Monitoring of Stem Water Content of Native and Invasive Trees in Arid Environments Using GS3 Soil Moisture Sensors

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Dielectric soil moisture sensors have the potential for nondestructive and real-time monitoring of the stem water content ($\theta_q$) of living trees. This study was conducted to investigate the water use characteristics of trees in drylands through monitoring of $\theta_q$ using newly developed capacitance sensors (GS3). The plants used for data collection were Prosopis juliflora (Sw.) DC. (mesquite, invasive) in Sudan and Tamarix ramosissima Ledeb. (tamarisk, invasive) and Prosopis pubescens Benth. (screwbean mesquite, native) in the United States. The GS3 probes were installed into the trunks of two trees for each species. Stem-specific calibration equations and temperature calibration equations were derived through laboratory experiments and analysis of field observation data. The temperature calibration equations reduced inappropriate variations of $\theta_q$ caused by daily fluctuations in stem temperature, suggesting that these are essential for correct interpretation of monitoring data of $\theta_q$ in arid environments. The $\theta_q$ of the mesquite trees in Sudan clearly increased after heavy rainfall events and started decreasing when the soil water content became close to the wilting point. These findings indicate that mesquite trees use soil water in rainy seasons, even though they are generally considered to use groundwater through deep tap roots. The $\theta_q$ of neither species in the United States responded clearly to rainfall events, indicating that they depend on shallow saline groundwater. The $\theta_q$ of the tamarisk decreased monotonically throughout the monitoring period, apparently in response to feeding damage caused by the tamarisk leaf beetle (Diohabda sp.), which had been released for biological control of tamarisk.

Nondestructive methods of soil water monitoring have long been desired for environmental evaluation and optimum agricultural water management. In recent years, dielectric soil moisture sensors such as time domain reflectometry (TDR), amplitude domain reflectometry (ADR), and capacitance probes have been developed that take advantage of the relatively high permittivity of water to estimate the volumetric water content (e.g., Topp et al., 1980). All types of dielectric moisture sensors output an electrical signal that varies depending on the apparent dielectric permittivity of the sensing volume of porous materials. Because wood is also a porous material, dielectric moisture sensors have the potential for measurement of volumetric water content in wood. If the water content of the trunk (xylem) of living trees can be monitored by dielectric moisture sensors, these sensors can be used to enable suitable irrigation through real-time detection of plant water stress, clarify water use mechanisms of natural trees, and evaluate the water storage ability of tree stems.

Since the 1990s, several trial studies have been conducted to measure stem water content using TDR methodology (Constantz and Murphy, 1990). Holbrook and Sinclair (1992)
estimated the contribution of stem water storage to the water balance of palm trees [Sabal palmetto (Walter) Lodd. ex Schult. & Schult. f.] using TDR in Florida. Nadler et al. (2003) monitored the stem water content of lemon trees [Citrus limon (L.) Burman f.] under different irrigation management programs in Israel with three-rod (70 mm) TDR probes and found that water stress was reflected in the TDR-measured stem water changes but that these changes were too small for routine irrigation control. Irvine and Grace (1997) measured the stem water content of Scots pine (Pinus sylvestris L.) using short (50-mm) TDR probes. Nadler et al. (2006) also monitored the stem water content of a mango tree (Mangifera indica L.) in Israel using short (29–70-mm) TDR probes and found that the response of the stem water content to root zone applied salinity and water stress were negative and positive, respectively. Sparks et al. (2001) monitored the stem water content, ice fraction, and losses in xylem conductivity of lodgepole pine (Pinus contorta Douglas ex Loudon) using TDR probes in Idaho. Hernández-Santana et al. (2008) measured the stem water content of two Mediterranean Quercus species in Spain using TDR and reported seasonal variation of the stem water content associated with decreases in water available in the soil. Kumagai et al. (2009) measured the sap flow and stem water content of Japanese cedar and cypress using constant-heat sap flow probes and ADR probes and confirmed that stem water storage has impacts on the transpiration stream. Development of species-specific equations describing the relationship between probe output (apparent dielectric permittivity) and stem water content are also important to the accurate determination of stem water content (Wullschlégler et al., 1996; Hernández-Santana and Martínez-Fernández, 2008). Zhou et al. (2015) developed a new frequency domain inner fringing capacitor sensor for measuring the stem water content of crops.

Although several studies have been conducted to evaluate stem water, there have been few studies to monitor the stem water content of wild trees in arid environments using dielectric sensors. Wild trees in arid regions have efficient water use characteristics to cope with limited water resources so that they can survive harsh conditions. Additionally, a new dielectric moisture sensor that uses the capacitance method, the GS3 probe (Decagon Devices Inc.), has been developed. This probe may be an alternative to TDR and ADR probes because it is inexpensive, tough, and easy to operate. Hao et al. (2013) used this probe to monitor the stem water content of paper birch (Betula papyrifera Marshall) trees in Massachusetts. Thus, the main objective of this study was to investigate the water use characteristics of trees in arid environments through monitoring of soil and stem water content using GS3 and other dielectric moisture probes. In addition, the outputs of dielectric moisture sensors are usually affected by temperature (e.g., Wraith and Or, 1999; Fares and Polyakov, 2006), and large temperature variations in arid environments appear to seriously impact probe outputs. Therefore, temperature calibrations were conducted in addition to stem-specific calibrations (water content calibrations), and the importance of temperature calibration was determined.

Materials and Methods

Plant Materials

The plants used for data collection were Prosopis juliflora, Tamarix ramosissima, and Prosopis pubescens. Prosopis juliflora, commonly known as mesquite, is native to South and Central America and the Caribbean but has been introduced into arid and semiarid regions worldwide (Gallaher and Merlin, 2010; Pasiecznik et al., 2001). Mesquite is a typical phreatophyte that extends its roots rapidly into deep aquifers (Nilsen et al., 1983). Because mesquite can use groundwater through deep tap roots, this species can survive in arid environments and thus efficiently compete with many native plant species (Pasiecznik et al., 2001). As a result, mesquite is listed as one of the world’s 100 worst invasive alien species (World Conservation Union, 2004). In addition to destroying ecological systems, mesquite depletes subsurface water resources. Yasuda et al. (2014) observed that changes in the groundwater level (about the 23-m depth) closely followed root water uptake by mesquite in Sudan.

Tamarix ramosissima (tamarisk, also known as saltcedar) is native to southeastern Europe and Asia and is a major invasive species in southwestern and arid regions in the United States. Tamarisk is also listed as one of the world’s 100 worst invasive alien species because it causes reduced biodiversity in riparian zones (Bateman and Paxton, 2010). Tamarisk is a salt-tolerant species that spreads rapidly in river systems by using shallow saline groundwater (Imada et al., 2012). In 2001, the northern tamarisk leaf beetle (Chrysomelidae: Diorhabda carinulata Desbrocher) was released in the United States for the biological control of Tamarix spp. (DeLoach et al., 2003). The beetles feed on the epidermis of stems and leaves, causing partial or complete defoliation of tamarisk multiple times throughout a growing season, eventually resulting in tree mortality. Prosopis pubescens (screwbean mesquite) is native to the southwestern United States and therefore has a high tolerance for hot and dry environments (Zappala et al., 2014). Although screwbean mesquite has also been introduced to areas in India, Pakistan, and southern and southwestern Africa, these introductions have rarely been successful.

Dielectric Moisture Sensors

GS3 dielectric probes (Decagon Devices Inc.) were used to monitor the stem water content of trees in this study. The GS3 probes use the capacitance method and are well known as low-cost, commercially available soil moisture sensors. In addition to water content, GS3 probes can measure bulk electrical conductivity and temperature. The GS3 has three rigid steel needles (5.5 cm in length and 0.30 cm in diameter) as sensing probes and can therefore be installed into stems. Before installing the probes, the skins of the target stems were shaved, after which holes slightly larger (0.32 cm in diameter) than the steel needles were drilled into the stems using an electric drill. It should be noted that a special drill guide was made and used to drill the holes in some stems to alleviate
the need to train the operator on how to drill the holes without the guide. The probes were gently hammered until the needles were completely installed into the stems, after which the slight gaps between the sensor overmold and the stems were sealed with silicone caulking to prevent infiltration of rainwater and evaporation of stem water. The edges of the needles were also sealed in case the lengths of the needles were longer than the diameter of the stem. The entire sensors and stems were covered with aluminum heat-insulating materials to reduce heating by direct sunlight. The temperature sensor of the GS3 probe is not in the tree needles but rather in the sensor overmold. The temperature measured at the sensor overmolds (on the surface of the stems) was considered to be the stem temperature in this study; however, the actual temperature in the stems might have been slightly different.

Another type of dielectric moisture sensor, ECH2O probes (Models 5TM, 5TE, and 10HS, Decagon Devices Inc.), was used to monitor the soil water content. All probes, including the GS3, were connected to EM50 dataloggers (Decagon Devices Inc.), and data were recorded every 10 to 30 min throughout the monitoring period.

Study Sites

Two study sites were established in Sudan and the United States in 2012. The Sudan site was established in a Prosopis juliflora community in Soba, Khartoum (15°31′8.3″ N, 32°36′52.2″ E), next to the campus of the College of Forestry and Range Science, Sudan University of Science and Technology. Annual precipitation at the site is about 150 mm, and the rainy season is from June to September. The groundwater level at this site was about 25 m. Two Prosopis juliflora trees were selected for installation of GS3 probes (hereafter PS1 and PS2) to monitor the stem water content in June 2012. The diameters of the stems of PS1 and PS2 were 7 and 4 cm, respectively. Additionally, three ECH2O 5TM probes were set at soil depths of 5, 15, and 30 cm near the trees (Fig. 1). The monitoring data from July 2012 (the beginning of the rainy season) to October 2012 (the end of the rainy season) were analyzed in this study.

The site in the United States was established in a mixed community of Tamarix ramosissima and Prosopis pubescens in Mesquite, NV (36°42′8.9″ N, 114°15′29.3″ W) near the Virgin River. The study site has an annual precipitation of about 400 mm and a groundwater level of about 1 m. In addition, the salinity of the groundwater was high (electrical conductivity = 18 dS m⁻¹), and salt accumulation was observed at the soil surface. Two Prosopis pubescens trees (hereafter PU1 and PU2) and two Tamarix ramosissima trees (hereafter TU1 and TU2) were selected for installation of the GS3 probes in April 2012. The diameters of the stems of PU1, PU2, TU1, and TU2 were 8, 11, 8, and 9 cm, respectively. The soil water content was measured using ECH2O 5TE probes at depths of 5 and 30 cm and an ECH2O 10HS probe at 80 cm. Monitoring at this site was conducted from April 2012 to November 2013; however, the soil water content for PU1 and PU2 are partly lacking because of problems with the probes and dataloggers. Meteorological conditions (precipitation, air temperature and humidity, wind speed and direction, global solar radiation, and barometric pressure) were monitored at both the Sudan and US sites. Pressure-type water level gauges were set in observation wells (at the 25-m depth in the Sudan and 2.5 m in the United States) to monitor groundwater levels at both sites.

Water Content and Temperature Calibration

Laboratory calibration experiments were performed to elucidate the relationships between probe outputs and the actual water content in the stems. The stems with GS3 probes at the US site were cut and brought back to the laboratory for the calibration experiments. The stems at the Sudan site could not be cut because the monitoring continued. Therefore, stems with the same diameters as PS1 and PS2 were cut from other trees and new GS3 probes were installed into these samples. These sample and probe combinations were then used as substitutes for PS1 and PS2 in the calibration experiments.

The output of the GS3 is the volumetric water content calculated by the default calibration equation provided by the manufacturer (Decagon Devices, 2011). This probe output is referred to here as the apparent water content (\( \theta_p, \text{m}^3\text{m}^{-3} \)). Initially, the stem samples with the probes were placed into water for >2 wk. After confirming that there had been no change in the probe output (\( \theta_p \))
and the weight of the samples, meaning that the samples had been almost saturated, the stem water content was changed by evaporation in seven or eight steps between near saturation and air dry for each stem. At each water content step, the values of the actual stem water content were calculated by the weight of the stem with the probe using an electronic balance. These water content values are referred to here as actual $q_a$ ($m^3 m^{-3}$). All experiments were conducted under a constant temperature condition ($25 ^\circ C$). The relationships between the actual water content ($q_a$) and apparent water content ($q_p$) are shown in Fig. 2. Root mean square errors (RMSEs) between $q_a$ and $q_p$ are also shown in Table 1. For stems at the US site, $q_p$ was in relatively good agreement with $q_a$ (RMSE = 0.0307–0.0724 $m^3 m^{-3}$), indicating that the default calibration equations for soils provided by the manufacturer can be used to estimate the stem water content with relatively high accuracy for some tree species. The relationship between $q_p$ and $q_a$ was fit using a second-degree polynomial function for every stem and probe combination:

$$g(\theta) = a_0 + a_1 \theta + a_2 \theta^2$$

[1]

where $a_0$ to $a_2$ are the fitting coefficients (Table 1).

Monitoring by the GS3 probes was severely affected by changes in temperature in the stems, even though the stems were covered with heat-insulating materials. Therefore, a calibration method proposed by Saito et al. (2009) was applied to reduce the temperature effect. In this method, the probe output ($q_p$) is expressed by combining the calibration equations for water content (first term) and temperature (second term):

$$\theta_p = g(\theta) + f(\theta)(T - T_r)$$

[2]

where $T$ is the temperature of the medium and $T_r$ is the reference temperature ($25 ^\circ C$), $g(\theta)$ is the relationship between $\theta_p$ and $\theta_a$ at $T_r$ (Fig. 2 and Eq. [1]), $f(\theta)$, which is the relationship between $dq_p/dT$ (the slope values of the linear responses of $\theta_p$ to $T$) and $\theta$, indicates the temperature dependence of $\theta_p$ on water content and was obtained by applying temperature changes to samples under constant water content steps in the calibration experiment. The detailed derivation was shown by Saito et al. (2009). Furthermore, Saito et al. (2013) proposed an approach to derive $f(\theta)$ through analysis of time series of field observation data without conducting laboratory experiments. Although this approach was originally developed for monitoring soil water content, it was applied to the monitoring results of the stem water content in the present study. In this approach, $f(\theta)$ can be derived using maximum and minimum soil temperatures and the daily variation in $q_p$ for each day in a monitoring period, on the assumption that daily variations in

<table>
<thead>
<tr>
<th>Tree †</th>
<th>RMSE $g(\theta)$</th>
<th>$a_0$</th>
<th>$a_1$</th>
<th>$a_2$</th>
<th>$f(\theta)$</th>
<th>$b_0$</th>
<th>$b_1$</th>
<th>$b_2$</th>
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<tbody>
<tr>
<td>PS1</td>
<td>0.0617</td>
<td>0.1416</td>
<td>0.3742</td>
<td>0.2861</td>
<td>−0.0075</td>
<td>0.0452</td>
<td>−0.050</td>
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<tr>
<td>PS2</td>
<td>0.0952</td>
<td>0.1836</td>
<td>0.040</td>
<td>0.5439</td>
<td>0.0003</td>
<td>−0.001</td>
<td>0.0112</td>
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<tr>
<td>PU1</td>
<td>0.0469</td>
<td>0.0744</td>
<td>0.8852</td>
<td>−0.3719</td>
<td>−0.0938</td>
<td>0.4615</td>
<td>−0.5609</td>
<td></td>
</tr>
<tr>
<td>PU2</td>
<td>0.0724</td>
<td>0.1029</td>
<td>0.9786</td>
<td>−0.6379</td>
<td>−0.0002</td>
<td>0.0126</td>
<td>−0.0227</td>
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</tr>
<tr>
<td>TU1</td>
<td>0.0371</td>
<td>0.0986</td>
<td>0.2947</td>
<td>0.9476</td>
<td>−0.0056</td>
<td>0.0289</td>
<td>−0.0234</td>
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</tr>
<tr>
<td>TU2</td>
<td>0.0307</td>
<td>0.0388</td>
<td>1.0087</td>
<td>−0.1866</td>
<td>−0.0062</td>
<td>0.0424</td>
<td>−0.0529</td>
<td></td>
</tr>
</tbody>
</table>

† PS1 and PS2, Prosopis juliflora at the Sudan site; PU1 and PU2, Prosopis pubescens at the US site; TU1 and TU2, Tamarix ramosissima at the US site.
were caused only by daily fluctuations in $T$ except for rainy days. The $\theta_p$ and $T$ values for the Sudan site (July–October 2012) and the US site (March–September 2013) were analyzed, after which $f(\theta)$ was derived using the responses of $\theta_p$ to daily fluctuations in $T$ for each stem and probe combination, and $f(\theta)$ was fit using a second-degree polynomial function for every stem and probe combination:

$$f(\theta) = b_0 + b_1\theta + b_2\theta^2$$  \[3\]

where $b_0$ to $b_2$ are fitting coefficients (Table 1). Substituting Eq. [1] and [3] into Eq. [2] gives the calibration equation describing the probe output ($\theta_p$) as a function of $\theta$ and $T$. The calibrated water content was obtained by solving Eq. [2] by substituting the values of $\theta_p$ and $T$ from the GS3 probes and $T_r (= 25)$ into the equation for every stem and probe combination. The same approach was applied to the soil water content monitoring results at the Sudan site by the ECH2O 5TE probes because these were also affected by soil temperature.

## Results and Discussion

### Temperature Calibration and Daily Variation in Stem Water Content

Examples of comparisons of the calibrated stem water content ($\theta_{st}$, m$^3$ m$^{-3}$) with the apparent stem water content ($\theta_p$) are presented in Fig. 3. The $\theta_p$ of both PS1 and PU2 showed clear daily variations that correspond to the daily fluctuation of $T$. In contrast, such variations in $\theta_{st}$ were remarkably reduced, indicating that the approach of Saito et al. (2013) successfully reduced the effects of the daily fluctuation of $T$ on $\theta_{st}$. The $\theta_{st}$ of PS1 increased clearly after the rainfall event. It appeared that $\theta_p$ of PS1 also increased after the rainfall event; however, it is difficult to judge whether this increase in $\theta_p$ was caused by the rainfall event because $T$ also increased after the rainfall event. The $\theta_p$ of PU2 did not appear to respond to the rainfall event at all, even though $\theta_{st}$ clearly responded. These results suggest that temperature calibration is essential for correct interpretation of monitoring data of stem water content in arid environments.

Although the temperature calibration remarkably reduced the effect of $T$, $\theta_{st}$ still showed slight variations that seemed to be caused by daily fluctuations in $T$. Similar slight variations were also seen in all other stems in this study, suggesting that the daily variations in stem water content caused by water consumption (transpiration) and/or storage (root water uptake) within 1 d could not be observed because of error in the temperature calibration. This probably occurred because (i) the daily variation in stem water content of trees in arid environments was originally too small to be detected by the GS3 probe considering the error of the temperature calibration, and (ii) the daily fluctuation of $T$ in the thin stems (4–11 cm in diameter) was large in the arid environments. Moreover, the differences between $T$ measured at the sensor over-molds and the actual temperature in the stems might have affected the results of the temperature calibration. Therefore, (i) improvement of the calibration method, (ii) further ingenuity to reduce temperature variations of stems, and (iii) additional monitoring of
the temperature inside the stems may be needed to evaluate daily variations in stem water content in arid environments.

**Monitoring Results for the Sudan Site**

Variations in $\theta_{st}$ of the mesquite trees, soil water content, daily mean stem temperature (PS1), and daily precipitation in the rainy season in 2012 are shown in Fig. 4. The groundwater level data (24.8 m deep on average) are not shown because the data had been disturbed frequently by the effect of pumping from nearby wells.

First, we focus on the variation in $\theta_{st}$ of PS1. On 30 July, 10.4 mm of precipitation was observed at the site and only the soil moisture sensor at 5 cm responded to this event. On 1 and 2 August, a total of 47.0 mm of precipitation was observed and the soil water content at 15 and 30 cm increased drastically, at which point the $\theta_{st}$ of PS1 increased clearly. These findings suggest that PS1 used the soil water below the 15-cm depth after the heavy rainfall event. Although the soil water content started decreasing the next day, $\theta_{st}$ of PS1 increased continuously with time, and the maximum value reached 0.64 m$^3$ m$^{-3}$ on 29 August. The $\theta_{st}$ started decreasing from next day, at which point the soil water content at the 15-cm depth was 0.19 m$^3$ m$^{-3}$ and at 30 cm was 0.21 m$^3$ m$^{-3}$. These soil water content values were approaching the water content at the wilting point (0.18 m$^3$ m$^{-3}$) obtained from the water retention curve of the soil at this study site, indicating that $\theta_{st}$ started decreasing because root water uptake became difficult owing to drying of the soil. These results suggest that *Prosopis juliflora* uses soil water from below 15 cm during rainy seasons, even though this species is generally considered to use groundwater through deep tap roots. The $\theta_{st}$ of PS2 also responded to the rainfall events; however, the values and variations of $\theta_{st}$ of PS2 were smaller (0.20–0.30 m$^3$ m$^{-3}$) than those of PS1 (0.38–0.64 m$^3$ m$^{-3}$) throughout the monitoring period. One of the reasons may have been because the stem of PS2 was thinner (4-cm diameter) than that of PS1 (7-cm diameter).

A large variation in $\theta_{st}$ between the dry season (0.38 m$^3$ m$^{-3}$) and rainy season (0.64 m$^3$ m$^{-3}$) was observed, meaning that a large amount of water was stored in the stem in the rainy season. Waring et al. (1979) estimated that 30 to 50% of the transpired water was extracted from water stored in the stem sapwood of Scots pine. Holbrook and Sinclair (1992) estimated that water stored in the stem supplied 20 to 40% of the total water lost by transpiration of palm trees. The water stored in the stem of mesquite in Sudan also seemed to contribute considerably to transpiration, especially after 30 August when the soil was dry and only $\theta_{st}$ decreased. However, it is difficult to perform a quantitative evaluation for the contribution only from $\theta_{st}$ monitoring because the daily consumption and storage of the stem water could not be observed due to the remaining error in the temperature calibration. Further studies to enable accurate monitoring of $\theta_{st}$ and the combinatorial monitoring of $\theta_{st}$ and other factors (e.g., sap flow and transpiration measurements) related to the water use characteristics of trees are warranted.
Monitoring Results for the US Site

Variations in $\theta_s$, soil water content, groundwater level, daily mean stem temperature (TU1), and daily precipitation from April 2012 to November 2013 are shown in Fig. 5. The groundwater level was shallow (1.23 m deep on average) throughout the monitoring period and showed a reverse trend from the stem temperature, i.e.,
The soil water content at the site was basically high because of (i) a continuous supply of capillary water from the groundwater and (ii) overestimation of capillary water from the groundwater caused by the salinity dependence of the ECH2O probes (e.g., Saito et al., 2008) because the groundwater at the site is shallow and saline (electrical conductivity: 18 DS m−1). The θ_{st} of both tree species responded to some rainfall events (A, B, and C in Fig. 5); however, variations having no relationship with rainfall were also seen. Furthermore, the responses to the rainfall events were weaker than those of Prosopis juliflora at the Sudan site. These results indicate that Prosopis pubescens and Tamarix ramosissima at this study site depend on the shallow saline groundwater without depending heavily on rainwater. It was found that both species at this site depend on groundwater because the stable O isotope ratios of water in the stems of both species were almost equal to that of the groundwater (Saito et al., 2014). These results also indicate that Prosopis pubescens has salt tolerance equal to that of tamarisk, which is well known to be tolerant of high salt levels. The θ_{st} of PU1 and PU2 appeared to decrease sharply several times in winter (D in Fig. 5); however, these were not actual decreases in water content but rather the result of decreased permittivity in response to partial freezing of the stem water.

The long-term variations in θ_{st} of the screwbean mesquite and tamarisk were significantly different throughout the monitoring period. The values of θ_{st} for PU1 and PU2 at the beginning of the monitoring period were 0.37 and 0.29 m3 m−3, respectively, while they were 0.40 and 0.36 m3 m−3 at the end of the monitoring period. In contrast, θ_{st} of TU1 and TU2 showed a monotonic decrease, with lower levels occurring during summers and almost constant levels during the other seasons. This appeared to be in response to damage caused by feeding on the trees by the tamarisk leaf beetle, which had been released as a biological control measure. At the US site, large outbreaks of the beetles were observed in 2012 (after their arrival at the site in 2011), and the leaves of the tamarisk trees are fed on repeatedly throughout the growing season. Therefore, the tamarisk trees did not maintain normal vital activities including root water uptake and transpiration owing to a lack of leaves; hence, they were not able to acquire enough water to maintain the stem water content, especially during summer.

**Conclusions**

Monitoring of θ_{st} of mesquite, tamarisk, and screwbean mesquite trees was conducted using newly developed capacitance sensors (GS3) under different arid environments. Monitoring of θ_{st} and the soil water content clarified the various water use characteristics of these trees. The mesquite trees in Sudan used soil water during the rainy season, even though this species is generally considered to use groundwater obtained through deep tap roots. The trees at the US site depend on the shallow saline groundwater without heavily depending on rainwater. Monitoring of θ_{st} indicated that the condition of the tamarisk trees was declining because of feeding damage caused by the tamarisk leaf beetle. These findings indicate that dielectric sensors may be useful as tools for evaluating the biological control of tamarisk.

The temperature calibration equations derived though analysis of field observation data greatly reduced variations in θ_{st} caused by daily fluctuations of stem temperature, suggesting that these are essential for correct interpretation of θ_{st} monitoring data collected from arid environments. However, daily variations of θ_{st} caused by water consumption (transpiration) and/or storage (root water uptake) within 1 d could not be observed because of the remaining error in the temperature calibration. Accordingly, further improvements in the calibration method and measurement techniques are needed. Simultaneous analysis of θ_{st} and the electrical conductivity and/or sap flow also has the potential to clearly quantify the water use characteristics of trees. Further studies to enable accurate monitoring of θ_{st} and the combinatorial monitoring of θ_{st} and other factors related to the water use characteristics of trees are warranted.

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