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# *In situ* measurement of stem water content and diurnal storage of an apricot tree with a high frequency inner fringing dielectric sensor

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ABSTRACT

Stem water content (StWC) is a key parameter characterizing plant water relations. However, a reliable yet non-invasive method of determining StWC in trees has not been developed. Here we examined an inner fringing frequency domain (FD) sensor in a 12-year old apricot tree. Two strap rings operating at 100 MHz accurately measured StWC in stems 4–12 cm in diameter. Effective sensing depth (ESD) inside the stems, and the allowable maximum stem diameter (AMStD) were systematically evaluated. To determine ESD, a novel experimental method, stepwise stem core removal (SStCR), was developed, and combined with numerical simulation using a High Frequency Structure Simulator (HFSS). The experimental and analytical approaches were in good agreement, demonstrating that the ESD must include substantial sapwood. In apricot, with ring-porous distribution of xylem vessels, performance was excellent up to AMStD ≤ 8 cm following temperature correction. In the current study, we characterize diurnal patterns of water loss and recharge in stems of varying diameter, demonstrate hysteresis in water content between stems of different sizes and heights in the canopy, and evaluate potential interactions with ambient temperature fluctuations. The inner fringing FD sensor can be easily constructed at low cost, suggesting the potential for routine measurement of StWC in diverse woody plants.

## 1. Introduction

Trees rely on internal water storage and resulting capacitance to meet changing evaporative demand and to balance out of phase crown water loss and root water uptake (Tyree and Yang, 1990; Turcotte et al., 2011; Hentschel et al., 2014). The diurnal variation of stem water content (StWC) reflects water discharge out of stem tissues in the early morning and recharge at night, exhibiting an opposite phase to sap flow rate (Fernández and Cuevas, 2010). Tree stems therefore function not only in long-distance transport of water, between roots and leaves via xylem conduits, but also as a water reservoir in the living cells of the bark parenchyma, phloem, and cambium (Lassoie, 1973; Waring and Running, 1978; Waring et al., 1979; Zweifel et al., 2000; Steppe et al., 2006). On one hand, diurnal changes in StWC are closely related to diurnal variation of stem water potential (Holbrook, 1995; Wullschleger et al., 1997; Zweifel et al., 2001; Tyree and Zimmermann, 2002; Dzikiti et al., 2007; Fernández and Cuevas, 2010). On the other hand, stem water storage is an integral part of tree water dynamics, buffering changes in water potential and enabling trees to extend carbon assimilation into drought periods and over winter (Beedlow et al., 2017).

For *in situ* measurement of StWC of plants, diverse sensor techniques have been employed. In general, noninvasive measurement is preferred, in order to avoid damage to stem tissues during sensor installation. However, among currently available noninvasive techniques (Table 1), gamma-ray densitometry poses a potential risk of radiation exposure, which restricts its wide application, though it may be highly accurate. The MRI method is noninvasive and safe, but is expensive and impractical for long-term monitoring of plant water status in the natural environment. An outer fringing frequency domain (FD) sensor has been shown to perform well for soil measurements under ambient conditions (Sun et al., 2006). An inner fringing FD sensor operating at 100 MHz has only been tested in the laboratory and applied to sunflower and tomato under greenhouse conditions (Zhou et al., 2015). This technology has not been applied to woody species, in which capacitance

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**Nomenclature**

| | |
|---|---|
| $T_a$ | Ambient temperature |
| AMStD | Allowable maximum stem diameter |
| $D_c$ | Diameter of experimentally removed core hole from stem |
| ESD | Effective sensing depth |
| EC | Electrical conductivity |
| E-Field | Electric field |
| EM | Electromagnetism |
| $D_e$ | Equivalent distance between two electrodes |
| FEM | Finite element method |
| FD | Frequency domain |
| HFSS | High frequency structure simulator |
| LVDT | Linear variable displacement transducer |
| MRI | Magnetic resonance imaging |
| PPFD | Photosynthetic photon flux density |
| $S_{out}$ | Sensor output |
| $D_s$ | Stem diameter |
| RH | Relative humidity |
| SStCR | Stepwise stem core removal |
| StWC | Stem water content |
| TDR | Time domain reflectometry |
| 2D | Two dimensional |
| VPD | Vapor pressure deficit |

**Table 1**
Previous studies of stem water content (StWC) measurement.

| Sensor type | Setting style | Reference |
|---|---|---|
| Dendrometer or linear displacement transducers (LVDT) | Invasive or Noninvasive | Byram and Doolittle (1950), Phipps and Gilbert (1960), Holmes and Shim (1968), Fernández and Cuevas (2010), Sallo et al. (2017) |
| Gamma-ray densitometry | Noninvasive | Edwards and Jarvis (1983), Brough et al. (1986) |
| Magnetic resonance imaging (MRI) | Noninvasive | Reinders et al. (1988), Windt et al. (2009), Choat et al. (2010), De Schepper et al. (2012) |
| X-ray computer tomography | Noninvasive | Raschi et al. (1995) |
| Time domain reflectometry (TDR) | Invasive | Constantz and Murphy (1990), Holbrook et al. (1992), Wullschleger et al. (1997), Irvine and Grace (1997), Sparks et al. (2001) |
| Frequency-domain (FD) capacitance sensors | Invasive or Noninvasive | Holbrook et al. (1992), Kumagai et al. (2009), Hao et al. (2013), Beedlow et al. (2017) |

The internal structure of woody stems differs from herbaceous plants. Trees have generally.

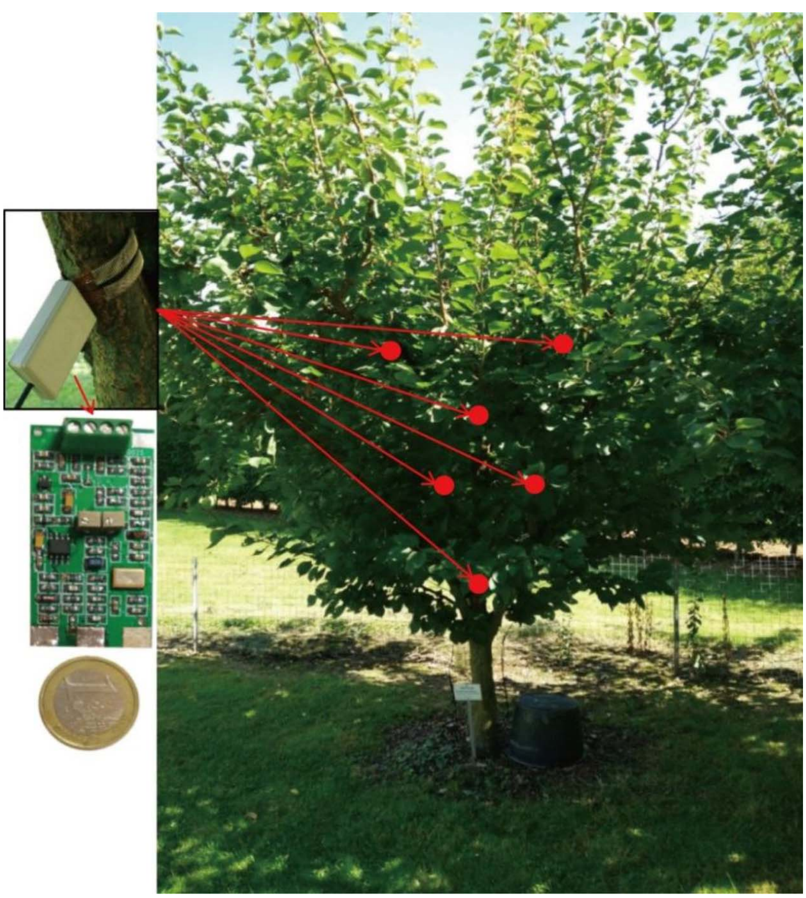

**Fig. 1.** Experimental scene with inner fringing frequency domain (FD) sensors mounted using strap rings on a 12-year-old apricot tree with a series of stem diameters (Ds = 4, 6, 8, 10, and 12 cm). Each strap-ring incorporated an elastic segment to adapt to stem growth. In addition, a sensor was mounted on a cut and dried stem ($D_s$ = 4 cm).

may be substantial and fluctuations in StWC large and critical to drought survival (Tyree and Ewers, 1991). The FD sensor also remains unproven in the natural environment with large diurnal trends in ambient conditions.

The internal structure of woody stems differs from herbaceous plants. Trees have generally larger stems and thicker bark, with potentially large reserves of stored water (Tyree and Ewers, 1991). In trunks and woody stems with substantial bark thickness, the bark