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Calibration of a combined dielectric probe for soil moisture and porewater salinity measurement in organic and mineral coastal wetland soils

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ABSTRACT

Accurate measurement of soil moisture (θ), bulk electrical conductivity (σ_b), and porewater electrical conductivity (σ_w) in the vadose zone is critical for a wide range of environmental monitoring applications. The use of combined dielectric probes allows for the automated collection of high-resolution, long-term data, however variation in probe response to different soil types can lead to unacceptably large measurement errors, especially in soils with high organic content such as those found in wetlands. The objectives of this study were to calibrate and field-test a combined, capacitance-based dielectric probe for three soil series encountered in the floodplain of a southeastern (USA) coastal river where watershed modifications have led to reduced freshwater flow and saltwater intrusion. To calibrate the probe, floodplain soils were categorized into three groups: a low organic content fine sand; a moderately organic, depositional fluvent soil; and a highly organic muck. PVC soil cores were packed at field bulk density, and θ and σ_b were measured in the lab over a range of soil moistures (pressure potentials of 0–333 cm H_2O) and σ_w values (0.01–1.0 S/m). Soil dielectric properties measured with the probe were used to test several potential models relating real and imaginary dielectric constants to θ, σ_b, and σ_w. Soil-specific calibrations improved θ estimation over standard manufacturer calibrations, particularly for the more organic soils. Of all θ–σ_b–σ_w models tested, the empirical relationship proposed by Vogeler et al. (1996) performed the best (overall $R^2 = 0.97$ for the three soils), though all models performed well in all soils ($0.94 \le R^2 \le 0.98$) and each can be selected for the specific range of σ_b expected in the field. Calibrations were successfully tested in the field by comparing in-ground probe estimates of σ_w with collocated soil water samples. These calibrations add to the limited published data available for soils of high organic content and support accurate monitoring of the vadose zone in coastal wetlands to inform restoration and management of these valued ecosystems.

1. Introduction

Accurately quantifying soil moisture and electrical conductivity (i.e., salinity) is critical for numerous agricultural (e.g., Kannan et al., 2010; Suweis et al., 2010), engineering (e.g., Fang-zhi and Xiao-ping, 2010), and environmental (e.g., Rodriguez-Iturbe et al., 2007; Suweis et al., 2010) applications. Multiple methods for the indirect, non-destructive, *in-situ* measurement of vadose zone soil moisture (θ) are available including: time domain reflectometry (TDR); capacitance-based frequency domain reflectometry (FDR); impedance-based amplitude domain reflectometry (ADR); phase transmission; and time domain transmission (TDT) (Muñoz-Carpena et al., 2005a). These dielectric methods all estimate θ and, where applicable (i.e., TDR and FDR), bulk electrical conductivity (σ_b) by measuring soil dielectric properties (e.g., Giese and Tiemann, 1975; Topp et al., 1980).

Most commercially available dielectric probes use manufacturer-specified calibration equations (pre-programmed or applied during post-processing), to relate measured dielectric properties to θ and σ_b, however improved accuracy can typically be achieved through soil-specific calibration (e.g., Dirksen and Dasberg, 1993; Seyfried and Murdock, 2004). For soils with atypical dielectric behavior (e.g., organic soils, volcanic soils, or mineral soils with unusually high water content), a soil-specific calibration is required (e.g., Muñoz-Carpena et al., 2005b; Shibchurn et al., 2005). Furthermore, in applications where the electrical conductivity (EC) of the porewater, rather than the bulk soil, is important, additional calibration is required to relate σ_b to porewater EC (σ_w) (i.e., soil solution EC). Several models relating σ_b to σ_w as a non-linear function of θ have been developed and applied to mineral soils (Muñoz-Carpena et al., 2005b; Rhoades, 1976; Rhoades et al., 1989; Vogeler et al., 1996).

For ecological studies in coastal wetlands, the ability to measure θ, σ_b, and σ_w *in-situ* with a rugged, automated probe across a range of

Abbreviations: EC, electrical conductivity; 4e probe, four-electrode probe; SWCC, soil water characteristic curve.

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soil types – from highly organic to mineral – is important to improve our understanding of vegetation responses to hydrological dynamics and to inform ecological management and restoration of valued ecosystems. For example, the specific life-cycle requirements of many floodplain plant species (Burns and Honkala, 1990; Conner, 1988; Conner and Toliver, 1987; Conner et al., 1986; Middleton, 1999, 2000, 2002) dictate that restoration and management plans not only reestablish historical surface water dynamics (e.g., hydroperiod and salinity), but also maintain σ_w below critical levels for freshwater vegetation (Corwin and Lesch, 2005; Kaplan et al., 2010) and periodically achieve an appropriate θ regime to facilitate germination of desired species in the floodplain (Middleton, 2000). One such ecosystem where vadose zone conditions are critical for the maintenance of ecosystem health is the Loxahatchee River (Fig. 1), a southeastern (USA) coastal river where watershed modifications and management over the past century have led to reduced freshwater flow, inadequate hydroperiod, and saltwater intrusion into historically freshwater wetlands (South Florida Water Management District [SFWMD], 2002, 2006). Ecosystem restoration and management efforts for the Loxahatchee River (SFWMD, 2006) and many other coastal rivers (e.g., King et al., 2009) are underway to protect and restore degraded floodplain plant communities.

Accurate measurement of θ and σ_w in the floodplain of the Loxahatchee River is needed (SFWMD, 2006) to evaluate the effectiveness of state-mandated Minimum Flows and Levels (MFLs; Chapter 40E−8 of the Florida Administrative Code) and to guide adaptive management of restoration plan implementation. However, the largest source of uncertainty in measuring θ and σ_w with dielectric probes is due to variation in response from different soil types (Seyfried and Murdock, 2004). For example, the standard empirical relationship relating θ to the soil dielectric constant (K) through a third order polynomial (Topp et al., 1980), while valid for a wide range of mineral soils, tends to underestimate θ in soils with high clay content (Dirksen and Dasberg, 1993), highly organic soils like peat (Shibchurn et al., 2005), and naturally aggregated volcanic soils due to their low bulk densities and large surface areas (e.g., Regalado et al., 2003). Soils in the Loxahatchee River floodplain represent a gradient from a highly organic, unconsolidated muck to a low organic content sand. Therefore, a soil-specific probe calibration for the soil series with high organic content encountered in the floodplain of the Loxahatchee River – and a combined dielectric probe capable of long-term deployment under rugged field conditions and saline water – is required.

One such probe is the Hydra probe (Stevens Water Monitoring Systems, Inc., Portland, OR, USA), a coaxial impedance dielectric sensor (Bellingham, 2009). The probe can be used in a wide range of environmental conditions, including freezing soils; responds quickly to changing soil moisture; works well with near surface positioning; is easy to use in automated data collection systems; is moderately priced; and can be highly accurate after calibration (Muñoz-Carpena et al., 2005a). The probe was originally calibrated for Hart sand, Wilder silt, and Ft. Edwards clay (Campbell, 1990). It has subsequently been calibrated for the gravelly sand of the Dry Valleys region of Antarctica (Wall et al., 2004); a very gravelly sandy loam comprised of mixed calcareous alluvium from Arizona; and other various loams (Seyfried and Murdock, 2004). It has been used to monitor θ, σ_b, and temperature for a variety of field projects, including the National Aeronautic and Space Administration's (NASA) Advanced Microwave Scanning Radiometer for the Earth Observing System (Jackson and Cosh, 2003) and the Natural Resource Conservation Service's (NRCS) Soil Climate Analysis Network (Stevens Water Monitoring Systems, Inc, 2006). Despite its advantages, the probe, which measures dielectric properties at 50 Mhz, is more sensitive to variations of soil type, particularly clay content and clay type, than probes that use a higher sampling frequency (Shibchurn et al., 2005). Additionally, previous work (Holden, 1997; Paquet et al., 1993; Pepin et al., 1992; Shibchurn et al., 2005; Topp and Davis, 1985) has shown that dielectric probe calibrations in organic soils are highly variable, indicating that these soils require special calibration. The objectives of this study were to calibrate and field-test a combined, capacitance-

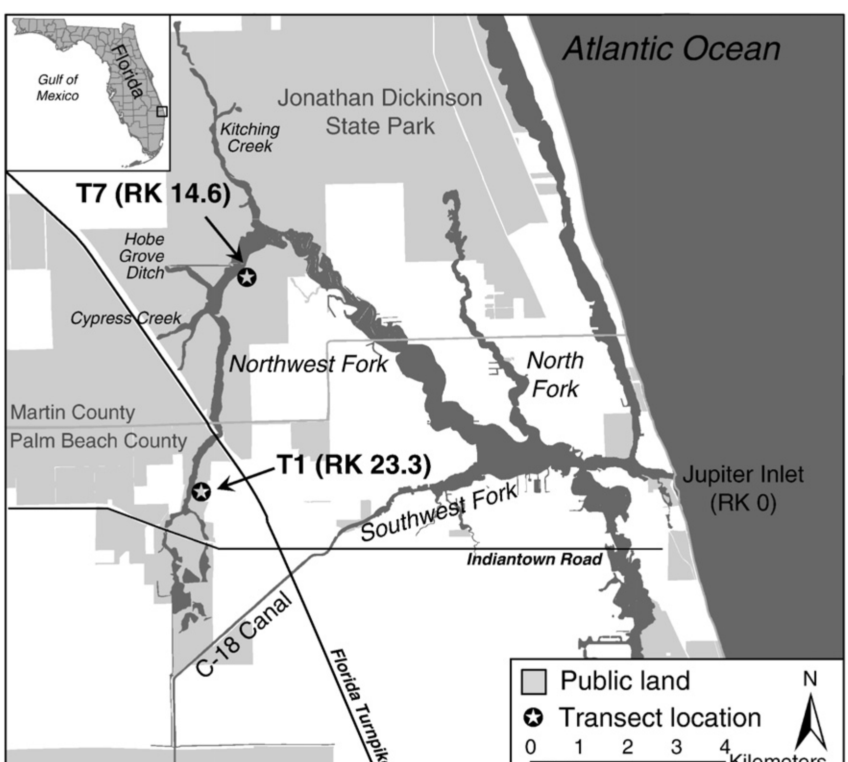

Fig. 1. The Loxahatchee River and surrounding area with experimental transect locations (T1/T7). Transect notation is followed by distance from river mouth (river kilometer, RK). Modified from Kaplan et al. (2010).

based dielectric probe for three soil series encountered in a coastal floodplain, ranging from sandy mineral to highly organic. This study is the first effort of which we are aware to calibrate the probe for highly organic, unconsolidated soils, and the calibrations presented here add to the limited published data available for these types of soils.

2. Materials and methods

2.1. Field soil sampling and characterization

A detailed soil survey was conducted in 2004 to classify Loxahatchee River coastal floodplain soils according to drainage class and series by the USDA-NRCS (Li et al., 2005). Based on this characterization (Table 1) and proposed vadose zone monitoring locations (Kaplan et al., 2010), soil samples were collected from two previously established vegetation transects perpendicular to the Loxahatchee River (Fig. 1). Transect 1 (T1) is in an upstream, riverine area, 23.3 km upstream of the river mouth (denoted as river kilometer 23.3, or RK 23.3) not impacted by tides. Soils on T1 consist of two distinct series: Winder fine sand (a fine-loamy, siliceous, superactive, hyperthermic Typic Glossaqualf; Soil Survey Staff, 1981) at higher elevations; and fluvents – stratified entisols made up of interbedded layers of sand, clay, and organic matter, typical of areas with frequent flooding and deposition (Sumner, 2000) – at lower elevations. Transect 7 (T7) is in a downstream, transitional area (RK 14.6) that receives tidal flooding of varying salinity over most or all of its length. Soil on T7 is highly organic, unconsolidated Terra Ceia Variant muck (a euic, hyperthermic Typic Medisaprist; Soil Survey Staff, 1981) with depths of over 1 m, underlain by sand (SFWMD, 2006). Transect cross-sections with probe installation locations are shown in Fig. 2.

Soil samples were taken within a 15-cm radius of probe installation locations (Fig. 2) and were used to obtain soil properties, soil water characteristic curves (SWCCs), and to calibrate probes. For the Winder fine sand and fluvent soils, trenches (~30×95 cm) were excavated in two locations using shovels, and undisturbed bulk density (ρ_b) samples were taken from the vertical face of the trench at depths of 0–5, 30–35, 60–65, and 90–95 cm by gradually inserting thin-wall stainless steel cups (volume = 210 cm^3) into the freshly exposed soil. Additional undisturbed saturated hydraulic conductivity (K_s) samples were taken at each specified depth by pressing PVC cylinders into the soil, avoiding compression. For the Terra Ceia muck, undisturbed soil samples were collected at three locations (at the same four depths described above) using a ring-lined barrel sampler, due to the soil's unconsolidated nature. Disturbed soil samples for the probe calibration and SWCCs were then collected using a shovel from depths of 0–30, 30–60, 60–90, and 90–120 cm at two locations for the Winder fine sand and fluvent and three locations for the Terra Ceia muck. These larger (approximately 0.04 m^3) samples represented composite samples over each 30-cm interval in order to minimize the variability of physical characteristics for the soil probe calibration. These

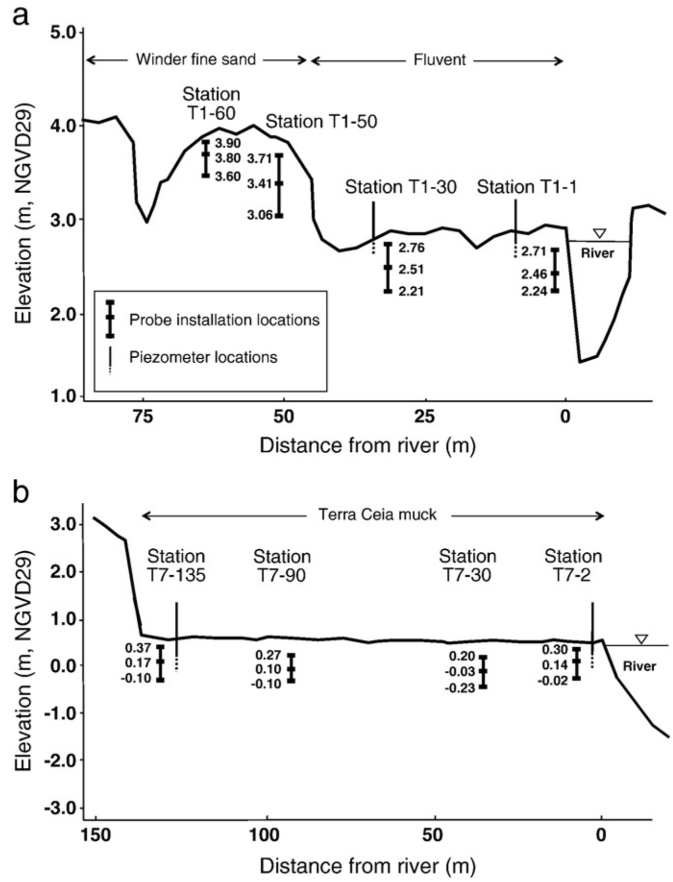

Fig. 2. Topography, soil series, and layout of vadose zone monitoring stations on (a) Transect 1 (b) and Transect 7. Station names denote transect number (T1/T7) and distance from the river (m). Probe installation elevations (m, NGVD29) listed below each station. Modified from Kaplan et al. (2007, 2010).

samples were later re-packed to field ρ_b (as measured in undisturbed samples) in calibration cells for probe calibration and to develop SWCCs (see following sections for cell construction details). Care was taken to sample in areas as few live roots as possible, however live roots were ubiquitous (particularly in the mangrove swamp on T7), making additional repeated samples necessary.

Undisturbed soil samples were used to measure ρ_b using the core method (e.g., Culley, 1993) and K_s using the constant head method (Klute, 1986). Additionally, cation exchange capacity (CEC) was determined following Sumner and Miller (1996) and percent carbon (%C) was analyzed using a carbon, nitrogen, and sulfur (CNS) elemental analyzer (Vario MAX, Elementar Americas, Mt. Laurel, NJ). Inorganic carbon was measured using the pressure-calcimeter method (USDA, 1996). Organic carbon was calculated based on the differences between the total carbon and inorganic carbon. Saturated soil moisture content (θ_s) was calculated by weighing saturated and oven-dried soil samples in calibration cells. Soils with high organic content were dried at 86 °C (after O'Kelly, 2005) and mineral soils were dried at 105 ° C until they achieved constant weight.

Table 1
Field soil characterization.

	Distance to river (m)	Soil map unit	Soil description by depth (cm)
Transect 1	55	Winder fine sand	0–90: fine sand 90–120: sandy clay loam
	30	Fluvent	0–30: clay 30–50: sandy clay 50–80: fine sand 80–120: loamy sand
Transect 7	130	Terra Ceia muck	0–40: muck
	80	Terra Ceia muck	0–180: muck >180: sand
	2	Terra Ceia muck	0–130: muck >130: sand

2.2. Laboratory equipment

2.2.1. Combined dielectric probe

The Hydra coaxial impedance combined dielectric probe is composed of a probe head, a multiconductor cable, and four probe sensing tines (Fig. 3a). The probe head generates a 50-MHz electrical signal that propagates along the sensing tines, most of which is absorbed by the soil. The portion of the wave that reflects creates a standing wave, which characterizes the dielectric constant (K). The

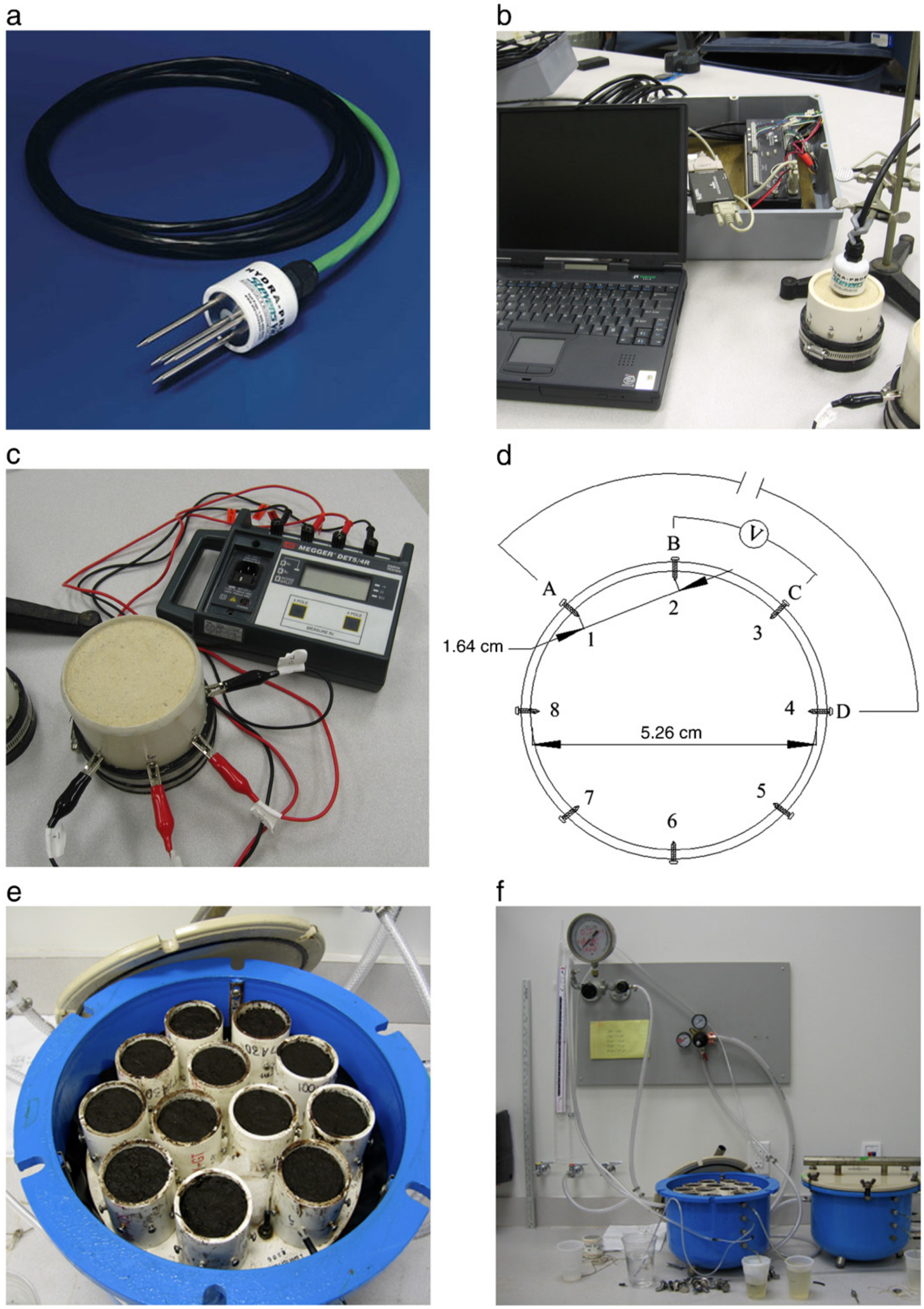

Fig. 3. Laboratory equipment used in the probe calibration: (a) Hydra combined dielectric probe; (b) taking a reading with the probe using CR-10 datalogger and laptop; (C) 4-electrode probe and sample cell; (d) sample cell schematic; and (e–f) pressure plate apparatus.

soil dielectric permittivity (ε) is related to K and the permittivity of free space (ε_o) by:

$$\varepsilon = K\varepsilon_0 \quad (1)$$

$$K = \varepsilon_r - i\varepsilon_i \quad (2)$$

where K is a complex number composed of real (ε_r) and imaginary (ε_i) dielectric constants (Campbell, 1990). Through calibration, ε_r can be related to θ and ε_i can be related to σ_b (Seyfried and Murdock, 2004). Porewater EC (σ_w) can then be estimated as a function of σ_b and θ through additional calibration (described below). The probe cable provides 12 V DC power and carries four output DC data channel voltages (0 to 2.5 V; three to calculate ε_r and ε_i based on K and one to calculate soil temperature). Voltages from the probe were collected using a CR10/CR10-X data logger (Campbell Scientific, Logan, Utah, USA) (Fig. 3b). The sensing tines form the soil sensing volume (3 cm diameter × 5.7 cm long), from which the dielectrical response is measured.

2.2.2. Reference four-electrode probe and soil sample cells

The four-electrode (4e) probe method was used to measure sample σ_b using a digital earth tester (DET5/4R, Biddle Megger, Chandler, AZ, USA) (Fig. 3c). The method was first developed by Wenner (1915), and has been used to evaluate θ and σ_b under field conditions since 1931 (McCorkle, 1931). The original method calls for four evenly spaced metal rods (electrodes) to be inserted into the ground along a line. The 4e probe then measures electrical resistivity (*ER;* i.e., the inverse of EC) by passing an alternating current between the two outside electrodes. The change in voltage (ΔV) is measured between the two inner electrodes. The ratio of the voltage and current is used to determine electrical resistance (*ER*) according to Rhoades (1976) and Nadler and Frenkel (1980):

$$ER = \frac{K_g \Delta V}{I} \quad (3)$$

where *ER* has units of [Ohm m], K_g is a geometric coefficient related to the geometric arrangement of the electrodes, and I is the electrical current [ampere]. The value of σ_b [S/m] is then calculated by taking the inverse of *ER*.

Electrode placement need not be linear (as in the Wenner array), but can be arranged as required as long as electrodes are evenly spaced. For the case of a circular four-electrode probe, Nadler et al. (1983) found results to be comparable to the original linear array with the geometric coefficient given by:

$$K_g = 2\pi d \quad (4)$$

where d is the distance between probes. For this study, circular soil sample "cells" (Nadler et al., 1982) were constructed out of 6-cm lengths of 5.26-cm inner diameter (nominally 2-in) schedule 40 PVC pipe (cell volume = 129.51 cm^3) (Fig. 3d). Eight screws were inserted through the PVC pipe and into the cell at equal intervals around the cell's circumference and midpoint along its length to serve as electrodes. The average distance between bolts (d in Eq. (4)) was calculated for each individual cell to decrease measurement errors between cells (average d across all cells and electrodes was 1.64 cm).

2.2.3. Pressure plate extractor

The pressure plate extractor method (Richards, 1948; Richards and Fireman, 1943; Topp et al., 1993) was used to generate soil water characteristic curves (SWCC) and control sample θ during calibration (Fig. 3e–f). Soil cells were saturated, placed in the extractor chamber on ceramic plates with maximum bubbling pressures of 1000 cm H_2O, and a known pressure was applied, forcing soil water through the pressure plate and out of the extractor until equilibrium was reached. Pressure potentials (ψ) of 0, 10, 50, 100, and 333 cm H_2O (i.e., 0, 1, 5, 10, and 33.3 kPa) were applied to the Winder fine sand; $\psi = 0$, 10, 15, and 40 cm H_2O (i.e., 0, 1, 1.5, and 4 kPa) were applied to the fluvent; and $\psi = 0$, 10, 15, and 25 cm H_2O (i.e., 0, 1, 1.5, and 2.5 kPa) were applied to the Terra Ceia muck. These represent estimates of equivalent water table drawdown observed in the floodplain experimental site (Kaplan et al., 2010) and are representative of the likely range of soil moisture experienced in the field based on the site's shallow water table (Skaggs et al., 1978; Wellings and Bell, 1982) and high relative humidity (RH) environment (average daily RH at a weather station 4.2 to 9.7 km from the two study transects was 76.5% ± 7.7 (std. dev.) from 2004 to 2008; data from the SFWMD environmental database, DBHYDRO, available at: http://www.sfwmd.gov/dbhydroplsql/show_dbkey_info. main_menu, station JDWX). Residual soil moisture content (θ_r) and additional Mualem–van Genuchten model parameters were estimated by fitting pressure plate extractor data using the RETC (RETention Curve) program developed by the U.S. Salinity Laboratory (van Genuchten et al., 1991) with the $m = 1 - 1/n$ assumption.

2.3. Calibration procedure

Sub-samples of each of the three soil types were packed to measured field ρ_b into the calibration cells described above for calibration. The experimental design for calibration consisted of establishing five levels of σ_w (0.01, 0.1, 0.25, 0.5, and 1 S/m) and four to five levels of θ (depending on soil type, as described above). To saturate the soil, cells were slowly soaked with DI water mixed with a small amount of thymol (to prevent bacterial and fungal growth). The σ_w in each cell was obtained by creating slow saturated (piston) flow with a saline solution (NaCl [Morton coarse kosher salt, Chicago, IL, USA] dissolved in DI water) from a top reservoir until the drainage solution reached a constant EC as measured with a handheld laboratory EC meter (model AP50, Denver Instrument Company, Denver, CO, USA). At least three pore volumes were run through the samples. Following Nadler and Frankel (1980), we assumed that the sample porewater had reached the target σ_w once the inflow and outflow had the same EC. After saturation, the bottom of the cells were sealed with parafilm (previously zeroed on the balance) and weighed.

Porewater from saturated samples was extracted using the pressure plate extractor. Once samples had reached equilibrium values of θ (as quickly as one day for $\psi = 10$ cm and up to 20 days for $\psi = 333$ cm), eight *ER* measurements were taken by rotating the array around the core for calculation of the average σ_b in each sample cell (Fig. 3c). Mean coefficient of variation (CV) around average σ_b values was 12.0%, 16.0%, and 12.3% for the Winder fine sand, fluvent and Terra Ceia muck soils, respectively. Next, the combined dielectric probe was inserted into the sample cell to measure ε_r and ε_i (Fig. 3b). Finally, samples were weighed to obtain gravimetric θ. Following Kim et al. (2000), actual soil sample volumes were also confirmed for calculation of volumetric θ, since high clay and organic soils like the fluvent and Terra Ceia muck may shrink or deform when dried beyond some threshold. Each Ψ–σ_b combination was replicated three times, however soil heterogeneity and inherent experimental variability resulted in small differences among the three "replicates" (as evidenced, for example, by the error bars in the SWCC in Fig. 4). For purposes of the calibration, each sample was treated as an individual data point, for a total of 195 soil samples (i.e., for the Winder fine sand there were 5 EC treatments × 5 θ values × 3 replicates = 75 samples, and for the fluvent and Terra Ceia muck there were 5 EC treatments × 4 θ values × 3 replicates = 60 samples each).

2.3.1. Soil moisture (θ) and bulk electrical conductivity (σ_b) calibration

We fit individual relationships for each of the three soil types following the third-order polynomial model used by Topp et al.

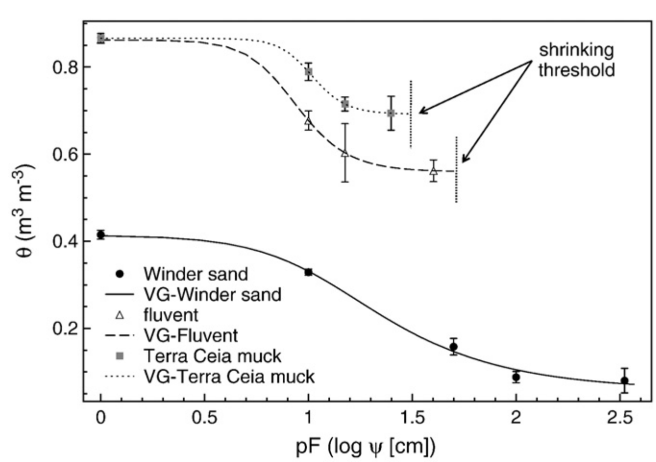

Fig. 4. Soil water characteristic curves (SWCCs) for the three soils investigated in this study. Symbols are measured pressure plate extractor data and lines are modeled SWCCs fitted using the van-Genuchten (VG) equation. Error bars represent 95% confidence intervals.

(1980) using the real component of K measured by the dielectric probe (ε_r):

$$\theta = a\varepsilon_r^3 + b\varepsilon_r^2 + c\varepsilon_r + d. \tag{5}$$

We also compared our calibration for Winder fine sand to the sand calibration provided by the manufacturer (developed for Hart sand; Campbell, 1990) to confirm our calibration methods and investigate soil-specific differences. To calibrate the dielectric probes for σ_b in the three soils, we used the model presented by Campbell (1990):

$$\sigma_b = \omega\varepsilon_0\varepsilon_i \tag{6}$$

where σ_b has units of [Siemens (S) m^{-1}], ω is the angular frequency of the probe ($2\pi{*}5\times10^7$ Hz [s^{-1}] for the 50 MHz Hydra probe), and ε_o has a value of 8.85×10^{-12} [F m^{-1}].

2.3.2. Porewater electrical conductivity (σ_w) calibration

Four models describing the relationship between θ, σ_b, and σ_w were tested. The first model (referred to as Linear 1), was proposed by Rhoades (1976) and is given by:

$$\sigma_b = \theta T\sigma_w + \sigma_s' \tag{7}$$

$$T = \alpha\theta + b \tag{8}$$

where T is soil tortuosity; σ_s' represents the EC of the soil's solid phase (which can be as low as zero in some soils, such as coarse sand) and a and b are empirical constants. Therefore, for a fixed θ, Eqs. (7) and (8) can be combined as:

$$\sigma_b = \left(a\theta^2 + b\theta\right)\sigma_w + \sigma_s' \tag{9}$$

for $\sigma_b > \sigma_s'$ and $\theta > -b/a$. A second model (referred to as Linear 2) proposed for high surface area, naturally-aggregated volcanic soils (Muñoz-Carpena et al., 2005b) replaces the σ'_s term from the Linear 1 model with a variable term as a function of θ:

$$\sigma_b = \left(a\theta^2 + b\theta\right)\sigma_w + c\theta^2 \tag{10}$$

for $\sigma_b > c\theta^2$ and $\theta > -b/a$.

Rhoades et al. proposed (1989) a model for soils that do not exhibit a linear relationship between σ_b and σ_w at a fixed θ for low values of σ_w (referred to as Non-linear), given by:

$$\sigma_b = [\theta - (c\theta + d)]\sigma_w + \frac{(\theta_{sol} + c\theta + d)^2}{\theta_{sol}}\sigma_s \tag{11}$$

for $\theta > d/(1-c)$ and $\sigma_b > [(\theta_{sol} + c\theta + d)^2/\theta_{sol}]\,\sigma_s$, where c and d are empirical constants and θ_{sol} is the soil solid content (i.e., the complement of the void ratio), calculated as ρ_b/ρ_s. Here, compared to Eq. (7), σ_s' is not considered constant (as suggested by Nadler and Frenkel, 1980), and the equation includes the effect of solute distribution in the mobile pore water (last term in Eq. (11)). A final model considered in this study (referred to as Empirical) was derived by Vogeler et al. (1996) by fitting an arbitrary equation to experimental results obtained with aggregated volcanic soils, and is given by:

$$\sigma_b = (c\theta - d)\sigma_w + (a\theta - b) \tag{12}$$

for $c\theta > d$ and $\sigma_b > a\theta - b$. Although this equation offers additional flexibility compared to the other three equations, it lacks a physical basis and increases the number of required parameters (Muñoz-Carpena et al., 2005b).

For each of the four proposed models, performance was assessed by comparing σ_b as measured with the 4e probe with modeled σ_b,

Table 2
Measured and modeled physical properties of three floodplain soils encountered in the floodplain of the Loxahatchee River.

Soil	No. samples	ρ_b[a]	K_s[b]	%C[c]	CEC[d]	θ_s[e]	θ_r[f]	α[g]	n[h]
Winder fine sand	8	1.36 ± 0.16[i] (1.06–1.55)	7.48 ± 3.39 (7.02–11.62)	0.39 ± 0.54 (0.01–1.70)	0.59[j]	0.42 ± 0.02 (0.39–0.45)	0.06 ± 0.03[k]	0.08 ± 0.02	1.94 ± 0.31
Fluvent	8	0.80 ± 0.38 (0.30–1.22)	23.07 ± 29.64 (0.19–69.92)	3.86 ± 3.96 (0.45–11.12)	39.7 ± 46.9 (5.7–126.3)	0.86 ± 0.01 (0.84–0.89)	0.56 ± 0.04	0.13 ± 0.04	3.95 ± 3.27
Terra Ceia muck	12	0.23 ± 0.14 (0.14–0.54)	1.57 ± 2.43 (0.19–7.45)	12.83 ± 8.82 (3.72–24.66)	90.5 ± 69.1 (14.6–149.5)	0.87 ± 0.03 (0.81–0.92)	0.69 ± 0.04	0.10 ± 0.01	5.69 ± 5.03

[a] Field bulk density [g cm^{-3}].
[b] Saturated hydraulic conductivity [m d^{-1}].
[c] Percent organic carbon.
[d] Cation exchange capacity [cmol kg^{-1}].
[e] Saturation soil moisture from oven measurements [m^3 m^{-3}].
[f] Residual soil moisture [m^3 m^{-3}] calculated from fitting SWCC.
[g] Related to the inverse of the air entry suction [cm^{-1}].
[h] Measure of the pore size distribution [-].
[i] Mean ± SD (range in parenthesis).
[j] Only one CEC sample for this soil.
[k] Fitted SWCC parameters ± 95% confidence interval (for θ_r, α, and n).

calculated based on known σ_w (i.e., from one of the five EC treatments), θ values from oven measurements, and requisite empirical parameters. Goodness-of-fit was quantified with the Nash Sutcliffe coefficient of efficiency ($-\infty \leq C_{eff} \leq 1$; Nash and Sutcliffe, 1970), Akaike's information criterion (AIC; Akaike, 1974), and the root mean square error (RMSE). C_{eff} compares the variance about the 1:1 line to variance of the observed data, with $C_{eff}=1$ indicating that the plot of predicted vs. observed data matches the 1:1 line. The AIC is a statistical criterion that balances goodness-of-fit with model parsimony by rewarding goodness-of-fit but including a penalty term based on the number of model parameters.

2.4. Field testing of porewater electrical conductivity (σ_w) calibration

Four piezometers were installed at the experimental transects, including two in fluvent soils at stations T1-1 and T1-30 and two in Terra Ceia muck soils at stations T7-2 and T7-135 (Fig. 2). No piezometers were installed in higher elevation areas with Winder fine sand, where groundwater was deeper. Piezometers were constructed from 5.26 cm inner diameter (nominally 2-in), flush-thread PVC screen and casing (ASTM F-480), fitted with a PVC well point. Screened sections were 15 cm long, with the midpoint of the screened section centered at probe installation depths, and were covered with filter fabric secured by hose clamps to prevent intrusion of soil fines into the piezometer casing.

Shallow groundwater samples were collected during field visits (every 2 to 4 weeks) when the water table intersected the screened section of the piezometers (which was often the case in these lower floodplain soils). Samples were collected using a reusable plastic bailer after purging at least one piezometer volume (or until the piezometer was empty). The shallow groundwater EC (GWEC) of the samples was analyzed in the field using a handheld EC meter (model AP50, Denver Instrument Company, Denver, CO, USA) previously calibrated in the lab following manufacturer specifications. These data were compared with field σ_w calculated using θ and σ_b (as measured by the dielectric probe with the calibrations presented herein) and the best performing θ–σ_b–σ_w model from the laboratory studies (see Results section). While GWEC and σ_w are not explicitly comparable (piezometers collect freely-draining shallow groundwater while σ_w is the EC of the porewater), the comparison under saturated conditions may give an indication of the usefulness of the equations developed in this study for application in field conditions.

3. Results and discussion

3.1. Soil characterization

The field soil survey indicated the presence of two primary mineral soil series on Transect 1 (Winder fine Sand and fluvent) and one organic soil series on Transect 7 (Terra Ceia muck). Soil characterization with depth and distance along each transect is given in Table 1. Physical properties of these soils are presented in Table 2. In general, the Winder fine sand has the highest ρ_b of the three soils (average $\rho_b = 1.36$ g cm^{-3}; i.e., within the expected range for a mineral soil) and a moderate K_s (average $K_s = 7.48$ m d^{-1}; typical of a fine- to medium-grained sand [Brassington, 1988]). This sandy soil also has the lowest carbon content and cation exchange capacity (CEC) of the three soils. Average ρ_b for the fluvent soil was lower

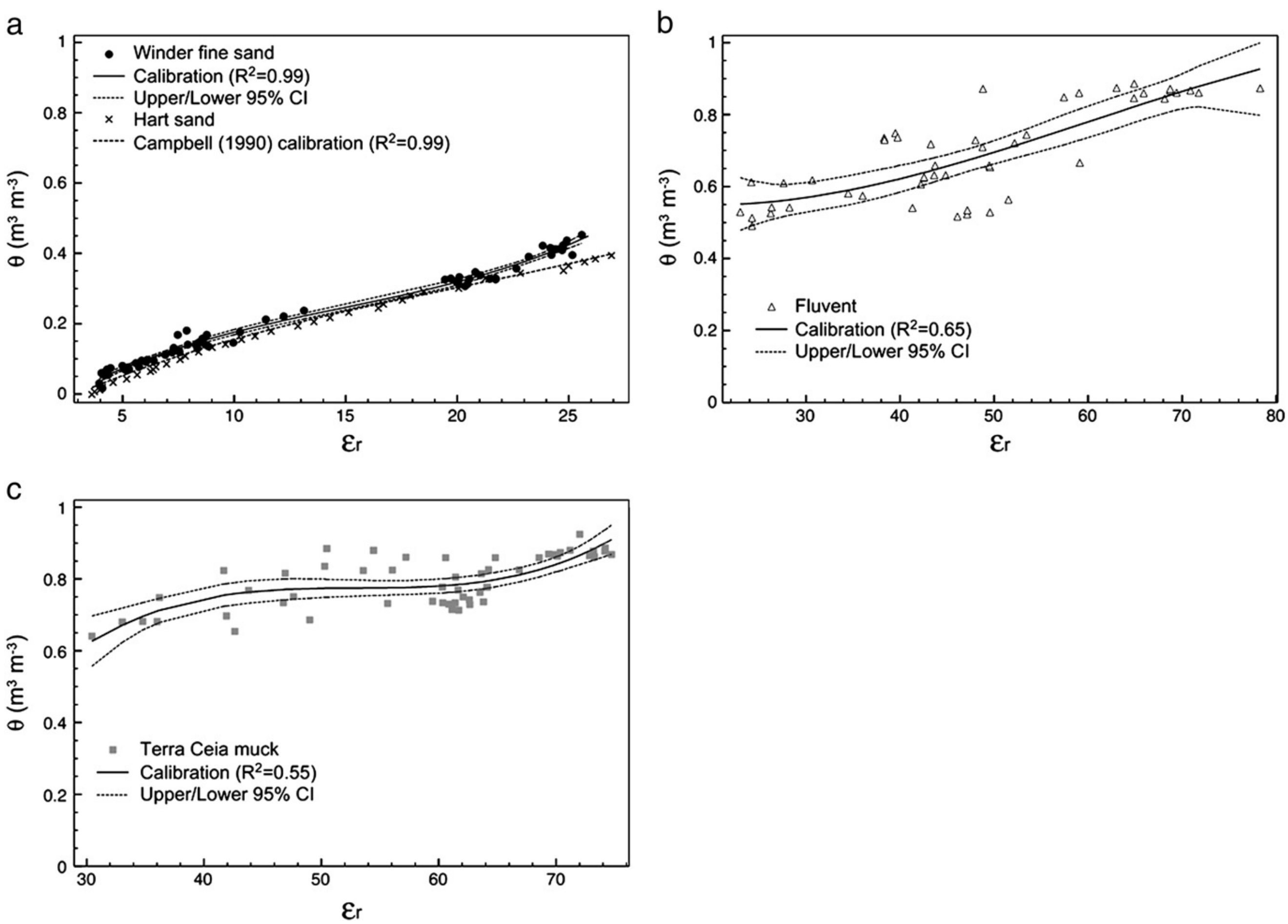

Fig. 5. Soil moisture (θ) calibration as a function of the real dielectric consent (ε_r) for: (a) Winder fine sand and Hart sand; (b) fluvent; and (c) Terra Ceia muck. Dashed lines represent upper and lower 95% confidence intervals (CI). Calibration parameters are given in Table 3.

Table 3
Model parameters and goodness-of-fit statistics for polynomial relationships[a] between real dielectric constant (ε_r) and soil moisture (θ) for three floodplain soils (after Topp et al., 1980).

Soil	a	b	c	D	R^2
Winder fine sand	4.42×10^{-5}	-1.97×10^{-3}	4.24×10^{-2}	-9.55×10^{-2}	0.99
Fluvent	-1.79×10^{-6}	3.22×10^{-4}	-1.07×10^{-2}	6.49×10^{-1}	0.65
Terra Ceia muck	1.27×10^{-5}	-2.02×10^{-3}	1.07×10^{-1}	-1.12×10^{0}	0.55

[a] For $\theta = a\varepsilon_r^3 + b\varepsilon_r^2 + c\varepsilon_r + d$.

($\rho_b = 0.80$ g cm^{-3}), and varied with depth. For soils between 0 and 60 cm below the ground surface (bgs), ρ_b was 0.65 g cm^{-3} or less for all samples, indicating higher organic content and an unconsolidated nature, while average ρ_b in deeper soils was higher (1.15 g cm^{-3}), indicating an increasing mineral content with depth. K_s values for the fluvent were variable across all depths, due to the unconsolidated and layered nature of the soil (interbedded layers of sand clay and organic matter; see Table 1). The fluvent had moderately high and variable organic content and CEC. The Terra Ceia muck found on Transect 7 has extremely low ρ_b and K_s values typical of these highly organic soils (average %C = 12.83). In all soils, additional variation in hydraulic properties may be attributed to the variable presence of small fragments of very fine roots or other fibric material in soil samples. Given the variability of soil properties with depth (particularly in the layered fluvent soil) probe calibrations were performed on composite soil samples taken from the 0–30 cm interval. This is consistent with the focus of restoration and management efforts on surficial floodplain soils (i.e., in order to provide beneficial environmental conditions for seed germination and the survival of young, shallow-rooted seedlings).

SWCCs were developed for each soil by plotting θ at each pressure step (averaged across all EC treatments and replicates) against log(ψ) (Fig. 4). Due to their high porosity, the fluvent and Terra Ceia muck have substantially higher θ at each pressure step than the Winder sand. Because of their high organic content, and unconsolidated nature, these soils were observed to shrink at higher pressures (organic soils are known to shrink irreversibly when dried beyond some threshold not normally experienced in natural conditions; e.g., Ewing and Vepraskas, 2006), and were therefore not exposed to higher pressure steps, since σ_b measurement becomes impossible when the soils shrink enough to lose contact with the 4e probe electrodes. This does not present a limitation to this study since this range of drawdown (<0.5 m) is similar to the range observed in the field. Fitted SWCC curves are graphed with measured data and 95% confidence intervals in Fig. 4. Estimates of the Mualem–van Genuchten model parameters θ_r, α, and n are given in Table 2 (θ_s was measured directly and it was assumed that the parameter $m = 1 - 1/n$). High values of θ_r for the fluvent and Terra Ceia muck soils are similar to those measured in other low ρ_b, organic tropical peat soils (Katimon and Melling, 2007).

3.2. Soil moisture (θ) calibration

Fig. 5 shows the observed relationships between ε_r (measured by the dielectric probe) and θ (measured gravimetrically) for the Winder fine sand, fluvent, and Terra Ceia muck, as well as the 95% confidence intervals (CI) for each calibration curve. Polynomial fit parameters for the three soil-specific calibrations are given in Table 3. In Fig. 5a, the calibration for Winder fine sand is compared with the manufacturer-supplied sand calibration, which was developed using Hart sand (Campbell, 1990). Calibration curves for the two sandy soils follow a similar trend, but diverge at high values of ε_r, where differences in estimated θ are as high as 0.07 m^3 m^{-3}. Differences between the two calibrations are likely due to the coarser structure of the Hart sand ($\rho_b = 1.66$ g cm^{-3}; Campbell, 1990) compared to the Winder fine sand (average $\rho_b = 1.36$ g cm^{-3}; Table 2).

Relationships between ε_r and θ for the fluvent and Terra Ceia muck soils are shown in Fig. 5b–c. Polynomial fits for these relationships ($0.55 \le R^2 \le 0.65$) show greater inter-sample variability than that observed in the Winder fine sand. There are several possible explanations for this observed variation. For the fluvent (Fig. 5b), noise in the ε_r–θ relationship is likely due to the heterogeneous nature of the soil. Although disturbed soil samples collected in the field represented a composite over the 30-cm sampling interval depth, individual fluvent sample cells still represented a range of soil textures and %C content. These results also show a large range in probe-measured ε_r when θ is at or near saturation (i.e., ε_r from 60 to 80), suggesting that increases in ε_r above a certain θ threshold may not be indicative of increased moisture. For the Terra Ceia muck (Fig. 5c), the ubiquitous presence of many fine mangrove roots and other fresh organic matter provided inter-sample variation when quantifying dielectric properties of the soil and

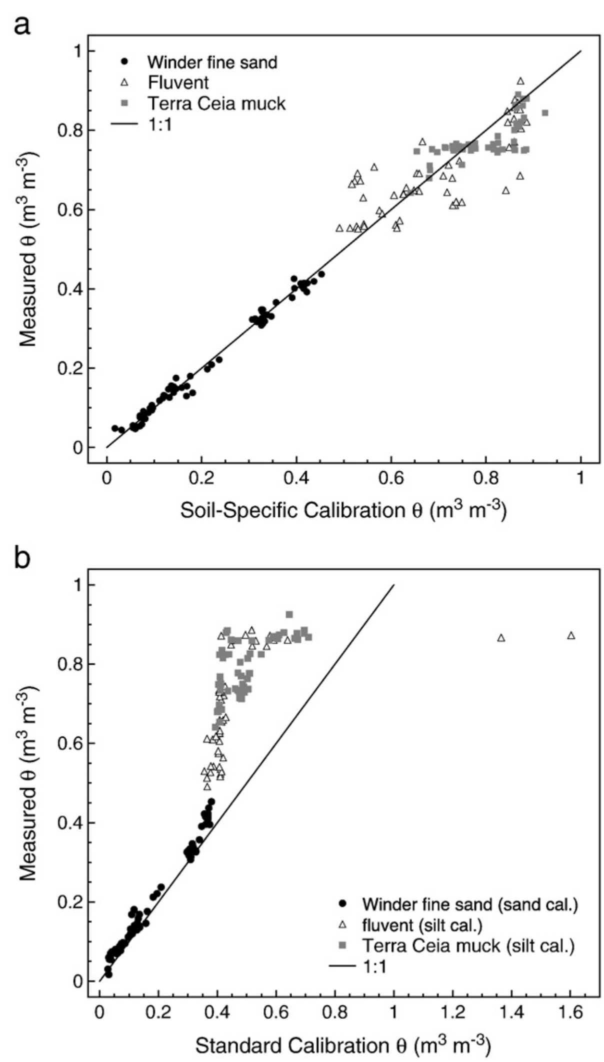

Fig. 6. Measured vs. observed soil moisture (θ) using: (a) the soil-specific calibrations developed in this study, and (b) the best standard calibration provided with the combined dielectric probe, illustrating the need for soil-specific calibrations in these floodplain soils.

developing the ε_r–θ relationship. In these soils, high clay content (fluvent) and high %C (both soils) resulted in observed shrinking and swelling behavior, which – though limited at the relatively low pressures applied – may have added additional experimental error.

Despite these limitations, these soil-specific calibrations represent a marked improvement (Fig. 6a) over using a standard calibration provided by the manufacturer (e.g., sand, silt, or clay) (Fig. 6b). For the fluvent and Terra Ceia muck, the standard silt calibration provided the "best" estimate of observed θ, but considerably under-predicted θ at low and middle values and dramatically over-predicts θ at higher values (e.g., yielding $\theta>1$). Additionally, although the noise in the ε_r–θ relationship for these soils yields only fair goodness-of-fit with the polynomial model, the new calibration equations presented here provide a basis for measuring θ in these floodplain soils, which are naturally highly variable under field conditions. The effect of uncertainty in θ calculated with these relationships on measured σ_w is explored in Section 3.4.

3.3. Bulk electrical conductivity (σ_b) calibration

Relationships between ε_i (measured by the dielectric probe) and σ_b (measured with the 4e probe) for the three soils are shown in Fig. 7. For the Winder fine sand (Fig. 7a), calibration results closely matched the manufacturer-supplied calibration (i.e., $\sigma_b=0.0029^*\varepsilon_i$ for this study vs. $\sigma_b=0.0028^*\varepsilon_i$ as provided by the manufacturer). The fluvent and Terra Ceia muck show a deviation from this relationship due to dielectric losses (slope = 0.0020; Fig. 7b–c), suggesting that the high organic matter content of these soils influences this relationship. Comparing the slope of these ε_i–σ_b relationships with Eq. (6), we found it necessary to introduce a constant, k_c [-], that embodies deviations due to soil type:

$$\sigma_b = k_c \omega \varepsilon_0 \varepsilon_i. \tag{13}$$

Given $\varepsilon_0 = 8.85\times10^{-12}$ F m^{-1}, $\omega = 2\pi^*5\times10^7$ Hz, and the observed slopes, it follows that $k_c=1.04$ for the Winder fine sand and $k_c=0.72$ for both the fluvent and Terra Ceia muck.

3.4. Porewater electrical conductivity (σ_w) calibration

Fig. 8 shows the relationship between observed and predicted σ_b for each proposed model. Equation parameters and goodness-of-fit statistics for each soil type are summarized in Table 4. All four equations performed very well in all soils ($0.94\le C_{eff}\le0.98$). The Empirical equation (Vogeler et al., 1996; Fig. 8d) gave the best overall model fitting (average $C_{eff}=0.97$), however differences were small (Table 4). Despite the smaller number of fitted parameters in the Linear 1 (Rhoades, 1976), Linear 2 (Muñoz-Carpena et al., 2005b), and Non-linear models (Rhoades et al., 1989), the Empirical model also yielded slightly better (i.e., lower) AIC values than the more parsimonious and physically-based equations for two of the three soils (fluvent and Terra Ceia muck), while the Non-linear equation (Rhoades et al., 1989) had the lowest AIC for the Winder

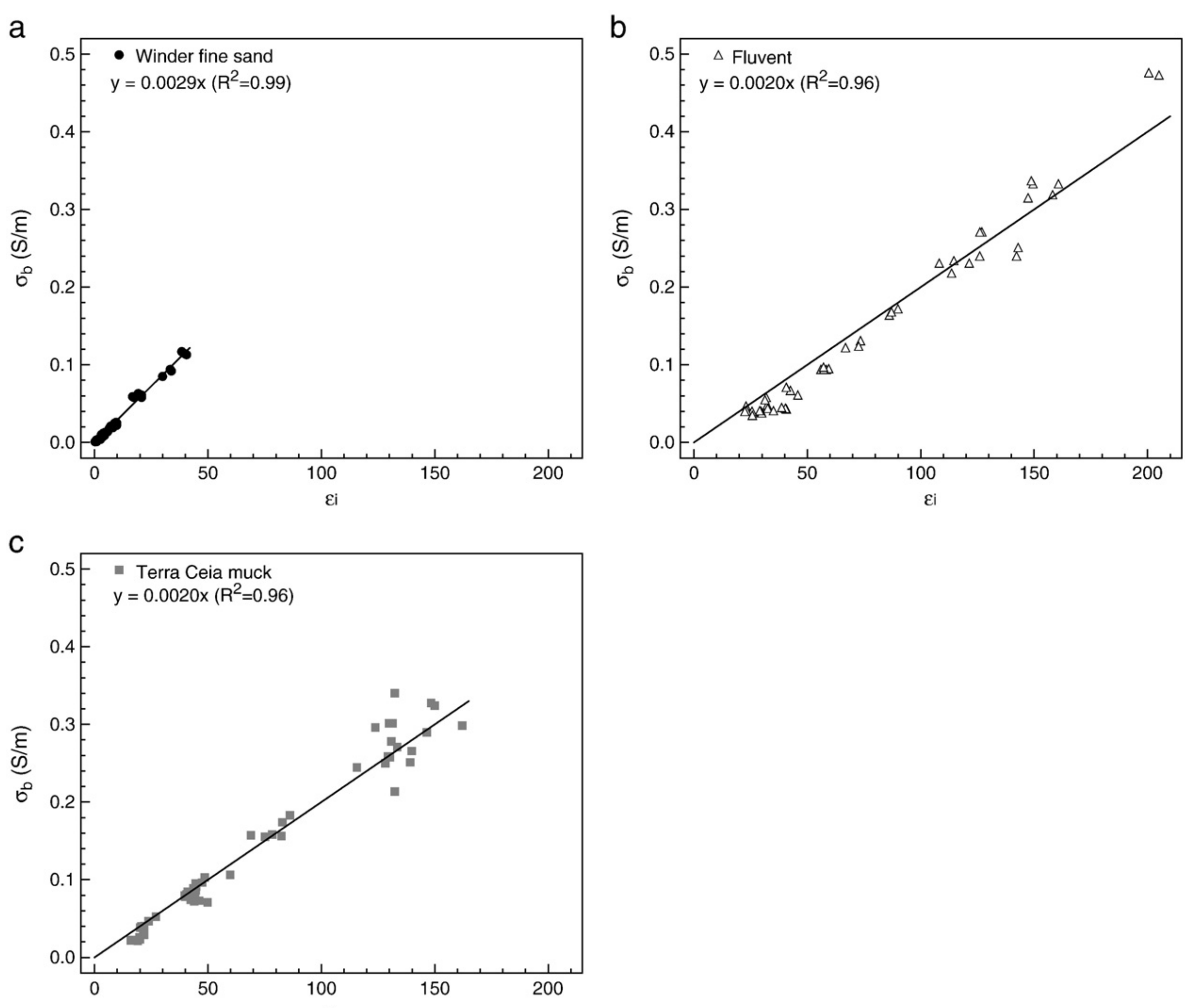

Fig. 7. Relationship between the imaginary dielectric constant (ε_i) and bulk electrical conductivity (σ_b) for: (a) Winder fine sand; (b) fluvent; and (c) Terra Ceia muck. Note difference in range of measured ε_i, particularly for Winder fine sand (a) compared with fluvent and Terra Ceia muck soils (b and c).

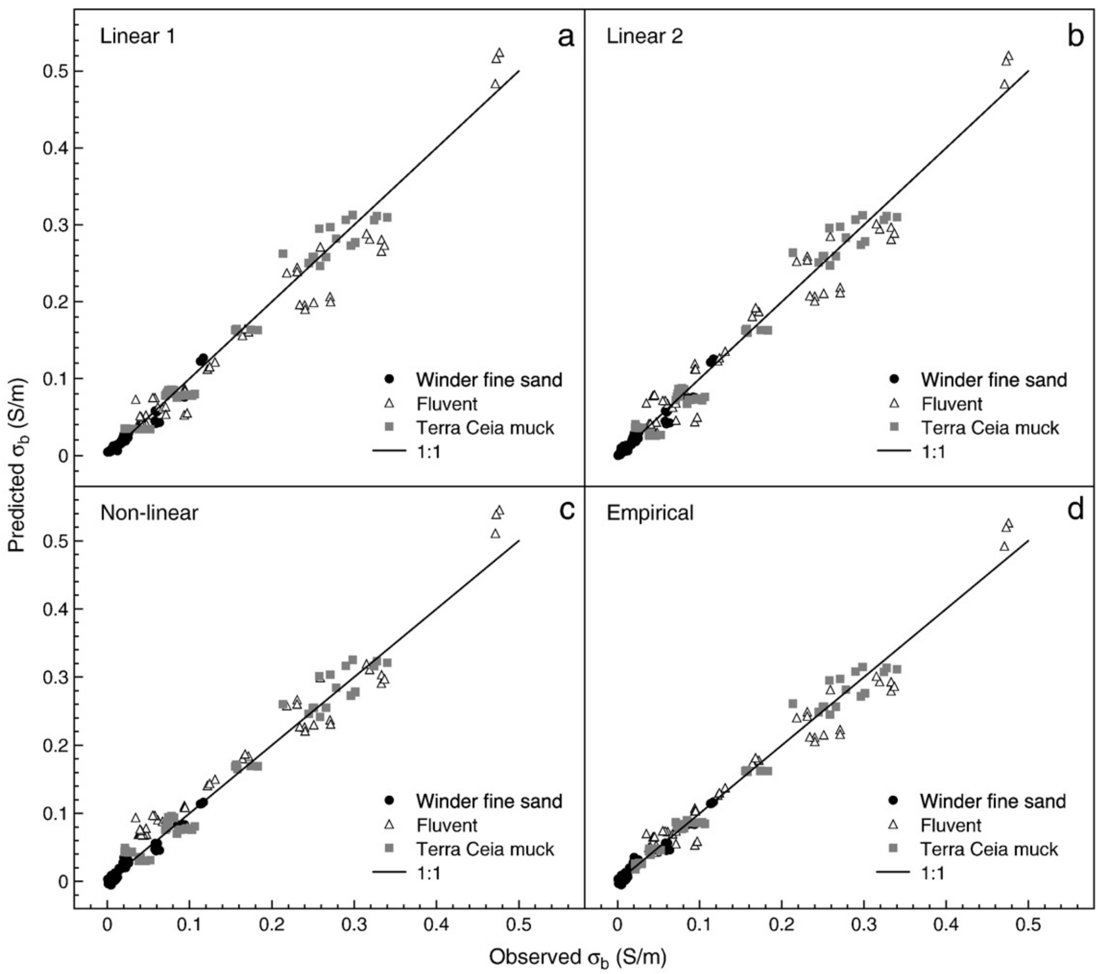

Fig. 8. Observed vs. predicted bulk electrical conductivity (σ_b) for all soils calculated using the four models given in Eqs. (9)–(12): (a) Linear; (b) Linear 2; (c) Non-linear; and (d) Empirical. Calibration parameters and goodness-of-fit statistics are given in Table 4.

fine sand. While the Empirical model provided the tightest fit around the 1:1 line for low EC values ($\sigma_b \leq 0.2$ S/m), the Non-linear model (Fig. 8c) yielded the best results at moderate EC ($0.2 \leq \sigma_b \leq 0.4$ S/m). All models slightly over-predict σ_b at high EC in the fluvent and show some variation at moderate EC levels in the fluvent and Terra Ceia muck soils (Fig. 8a–d). In general, all models performed satisfactorily for these unique soils and selection of the best model may be influenced by the expected range of EC encountered in the field.

The applicability of these equations is limited by the range of θ under which they can be applied and under which they were tested in this study. In general, the slope of the σ_b–σ_w relationship is steeper for lower θ (e.g., Muñoz-Carpena et al., 2005b). For example, at low moisture contents ($\theta \leq 0.10$) all four equations yield extremely high estimates of σ_w in the Winder fine sand and even produce negative relationships when θ falls below approximately 0.05 m^3 m^{-3}. This is in agreement with Hilhorst (2000), who found that calibrations for σ_w as a function of σ_b and θ generally do not hold for low θ, and was recently confirmed in a study using the Hydra probe by Leao et al. (2010). Thus, the calibration equations developed here should not be applied outside of the θ and EC ranges explored in this study (i.e., at

Table 4
Fitted model parameters (a, b, c, and d), physical soil parameters (σ_s and θ_{sol}), Nash–Sutcliffe coefficient of efficiency (C_{eff}), Akaike's Information Criteria (AIC), and root mean square error (RMSE) for four models (see Eqs. (9)–(12)) relating bulk EC (σ_a) and porewater EC (σ_w) in Winder fine sand (WFS), fluvent, and Terra Ceia muck (TCM) soils. Bold AIC values indicate best model for each soil type by AIC. See text for full explanation of parameters.

Model	Soil	a	B	c	d	σ_s	θ_{sol}	C_{eff}	AIC	RMSE (S m^{-1})
Linear 1	WFS	1.4876	−0.0481	–	–	0.0040	–	0.96	−493.6	0.0059
	Fluvent	0.8756	−0.2092	–	–	0.0491	–	0.95	−211.8	0.0277
	TCM	−0.1532	0.7760	–	–	0.0293	–	0.98	−302.0	0.0160
Linear 2	WFS	1.3090	0.0128	0.0346	–	–	–	0.96	−490.6	0.0060
	Fluvent	0.5929	−0.0085	0.0991	–	–	–	0.95	−215.0	0.0280
	TCM	−0.3497	0.9435	0.0408	–	–	–	0.97	−288.6	0.0178
Non-linear	WFS	–	–	0.3177	0.0648	0.0050	0.580	0.97	**−502.7**	0.0059
	Fluvent	–	–	−0.1062	0.4839	0.0295	0.548	0.94	−206.8	0.0400
	TCM	–	–	0.4696	−0.1023	0.0226	0.096	0.97	−283.2	0.0190
Empirical	WFS	0.0041	−0.0035	0.6820	0.0648	–	–	0.97	−500.1	0.0055
	Fluvent	0.0546	−0.0138	1.0316	0.4360	–	–	0.96	**−223.6**	0.0252
	TCM	−0.1537	−0.1535	0.8809	0.1848	–	–	0.98	**−310.9**	0.0143

Table 5
Average percentage change in porewater electrical conductivity (σ_w) for a given soil moisture (θ) error of ± 0.02 m^3 m^{-3} for Winder fine sand (WFS) and ± 0.05 m^3 m^{-3} for fluvent and Terra Ceia muck (TCM) over a range of θ and bulk electrical conductivity (σ_b). For the WFS, θ was varied between 0.1 and 0.4 m^3 m^{-3}; for the fluvent and TCM soils θ was varied between 0.6 and 0.9 m^3 m^{-3}. For all soils, σ_b was varied between 0.01 and 1.0 S m^{-1}.

θ − WFS (m^3 m^{-3})	σ_b − WFS (S m^{-1})			θ − fluvent/TCM (m^3 m^{-3})	σ_b − fluvent (S m^{-1})			σ_b − TCM (S m^{-1})		
	0.01	0.10	1.00		0.01	0.10	1.00	0.01	0.10	1.00
0.4	8.3%	6.7%	6.6%	0.9	0.0%	18.0%	10.9%	0.0%	1.3%	6.8%
0.3	11.4%	9.9%	9.9%	0.8	0.0%	20.0%	13.8%	0.0%	1.9%	8.2%
0.2	21.3%	19.9%	19.8%	0.7	0.0%	24.5%	18.9%	0.0%	2.9%	10.2%
0.1	80.3%	80.1%	80.0%	0.6	0.0%	36.2%	30.9%	0.0%	5.2%	13.3%

θ<0.10 for the Winder fine sand; θ<0.50 for the fluvent; and θ<0.70 for the Terra Ceia muck; or at σ_w>1 S/m). In the case of the field application of these equations to the Loxahatchee River, only the Winder fine sand has been shown to experience θ values lower than those explored in this calibration study (Kaplan et al., 2010). For these soils, calculating σ_w when θ<0.10 is likely not possible.

Finally, we performed a sensitivity analysis to determine the effect of uncertainty in θ measurements on estimated σ_w for each soil over a range of θ and σ_b. Based on the range of moistures explored in the lab calibration, we varied θ from 0.1 to 0.4 m^3 m^{-3} for the Winder fine sand and from 0.6 to 0.9 m^3 m^{-3} for the fluvent and Terra Ceia muck. Values of σ_b were also varied over the experimental range (0.01 to 1.00 S m^{-1}). Table 5 summarizes the average percent change in σ_w for a given error in θ (taken as ± 0.02 m^3 m^{-3} for the Winder fine sand and ± 0.05 m^3 m^{-3} for the fluvent and Terra Ceia muck given their larger uncertainty range—see Fig. 5). These results indicate that the calibrations presented here can provide good estimates of σ_w even with some uncertainty around measured θ. In general the equations are most sensitive to θ errors at low θ. For example, the calibration for Winder fine sand is highly sensitive at the lowest θ values, however this is at the low range of the equation's applicability, and reflects the general sensitivity of porewater EC calibration equations at low moisture contents (Hilhorst, 2000; Leao et al., 2010; Malicki and Walczak, 1999). The calibration for Terra Ceia muck, on the other hand, was the least sensitive to errors in θ, with percent changes in σ_w of 0.0% to 13.3% over the range of θ and σ_b. Given these results, further work to reduce error in the estimation of θ would

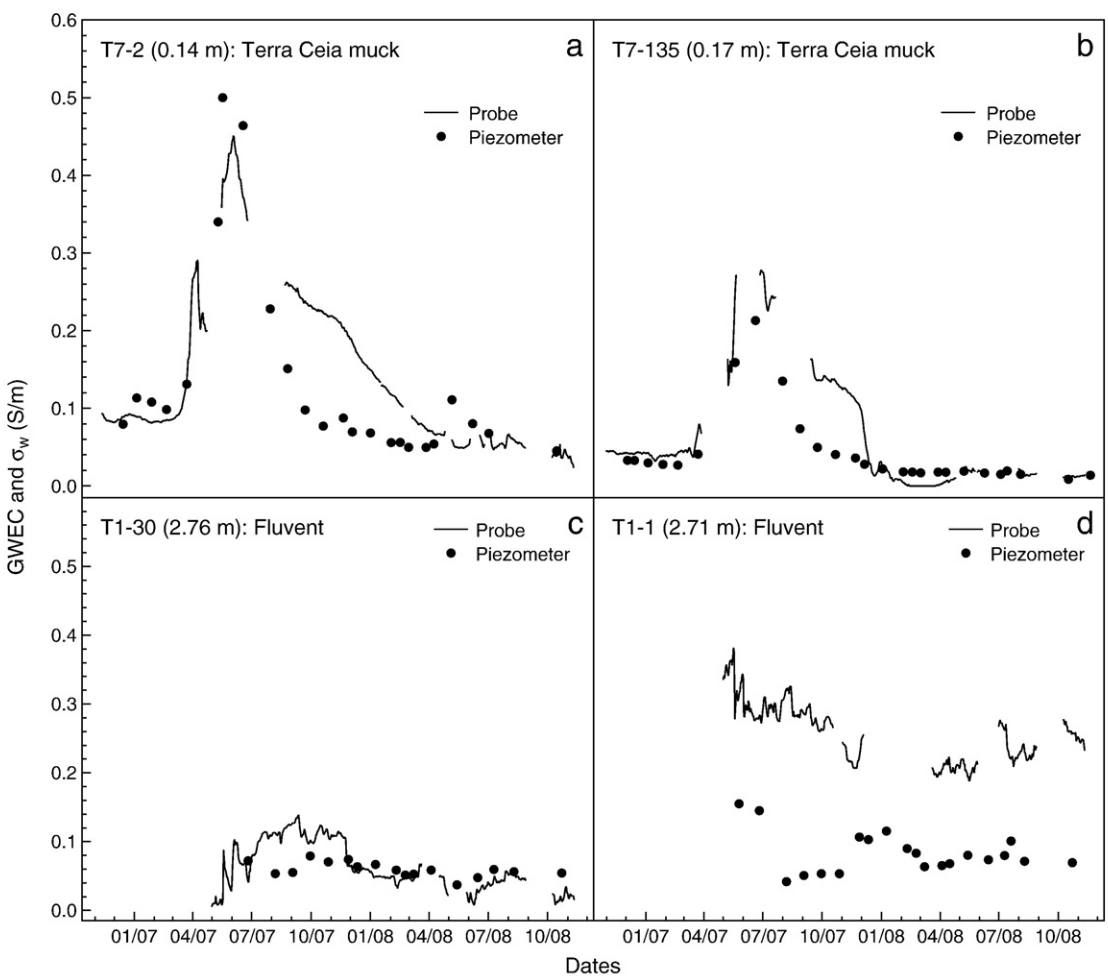

Fig. 9. Comparison of measured groundwater electrical conductivity (GWEC) and porewater electrical conductivity (σ_w) estimated by the dielectric probe using the calibrations developed on this study at: (a–b) two locations on Transect 7 (T7); and (c–d) two locations on Transect 1 (T1) (see Fig. 2). Gaps in probe readings represent missing data.

clearly be beneficial. However, given the natural variability of soils in the field, these results provide a good first estimate of σ_w despite uncertainty in the measurement of θ.

3.3. Field testing of porewater electrical conductivity (σ_w) calibration

Fig. 9 compares σ_w estimated with the dielectric probe (calculated using the calibrations presented herein and the Empirical model) with shallow groundwater EC collected from piezometers in the field when soils were saturated. The calibrated probes do a good job capturing the EC spike on T7 that occurred in the summer of 2007, which was caused by an extended drought, reduced freshwater flow, and a peak in surface water salinity (Kaplan et al., 2010). The probe matched both the timing and the magnitude of the EC peak in Terra Ceia soils close (Fig. 9a) and far (Fig. 9b) from the river on this transect. After the peak, however, the shallow GWEC "freshens" much more quickly than σ_w, which returns to background levels only after nearly 7 months (compared to approximately 4 months for GWEC). This is likely due to the fact that shallow groundwater samples represent freely draining (mobile) water while the probe measures EC in the porewater (mobile and immobile). These data suggest that porewater remains saline considerably longer than groundwater after an incursion of salt water, a potentially important factor for determining the ecological impacts of saltwater intrusion in freshwater wetlands.

Results of the field-testing for fluvent soils on T1 were mixed (Fig. 9c–d). This area does not receive tidal flooding and GWEC samples were less variable relative to those from T7. Values of σ_w measured by the probe at station T1-30 (Fig. 9c) matched GWEC well, however at station T1-1, σ_w was consistently higher than GWEC. This difference in probe response is most likely due to soil heterogeneity in this layered soil. Values of σ_b measured at station T1-1 were also higher than σ_b at T1-30 by ~2–3× (not shown), suggesting that differences in measured EC at these two closely-located, similarly-inundated stations are due to soil properties. Future field experiments to extract porewater for comparison with probe readings (as opposed to GWEC) will help to corroborate these results and provide an improved validation of the laboratory calibrations for these floodplain soils.

Conclusions

A coaxial impedance dielectric sensor was calibrated to three soil series found in the floodplains of the Loxahatchee River (FL, USA), representing a range of mineral to organic soils: Winder fine sand, fluvent, and Terra Ceia muck. These types of probes have rarely been calibrated to highly organic soils, likely due to their unique behavior, (i.e., high shrink/swell potential that makes it difficult to work with in the lab). Specific third-order polynomial relationships were found between the real dielectric constant (ε_r) and θ for each of the soils that improve probe performance compared with standard manufacturer calibrations. Linear relationships were found between the imaginary dielectric constant (ε_i) and bulk electrical conductivity (σ_b), which also differed from the standard calibrations for the fluvent and Terra Ceia muck soils, due to their different dielectric properties. Finally, four equations relating θ, σ_w and σ_b were tested. All four equations performed well in all soils ($0.94 \leq R^2 \leq 0.98$), however the Empirical equation (Vogeler et al., 1996) performed best across all soil series, likely due to additional flexibility from an additional parameter (4 vs. 2 or 3 for other equations). The specific range of σ_b can influence the selection of the best θ–σ_w–σ_b relationship, since some models performed better in particular σ_b ranges than others. These relationships were tested against shallow groundwater EC data collected in the field and found to be useful for comparing the evolution of GWEC and σ_w patterns under saturated conditions.

One limitation to the calibration methodology presented here is that for organic or high clay soils that often shrink when they are dried, reliable measurements of volumetric soil moisture cannot be obtained beyond a certain soil suction (or equivalent water table drawdown). However, the soils investigated here do not usually experience the drawdown needed for shrinkage in the floodplain under field conditions. Care should also be taken if applying these calibrations at higher EC values than tested here. In general, the calibration curves presented here should not be applied at $\theta<0.10$ (for the Winder fine sand); at $\theta<0.50$ (for the fluvent); at $\theta<0.70$ (for the Terra Ceia muck); or at values of $\sigma_w>1$ S/m. This study is among the first attempts to characterize a group of soils representing a wide range of organic matter content and shows that a combined dielectric probe, in conjunction with specific calibrations for each soil series and previously-proposed equations relating θ, σ_b, and σ_w, can be used as a powerful tool to obtain two of the most important state variables in the ecological management of coastal floodplain wetlands: soil moisture and porewater salinity.

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Note: Trade name of dielectric probe is given to identify product. This research was not funded by the probe manufacturer and should not be considered an endorsement of any specific product.

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