AN ACCURACY ASSESSMENT OF LONG-TERM SOIL MOISTURE MONITORING IN TEXAS

A Thesis

by

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ABSTRACT

Long-term soil moisture monitoring sites are a source of data both for drought forecasting and hydrological and land surface modeling validation. Uncertainties in soil moisture monitoring data are not well documented and more knowledge can improve the interpretations based on these data. Texas has 23 locations with long-term soil moisture monitoring, supported by the Soil Climate Analysis Network (SCAN) and the U.S. Climate Reference Network. Both networks use Stevens Water HydraProbes for measuring soil moisture and one manufacturer-provided calibration equation for all locations. The Texas SCAN sites contain soils with vertic properties and soils with large texture discontinuities with depth, which may create distinct sources of uncertainties in soil moisture measurement. The objectives of this study were to 1) compare the default calibration to soil specific calibrations made in the lab and in-situ, 2) assess temporal and spatial uncertainties associated with using the HydraProbe, and 3) report errors and recommend methods for reducing uncertainty in SCAN data. Calibration equations were developed in the laboratory and in-situ for an Alfisol and a Vertisol. These two soils were also monitored over 18 months to 1 m depth with HydraProbes and a neutron moisture meter. Additionally, nine SCAN locations were sampled at three soil moisture conditions, field capacity, very dry and somewhere in between. Results showed root mean squared errors (RMSE) of 0.077, 0.051, and 0.035 m3m-3 for the default, lab, and in-situ calibrations for the Alfisol and 0.167, 0.077, and 0.045 m3m-3 for the Vertisol.

The data varied from 0.045 to 0.174 m3m-3 RMSE and 0.004 to 0.120 m3m-3 bias for individual SCAN sites. Soil properties of clay, pH, CEC, exchangeable cations, or bulk density did not explain trends in SCAN errors; however, a positive linear relationship between SCAN prediction errors and soil moisture was found. This study uniquely documents temporal and spatial variability in long-term soil monitoring networks in Texas and provides some documentation of errors to modelers and land use planners using soil moisture data for model evaluation.

DEDICATION

This thesis is dedicated to family and friends whom have been my role models and guides through this journey. Without them, my success would not be possible. I would like to specially thank my parents whose unconditional support pushed me to be the best I can be, and husband who stuck by me through thick and thin. Throughout the years I have been blessed to have wonderful, dedicated, and passionate teachers. They have set a new standard for anyone involved in education. Harryette and Jack Ehrhardt, my second family, taught me many things which have enabled me to be successful. Their love and compassion to everyone taught me that no matter whom you are and how successful you are everyone should be treated with respect, love, and compassion. Cristine Morgan, my second mom, has not only provided me with the tools to succeed as a soil scientist, but in life. Without her support, advice, and constant push to step out of my comfort zone, I might not be here today.

The most important thing that these wonderful people have taught me though is to face your fears and not let that stop you, to not look at the talents we wish we had but instead focus on the best we can be and appreciate our unique gifts.

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Contributors

This work was supervised by a thesis committee consisting of Professors Cristine Morgan and Jim Heilman of the Department of Department of Soil and Crop Science and Professor Georgianne Moore of the Department of Ecosystem Science and Management.

All other work conducted for the thesis was completed by the student independently.

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NOMENCLATURE

CEC	Cation exchange capacity
EM	Electromagnetic waves
FDR	Frequency domain reflectometry
GPR	Ground penetrating radar
NMM	Neutron moisture meter
NRCS	Natural Resources Conservation Service
RMSE	Root mean squared error
SCAN	Soil Climate Analysis Network
TDR	Time domain reflectometry
USCRN	United States Climate Reference Network
USDA	United States Department of Agriculture

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CHAPTER I

INTRODUCTION AND LITERATURE REVIEW

Measurements of soil moisture are used by many science disciplines and natural resource planners. For example, at the field scale, measurements of soil moisture are used in agriculture for irrigation scheduling, at the regional scale, these measurements are used for natural resource management such as drought forecasting, and at the continental scale, these measurements are used to better understand changes in land use and climate and test or validate models that simulate soil moisture and land-surface exchanges (Klein et al., 1997; Butler et al., 1999; Bratton et al., 2000; Robock et al., 2000). As a general rule, end users of soil moisture monitoring data generally do not discuss the uncertainty in these soil moisture measurements even though the strength of any conclusion based on these measurements depends on knowledge of the error or uncertainty. Regardless, these data are very much needed and currently used long-term monitoring networks for soil moisture continue to expand and be available for download on the internet (Soil Survey Staff, 2017).

To address the need of long-term soil moisture data, several long-term soil moisture monitoring networks throughout the United States have been established. A few examples of such networks are: Soil Climate Analysis Network (SCAN) (Soil Survey Staff et al., 2017), the United States Climate Reference Network (USCRN) (Bell et al., 2013; Diamond et al., 2013) and the Oklahoma Mesonet (Brock et al., 1995;

McPherson et al., 2007). These long-term soil moisture monitoring networks, however, do not report errors that maybe caused by site-specific soil property variation across location and depth, installation procedures, no instrument bias associated with the use of default manufacturer calibrations. The usefulness of these soil data could be improved by assessment of soil-specific or general uncertainty associated with the variability of soil properties.

These unaccounted errors are concerning to users of these monitoring networks, particularly in Texas because of the types of soils that are predominate across the state. Texas has many soils that are high in clay and many soils that have an abrupt texture change with depth. The high clay soils are unique because they change volume with moisture changes and hence can form cracks upon drying. These cracks might cause a contact loss with soil moisture monitoring equipment. Soils with an abrupt texture change have a different hydrology than the high clay soils; a very sandy soil over a very clayey soil might exaggerate biases associated with using factory calibrations due to a texture differences. Additionally, Texas soils can have wide variation in clay types which result in differences in specific surface area and cation exchange capacity, two soils with the same clay content but different mineralogies. Particularly, some high-clay soils of Texas are high in smectitic clays that shrink and swell causing loss of contact with soil moisture monitoring devices(Veldkamp and O’Brien, 2000; Hamed et al., 2006; Ojo et al., 2015; RoTimi Ojo et al., 2015).

With so many possible combinations of properties known to affect soil moisture measurements, the question of accuracy and or bias in the long-term monitoring networks arises. To address concern of errors of long-term soil moisture monitoring networks, this study aims to compare the manufacturer calibration to soil-specific laboratory and in-situ field calibrations, as well as evaluate error associated with manufacture calibration in representative soils of Texas. This study focuses on sites across Texas that are monitored by the SCAN network. Upon completion of this project, this project will allow for a comparison of manufacture calibration versus soil-specific calibration, estimate of error associated with Texas soils, and provide correction information for current SCAN sites.

The overall objective of this study is to quantify and understand the source of bias and/or error in soil moisture measurements for SCAN. My specific objective is to assess the spatial and temporal reliability and accuracy of soil moisture probes installed for soil moisture observation as well as provide estimations of the uncertainty of these probes across Texas soils. Accordingly, this research pursues answers to the following questions: (i) How different is a soil-specific calibration for soil moisture measurements using the HydraProbe SDI-12?, (ii) What is the level of accuracy of the SCAN soil moisture measurements between and within SCAN sites?, and (iii) Can the HydraProbe errors be corrected using knowledge of soil characterization data? The study findings will provide a basis for effective calibration procedures and provide quantitative results on the uncertainty of SCAN soil moisture data in Texas. Even though it focuses on the HydraProbe, the results will provide valuable guidelines for similar soil moisture probes and long-term soil moisture monitoring networks.

Literature Review

Long-term soil moisture monitoring networks are mostly used by researchers for development of soil moisture remote sensing missions as well as agricultural and environmental management, weather forecasting, and other associated endeavors (Cosh et al., 2016). These networks aim to provide real time continuous soil moisture data in a non-destructive method. A properly functioning network requires the ability to transmit the information in real time, log data measurements, and respond to changes in soil moisture. USCRN and SCAN achieve this functionality by using the Stevens Water HydraProbe. USCRN consists of 114 stations placed throughout the contiguous US in a wide range of vegetation such as grassland, desert, shrub land, and pasture as well as a range of soil textures from sandy loam to clay (Bell et al., 2013; Diamond et al., 2013). The Oklahoma Mesonet achieves this functionality by using a variety of soil moisture sensors. The Oklahoma Mesonet consists of 121 stations placed mostly on grasslands and is representative of soil variability across Oklahoma (Board of Regents of the University of Oklahoma, 2017).

In 1990, a plan was proposed to establish a national soil climate network to meet the growing demands of global climate change community, modelers, resource managers, soil scientists, ecologist, and others. In 1999, SCAN was established for agricultural, resource, and watershed management purposes to monitor soil climate. The SCAN network was installed and is maintained by the USDA NRCS. SCAN is currently composed of 218 stations across the U.S. and Puerto Rico. All stations within the network have a standard configuration with some variation upon user request. Data collected by SCAN include air temperature, relative humidity, wind speed and direction, solar radiation, barometric pressure, soil dielectric constant, bulk soil electrical conductivity, soil moisture, precipitation, and soil temperature at depths of 2, 4, 8, 20 and 40 inches which are approximately 0.05, 0.10, 0.20, 0.50, and 1.00 m at hourly intervals (Schaefer et al., 2007). These data are acquired remotely and available online at the NRCS website. Soil moisture, soil dielectric constant, bulk soil electrical conductivity, and soil temperature is collected by the Stevens HydraProbe. The Stevens HydraProbe is time-frequency domain reflectometry instrument.

Soil moisture measurement reflects the capture of rainfall, loss of water from evapotranspiration and drainage, and the movement of water through the soil profile. Several techniques exist for monitoring moisture. Measuring soil water content can be direct or indirect, destructive or non-destructive, and have different measurement volumes.

One of these methods is the gravimetric method. The gravimetric method measures the mass of water in soil. It involves obtaining the weight of a soil sample before and after drying at 105 ˚C. The gravimetric water content is the ratio of the mass of water in the sample to that of dry soil. The volume of measurement is limited only by ability to excavate, dry, and weigh the samples. More useful data includes the measuring the mass within a known volume of soil along with gravimetric moisture measurement so that the volumetric water content can be quantified. Volumetric water content is the ratio of the volume of water in the sample to that of the sample. The volume of the sample used for this measurement varies widely with soil coring devices, soil type, and sampling depth. Sampling depth depends on the needs of the information and ability to get an accurate volumetric sample. Samples are obtained by coring into the soil, which is destructive, difficult, and time consuming. Getting a representative volume sample without compacting or losing part of the sample requires extra care and sampling at an ideal soil moisture which varies according to soil type. Usually, the sample volume adds the most significant portion of error. In good conditions, the error associated with volumetric water content measurements is ± 0.5% (Topp and Ferre, 2002). Clearly the destructive nature of measurement makes long-term moisture monitoring by coring methods unfeasible as the sample area of interest can be eventually exhausted or highly disturbed. These methods are the most accurate to measure soil moisture and are generally used to calibrate non-destructive soil moisture measuring devices.

Another method is the neutron moisture meter (NMM), which is an indirect, nondestructive method for measuring soil moisture. It consists of a radioactive source that emits non-directional neutrons and a detector which measures thermalization of these neutrons by hydrogen in soil. Hydrogen atoms in water and in other soil constituents thermalize (slow down) high energy neutrons. The detector in the meter counts the slow neutrons. This rate of neutron count is a measure of the water content in the soil sample (Evett et al., 2003; Chávez and Evett, 2012). A count ratio is calculated by taking the measured neutron count rate in the soil and dividing by a standard neutron count rate done on site before soil moisture measurements. The count ratio is used in a calibration equation, which is usually a linear equation between count ratio and measured volumetric water content (Evett et al., 2003).

Depending on the quantity of moisture in the soil, a NMM can detect water in samples of radii ranging between 0.15 m (wet soil) and 0.50 m (dryer soil). A 0.05 m diameter access tube is generally installed to 1 to 3 m below the soil surface for depth-based reading. There are advantages and disadvantages to the relatively large volume of soil measured by a NMM. An advantage with measurements obtained using a NMM is the relatively low absolute error (Gee and Or, 2002). Disadvantages include difficulty in detecting discontinuity or sudden changes in gradients of water content that may be present. Automatic logging of soil moisture is not possible with NMMs since a person is required to be present throughout the process.

Another method is by installing soil moisture sensors. There are types of soil moisture sensors, each of which determine soil moisture with a different method. One of this methods is time domain reflectometry. Time domain reflectometry (TDR) is an indirect, nondestructive method for measuring and monitoring soil moisture. TDR instruments have an oscilloscope and a pulse generator. The pulse generator is connected to a waveguide which the pulse travels to the probe. The waveguide is generally a coaxial cable connected to the instrument; the probe consists of two to three inflexible electrodes. The oscilloscope or similar electronic system captures the reflected pulse at very small increments along the waveguide to create a waveform. The data logger controls the apparatus and interprets data from the TDR instrument. Calibration may be through a linear regression between pulse speed and volumetric water content or by using dielectric permittivity (Chávez and Evett, 2012). TDR accuracy is controlled by pulse rise time and receiver sampling rate.

Without calibration, TDR provides water content from 0 to 0.5 m^3m^{-3} with accuracy ranging from 0.01 to $0.02m^3m^{-3}$ (Huisman et al., 2001). Calibration includes a linear equation between pulse speed and volumetric water content or by using dielectric permittivity (Chávez and Evett, 2012). Limitations to TDR accuracy is the broad frequency and dispersal of the pulse as it travels through the waveguide and high sensitivity to change around probe tines (Evett et al., 2003; Furse et al., 2006). TDR instruments measure soil volumes ranging from $1x10^{-5}$ to 0.001 m^3 (Huisman et al., 2001). Because of the small measurement volume and importance of good contact around the probe, long-term data collected when the soil is at very low water content might have more error or a bias because soil may pull away from the sensor. TDR instruments are used in long term monitoring because data can be collected at regular time intervals by a data logger (Evett, 2003; Evett et al., 2009; Coopersmith et al., 2015).

Another method for a soil moisture sensor to determine soil moisture is frequency domain reflectometry. Frequency domain reflectometry (FDR) is an indirect, nondestructive method for measuring and monitoring soil moisture. FDR probes consist of an inductor-capacitor (LC) oscillation circuit that produces a high-frequency oscillating electric field. Once inserted into a dielectric medium, a relative dielectric constant is measured from frequency change and related to soil moisture content (Haibo et al., 2013). Essentially, FDR probes measure the capacitance of the dielectric medium. FDR probes have an advantage over TDR probes by being relatively less expensive and requiring lower power. Calibration of FDR probes may be through a linear regression between water content and frequency (Furse et al., 2006; Böhme et al., 2013; Haibo et al., 2013). FDR probe measurements can be influenced by soil characteristics such as texture and salinity.

Ground penetrating radar (GPR) systems are an indirect, nondestructive method to measure soil moisture. GPR systems work on the same principal as TDRs. However, they do not require direct contact with the soil and the probe. In a GPR, a transmitter produces pulses of high-frequency electromagnetic (EM) waves. A receiving antenna detects the impulses and measures them as a function of time. The depth penetration of GPR systems depends on their center frequency and electrical conductivity of the soil. GPR systems have high sensitivity to soil texture and electrical conductivity. For soils with low conductivity, the depth penetration at low frequencies (50 – 100 MHz) is up to tens of meters, and at high frequencies (450 – 900 MHz) less than ten meters. For high conductivity soils such as clay, the depths are less (Roth et al., 1992; Leao et al., 2010). Accuracy is highly variable ranging from 0.02 to 0.03 m^3m^{-3} depending on the frequency used (Huisman et al., 2001). The high sensitivity to texture limits the range of soils where the technique is useful. GPR sensors work best at soils with low conductivity and sandy texture (Huisman and Hubbard, 2003). GPR sensors do not measure the volume of soil moisture directly. Unlike TDR systems, GPR networks have large sensing volume. Therefore they can provide rapid and non-disturbing soil moisture measurements over extensive areas. The calibration equation relates the dielectric permittivity and texture with the volumetric water content (Persson and Berndtsson, 1998). GPRs are not used for long term soil moisture monitoring due to low depth penetrations.

The focus of this study is on the Stevens HydraProbe's calibration and accuracy, which is used in most long-term soil moisture monitoring stations (Brock et al., 1995; McPherson et al., 2007; Bell et al., 2013; Diamond et al., 2013; Soil Survey Staff et al., 2017). The HydraProbe is a FDR probe that measures soil water content, dielectric permittivity, electrical conductivity and soil temperature. The HydraProbe is composed of a tine assembly, a base plate and a body housing all electrical components. There are four tines measuring 4.5 cm long and 0.03 cm wide with three placed in an equilateral triangle formation and the fourth at the center. The HydraProbe uses the tines as a wave guide for a 50-MHz signal which is created by the probe body. The tines are inserted into a medium, and the probe measures electromagnetic wave behavior. This signal response is converted into dielectric permittivity (Stevens Water Monitoring Systems Inc., 2007).

The HydraProbe has a default factory calibration set to "loam" soils. A number of studies have found that high water contents and materials that fall outside of manufacturer calibration affect the accuracy of this calibration. As such, a soil-specific calibration has been suggested to improve the accuracy of measurements (Hornbuckle and Logsdon, 2006; Vaz et al., 2013; Burns et al., 2014; Ojo et al., 2015; RoTimi Ojo et al., 2015). Soil-specific calibrations have been performed and compared to the standard "loam" calibrations. One such calibration on a Vertisol found an improvement of RMSE from 0.129 to 0.014 (RoTimi Ojo et al., 2015), and in other fine-textured soils the "loam" calibration has been shown to over predict soil moisture, by over 0.05 m^3 m^{-3}

(Vaz et al., 2013). On the other hand, Kammerer et al. (2014) calibrate the HydraProbe for a loam soil and the calibration was found to be very similar to the factory calibration.

Seyfried et al. (2005) investigated laboratory-based HydraProbe calibrations for 34 soils that varied in texture. The quality of soil-specific calibrations compared to the "loam" calibration varied by 0.2 to 3%, but the quality was not dependent on clay content. Seyfried et al (2005) found that the calibration quality was correlated with dielectric loss, which is more associated with clay mineralogy than clay content. The properties of clay mineralogy that affect dielectric loss are surface area, cation exchange capacity.

Though there are papers in the literature that deal with HydraProbe calibration assessment in laboratory calibrations, one area that is poorly explored is how well the HydraProbe performs in the field and compares to other field measurements of soil moisture.

CHAPTER II

MATERIALS AND METHODS

Site Descriptions

This project has two primary measurement components; one is temporal assessment of the behavior of two monitoring sites, and the second is a spatial, state-wide assessment of nine of fourteen SCAN sites across Texas.

The temporal assessment component of this project was established at the O.D. Butler Jr. Animal Science Complex, which is managed by the Department of Animal Science at Texas A&M University. This complex contains soils that represent four of the five alluvial terraces of the Brazos River and includes the Brazos river floodplain. At the O.D. Butler Complex, two soils, Silawa and Ships, were selected for observation with FDR sensors and NMM for monitoring. Each soil was sampled by horizon and soil characteristics including particle size analysis by pipette (Gee and Or, 2002), CEC, and cations. Analyses were performed by the Texas A&M Agrilife Soil Characterization Lab (Texas A&M Agrilife, 2016).

The Silawa soil series is located on an old alluvial terrace of the Brazos River, N 30.562365 and W 96.410238. Silawa is a very deep, well drained, moderately permeable soil developed from old alluvial deposits ranging from sandy to loamy textures. Silawa is classified as a fine-loamy, siliceous, semiactive, thermic Ultic Haplustalfs (Soil Survey Staff, 2013). This soil was chosen because of its sandy surface texture and abrupt

Table 1. Soil characterization data for the Silawa and Ships soil series.

Soil Series and Horizon	Horizon Depth	Texture Class	Clay Content	Organic Carbon	CEC	pH
	——cm——		————————	%————————	meq100 g^{-1}	
Silawa Ap and E	0-33	Loamy fine sand	4.1	0.33	2.6	4.8
Silawa Bt	33+	Sandy clay	42.9	0.36	18.8	5.0
Ships Ap	0-16	Silty clay	58.6	0.94	41.1	7.9
Ships Bss	16-110	Clay	63.4	0.73	44.2	7.9

textural change to a sandy clay in the subsurface, argillic horizon (Table 1). The horizon boundary between the sandy E and clayey Bt horizon has a wavy topography and abrupt distinctness. The oven-dry bulk density is 1.56 g cm^{-3}. The vegetation is dominated by perennial pasture grasses, and the slope is 1 to 3%, located on the summit. The Bt horizon has strongly developed prismatic structure with sand coats around the prisms of the upper Bt. These sand coats indicate that the soil prisms shrink enough when dry to allow the sands from the overlying sandy soil to fill in the shrinkage cracks.

The second site contains the Ships soil series, located on the flood plain of the Brazos River, N 30.547461 and W 096.413080. The Ships soil is a very deep, moderately well drained, slowly permeable soil, developed from clayey textured alluvium. The classification of this series is very fine, mixed, active, thermic Chromic Hapludert (Soil Survey Staff, 2013). The soil survey indicates that Ships can form gilgai microtopography; however, none is clearly present at the site. The Ships soil was selected for this study because of its high clay content and shrink swell behavior. The Coefficient of Linear Extensibility (COLE) of Ships classifies in the high shrink-swell class. The Ships clay has mixed minerology that is composed of mica, montmorillonite, vermiculite, and to a lesser extent, kaolinite. The slope is 0 to 1%. The horizon transition between the surface horizon and subsurface is a smooth abrupt boundary. The oven-dry bulk density is 1.35 gcm^{-3}. These soil characteristics were obtained from the Texas A&M University Soil Characterization Laboratory. The vegetation of the site is grazed pastureland with mixed annual and perennial grasses.

Soil-specific Lab Calibration of HydraProbes

There are several proposed methods to lab calibrate soil moisture sensors (Gabriel et al., 2010; Kinzli et al., 2012; De Carteret et al., 2013; Burns et al., 2014; Ojo et al., 2015; Matula et al., 2016; Provenzano et al., 2016; Gasch et al., 2017). For this study, a modified version of a calibration procedure by Meter was used (Cobos and Chambers, 2010). First, we collected 15 cores to 1.2 m deep from each soil using a Giddings hydraulic soil sampler. Each soil core was separated into a surface and subsurface horizon. The cores were air dried at 60°C, ground, and passed through a 0.002-m sieve. Once ground, a volume of 328.51 mL was subsampled and mixed to six volumetric water contents to represent a range in volumetric water contents from wilting point to field capacity. Bulk density values include the following: 1.5 g cm^{-3} for the sandy Silawa surface (A and E), 1.2 g cm^{-3} for the clayey Silawa subsoil (Bt), and 1.2 g cm^{-3} for all of Ships horizons (Ap and Bss).

Each sample was prepared by gradually pouring water into the sample then covering the container with parafilm, and allowing it to sit for approximately an hour. Then the sample was poured onto a tray and lightly mixed by hand to assist an even distribution of water throughout the soil. After preparation, the sample was placed in the refrigerator to equilibrate throughout and to reduce water loss via evaporation.

Next, each sample was packed to the pre-calculated bulk density using a drop weight into a pvc pipe. Once packed, each HydraProbe was inserted into the sample, and dielectric permittivity was recorded from the sensor. Two to three dielectric permittivity readings were recorded for each probe and soil moisture to determine sensor stability.

This step was repeated for each prepared water content. A volumetric subsample from the mixed soil sample was oven dried to verify water content. Linear regression was used to relate the square root of dielectric permittivity and volumetric soil water content. An ANCOVA analysis was used to test whether individual calibration equations for each probe were significantly different. The ANCOVA was run in Matlab (Matlab R2017a, The Mathworks, Inc.) using the anova function (Chatterjee and Hadi, 2006). Inter-sensor variability was calculated by subtracting the measured soil moisture from each calculated soil moisture and then averaging the differences.

Field Calibration of Neutron Moisture Meter

A neutron moisture meter (NMM) was used at the Ships and Silawa sites as a comparison to the HydraProbe and to nondestructively monitor soil moisture over time. The NMM was field-calibrated in-situ. For calibration, an aluminum access tube was installed to 1.2 m depth by auguring a hole with a hydraulic soil coring machine. The aluminum access tube was inserted into the hole with a snug fit. The NMM counts were recorded in 0.10 m increments from 0.10 m to 1.10 m depths, twice, by taking counts while lowering and raising the source. After collecting NMM counts, four soil cores were collected within the immediate vicinity of the installed access tube. Each core had a 0.09 m diameter and was cut into 0.10 m increments starting at 0.05 m and ending at 1.15 m; the segments were weighed at field moisture and after oven drying at 105°C for several days. Gravimetric water content was converted to volumetric water content using the volume of each segment and dry soil mass. A regression was created to test the correlation strength between count ratio and volumetric water content using the average of two count ratios for each depth (counts/standard) and volumetric water content representing the average of four cores. Regressions were performed in Matlab using the polyfit function (Matlab R2017a, The Mathworks, Inc.). Surface and subsurface NMM equations were created.

The NMM calibration was performed in the field and was specifically related to texture, one for the sandier textured soil and one for clayer textured soil (Fig. 1). A different calibration equation for the surface (<0.30 m) was also created to account for the NMM accuracy at shallow depths due to escaping neutrons near the surface (Stone et al., 1955; Graecen and Hignett, 1979; Williamson and Turner, 1980; Evett et al., 2003; Tokumoto et al., 2011). The RMSE for the neutron calibration equations are between 0.008-0.039 m^3m^{-3} (Table 2). RMSE increased as clay increased and between subsoil and surface. The Ships and Silawa soils have vertic properties, possibly leading to higher error due to escaping neutrons through cracks. Each NMM calibration equation was tested against one another and at the different depths using ANCOVA. There was no significant difference (p-value < 0.001, data not shown) between the two NMMs, depths, or soil. Even though there was no significant difference between NMM calibration equations, separate calibration equations for each NMM by soil series and depth were used (Table 2), to increase soil moisture measurement accuracy (Evett et al., 2003, 2006, 2009).

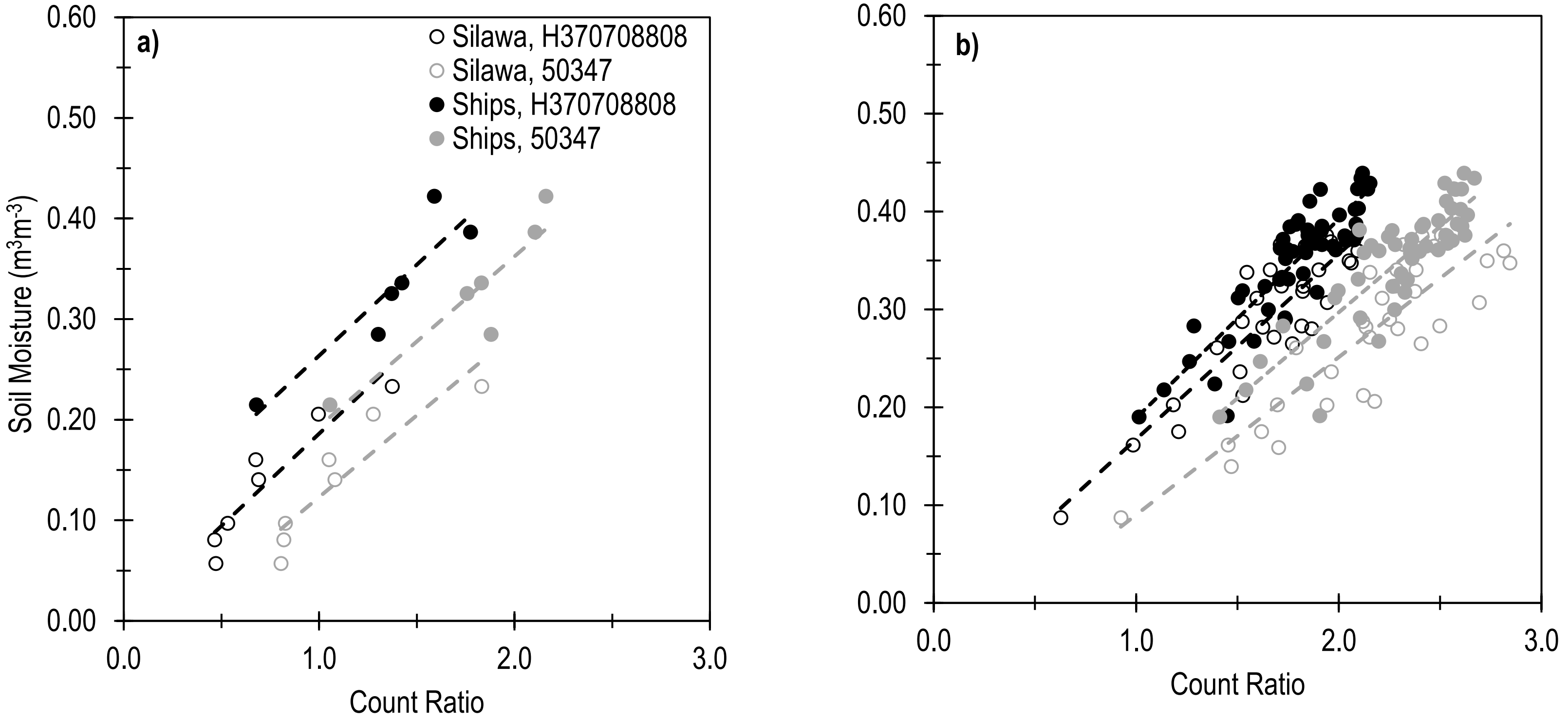

Figure 1. Soil specific neutron moisture meter (NMM) calibrations performed in-situ for two probes which are identified by their serial numbers. Two depths are calibrated, a) 10 cm depth and b) a 20 to 110 cm depth for both Silawa and Ships soil series. Regression results are presented in Table 2.

Table 2. Root mean squared error (RMSE) and the number (n) of data points for each regression of the two neutron moisture meter calibrations (meters are identified by serial number) for each soil series and depth.

Soil Series with Corresponding Depth	Regression Equations		RMSE		
	H370708808	50347	H370708808	50347	n
——— cm ———			——— m^3m^{-3} ———		
Silawa 10	$y = 0.183x + 0.003$ $r^2 = 0.87$	$y = 0.163x - 0.040$ $r^2 = 0.84$	0.022	0.008	7
Silawa 20 -110	$y = 0.189x - 0.022$ $r^2 = 0.78$	$y = 0.161x - 0.071$ $r^2 = 0.76$	0.039	0.014	39
Ships 10	$y = 0.181x + 0.083$ $r^2 = 0.84$	$y = 0.169x + 0.024$ $r^2 = 0.83$	0.027	0.017	7
Ships 20 -110	$y = 0.203x - 0.014$ $r^2 = 0.78$	$y = 0.176x - 0.054$ $r^2 = 0.76$	0.030	0.021	57

Installation of HydraProbes and Monitoring

HydraProbes were installed in March and April 2016 at the Silawa and Ships site, respectively. For installation, a small pit was hand-dug to 1.1 m deep using a shovel and posthole digger to minimize disturbance. Two HydraProbes were horizontally installed at each of the following depths: 0.10, 0.20, 0.30, 0.50, and 1.00 m. At the Ships site, the probes were installed in triplicate at the 0.1 and 0.2 m depths, each about 0.20 m apart from each other. After each probe was installed, the hole was backfilled using soil from the appropriate depth and tamped to return to approximate bulk density. The area was fenced off to avoid disturbance from sheep and cattle. After installing the HydraProbes, four aluminum access tubes were installed within 0.5 m of the hand-dug hole for soil moisture monitoring by the NMM.

Over the next 18 months, HydraProbe readings were collected approximately every 2 weeks. NMM measurements were taken at the access tubes installed at each site and were acquired using 30 second count times. A total of 20 sets of NMM measurements were acquired over the 18 month period. Soil moisture measurements from the HydraProbe and the NMM were compared using linear regression to develop a field in-situ calibration. Additionally, an analysis of dry-down and wet-up periods was done to determine if hysteresis a trend existed.

SCAN Site Description

There are 14 SCAN stations located throughout Texas (Soil Survey Staff et al., 2017). For this study, 9 out of the 14 were considered. These nine were selected based on long-term data availability and ability to drive to the site within one day (Fig. 2). The stations are located in Beaumont, Kingsville, Knox City, Riesel, San Angelo, Stephenville, Uvalde, Vernon, and Weslaco, Texas. These sites are primarily in very deep farmland soils and have relatively high water holding capacities. Six of the sites are identified as Mollisols and four of those have vertic properties. One of the sites is classified as a Vertisol; hence five of the sites have high shrink-swell potential. Two sites are Alfisols, Palustalfs specifically, meaning they have well developed sandy A and E horizons and a well-developed argillic horizon that decreases in clay with depth (Table 3 and 4). The soils at these SCAN site are well represented by the Ships and Silawa monitoring sites.

SCAN Data Collection

Soil cores were collected at the SCAN sites to provide ground truthing of the currently installed HydraProbes that contribute to the SCAN. The HydraProbes were installed at 0.05, 0.10, 0.20, 0.50, and 1.00 m depths and use the standard factory calibration for “loamy soil” as reported on the SCAN website (Soil Survey Staff et al., 2017). There is no duplication of sensors by depth. Soil moisture data is automatically logged hourly. At each site, five cores were collected for measuring volumetric water content and on three different dates to capture a range of soil moistures. Each soil core was located approximately 5 to 15 m from the SCAN installation and collected to 1.20 m or to the depth of a coring-restrictive horizon. The soil cores had a diameter of 8.89 cm and were cut into 10 sections selected to surround the depth of the HydraProbe

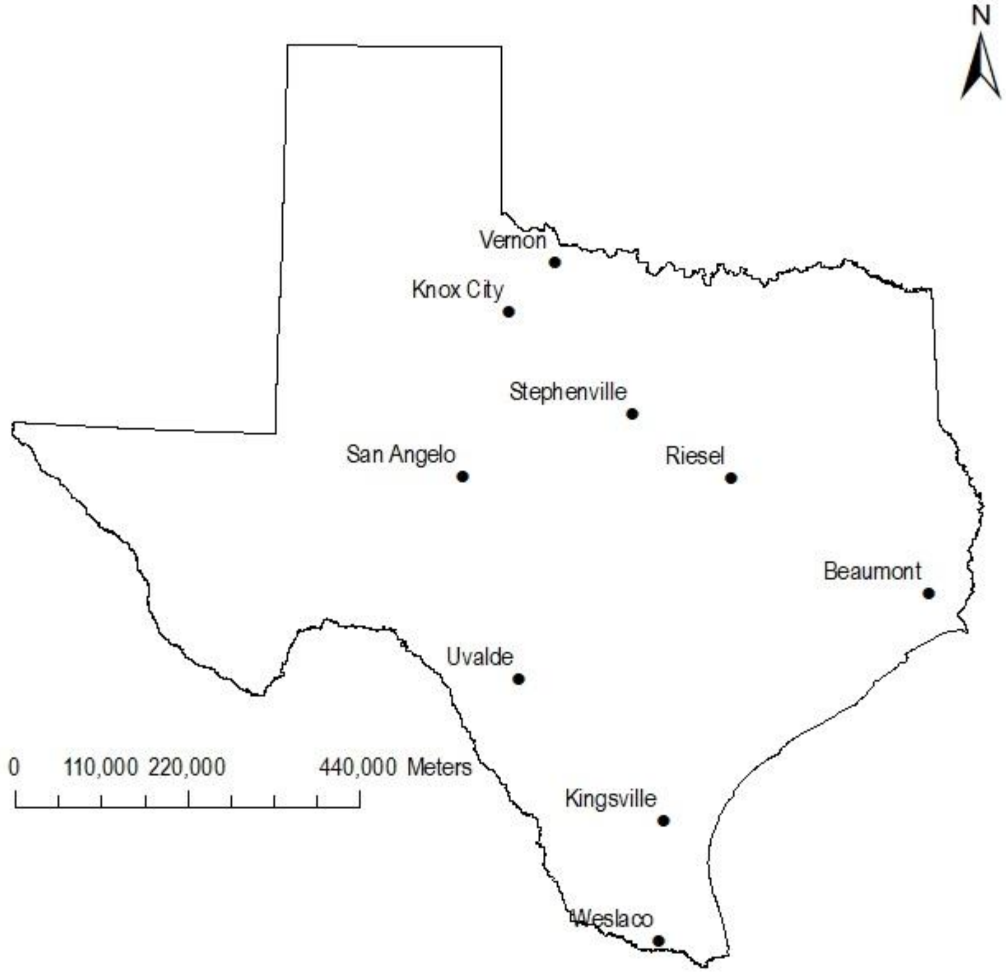

Figure 2. Location of nine Soil Climate Analysis Network (SCAN) sites across Texas, USA.

Table 3. Soil series name, taxonomic classification, and profile clay content, for each of the nine Soil Climate Analysis Network (SCAN) in this study (National Cooperative Soil Survey).

Site	Soil Series	Taxonomy	Depth 5	10	20	50	100
			cm				
			Clay Content				
			%				
Beaumont	Labelle	Fine, smectitic, hyperthermic oxyaquic Vertic Argiudoll	15.1	15.1	15.1	20.1	31.1
Kingsville	Cranell	Fine, smectitic, hperthermic Vertic Haplustoll	24.4	22.8	23.7	27.8	31.6
Knox City	Altus	Fine-loamy, mixed, superactive, thermic Pachic Argiustoll	12.1	14.2	14.2	22.8	13.7
Riesel	Houston Black	Fine, smectitic, thermic udic Haplustert	56.6	56.6	57.9	61.0	61.6
San Angelo	Angelo	Fine, mixed, superactive, thermic Pachic Argiustoll	39.1	39.1	41.0	44.4	39.6
Stephenville	Windthorst	Fine, mixed, active, udic Paleustalf	10.9	10.9	10.9	39.9	16.7
Uvalde	Knippa	Fine, mixed, superactive, thermic Vertic Calciustoll	45.9	45.9	46.2	48.8	39.8
Vernon	Wichita	Fine, mixed, superactive, thermic Typic Paleustalf	24.6	25.0	31.9	36.4	45.2
Weslaco	Hidalgo	Fine-loamy, mixed, active, hyperthermic Typic Calciustoll	20.6	20.6	18.8	21.1	23.3

Table 4. Soil series name and inorganic carbon content for each of the nine Soil Climate Analysis Network (SCAN) in this study (National Cooperative Soil Survey).

Site	Soil Series	Depth 5	10	20	50	100
		cm				
		Calcium Carbonate Equivalent				
		%				
Beaumont	Labelle	0	0	0	0	1
Kingsville	Cranell	0	0	0	0	12
Knox City	Altus	0	0	0	0	3
Riesel	Houston Black	19	19	15	15	15
San Angelo	Angelo	11	11	11	12	48
Stephenville	Windthorst	0	0	0	14	10
Uvalde	Knippa	27	27	28	30	54
Vernon	Wichita	0	0	6	12	13
Weslaco	Hidalgo	2	2	2	9	14

installations with larger intervals where there is no probe installed; 0.00 to 0.07, 0.07 to 0.15, 0.15 to 0.25, 0.25 to 0.40, 0.40 to 0.50, 0.50 to 0.60, 0.60 to 0.75, 0.75 to 0.90, 0.90 to 1.00, and 1.00 to1.10 m. Upon collection, each core was placed in a paper bag and a plastic bag during transport to the lab to prevent water loss. In the lab, each core section was weighed moist and re-weighed after oven drying at 105°C for several days. Gravimetric water contents were converted to volumetric by using the volume and dry mass of each core segment. The final volumetric water content by depth increment was calculated by taking an average of the five cores. Water contents that were more than two standard deviations of from the average were removed from the average, assuming the collection of the estimated core volume was in error. All removed data had reasonable gravimetric moisture but unreasonable bulk densities. These volumetric water contents, by depth were compared to their corresponding HydraProbe measurements for the day by using regression analysis. Residuals of these regressions were plotted against

HydraProbe measured clay content and soil moisture to assess potential causes in HydraProbe error.

CHAPTER III

RESULTS AND DISCUSSION

Soil-Specific Lab Calibration of HydraProbe

Using a soil-specific laboratory calibration with 22 HydraProbes, the inter-sensor variability was found to be consistent with the manufacture reported inter-sensor variability. The average inter-sensor variability for the HydraProbe in our experiment was 0.01 m^3m^{-3}. Others have also shown inter-sensor variability to be relatively small (Seyfried et al., 2005; Burns et al., 2014; Kammerer et al., 2014; Coopersmith et al., 2015; Wilson et al., 2016). This conclusion is supported by our soil-specific laboratory calibrations, where a single-soil calibration equations produced using different HydraProbe sensors were found to be not significantly different (p-value <0.001; data not shown). Hence soil-specific lab calibrations reported in the following results are based on soil type only, assuming sensors are interchangeable.

Soil-specific lab calibrations were significantly different from the default factory “loam” calibration equation. The comparison between the soil-specific lab calibration and that of the default “loam” calibration primarily varied according to clay content (Fig. 3). The sandy soil, Silawa A and E, had a larger slope, and the clayey soils had a smaller slope than the default factory calibration equation. The soil-specific lab calibration for the two clayey soils (Silawa Bt and Ships A and Bss) were quite similar, and one regression for both soils would provide similarly accuracy; however, statistically the

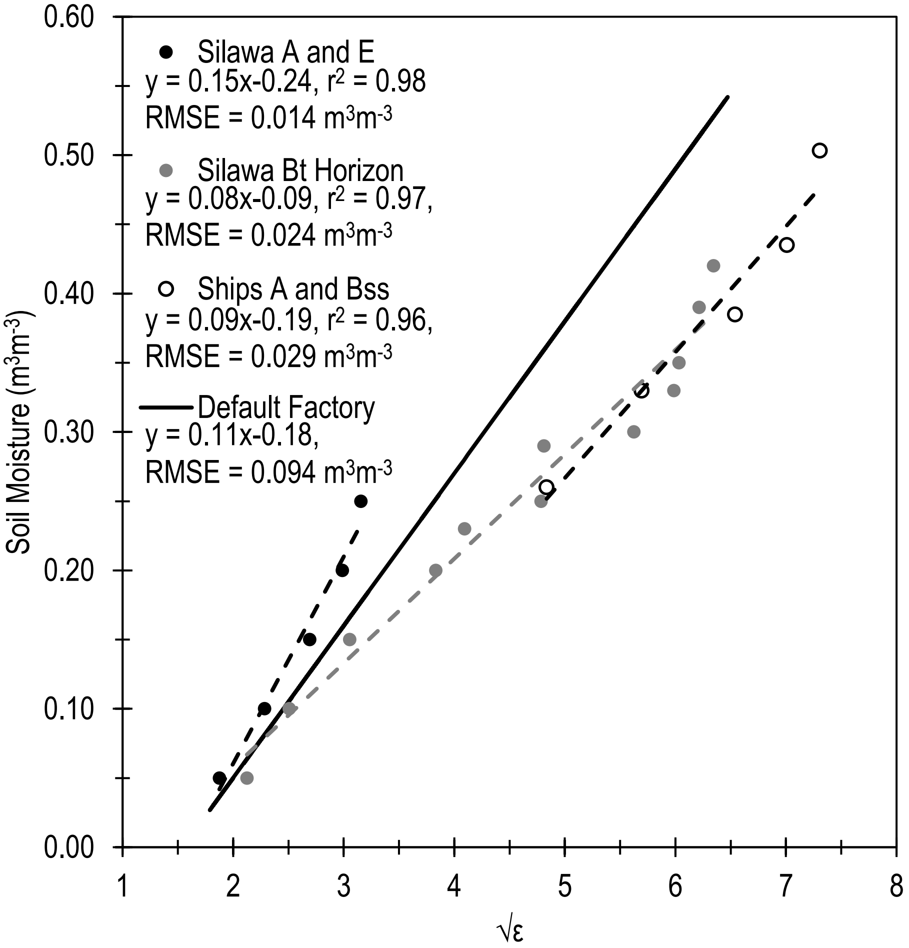

Figure 3. Soil-specific linear regression of square root of real dielectric permittivity (√ε) and soil moisture measured with the HydraProbe compared to the default factory calibration. Soil horizons grouped by clay content and soil series. Equations provided are significantly different from each other at α = 0.001.

regression lines for both soils are different (p-value<0.001). The slight difference may be because of different mineralogies or other soil property characteristics. Silawa is primarily smectitic and Ships has a mixed clay minerology. The sandy soil calibration (Silawa A and E) has a steeper slope and starts to differ from the default factory calibration at about 0.20 m^3m^{-3}. The opposite occurs with the clayer textures; Silawa Bt and Ships water contents were overestimated by the default calibration. The Silawa Bt calibration begins to differ from the default factory calibration at about 0.15 m^3m^{-3} volumetric water content. Gabriel et al. (2010) and Rotimi Ojo et al. (2015) report similar trends in slope and soil texture. Therefore to have a more accurate measure of soil moisture that is closer to an accuracy goal of 0.04m^3m^{-3}, which is discussed by SMOS research, a soil-specific calibration should be applied (Entekhabi et al., 2010; Kerr et al., 2010).

Soil moisture estimations using a soil-specific lab calibration in comparison to the default factory resulted in a range of errors. The RMSE of the soil-specific calibrations were 0.014 m^3m^{-3} for Silawa A and E, 0.024 m^3m^{-3} for Silawa Bt, and 0.029 m^3m^{-3} for Ships. The RMSE of the default factory equations for all the soils was 0.094 m^3m^{-3} (Fig. 3). These differences between default and soil-specific calibrations matter most when the soils are wetter. The default factory calibration underestimated soil moisture by 0.014 m^3m^{-3} for the loamy sand, Silawa A&E, and overestimates soil moisture by 0.027 m^3m^{-3} for the clayer soil, Bt and Ships horizons. For the loamy sand, Silawa A and E, the default factory and the soil-specific calibration are very close in estimating soil moisture, but as the soil moisture increased and clay content increased

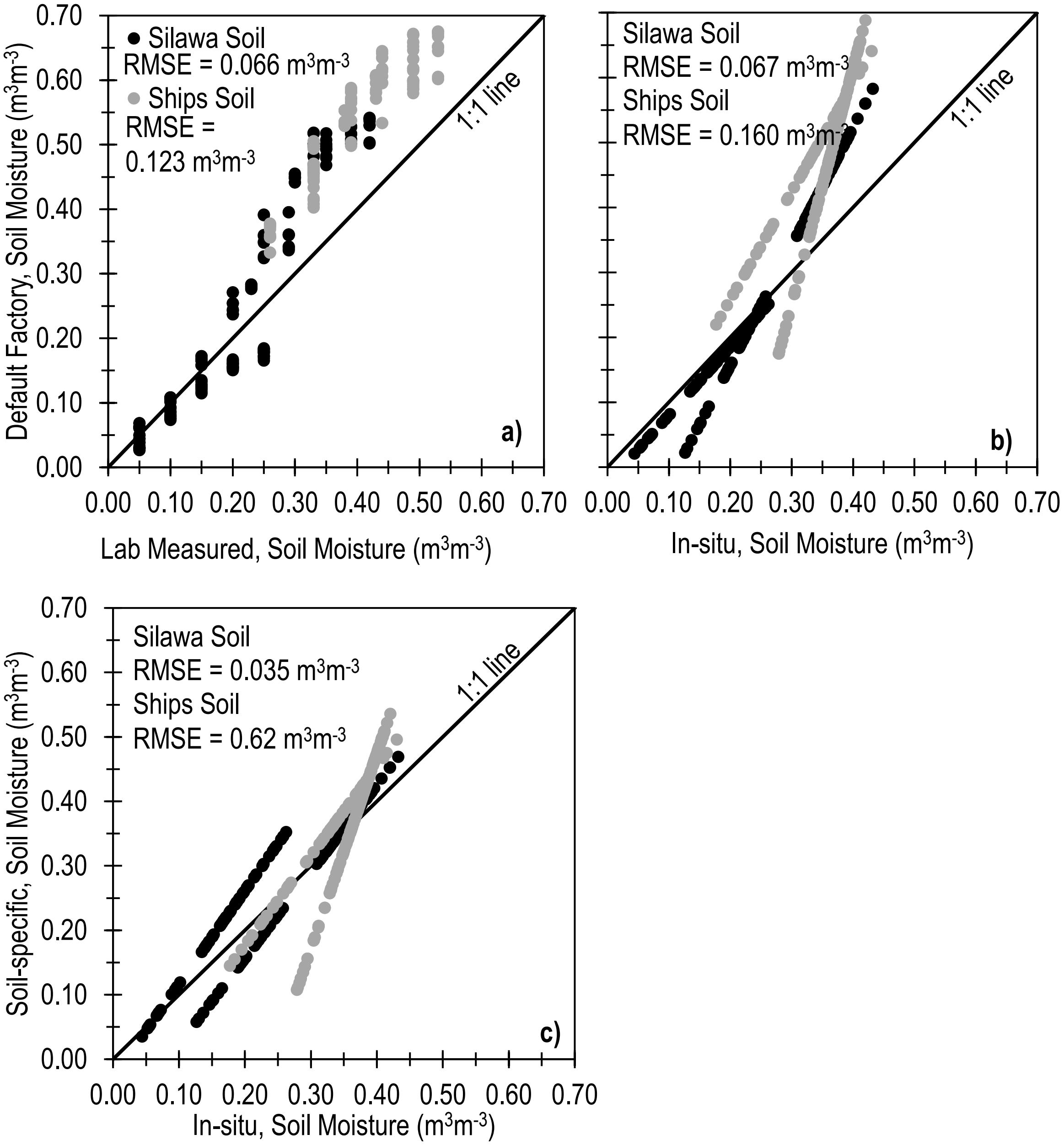

Figure 4. A comparison of predicted soil water contents of the default and the soil-specific lab calibration, the default and the in-situ calibration, and the soil-specific lab calibration and in-situ calibration of the HydraProbe.

the default factory overestimated soil moisture (Fig. 4a). Cosh et al. (2016), RoTimi Ojo et al. (2014), and Burns (2014) found applying a site-specific calibration reduced soil measurement error and reported similar RMSE to our experiment. RoTimi Ojo et al. (2014 and 2015) also reported a similar trend and RMSE improvement to our clayey texture soil-specific laboratory calibrations. This means, default factory calibration is useful to monitor trends and approximate soil moisture, but not so useful for accurate soil moisture measurement.

In-Situ Calibration of the HydraProbe

Soil-specific lab calibration of the HydraProbe has been intensively researched; however, the feasibility and accuracy of an in-situ field calibration of the HydraProbe using the NMM has not yet been explored (Kinzli et al., 2012; De Carteret et al., 2013; Burns et al., 2014; Kammerer et al., 2014; Matula et al., 2016; Provenzano et al., 2016). For in-situ calibration, linear regression equations were developed using the square root of real dielectric permittivity, a measurement parameter from the HydraProbe, and the in-situ soil moisture, measured with the soil-specific calibrated NMM (Fig. 5). The in-situ calibration equations of the HydraProbe were developed individually from NMM calibration equations from Fig. 1. The equations presented in Fig. 5 were found to be significantly different from each other and from the soil-specific lab calibration equations ($p\text{-value}<0.001$). For each case, the in-situ calibration has a smaller slope than the soil-specific lab calibration. Similarities between the soil-specific lab calibration and

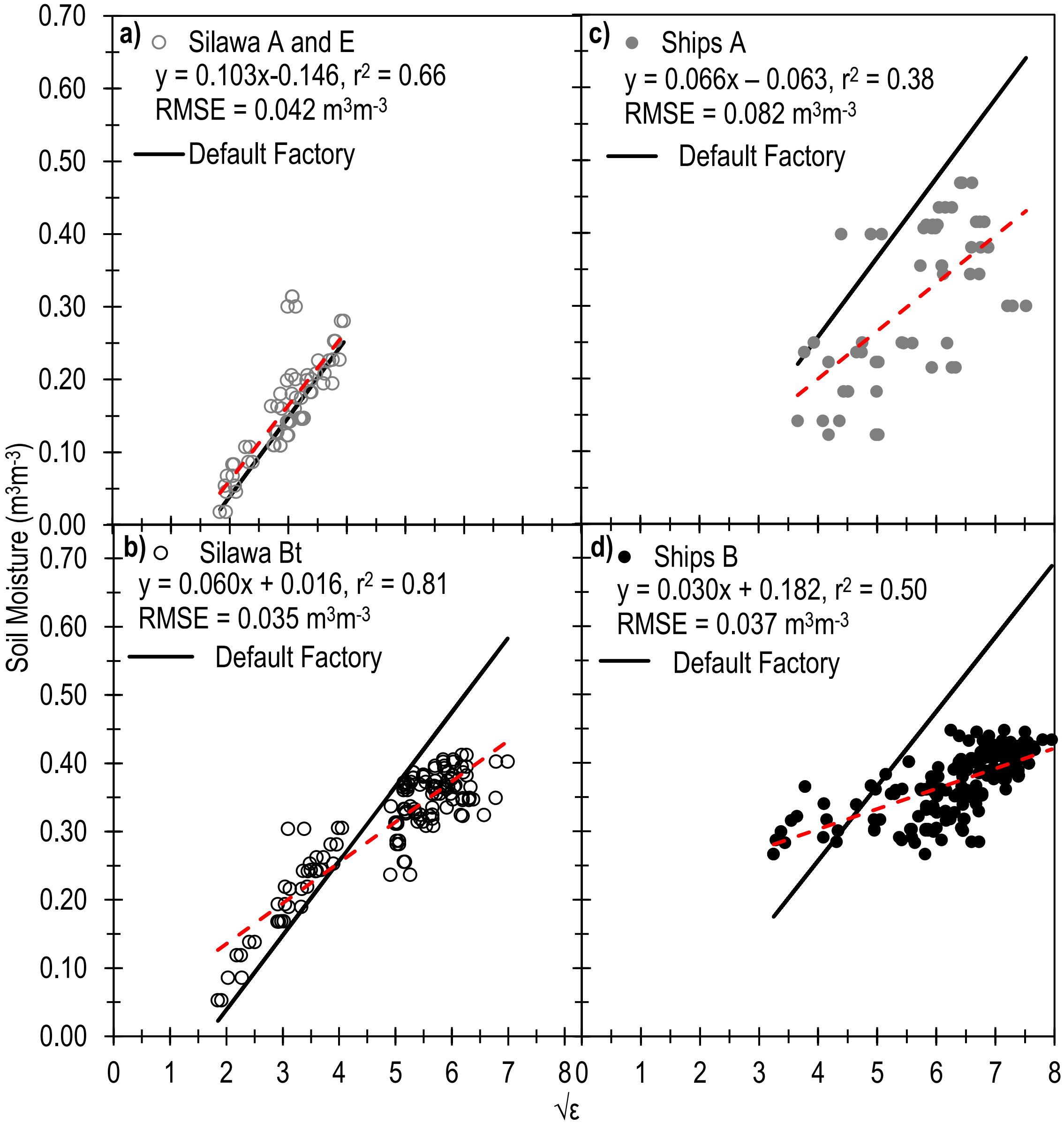

Figure 5. In-situ calibration of the HydraProbe by regressing the square root of real dielectric permittivity (√ε) to volumetric soil moisture as measured with the neutron moisture meter (NMM) (regression displayed by dashed red line). The default factory (bold black line) calibration is displayed for comparison.

the in-situ calibration do exist. For example, similar to the soil-specific lab calibration, the sandy Silawa A and E in-situ calibration has a steeper slope and tighter data points about the regression compared to calibration equations of the clayeyer soils. The RMSE values of the in-situ calibration of Silawa (0.042 and 0.035 m^3m^{-3}) are higher than the soil-specific lab calibration (0.014 and 0.094 m^3m^{-3}). The error and scatter increase as soil moisture increases in the clayer soils, which results in not capturing the range of soil moisture very well. Above 0.25 m^3m^{-3}, the relationship between soil water content and dielectric permittivity has a lot of scatter for both Silawa and Ships subsurface soils (Fig. 5). This scatter is more predominant in Ships than Silawa. Ships has 20% more clay than Silawa throughout the profile and variable void space from more shrinking and swelling both of which may account for the poorer calibration results. Figure 5c shows what is likely a result of cracking and variability in void space, compared to Fig. 6d. The RMSE for Ships for the field is 0.060 m^3m^{-3} and the soil-specific lab RMSE was 0.029 m^3m^{-3}. In comparison to the soil-specific lab calibration, the in-situ calibration has greater error; however the in-situ calibration is closer to the NMM soil moisture measurements; of course the better fit is expected because the NMM measurements are used in the calibration. The gain from performing an in-situ calibration is minimal, and the soil-specific lab calibration achieves a greater range of soil moisture for developing a linear relationship. Therefore, we think the lab calibration is the preferred method. However, another interesting result of the in-situ calibration is the effect of the measurement volume. The HydraProbe has a very small measurement radius (2.1 cm) while the NMM has a measurement radius of about 20 cm in very wet soils and rarely greater than 30 cm,

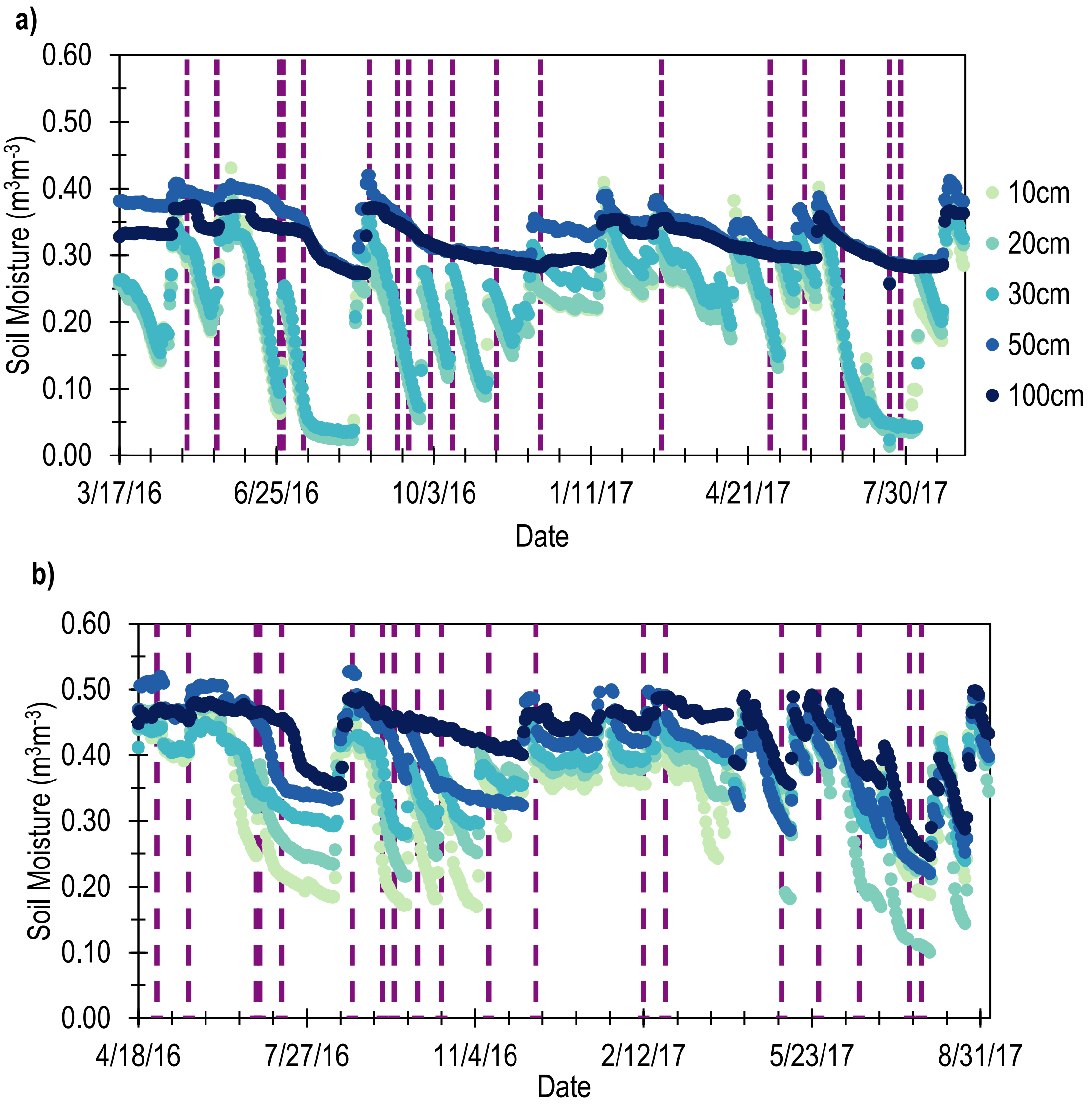

Figure 6. HydraProbe soil moisture over time for both soils, a) Silawa b) Ships over an 18 month period. Purple dashed lines indicate occasions at which neutron moisture meter measurements were taken.

except in extremely dry sandy soils (Grant, 1975). One possible reason HydraProbe measurements vary while the NMM measurements do not (see Fig. 7d) is the difference in the amount of soil being measured. Small changes in moisture and contact can make a larger difference for the HydraProbe. Our results are in agreement with Kinzli et al. (2012) who developed a field calibration using gravimetric soil moisture and observed a similar trend; in-situ calibration worked well for sandy soil, but at higher clay content and soil moisture, clusters occurred.

Assessment of HydraProbe at Two Monitoring Sites

To evaluate the performance of the HydraProbe and each of the calibrations over time, two monitoring sites were established, one each at the Silawa and Ships sites. The monitoring data exhibited normal wet-up and dry-down behavior, which corresponded to rainfall and winter/summer seasons (Fig.7). When analyzed separately, the wet-up and dry-down periods had no discernable pattern that necessitated a separate calibration over either period. Occasions when neutron moisture measurements were taken are also illustrated by purple dashed lines in Fig.7. In general, with the soil-specific lab calibration, the HydraProbe performed well in all depths of the Silawa soil, and seemed rather insensitive to water content fluctuations in the Ships (Fig. 6). For comparison HydraProbe results using the default factory calibration and the in-situ calibration are also shown (Fig. 6a and 6d). For the Ships soil series, water content is overestimated by the HydraProbe default calibration. A soil-specific lab calibration reduces the error by

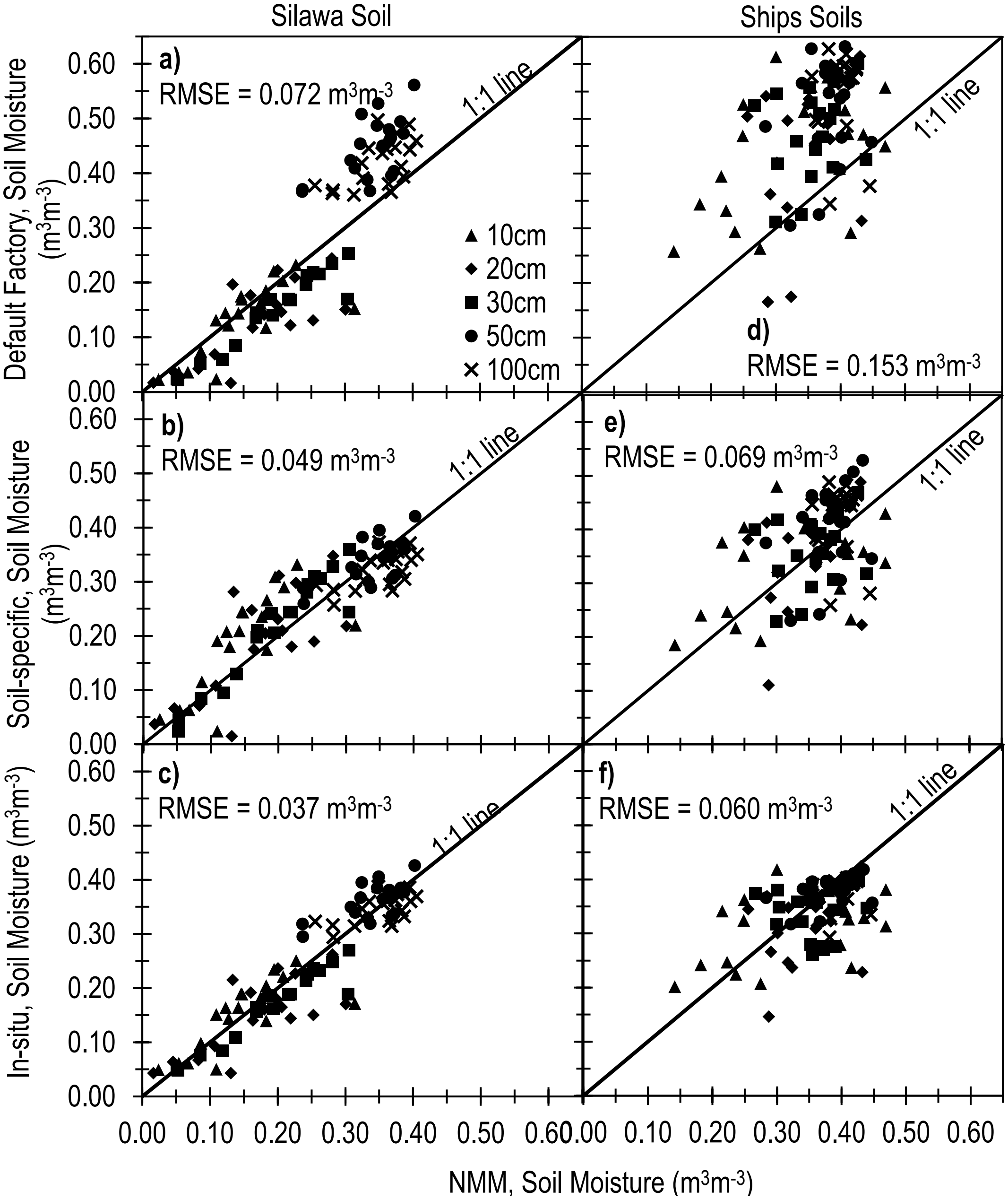

Figure 7. Soil moisture as measured with neutron moisture meters (NMM) in comparison to HydraProbe measurements using the default factory calibration, soil-specific lab calibration and in-situ calibration for each soil series. HydraProbe measurements represent 0 to 100 cm depths and a time span of 18 months.

more than half compared to the default factory calibration. At drier water contents, more variation exists in soil moisture measurement with the NMM, than is captured by the HydraProbes. This insensitivity may be from the HydraProbe losing contact in soils with vertic properties. In the Silawa, the data more closely follow the one-to-one line relative to the Ships soil. The soil-specific lab calibration agrees with the NMM soil moisture for the sandy Silawa A&E horizon, but for the clayer Silawa Bt, soil moisture is overestimated with the soil-specific lab calibration. In general, by using a soil-specific lab calibration as opposed to the default factory calibration, error is reduced and the HydraProbes capture the range in soil moisture.

In-situ calibration should perform the best in comparison to the soil specific lab calibration, because the NMM measurements were used in the in-situ regression calibration. Water content determined with the in-situ soil calibration better captures the range in water content. Overall the data scatter with the in-situ calibration is reduced, especially in the Ships soil, in comparison to the soil-specific lab calibration (Fig. 6). In the Silawa soil series one set of outliers disappear with the use of the in-situ calibration, and less bias is apparent with sensor depth. In both the soil-specific and in-situ calibration no trend in bias or error occur with depth (Fig. 6b and 6c). In the Ships soil, some of the error does appear to be related to soil depth. At the surface, 10 to 20 cm, and below 0.30 m^3m^{-3}, scatter is apparent in HydraProbe soil moisture measurements. For a clay soil, 0.30 m^3m^{-3} is dry corresponds with soil cracking (Neely, 2014) and is nearing permanent wilting point (Rawls et al., 1992). We suspect that the measurement volume of the HydraProbe probes is problematic for these soils during cracking. After rainfall, the HydraProbe reports a change in water content, but the NMM does not, probably due to different measurement support.

The in-situ calibration yielded the lowest error as it captured natural soil moisture cycles, soil variability associated with intactness and cracking, but only with a slight improvement over the soil-specific lab calibration. The soil-specific lab calibration captures a larger range in soil moisture estimates than the in-situ calibration but not a tighter fit to in-situ NMM measurements.

SCAN

Soil moisture for the Soil Climate Analysis Network (SCAN) is monitored using the HydraProbes. Because the results of our two monitoring sites indicated an improvement by soil-specific lab calibration, performance was evaluated for the SCAN HydraProbes for the state of Texas, with a Texas-wide field calibration in mind. For this evaluation and potential calibration, we compared each HydraProbe soil moisture measurements at moist and dry field soil condition to an average of 5 soil moistures determined by the volumetric core method. The soils varied in clay content and geography (Table 1). Results indicate an overestimate of water content by the HydraProbes compared to core soil moisture especially as moisture content increased (Fig. 8). Results are consistent to the findings from our soil-specific lab calibrations and from the two monitoring sites. In general, the probes overestimate soil moisture especially over 0.15 m^3m^{-3}.

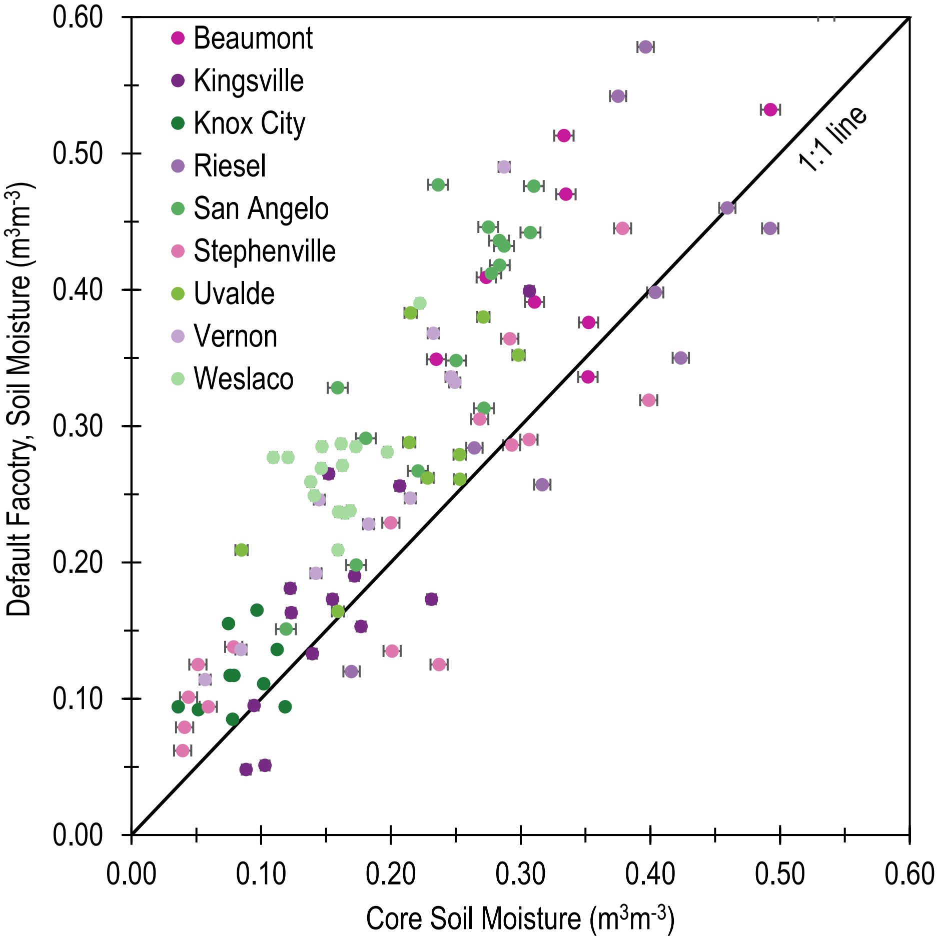

Figure 8. Soil Climate Analysis Network (SCAN) average of five soil moistures determined by the core method compared to the reported station soil moisture, which is measured by the HydraProbe, using default factory calibrations. Bars represent standard deviation.

To identify and predict this error as a function of a soil property, we analyzed the error as a function of clay content and other soil properties that might explain the behavior. Clay is the factor used to determine different calibration equations in the manual, in the literature, and in our soil-specific lab calibrations (Stevens Water Monitoring Systems Inc., 2007). When the error was plotted as a function of clay content, a weak polynomial trend appears (Fig. 9). Interestingly the highest-clay, most intrinsic shrink-swell soil (purple dots, Houston Black Clay) had residuals without any bias. Figure 9 also illustrates much variability in the residuals at each site. Because some literature suggests that other soil properties, such as salinity, might affect the probe calibration, therefor an error analysis as a function of CEC, pH, and exchangeable cations was conducted (data not shown), and no trend was found. Residuals were also analyzed by depth and bulk density, and no trend was found. Next, we analyzed the residuals as a function of soil moisture (Fig. 10), and found a weak, $r^2 = 0.32$, but significant correlation of the residuals to soil moisture. This clear relationship between HydraProbe error and soil moisture is expected based on our previous calibration results. Also based on calibration results of the Ships and Silawa soils and the literature, we could have hypothesized the clay content is useable to pre-determine the extent of the soil moisture bias in a HydraProbe estimate of soil moisture. However Fig. 9 provides evidence that contradicts this hypothesis. Even if the Riesel (Haplustert) points in Fig. 9 are ignored, the San Angelo (Argiustol) also shows evidence against the hypothesis, while the Vernon (Paleutal) shows a clear trend for clay content affecting HydraProbe soil moisture predictions just like the Silawa soil. Both of these soils, Silawa and Vernon, are Paleustalfs. While this evidence is frustrating, it leads us to the conclusion that the best Texas-wide SCAN calibration is just to add a soil moisture correction to the

HydraProbe predictions, to remove the soil moisture bias. HydraProbe prediction of soil moisture across the SCAN sites were reduced by half, from a RMSE of 0.094 m3m-3 and bias of 0.009 m3m-3 to an RMSE of 0.056 m3m-3 and bias of 0.003 m3m-3 (Figs. 10 and 11).

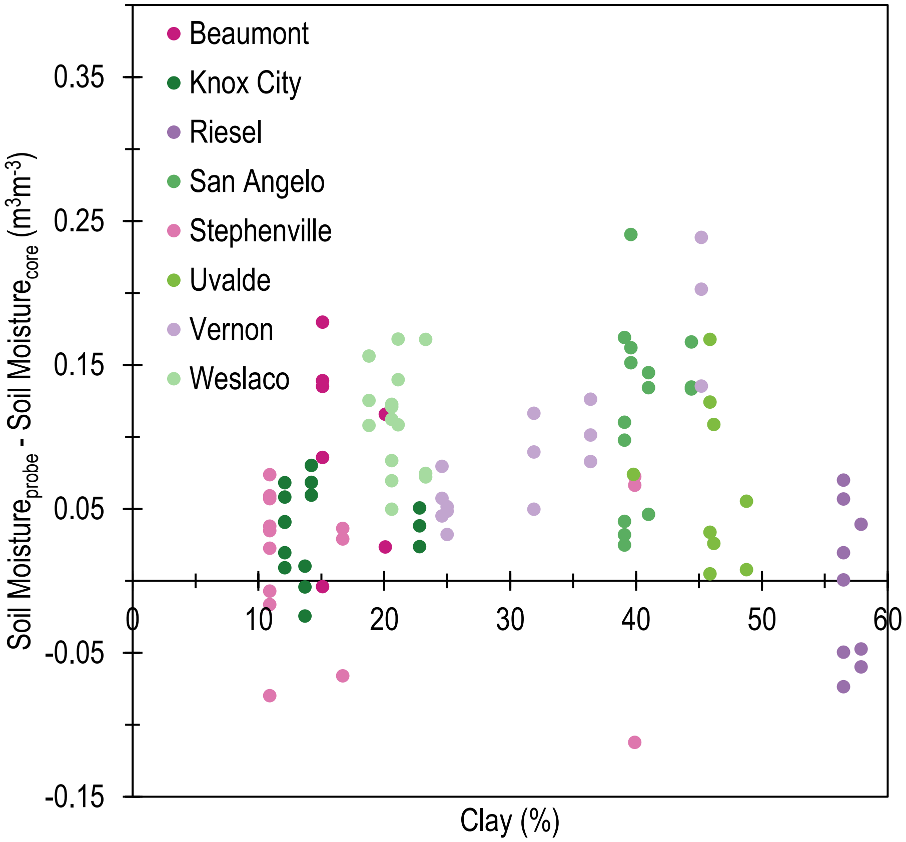

Figure 9. Soil moisture regression from the nine Soil Climate Analysis Network (SCAN) sites, core method compared to HydraProbe soil moisture with the default factory calibration, as a function of clay.

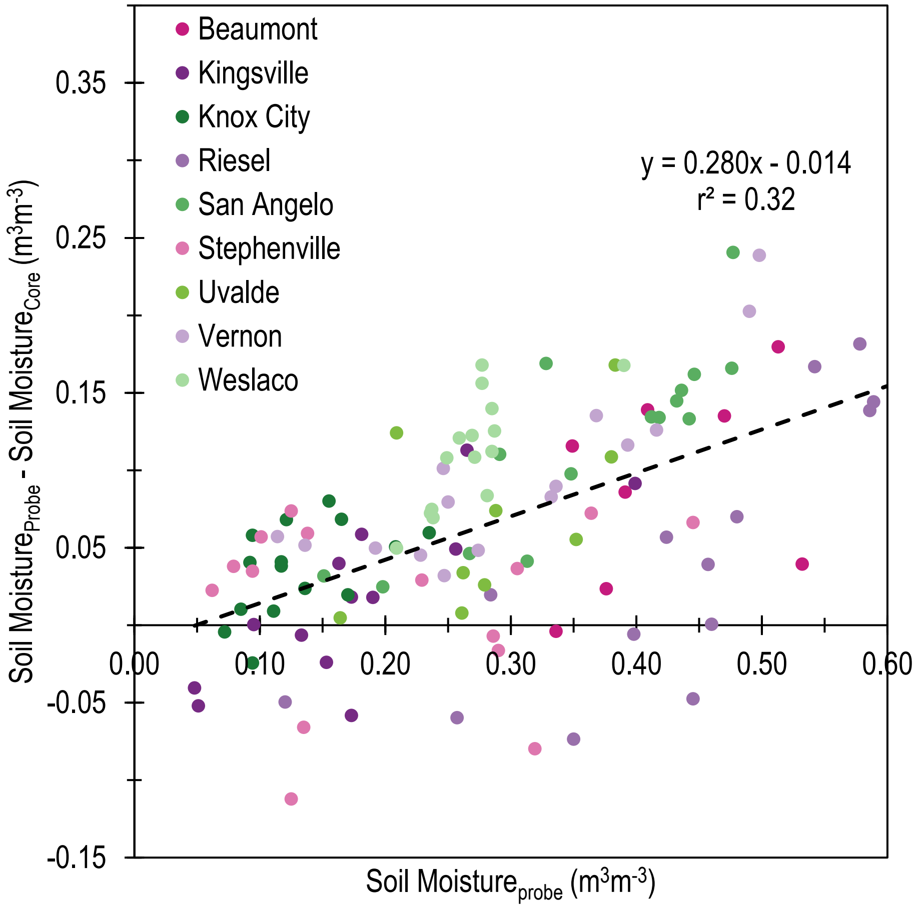

Figure 10. Soil moisture regression from the nine Soil Climate Analysis Network (SCAN) sites, core method compared to HydraProbe soil moisture with the default factory calibration, as a function of soil moisture as measured with the HydraProbe.

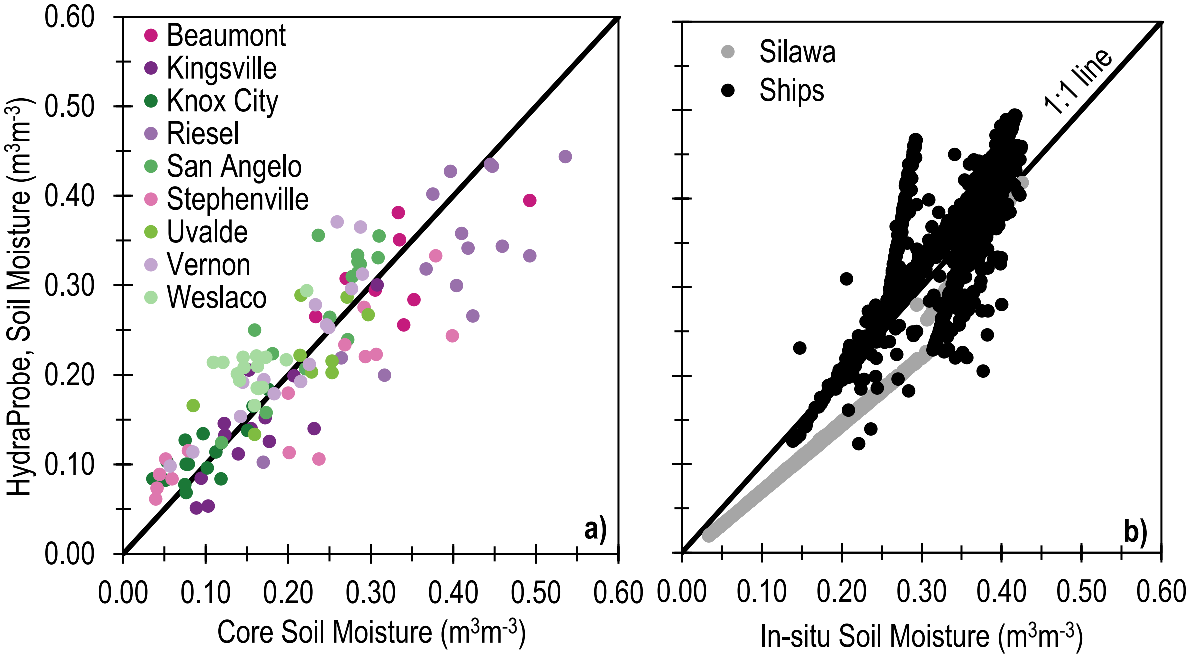

Figure 11. Bias removal of soil moisture using the equation in Figure 10 for a) Soil Climate Analysis Network and for b) Silawa and Ships site.

To test the applicability of the SCAN bias correction based on soil moisture, we applied it to the Ships and Silawa measurements. Though not as good as the soil-specific lab and in-situ calibrations the SCAN bias correction reduced RMSE values of the Ships and Silawa sites from 0.139 m^3m^{-3} to 0.063 m^3m^{-3}. Based on the variability on soil properties represented by the SCAN soils used for the bias correction, we conclude this correction could be applied to improve other SCAN and CRN sites across the US if no other information is available. Soils that we used in the SCAN correction the large range in clay content (12 to 62 %; Table 3), 2:1 smectitic clays and mixed minerology in clay fraction, and low salinity. Calcium carbonate equivalent ranged from 0 to 54 % (Table 4). Therefore, these results could be applied to SCAN sites in the Midwestern United States. This correction is likely least applicable is the Southeast and Southwestern United States where soil are dominated by kaolinite and soluble salts, respectively Additionally this research is more applicable for correction of wetter soil moisture contents as for the dry soil moisture contents the HydraProbe performs decently.

CHAPTER IV

CONCLUSION

A soil-specific lab calibration for surface and subsurface soil, an Alfisol and a Vertisol, was developed. After inter-sensor variability was determined to be negligible, three soil-specific equations were created. Soil-specific lab calibrations were significantly different from the default factory “loam” calibration, and appeared to vary primarily according to clay content. Two of the soil-specific data sets, which were the sandy clay subsoil of the Alfisol and clay subsoil of the Vertisol, appeared to need one equation; however, statistically the equations were different. It was unclear if the differences of 20% clay between the samples or smectitic versus mixed minerology contributed to the difference. Using a soil-specific calibration, the prediction error was reduced by half. The RMSE from using the default factory “loam” calibration was 0.094 m^3m^{-3} while the soil-specific lab calibration RMSE’s averaged 0.022 m^3m^{-3}. Most of the error occurred in the wet end of the clayey soils.

An in-situ calibration of the HydraProbe was developed for the same two soil series, by creating linear regression equations between dielectric permittivity and soil moisture measured with the calibrated NMM. Four equations resulted, and each of the four equations was found to be significantly different from each other and the soil-specific laboratory calibrations. There were some similarities between the soil-specific lab calibration and the in-situ calibration, such as slope and trends according to soil type.

The average RMSE for the in-situ calibrations was 0.034 m^3m^{-3}, which is larger compared to the soil-specific lab calibration. We hypothesis this is due to different instrument measurement volume and fluctuations in void space volume. The gain for performing an in-situ calibration is minimal, therefore depending on funding and data accuracy goals a soil-specific lab calibration is likely sufficient.

To evaluate the HydraProbe and calibration performance over time, two monitoring sites at each of the two soil series was established and monitored for 18 months. In the sandier soil the HydraProbe soil-specific lab calibration performed well; however, in the clayey soil the HydraProbe seemed rather insensitive to water content fluctuations compared to the NMM. In general, soils moisture was over estimated by the HydraProbe default factory “loam” calibration in the clayey soils and underestimated in the sandy soil; therefore, some sort of soil-specific calibration is needed.

Nine of the Texas SCAN soil moisture sites were also assessed to quantify the uncertainty in HydraProbe measurement. In general, the HydraProbe measurements overestimated soil moisture by 0.052 m^3m^{-3} compared to the field-determined soil moisture via core method. These results were consistent results from our two monitoring sites, as the SCAN sites had a range in clay content, 10.9% to 61.6%. To try and improve soil moisture predictions with the HydraProbe and understand the source of the error, the residuals from the HydraProbe prediction and soil core measurements were analyzed as a function of soil characterization data. Surprisingly there was no correlation found between the residuals and clay content, pH, CEC, exchangeable cations, or bulk density. Soil moisture was positively and linearly correlated, $r^2 = 0.32$ with the residuals.

New HydraProbe soil moisture predictions using the default factory calibration and a soil moisture trend removal improved the RMSE from 0.094 m^3m^{-3} to 0.056 m^3m^{-3} and eliminated all bias.

Based on our results, soil-specific calibrations for the HydraProbe are recommended for clayer soils. Long-term monitoring of soil moisture in clayey soil is difficult and the data from this study is not convincing that the HydraProbe accurately measures soil moisture, in-situ, in clayey soils. However, this study compared HydraProbe measurements to NMM and certainly the NMM is averaging soil moisture over larger volumes. Additionally in looking across nine soils in Texas, in-situ HydraProbe measurements can be improved by a simple trend removal as a function of soil moisture. This study has contributed to our knowledge of HydraProbe performance in in-situ conditions across multiple soils and in clayey soils. This study also provides some ground-truthing data for users of the Texas SCAN sites.

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