric technique where a soil sample is collected, weighed, dried in an oven and then weighed again with the difference being the amount of water in the soil sample (Black, 1965). While this method is accurate and simple, it is destructive and only provides a unique spatial and temporal snapshot of soil moisture at that particular time. The method is also labour intensive and time consuming. Non-destructive methods such as the neutron probe, impedance probes or Time Delay Reflectometry (TDR) can be inserted into the ground and a reading taken without soil sampling with a soil moisture value obtained instantaneously. Alternatively, nests of probes can be placed at different depths at the same point and left to log continuously providing a continuous stream of data at that point (Rüdiger et al., 2007; Smith et al., 2012; Tetlock, Toth, Berg, Rowlandson, & Ambadan, 2019). However, these instrumental methods still require the device to be moved from point to point if hillslope or catchment scale data is needed and furthermore, they require calibration. Calibration is time-consuming if there are large differences in soil properties across a study area.

Over recent decades, portable and easy to use measures of soil moisture have been developed (Kaleita, Heiman, & Dodgson, 2005; Walker, Willgoose, & Kalma, 2004). The methods examined here rely on the dielectric properties of soil, which are then converted into a voltage that is proportional to the water content. However, the dielectric properties of soil are not just related to the amount of water in a soil, it is also related to soil chemistry (e.g. the amounts of salts present) as well as its textural properties. Therefore to be able to accurately and reliably quantify an absolute soil moisture, these indirect measures require calibration to account for the various properties of the soil of interest (Kaleita et al., 2005; Walker et al., 2004). This requires soil to be collected from the site of interest, wetted to field capacity and then allowed to dry over a period of days and weeks while at the same time weighing the mass of soil. This process is labour intensive and time consuming (Kaleita et al., 2005; Walker et al., 2004). If an instrument is to be used over a large area with different soil properties then a site specific calibration can prove to be logistically challenging. The alternative to site/soil specific calibration is manufacturer calibration. Most instrument manufacturers offer generic calibration data based on soil properties, although exact techniques vary between devices (Vaz, Jones, Meding, & Tuller, 2013).

The accuracy and calibration of soil moisture probe measurements has been studied intensely (Huang, Akinremi, Sri Rajan, & Bullock, 2004; Matula, Batkova, & Legese, 2016; Rowlandson et al., 2018; Rowlandson et al., 2013; Seyfried, Grant, Du, & Humes, 2005; Seyfried & Murdock, 2004). There are several studies that suggest using calibration equations for individual soil types for greater accuracy (Caldwell, Bongiovanni, Cosh, Halley, & Young, 2018; Huang et al., 2004; Seyfried & Murdock, 2004; Vaz et al., 2013), although Rowlandson et al. (2018) showed the temporal transferability of calibration equations from one year to the next increased the error of the probes compared to temporally derived calibration efforts. The requirements to gain soil texture information before conducting a soil moisture probe field campaign can be time consuming and difficult, further adding to the complexities in calibrating equipment. Additionally clay soils can often reduce the sensors ability to provide accurate results (Bittelli, Salvatorelli, & Pisa, 2008; Vaz et al., 2013). These challenges mean manufacturer calibrations are commonly used rather than site specific relationships, despite their limitations.

Here we assess two different hand-held and portable soil moisture probes, a Theta Probe and the CS659, for their ability to quantify soil moisture across two large catchments using manufacturer calibration. The catchments are located in the south-east of Australia and are predominately clay soils further adding to the difficulties of soil moisture measurement. The soil sampling and analysis here formed part of a larger project examining hydrology, sediment transport and soil carbon concentration in the catchments (Gibson, Verdon-Kidd, Hancock, & Willgoose, 2020; Hancock & Coulthard, 2012; Hancock, Coulthard, Martinez, & Kalma, 2011; Hancock, Wells, Martinez, & Dever, 2015; Kunkel, Hancock, & Wells, 2019; Kunkel, Wells, & Hancock, 2016; Martinez, Hancock, & Kalma, 2009, 2010; Martinez, Hancock, Kalma, & Wells, 2008; Rüdiger et al., 2007; Wells et al., 2019). We demonstrate that for the clay soils examined, the manufacturer calibrations are reliable for comparable measurements of soil moisture.

## 2 Site description

The study site is located within the Goulburn River catchment (6540 km$^2$), in the Hunter Valley region of New South Wales, Australia (Figure 1) approximately 200 km north-west of Newcastle (Kunkel et al., 2016; Rüdiger et al., 2007). The Krui River catchment (562 km$^2$) and the Merriwa River catchment (808 km$^2$) represent two of the 12 major sub-catchments within the Goulburn River catchment, located in the northern half of the region. In recent years, the Krui and Merriwa catchments have been a focus for soil carbon assessment as well as examining hydrology and sediment transport as they have a consistency of geology, soil, vegetation, landuse and relatively easy site access (Hancock & Coulthard, 2012; Hancock et al., 2011; Hancock et al., 2015; Kunkel et al., 2019; Kunkel et al., 2016; Martinez et al., 2009, 2010; Martinez et al., 2008; Rüdiger et al., 2007).

The Krui catchment extends from 31°49'S to 32°13'S and 150°02'E to 150°21'E, with elevations ranging from approximately 200 m in the south (Merriwa Plateau) to 1200m in the north (Liverpool Range). The Merriwa catchment extends from 150°14' E to 150deg32' E and 32deg23' S to 31deg49' S, with elevations ranging from approximately 200 m in the south to 1200 m in the north. The Krui and Merriwa catchment are considered geomorphologically similar (Kunkel et al., 2016). The predominant land use in the region is cattle grazing, although sheep grazing does occur. There are large areas that are subject to cropping, such as Lucerne, oats, barley and sorghum, mostly located in the lower reaches of the catchments. The vast majority of the catchment is covered with clay soils (i.e. over 50% clay).

[ **FIGURE 1** ]

## 3 Methods

In this study, we use the Delta-T Theta Probe (Type ML2x) with a Measurement Engineering Australia (MEA) reader and the Campbell Scientific CS659 to quantify soil moisture across both the Krui and Merriwa River catchments (Figure 2).

[ **FIGURE 2** ]

The Delta-T Theta Probe (Delta-T Devices Ltd., 1999) body is approximately 12 cm long and has a set of four 6 cm long stainless steel probes at its base mounted in a sealed unit containing electronics. The Theta Probe is an impedance sensor operating at 100 MHz (Matula et al., 2016). To measure soil moisture it generates a radio signal that is transmitted along the stainless-steel rods used to determine the dielectric constant of the soil. When inserted into the soil, some of the radio signal is absorbed by the soil with the reflected signal also measured with the ratio between the signals being a measure of soil moisture (Delta-T Devices Ltd., 1999). The ratio of the transmitted and received signal is converted to a voltage of between 0 and 1 Volts. Quoted accuracy is +- 5%, using manufacturer calibration, within a soil moisture range of 5-50%.

The Campbell Scientific CS659 has two 12 cm long stainless-steel rods with a sealed body containing electronics. Soil moisture is read using the Hydrosense II reader. The CS659 is a transmission line oscillator (TLO) device, similar to TDR, operating at 175 MHz as described by Caldwell et al. (2018). It measures an electromagnetic pulse and the elapsed travel time of the pulse's reflection. This is then used to calculate soil volumetric water content. The electromagnetic pulse is attenuated by ions in the soil solution and soil mineralogy. The reported accuracy is +- 3% in typical soils (Campbell Scientific Inc., 2019).

### 3.1 Field sampling

The field sampling (soil samples and in-situ instrumental soil moisture measurement) was conducted across the Krui in June/July 2014 and Merriwa catchment in November 2015 to January 2016 (referred to as 2015) (Kunkel et al., 2019) (Figure 3), the Krui locations were sampled again during August and November 2018. A summary of all data collected is available in Table 1. The sample points were pre-determined and located so that an approximately even spatial coverage of the catchment was obtained however, in reality, this was limited by physical access and changes in land use. For this study all samples and instrumental soil moisture data were collected from hillslopes and upslope areas well away from any trees in areas dominated by grassland and were considered representative of the local surrounds.

[ **FIGURE 3** ]

In 2014 for the Krui catchment, upon arrival at the predetermined site (Figure 3), a 0.5 m by 0.5 m quadrat was placed on the ground. From within this quadrat two soil cores (1 x 21 cm long and 9.5 cm diameter; 1 x 12 cm long and 9.5 cm diameter) were collected. The Theta Probe was directly inserted into the 21 cm and 12 cm cores that had been inserted into the ground before they were removed to get a measurement directly at the core location. The remaining three measurements were collected from within the 0.5 m by 0.5 m quadrat but outside the cores (five Theta Probe readings in total).

In 2015 (Merriwa catchment), a similar sampling method was employed however after insertion of the 2 steel cores, the CS659 probe was inserted into each of the cores and a single measurement recorded (two CS659 measurements in total). During the field campaign for the Merriwa catchment, the additional soil moisture measurements were not collected based on results from the previous sampling campaigns indicating they were not required for subsequent campaigns.

The 2018 Krui campaign followed a similar methodology as the 2015 Merriwa campaign although in addition to the CS659 measurement, a Theta Probe measurement was taken (i.e. 2 measurements from inside each soil core).

To collect the soil samples, the steel cores were placed within the 0.5 m by 0.5 m quadrat, a steel cap placed on top and the core inserted into the ground using a hammer until flush with the ground surface. The cores were then carefully removed, bagged and transported to The University of Newcastle soil laboratory for analysis. Soil moisture was determined by the gravimetric method and converted to volumetric soil moisture using the volume of the core and mass of samples (Rayment & Higginson, 1992). A soil texture analysis was also completed via sieving and the hydrometer method (Ashworth, Keyes, Kirk, & Lessard, 2001).

For all sampling campaigns, a similar number of sites were sampled and soil cores collected using both the Theta Probe and CS659 instruments. For the Krui catchment there were 51 and 53 samples collected in 2014 and 2018, respectively. In 2015, 50 samples were collected in the Merriwa catchment (Table 1). As 12 cm and 21 cm cores were taken at each site, this results in a total of 308 samples available for analysis.

[ **TABLE 1** ]

## 4 Results and Discussion

### 4.1 Gravimetric, Theta Probe and CS659 data

The results show that for all soil moisture data sets there is a considerable range from low soil moisture (approximately wilting point) through to higher soil moisture (approximately field capacity). Therefore, the data provides a good test of the capability of the instruments (Table 2). For all of the sites measured, there was very little difference in the average gravimetric soil moisture between the different depth cores. The minimum and maximum were also showing very similar trends between the core depths.

The gravimetric soil moisture data provided a range that is well within the range of moisture values that the Theta Probe and CS659 are designed to measure (between 5% and 50%). The Theta Probe produced a very similar soil moisture mean and range to that of the gravimetric soil moisture for 2014 (Table 2), while in 2015 the CS659 produced a considerably higher soil moisture mean and range. For many sites the CS659 produced a value which was at the maximum readable range (50.8%). Additionally as this study focuses on clay soils, which are conductive, there are dielectric losses that cause TDR, or TLO, readings to overestimate soil moisture (Bittelli et al., 2008). The readings of each device produced similar statistics when comparing between the 12 cm and 21 cm cores. This similarity is also featured when plotting the core soil moisture against each other for each location (Figure 4). The R value when comparing the two depths is 0.89 while also showing a close match to the 1:1 line. This may only hold true for this particular catchment and core collection times and should be investigated before applying this relationship elsewhere.

Soil moisture gauging stations have shown similar phenomena over the Krui catchment when comparing 0-5 cm and 0-30 cm in-situ measuring sensors (Senanayake et al., 2017). This results is similar to studies in the Mahurangi river catchment, New Zealand where 6 cm and 30 cm soil moisture distributions have been shown to have similar means (David. J. Wilson et al., 2003).

[ **TABLE 2** ]

[ **FIGURE 4** ]

### 4.2 Comparison of gravimetric soil moisture and instrument data

Table 3 contains a statistical summary of the regression analyses between the probe and gravimetric data, including a root mean square error (RMSE). All results were significant, with $p < 0.05$. These values are referred to throughout the discussion for the various comparisons.

[ **TABLE 3** ]

In 2014, a strong correlation was observed using an average of all five Theta Probe values for both the 12 cm and 21 cm cores (Figure 5). When performing a correlation with a single instrument measurement, rather than the average of five measurements, and the gravimetric soil moisture, the R value is slightly reduced (Table 4). The first reading of the five (i.e. SM1) was taken within the soil core, simulating an in-situ measurement, and hence produced a slightly higher R value, although other nearby measurements also produced satisfactory results. The averaging of the five readings still produced better results than a single reading within the core, demonstrating that the use of more than a single probe reading at any one point, will likely increase the correlation with the gravimetric soil moisture. The reduction in R may be due to small localised horizontal soil moisture variation that is not detected with a single reading. Any further reference to 2014 results within this paper is from the average of all five readings as presented in Figure 5.

[ **FIGURE 5** ]

[ **TABLE 4** ]

The CS659 measurements from the 2015 campaign, were from a single reading inside each of the cores. Strong and significant correlations were observed for both 21 cm and 12 cm cores (Figure 6). However, it should be noted that there appears to be a grouping of high soil moisture values at approximately 50% soil moisture when using the CS659. This suggests that the CS659 may be better suited to soils with lower soil moisture content, possibly because the clay soil is affecting the accuracy of the TLO reading due to its conductivity (Bittelli et al., 2008). The 2015 samples have an average clay content of 54%. Additionally, the manual for the CS659 mentions the potential for reduced accuracy due to high clay soils and the presence of significant volume of rocks in the soil (Campbell Scientific Inc., 2019), both of which were observed in the field. There is a clear bias of the CS659 results from the 2015 samples overestimating the gravimetric soil moisture. Despite this, the CS659 probe produced a correlation with all points within the 95% prediction line (Figure 6) and a RMSE of ~2.3% for both core sizes (Table 3).

[ **FIGURE 6** ]

In 2018 as both the Theta Probe and CS659 were used, it provides a way to compare the two devices based on the same field campaign. The results for 2018 show that both of the tested devices had a reduced R value from previous field measurements (Figure 7). It is worth noting that the average gravimetric moisture content is very low for this field campaign. The dry conditions may produce relationship with lower correlation compared to the 2014 and 2015 campaigns. An example of this poor correlation is noticeable in the regression for the 21 cm core measured with the Theta Probe shown in Figure 7. The results for the other three regressions all give R values of approximately 0.5, while this is returning a value of 0.31. We suggest that this may be due to the Theta Probe having only a 6 cm deep measurement, whereas the CS659 has longer probes to improve its estimation of soil moisture in the 21 cm core.

[ **FIGURE 7** ]

Figure 8 displays all the field campaign data combined. The results from this comparison shows a weaker correlation when combining the Theta Probe and CS659 measurements. This is expected as the probes function differently. When separating the Theta Probe and CS659 results the R value increases, further suggesting that these probes cannot be used in combination for the same field experiment. Although the CS659 regression is producing a higher R value, the Theta Probe is presenting much closer to the 1:1 line presented on the plot. This is evident as the gradient coefficient in the regression equations for the Theta Probe is 0.54 and 0.60 whereas the CS659 regression produces value of 0.32 and 0.34 (Figure 8). The y-intercept also shows a differing bias between the instruments. The lower R value for the Theta Probe's combined results is likely affected by the poor correlation seen in 2018 during the significantly dry period.

Interestingly correlations that combine all readings of a single device show a RMSE of 6.6-7% and 3.3-3.4% for the Theta Probe and CS659, respectively. This is higher than expected based on values reported in device manuals (+-5% for the Theta Probe and +-3% for the CS659). The higher RMSE found for the Theta Probe may be due to the 6 cm probe length being mismatched with the 12 and 21 cm core depths. This is in comparison to the CS659's 12 cm penetration depth which when combined returned a much lower RMSE.

[ **FIGURE 8** ]

As the field sites were clay dominated soils, a further correlation was computed with the soil moisture data for the various probes compared to the percent clay (not presented). The clay percentage and instrument soil moisture showed a poor correlation. For example, the 2014 results based on the texture for the 12 cm and 21 cm cores produced an R value of 0.18 and 0.21 respectively. Additionally, no acceptable correlation was found with the sand or silt soil texture percentages.

For all datasets, neither the Theta Probe nor CS659 demonstrated a 1:1 relationship with gravimetric soil moisture as demonstrated by the slope of the regression (Figures 5, 6, 7 and 8). However, the Theta Probe produced a plot that is closer to the 1:1 line compared to the CS659. If the instruments are to be used for a true or actual soil moisture they require calibration as discussed by Vaz et al. (2013). The Theta Probe will likely produce a value closer to the true gravimetric soil moisture when comparing manufacturer calibrated readings. If a value is required for comparison, this can be obtained with a level of confidence based on the findings here with either probe as a long as potential limitations of each are known, especially in a clay rich environment. The RMSE of each field campaign results, presented in Table 3, shows values approximately equal to the quoted accuracy reported in the manuals of +-5% for the manufacturer calibrated Theta Probe (Delta-T Devices Ltd., 1999) and +-3% for the CS659 (Campbell Scientific Inc., 2019).

The probes performed well across a range of moisture contents, as presented in Table 2, with extremes of wet and dry conditions. Where possible for optimal results, it is suggested that field campaigns be targeted during time periods where moisture content is in the mid-range to avoid potential reductions in correlation as discussed in this paper. Multiple readings at a single site will likely improve results (Table 4 and Figure 5). The results show that the relatively shallow measurements of the probes can estimate soil moisture at deeper depths based on these 12 and 21 cm core readings. The differences in the slope found for each regression equation may be caused by soil moisture distributions from within each soil core. The difference in y-intercept of the regression equation indicates a differing bias of each probe.

The results of this work may aid in the conversion of soil moisture time series measured with similar equipment to an equivalent gravimetric soil moisture. The use of a regression equation, similar to that calculated for this study was found to be the most effective method for calibration in lab analysis by Matula et al. (2016).

## 5 Conclusion

Here we have examined the ability of portable (handheld) soil moisture probes to measure soil moisture across two large catchments. The results demonstrate these probes can be used with a level of confidence for comparable soil moisture in areas predominately covered by clay.

The method employed here took either five soil moisture readings within close proximity to each other (with a 0.5 m by 0.5 m quadrat) or single readings from within a soil core within the 0.5 m by 0.5 m quadrat. A single reading using a Theta Probe or the CS659 can produce a reliable measure of soil moisture, although taking more measurements will likely improve results. Neither of the instruments demonstrated a 1:1 fit with gravimetric soil moisture, although they do allow a reliable measurement of comparable moisture. Therefore, a direct conversion between the instrumental data and actual soil moisture is not possible.

The results demonstrate that both methods can provide a reliable measure of soil moisture at both 12 cm and 21 cm depths. This is an important finding as these depths are the most biologically active soil depths. The findings suggest that a single well-planned field sampling campaign can quantify soil moisture across large catchments. A further point is that large areas such as that examined here can be covered by car in less than a day with soil moisture readings taken and with a good measure of reliability. How transferable these results are to different soils and sites needs to be assessed on a case by case basis.

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Table 1. Number of soil cores collected and core depth, Theta Probe and CS659 measurement data.

| | **Krui 2014** | **Merriwa 2015** | **Krui 2018** |
|---|---|---|---|
| **No. of samples sites (12 and 21cm cores)** | 51 | 50 | 53 |
| **Soil moisture probe** | Theta Probe | CS659 | Theta Probe & CS659 |
| **Number or readings at each point** | 5 within a 0.5 m by 0.5 m square, including 1 in each core | 1 in each core | 1 in each core by each probe |

Table 2. Gravimetric and instrumental soil moisture (%) data from the Krui and Merriwa catchments.

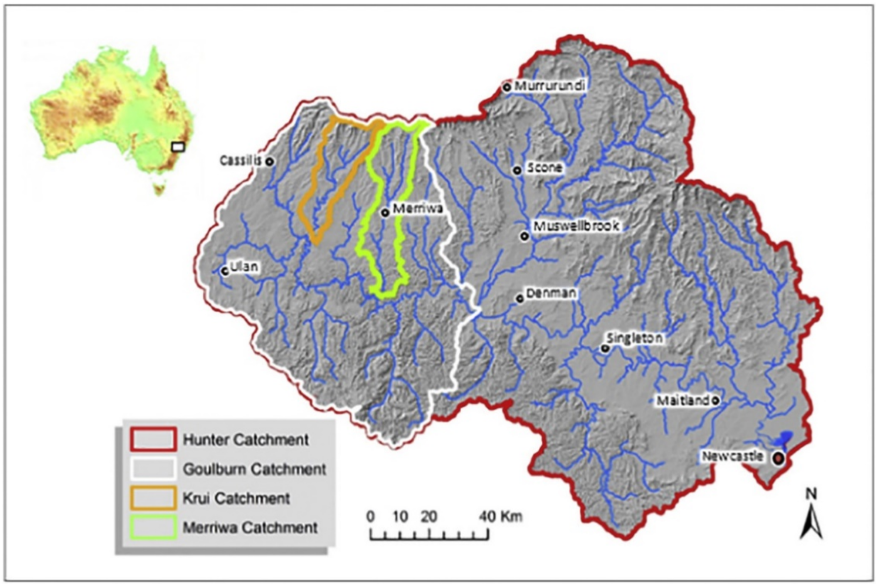
| **Core Location and Size** | **Gravimetric Average** | **Gravimetric Min** | **Gravimetric Max** | **Device Used** | **Instrument Reading Average** | **In M** |
|---|---|---|---|---|---|---|
| Krui 2014 (12 cm) | 23.5 | 7.0 | 44.3 | TP | 22.7 | 6. |
| Krui 2014 (21 cm) | 23.8 | 8.1 | 38.9 | TP | | |
| Merriwa 2015 (12 cm) | 20.5 | 11.7 | 27.8 | CS659 | 41.1 | 19 |
| Merriwa 2015 (21 cm) | 20.9 | 13.2 | 27.9 | CS659 | 39.8 | 14 |
| Krui 2018 (12 cm) | 13.5 | 4.6 | 23.8 | TP | 23.2 | 6. |
| | | | | CS659 | 22.6 | 4. |
| Krui 2018 (21 cm) | 13.2 | 4.8 | 23.8 | TP | 19.9 | 6. |
| | | | | CS659 | 20.8 | 7. |

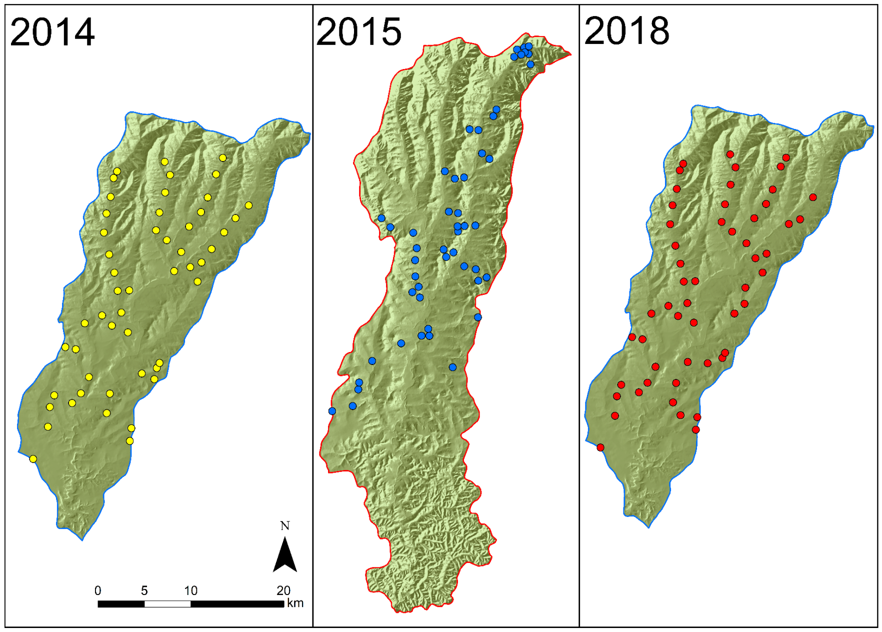
Table 3. Statistical Summary of each linear regression model. SE is the standard error and RMSE is the root mean square error (%).

| **Year(s)** | **Core Depth** | **Instrument** | **Intercept Value** | **Intercept SE** | **Intercept p-value** | **Slope Value** | **Slope SE** | **Slope p-value** | **Regres RMSE** |
|---|---|---|---|---|---|---|---|---|---|
| 2014 | 12 cm | TP | 6.398 | 1.875 | 0.001 | 0.753 | 0.077 | <0.001 | 4.740 |
| 2014 | 21 cm | TP | 7.343 | 1.750 | <0.001 | 0.719 | 0.071 | <0.001 | 4.370 |
| 2015 | 12 cm | CS659 | 7.424 | 1.416 | <0.001 | 0.318 | 0.034 | <0.001 | 2.270 |
| 2015 | 21 cm | CS659 | 7.811 | 1.437 | <0.001 | 0.330 | 0.035 | <0.001 | 2.330 |
| 2018 | 12 cm | TP | 5.608 | 1.828 | 0.003 | 0.341 | 0.075 | <0.001 | 3.980 |
| 2018 | 21 cm | TP | 9.116 | 1.837 | <0.001 | 0.205 | 0.087 | 0.023 | 4.420 |
| 2018 | 12 cm | CS659 | 8.185 | 1.393 | <0.001 | 0.230 | 0.056 | <0.001 | 4.020 |
| 2018 | 21 cm | CS659 | 8.281 | 1.388 | <0.001 | 0.244 | 0.061 | <0.001 | 4.010 |
| All Years | 12 cm | TP & CS659 | 9.251 | 1.060 | <0.001 | 0.309 | 0.036 | <0.001 | 6.050 |
| All Years | 21 cm | TP & CS659 | 9.073 | 0.988 | <0.001 | 0.337 | 0.035 | <0.001 | 5.870 |
| 2014 & 2018 | 12 cm | TP | 5.584 | 2.088 | 0.009 | 0.560 | 0.086 | <0.001 | 6.970 |
| 2014 & 2018 | 21 cm | TP | 5.178 | 1.862 | 0.006 | 0.618 | 0.082 | <0.001 | 6.590 |
| 2015 & 2018 | 12 cm | CS659 | 6.602 | 0.858 | <0.001 | 0.325 | 0.025 | <0.001 | 3.350 |
| 2015 & 2018 | 21 cm | CS659 | 6.719 | 0.835 | <0.001 | 0.344 | 0.025 | <0.001 | 3.360 |

Table 4. The correlation coefficient (R value) of each individual instrument soil moisture (SM) reading from 2014 samples when compared to 12 cm and 21 cm cores (see Table 1 for sampling description).

| | SM1 | SM2 | SM3 | SM4 | SM5 |
|---|---|---|---|---|---|
| **12 cm** | 0.798 | 0.754 | 0.725 | 0.726 | 0.731 |
| **21 cm** | 0.782 | 0.719 | 0.724 | 0.788 | 0.774 |





2014
2015
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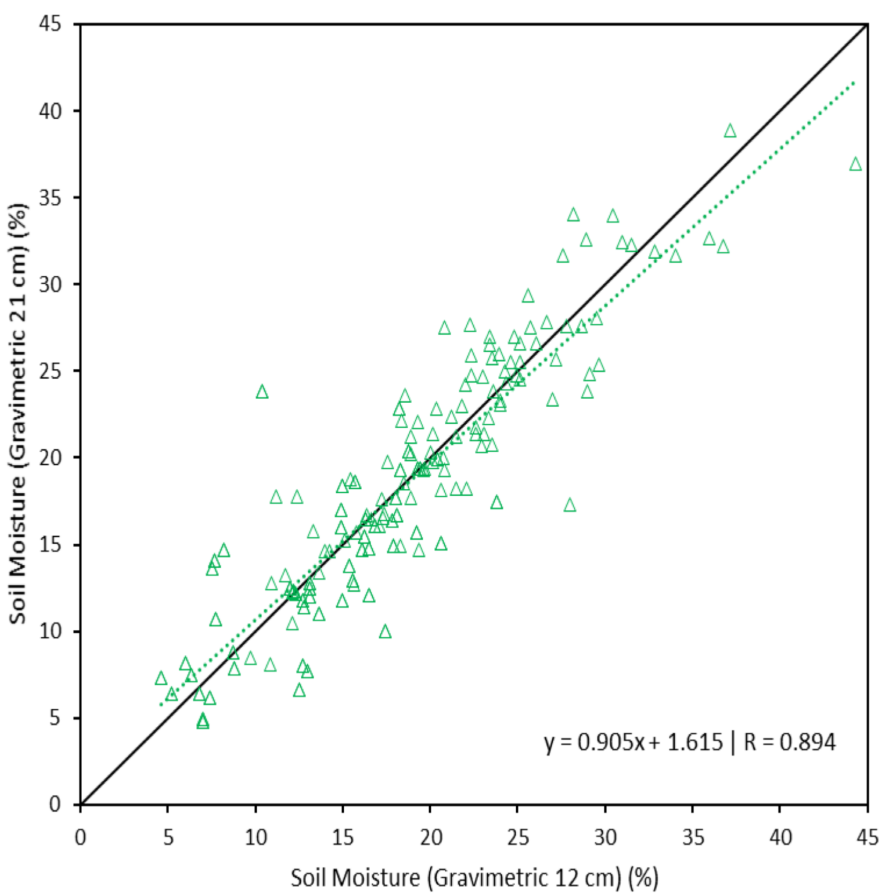
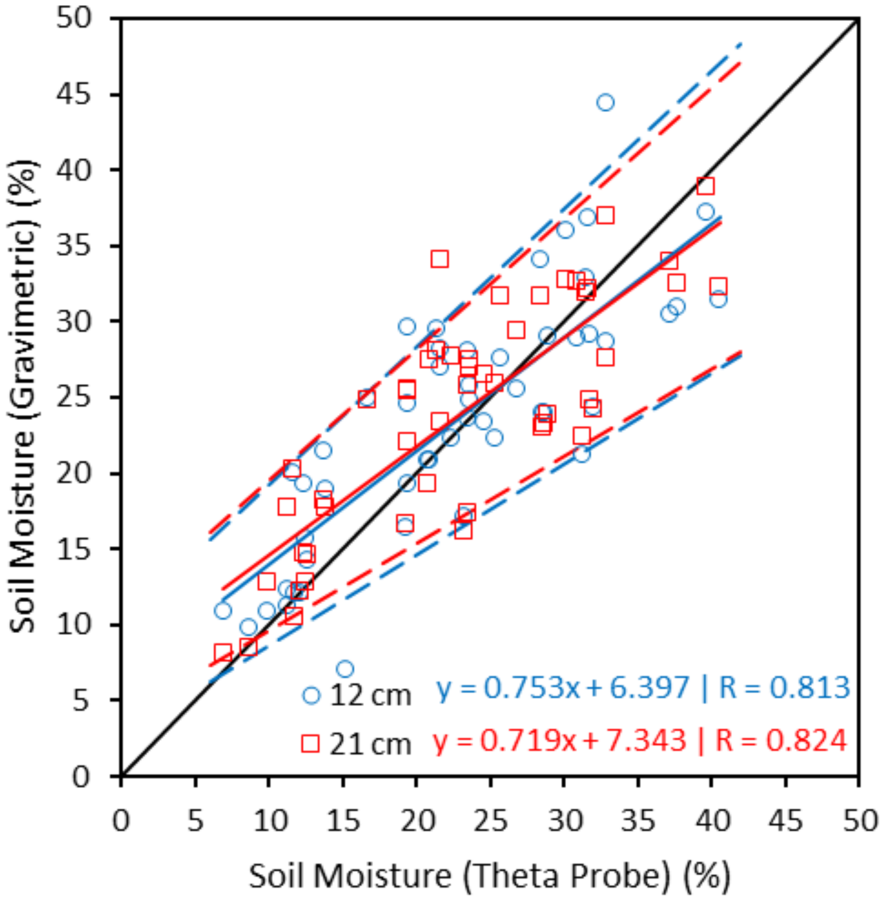
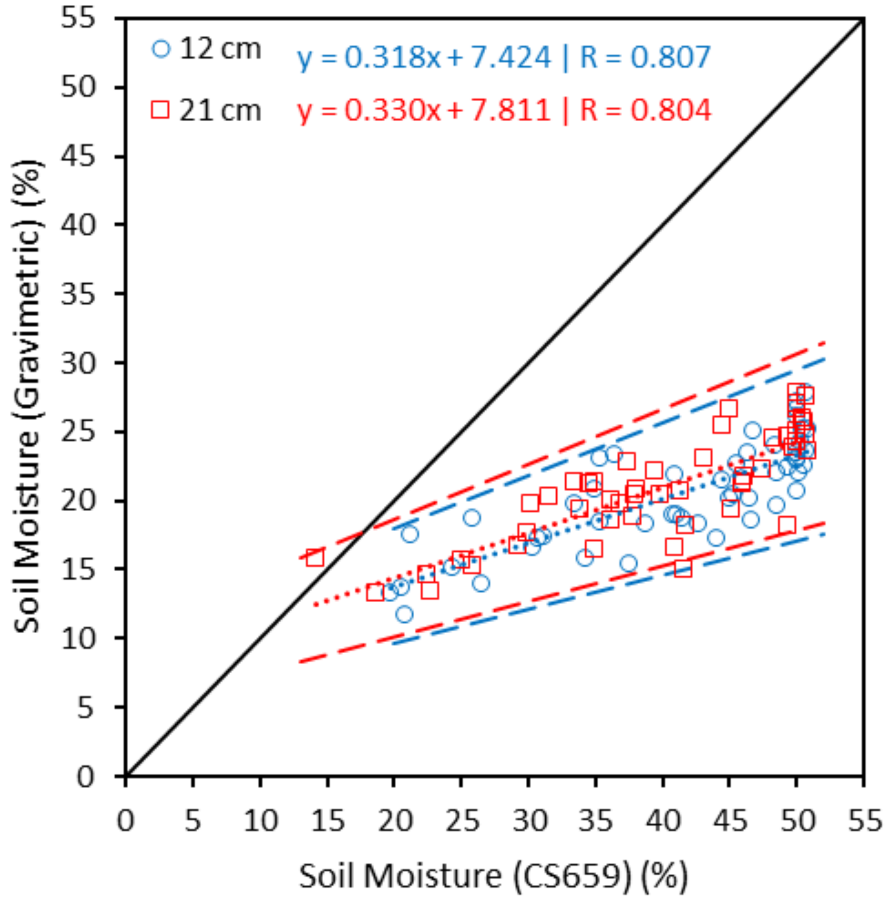
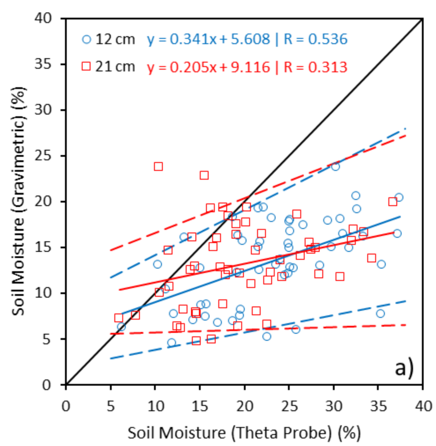
N
0
5
10
20
km


Soil Moisture (Gravimetric 21 cm) (%)
Soil Moisture (Gravimetric 12 cm) (%)
y = 0.905x + 1.615 | R = 0.894
0
5
10
15
20
25
30
35
40
45

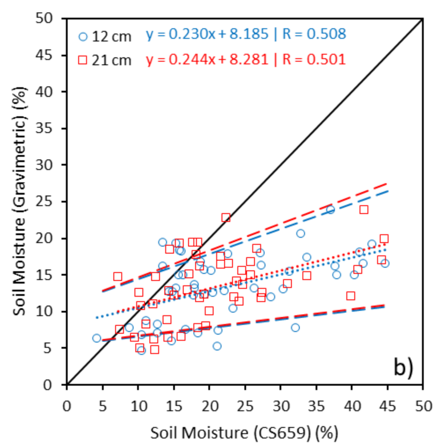

Soil Moisture (Gravimetric) (%)
Soil Moisture (Theta Probe) (%)
12 cm
y = 0.753x + 6.397 | R = 0.813
21 cm
y = 0.719x + 7.343 | R = 0.824
0
5
10
15
20
25
30
35
40
45
50



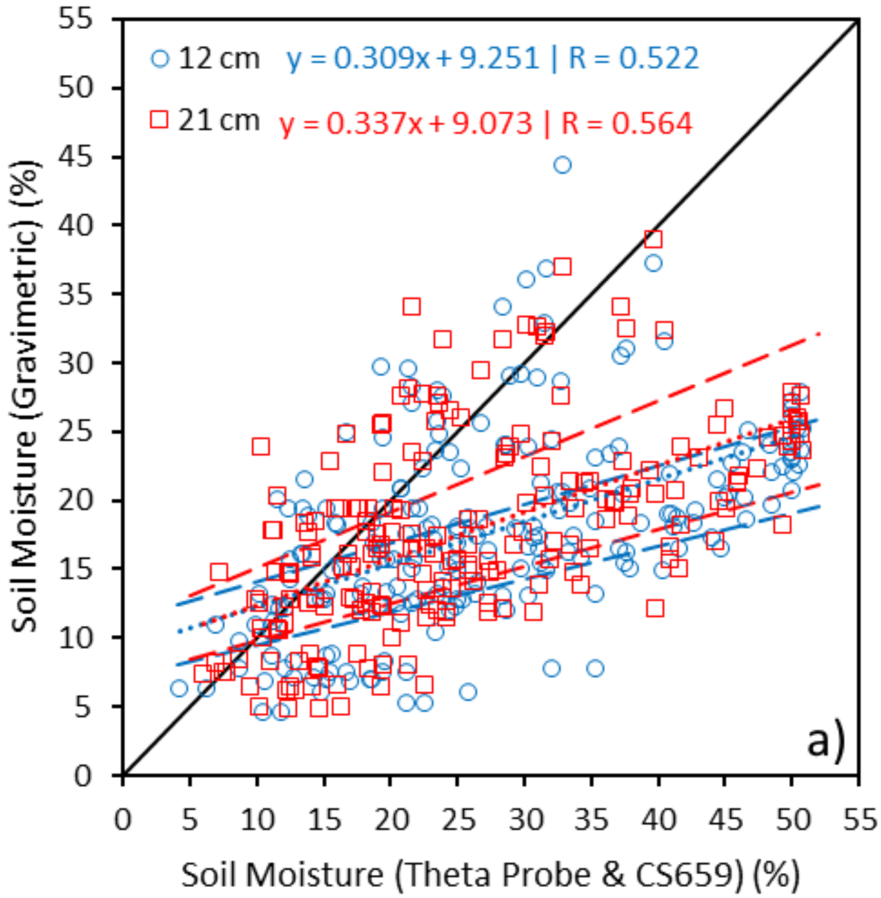
12 cm
y = 0.318x + 7.424 | R = 0.807
21 cm
y = 0.330x + 7.811 | R = 0.804
Soil Moisture (Gravimetric) (%)
Soil Moisture (CS659) (%)

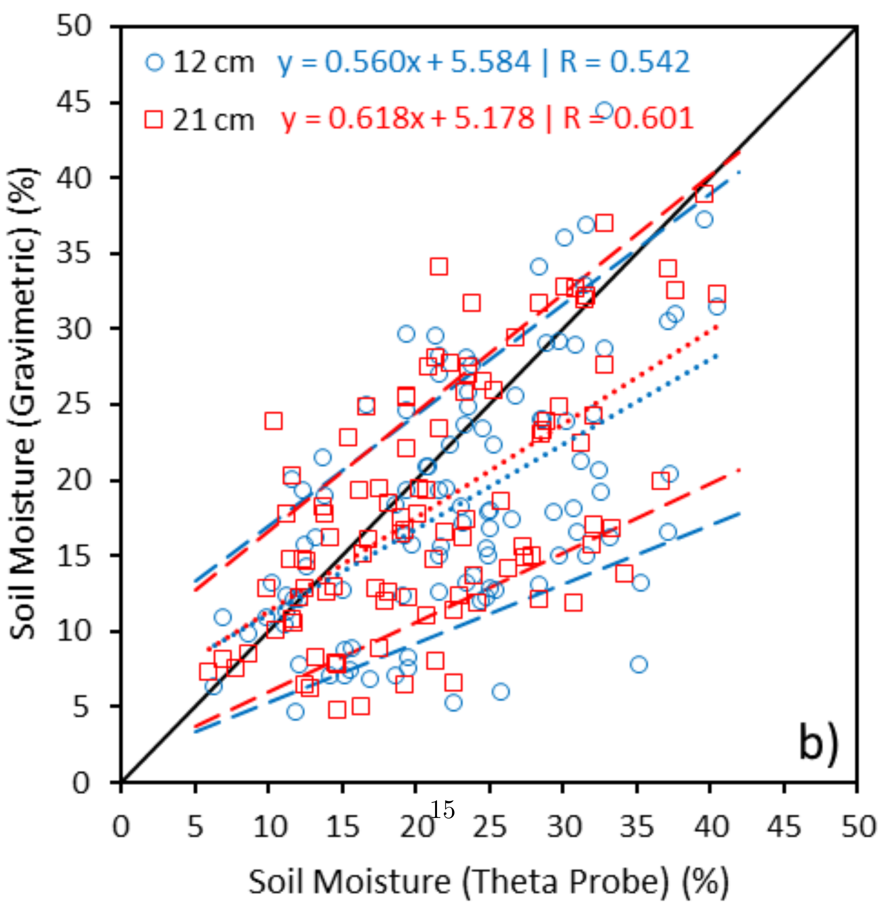



12 cm
y = 0.341x + 5.608 | R = 0.536
21 cm
y = 0.205x + 9.116 | R = 0.313
Soil Moisture (Gravimetric) (%)
Soil Moisture (Theta Probe) (%)
a)

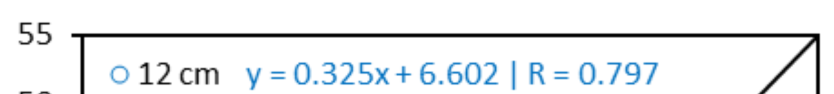



12 cm
y = 0.230x + 8.185 | R = 0.508
21 cm
y = 0.244x + 8.281 | R = 0.501
Soil Moisture (Gravimetric) (%)
Soil Moisture (CS659) (%)
b)


12 cm y = 0.309x + 9.251 | R = 0.522
21 cm y = 0.337x + 9.073 | R = 0.564
Soil Moisture (Gravimetric) (%)
Soil Moisture (Theta Probe & CS659) (%)
a)


12 cm y = 0.560x + 5.584 | R = 0.542
21 cm y = 0.618x + 5.178 | R = 0.601
Soil Moisture (Gravimetric) (%)
Soil Moisture (Theta Probe) (%)
b)




12 cm y = 0.325x + 6.602 | R = 0.797