Relations between Soil and Tree Stem Water Content and Bulk Electrical Conductivity under Salinizing Irrigation

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ABSTRACT

In a semiarid region in a grapefruit (Nucellar 'Marsh seedless, *Citrus paradise* Macf.) orchard irrigated with salinized waters, the water content (θ) and bulk electrical conductivity (σ_a) of the trees' stems and the root-zone soil was monitored by time domain reflectometry (TDR) and electrical conductivity meter for a year. For the purpose of irrigation scheduling the objective was to verify correlations between (i) stem and soil θ and (ii) stem and soil σ. Measured θ_{soil} and $\sigma_{a,\,soil}$ were in good agreement with the irrigation treatments, peaking in summer and decreasing during autumn. Only a weak correlation between stem's σ_a and θ and the soil's parameters was found and attributed to time after installation of probes in the stem; the higher $\sigma_{a,\,stem}$ (5–10 $\times$ 10^{-2} dS m^{-1}), measured up to three months after installation, were accredited to the salt content of ruptured stem cells. After curing of the installation wound the insulating effect of the cells' membranes may explain the lower $\sigma_{a,\,stem}$ (2–5 $\times$ 10^{-2} dS m^{-1}) measured 3 to 12 mo after installation. Periods of θ_{soil} increase (day of year [DOY] = 80–200, and 200–280) observed by the soil probes indicated surplus irrigation. Presently the rate, intensity, and variability of the grapefruit stem reaction to soil water status and salinity leaves the soil parameters as better indicators for accurate irrigation scheduling.

In arid regions salinization of good quality water sources caused by extensive water recycling is gradually pushing farmers to irrigate with low quality waters. In such regions irrigation is essential to avoid yield losses during long periods without rainfall. In Israel approximately 8000 ha of citrus orchards, recently planted in the southwestern semiarid Negev region, are irrigated with treated sewage waters (TSW). Present day Cl^-_{irr} and Na^+_{irr} content (approximately 220–240 and 130 mg L^{-1}, respectively) of these waters are expected to deteriorate to 350 and 195 mg L^{-1}, respectively, in a few years.

Using marginal water requires maintaining a delicate balance between water and salt stresses and farmers will welcome monitoring tools that will enable more accurate irrigation rates and early warning of hazardous buildup of salinity. Commonly, the soil θ and salinity levels are monitored assuming a close and positive correlation with these levels in the plant. However, the number and location of the probes needed (e.g., tensiometers, TDR) to represent the constantly changing roots depth distribution and effective size are unknown. Direct measurement of stem θ and σ reflects trees water needs and will eliminate the need to find the integrated effect on the plant of salinity and water distribution in the root zone as a function of soil type, growing season, irrigation technology, and crop morphology.

Previous studies based on direct stem sampling and indirect measurement of θ_{stem} (reduction in stem diameter or Ψ, Naor et al., 1995) have found that in water-stressed trees stems may give up to half their stored waters to the leaves (Waring and Running, 1978) before recharged by the roots. Preliminary sampling of leaves and stem in the present study orchard showed for three rootstocks good correlations among X_{irr}–X_{xylem}–X_{leaves}, where X is Cl^- or Na^+ (Levy et al., 1999).

The TDR technology, which can accurately measure θ and resistivity of mineral and organic matrixes, was used in soil and stem.

Nadler et al.'s (1984) protocol was used to calculate the σ of the pores soil solution (σ_w). Transforming $\sigma_{a,\,stem}$ measurements of the living organism into σ of the sap flow may not be as simple as for soils. Parameters not directly related to the salinity of the irrigation water, like nonuniform stem cross-section distribution of θ_{stem} and σ, or plant disease, may affect $\sigma_{a,\,stem}$–C_{irr} relations. Access to an experiment testing white grapefruit rootstock tolerance to salinity (Cl^- ~ 230–800 mg L^{-1}) enabled our study of soil–stem relations. The objective was to verify if there is a relationship between (i) stem and soil water content ($\theta_{stem} - \theta_{soil}$) and (ii) bulk electrical conductivity of the stem ($\sigma_{a,\,stem}$) and soil solution electrical conductivity ($\sigma_{w,\,soil}$). A good correlation may help in irrigation scheduling and give an early warning of hazardous salinity levels.

MATERIALS AND METHODS

Experimental Design

The study was performed in an experimental grapefruit orchard grafted on three different rootstocks (troyer citrange [*Citrus sinensis* × *Poncirus trifoliata*], cleopatra [*Citrus Reshni* (*Reticultar*)], and volkameriana [*Citrus Volkameriana Chapot*]) at Bsor experimental farm, in the southwestern Negev region (31.15°N, 34.25°E) of Israel (Levy et al., 1999). Climate is Mediterranean with hot, dry summer and warm, rainy winter (November–March). The annual precipitation ranges 150 to 350 mm yr^{-1} (average = 280 mm yr^{-1}). Evaporation rate of a Class A pan stationed 0.4 km away was 220 ± 40 mm mo^{-1} during the summer. The orchard was planted in July 1966 at a distance of 6 by 3 m on a fine sand regosol (Xeric Torripsament) of 40 to 50 clay, 50 to 70 silt, 700 fine sand, and 180 to 220 g kg^{-1} of coarse sand. Groups of three trees along the row received different salinity levels increasing in five steps along the row. The trees were irrigated twice a week at a rate

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Abbreviations: C_{ionic}, ionic concentration; l_a, apparent length of a transmission line (=dielectric length); TDR, time domain reflectometry; TSW, treated sewage water; θ, volumetric water content (m^3 m^{-3}); σ, bulk electrical conductivity (dS m^{-1}); ε, dielectric constant; ψ, water potential.

of 3.0 mm d^{-1} between May to October. The irrigation water consisted of TSW (Cl^{-} = 220–240 mg L^{-1}, 1.5 ± 0.2 dS m^{-1}; the 0.4 dS m^{-1} salinity range depends on TSW dilution ratio with rainwater during winter underground storage). Concentrated saline solution was prepared by dissolving $CaCl_2$ and NaCl at a 1:2 ratio (w/w) and was injected into the irrigation system by a hydraulic fertilizer pump, controlled by an irrigation computer which received its feedback from inline σ and temperature sensors.

The five salinity levels were achieved by dilution and the amount of irrigated water was equal in all salinities and all rootstocks (Levy et al., 1999).

TECHNIQUES

The dielectric constant of water ($\varepsilon_w \approx 80$) is larger than that of other soil constituents ($\varepsilon_{air} = 1$, $\varepsilon_{solids} = 2$–5) and any change in ε_{bulk} of the composite material (water, soil, air) reflects a change in θ (Topp et al., 1980). An empirical relationship converts TDR measurements of ε into θ values. Two calibration equations were used: Topp et al. (1980) for the soil, and Wullschleger et al. (1996) for the stem. Wullschleger et al. (1996) produced a single calibration curve for four different tree species (red maple [*Acer rubrum* L.], white oak [*Quercus alba* L.], chestnut oak [*Quercus prinus* L.], and black gum [*Nyssa sylvatica* Marsh.]) that were in good match with Constantz and Murphy (1990) calibration. The combined data were fitted to the a second-order quadratic equation

$$\theta = -0.251 + 4.66 \times 10^{-2}\,\varepsilon - 4.93 \times 10^{-4}\,\varepsilon^2 \quad [1]$$

Similar calibration equations were obtained by Green and Nadler (unpublished data) from kiln dry wood blocks that, after saturation with water under a vacuum, were equilibrated at different pressures on a standard soil pressure plate. The gradually drying blocks were then weighed and ε was determined by TDR in the moist wood after each drying stage.

Soil Water Content

Five TDR probes were installed into the root-zone soil of each tree. The soil TDR probes were 200 mm long and made from three rods of 3-mm diameter stainless steel, at 50 mm spacing. The soil probes were installed vertically at depths of 0.1 to 0.3, 0.3 to 0.5, 0.5 to 0.7, 0.7 to 0.9, and 0.9 to 1.1 m below the soil surface. A 4.0-m coaxial cable (RG58U) connected each of the probes to a cable tester (Tektronix 1502B, Tektronix, Beaverton, OR). The apparent length, l_a, was determined from the TDR trace by manual identification of the probe's end-point reflection. The apparent dielectric is calculated using: $\varepsilon = (l_a/l)^2$, where l (mm) is the actual length of the TDR probes (70 for stem probes and 200 for the soil probes) and converted to θ_{soil} by Topp's equation. Under the experiment salinity levels, and according to a recent review (Robinson et al., 2003), the maximal salinity effect on θ_{soil} is <0.01 m^3 m^{-3}.

Stem Water Content

Three TDR probes were installed into the stem of each tree. Holes of 2.9 mm in size were drilled, through a metal leader 0.3 to 0.6 m above the soil level and the probes were installed (two horizontally, namely, rod planes in right angles to the stem) and the third was installed vertically (namely, rods in plane parallel to the stem) into the 0.12- to 0.13-m trunk. The stem probes were 70 mm long three rods of 3-mm diameter stainless steel at 20-mm spacing and were installed some 50 d before measurements commenced, to minimize the risk of wound recovery effects (Wullschleger et al., 1996). In total 18 trees each had three TDR probes installed: 10 troyer trees (duplicating all five salinities), four cleopatra trees (duplicating the two extreme salinities), and four volkameriana trees (duplicating the two extreme salinities). Stems diameter ranged 0.13 ± 0.01 m, implying rods penetration to the center of the stem. The $l_{a,\,stem}$ was manually measured with the1502 Cable tester and converted into θ_{stem} using Eq. [1].

Measuring σ_a and Calculating σ_w of Both the Soil Pores and the Stem Xylem Solutions

A portable electrical conductivity meter (EcoScan Con5 EUTECH Instruments, Singapore) was used to manually measure the bulk stem σ at the same time that θ was measured. Applying an existing protocol (Nadler et al., 1984) on θ and σ_a and using air-dry water content to identify the soil texture we have calculated the σ of the soil solution (σ_w, Fig. 1). For salt mass balance calculations an effective root-zone volume = 2.5 m^3 was assumed. The protocol was found unsuitable for evaluating $\sigma_{w,\,stem}$. Maximal accumulated salts in the root zone ranging 27.8 to 51.6 (mmol 2.5 m^{-3}, Fig. 2) were calculated by summing up the product $\theta \times \sigma_w$ for each soil layer, assuming 1 dS m^{-1} ~ 0.01 mmol and $V_{root\ zone}$ = 2.5 m^3.

RESULTS

Variability

In spite of the careful planning, θ and σ_a variability in all treatments was large and scatter is demonstrated for the stem probes (Table 1) on an arbitrary day (DOY = 193). The wide variability is natural (tree size, transpiration, fluctuations in size of salinity residing in the stem center) and technical (faults in salt injection pump, lines plugging). The reader's attention is drawn to three extreme examples: (1) The wide range of θ_{stem} measured by the three probes installed in the troyer (Fig. 1, 2nd column), or in the cleopatra, and volkameriana (SE_θ = 0.04–0.10 m^3 m^{-3}, Table 1). These wide ranges are in agreement with similar water content distributions in stems of oaks and redwoods ($\Delta\theta$ = 0.08–0.26 m^3 m^{-3}, Constantz and Murphy, 1990), in red maple and white oak (Wullschleger et al., 1996), and in pines (Irvine and Grace, 1997). (2) In the troyer, under three different irrigation waters (σ_{irr} = 2.5, 2.9, and 3.4 dS m^{-1}), salts have accumulated to similar levels (47.0, 49.1, and 47.6 mmol 2.5 m^{-3}, respectively, Fig. 2c). (3) Trees 17 and 18 (volkameriana, σ_{irr} = 3.4 dS m^{-1}, Fig. 2b) got the same irrigation waters and belong to the same tree triplet, but have maximal salt accumulation of 41.6 and 52.5 mmol 2.5 m^{-3}, respectively (Fig. 2b).

Averaged annual changes in soil's σ_w and θ for white grapefruit trees on a troyer rootstock irrigated with three salinity levels are presented in Fig. 1 (two right columns). The σ_w of the four lower soil layers (the upper 0.2 m is overlooked because it fluctuates between well leached to dry) ranged from 6 to 12 to 10 to 24 (dS m^{-1}, data not shown) reflecting the gradual increasing σ_{irr} of the salinity treatments. Maximal σ_w were obtained for all treatments around DOY = 260.

However, contrary to simple intuition, only a weak correlation was found between the soil's θ and σ_w and the stem's θ and σ_a. Stem's σ_a and θ (Fig. 1, two left columns) did not follow soil's σ_w and θ (Fig. 1, two right

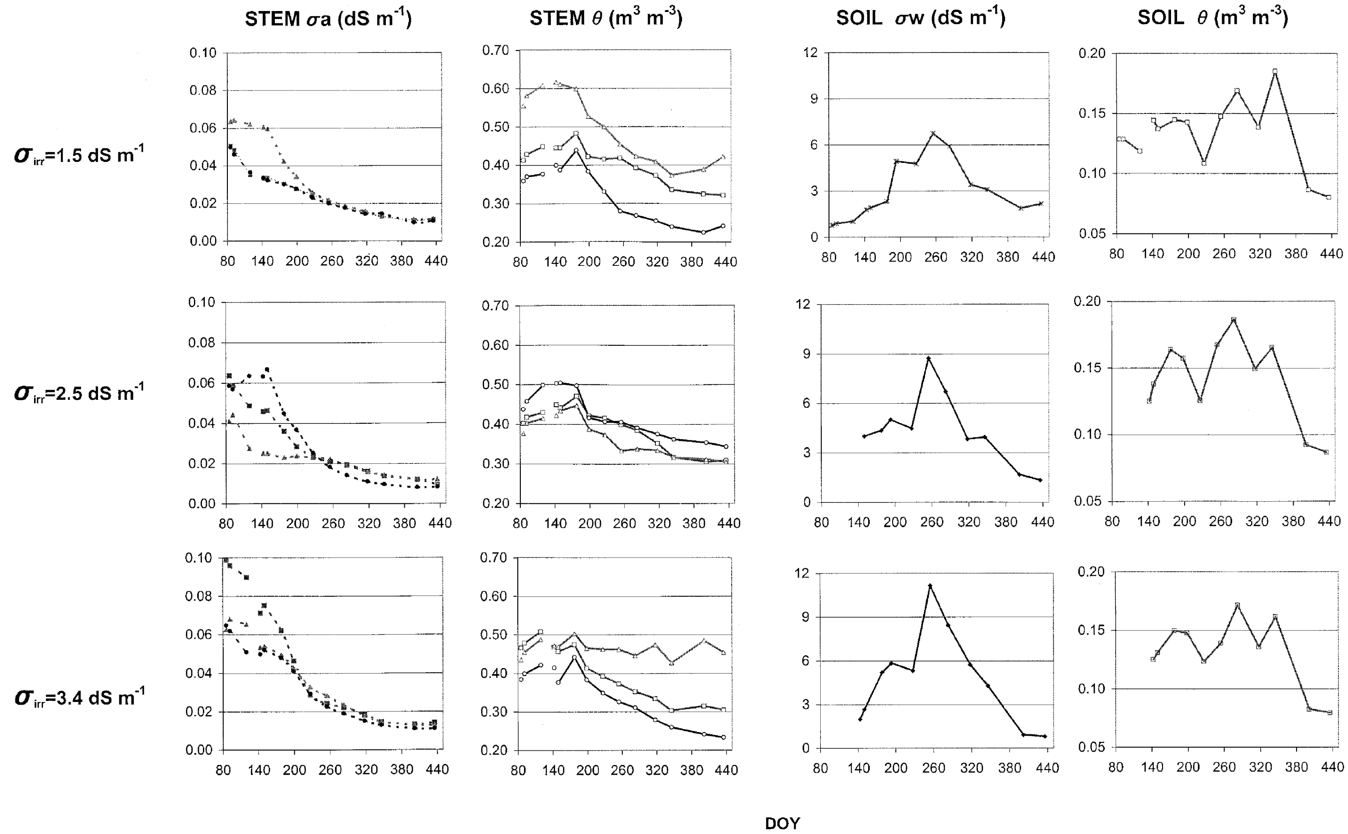

Fig. 1. Bulk stem electrical conductivity (σ) (σ_a, by electrical conductivity meter) and water content (θ) (by time domain reflectometry [TDR]) and soil σ_w and θ as a function of time (days of year 2002) for a white grapefruit grafted on a troyer rootstock for three salinity of irrigation waters.

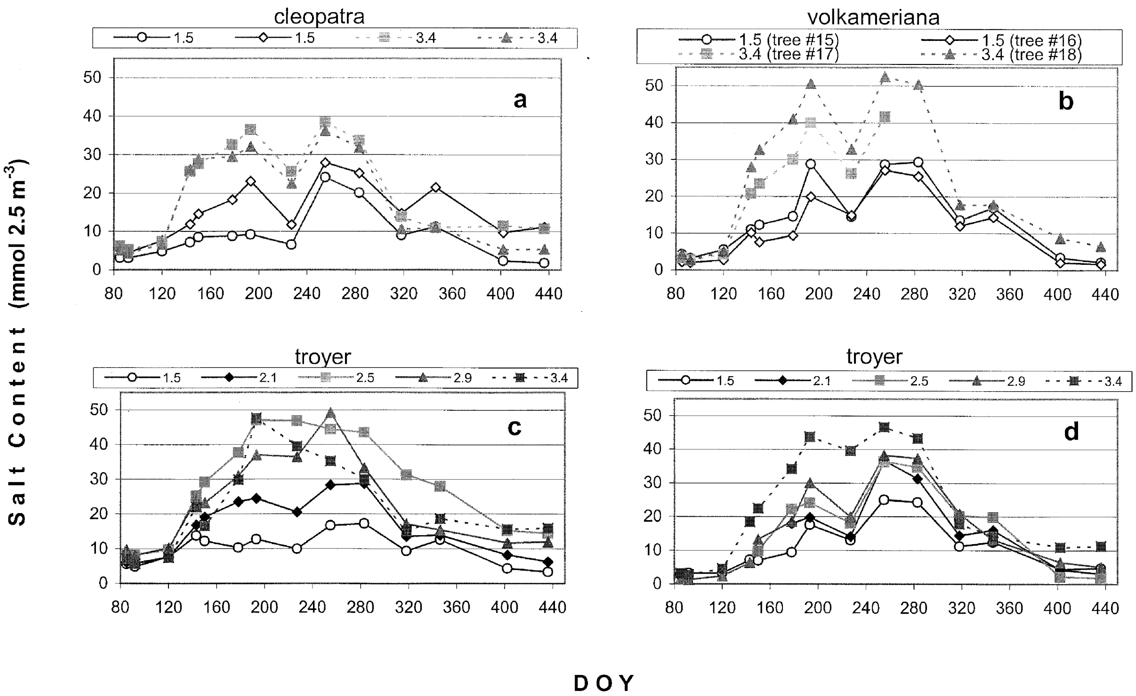

Fig. 2. Salts accumulated in the root zone (mmol/2.5 m^{-3}) as a function of time (days of year, 2002) in the 0.1- to 1.1-m soil profile for the five salinity levels of irrigation water for the troyer trees (lower row) and two extreme salinity levels for the cleopatra and volkameriana trees (upper row). (Legend shows $\sigma_{\text{irrigation waters}}$).

Table 1. Averaged bulk electrical conductivity (σ_a) and water content (θ) values (from three stem probes) and standard error (shown in parentheses) on an arbitrary day (DOY = 193).

		Irrigation water salinity, dS m^{-1}				
		1.5	2.1	2.5	2.9	3.4
Troyer	θ	0.337 (0.078)	0.423 (0.018)	0.558 (0.113)	0.451 (0.116)	0.487 (0.086)
	σ_a	0.021 (0.010)	0.025 (0.008)	0.046 (0.012)	0.050 (0.035)	0.033 (0.003)
Cleopatra	θ	0.328 (0.122)	n.a.	n.a.	n.a.	0.389 (0.111)
	σ_a	0.030 (0.012)	n.a.	n.a.	n.a.	0.035 (0.019)
Volkameriana	θ	0.454 (0.036)	n.a.	n.a.	n.a.	0.431 (0.101)
	σ_a†	0.039 (0.018)	n.a.	n.a.	n.a.	0.042 (0.029)

† Difference in $\sigma_{a,\,stem}$ induced by the two extreme irrigation waters (1.5 and 3.4 dS m^{-1}) are the smallest of all rootstock because volkameriana is the most salt resistant.

columns) although measured at the same time. Between DOY 80 to 180, θ_{stem} values were the highest throughout the year when θ_{soil} levels were lowest. Between DOY 180 to 340 θ_{stem} values steadily decreased while the opposite was true for the θ_{soil}. Between DOY 340 to 440 rate of θ_{stem} decreasing trend slowed down and occasionally even switched direction and started to increase, while θ_{soil} values decreased (Fig. 1). A similar mismatch was found between $\sigma_{w,\,soil}$ and $\sigma_{a,\,stem}$: between DOY 80 to 180, $\sigma_{a,\,stem}$ is highest and steeply decreases, leveling off during DOY 180 to 440, while $\sigma_{w,\,soil}$ is lowest on DOY 80 to 180, peaks at DOY ~ 240, and decreasing by a sharp salt leaching period (DOY = 240–340, Fig. 1). Similar opposing trends were found for the two other rootstocks (data not shown).

DISCUSSION

θ_{stem}–θ_{soil} Relations

Stem water content reflects the steady-state balance between roots water uptake and leaves water use. A monotonously increasing θ_{soil} from DOY = 80 to 260 for all five salinity treatments (only three are presented, Fig. 1) imply a water surplus but θ_{stem} levels have decreased during this period. Such seemingly contradicting situations, attributed to biological mechanisms beyond the scope of the present study, were cited by Borchert (1994): steep gradients between trunk and outer branches (Hinckley et al., 1991), declining $\theta_{sapwood}$ while θ_{bark} increases (Gibbs, 1958), Ψ_{stem} near saturation while $\Psi_{older\ leaves}$ on that stem are very low, or a decreasing Ψ_{stem} during a drought period.

$\sigma_{a,\,stem}$–$\sigma_{w,\,soil}$ Relations

Past studies showed that increasing the salinity of the soil solution causes salt accumulation in the leaves. Salts must flow through the stem, the only path between soil and leaves, but no direct relations between $\sigma_{w,\,soil}$ and $\sigma_{a,\,stem}$ were found. For a better understanding of this mismatch we should look deeper into the meaning of $\sigma_{a,\,stem}$ and consider its θ dependence.

The $\sigma_{a,\,stem}$ measurements can be conducted in either healthy, living, intact cells or in ruptured cells and diseased tissues. The former are undisturbed and continuous, while the later are single time, short, and disturbed. Obviously the results will reflect different situations.

Intact Tissue

The σ of a medium is proportional to the number and mobility of the electrical charges (ions and dissociated molecules). The passage of an electric current in a solution such as found in plant tissues is by the movement of ions. Plant cells are leaky capacitors and each cell can be considered as a capacitance in parallel with a resistance and the ratio between the applied voltage and the resulting current is the impedance. The path of current in healthy tissues is through channels of the cell walls. When an alternating voltage is applied to a tissue the resulting current is related to impedance due to a separation of charges (ions) at tissue boundaries. In healthy tissues the membrane-screened ions are limited in their contribution to σ_a (Tattar and Blanchard, 1976). The amount of ions in the interstitial fluids of plants is also a function of the relative metabolic activity of tissues. Cambial tissues of woody plants were found to have the highest σ. $\sigma_{a,\,plant\ tissue}$ depends nonlinearly on the tissue free water (Blanchard et al., 1983). However, when free water becomes limiting $\sigma_{a,\,tissue}$ becomes dependent on θ_{tissue}. As long as a cell is metabolizing normally, its electrical properties will reflect primarily changes in metabolic rate like ions transfer.

Injured Tissues

Upon disturbance or injury to the membrane, depolarization and electrolyte loss occur releasing electrolytes into the intercellular spaces causing a large local increase of ionic concentration (C_{ionic}) affecting σ_{tissue}. Protoplasm cells containing high concentrations of K^+ release them when the resistance meter electrodes are inserted through the bark into the wood (Blanchard et al., 1983). In the absence of the insulation membranes effect, injured tissue has higher σ_a than intact stems. The σ of ruptured cambial zones of living trees have been used to identify tree vigor, periodic growth, dormancy, cold temperature injuries, and infectious diseases (Tattar and Blanchard, 1976).

Water content Effect on $\sigma_{a,\,stem}$–$\sigma_{w,\,soil}$ Relations

The $\sigma_{a,\,stem}$–θ_{stem} relations for the five salinity treatments are positive ($R^2_{adj} = 0.605$, troyer trees, Fig. 3) as theoretically expected from aqueous systems but σ_a scatter reached ±50%. (The σ_w calculated from these σ_a will have an even higher scatter). In a rare case that θ_{stem} is constant, $\sigma_{a,\,stem}$ changes caused by higher C_{ionic} of

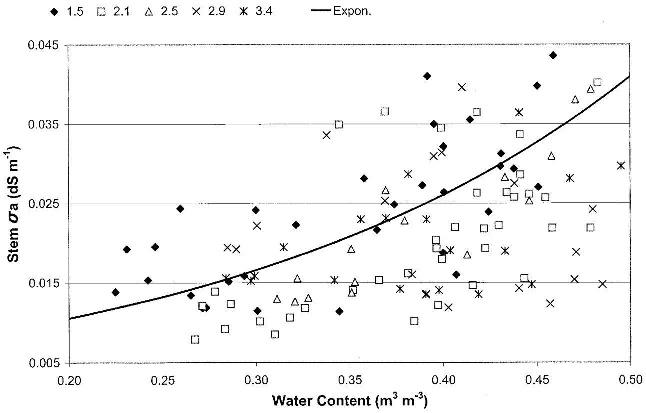

Fig. 3. Stem's bulk electrical conductivity and water content (σ_a–θ) relations for the five troyer trees when irrigated by the five salinity levels. (Legend shows $\sigma_{\text{irrigation waters}}$).

the xylem solution may be easier to observe. But in the period DOY 240 to 440, while salts accumulated in the soil profile, $\sigma_{a,\text{ stem}}$ of the troyer trees decreased by up to 0.03 dS m^{-1} maybe because of a θ decrease by 0.05 to 0.07 (m^3 m^{-3}). Namely, decreasing θ_{stem} may have masked $\sigma_{a,\text{ stem}}$ increases that were caused by salinity changes. Such findings imply that salinity appraisal by $\sigma_{a,\text{ stem}}$ measurements that are not accompanied by θ_{stem} values are only partially useful. Still, $\sigma_{a,\text{ stem}}$ measurements without θ_{stem} may be enough to locate changes in metabolic rates (Davis et al., 1979; Borchert 1991), observe plant diseases, plant vigor (Shortle et al., 1977), or measure periodic rate growth (Blanchard et al., 1983) but not for evaluating salinity levels with a reasonable accuracy.

Having in mind the difference between $\sigma_{a,\text{ intact}}$ cells and $\sigma_{a,\text{ injured}}$ cells, we can interpret the present study $\sigma_{a,\text{ stem}}$ annual changes (Fig. 1) by dividing them into two periods. (i) Those measured during the first two or three months after probes installation when the wound was fresh or curing (DOYs ~ 80–160), and (ii), $\sigma_{a,\text{ stem}}$ measured after the wound have significantly healed (DOY ~ 160–440).

Surplus irrigation was evidenced throughout the season. The water content was always measured just before the next irrigation event (=maximal water stress), and the θ increasing trend for periods of weeks (Fig. 1) indicates irrigation rates above the tree's needs and potential drainage. Similar excess was shown for lemon [*Citrus limon* (L.) Burman f.] trees in the same region (Nadler et al., 2003).

In conclusion, under this study's specific experimental conditions, the correlations between $\sigma_{a,\text{ stem}}$–$\sigma_{w,\text{ soil}}$ and θ_{stem}–θ_{soil} were not satisfactory to the point of recommending irrigation scheduling according to stem properties. We hope this study will be a starting point for further studies.

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REFERENCES

Blanchard, R.O., W.C. Shortle, and W. Davis. 1983. Mechanism relating cambial electrical resistance to periodic growth rate of balsam fir. Cand. J. For. Res. 13:472–480.

Borchert, R. 1994. Electrical resistance as a measure of tree water status during seasonal drought in a tropical dry forest in Costa Rica. Tree Physiol. 14:299–312.

Borchert, R. 1991. Growth periodicity and dormancy. p. 219–243. *In* A.S. Raghavendra (ed.) Physiology of trees. John Wiley, New York.

Constantz, J., and F. Murphy. 1990. Monitoring storage moisture in trees using time domain reflectometry. J. Hydrol. (Amsterdam) 119: 31–42.

Davis, W., A. Shigo, and R. Weyrick. 1979. Seasonal changes in electrical resistance of inner bark in red oak, red maple and eastern white pine. For. Sci. 25:282–286.

Gibbs, R.D. 1958. Patterns in seasonal water content of trees. p. 45–49. *In* K.V. Thimann (ed.) The physiology of forest trees. Ronald Press, New York.

Hinckley, T.M., H. Richter, and P.J. Schulte. 1991. Water relations. p. 137–162. *In* A.S. Raghavendra (ed.). Physiology of trees. John Wiley, New York.

Irvine, J., and J. Grace. 1997. Non-destructive measurement of stem water content by time domain Reflectometry using short probes. J. Exp. Bot. 8:813–818.

Levy, Y., D. Columbus, D. Sadan, and J. Lifshitz. 1999. Trickle linear gradient for assessment of the salt tolerance of citrus rootstocks in the orchard. Irrig. Sci. 18:181–184.

Nadler, A., H. Frenkel, and A. Mantel. 1984. Applicability of the four-probe technique under extremely variable water contents and salinity distribution. Soil Sci. Soc. Am. J. 48:1258–1261.

Nadler, A., E. Raveh, U. Yermiyahu, and S.R. Green. 2003. Evaluation of TDR use to monitor water content in stem of lemon trees and soil and their response to water stress. Soil Sci. Soc. Am. J. 67:437–448.

Naor, A., I. Klein, and I. Doron. 1995. Stem water potential and apple size. J. Am. Soc. Hortic. Sci. 120:577–582.

Robinson, D.A., S.B. Jones, J.M. Wraith, D. Or, and S.P. Friedman. 2003. A Review of advances in dielectric and electrical conductivity measurements using time domain reflectometry: Simultaneous measurements of water content and bulk electrical conductivity in soils and porous media. Vadoze Zone J. 2:444–475.

Shortle, W.S., A.L. Shigo, P. Berry, and J. Abusamra. 1977. Electrical resistance in tree cambium zone: Relationship to rates of growth and wound closer. For. Sci. 23:326–329.

Tattar, T.A., and R.O. Blanchard. 1976. Electrophysiological research in plant pathology. Ann. Rev. Phytopathol. 14:309–325.

Topp, G.C., J.L. Davis, and A.P. Annan. 1980. Electromagnetic determination of soil water content: Measurements in coaxial transmission lines. Water Resour. Res. 16:574–582.

Waring, R.H., and S.W. Running. 1978. Sapwood water storage: Its contribution to transpiration and effect upon water conductance through the stems of old-growth Douglas fir. Plant Cell Environ. 1:131–140.

Wullschleger, S.D., P.J. Hanson, and D.E. Todd. 1996. Measuring stem water content in four deciduous hardwood with a time domain reflectometry. Tree Physiol. 16:809–815.