Published May 15, 2015

RESEARCH

Plant Growth Regulator and Soil Surfactants' Effects on Saline and Deficit Irrigated Warm-Season Grasses: I. Turf Quality and Soil Moisture

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ABSTRACT

A study was conducted at New Mexico State University in Las Cruces, NM, from 2010 to 2012 to investigate the effects of deficit irrigation on bermudagrass (*Cynodon dactylon* L.) cultivar Princess 77 and seashore paspalum (*Paspalum vaginatum* Swartz) cultivar Sea Spray treated with either soil surfactants [Revolution (modified methyl capped block copolymer) or Dispatch (alkyl polyglucoside blended with a straight block copolymer)] or a plant growth regulator [Trinexapac-ethyl (TE); 4-(cyclopropylhydroxymethylene)-3,5-dioxocyclohexanecarboxylic acid]. Irrigation was applied daily at 50% reference evapotranspiration from either a sprinkler or a subsurface drip system with either potable (electrical conductivity [EC] = 0.6 dS m^{-1}) or saline (2.3 dS m^{-1}) water. Normalized Difference Vegetation Index (NDVI) and visual ratings were determined monthly to assess stand quality and turf stress. Princess 77 treated with TE showed the highest quality and the highest NDVI (0.655) on 10 out of 15 sampling dates. Positive effects of TE applications were also observed on Sea Spray quality, NDVI, and fall color retention. Subsurface drip irrigation resulted in higher quality and NDVI during the third year of the study when compared with sprinkler irrigation. Salinity buildup in the root zone did not negatively affect visual quality of the tested warm-season species. Generally, sprinkler irrigation system and turf treated with Revolution promoted higher water distribution uniformity (lower standard deviations) than the other treatments. Further research is needed to investigate if greater drought tolerance of subsurface drip–irrigated turf is the result of increased water-use efficiency due to altered root morphology.

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Abbreviations: EC, electrical conductivity; EC_{50}, salinity levels that reduce shoot growth by 50%; ET, evapotranspiration; ET_0, reference evapotranspiration; ET_{OS}, reference evapotranspiration for short grass; NDVI, Normalized Difference Vegetation Index; PGR, plant growth regulator; SDI, subsurface drip irrigation; TDR, Time Domain Reflectometer; TE, Trinexapac-ethyl.

Lawns and recreational turf areas are considered nonessential in many communities in the drought-stricken southwestern United States because they need to be irrigated with considerable amounts of water during the summer to maintain their aesthetic value. However, irrigated green space provides the public with other important functional, recreational, and aesthetic benefits (Beard and Green, 1994). Moreover, despite the widely held belief of critics that water is wasted by irrigating nonessential crops, turfgrass areas have gained economic importance that exceeds many agricultural food and feed crops. In New Mexico, the green industry as a whole contributed $975 million to the state's economy during the fiscal year of 2004 to 2005 (Diemer, 2006) and represents a sizeable portion of tourism in the state.

However, because of drought conditions in the southwestern United States, potable water allocated to the irrigation of agricultural crops and recreational areas is limited. The thirty-year monthly average precipitation recorded from 1971 to 2000 in Las

Published in Crop Sci. 54:2815–2826 (2014).
doi: 10.2135/cropsci2013.10.0707
Freely available online through the author-supported open-access option.

Cruces, NM was 234 mm (Western Regional Climate Center, 2012). Conversely, cumulative reference evapotranspiration (ET_0) can reach and exceed 1600 mm per year. Beard (2002) reported an average deficit of 740 mm between annual potential evapotranspiration (ET) and rainfall in Albuquerque. Such a deficit can be even higher in the southern part of the state, where average summer temperatures are usually higher, resulting in a higher ET. In fact, the average deficit between ET and annual rainfall in El Paso, TX, located only 65 km from Las Cruces, was calculated to be as high as 895 mm (Beard, 2002). This value is among the highest in the country, only following Phoenix, AZ and Las Vegas, NV. Moreover, this deficit increases during late spring and summer months when the plants are fully growing and require the greatest amount of water to keep their physiological status balanced. Hence, the existing gap between cumulative ET_0 and precipitation needs to be bridged entirely through irrigation because rainfall is absent. As a result, 50% or more of urban domestic summer water use goes to outdoor watering (Devitt and Morris, 2008; Kjelgren et al., 2000) during the summer months when water restrictions on the amount of potable water allocated to residential areas are often implemented (Albuquerque Bernaillo County Water Utility Authority, 2007).

Combining the economic importance of the turfgrass industry with the limited availability of potable water in the region drives research efforts towards the development of water conservation strategies. Five main strategies have been proposed to conserve potable water used to irrigate landscape areas in arid and semiarid regions (Leinauer et al., 2010). 1. Replacing potable water with recycled (reclaimed), brackish, or any impaired water unfit for human consumption. 2. Applying irrigation following climate data, but without completely replacing ET (deficit irrigation). 3. Promoting the use of drought resistant turf species that can survive on less water than traditionally used turfgrasses. This strategy is currently imposed by many municipalities in the Southwest. 4. Increasing irrigation efficiency through irrigation systems that exhibit an improved water distribution. 5. Combining two or more measures may have the largest impact on reducing potable water spent on outdoor irrigation.

In an effort to conserve potable water, a variety of nonpotable water sources can be utilized for turfgrass irrigation. These include recycled water (also referred to as treated effluent or reclaimed water), gray water, coalbed methane-produced water, saline ground water, brackish surface or ground water, surface storm water, and irrigation return water (Duncan et al., 2009). Saline groundwater is abundantly available in the Southwest and economic benefits can result from the use of recycled water. Huck et al. (2000) estimated that using alternative water sources can reduce overall irrigation costs by 20% or more compared with using potable water. However, nonpotable water is often saline and can contain high levels of Na and other ions detrimental to plants (Marcum et al., 1998; Suplick-Ploense et al; 2002). Using these waters for irrigation can negatively affect plants and the underlying soil due to salt accumulation (Magesan, 2001). Remediation strategies such as planting salt-tolerant species and leaching salts from the root zone have been widely suggested (Ayers and Westcot, 1985; Carrow et al., 2000; Duncan et al., 2009; Huck et al., 2000). To determine the long-term viability of using nonpotable water for irrigation, it is important to assess the ability of soils and plants to withstand continued salt accumulation.

Deficit irrigation consists of irrigating turfgrass areas without replacing the maximum water loss or ET (Feldhake et al., 1984). Deficit irrigation has been proposed as an important water conservation strategy, especially in areas where precipitation is sufficient to guarantee turfgrass quality without a considerable loss of functionality (Shearman, 2008). This approach becomes essential in areas where the cost of water is too high to provide daily irrigation or where water restrictions are applied by municipalities. Appropriate turf species that can maintain quality during mild drought stress or grasses that can fully recover from long-term water deficits should be used for landscape areas when water restrictions are expected (Devitt and Morris, 2008; Kneebone et al., 1992).

When selecting turfgrasses for the purpose of water conservation, a number of factors must be considered. These include quality and functional expectations and high temperature and salinity tolerance (if nonpotable saline water is to be used for irrigation). Several studies have reported relative salt tolerances of a number of warm and cool season grasses (e.g., Alshammary et al., 2004; Dean et al., 1996; Duncan et al., 2009; Marcum, 1999). All concluded that with the exception of alkaligrass [*Puccinellia distans* (Jacq.) Parl.] and tall fescue (*Festuca arundinacea* L.) (Sevostianova et al., 2011a), most warm-season grasses are more salt tolerant than cool-season grasses. Based on these studies, the logical conclusion would be that warm-season grasses should be grown in areas affected by drought and where the use of saline water for irrigation is encouraged. Until recently, the use of warm-season grasses in transition zone climates had been difficult because their growing season barely exceeds 6 mo (Sevostianova et al., 2011b). However, a shorter growing season and the associated shorter irrigation period results in less water needed to maintain turf areas.

Lack of potable water can have negative consequences on the plant unless properly monitored. Plants become drought stressed, particularly if irrigation is applied nonuniformly and adequate amounts do not reach the root zone (Carrow, 2004). Turfgrass areas are frequently irrigated with inefficient sprinkler systems (Devitt and Morris, 2008) that are subjected to wind drift, evaporation of water

Table 1. Monthly average air temperatures, precipitation, and reference evapotranspiration (ET_0) for the Turfgrass Salinity Research Center in Las Cruces, NM during the research period (January 2010 to December 2012).

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Air temperature, °C												
2010	5.4	8.3	11.6	17.1	22.3	28.2	27.1	27.4	24.8	19.0	10.4	8.9
2011	6.0	7.0	16.2	20.0	22.2	29.5	29.4	29.0	25.2	18.5	10.6	4.0
2012	8.0	9.3	13.9	21.2	23.3	29.6	27.5	28.6	23.6	19.2	11.9	
Precipitation, mm												
2010	26	10	0	4	0	14	71	34	43	10	0	1
2011	0	0	0	0	0	17	31	16	11	7	8	32
2012	20	1	0	0	16	1	27	8	45	0	2	
ET_0, mm												
2010	57	79	134	179	235	234	210	200	169	130	70	60
2011	73	88	162	214	250	272	254	210	183	133	77	42
2012	73	97	151	177	237	276	219	218	152	132	122	

from the soil surface, and runoff. In contrast, subsurface drip irrigation (SDI) applies water directly to the root zone, avoiding the problems an inefficient sprinkler system might create. Arguments against the use of subsurface irrigation include high installation costs, difficulty in determining spacing and depth of pipes or emitters, potential interference with maintenance practices (such as aerification or pesticide applications), difficulty in monitoring underground systems, potential root intrusion and clogging of the drip emitters, the inability to establish turf from seed when irrigated below the surface, and the inability to leach salts (Leinauer and Devitt, 2013). Beard (1973) predicted limited or no success for subsurface irrigation on turf. Findings by Sevostianova et al. (2011a) confirmed some of these concerns and suggested that sprinklers are more efficient than subsurface drip lines in leaching salt from the root zone.

The chemical industry has introduced new solutions to conserve potable water in the form of soil surfactants and/or plant growth regulators (PGR). Nonionic soil surfactants, also called wetting agents, have been commonly used in the turf industry to improve infiltration, percolation, and the rewetting of hydrophobic, repellent turfgrass root zones (Cisar et al., 2000; Karnok et al., 2004; Kostka and Bially, 2005). Surfactants disrupt the cohesive forces of water molecules responsible for expressing surface tension, which in turn allows water to distribute more evenly over sand particles and allows for better penetration of water into hydrophobic root zones (Baird, 1993; Karnok and Tucker, 2000). More recently, these surfactants have also been proposed for their role in water conservation (Leinauer and Devitt, 2013). Plant growth regulators are chemical compounds that decrease plant growth by inhibiting either cell division (type I) or gibberellic acid synthesis (type II) (Fry and Huang, 2004). With the introduction of TE (Primo Maxx) in the 1990s, the application of PGRs has become a common practice to maintain high quality turf. Particularly, golf course superintendents use these products on bermudagrass fairways to decrease mowing frequency. Moreover, several reports have documented either lower ET rates or increased turf quality during short drought periods for cool-season grasses treated with TE (Fry and Jiang, 1998; King et al., 1997; Marcum and Jiang, 1997).

To our knowledge, no published field studies have investigated the interaction effects of TE and surfactants with other water conservation strategies such as saline irrigation water and SDI. The objective of this study was to investigate the effects of soil surfactants and TE on two warm-season turfgrass species subjected to drought and salinity stress. Turf performance of Princess 77 bermudagrass and Sea Spray seashore paspalum were investigated when irrigated at 50% ET_0 using two water qualities (potable vs. saline) from two differing irrigation systems (sprinkler vs. subsurface drip).

MATERIALS AND METHODS

A three-year (2010– 2012) field study was conducted at the New Mexico State University Turfgrass Salinity Research Center in Las Cruces (arid, 1265-m elevation) to investigate the responses of Sea Spray seashore paspalum and Princess 77 bermudagrass to multiple environmental stresses. Plots were originally established in spring of 2009 and had reached complete ground cover in fall of 2009. The soil was a sandy skeletal mixed thermic Typic Torriorthent. Climate data during the study period were collected by a weather station located in close proximity to the study area (Table 1).

Plots were irrigated with either potable water (EC = 0.6 dS m^{-1}) or saline ground water (EC = 2.3 dS m^{-1}) from a shallow saline aquifer. Chemical constituents of both water sources are listed in Table 2. Irrigation was provided either by means of a Toro DL2000 subsurface drip irrigation system or a Toro MPR sprinkler system (The Toro Company, Bloomington, MN). Toro pop-up spray heads were positioned at the corner and along the sides of each main block. Subsurface drip lines were installed at a soil depth of 10 cm with drip emitters and drip lines spaced 33 cm apart. The subsurface drip system was operated at 200 kPa, which ensured emitter delivery rates of 2 L h^{-1}. Irrigation audits on the sprinkler system were performed three times a year to ensure a distribution uniformity of >0.7.

Table 2. Chemical analysis of potable and saline water used in the study.

	Water quality†	
	Potable	Saline
pH	7.63	7.69
Electrical conductivity, dS m^{-1}	0.57	2.25
Carbonate, mmol L^{-1}	n.d.	n.d.
Bicarbonate, mmol L^{-1}	2.19	3.52
Residual Na_2CO_3, mmol L^{-1}	n.d.	n.d.
P, mmol L^{-1}	0	0
K, mmol L^{-1}	0.12	1.0
Mg, mmol L^{-1}	0.75	2.53
Ca, mmol L^{-1}	2.62	7.93
Na, mmol L^{-1}	2.12	12.0
Na adsorption ratio	1.87	5.25

† n.d., not detected.

To replace water loss from the turf stand, plots were irrigated at 80% of reference evapotranspiration for short grass (ET_{OS}, Snyder and Eching, 2007) from 15 March to 31 May and from 1 October to 15 November. During dormancy (16 November to 14 March), plots were irrigated once every two weeks. On the basis of Bañuelos et al. (2011), who reported drought stress in seashore paspalum and bermudagrass when irrigated below 66% ET_{OS}, we imposed drought stress during the main growing season (1 June to 30 September) through irrigation at 50% ET_{OS} (Snyder and Eching, 2007). Irrigation run times were calculated every Monday morning on the basis of the previous week's ET_{OS}, and plots received the daily equivalent of 7% of the weekly ET_{OS}. Each sprinkler or subsurface irrigation main plot was provided with a separate solenoid valve and pressure regulator. Irrigation water use for each irrigated block was recorded by means of water meters (Invensys Process Systems Inc., Plano, TX) and run times were calculated on the basis of emitter and sprinkler delivery rates compared with water meter readings. Grasses were treated monthly from June to September with either a wetting agent (Revolution at 20 L ha^{-1} mo^{-1} or Dispatch at 2.3 L ha^{-1} mo^{-1} [Aquatrols, Paulsboro, NJ]) or a PGR (TE at 1.6 L ha^{-1} mo^{-1} [Syngenta Professional Products, Greensboro, NC]) and compared with an untreated control. Revolution was selected on the basis of the widespread use of this wetting agent by golf course superintendents in the area and Dispatch was selected on the basis of manufacturer recommendations for use as a component to improve infiltration as part of a salinity management (anecdotal data and S.J. Kostka, personal communication, 2009).

During the 3-yr research period, plots were mowed two to three times per week at a height of 2 cm using a reel mower with clippings collected. Fertilization consisted of 5 g N, 2.2 g P, and 4.2 g K m^{-2} applied during beginning of April, mid-May, mid-August and mid-October. Composite soil samples of each irrigated main plot were collected at depths of 0 to 10 cm and 10 to 20 cm in March, June, and November of each year to monitor salt accumulation in the root-zone.

To assess turf quality, visual ratings on a scale from 1 (dead) to 9 (dense, dark green, uniform) were collected every 2 wk from June to September and subsequently averaged for each month. A rating of 6 indicated the lowest acceptable quality. Normalized Difference Vegetation Index readings were collected to quantify stress (Park et al., 2007) on the same day as visual quality ratings by means of a Greenseeker (NTech Industries, Ukiah, CA) handheld optical sensor unit (model 505). Digital image analysis was used to evaluate percent green cover. Images taken on 15 November of each year were analyzed using SigmaScan Pro 5 (Systat Software Inc., San Jose, CA) (Karcher and Richardson, 2003). Volumetric water content from 0 to 7.5 cm depths was recorded monthly. Nine soil moisture readings per plot were collected by means of a Time Domain Reflectometer (TDR) (Fieldscout TDR300, Spectrum Technologies, Inc.) 24 h after an irrigation event. Readings were averaged and a standard deviation of the mean was calculated as a measure of soil moisture uniformity (Miller, 2006; Soldat et al., 2010).

The experimental design was a completely randomized split-plot with a combination of irrigation system and water quality as whole plot (12 m by 6 m) and grass species (6 m by 6 m), chemicals (2 m by 2 m), and sampling dates as subplot treatments. Treatments were replicated three times. The data were subjected to ANOVA using SAS Proc Mixed (version 9.2; SAS Institute, Cary, NC) followed by multiple comparisons of means using Fisher's protected least significant difference test at the 0.05 probability level. Initial statistical analysis revealed a significant grass species effect including significant interactions with other treatment variables. To reduce the results to a manageable size and to present the findings in a somewhat comprehensible length, data were subsequently analyzed again and are presented separately for each grass species.

RESULTS

Turfgrass Visual Quality

Analysis of turf quality data revealed a significant year × water quality × irrigation system interaction and a significant year × month × chemical treatments interaction for both Princess 77 (Table 3) and Sea Spray (Table 4). Therefore, data were first averaged over month and chemical treatments and are presented separately for each year, water quality, and irrigation system (Table 5). Second, data were averaged over water quality and irrigation system and are presented separately for each combination of year, month and chemical treatment (Fig. 1).

Visual quality of Princess 77 and Sea Spray irrigated with saline water was acceptable (equal to or higher than 6.0) on most sampling dates, regardless of the irrigation system used (Table 5). The visual appearance of sprinkler-irrigated turf with potable water was better than irrigation with SDI in 2010 and 2011 (Table 5), but quality for both species dropped below the minimum acceptable level of 6 by 2012. Visual quality of Princess 77 irrigated with saline water did not differ between irrigation systems throughout the study period. However in 2012, Sea Spray irrigated with saline water from SDI exhibited higher quality than Sea Spray irrigated from a sprinkler system (Table 5).

When data were averaged over water quality and irrigation system, quality was greater for 5 out of 15 rating dates for Sea Spray treated with TE and for 12 out of 15 dates

Table 3. Results of ANOVA testing the effects of year, month, water quality, irrigation systems, chemicals, and their interactions on turf quality, Normalized Difference Vegetation Index (NDVI), soil moisture uniformity, and on percent green cover in November of Princess 77 bermudagrass [*Cynodon dactylon* (L.) Pers.]. Only main effects and interactions that were significant for at least one measured parameter are presented.

	Quality	NDVI	Soil moisture uniformity	Green cover
Year (Y)	***	***	***	***
Month (M)	NS†	***	NS	n/a‡
Water quality (W)	NS	NS	***	NS
Y × W	***	NS	NS	NS
Irrigation (I)	NS	NS	***	*
Y × I	NS	NS	NS	**
Y × W × I	***	***	*	NS
Chemicals (C)	***	*	NS	***
W × C	NS	NS	NS	**
I × C	NS	NS	***	NS
Y × M × C	***	NS	NS	n/a

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

*** Significant at the 0.001 probability level.

† NS, not significant at the 0.05 probability level.

‡ n/a, not applicable.

Table 4. Results of ANOVA testing the effects of year, month, water quality, irrigation systems, chemicals, and their interactions on turf quality, Normalized Difference Vegetation Index (NDVI), soil moisture uniformity, and percent green coverage in November of Sea Spray seashore paspalum (*Paspalum vaginatum Swartz*). Only main effects and interactions that were significant for at least one measured parameter are presented.

	Quality	NDVI	Soil moisture uniformity	Green cover
Year (Y)	***	***	***	***
Month (M)	***	***	NS†	n/a‡
Water Quality (W)	NS	NS	***	NS
Irrigation (I)	NS	NS	***	NS
Y × I	***	***	*	***
Y × M × I	NS	NS	***	NS
Y × W × I	***	***	***	NS
Chemicals (C)	***	NS	*	***
Y × M × C	*	NS	NS	n/a
Y × I × C	NS	***	NS	n/a

* Significant at the 0.05 probability level.

*** Significant at the 0.001 probability level.

† NS, not significant at the 0.05 probability level.

‡ n/a, not applicable.

for Princess 77 treated with TE compared with control or turf treated with soil surfactants (Fig. 1). Dispatch increased quality of Sea Spray on several rating dates during the first 2 yr of the study, whereas during the third year there was no difference in quality among chemical treatments (Fig. 1). On Princess 77, wetting agents improved turf quality when compared with the control only in 2010 and in June of 2011. Princess 77 showed higher quality in July and August of all 3 yr, and Sea Spray showed higher quality in June and August in 2010 and 2011, while lower qualities were recorded in October when grasses entered dormancy (Fig. 1).

Normalized Difference Vegetation Index

Normalized Difference Vegetation Indices recorded on Princess 77 were affected by chemical treatments and the interactions among year, water quality, and irrigation system (Table 3). The highest NDVIs on Princess 77 were measured on plots treated with TE (0.655), followed by Revolution (0.649) and Dispatch (0.645), which did not differ from untreated control plots. When Princess 77 data were averaged over month and chemicals and presented separately for irrigation system, water quality, and year (Table 5), NDVIs in 2010 did not differ, regardless of the water quality or the irrigation system used (Table 5). In 2011, while NDVIs recorded on Princess 77 irrigated from a sprinkler system reached 2010 levels, a decline was observed on drip-irrigated turf (Table 5). Similar to the results for visual quality, the lowest NDVI was recorded (0.576) in 2012 on Princess 77 irrigated with potable water from a sprinkler system.

Similar to Princess 77, the interaction of year, water quality, and irrigation system affected NDVI readings recorded on Sea Spray (Table 4). The highest indices were measured during the first year of the study (Table 5). Beginning in 2011, NDVI started to decline and, similar to visual quality, lowest values were recorded during the last year on Sea Spray irrigated from sprinklers with potable water. The interaction among year, irrigation system, and chemical treatment affected NDVI for Sea Spray (Table 4); hence data were averaged over month and water quality. In 2010, none of the chemical treatments affected NDVI readings for either of the irrigation systems (Table 6). With the exception of turf irrigated from the sprinkler system and treated with TE, Sea Spray exhibited lower indices in 2011 compared with 2010 (Table 6). In 2011, the highest NDVI values were recorded on sprinkler-irrigated Sea Spray receiving TE (Table 6). None of the other chemical treatments affected NDVI for either sprinkler or subsurface drip-irrigated turf in 2011. In 2012, untreated and Revolution-treated Sea Spray irrigated from SDI exhibited higher NDVIs compared with sprinkler-irrigated Sea Spray.

Visual quality and NDVI were significantly correlated, producing regression coefficients of 0.57 for Princess 77 and 0.58 for Sea Spray. However, a noticeable portion of the variation in NDVI could not be explained by the variation in visual quality. A similar relationship between NDVI and turf quality in warm-season grasses were reported by others (Bell et al., 2009; Schiavon et al., 2011; Sevostianova et al., 2011b; Trenholm et al., 1999).

Table 5. Turf quality and Normalized Difference Vegetation Indexes (NDVI) in 2010, 2011, and 2012 for Princess 77 bermudagrass [*Cynodon dactylon* (L.) Pers.] and Sea Spray seashore paspalum (*Paspalum vaginatum Swartz*) irrigated with either sprinkler or subsurface drip irrigation (SDI) in combination with saline (electrical conductivity [EC] = 2.3 dS m^{-1}) or potable (EC = 0.6 dS m^{-1}) water. Quality ratings were taken on a scale from 1 to 9; with 1 = poor quality, dead grass and 9 = excellent, perfect quality. Values represent an average of 60 data points and are pooled over four treatments (Control, Trinexapac-ethyl, Revolution, and Dispatch) and 5 mo (June to October).

	SDI						Sprinkler					
	Potable water			Saline water			Potable water			Saline water		
	2010	2011	2012	2010	2011	2012	2010	2011	2012	2010	2011	2012
Visual quality												
Princess 77	6.1c†	6.2bc	6.3b	6.0c	6.4ab	6.4ab	6.6a	6.6a	5.6d	6.1c	6.6a	6.4ab
Sea Spray	6.0c	6.4b	6.9a	6.3bc	6.6ab	6.7ab	6.8a	6.6ab	4.7d	6.4b	6.3bc	6.1c
NDVI												
Princess 77	0.674ab	0.644d	0.620fg	0.668ab	0.651c	0.619fg	0.696a	0.669ab	0.576h	0.668ab	0.67ab	0.627ef
Sea Spray	0.695ab	0.663c	0.648d	0.699ab	0.656cd	0.632e	0.725a	0.661c	0.570g	0.69ab	0.635e	0.619f

† Within rows, values followed by the same letter are not significantly different according to LSD (0.05).

Soil Moisture Uniformity

Analysis of variance revealed a significant three-way interaction among year, water quality, and irrigation system and a two-way significant interaction between irrigation system and chemical treatment affecting soil moisture distribution on Princess 77 (Table 3). Therefore, data were averaged over month and chemical amendment and are presented separately for each year, water quality, and irrigation system (Table 7). Furthermore, data were averaged over year, month, and water quality and are presented separately for each irrigation system and chemical (Fig. 2). Soil moisture distribution in Sea Spray was also affected by the significant interaction of year, water quality, and irrigation system (Table 4). Hence, data were first averaged over month and chemical treatment (Table 7) and secondarily over year, month, water quality, and irrigation system.

Soil moisture was distributed most uniformly (lowest standard deviation values) on Princess 77 sprinkler-irrigated with saline water in 2012 (Table 7). Standard deviations calculated from volumetric water content on SDI plots were generally higher than those on sprinkler-irrigated plots (Table 7). When data were pooled over year, month, and water quality, sprinkler-irrigated Princess 77 exhibited greater moisture uniformity, regardless of the chemical modifications (Fig. 2). Subsurface drip-irrigated turf that was left untreated or treated with TE or Dispatch had the highest standard deviations for soil volumetric water content. Revolution was the only chemical treatment that lowered the soil moisture standard deviation on drip-irrigated Princess 77 compared with control (0.43 and 0.37, respectively; Fig. 2).

Similar to Princess 77, soil moisture was more uniform on seashore paspalum irrigated with saline water from a sprinkler system compared with drip-irrigated (Table 7). Moreover, standard deviations were higher in 2011 than in 2010 or 2012 (Table 7). When data were presented separately for each chemical treatment, Revolution-treated Sea Spray had the most uniform soil moisture distribution (SD = 0.34) compared with all other chemically-treated Sea Spray. No differences in soil moisture distribution were detected among control and Sea Spray treated with either TE or Dispatch.

Percentage of Green Cover in Fall

Percentage of green cover of Princess 77 in November was affected by irrigation × year interaction and by water by chemical interaction (Table 3). When data were pooled over month, water quality, and chemical treatment, the highest percentage of green cover was found in sprinkler-irrigated turf in 2010 (57%), followed by drip-irrigated turf in the same year (48%) (Fig. 3). However, percent green cover of sprinkler-irrigated Princess 77 did not differ from those of drip-irrigated turf in 2011 (39 and 36%, respectively). Percent of green cover was the lowest in 2012, but no differences were found among irrigation systems (Fig. 3). When data were pooled over year, month, and irrigation system, Princess 77 treated with TE achieved 41 and 43% green cover when irrigated with saline and potable water and had a higher percentage of green cover than turf irrigated with saline water and treated with Revolution (Fig. 4).

Similarly to Princess 77, green cover of Sea Spray in the fall was also affected by irrigation × year interaction; green coverage was highest in 2010, with sprinkler-irrigated Sea Spray reaching 61% and drip-irrigated Sea Spray achieving 56% (Fig. 3). However, while no differences were found between 2010 and 2011 for drip-irrigated Sea Spray, percent green cover of sprinkler-irrigated turf dropped by 23% in the second year of the study (Fig. 3). Drip-irrigated Sea Spray also achieved higher green cover in 2012 (42%) compared with sprinkler-irrigated Sea Spray (36%) (Fig. 3). Chemical treatment also affected percentage of green cover in November (Table 4). Sea Spray treated with TE and Dispatch achieved the highest green cover with 50 and 48%, respectively; Sea Spray

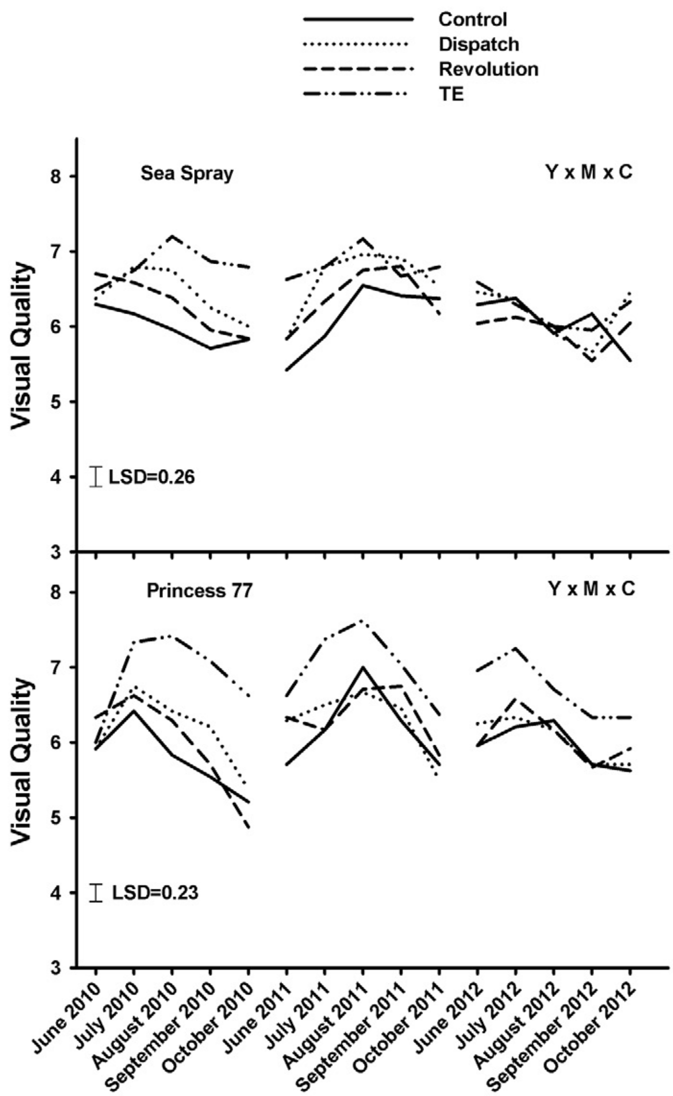

Figure 1. Turf quality from June to October in 2010, 2011, and 2012 for Princess 77 bermudagrass [*Cynodon dactylon* (L.) Pers.] and Sea Spray seashore paspalum (*Paspalum vaginatum Swartz*). Quality ratings were taken on a scale from 1 to 9, with 1 = poor quality, dead grass and 9 = excellent, perfect quality. Values represent an average of 48 data points and are pooled over two water qualities (saline [electrical conductivity (EC) = 2.3 dS m^{-1}] and potable [EC = 0.6 dS m^{-1}]), two irrigation systems (sprinkler and subsurface drip) subjected to four chemical treatments (Control, Trinexapac-ethyl [TE], Revolution, and Dispatch). Y × M × C, year × month × chemical treatments interaction.

treated with Revolution showed the lowest green cover with 45%, but they did not differ from control (47%).

DISCUSSION

The shortage of potable water in the desert Southwest has led to the implementation and enforcement of water conservation strategies to irrigate landscape areas. However, when only limited potable or saline water is available to irrigate turf areas, physiological drought and reduced quality may be observed on turf stands. Such effects need to be properly monitored to avoid significant loss of turf color and

Table 6. Normalized Difference Vegetation Indexes in 2010, 2011, and 2012 for Sea Spray seashore paspalum (*Paspalum vaginatum Swartz*) treated either with Trinexapac-ethyl (TE), Revolution, Dispatch, or untreated (Control) and irrigated with either sprinkler or subsurface drip irrigation (SDI). Values represent an average of 30 data points and are pooled over two water qualities (potable [electrical conductivity (EC) = 0.6 dS m^{-1}] and saline [EC = 2.3 dS m^{-1}]) and five sampling months (June to October).

Irrigation	Treatment	2010	2011	2012
SDI	Control	0.699ab†	0.647efgh	0.629ghij
	TE	0.689abc	0.656efg	0.645efgh
	Revolution	0.714a	0.647defg	0.610i
	Dispatch	0.703a	0.656ef	0.640efghi
Sprinkler	Control	0.699ab	0.652defg	0.580k
	TE	0.696ab	0.678bcd	0.644efgh
	Revolution	0.711a	0.636ghi	0.588k
	Dispatch	0.706a	0.656cdef	0.620hi

† Within rows and columns, values followed by the same letter are not significantly different according to LSD (0.05).

functionality. Salinity levels of the saline irrigation water used in this study match those of recycled water used for irrigation in the Southwest (Duncan et al., 2009; Huck et al., 2000). Salinity tolerance has been defined as the ability to tolerate salinity levels (in EC units) that reduce shoot growth by 50% (EC_{50}) (Duncan and Carrow, 2000). In a study comparing twelve hybrid bermudagrass genotypes, Bauer et al. (2009) found 10.7 dS m^{-1} to be the salinity level that caused a 50% reduction in 'FLoraTeX' shoot growth. This was considerably lower than values reported by Marcum and Pessarakli (2006), who found that in a comparison of 35 bermudagrass cultivars, a salinity threshold of 26 dS m^{-1} inhibited shoot growth by 50%. The average EC_{50} value for seashore paspalum is reported to be 33 dS m^{-1} (Duncan and Carrow, 2000). However, the majority of the studies determining salinity thresholds for different species and varieties were conducted in controlled environments; selecting cultivars on the basis of these studies can be misleading. Under field conditions, additional environmental stresses such as drought, cold, or heat can worsen turf quality to a greater extent than a single stress would. This would suggest that much lower salinity levels than those reported from greenhouse studies might be sufficient to cause a 50% reduction in shoot growth under field conditions. Salinity values comparable to these studies were never reached in our study, indicating that natural rainfall was sufficient to mitigate salt accumulation in the root zone throughout the year (Table 8). Therefore, quality of Sea Spray and Princess 77 irrigated with saline water were never lower than those of plants irrigated with potable water, and salinity had little to no effect on NDVI. Salinity was also not problematic when saline water was applied through SDI. Although our results confirm those of Sevostianova et al. (2011a) and Schiavon et al. (2012, 2013), who documented increased salinity levels in soil irrigated through SDI, quality and NDVI of

Table 7. Soil moisture uniformity (standard deviation of nine volumetric water content readings taken by a hand-held Time Domain Reflectometer probe) in 2010, 2011, and 2012 for Princess 77 bermudagrass [*Cynodon dactylon* (L.) Pers.] and Sea Spray seashore paspalum (*Paspalum vaginatum Swartz*) plots irrigated with either sprinkler or subsurface drip irrigation (SDI) in combination with saline (electrical conductivity [EC] = 2.3 dS m^{-1}) or potable water (EC = 0.6 dS m^{-1}). Values represent an average of 60 data points and are pooled over four treatments (Control, Trinexapac-ethyl, Revolution, and Dispatch) and five sampling months (June to October). Lower values indicate greater soil moisture uniformity.

	Soil moisture uniformity											
	SDI						Sprinkler system					
	Potable water			Saline water			Potable water			Saline water		
	2010	2011	2012	2010	2011	2012	2010	2011	2012	2010	2011	2012
Princess 77	0.47c†	0.62a	0.34e	0.33e	0.52bc	0.23f	0.41d	0.55b	0.24f	0.21f	0.39d	0.15g
Sea Spray	0.51c	0.71a	0.53c	0.47cd	0.65b	0.39e	0.33f	0.50cd	0.26g	0.26g	0.45d	0.20h

† Within rows, values followed by the same letter are not significantly different according to LSD (0.05).

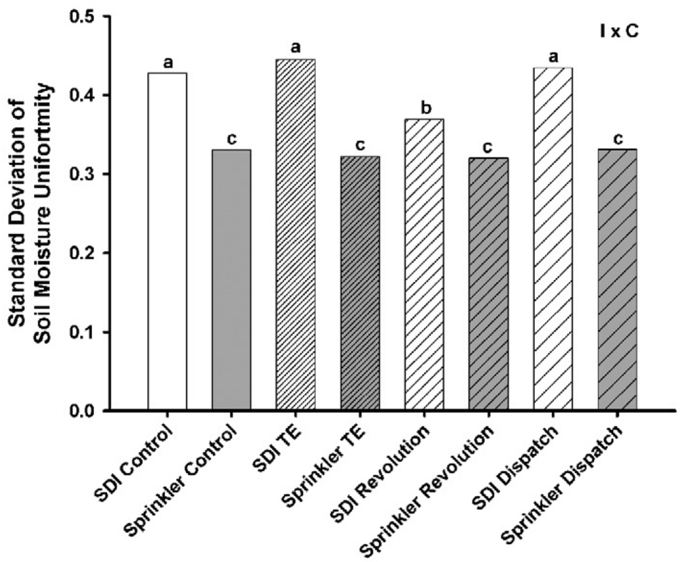

Figure 2. Soil moisture uniformity (standard deviation of nine volumetric water content readings taken by a hand-held TDR probe) in Princess 77 bermudagrass [*Cynodon dactylon* (L.) Pers.] irrigated with either sprinkler or from a subsurface drip irrigation (SDI) and treated with either Trinexapac-ethyl (TE), Revolution, or Dispatch. Values represent an average of 90 data points and are pooled over two water qualities (saline [electrical conductivity {EC} = 2.3 dS m^{-1}] and potable [EC = 0.6 dS m^{-1}]), 3 yr (2010 to 2012), and five sampling months (June to October). I × C, irrigation system × chemical treatments interaction.

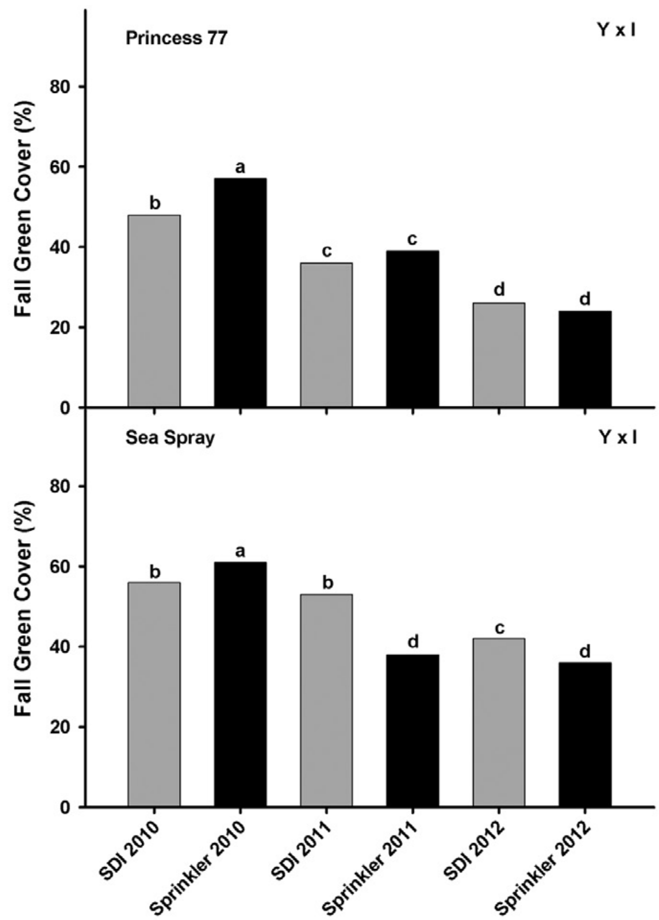

Figure 3. Percentage of green cover in November of Princess 77 bermudagrass [*Cynodon dactylon* (L.) Pers.] and Sea Spray'seashore paspalum (*Paspalum vaginatum* Swartz) (0–100%, assessed through Digital Image Analysis) irrigated with either sprinkler or subsurface drip irrigation (SDI) in 2010, 2011, and 2012. Values represent an average of 24 data points and are pooled over two water qualities (saline [electrical conductivity {EC} = 2.3 dS m^{-1}] and potable [EC = 0.6 dS m^{-1}]) and four chemical treatments (Control, trinexapac-ethyl, Revolution, and Dispatch). Y × I, year × irrigation system interaction.

subsurface-irrigated turf did not differ for two of the 3 yr between those given saline water and those receiving potable water. These results suggest that it is possible to maintain acceptable quality in warm-season species in an arid environment with deficit irrigation (50% ET_{OS}) and saline water.

Subsurface drip irrigation outperformed the sprinkler system in 2012 for both grasses. Visual quality and NDVI values were higher on turf irrigated with potable water when irrigated with SDI. Recent studies (Schiavon et al., 2011; Sevostianova et al., 2011b) have shown that SDI can be used to irrigate seashore paspalum and bermudagrass without significant loss of quality or functionality, but to our knowledge, no published study has ever reported greater quality of warm-season species when irrigated with SDI compared with sprinkler irrigation. The better quality of drip-irrigated turf observed in 2012 could not

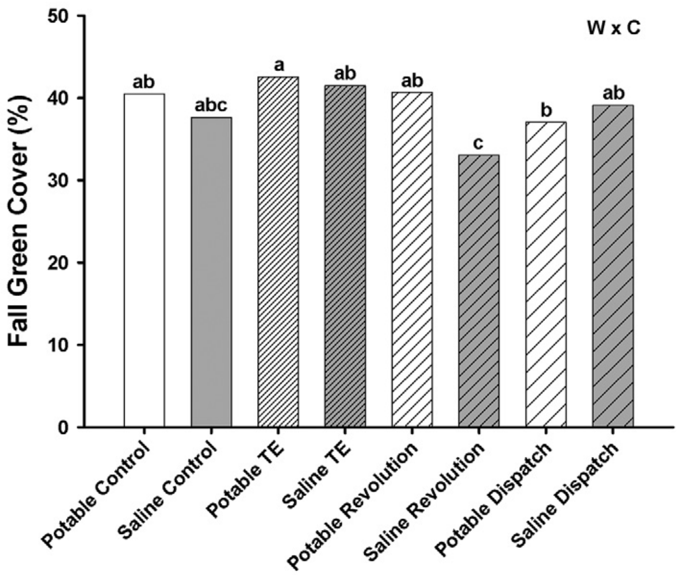

Figure 4. Percentage of green cover in November (0–100%, assessed through Digital Image Analysis) of Princess 77 [*Cynodon dactylon* (L.) Pers.] bermudagrass treated either with Trinexapac-ethyl (TE), Revolution, or Dispatch and irrigated with saline (electrical conductivity {EC} = 2.3 dS m^{-1}) or potable (EC = 0.6 dS m^{-1}) water. Values represent an average of 72 data points and are pooled over two irrigation systems (subsurface drip irrigation and sprinkler), 3 yr (2010 to 2012), and four chemical treatments (Control, trinexapac-ethyl, Revolution, and Dispatch). W × C, water quality × chemical treatments interaction.

be explained by better water distribution, as the variation among volumetric water content taken on sprinkler-irrigated plots was lower than on SDI turf regardless of the chemical amendment used (Fig. 4). A research scenario that includes perfectly square or rectangular plots with sprinklers heads placed precisely in each of the four corners is commonly used in turfgrass field experiments and could result in a more uniform water distribution than on SDI plots. However, such a situation does not necessarily represent a real-world situation and more research is necessary to investigate if applying water directly to the rootzone results in fewer losses and in more efficient irrigation when the irrigated area is irregularly shaped, similar to turf areas in a typical landscape.

Climate data indicated that 2010 had the highest amount of precipitation of the 3-yr study period, with 172 mm of rainfall from June to November. The 2 yr that followed were exceptionally dry, with rainfall amounts from June to November of 90 mm in 2011 and 83 mm in 2012. Average monthly air temperatures were also higher in 2011 and 2012 compared with 2010, resulting in higher ET_0 rates. Shearman (2008) stated that deficit irrigation as a water conservation strategy needs to be followed by sufficient rainfall for grasses to recover. During the first year of the study, precipitation was sufficient to prevent the grasses from developing severe drought-stress symptoms. However, rainfall during 2011 and 2012 was insufficient even for warm-season grasses to recover; stress developed and became especially apparent on the sprinkler-irrigated plots during the third year of the study. Moreover, limited rainfall coupled with higher ET rates that can increase the loss of water from the soil surface may have enhanced drought effects on turf plants further. Evaporation losses during irrigation can be assumed for sprinkler systems and if irrigation amount is already limited to 50% ET_0, these losses could further contribute to drought stress and decrease stand quality. Hence, an irrigation system that applies water directly to the root zone may be preferable under these drought conditions, as SDI may help explain a healthy root system even under very limited irrigation. However, no data are available on the effect of SDI on turfgrass root systems. More research is needed to determine whether or not SDI has a positive effect on root biomass production and whether or not greater turf quality of SDI-irrigated plots is the result of more efficient uptake of water.

The benefits of TE applications have been previously documented in drought-stressed grasses (McCann and Huang, 2007) and in plants irrigated with saline water (Baldwin et al., 2006). In our experiment, TE had a positive effect on turf quality, especially on Princess 77. Princess 77 treated with TE exhibited higher quality (Fig. 1), higher NDVI, and greater green cover in the fall. Increased fall color for TE-treated bermudagrass has also been reported by Richardson (2002). Trinexapac-ethyl also had positive effects on Sea Spray, but to a lesser degree. Quality of TE-treated Sea Spray plots showed improvement on only 5 of 15 sampling dates. Normalized Difference Vegetation Index values were higher in sprinkler-irrigated Sea Spray treated with TE compared with untreated grasses only at the end of the studies (Table 5).

Applications of Revolution helped increase soil moisture uniformity in all Sea Spray and in SDI-irrigated Princess 77. These results are in agreement with findings of Soldat et al. (2010), who reported not only improved moisture uniformity but also enhanced quality of creeping bentgrass treated with soil surfactants. In our study, no beneficial effects on plant stand quality were observed as a result of applying soil surfactants. However, the study conducted by Soldat et al. (2010) did not include salinity as a treatment, and the application of soil surfactants in combination with saline water could offset any beneficial effects of wetting agents. More research is needed to investigate the effects of soil surfactants when saline water is used for irrigation, including a broader spectrum of soil-surfactant chemistries. Treated soils might exhibit higher salt concentrations with increased moisture retention or lower concentrations with chemistries formulated to move water through the profile.

Our results indicate that appropriate water conservation strategies can be applied in arid zones without a significant loss of functionality of the turf stand. Salinity

Table 8. Root zone electrical conductivity (EC), sodium adsorption ratio (SAR), and Na concentration at depths of 0 to 10 cm and 10 to 20 cm during the study (March, June, and November 2010, 2011, and 2012) irrigated with either sprinkler or subsurface drip irrigation (SDI) in combination with saline (EC = 2.3 dS m^{-1}) or potable water (EC = 0.6 dS m^{-1}). Soil analyses were conducted on a composite sample from all replicates and data cannot be analyzed for significant differences.

Water quality	Irrigation system	March			June			November		
		EC	SAR	Na	EC	SAR	Na	EC	SAR	Na
		dS m^{-1}		$mmol_c$ L^{-1}	dS m^{-1}		$mmol_c$ L^{-1}	dS m^{-1}		$mmol_c$ L^{-1}
2010										
						0–10 cm				
Potable	Sprinkler	0.5	1.4	1.9	1.2	1.6	2.9	0.7	0.7	1.3
	SDI	0.4	1.8	2.7	1.1	2.9	4.2	0.9	1.4	2.6
Saline	Sprinkler	0.8	0.9	2.9	1.9	3.7	7.4	1.4	1.4	3.0
	SDI	3.0	2.1	3.9	4.9	7.2	21.6	3.3	1.6	5.6
						10–20 cm				
Potable	Sprinkler	0.3	0.7	1.7	0.8	1.5	2.1	0.7	1.3	1.9
	SDI	0.4	1.7	2.4	1.4	2.9	5.1	0.5	1.2	1.8
Saline	Sprinkler	0.8	0.7	2.6	2.9	3.3	10.1	1.5	2.0	4.0
	SDI	2.9	1.9	2.8	4.6	6.7	22.4	2.6	3.6	9.4
2011										
						0–10 cm				
Potable	Sprinkler	1.0	1.1	2.2	1.2	1.6	2.9	0.7	0.8	1.4
	SDI	1.1	2.4	4.6	1.1	3.3	7.0	1.8	2.9	4.2
Saline	Sprinkler	2.3	2.1	5.5	1.9	3.7	7.4	2.1	3.8	7.6
	SDI	2.8	4.7	11.4	4.0	8.2	22.4	3.4	6.0	11.5
						10–20 cm				
Potable	Sprinkler	1.7	1.3	1.9	0.8	1.5	2.1	0.8	1.3	2.1
	SDI	0.8	1.9	2.9	1.4	2.9	5.1	1.2	2.1	3.8
Saline	Sprinkler	3.0	3.2	9.3	2.9	3.3	10.1	2.3	3.3	7.6
	SDI	1.6	2.5	5.2	4.6	8.7	21.6	2.1	6.3	14.1
2012										
						0–10 cm				
Potable	Sprinkler	0.8	2.2	2.9	0.8	1.9	4.1	1.6	3.9	1.9
	SDI	0.4	0.5	1.2	1.6	4.1	5.8	1.7	4.7	2.1
Saline	Sprinkler	0.5	1.4	1.6	3.2	4.4	14.5	4.0	16.7	5.3
	SDI	0.8	1.6	2.6	3.9	5.9	14.8	7.0	29.5	6.4
						10–20 cm				
Potable	Sprinkler	0.4	0.4	1.1	1.0	0.9	3.0	0.7	2.4	1.8
	SDI	0.5	0.8	1.4	1.0	3.4	1.6	1.5	5.2	2.7
Saline	Sprinkler	1.6	1.3	2.8	1.3	2.7	4.6	2.7	13.5	6.3
	SDI	0.8	2.6	3.1	3.1	5.8	15.0	3.9	16.9	5.5

accumulation of our irrigation water matched those of recycled water commonly used to irrigate turf areas in the Southwest. Salinity accumulation in the root zone during the year did not negatively affect quality of salt-tolerant warm-season species. Over the course of the three-year study, chemical treatments and drip irrigation had a positive effect on stand quality. After 3 yr of prolonged drought stress, the quality of sprinkler-irrigated grasses dropped below an acceptable rating of 6. Our results suggest that TE in combination with SDI may help to maintain plant stand quality and functionality during drought conditions.

Acknowledgments

This work was made possible in part by funding from the National Science Foundation's Engineering Research Center for Re-inventing the Nation's Urban Water Infrastructure, ReNUWlt (NSF EEC-028968). Financial support was also provided by the New Mexico State University's Agricultural Experiment Station, Facilities and Services, by the Cooperative State Research, Education, and Extension Service, U.S. Department of Agriculture under Agreement No. 2005-3446115661 and 20054504903209, by Aquatrols Corp., Rio Grande Golf Course Superintendents Association, Southwest Turfgrass Association, Seeds West Inc., Simplot Jacklin Seed, The Toro Co., and United States Golf Association. Support and technical assistance from Dr. Mary O'Connell and her team is also greatly appreciated. The authors are further grateful for the donations from Helena Chemical Company and Syngenta AG and for the help of Karl Olson and Jon Kimmel, golf course superintendents at New Mexico State University's golf course.

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