Foliar Damage, Spectral Reflectance, and Tissue Ion Concentrations of Trees Sprinkle Irrigated with Waters of Similar Salinity but Different Chemical Composition

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Abstract. We investigated foliar damage to five landscape species sprinkler irrigated with either reuse water or one of five synthesized saline waters that contained elevated single salts mixed with Colorado River water, all having similar electrical conductivities. The experiment allowed us to compare the impact of elevated concentrations of Na, Mg, Ca, Cl, and SO₄ on an index of visual damage (IVD), tissue ion concentrations, and spectral reflectance. Waters containing elevated concentrations of MgCl₂ or NaCl caused greater foliar damage than did MgSO₄, Na₂SO₄, CaSO₄, or reuse water, as recorded in higher IVD values ($p < 0.05$). Privet and elm were damaged to a greater extent (higher IVD values) than were desert willow, guava and laurel ($p < 0.05$). Higher IVD values were recorded for all species irrigated with the MgCl₂ waters, with mortality recorded in privet. Tissue nutrient concentrations were correlated with the IVD values. In the case of guava, 61% of the variability in the IVD could be accounted for based on N, P and K ($P < 0.01$). On a treatment basis, the single salts added to the municipal water showed little correlation with the IVD values, except in the case of MgCl₂, where Mg was included in the regression equation ($r^2 = 0.82$, $P < 0.01$, IVD $\uparrow$ as SO₄ $\downarrow$, Mg and P $\uparrow$). Eleven different spectral indices separated based on treatment and/or species ($P < 0.05$). In elm, 70% of the variability in the IVD could be accounted for by including Red Edge, Normalized Difference Vegetation Index (NDVI) and Water Band Index (WBI)/NDVI. A mixed response was observed to a post 30-day irrigation rinse in an attempt to reduce IVD values. Based on our results, care should be given to monitoring not only the EC (and osmotic potential) but also the ionic composition when saline waters are blended with other water sources, with the aim of minimizing the concentration of Mg, Cl, and Na.

In arid regions where water resources are limiting and population growth outstrips water conservation efforts, greater consideration is being given to the use of lower quality waters. Reuse water (treated sewage effluent) in particular, has been adopted in most regions of the U.S. as acceptable water for landscape irrigation, especially large turfgrass areas such as golf courses, parks and cemeteries (U.S. Golf Association, 1994). However, in a recent

survey of superintendents in the southwestern U.S., 73% of the respondents who irrigated with reuse water indicated that reuse water had a negative impact on shrubs and trees growing on golf courses (Devitt et al., 2004).

Application of waters containing soluble salts (such as reuse water) directly to the foliage of shrubs and trees, whether intentionally or unintentionally, has led to foliar damage being documented by a large number of scientists (Hoffman et al., 1989; Jordan et al., 2001; Maas et al., 1982; Quist et al., 1999). However, because the quality of reuse water varies from region to region, as does environmental demand and species selection, the response has been highly variable. Jordan et al. (2001) reported that only 6 out of 20 tree species spray irrigated with reuse water had an acceptable index of visual damage and that the damage was very similar when a comparison was made between reuse water and a synthesized saline water (similar electrical conductivity as the reuse water but without residual chlorine and

trace organics). The amount of foliar damage was linked to a species-dependent sodium response.

In southern Nevada, satellite wastewater treatment plants are being built that divert wastewater during the early morning hours to avoid the water softener salts, which are sent on in the diverted flow to the main treatment plant. Groundwater chemistry of the primary and shallow aquifers varies throughout the valley and the extent of blending with these waters and Colorado River water varies from site to site, contributing to reuse based irrigation waters of variable ionic composition.

The objective of this study was to investigate foliar damage to five ornamental landscape species sprinkler irrigated with waters containing different elevated concentrations of cations and anions. Reuse (tertiary treated sewage effluent) water and five synthesized waters of similar electrical conductivity but varying in specific ion composition were used as irrigation sources, so that a comparison could be made between the relative impacts of Na, Ca, Mg, Cl, and SO₄ on foliar damage, spectral reflectance and leaf tissue ion concentrations.

Materials and Methods

Research was conducted at the Clark County Sanitation District (CCSD) in Las Vegas, Nev., and involved five tree species (Table 1), and six qualities of water (irrigation plots) with each tree species replicated three times within each water quality treatment ($n = 15$ for species per plot, $n = 90$ for all trees in six plots). Irrigation plots were separated, with 15-m alleys to minimize drift to adjacent plots. The six irrigation treatments consisted of sprinkler-applied reuse water and five synthesized waters with similar electrical conductivities (ranging from 1.86 to 1.95, with no statistical difference between treatments) to the reuse water but different in ionic composition. Salts of CaSO₄•2H₂O, MgSO₄•7H₂O, MgCl₂•6H₂O, NaCl and Na₂SO₄ were blended with potable water in separate storage containers to obtain electrical conductivities statistically similar to reuse water and distributed to irrigation plots. All waters used in this experiment originated from Colorado River water and were provided by CCSD. Samples of the water were collected after each batch preparation (3754 L) and analyzed for electrical conductivity with a conductivity bridge (model RC-20; Beckman Industrial, Cedar Grove, N.J.) and major cations and anions were quantified using atomic absorption spectrophotometry [model 200 A; Buck Scientific, East Norwalk, Conn. (Ca, Mg, Na and K)], spectrophotometry [model

Table 1. Ornamental landscape species used in the foliar study.

Common name	Species
Desert Willow	<i>Chilopsis linearis</i> (Cav.) Sweet
Japanese Privet	<i>Ligustrum japonicum</i> Thunb.
Drake Elm	<i>Ulmus parvifolia</i> Jacq. 'Drake'
Guava	<i>Feijoa sellowiana</i> (O. Berg)
	O. Berg
Laurel	<i>Sophora secundiflora</i> (Ortega)
	Lag. ex DC

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Table 2. Average chemical composition of treatment waters used in the foliar study.

Parameter	Municipal	Reuse	CaSO ₄	MgSO ₄	MgCl ₂	NaCl	Na ₂ SO ₄
EC (dS·m ⁻¹)	0.86	1.94	1.90	1.86	1.95	1.93	1.94
Na (mEq·L ⁻¹)	3.31	10.03	4.93	5.42	5.11	12.03	13.33
K (mEq·L ⁻¹)	0.02	0.90	0.28	0.27	0.30	0.29	0.26
Ca (mEq·L ⁻¹)	3.32	6.20	15.76	4.33	4.21	4.09	4.24
Mg (mEq·L ⁻¹)	3.12	3.05	1.94	8.78	7.73	1.82	1.84
Cl (mEq·L ⁻¹)	2.66	7.33	3.29	2.71	12.06	10.31	2.52
SO ₄ (mEq·L ⁻¹)	4.60	8.81	18.58	17.70	5.24	5.20	15.15
pH	8.00	7.84	7.87	7.97	7.94	7.90	7.99
OP ^z (MPa)	---	-0.113	-0.098	-0.113	-0.110	-0.108	-0.105

^zOP = osmotic potential; measured at 25% evaporation.

Table 3. Summary of vegetation indices used to assess treatment effects [R = reflectance at a specified wavelength (nm)]. Sources: Field et al., 1994; Gamon and Surfus, 1999; Gamon et al., 1997; Peñuelas et al., 1993a, 1993b, 1995; Peñuelas and Filella, 1998; Serrano et al., 2000.

Index	Description	Wavelengths (nm)
PRI	Photochemical reflectance index	$(R_{531} - R_{570}) / (R_{531} + R_{570})$
SR	Simple ratio	(R_{800} / R_{660})
Chl	Chlorophyll index	$(R_{750} - R_{705}) / (R_{750} + R_{705})$
NDPI	Normalized total pigment to chlorophyll a index	$(R_{680} - R_{435}) / (R_{680} + R_{435})$
SIPI	Structure insensitive pigment index	$(R_{800} - R_{445}) / (R_{800} - R_{680})$
WBI	Water band index	(R_{900} / R_{970})
NDVI	Normalized difference vegetation index	$(R_{800} - R_{660}) / (R_{800} + R_{660})$
NPQI	Normalized phaeophytinization index	$(R_{415} - R_{435}) / (R_{415} + R_{435})$
λ_{RE}	Red edge (wavelength of maximum slope)	(between 680 and 740 nm)
R:FR	Red to far red index	R_{660} / R_{730}
WBI:NDVI	Water band index to NDVI	WBI/NDVI

UV-120-02; Shimadzu Corp., Columbia, Md. (SO₄), chloride titration [digital chloridometer, model 4425; Haake Buchler Instruments, Paramus, N.J. (Cl)] and titration (HCO₃/CO₃) (Table 2).

Trees were not planted in the ground because the soil at the research site adjacent to the sewage treatment plant was highly saline with a shallow water table (≈ 180 cm). Each tree was left in its original #15 standard nursery container (57.0 L). To moderate container soil temperatures and promote drainage, containers with trees were placed in a second, in-ground, #15 container (pot in pot), containing a 10-cm layer of pea gravel, which prevented the containers from lodging. Exposed soil surfaces in each pot were mulched with a 5-cm layer of pine bark and covered with shade cloth to minimize evaporative water loss. Exposed container surfaces were painted white and wrapped in white, plastic-covered R-19 insulation to help modulate temperature extremes. Soil samples were taken to a depth of 30 cm in all containers before the experiment and at the end of the experiment. Soil salinity was measured using the saturation extract technique (U.S. Salinity laboratory, 1954). Electrical conductivity was measured with a conductivity bridge with all measurements adjusted to 25 °C.

The site was equipped with an automated weather station (Campbell Scientific, Logan Utah). Meteorological variables monitored included relative humidity, temperature, wind run, solar radiation and rainfall. The modified Penman combination equation was used to estimate potential evapotranspiration (ET₀). The yearly ET₀ for August 2002 to July 2003 was 188 cm, with an average temperature of 29 ± 5 °C, average wind speed of 3.4 ± 2.9 m·s⁻¹ and an average relative humidity of $28\% \pm 17\%$.

Each plot received its irrigation treatment via nine sprinkler heads (model 200; Hunter Industries) mounted on 183 cm risers, operating

within manufacturers specifications. Amounts of applied irrigation were measured by time (10 min per application), which wetted leaf surfaces beyond the point of runoff. Sprinkler irrigation events (199 total) occurred between the start up date of 4 Aug. 2002 and the last irrigation on 15 Sept. 2003. Sprinkler irrigations paralleled overhead irrigations in local mixed landscapes occurring four to five times per week during daylight hours in the summer months and reduced to as low as twice per week during the months of December and January. Tensiometers (model 2710; Soil Moisture Equipment Corp., Santa Barbara, Calif.) for measuring soil matric potential were placed at the 15-cm depth in one pot of each species in each plot for monitoring purposes. Daily tensiometer measurements were taken with a pressure transducer. If the soil matric potential exceeded a set threshold of -0.02 MPa (-0.03 MPa for desert willow), a 10-L application of the appropriate treatment water was applied directly into the pot via a garden hose. Drainage from the containers was never impeded and tensiometer feedback assured that moisture stress was not a compounding factor to the presence of soluble salts. At the end of the 13.5-month experimental period, all plots were switched to municipal water for a postleaching experiment (second phase of study). Municipal water (0.86 dS·m⁻¹) was applied through overhead sprinkler heads every day for 30 consecutive days (14.5-month total experimental period), at 10 minutes per day. All trees were fertilized in April 2003 with a 15N-6.45P-12.45K fertilizer at the rate of 6.8 g of N per tree.

The plant water status of the trees was monitored bimonthly by measuring mid-day leaf water potential with a pressure bomb (Soilmoisture Equipment Corp.). Chlorophyll was indirectly assessed with a chlorophyll meter (Spad 502; Minolta Corp., Japan). Tissue ion concentrations were measured at the

end of the 13.5-month experimental period in representative leaf tissue (40 random leaves of similar age) from the canopies of each tree in each plot. Based on the response to post irrigation rinse treatments, only guava and elm were tissue sampled for ion analysis at the end of the rinse period. Briefly, leaves were rinsed with distilled water and dried at 70 °C for 48 h and then ground to a fine powder with a stainless steel mill. The ground tissue samples were sent to a commercial laboratory (A&L Laboratory, Modesto, Calif.) for major cation and anion analysis.

Monthly visual evaluations were completed on one tree of each species in each treatment (same tree). Four times a season, complete visual evaluations were done on all 90 trees (minus those that died). All of the privets in the reuse plot died due to breakage during a high windstorm 2 weeks before the end of the experiment. Evaluations for the privets in the reuse plot, taken in the prior month were used in the final evaluation. Complete visual evaluations were also done at the end of the 30-d post rinse period. Assessments were based on six visual parameters; absence of crown dieback, overall canopy discoloration, presence of dead leaves, presence of deformed leaves, discolored leaves and tip damage. Except for absence of crown dieback, each parameter was evaluated on a 1 to 9 scale (where 1 = 10% and 9 = 90% damage, respectively). Absence of crown dieback was evaluated on a 1 or 0 basis (where 1 = dieback and 0 = no dieback). An index value of visual damage (IVD) (Jordan et al., 2001) was generated based on giving equal weight to a canopy-based assessment value (canopy dieback plus overall canopy discoloration) and a leaf level assessment value (average rating of leaf discoloration, deformed leaves, tip damage and presence of dead leaves).

Field-based spectra (350 to 1100 nm) for each tree within each treatment were acquired using a spectrometer (Unispec; PP Systems Inc., Haverhill, Mass.). A bifurcated fiber optic cable was attached to the Unispec detector and internal light source at one end and a leaf clip at the other end. The leaf clip was clipped onto separate leaves (three per tree) from each tree to measure spectral signatures. Only mature leaves were measured and the leaf clip was placed at the midleaf position but not on a primary vein to ensure consistency and comparability within the spectral data. Spectral measurements were acquired on 28 Aug. 2003 from 12:20 to 15:40 HR (end of water treatments) and on 15 Oct. 2003 from 09:00 to 11:00 HR (end of rinse). A suite of vegetation indices (Table 3) was calculated for each spectral measurement and average values were calculated for each tree species within each treatment.

A controlled evaporation study was conducted in the laboratory with the six irrigation waters to assess evapoconcentration that might occur on leaves. One hundred ml of water from each irrigation sample was placed in a 150 mL large-mouth flask. The flasks were then placed in a water bath at 37 °C under an open hood. Separate irrigation water samples were evaporated down 25%, 45%, 75%, and 95% based

Fig. 1. Index of visual damage (IVD) for all five species at the end of 13.5 months of sprinkler irrigating with six different water qualities. An acceptable IVD value of 2.0 is designated by a horizontal line.

Table 4. Tissue ion concentrations separated by irrigation treatment^a for each species at the end of the experiment.

Treatment	Ion concn (g·kg ⁻¹)				
	Na	Ca	Mg	Cl	SO ₄
Guava					
Reuse	2.7 ab	22.9 b	5.1 a	7.8 b	1.0 a
CaSO ₄	1.9 ab	26.1 b	5.4 a	10.9 b	3.4 a
MgSO ₄	1.1 a	12.7 a	8.1 a	6.2 ab	2.0 a
MgCl ₂	4.2 b	16.2 ab	10.4 b	7.2 b	0.6 a
NaCl	4.7 b	23.7 b	5.8 a	9.5 b	1.5 a
Na ₂ SO ₄	2.7 ab	21.8 b	6.2 a	5.0 a	2.7 a
Desert willow					
Reuse	4.0 a	12.3 a	7.0 a	8.1 a	1.7 a
CaSO ₄	3.5 a	17.1 a	7.3 a	8.8 a	4.0 a
MgSO ₄	3.8 a	10.7 a	13.9 b	8.3 a	4.7 a
MgCl ₂	1.6 a	11.6 a	13.3 b	7.3 a	2.2 a
NaCl	3.0 a	18.2 a	8.9 a	8.3 a	1.5 a
Na ₂ SO ₄	1.7 a	11.3 a	11.0 ab	8.0 a	2.5 a
Elm					
Reuse	5.4 b	17.8 ab	5.2 a	4.8 a	0.8 a
CaSO ₄	3.7 ab	24.3 b	3.6 a	3.6 a	4.8 b
MgSO ₄	2.0 a	14.2 ab	7.1 ab	3.8 a	1.8 ab
MgCl ₂	2.9 ab	13.0 a	8.8 b	5.0 b	0.4 a
NaCl	3.6 ab	19.5 ab	5.5 a	4.7 a	0.7 a
Na ₂ SO ₄	3.1 ab	19.4 ab	5.0 a	3.7 a	2.8 b
Laurel					
Reuse	2.0 a	17.9ab	5.3 a	3.6 a	0.7 a
CaSO ₄	0.7 a	18.7 ab	4.3 a	4.6 a	2.3 ab
MgSO ₄	0.8 a	12.6 a	10.7 b	3.3 a	2.8 ab
MgCl ₂	0.7 a	12.3 a	8.8 b	5.0 a	1.4 a
NaCl	2.3 a	19.0 ab	7.5 b	10.4 b	2.4 ab
Na ₂ SO ₄	0.7 a	24.8 b	9.0 b	4.2 a	4.2 b

^aMean separation within columns by LSD, $P < 0.05$.

on weight change (replicated). One to five ml of water was carefully pipetted for chemical analysis from each flask (avoiding glass walls) immediately after the evaporation point had been obtained. Only in the case of the 95% evaporation MgCl₂ samples were suspended salts observed. These samples were centrifuged at 2000 rpm for 20 min and carefully decanted and passed through a fine porosity high flow rate glass filter before analysis. All samples

were analyzed for electrical conductivity with a conductivity bridge with all measurements adjusted to 25 °C. Samples were also analyzed for Ca and Mg by titration, Cl with a Cl titrator, Na with a flame photometer (model 2655; Cole Parmer Instrument, Chicago Ill.), SO₄ with a spectrophotometer and vapor pressure with a vapor pressure osmometer (model 5100C; Wescor Inc., Logan Utah).

The data were analyzed with descriptive

statistics, analysis of variance (ANOVA) and/or linear and multiple linear regression analysis. Multiple regressions were performed in a backward stepwise manner, with deletion of terms occurring when P values for the t test exceeded 0.05.

Results

Treatments. Soil samples taken before the study indicated no statistical difference in soil salinity between species, with an average value (2.28 ± 0.65 dS·m⁻¹) below the classification for a saline soil (4.0 dS·m⁻¹) (U.S. Salinity Laboratory, 1954). However, after 13.5 months of irrigating with the 6 different waters, EC_e values separated based on treatment ($P < 0.001$) and species ($P < 0.01$) with no treatment by species interactions. The CaSO₄ treatment had the highest EC_e values (2.91 dS·m⁻¹), statistically different from all other treatments and willow had the highest EC_e values among species (2.57 dS·m⁻¹), statistically different from the guava and privets (2.08 and 2.03 dS·m⁻¹, respectively). All of these average treatment and species soil salinity values were also less than the classification for a saline soil. Mid-day leaf water potential showed a statistical separation based only on species ($P < 0.001$) and not on water treatment, with no decreasing trend with time. No visual symptoms were observed to suggest plant water stress, indicating that the matric sensor feedback was effective in scheduling irrigation volumes and frequencies to minimize a significant decline in soil moisture or rise in soil salinity. Trunk diameter and tree height separated by species ($P < 0.001$) but not by water treatment or by an interaction, indicating that the degree of foliar damage was not directly related to these growth factors over a growing period of 13.5 months. Spad measurements however, did separate by species, water treatment and by a treatment × species interaction ($P < 0.001$), suggesting that if the foliar damage study had been maintained over several growing seasons, a reduction in leaf level chlorophyll production would eventually translate into a reduction in overall growth. No significant correlations existed between spad measurements and tissue ion concentrations.

Visual damage. At the end of the 13.5-month experimental period, the index of visual damage (IVD) separated by water quality treatment, species and by a species × treatment interaction ($P < 0.001$). IVD values increased in association with the following water quality treatments; reuse (2.08), Na₂SO₄ (2.18), MgSO₄ (2.34), CaSO₄ (2.51), NaCl (3.30), and MgCl₂ (5.19), with statistical separation between MgCl₂ and all other treatments and NaCl and all other treatments. The fact that IVD's for the NaCl treatment were significantly higher than the Na₂SO₄ treatment and that the IVD's for the MgCl₂ treatment were significantly greater than the MgSO₄ treatment suggests a Cl vs. SO₄ response. Although no statistical differences in the IVD's existed between the three SO₄ treatments, a clear separation occurred between MgCl₂ and NaCl treatments. Visual damage also increased according to

Table 5. ANOVA results for species and treatment effects on 11 spectral indices.

Effect	Red Edge	Chl	PRI	SIPI	WBI	NDPI	NDVI	WBI/NDVI	NPQI	SR	R/FR
Species	***	***	***	*	***	**	***	***	***	***	**
Treatment	*	**	**	**	*	***	**	*	NS	**	*

NS,*,**,***Nonsignificant or significant at $P < 0.05$, 0.01, or 0.001, respectively.

Table 6. Multiple regression results for tissue ion concentrations and spectral indices.

Species	Regression	Ca	Mg	K	Na	Cl	SO ₄
Elm	R^2	0.71**	0.80***	0.91***	0.40*	0.66**	0.71***
	Regressors	SR,PRI NDPI	SR, SIPI NDPI	PRI,SIPI WBI	PRI,RED	CHL,NDVI	SIPI,NDPI
Guava	R^2	NS	0.69***	0.32*	0.55**	NS	NS
	Regressors		NDPI,R/FR SIPI	CHL	WBI,NPQI WBI/NDVI		
Privet	R^2	NS	NS	NS	NS	NS	NS
	Regressors						
Willow	R^2	NS	0.48***	NS	NS	NS	NS
	Regressors		SIPI				
Laurel	R^2	NS	0.49**	NS	NS	NS	NS
	Regressors		NPQI,NDPI				

NS,*,**,***Nonsignificant or significant at $P < 0.05$, 0.01, or 0.001, respectively.

Fig. 2. Index of visual damage (IVD) for guava at the end of the 13.5-month experimental period (six water qualities) compared to the end of the 30-d postirrigation rinse period. An acceptable IVD value of 2.0 is designated by a horizontal line.

species as follows: laurel (1.95), guava (2.72), willow (2.76), privet (3.49), and elm (3.75), with statistical separation between laurel and all species, privet and all species and elm and all species ($P < 0.05$). Highest IVD values for all species occurred in the $MgCl_2$ treatment with no values below the acceptable IVD rating of 2.0 (Jordan et al., 2000). IVD values of 10.0 were assigned to the privets in the $MgCl_2$ treatment because of mortalities. No other species died in any of the other water quality treatments. Slightly lower IVD values occurred in the NaCl treatment compared to the $MgCl_2$ treatment but still all values exceeded 2.0. Only in the reuse treatment did 4 of the 5 species have acceptable IVD values (Fig. 1).

Tissue nutrient concentrations vs. IVD. Tissue samples harvested at the end of the 13.5-month experimental period were analyzed for macro and micronutrients (Table 4, macro

nutrients only). Analysis of variance indicated a significant treatment effect ($P < 0.01$) for all nutrients except K, Mn, and Cu, a significant species effect ($P < 0.05$) for all nutrients except Mn and Zn and significant treatment $\times$ species interactions ($p < 0.05$) for Cl, B, Zn, Al, and N (privet not included because of mortalities in the $MgCl_2$ treatment and wind damage in the reuse treatment). Tissue concentrations were then regressed against IVD values in a backward stepwise fashion, eliminating tissue nutrients that were not significant at the $P < 0.05$ level. Because the sample size per species was about 18 (some variation due to mortalities or severe wind damage—privets and elms) only three regressors were accepted, with the aim of maintaining a ratio at or near five samples per regressor (minimizing the risk of multicollinearity, Grossman et al., 1996). Only 33% of the variability in the IVD values

of laurel could be accounted for based on Ca and Mn tissue concentrations ($R^2 = 0.33$, $P = 0.02$, IVD $\uparrow$ as Ca $\downarrow$). In guava, 61% of the variability in IVD values could be accounted for based on tissue nutrient concentrations of N, P, and K ($R^2 = 0.61$, $P = 0.01$, IVD $\uparrow$ as N and P $\downarrow$). Tissue nutrient concentrations of Mg, Mn and Fe accounted for 49% of the variability in the IVD values of willow ($R^2 = 0.49$, $P = 0.01$, IVD $\uparrow$ as Mg, Mn and Fe $\downarrow$). In privet (no reuse or $MgCl_2$ treatments due to mortalities) 96% of the variability in the IVDs could be accounted for based on N, K, and Mg ($R^2 = 0.96$, $P < 0.001$, IVD $\uparrow$ as N $\downarrow$). In elm 37% of the variability in the IVD values could be accounted for based on N and P ($R^2 = 0.37$, $P = 0.04$, IVD $\uparrow$ as N $\downarrow$). When all species were combined (max of 6 regressors accepted based on larger sample size), only 25% of the variability could be accounted for based on Na and B ($R^2 = 0.25$, $P \leq 0.001$, IVD $\uparrow$ as Na and B $\uparrow$). Combining species led to a lower R^2 value and the selection of entirely different tissue nutrients contributing to the correlation. The fact that the ANOVA demonstrated that Mn did not show significant differences based on treatment, species or by a treatment $\times$ species interaction indicated that some care should be taken in the interpretation of IVD regressions that included Mn (laurel and willow). When regressions were run a second time without Mn, the R^2 value for laurel increased (0.51, $P < 0.01$) and the tissue nutrients contributing to the correlation changed from Ca and Mn to N, Na, Cl and Cu ($P < 0.001$ for all four nutrients, reducing to three regressors reduced the $R^2 < 0.20$). Whereas with willow, the R^2 value changed little (0.47, $P < 0.001$) while the tissue nutrients contributing to the correlation remained Mg and Fe with P switching for Mn.

Backward stepwise regressions were also done on a treatment basis. Interestingly, the single salts that were added to each treatment showed little correlation with the IVD. In particular, Na and SO₄ were removed from the regression for the Na₂SO₄ treatment ($R^2 = 0.25$, $P < 0.05$, IVD $\uparrow$ as K $\uparrow$), Na and Cl were removed from the regression for the NaCl treatment ($R^2 = 0.61$, $P < 0.05$, IVD $\uparrow$ as B, Fe and P $\uparrow$), Mg and SO₄ were removed from the

Table 7. Comparison of average spectral indices (all treatments) before (E = end) and after a 30-d rinse period (R = rinse) for willow, guava, elm, and laurel.

Effect	Treatment	Red Edge	Chl	PRI	SIPI	WBI	NDPI	WBI/NDVI	NDVI	NPQI	SR	R/FR
Willow	E				1.07***		0.62***	1.70***			4.28***	0.27***
	R				1.10		0.56	1.90			3.61	0.32
Guava	E				1.06*				0.72	-0.004***	6.77***	0.19**
	R				1.07				0.67	-0.021	5.29	0.23
Elm	E	707*	0.37*			1.032**	0.21**	1.41***	0.74***	-0.04***	7.04***	0.17***
	R	710	0.41			1.029	0.18	1.48	0.70	-0.02	5.95	0.21
Laurel	E					1.06***		1.42***	0.74***		7.04***	0.17***
	R					1.08		1.60	0.65		4.92	0.24

***Significant at $P < 0.05$, 0.01, or 0.001, respectively

regression for the MgSO_4 treatment ($R^2 = 0.57$, $P < 0.05$, IVD $\uparrow$ as Na and Ca $\uparrow$ and Cl $\downarrow$), Ca and SO_4 were removed from the regression for the CaSO_4 treatment ($R^2 = 0.32$, $P < 0.05$, IVD $\uparrow$ as K $\uparrow$ and Cl $\downarrow$) and only in the case of the MgCl_2 treatment was Mg included in the regression equation ($r^2 = 0.82$, $P < 0.01$, IVD $\uparrow$ as $\text{SO}_4\downarrow$, Mg and P $\uparrow$), suggesting a possible role of suppression in addition to accumulation for these major cations and anions.

Spectral reflectance indices vs. IVD. Spectral reflectance measured at the leaf level in the 400- to 1100-nm range (end of experiment) was used to generate eleven different indices as reported in Table 3. Analysis of variance (general linear model with no interactions, missing privet data, Table 5) indicated significant differences based on treatment ($P < 0.05$, except NPQI (normalized phaeophytinization index) and species ($P < 0.05$). The indices were regressed in a backward stepwise fashion against IVD values, as described in the tissue nutrient section. In laurel, 63% of the variability in the IVD could be accounted for by including the simple ratio (SR), chlorophyll index (CHL), and the red edge (Red Edge), ($R^2 = 0.63$, $P < 0.001$, IVD $\uparrow$ as CHL $\downarrow$). In guava, SR and NDVI (normalized difference vegetation index) accounted for 58% of the variability in the IVD ($R^2 = 0.58$, $P < 0.001$, IVD $\uparrow$ as NDVI $\downarrow$). Whereas, in willow, 51% of the variability in the IVD could be accounted for by including NDVI, CHL, and PRI (photochemical reflectance index) ($R^2 = 0.51$, $P < 0.01$, IVD $\uparrow$ as CHL $\downarrow$). In elm, 70% of the variability in the IVD could be accounted for by including Red Edge, NDVI and WBI/NDVI (water band index/NDVI) ($R^2 = 0.70$, $P < 0.01$, IVD $\uparrow$ as Red Edge, NDVI and WBI/NDVI $\downarrow$). Only 26% of the variability in the IVD of privet could be accounted for by including NDVI and R/FR (red reflectance–far-red reflectance) ($R^2 = 0.26$, $P < 0.05$, IVD $\uparrow$ as R/FR and NDVI $\downarrow$). When all species were combined, only 20% of the variability in the IVD could be accounted for based on including NPQI, NDPI (normalized total pigment to chlorophyll a index), WBI, SIPI (structure insensitive pigment index) and SR ($R^2 = 0.20$, $P < 0.001$, IVD $\uparrow$ as WBI, SIPI and SR $\downarrow$). This lower R^2 value associated with all species described by different spectral indices was similar to the response noted for the IVD tissue nutrient correlations, suggesting that the strong species effect does not warrant the further merging of data.

Spectral reflectance indices were also regressed against tissue ion concentrations for each species (Table 6). Only in the case of elm did significant correlations exist for all six of

the major cations and anions (R^2 ranging from 0.40* to 0.91***). In privet, no significant correlations existed, whereas in willow and laurel only one significant correlation existed (Mg). Tissue Mg concentrations revealed significant

correlations with spectral indices in four of the five species, with SIPI and/or NDPI included in each regression.

Plant response to postrinse treatment. At the end of the 30-d rinse period, soils were

Fig. 3. Average osmotic potential and electrical conductivity in the irrigation water as a function of evaporation for the six water qualities.

Fig. 4. Average concentration of chloride (mEq L^{-1}) in the irrigation water as a function of evaporation for the six water qualities.

Fig. 5. Hourly maximum relative humidity measured at the research site during June, July, and August. Horizontal line A designates the point of deliquescence (POD) for NaCl and horizontal line B designates the POD for MgCl_2 .

sampled, plants were visually evaluated for foliar damage (IVD) and then measured for leaf spectral reflectance and tissue sampled for ion analysis. Soil salinity values declined below preexperimental values ($1.88 \pm 0.78 \text{ dS}\cdot\text{m}^{-1}$) indicating that the post rinsing was very effective in leaching soluble salts from the containerized root zones. IVD values separated based on treatment, species and by a species $\times$ treatment interaction ($P < 0.001$). However, when a three way ANOVA was conducted including time as a factor, only guava had a significant time within species interaction (Fig. 2), whereas elm showed a significant ($P < 0.05$) change in the IVD (1.79 increasing to 4.46) only in the reuse treatment after the 30-day rinse period. A decision was made based on cost and the non significant IVD response to the rinse treatment in the laurel, privets and willow to tissue analyze only the guava and elms after the rinse period. When tissue ion concentrations were compared before and after the rinse period for guava (all treatments combined), all concentrations declined except nitrogen (increasing from 16.2 to $22.6 \text{ g}\cdot\text{kg}^{-1}$, $P < 0.05$) and sulfate (increasing from 2.0 to $6.6 \text{ g}\cdot\text{kg}^{-1}$, $P < 0.05$). However, when the NaCl treatment was isolated for guava (greatest decline in IVD after rinse, 3.79 to 1.75) only Ca showed a significant response ($P < 0.05$) to the rinse treatment, declining from 27.6 to $14.2 \text{ g}\cdot\text{kg}^{-1}$. Whereas in elm (reuse treatment, greatest increase in IVD after rinse, 1.79 to 4.46) only N and Ca showed significant separation ($P < 0.05$), with both increasing in response to the rinse treatment (Ca increasing from 17.7 to $24.1 \text{ g}\cdot\text{kg}^{-1}$ and N increasing from 29.9 to $36.6 \text{ g}\cdot\text{kg}^{-1}$). Unlike the IVD and the tissue ion concentrations, many spectral reflectance indices had significant changes in response to the rinse period. However, in the NaCl

treatment with guava, only the simple ratio changed significantly (decreasing rather than increasing, as would have been expected with a reduced IVD). Elm had the highest number of significant changes in indices in response to the rinse but again many changed in a direction opposite of what was expected (Table 7). The CHL index for the reuse treatment however did decrease (0.47 to 0.38 , $P < 0.05$) in response to the rinse as the IVD increased. The mixed results with the spectral indices after a post irrigation rinse may indicate that recovery had not yet translated into a visual rating improvement, which may require a longer period of time. Reflectance measurements were also not obtained directly over damaged areas, which remain after a rinse period occurs and are included in the visual rating.

Irrigation evapoconcentration. The irrigation waters were not established as iso-osmotic solutions but contained elevated single salts blended with Colorado River water. Since 50% of the electrical conductivity (EC) was based on mixed salts found in water from the Colorado River, similar elevated ECs had similar osmotic potentials (OP) (Fig. 3). This was especially true at lower evaporation rates (25% evaporation, $\text{OP} = 0.108 \pm 0.006 \text{ MPa}$). However, a clear concentration effect occurred after 75% evaporation (salinity increasing to values between 41 and $49 \text{ dS}\cdot\text{m}^{-1}$ at 95% evaporation, except for the CaSO_4 water which peaked at $23 \text{ dS}\cdot\text{m}^{-1}$). As was expected, waters dominated by specific ions (Ca, Mg, Na, Cl, SO_4) had higher concentrations of those specific ions. However, in only six out of the 30 cases (Mg, Na, Ca, Cl, SO_4 in the six irrigation waters), did the concentration at 95% evaporation exceed what would have been predicted by a simple 20-fold increase in concentration, with no consideration for precipitation or ion

pair formation. Chloride concentrations in the MgCl_2 treatment was higher than what would have been predicted ($1.24\times$ at $299 \text{ meq}\cdot\text{L}^{-1}$, Fig. 4), as was Mg in the reuse ($2.28\times$, $139 \text{ meq}\cdot\text{L}^{-1}$), Mg in the MgSO_4 ($2.41\times$, $431 \text{ meq}\cdot\text{L}^{-1}$), Mg in the MgCl_2 ($1.87\times$, $306 \text{ meq}\cdot\text{L}^{-1}$) and SO_4 in the MgCl_2 and NaCl treatments ($1.30\times$, 137 and $136 \text{ meq}\cdot\text{L}^{-1}$). These results would suggest that greater concentrations of both Mg and Cl would exist on the leaf surface during the final phase of evaporation (relative to a simple 20 fold evapoconcentration).

Foliar absorption of salts are linked to solubility and the point of deliquescence (POD), where the POD is defined as the humidity over a saturated solution containing solid salt (Schonherr, 2002). The POD values for the five salts added separately to the irrigation tanks range from a low of 33% for $\text{MgCl}_2\cdot 6\text{H}_2\text{O}$, $\approx 50\%$ for NaCl and $\text{MgSO}_4\cdot \text{H}_2\text{O}$ to 84% for Na_2SO_4 (Cziczko et al., 1999; Schonherr, 2002), ($\text{CaSO}_4\cdot \text{H}_2\text{O}$ not reported but assumed very high). Maximum relative humidity measured on a daily basis at the field site during the summer months of June, July and August are reported in Fig. 5 (time of maximum canopy development, transpiration, irrigation applications and foliar damage). The horizontal lines represent the POD for $\text{MgCl}_2\cdot \text{H}_2\text{O}$ (33%) and NaCl ($\approx 50\%$). The maximum relative humidity exceeded the POD for $\text{MgCl}_2\cdot \text{H}_2\text{O}$ 24% of the time during these summer months but exceeded the POD for NaCl only 8% of the time. The POD value was exceeded to a greater extent at night than during the day, with maximum relative humidity exceeding the POD of $\text{MgCl}_2\cdot \text{H}_2\text{O}$ 31% at night vs. 20% during the daylight hours.

Discussion

Foliar damage to landscape ornamentals spray irrigated with reuse water is a critical factor in lowering the acceptance of reuse water as an irrigation source on mixed landscapes, especially premiere golf courses. In this study, all plants were irrigated both at the soil surface and directly on the canopy. Soil salinity levels were in an acceptable range ($< 3.0 \text{ dS}\cdot\text{m}^{-1}$), yet foliar damage occurred. The contribution of leaf level damage associated with root level absorption cannot be ruled out, however, the low soil salinity levels would suggest that the damage was magnified by the foliar application. The IVD indicated a clear separation in the amount of damage based on treatment, with a significantly higher amount of damage with NaCl and MgCl_2 irrigation waters (8 to $12 \text{ meq}\cdot\text{L}^{-1}$ for each ion). Based on the salt treatments in this experiment, results would suggest that Cl salts are more damaging than SO_4 salts (NaCl treatment tissue Na $3.4 \text{ g}\cdot\text{kg}^{-1}$ vs Na_2SO_4 treatment tissue Na $2.0 \text{ g}\cdot\text{kg}^{-1}$, $P < 0.05$) and that Mg associated with Cl is more damaging than Na associated with Cl (death of privets, high IVDs in most treatments) (Fig. 1). Over 60 years ago, Wadleigh and Gauch (1944) cautioned that knowledge of both the cation and associated anion are necessary when describing the inhibitory effects of a given substrate. Although their studies were not based

on the foliar application of salts, our results would support this same cautionary statement. The IVD response was also species dependent (Fig. 1) with laurel showing the least amount of damage (IVD 1.95) and privet and elm showing the greatest amount of damage (IVD 3.49 and 3.75 respectively). IVD values were correlated with tissue ion concentration, with 33% to 96% of the variation being accounted for by a combination of three different tissue ion concentrations (different for each species). When IVD values were separated by treatments, only in the case of the $MgCl_2$ treatment was a major elevated ion (Mg) contributing to a significant amount of the variation in the IVD ($R^2 = 0.82$, $P < 0.01$, IVD $\uparrow$ as $SO_4\downarrow$, Mg and P $\uparrow$). This response suggests that elevated cations and anions in the irrigation water may be involved in the suppression of ion uptake as much as a concentration to toxic levels in the leaf tissue. Mg toxicity associated with $MgCl_2$ waters has been reported for guayule (Wadleigh and Gauch, 1944). Mg is known to have high mobility within plants yet little is known about Mg transporters in the plasma membrane (Mengel, 2002). Mg also has a relatively small ionic radius (Mg 0.71 Å vs. Ca 0.99 Å), which may be important with regards to diffusion pathways, contributing to elevated leaf concentrations. Foliar applications of $MgCl_2$ and $MgSO_4$ were shown to have the same efficiency with regards to increasing leaf Mg content of apples (Thalheimer and Paoli, 2002). Tissue concentration of Mg was elevated in the $MgCl_2$ and the $MgSO_4$ treatments, yet IVD values were lower for the $MgSO_4$ treatment.

Spectral indices correlated with IVD values in a similar range as tissue ion concentrations (R^2 values ranging from 0.26 to 0.70), suggesting that this technique with further development could potentially become a quick nondestructive tool in assessing foliar damage (species dependent). Although we are not aware of any previously published work correlating spectral indices with foliar damage associated with saline irrigation water, extensive work has been done correlating indices such as NDVI, WBI and SR to biomass, water status and overall plant health (Gamon et al., 1995; Ma et al., 1996; Penuelas et al., 1994; Sims and Gamon, 2003). Previous work has also been published correlating changes in spectral reflectance to nutrient status (Carter, 1994; Filella et al., 1995), diseases (Jones et al., 1992) and chlorophyll content (Gitelson et al., 1999; Filella and Penuelas, 1995). We believe that if canopy level reflectance had been measured instead of leaf level reflectance (integrating the entire canopy, damaged tissue and healthy tissue) a closer correlation would have occurred with IVD values. However, damaged tissue will remain on the intact leaves even after stress recovery, making interpretation of the spectral response difficult. This would suggest that obtaining both canopy and leaf level measurements would be invaluable. In our study, the chlorophyll index, NDVI, red edge and the simple ratio were four indices that were highly correlated with IVD values, while NDPI, SR, and PRI were more correlated with tissue ion concentrations. The spectral response was species dependent, with

elm showing significant correlations between spectral indices and IVD ($R^2 = 0.70^{***}$) and between spectral indices and major tissue ion concentrations ($R^2 = 0.40^*$ to 0.91^{***}). However, when data from multiple species were combined, poor results were obtained. These poorer results with mixed species suggest care should be taken when merging data and interpreting results.

Foliar absorption of salts have been reported to be regulated by a concentration gradient and diffusion process across the cuticle that is affected by humidity over the cuticular pores and by the hygroscopicity of the salt in question (Schonherr, 2002). The same principles that control cuticular penetration when applying nutrients in a foliar spray also apply when salt solutions such as reuse water are sprayed onto the leaf (although the response is not as definitive in a mixed salt solution). Those salts with lower points of deliquescence and higher solubility, which are applied under higher relative humidities, will be absorbed to a greater extent. The longer the salts remain in solution on the cuticle the greater the opportunity for absorption. In hot dry environments, leaf wetting times after irrigations during summer months have been measured to vary from 3 to 12 min (during the day) and to be species dependent (Devitt et al., 2003). However, if the point of deliquescence is exceeded, the opportunity time for absorption is increased beyond the normal leaf wetting time (especially at night). Greater foliar damage occurred in the $MgCl_2$ treatment, which was associated with higher Mg concentrations but not higher Cl concentrations in the leaf tissue. In all species except willow, higher Mg concentrations in the tissue led to lower Ca concentrations, which could have altered membrane integrity (Cramer, 2002). Tissue samples represented total leaf samples, as no attempt was made to isolate the foliar damaged tissue from the healthy tissue. Damaged areas were most likely the result of surface damage (salt burn associated with >40 dS·m $^{-1}$ water during final phase of evaporation), $MgCl_2$ treatment exceeding the POD 31% during night time hours, localized compartmentalization of unwanted ions and specific damage (tip and marginal damage) associated with imbalanced ionic concentrations (such as Mg vs. Ca).

Applying a post irrigation rinse during a time of active growth (30 consecutive days of 10-min irrigations with municipal water) led to a decrease in soil salinity, a decrease in the IVD of guava, a non response in laurel, privet and desert willow but a rise in foliar damage associated with elm irrigated with reuse water. Similar mixed results to a post irrigation rinse have been reported previously (Devitt et al., 2003). In this study the rinse treatment led to a significant decline in most macro and micronutrients in foliar samples. Comparing two species with the greatest contrast in IVD after the rinse treatment, elm IVD (reuse) increased while guava IVD (NaCl) decreased. The only contrasting factor was the change in tissue Ca concentrations, elm increasing by 36% (IVD $\uparrow$) while guava decreased in Ca concentration by 49% (IVD $\downarrow$).

Evapoconcentration of salts onto leaves spray irrigated with reuse water under arid conditions is higher because higher irrigation volumes are required to meet transpirational demand, rainfall is low, evaporation occurs over a shorter period of time and municipal waters (such as water diverted from the Colorado River) contain significantly higher salt loads (Devitt et al., 2003; Jordan et al., 2001). Irrigating with such waters will lead to significant foliar damage in many ornamental trees (Jordan et al., 2001). Although the electrical conductivity of the six waters were very similar (as were osmotic potentials) and the elevated specific cation or anion never exceeded 19 meq·L $^{-1}$, a wide range in response was observed, suggesting that when saline waters are blended with other water sources, care should be given to monitoring not only the EC (and OP) but also the ionic composition, with the aim of minimizing the concentration of Na, Mg, and Cl. Selection of species for landscapes must be based on research relevant to the specific region and water quality. Future research should include evaluating the difference in foliar damage based on irrigating during daytime hours vs. nighttime hours, establishing threshold spray irrigation times and evaluating the effect of adding $CaSO_4$ to reuse water to improve the Ca to Na, Ca to Mg, and SO_4 to Cl ratios.

Literature Cited

- Carter, G.A. 1994. Ratios of leaf reflectance in narrow wavebands as indicators of plant stress. *Intl. J. Remote Sensing* 15(3):697–703.
- Cramer, G.R. 2002. Sodium-calcium interactions under salinity stress, p. 205–227. In: A. Läuchli and U. Lüttge. *Kluwer (eds.). Salinity. Environment-plants-molecules*. Academic Publ., Dordrecht, Netherlands.
- Cziczko, D.J. and J.P.D. Abbatt. 1999. Infrared observations of the response of NaCl, $MgCl_2$, NH_4SO_4 and NH_4NO_3 aerosols to changes in relative humidity from 298 to 238 K. *J. Phys. Chem.* 104:2038–2047.
- Devitt, D.A., R.L. Morris, and D.S. Neuman. 2003. Impact of water treatment on foliar damage of landscape trees sprinkle irrigated with reuse water. *J. Environ. Hort.* 21:82–88.
- Devitt, D.A., R.L. Morris, D. Kopec and M. Henry. 2004. Golf course superintendents attitudes and perceptions toward using reuse water for irrigation in the southwestern United States. *HortTechnology* (in press).
- Field, C.B., J.A. Gamon, and J. Penuelas. 1994. Remote sensing of terrestrial photosynthesis, p. 511–527. In: E.D. Schulze and M.M. Caldwell (eds.) *Ecophysiology of Photosynthesis*. Springer Verlag, New York.
- Filella, I. and J. Penuelas. 1994. The red edge position and shape as indicators of plant chlorophyll content, biomass and hydric status. *Intl. J. Remote Sensing* 15(7):1459–1470.
- Filella, I., L. Serrano, J. Serra, and J. Penuelas. 1995. Evaluating wheat nitrogen status with canopy reflectance indices and discriminant analysis. *Crop Sci.* 35:783–789.
- Gamon J.A. C.B. Field, M.L. Goulden, K.L. Griffin A.E. Hartley, G. Joel, J. Penuelas, and R. Valentini. 1995. Relationships between NDVI, canopy structure, and photosynthesis in three California vegetation types. *Ecol. Appl.* 5(1):28–41.
- Gamon, J.A., L. Serrano, and J.S. Surfus. 1997. The

- photochemical reflectance index: an optical indicator of photosynthetic radiation-use efficiency across species, functional types, and nutrient levels. *Oecologia* 112:492–501.
- Gamon, J.A. and J.S. Surfus. 1999. Assessing leaf pigment content and activity with a reflectometer. *New Phytol.* 143:105–117.
- Gitelson, A.A., C. Buschmann, and H.K. Lichtenthaler. 1999. The chlorophyll fluorescence ratio F735/F700 as an accurate measure of chlorophyll in plants. *Remote Sensing Environ.* 69:296–302.
- Grossman, Y.L., S.L. Ustin, S. Jacquemoud, E.W. Sandersen, G. Schmuck, and J. Verdebout. 1996. Critique of stepwise multiple linear regression for the extraction of leaf biochemistry information from leaf reflectance data. *Remote Sensing Environ.* 56:182–193.
- Hoffman, G.J., P.B. Catlin, R.M. Mead, R.S. Johnson, L.E. Fancois, and D. Goldhamer. 1989. Yield and foliar injury responses of mature plum trees to salinity. *Irr. Sci.* 10:215–229.
- Jones, K.J., L.T. Las, and H.D. Shew. 1992. Infrared image analysis of turf disease control experiments in North Carolina. *Phytopathology* 82(10):1122.
- Jordan, L.A., D.A. Devitt, R.L. Morris, and D.S. Neuman. 2001. Foliar damage to ornamental trees sprinkler irrigated with reuse water. *Irrig. Sci.* 21:17–25.
- Ma, B.L., M.J. Morrison, and L.M. Dwyer. 1996. Canopy light reflectance and field greenness to assess nitrogen fertilization and yield of maize. *Agron. J.* 88:915–920.
- Maas, E.V., S. R. Grattan, and G. Ogatta. 1982. Foliar salt accumulation and injury in crops sprinkler irrigated with saline water. *Irr. Sci.* 3:157–168.
- Peñuelas, J., J.A. Gamon, K. Griffin, and C.B. Field. 1993a. Assessing community type, plant biomass, pigment composition, and photosynthetic efficiency of aquatic vegetation from spectral reflectance. *Remote Sensing Environ.* 46:1–25.
- Peñuelas, J., I. Filella, C. Biel, L. Serrano, and R. Save. 1993b. The reflectance at the 950–970 nm region as an indicator of plant water status. *Intl. J. Remote Sensing* 14:1887–1905.
- Peñuelas, J., J.A. Gamon, A.L. Fredeen, J. Merino, and C.B. Field. 1994. Reflectance indices associated with physiological changes in nitrogen and water limited sunflower leaves. *Remotes Sens. Environ.* 48:135–146.
- Peñuelas, J., F. Baret, and I. Filella. 1995. Semiempirical indexes to assess carotenoids chlorophyll-a ratio from leaf spectral reflectance. *Photosynthetica* 31(2):221–230.
- Peñuelas, J. and I. Filella 1998. Visible and near-infrared reflectance techniques for diagnosing plant physiological status. *Trends Plant Sci.* 3:151–156.
- Quist, T.M., C.F. Williams and M.L. Robinson. 1999. Effects of varying water quality on growth and appearance of landscape plants. *J. Environ. Hort.* 17:88–91.
- Schonherr, J. 2002. Foliar nutrition using inorganic salts: laws of cuticular penetration—Review paper, p. 77–84. In: M. Tagliavini, M. Toselli, L. Bertschinger, P. Brown, D. Neilsen, and M. Thalheimer (eds.). *Proc. Intl. Symp. Foliar Nutr. Perennial Fruit Plants*. ISHS, Lueven, Belgium.
- Serrano L., S.L. Ustin, D.A. Roberts, J.A. Gamon, and J. Penuelas. 2000. Estimating water content of chaparral vegetation from AVIRIS data. *Remote Sensing of Environment*, 74:570–581.
- Sims D.A., J.A. Gamon. 2003. Estimation of vegetation water content and photosynthetic tissue area from spectral reflectance: a comparison of indices based on liquid water and chlorophyll absorption features. *Remote Sens. Environ.* 84:526–537.
- United States Golf Association. 1994. *Wastewater Reuse for Golf Course Irrigation*. Lewis Publishers, Ann Arbor MI, p. 304.
- United States Salinity Laboratory. 1954. *Diagnosis and improvement of saline and alkali soils* (USDA handbook 60) USDA, Washington, D.C.
- Wadleigh, C.H. and H.G. Gauch. 1944. The influence of high concentrations of sodium sulfate, sodium chloride, calcium chloride, and magnesium chloride on the growth of guayule in sand culture. *Soil Sci.* 58:399–403.