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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 ($0.94 \leq R^2 \leq 0.98$) 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-

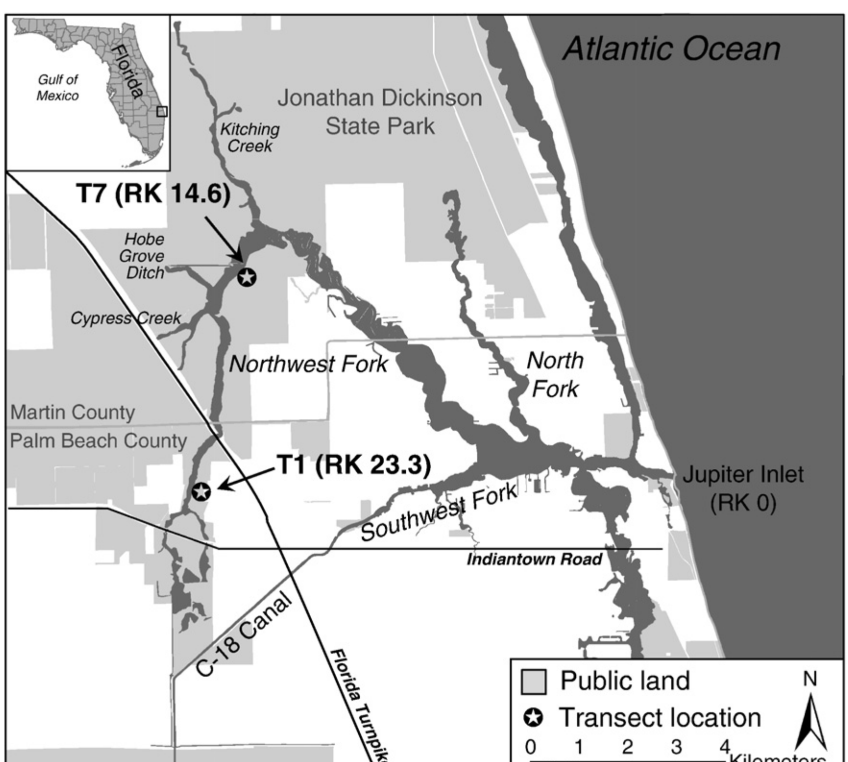

Fig. 1. The Loxahatchee River and surrounding area with experimental transect locations (T1/T7). Transect notation is followed by distance from river mouth (river kilometer, RK). Modified from Kaplan et al. (2010).