February 2012

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WRRI Technical Completion Report No. 358

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TECHNICAL COMPLETION REPORT NO. 358

Account Number 109558
February 2012

New Mexico Water Resources Research Institute
in cooperation with the
Departments of Extension Plant Sciences and Plant and Environmental Sciences,
New Mexico State University

The research on which this report is based was financed in part by the U.S. Department of the Interior, Geological Survey, through the New Mexico Water Resources Research Institute

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ACKNOWLEDGMENTS

Financial support of the study was provided by New Mexico State University's Agricultural Experiment Station, Office for Facilities and Services, Water Resources Research Institute, by the Cooperative State Research, Education, and Extension Service, U.S. Department of Agriculture under Agreement No. 2005-34461-15661 and 2005-45049-03209, and by Seeds West Inc. The authors are also grateful for the donations from Helena Chemical Company, Precision Porous Pipe, Pure Seed Testing, and Scotts Co, and for the help and support of Bruce Erhard, golf course superintendent at NMSU's golf course.

ABSTRACT

A study was conducted in New Mexico from 2005 to 2007 to investigate the effects of two potable water-saving strategies: irrigating with saline water and using subsurface systems, on changes in rootzone salinity and quality of nine warm-season and seven cool-season turfgrasses. Plots were irrigated using either sprinklers or subsurface drip with water of one of three salinity levels (0.6 dS m^{-1}, 2.0 dS m^{-1}, 3.5 dS m^{-1}). Turf plots were rated monthly for quality during the growing seasons. Warm-season grasses were assessed bi-annually for spring and fall color. Green cover on cool-season plots was determined using digital image analysis. Soil samples were collected bi-annually (June and November) and analyzed for electrical conductivity (EC), sodium (Na), and Sodium Adsorption Ratio (SAR) at depths of 0-10 cm, 10-20 cm, and 50-60 cm. Generally, changes in soil EC, Na content, and SAR reflected seasonal changes in irrigation and natural precipitation for both grasses. Electrical conductivity and Na values in 0-20 cm peaked in June of 2005 and 2006 and dropped to lower levels after the summer rainy season.

With the exception of moderately saline irrigated plots in 2005, summer EC on warm-season grasses did not differ between drip and sprinkler irrigated plots for any of the three water qualities. Electrical conductivity, Na, and SAR at a rootzone depth of 0-20 cm were highest in June 2006 reaching 4.7 dS m^{-1}, 1024 ppm, and 16.1, respectively. For most of the warm-season grasses tested, EC, Na, or SAR values showed no significant relationship with turf quality. Drip irrigation resulted in earlier green-up than sprinkler irrigation but had no effect on summer quality or fall color retention. Most of the warm-season grasses included in this study maintained an acceptable quality level when drip-irrigated with saline water.

Electrical conductivity and Na values were highest (6.1 dS m^{-1} and 943 ppm, respectively) in June of 2006 on drip irrigated plots of cool-season grasses at depths of 0-10 cm. Electrical conductivity was higher in drip irrigated plots than sprinkler irrigated plots on four of the six sampling dates. Irrigation type and water quality did not affect EC and Na at soil depths of 50-60 cm. For four of the seven grasses tested, EC, Na, or SAR values showed a significant but weak relationship ($0.18 < r^2 < 0.27$) with turf quality, indicating that more than one stressor affected visual ratings. With the exception of tall fescue [*Festuca arundinacea* (Schreb.)], cool-season grasses could not be maintained at acceptable quality levels when irrigated with saline water from either a sprinkler or a subsurface drip system. Based on these findings, with the exception of tall fescue, warm-season grasses appear to be the logical choice for turf areas irrigated with saline water from either a drip or a sprinkler system.

Keywords: turfgrass, saline water, grasses, saline irrigation

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INTRODUCTION

Rapid population growth and urban development in arid and semi-arid regions of the United States have resulted in a growing scarcity of potable water in these areas. Consequently, attention is being increasingly focused on the amount of potable water used for purposes considered non-essential to human society, such as irrigating landscapes or watering recreational areas such as home lawns, parks, golf courses and athletic fields. As a non-food crop, turfgrass provides the public with benefits to urban life that are less tangible, such as mitigation of heat island effects, erosion control, shade, providing a cool and safe surface for all sorts of exercise and athletic activities, and space for outdoor social gatherings. These benefits are extremely difficult to quantify economically because turfgrass has no measurable yield but can contribute significantly to local economies. In the United States, golf is a major revenue-producing industry that accounted for $33.2 billion worth of goods and services in the year 2002, generated 483,649 jobs nationwide (Haydu et al., 2008). In New Mexico, the turfgrass and golf sector contributed a total of $975,000,000 in revenues to the state's economy during the fiscal year of 2004-2005 (Diemer, 2006) and represents a sizeable portion of tourism in the state.

Despite the economic importance and continued public demand for green areas, turfgrass water consumption has been a major point of political debate in arid and semi-arid regions, particularly when 50% or more of urban domestic water used during the summer goes to outdoor watering (Kjelgren et al., 2000; Devitt and Morris, 2008). Many water rights activists insist that golf courses are strictly for recreation and serve no other purpose. Water restrictions on the amount of potable water allocated to golf courses are often the result (City of Albuquerque, NM, 2000). As part of a comprehensive conservation effort, one strategy to reduce or eliminate the use of potable water for irrigation is to irrigate with low quality non-potable water. Several sources of alternative water are available for turfgrass irrigation. These include recycled water (also referred to as effluent or reclaimed water), gray water, saline groundwater, brackish surface or groundwater, surface storm water, and irrigation return water (Duncan et al., 2009; Harivandi et al., 2008). Recycled or reused water has become a major source for irrigation, since large volumes are produced in urban areas and it is the only source of water that is growing while others are shrinking (Qian and Mecham, 2005). In the southwestern United States, 37% of all golf courses are currently irrigated with recycled water (Throssell et al., 2009). Saline groundwater extracted from shallow depths has also been suggested as a source of irrigation water for landscapes (Schaan et al., 2003). An estimated 75% of New Mexico's groundwater is considered saline or brackish and unusable for human consumption (Reynolds, 1962). About 15 billion acre-feet is classified as moderately saline to very saline and whether or not this huge reservoir of water can be used for irrigation purposes needs to be determined (Hernandez, 1985). Like saline groundwater, effluent water and most sources of impaired water usually contain a much higher concentration of salts than traditional irrigation water (Schaan et al., 2003; Dean-

Knox et al., 1998; Harivandi, 1994). Investigating the feasibility of using saline water to irrigate turf has been the subject of many studies (Dudeck et al., 1993; Marcum, 1999a; Marcum and Pessarakli, 2006; Devitt et al., 2007; Pessarakli et al., 2009). Schaan and others (2003) reported that a two-year cyclic irrigation practice, using saline groundwater at a rate of one, two, three, or four times per seven irrigation events during the peak water demand periods did not have significant effect on color or cover of overseeded bermudagrass *Cynodon dactylon* (L.). Dean and others (1996) found that color and percent cover of bermudagrass remained unchanged when irrigated with a mixture of saline and municipal water if the ratio of irrigation volume to potential evapotranspiration remained above a species-specific threshold.

The ability of turfgrass species and cultivars to handle high salinity can vary greatly. Generally speaking, cool-season grasses (C_3) produce lower quality turf than most warm-season grasses (C_4) when irrigated with saline water. Warm-season grasses withstand heat better and exhibit lower evapotranspiration rates than cool-season grasses (Beard, 1986). Moreover, C_3 grasses have lower salinity tolerance compared to C_4 grasses. The results of studies conducted by Dean and others (1996) supported the selection of bermudagrass over tall fescue *Festuca arundinacea* (Schreb.) in arid climates under saline irrigation. Alshammary and others (2004) noted that salinity tolerance of saltgrass *Distichlis spicata* (L.) was greater than that of three cool-season species.

Species within the C_3 and C_4 groups also show a wide range in salinity tolerance, as indicated by the ranking of these grasses for salinity tolerance reported by Carrow and Duncan (1998); Dean and others (1996); Harivandi (1994); Marcum (1999a); and Marcum and Murdoch (1990). Marcum (2005) and Marcum and others (2009) ranked the relative salinity tolerance of warm-season grasses in the following order (from most to least salt tolerant): inland saltgrass, alkali sacaton *Sporobolus airoides* (Torr.), common bermudagrass, zoysiagrass *Zoysia japonica* (Steud.), and buffalograss [*Buchloe dactyloides* (Natt.) Englem]. In a study of shoot growth response to salinity, Pessarakli and others (2009) found common bermudagrass to be most affected by salinity stress, followed by seashore paspalum *Paspalum vaginatum* (Swarz.) and inland saltgrass. Other studies have found seashore paspalum to be the most salt tolerant among warm-season grasses tested (Carrow and Duncan, 1998; Duncan and Carrow, 2000; Lee et al., 2004, 2007).

The species within the C_3 group also show a wide range in salinity tolerance, as indicated by the ranking of these grasses for salinity tolerance reported by Carrow and Duncan (1998). Based on the results of greenhouse container and hydroponic experiments comparing three cool-season grasses, Alshammary and others (2004) ranked alkaligrass [*Puccinellia distans* (L.) Parl] most salinity tolerant, followed by tall fescue, and then Kentucky bluegrass *Poa pratensis* (L.). Carrow and Duncan (1998) ranked salinity tolerance of cool and warm-season grasses using saturated paste levels that result in 50%

growth reduction. Perennial ryegrass *Lolium perenne* (L.) averages a 50% reduction in growth at 8-10 dS m^{-1} and fine fescue (*Festuca rubra* L.) at 8-12 dS m^{-1}. In the greenhouse study of Alshammary and others (2004), alkaligrass had the ability to maintain 50% shoot growth when grown in water at a salinity level of up to 28.5 dS m^{-1}. In the same study 50% shoot growth reduction was found for Kentucky bluegrass at 9.0 dS $m^{-1}$and tall fescue at 10.4 dS m^{-1}. Producing a consistent ranking of salinity tolerance among turfgrasses is difficult because results vary depending on the criteria and endpoints authors used to measure salinity tolerance (Marcum, 1999a).

Differences in salinity tolerance among cultivars within a given species can vary widely and can sometimes be greater than species differences. Varietal differences in salinity tolerance have been reported for zoysiagrasses (Marcum et al. 2003; Qian et al., 2000), bermudagrasses (Dudeck et al., 1983; Marcum and Pessarakli, 2006), seashore paspalum (Carrow and Duncan, 1998; Lee et al., 2005), inland saltgrasses (Marcum et al., 2005) and St. Augustinegrass [*Stenotaphrum secundatum* (Walt.) Kuntze] (Dudeck et al., 1993).

Suplick-Ploense and others (2002) studied five Kentucky bluegrass cultivars to determine the variability in salt tolerance within and among two *Poa* species and their hybrids during late winter and during summer time. Although Kentucky bluegrass was ranked as a salt-sensitive turfgrass in general, there was a broad range of variability in leaf firing and shoot and root growth reduction in response to salinity among cultivars.

Using salinity thresholds reported in the literature to select cool-season and warm-season grasses for field use can be misleading because most of the aforementioned studies (Dudeck et al., 1993; Marcum, 1999b; Lee et al., 2005; Marcum and Pessarakli, 2006; Pessarakli et al., 2009) were conducted under controlled-environment greenhouse conditions. Additional environmental stresses, such as drought, cold, or heat, all of which typify arid and semi-arid regions and can exacerbate the effects of salt stress, were not considered. Transitional semi-arid and arid climates are characterized by extreme diurnal and/or seasonal changes in weather conditions (the average diurnal range is 32.5ºF), creating difficult conditions for growing cool- and warm-season grasses. The growing season may barely exceed six months and low winter temperatures can cause damage to the warm-season grasses due to their low tolerance of cold temperatures. On the other hand, summer temperatures are high, making cool-season grasses difficult to sustain because of heat stress. Exposure to the added stresses from a harsh climate might change the outcome of a salinity trial and lead to decreased survival of a turfgrass, which it would otherwise tolerate.

A second strategy for reducing the amount of potable water used for irrigation purposes is to optimize irrigation efficiency. Sprinkler irrigation is the accepted practice for irrigating lawns and other turf areas despite a reported low efficiency in distributing water to the plant stand (Mecham, 2004). Incorrectly spaced and installed sprinkler heads, wind drift, and evaporation losses during the irrigation process all contribute to water losses that can increase overall water consumption and/or decrease plant stand quality. Subsurface drip systems that apply water laterally within the rootzone from line-source or point-source irrigation tiles have been introduced as a means of supplying irrigation water more efficiently than sprinkler systems. Advantages of these subsurface irrigation systems include the uninterrupted use of the turf area during irrigation, energy savings due to a lower operating water pressure, reduced disease pressure, and potential water savings because irrigation is applied directly in the rootzone and is not affected by wind drift or evaporation (Beard, 1973; Burt and Styles, 1999; Leinauer, 1998; Duncan et al., 2009). The benefits of subsurface drip irrigation have been extensively studied in agriculture (Camp et al., 1998; Bosch et al., 1992; Malash et al., 2008) but this technology only recently received attention in the field of turf management. Schiavon and others (2011) investigated turf quality of warm-season grasses over a four-year period and reported neither a decline in the performance of drip irrigation systems nor in the quality of tested grasses in an arid climate. Similarly, Choi and Suarez-Rey (2003) found no reduction in quality of bermudagrass turf that was drip irrigated with recycled water (EC_w of 0.95 dS m^{-1}).

While subirrigation systems distribute water more efficiently and uniformly (especially in times and areas of high winds), these systems may have some limitations in leaching salts from the rootzone. Applying water in excess of what plant growth requires is a necessary turf maintenance practice to leach salts from the rootzone and thereby avoiding salt accumulation. When drip irrigation systems in combination with saline water are used to irrigate turf areas the fraction of the rootzone above the emitters (where most of the roots are accumulated) that receives water only through capillary raise may not be sufficiently flushed with water to leach out the salts. Devitt and Miller (1988) suggested that by spacing drip lines at distances that allow leaching fractions to achieve high soil water content uniformity, salt buildup in the active rootzone could be reduced when drip-irrigating with saline water.

Because of the increasing pressure to conserve potable water, it is imperative that efforts be made to increase irrigation efficiency and to utilize recycled or other impaired water sources to sustain quality and functionality of turfgrass areas. New Mexico’s climate is characterized as transitional semi-arid to arid with wide seasonal and diurnal temperature fluctuations. Because of the cold winters, cool-season grasses are widely grown and are commonly found on residential turf areas and athletic fields in New Mexico. Furthermore, almost all golf courses grow cool-season turf on greens, tees, and fairways. Currently, information is lacking on the longer-term sustainability of warm- and cool-season grasses in transitional arid climates when irrigated with saline water from a subsurface drip system.

A study was conducted at New Mexico State University to assess the longer-term effects of water quality and type of irrigation on turf quality of several cool and warm-season grasses in the arid southwest. Moreover, we investigated whether or not salinity accumulation in the rootzone is a predictor of turfgrass quality for several turfgrass species and varieties.

MATERIALS AND METHODS

A study was carried out at the New Mexico State University's golf course in Las Cruces, NM (USDA Plant Hardiness Zone 8) from 2005 to 2007 on turf plots that were established in 2004. Monthly average temperature, precipitation, and reference evapotranspiration during the research period are listed in Table 1.

Table 1. Monthly average air temperatures (°C), precipitation (including 30-year average) (mm) and reference Evapotranspiration (ET_o) (mm) for Las Cruces, NM (USA) during the research period (January 2005 to December 2007).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	Air Temperature (°C)											
2005	8.3	9.3	9.2	17.3	22.2	27.1	28.8	25.7	24.5	16.8	11.2	6.4
2006	8	10.6	13.6	19.3	23.6	27.7	27.7	24.7	20.9	16.1	11.3	5.6
2007	5.3	9.1	14	17.1	21.6	26.3	26.8	27.3	24.2	17.9	11.6	6.4
	Precipitation (mm)											
2005	23	62	4	6	11	0	7	29	64	28	0	0
2006	1	4	0	1	9	6	33	127	112	61	4	3
2007	35	2	2	16	36	49	5	49	28	29	2	7
30-year mean	10	10	8	6	8	15	39	48	32	20	11	14
	ET_o (mm)											
2005	66	64	147	216	237	190	234	181	161	100	83	0
2006	75	54	84	178	223	231	210	162	146	103	78	0
2007	65	98	143	179	211	233	203	172	106	126	12	12

Warm-season grasses included bermudagrass *Cynodon dactylon* (L.) cultivars NuMex Sahara, Princess 77, Riviera, and Transcontinental; inland saltgrass *Distichlis spicata* (L.) cvs. A138 and DT16; seashore paspalum *Paspalum vaginatum* (Swartz) cvs. SeaDwarf and Sea Spray; zoysiagrass *Zoysia japonica* (Steud) cvs. De Anza. Cool-season grasses included tall fescue *Festuca arundinacea* (Schreb.) cultivars Southeast and Tar Heel II; perennial ryegrass *Lolium perenne* (L.) cvs. Brightstar SLT; alkaligrass *Puccinellia distans* (L) cv. Salty; and fine fescue *Festuca rubra* (L.) cv. Dawson. Plots were irrigated with potable, moderately saline, or saline water. Saline water consisted of water obtained from a saline aquifer that was pumped to the research site. Moderately saline water was prepared by mixing municipal water with saline groundwater to an EC of 2.0 dS m^{-1}. The United States Salinity Laboratory (1954) classifies the moderately saline water as C3-S1, high in salinity and low for sodium hazard and the saline irrigation water as C4-S2, very high in salinity and medium for sodium hazard. A detailed description of ion concentrations in the irrigation waters are listed in Table 2.

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

	Water Quality		
Constituents	Potable	Moderately saline	Saline
pH	7.98	7.69	7.52
Electrical conductivity (dS m^{-1})	0.6	2.0	3.5
Total Dissolved Solids (mg L^{-1})	400	1300	2200
Magnesium (meq L^{-1})	0.8	1.68	2.52
Calcium (meq L^{-1})	2.8	3.19	5.05
Sodium (ppm)	48	230	400
Sodium Adsorption Ratio (SAR)	1.55	6.41	8.94
Potassium (mg L^{-1})	4.6	28.0	51.2
Carbonate (meq L^{-1})	0.00	0.00	0.00
Bicarbonate (meq L^{-1})	2.84	6.43	9.95
Residual Sodium Carbonate (meq L^{-1})	not detected	1.56	2.38

Grasses were irrigated during the growing season from either a sprinkler or a subsurface drip system. From February to November irrigation was scheduled daily at 120% of reference evapotranspiration (ET_o) for cool-season grasses and at 110% of ET_o for warm-season grasses (Allen et al., 2005). Irrigation was scheduled daily using irrigation software (Nimbus™ II Central Control System, Rainbird Corp., Tucson, AZ) that also scheduled the golf course irrigation system. Climate data used to calculate ET_0 were collected at a weather station located on the golf course in close proximity to the study site. Irrigation for each sprinkler and subsurface drip main block was regulated by a separate solenoid valve and pressure regulator. The sprinkler system was comprised of eight Walla Walla MP2000 Rotators (Walla Walla Sprinkler Company, Walla Walla, WS) operated at 200 kPa and spaced 3.8 m apart to allow for uniform irrigation. Irrigation audits conducted bi-monthly during each year ensured a minimum distribution uniformity (DU) of 0.7 and provided data necessary to compare the irrigation systems actual water delivery rates with computer settings. The subsurface drip system consisted of porous emitterless line source pipes (Precision Porous Pipe, McKenzie, TN) with a diameter of 1.27 cm operated at 200 kPa. Each subsurface drip irrigated block had a flush valve installed to prevent sediments from potentially clogging the drip lines. The flush valve was located at the opposite corner of the water inlet and allowed for a 10 to 15 second-long flush cycle at the beginning of each irrigation cycle. The pipes were installed at a soil depth of 7.5 cm and spaced 30 cm apart. Irrigation water use on subsurface drip irrigated blocks was recorded by means of a water meter (Invensys Process Systems Inc., Plano, TX) and run times were calculated based on recorded water delivery rates minus the amounts that were lost in the flush cycles. Uniform water distribution on subsurface drip irrigated blocks was monitored three times over each growing season by taking 24 volumetric soil moisture readings at depths of 0-6 cm with a hand-held ThetaProbe soil moisture sensor (Delta-T Devices Ltd., Cambridge, England) 24 hours after an irrigation cycle. Soil moisture values were subsequently analyzed for distribution uniformity, similarly to DU calculations on sprinkler irrigated blocks. Uniform water distribution on subsurface drip irrigated blocks was monitored two times over each growing season by taking 24 volumetric soil moisture readings at depths of 0-6 cm with a hand held ThetaProbe soil moisture sensor (Delta-T Devices Ltd., Cambridge, England) 24 hours after an irrigation cycle. Soil moisture values were subsequently analyzed for distribution uniformity, similarly to DU calculations on sprinkler irrigated blocks. Establishing DU values for both sprinkler and drip irrigated plots were considered basic maintenance steps taken to ensure that the systems were operating within normal parameters. Therefore they are not reported or discussed in this paper.

The soil at the site consisted of a sandy loam, a sandy skeletal mixed thermic Typic Torriorthent, an entisol typical for arid regions. Chemical properties of the soil prior to turfgrass establishment and irrigation are listed in Table 3. During the growing season (March to November) plots were mowed biweekly at a height of 5 cm for warm-season grasses and at a height of 7.5 cm for cool-season grasses and clippings were collected. Plots were fertilized at a rate of 5 gN m^{-2} with 15-15-15 quick release fertilizer in April, June, August, and October. A micronutrient fertilizer (Pro-Mate®, Helena Chemical Company, Collierville, TN) containing calcium (1.0%), magnesium (4.3%), sulfur (18.2%), copper (0.3%), iron (14.3%), and manganese (2.6%) was applied in summer at a rate of 10 gm^{-2}. The pre-emergent herbicide Pendulum® (active ingredient 37.4% pendimethalin) was applied at a rate 0.65 ml m^{-2} in April to prevent weed germination. The systemic insecticide Merit® (active ingredient 75% imidacloprid) was applied at 0.5 g m^{-2} in June and August to prevent grub damage.

Turfgrass color and quality was assessed by means of a visual rating scale recommended by the National Turfgrass Evaluation Program (Krans and Morris, 2007). Turfgrass quality was determined monthly from March to November on a scale of 1-9, with 1=dead turf and 9=dark green, uniform turf.

The monthly ratings were averaged every three months (March to May, June to August, and September to November) and analyzed as three different seasons. Turfgrass color ratings were collected for warm-season grasses in March, April, October, and November to evaluate the plots for spring green- up and fall color retention. Plots were assessed on a scale of 1-9 with 1=brown, tan colored and 9=dark green turf. Normalized Difference Vegetation Indices (NDVI) readings were collected by means of a Greenseeker (NTech, Ukiah, CA) monthly from March to October in 2007. Photographic images from cool-season plots were taken monthly from March to November at full sunlight from one hour before until one hour after solar noon by means of a digital camera. The camera was mounted on a frame at a height of 150 cm that allowed for capturing the same area of 1.5 m by 1.5 m in the center of each plot every time photographs were taken. Digital images were analyzed for percent green coverage (SigmaScan Pro, Systat Software 132 Inc., San Jose, CA) (Karcher and Richardson, 2003). Coverage data were averaged every three months and correlated with visual quality. Correlations between coverage and NDVI data and visual quality data were subsequently run.

Composite soil samples were collected before the beginning of the study (Table 3) and then bi-annually in mid-June and mid-November from depths of 0-10 cm, 10-20 cm, and 50-60 cm using a 4.5-cm diameter soil auger. A mid-June sampling date was deemed appropriate as it is halfway through the growing period of warm-season grasses and historically marks the beginning of the rainy season. Therefore, rootzone salt accumulation from saline irrigation is expected to be highest in June. The November sampling date was selected because it marks the end of the growing period of warm-season grasses. Solutions were extracted with distilled water from the soil saturated paste and analyzed for EC (conductivity bridge) and Ca, Mg, and Na (plasma emission spectroscopy) (Fransen, 1989).

Table 3. Initial (pre-experiment) soil chemical characteristics at the research site.

	Depth (cm)		
Soil characteristics	0-10	10-20	50-60
pH	8.7	8.5	8.4
EC[1] (dS m^{-1})	0.22	0.21	0.23
Mg (meq L^{-1})	0.4	0.4	0.4
Ca (meq L^{-1})	2.4	2.2	1.7
Na (ppm)	16	14	28
Cl (meq L^{-1})	0.2	0.14	0.1
K (meq L^{-1})	0.3	0.1	0.1
Sodium Adsorption Ratio	0.59	0.53	1.17
Organic Matter (%)	0.4	0.4	0.4

[1] measured in a saturated paste extract.

The research area was 36 m x 70 m in size and was designed as a randomized complete block. A combination of irrigation system and water quality served as the whole block (7.5 m x 10 m) treatments and grasses (2.5 m x 2.5 m) and soil depths as the subplot treatments. All treatment factors were replicated three times. To test the effects of irrigation salinity level and irrigation system on rootzone salinity, turfgrass color, quality, cover, and NDVI, data were subjected to a repeated measures analysis using a compound symmetry covariance structure in SAS proc mixed (SAS Institute, Inc., Cary, NC). Fisher's LSD test at the 0.05 probability level was used to identify significant differences among means. Proc corr and proc reg (SAS Institute, Inc., Cary, NC) were used to correlate visual quality ratings with NDVI and percent coverage. Stepwise linear regression (Proc Reg, SAS Institute, Inc., Cary, NC) was used to investigate the relationship between summer turf quality and EC, Na, and SAR in the top 10 cm of the rootzone.

RESULTS

Warm-Season Grasses

Rootzone salinity at depths of 0-20 cm

The analysis of variance (ANOVA) (Table 4) for the two upper soil depths (0-10 cm and 10-20 cm) revealed significant three-way interactions between irrigation, water, and sampling date and between irrigation, depth, and sampling date for both EC and Na content. Rootzone EC and Na data were subsequently pooled over sampling depths and are displayed separately for each water quality and irrigation system at each sampling time (Figures 1 and 2). Data were also pooled over water qualities and are shown separately for each irrigation system and depth at each sampling date (Figures 3 and 4).

Table 4. Results of analysis of variance testing the effects of water quality, irrigation systems, sampling times, and their interactions on rootzone salinity (EC, Na, and SAR) at soil depths of 0-20 cm (in 10 cm increments hence depth as additional treatment) and 50-60 cm of warm-season turfgrasses. Highlighted interactions are discussed in the text.

	Soil depth					
	0-20 cm			50-60 cm		
	EC	Na	SAR	EC	Na	SAR
Irrigation (I)	n.s.[‡]	n.s.	n.s.	n.s.	n.s.	n.s.
Water Quality (W)	***	***	***	***	***	***
I*W	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Sampling Date (S)	***	***	***	***	***	***
I*S	*	*	n.s.	n.s.	n.s.	n.s.
W*S	***	***	***	*	***	***
I*W*S	***	*	n.s.	n.s.	n.s.	n.s.
Depth (D)	***	n.s.	n.s.			
I*D	***	**	n.s.			
W*D	n.s.	n.s.	n.s.			
I*W*D	n.s.	n.s.	n.s.			
D*S	n.s.	*	***			
I*D*S	***	*	n.s.			
W*D*S	n.s.	n.s.	n.s.			
I*W*D*S	n.s.	n.s.	n.s.			

*	Significant F test at the 0.05 level of probability
**	Significant F test at the 0.01 level of probability
***	Significant F test at the 0.001 level of probability
[‡]n.s.	Not significant at the 0.05 probability level

When data for potable, moderately saline and saline irrigated plots were pooled over both sampling depths (Figures 1 and 2), changes in EC and Na between summer and late fall on plots irrigated with moderately saline and saline water followed the same general patterns as those of irrigation amount and precipitation. Monthly irrigation amounts increased between March and June of each year but minimal precipitation during the same time period resulted in peak EC and Na values in June of 2005 and 2006 (Table 1). When data were pooled over irrigation systems and depths, highest EC and Na levels were observed in June 2006 on plots irrigated with moderately saline and saline water averaging 3.9 and 4.7 dS m^{-1} for EC and 747 and 1024 ppm for Na, respectively (Figures 1 and 2). Subsequent precipitation during the rainy season (July to October) and lower irrigation amounts from July to November (compared to March through June) reduced EC and Na by November. Above average cumulative monthly precipitation from April to October 2007 (Table 1) reduced salt build-up and both EC and Na content did not differ between June and November of 2007. When data were averaged over both irrigation systems and sampling dates in 2007, salinity readings on plots irrigated with moderately saline and saline water were 1.4 and 2.8 dS m^{-1} and Na values were 167 and 371 ppm, respectively (Figures 1 and 2). With the exception of saline irrigated plots in November 2005, electrical conductivity did not differ between drip and sprinkler irrigated plots for any of the three water qualities during the research period (Figure 1). In November 2005, plots sprinkler-irrigated with saline water exhibited greater electrical conductivity than drip irrigated plots (Figure 1). Type of irrigation system had no effect on Na content regardless of water quality (Figure 2).

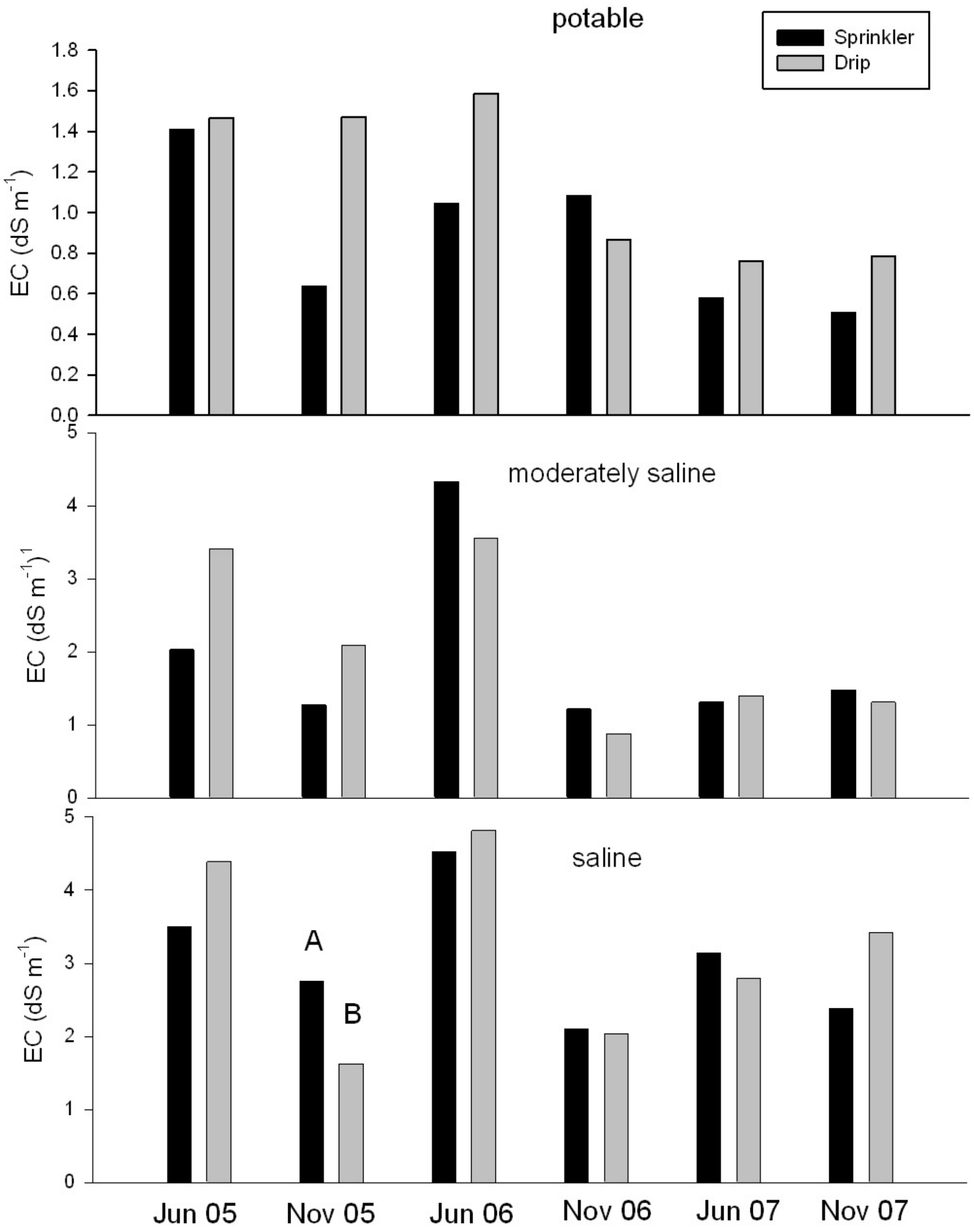

Figure 1. Electrical conductivity (EC, dS m^{-1}) of soil under warm-season grasses irrigated from a subsurface drip or sprinkler system with saline, moderately saline, or potable water. Data are pooled over soil depths from 0-10 cm and 10-20 cm depths. Letters denote the differences ($P<0.05$) in EC between the two irrigation systems separately for each sampling date.

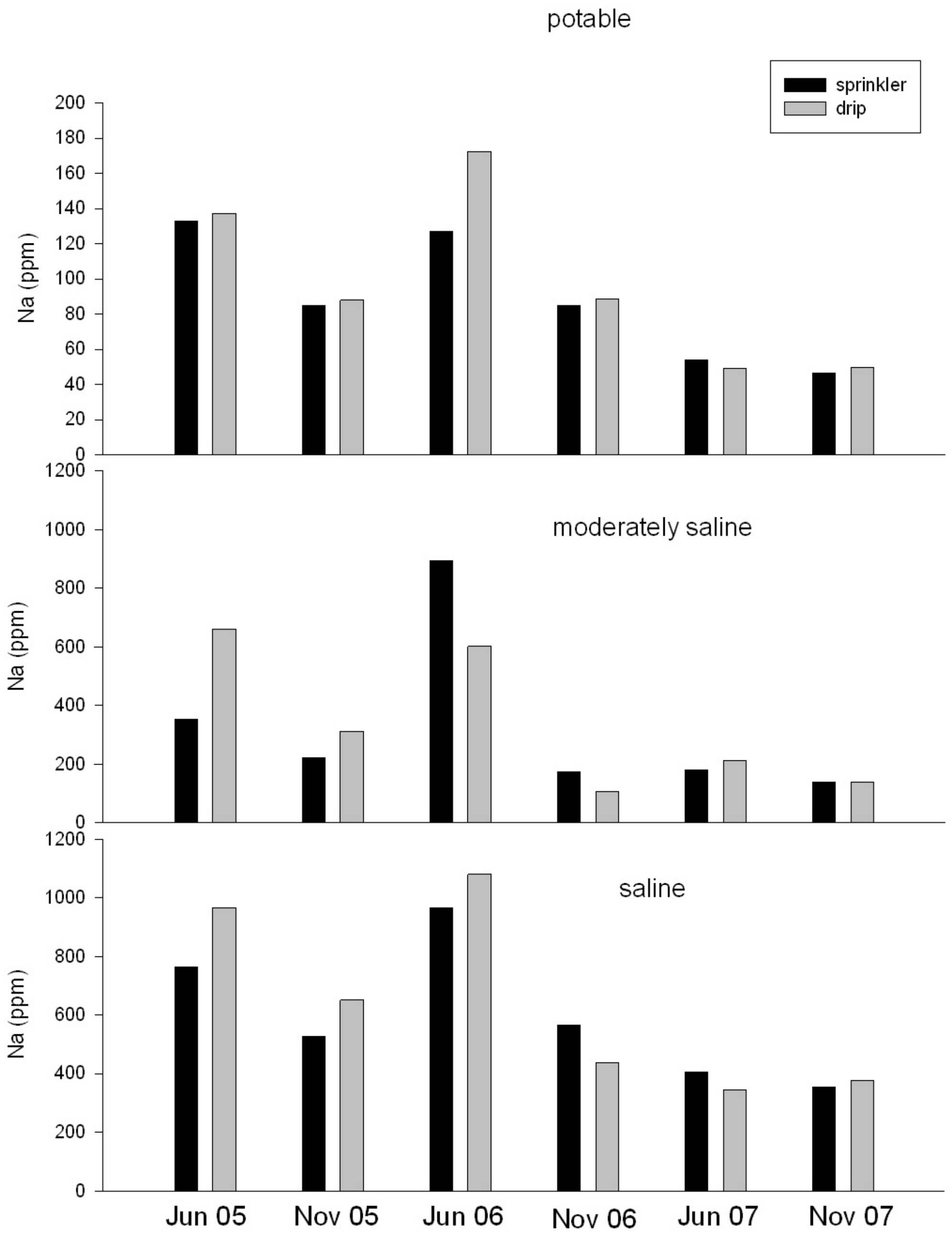

Figure 2. Sodium content (Na, ppm) of soil under warm-season grasses irrigated from a subsurface drip or sprinkler system with saline, moderately saline, and potable water. Data are pooled over soil depths from 0-10 cm and 10-20 cm depths.

When electrical conductivity and Na data were pooled over all three water qualities but analyzed separately for each depth and sampling date, EC was greatest in drip irrigated plots at depths of 0-10 cm in June of 2005 and 2006 (Figures 3 and 4). Electrical conductivity in sprinkler irrigated plots did not differ between the two upper soil depths on any of the sampling dates. EC in drip irrigated plots was either lower (June 2006) or similar to that measured in sprinkler irrigated plots at depths of 10-20 cm. These findings confirm our assumption that drip irrigation may not be as successful as sprinkler irrigation in leaching salts from the rootzone at depths above the drip lines. During the dry spring and early summer of 2005 and 2006 (Table 1) rootzone salinity under drip irrigated turfgrasses exceeded the levels found under sprinkler irrigation. However, the differences between sprinkler and drip irrigated soil EC values observed in the summer of 2005 and 2006 did not carry over into the fall and winter. Summer and fall precipitation reduced salts at both soil depths to similar levels for all treatments. Na content in drip irrigated plots at soil depths of 0-10 cm only exceeded that of sprinkler irrigated plots in June and November of 2005. For all other sampling dates, Na content at soil depths of 0-10 cm did not differ between drip and sprinkler irrigated plots. As observed for EC, Na content did not differ between the two depths in sprinkler irrigated plots (Figure 4). Also reflecting EC results, Na content in drip irrigated plots was either lower (June 2006) or similar to that measured in sprinkler irrigated plots at 10-20 cm depths. Sodium levels measured in November 2006, June 2007, and November 2007 did not differ between irrigation systems, soil depths, or sampling dates (Figure 4).

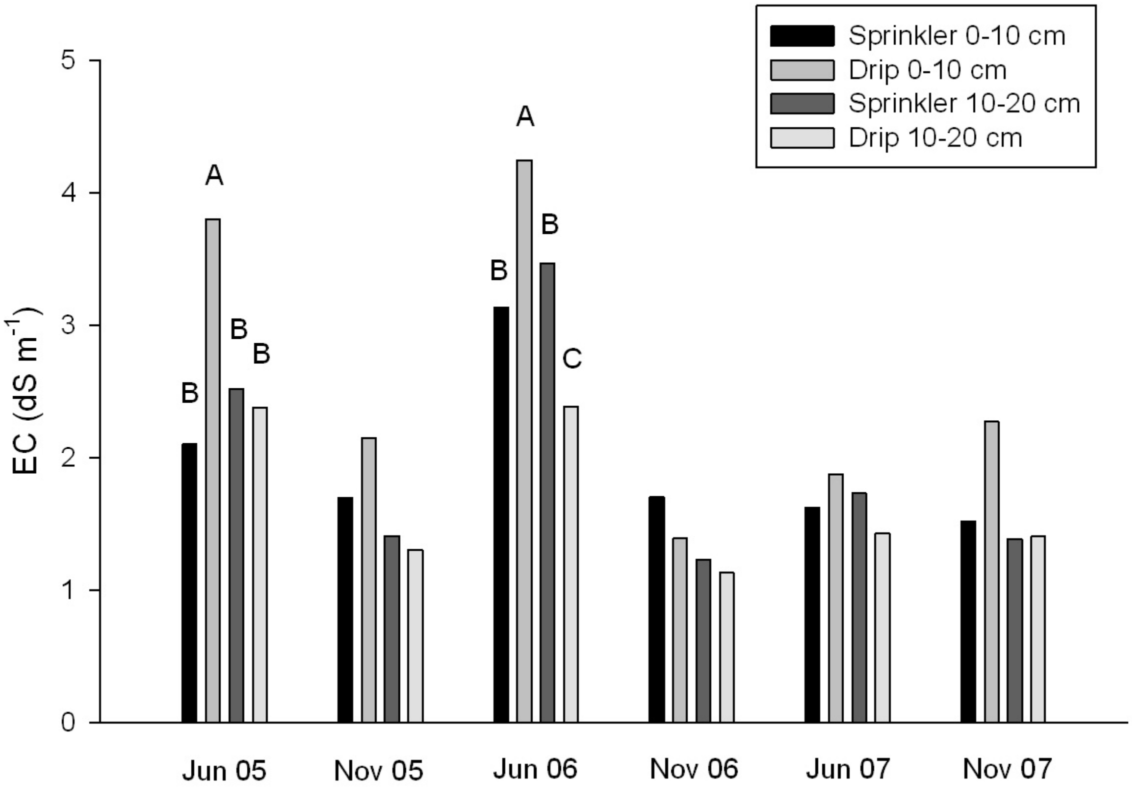

Figure 3. Electrical conductivity (EC, dS m^{-1}) in soil at 0-10 cm and 10-20 cm depths irrigated from a subsurface drip or sprinkler system. Data are pooled over three water qualities (potable, moderately saline, and saline). Letters denote the differences ($P<0.05$) in EC between the two irrigation systems and two depths separately for each sampling date.

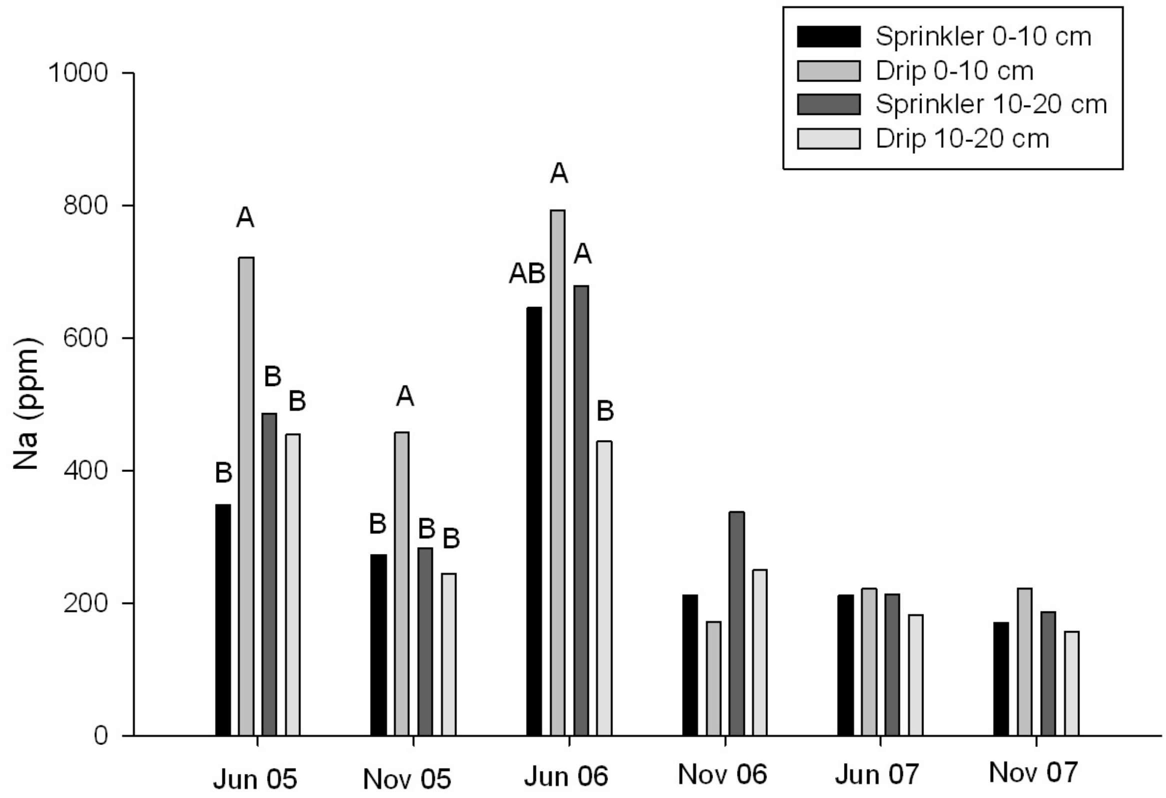

Figure 4. Sodium content (Na, ppm) in soil at 0-10 cm and 10-20 cm depths irrigated from a subsurface drip or sprinkler system. Data are pooled over three water qualities (potable, moderately saline, and saline). Letters denote the differences ($P<0.05$) in Na content between the two irrigation systems and two depths separately for each sampling date.

Sodium adsorption ratio values measured at soil depths of 0-10 cm and 10-20 cm reflected the SAR of the irrigation waters used in the study, with highest SAR values measured in plots irrigated with saline water, and lowest values in plots irrigated with potable water. SAR levels measured on plots irrigated with moderately saline water fell in between those measured on saline and potable irrigated plots (Figure 5). However, SAR values were not affected by irrigation system at either depth (Table 4). SAR values on plots irrigated with saline water did not differ between summer and fall of 2005 and reached an average of 16.1 when pooled over both depths, irrigation systems, and sampling dates. SAR on the same plots dropped from 18.6 (summer) to 14.6 (fall) in 2006 and increased from 9.4 (summer) to 12.2 (fall) in 2007 (Figure 5). SAR on plots irrigated with moderately saline water did not differ between summer and fall in 2005 and 2007, averaging 8.6 in 2005 and 4.9 in 2007. In 2006, SAR dropped from 13.4 (summer) to 5.0 (fall) when data were averaged over both irrigation systems and sampling depths (Figure 5). Plots irrigated with potable water exhibited lowest SAR values reaching a maximum value of 3.4 in June 2006 and a minimum of 1.2 in June of 2007 (Figure 5). November 2006 was the only sampling date for which SAR values in plots irrigated with moderately saline water did not differ from plots irrigated with potable water (Figure 5). For five of the six sampling dates SAR values were similar in both sampling depths. In November 2006, SAR was greater at depths of 10-20 cm than at 0-10 cm (Figure 6).

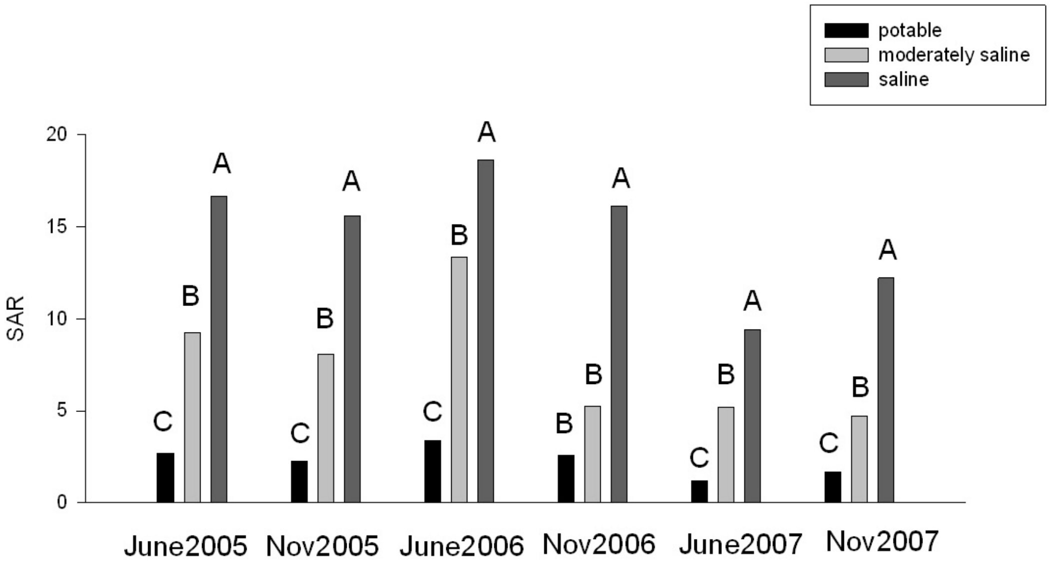

Figure 5. Sodium adsorption ratio (SAR) in soil at 0-20 cm depths irrigated with saline, moderately saline, or potable water. Data are pooled over two irrigation systems (subsurface drip and sprinkler) and two sampling depths (0-10 cm and 10-20 cm). Letters denote the differences ($P<0.05$) in SAR between the three water qualities separately for each sampling date.

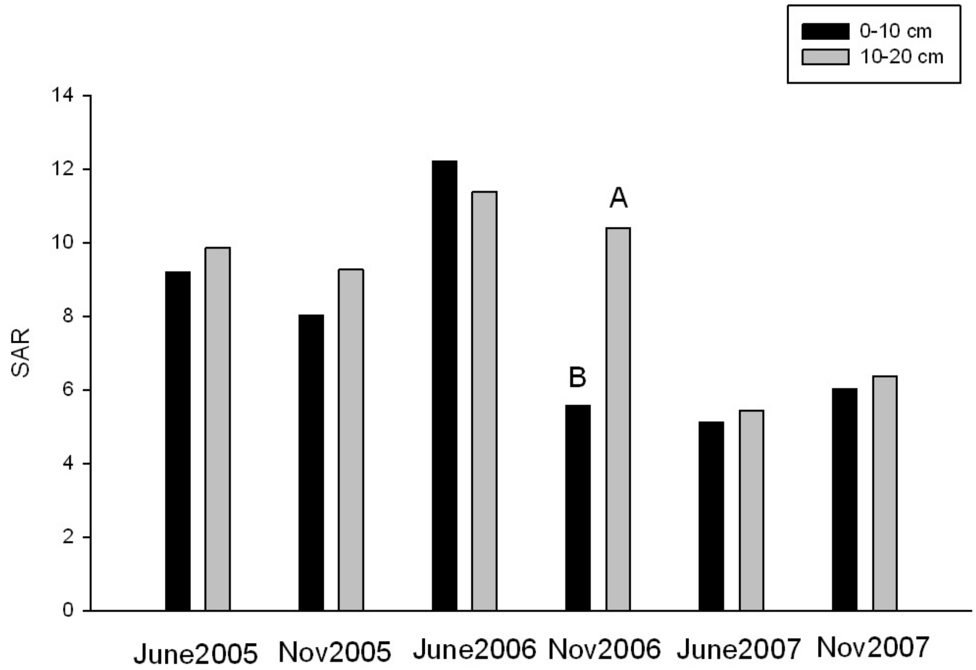

Figure 6. Sodium adsorption ratio (SAR) in soil at 0-10 cm and 10-20 cm depth. Data are pooled over two irrigation systems (subsurface drip and sprinkler) and three water qualities (potable, moderately saline, and saline). Letters denote the differences ($P<0.05$) in SAR between the two depths separately for each sampling date.

Rootzone salinity at depths of 50-60 cm

The ANOVA for the 50-60 cm soil depth (Table 4) revealed a significant two-way interaction between water quality and sampling date for EC, Na content, and SAR. Type of irrigation system had no effect on any of the three parameters regardless of water quality. The data were therefore pooled over irrigation systems and are presented separately for each water quality at each sampling date (Figure 7).

During 2005, EC was not affected by water quality averaging 2.1 and 1.3 dS m^{-1} in June and November, respectively. During 2006 and 2007, plots irrigated with saline water had highest EC levels and plots irrigated with potable water exhibited lowest EC (Figure 7). Electrical conductivity did not change between June 2006 and November 2007 on plots irrigated with potable water and averaged 0.7 dS m^{-1} for all four sampling dates. Electrical conductivity in plots irrigated with saline water was also similar between June and November for both 2006 and 2007 and reached 3.2 dS m^{-1} in 2006 and 2.2 dS m^{-1} in 2007. No clear trend could be established for EC in plots that received moderately saline irrigation water. In November of 2006 and November of 2007 moderately saline irrigation resulted in EC levels equal to potable irrigation, however in June of 2006 EC was equal to saline irrigation (Figure 7).

Sodium content and SAR were highest in plots irrigated with saline water and lowest in those irrigated with potable water throughout the research period (Figure 7). Sodium and SAR on potable irrigated plots did not change from June 2005 to November 2007, averaging 79 ppm for Na and 2.4 for SAR. Sodium content on saline irrigated plots dropped from 570 ppm (June) to 332 ppm (November) in 2005 and from 814 ppm (June) to 587 ppm (November). No change between June and November was measured in 2007 with Na averaging 324 ppm in 2007. SAR on plots irrigated with saline water did not change between summer and late fall in 2005, reaching an average of 10.7. In 2006 SAR on saline irrigated plots dropped from 18.4 (June) to 14.8 (November) and increased from 8.1 (June) to 12.5 (November) in 2007. Moderately saline irrigated plots exhibited Na and SAR levels similar to saline irrigated plots in June and November of 2005. From June 2006 to the end of the research period in November 2007, SAR values for plots irrigated with moderately saline water fell between those of plots irrigated with potable and saline water (Figure 7).

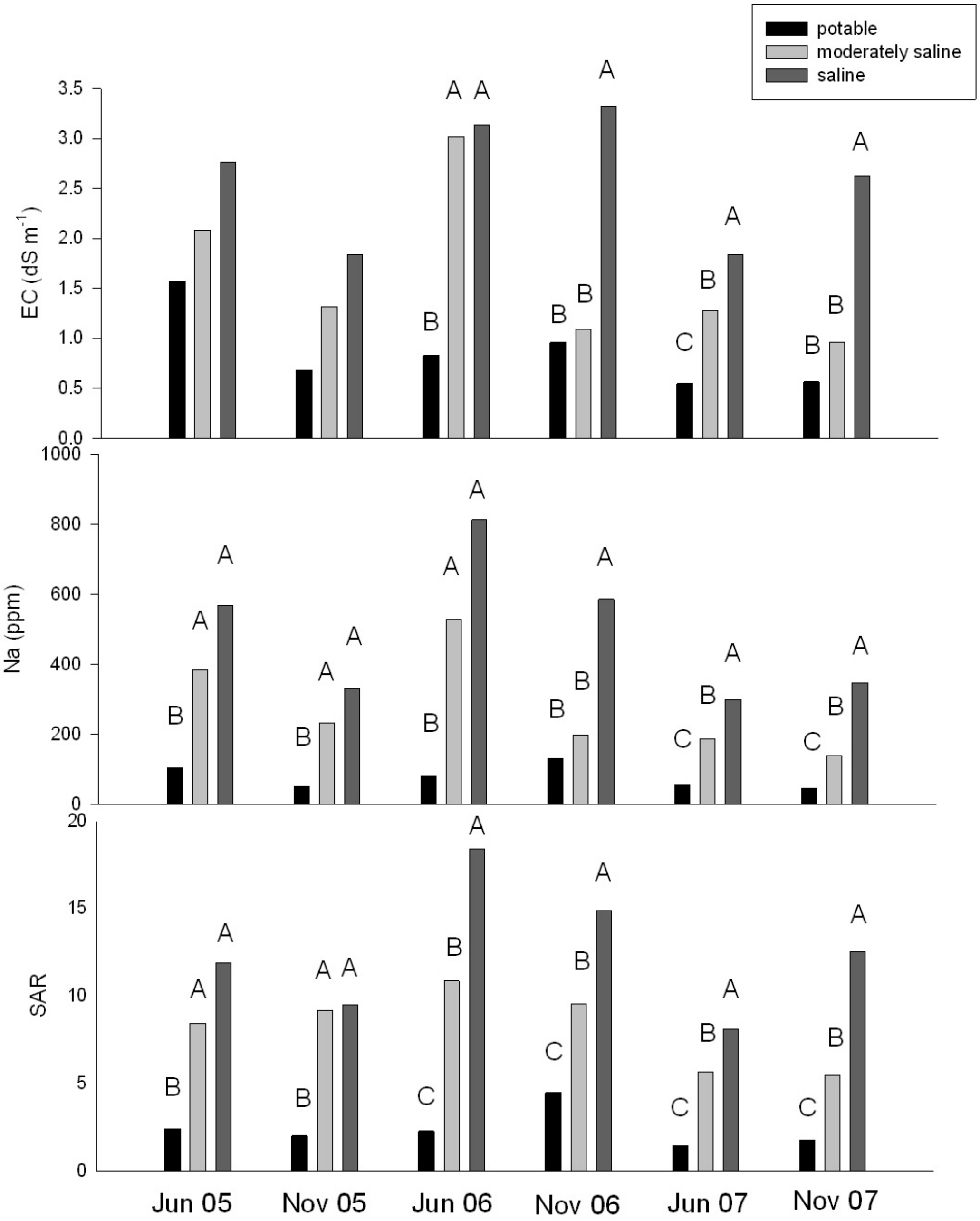

Figure 7. Electrical conductivity (EC, dS m^{-1}), sodium content (Na, ppm), and sodium adsorption ratio (SAR) in soil at 50-60 cm depths irrigated with saline, moderately saline, or potable water. Data are pooled over two irrigation systems (subsurface drip and sprinkler). Letters denote the differences ($P<0.05$) in EC, Na, and SAR between the three water qualities separately for each sampling date.

Turf quality

Results of the analysis of variance revealed significant three-way interactions between irrigation systems, water quality, and date and between cultivar, irrigation systems, and date (Table 5). When quality data were reanalyzed separately for each sampling date and pooled over cultivars, the interactions of irrigation system by water quality were not significant for any of the nine sampling dates. Data were subsequently pooled over irrigation systems and water qualities and are displayed separately for each sampling date (Figure 8). Turf quality data were also pooled over water qualities and are shown separately for each cultivar and irrigation system on each sampling date (Table 6).

Table 5. Results of analysis of variance testing the effects of water quality, irrigation systems, sampling dates, and their interactions on quality, spring green-up, and fall color retention of nine warm-season turfgrasses. Highlighted interactions are discussed in the text.

Effect	Quality	Spring Green-Up	Fall Color Retention	Quality 2007	NDVI
Cultivar (C)	***	***	***	***	***
Irrigation (I)	n.s.[‡]	*	n.s.	**	*
C*I	n.s.	n.s.	n.s.	**	n.s.
Water Quality (W)	n.s.	n.s.	n.s.	n.s.	n.s.
C*W	n.s.	n.s.	n.s.	n.s.	n.s.
I*W	n.s.	n.s.	n.s.	n.s.	n.s.
C*I*W	n.s.	n.s.	n.s.	n.s.	n.s.
Sampling Date (S)[†]	***	***	***	***	***
C*S	***	***	***	***	***
I*S	***	***	***	***	***
C*I*S	***	*	n.s.	***	*
W*S	***	n.s.	*	***	**
C*W*S	n.s.	n.s.	n.s.	n.s.	n.s.
I*W*S	***	**	**	n.s.	***
C*I*W*S	n.s.	n.s.	n.s.	n.s.	n.s.

*	Significant F test at the 0.05 level of probability
**	Significant F test at the 0.01 level of probability
***	Significant F test at the 0.001 level of probability
[‡]n.s.	Not significant at the 0.05 probability level
[†]	Sampling date for 'Quality' indicates monthly visual ratings that were averaged for seasons spring, summer, and fall throughout the research period (2005 to 2007). Sampling date for Quality 2007 and NDVI indicates monthly ratings and measurements from April 2007 to October 2007 only.

Turfgrass quality was lowest in spring for all three years, averaging 4.1, 4.0, and 3.9 in 2005, 2006, and 2007, respectively (Figure 8). Low turfgrass quality in spring can be attributed to the winter dormancy of the warm-season grasses, which resulted in loss of color and low quality ratings. Summer quality was rated at 6.1 in 2005, 6.7 in 2006, and 7.0 in 2007 when data were averaged over all cultivars, water qualities, and irrigation systems. Fall quality was greatest in 2006 averaging 7.0 and lowest in 2005 at 5.9 (Figure 8). During the three years of the investigative period, summer and fall turfgrass quality reached or exceeded the minimum acceptable quality of 6.0 when ratings were pooled over water quality, irrigation systems, and cultivars (Figure 8).

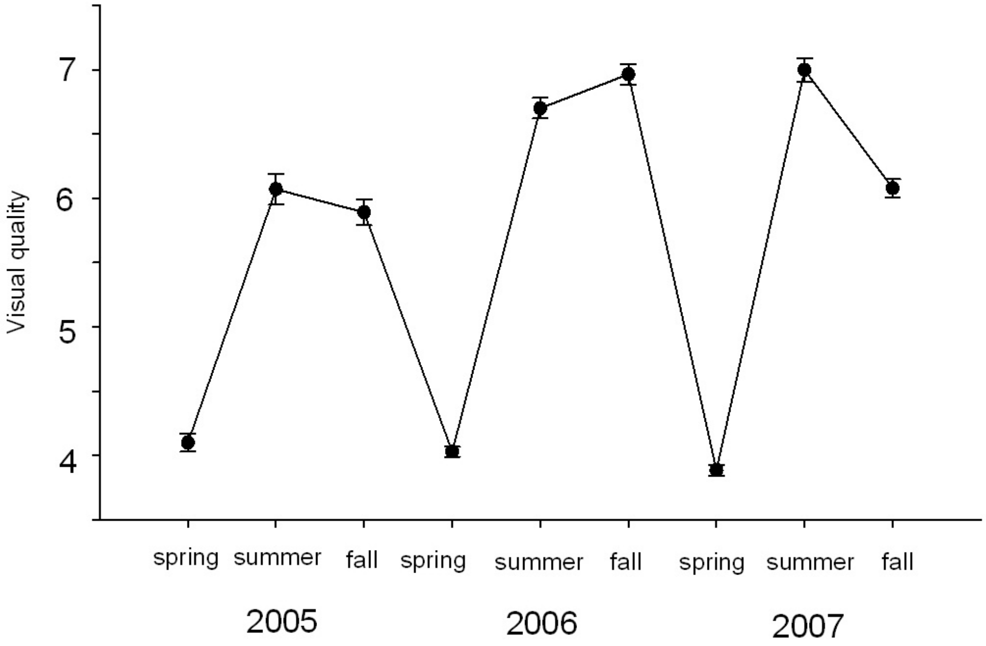

Figure 8. Visual quality of warm-season turfgrasses during spring, summer, and fall in 2005, 2006, and 2007. Data are pooled over nine cultivars, three water qualities, and two irrigation systems. Error bars indicate the standard error of the mean.

No clear trend could be observed in spring turf quality when irrigation systems were compared. In 2005, Sea Spray showed higher quality on drip irrigated plots than on sprinkler irrigated ones. In contrast, Riviera gave higher ratings on sprinkler irrigated plots than on drip irrigated plots in both 2005 and 2006 (Table 6). For all other grasses, type of irrigation system had no effect on spring quality. When quality data were averaged over all three years, Sea Spray exhibited highest spring quality and De Anza lowest (Table 6) averaging 4.7 and 3.3, respectively. Whether or not drip irrigation affected summer quality appeared to depend on the grass used and on the length of drip irrigation had been installed. Summer quality ratings were consistently lower on drip irrigated De Anza and Riviera than on their sprinkler irrigated counterparts throughout the research period (Table 6). In 2007, four years after the installation of the system, four of the nine drip irrigated grasses exhibited lower quality than the same grasses on sprinkler irrigated plots compared to only one cultivar at the beginning of the research period. Overall summer quality of (drip or sprinkler irrigated) Sea Spray and SeaDwarf was highest followed by Princess 77, whereas A138 exhibited lowest quality (Table 6). Fall quality on drip irrigated De Anza plots was also lower than on sprinkler irrigated plots, but all other grasses showed no difference in quality between the two irrigation systems. When data were averaged over the three years, SeaDwarf exhibited highest quality and DT16 and A138 lowest, averaging 7.8, 5.3, and 5.0, respectively (Table 6).

Table 6. Quality (from 1=worst to 9=best) of nine warm-season turfgrasses during spring, summer, and fall in 2005, 2006, and 2007. Data are pooled over three water qualities (potable, moderately saline, and saline) and values represent an average of nine readings (three water qualities and three replications).

Cultivar	2005		2006		2007		Mean
				Spring			
	Drip	Sprinkler	Drip	Sprinkler	Drip	Sprinkler	
A138	3.9c[‡]	3.4ef	4.3ab	4.2bc	3.7cd	3.9ab	3.9de
De Anza	2.8e	3.2f	3.3e	3.7e	3.4e	3.4d	3.3g
DT16	4.0c	3.9de	4.6a	4.6a	4.1b	3.8bc	4.2c
Princess 77	4.5b	4.4bc	3.6de	4.1cd	3.9bc	3.9bc	4.1cd
Riviera	3.4dB[†]	4.1cdA	3.8cdB	4.6aA	4.1b	4.0ab	4.0cd
NuMex Sahara	4.0c	3.5ef	3.6de	3.8de	3.7cd	3.6cd	3.7f
Sea Spray	5.9aA	5.4aB	4.1bc	4.5ab	4.4a	4.1ab	4.7a
SeaDwarf	4.9b	4.8b	3.9bcd	4.4ab	4.2ab	4.3a	4.4b
Transcontinental	3.9c	3.8de	3.7de	3.7de	3.6de	3.8bcd	3.7ef
				Summer			
A138	5.3c	4.9e	5.9d	6.1d	5.8e	6.0e	5.7e
De Anza	3.8dB	4.8eA	5.8dB	6.6cdA	6.4cdB	7.4bcA	5.8de
DT16	5.5c	5.7d	6.3cd	6.3d	5.9de	5.9e	5.9de
Princess 77	7.0b	7.2bc	6.7c	6.9bc	7.9a	7.7bc	7.2b
Riviera	5.4cB	6.7cA	6.8bcB	7.2bA	7.3bB	7.8bA	6.9c
NuMex Sahara	5.3c	5.2de	5.8d	6.3d	6.2cdeB	7.2cdA	6.0d
Sea Spray	8.3a	8.1a	7.5ab	7.9a	6.7bcB	7.7bA	7.7a
SeaDwarf	7.5b	7.8ab	7.9a	8.2a	7.9a	8.5a	8.0a
Transcontinental	5.5c	5.3de	6.2cd	6.3d	6.7c	6.9d	6.1d
				Fall			
A138	4.2e	4.2d	6.0e	5.7e	5.0e	5.2e	5.0f
De Anza	4.8dB	5.8bcA	6.3deB	7cdA	5.8bcdB	6.6bcA	6.0e
DT16	4.8d	4.6d	6.3de	5.7e	5.4de	5.1e	5.3f
Princess 77	6.7b	6.1b	7.4bc	7.3bc	6.8a	6.7bc	6.8c
Riviera	6.2bc	6.1bc	7.4b	7.0cd	6.0bc	6.4c	6.5d
NuMex Sahara	5.6c	5.5c	6.3de	6.7d	5.6cd	5.9d	5.9e
Sea Spray	7.7a	7.6a	7.9ab	7.8b	6.1b	6.9b	7.3b
SeaDwarf	7.6a	7.6a	8.3a	8.8a	6.9a	7.4a	7.8a
Transcontinental	5.7c	5.6bc	6.8cd	6.6d	5.7bcd	5.9d	6.0e

[‡,†] Values followed by the same letter are not significantly different from one another (Fisher's protected LSD, $\alpha=0.05$). [‡]Lower case letters denote differences between cultivars separately for each season (in columns), [†] Upper case letters denote differences between drip and sprinkler irrigation separately for each cultivar and year.

Spring green-up and fall color retention

Significant three-way interactions between cultivar, year, and irrigation systems, and between irrigation systems, water quality and sampling year affected spring green-up of nine warm-season cultivars during the three-year research period (Table 5). When green-up data were analyzed separately for each year, interactions between irrigation systems and water quality were not significant. When data were averaged over all sampling dates, water qualities, and irrigation systems, DT16 was the fastest to green-up, followed by A138. Riviera, NuMex Sahara, SeaDwarf, and Transcontinental were slowest to green-up (Table 7). When data were averaged over all cultivars, drip irrigated plots were faster to green-up than sprinkler irrigated plots in 2005 and in 2006. In 2007, no difference in speed of green-up between the two irrigation systems was observed (Table 7).

A significant interaction between sampling date and cultivars affected fall color retention. Data were subsequently analyzed separately for each sampling year. Sea Spray rated highest for fall color retention during all three years, joined by Sea Dwarf and DT16 in two of the three years. A138 and De Anza were the first grasses to go dormant as evidenced by the lowest fall color ratings in each of three years of the investigative period (Table 7). Fall color retention was not affected by water quality or irrigation system. These findings are supported by those of Schiavon and others (2011) who reported fastest spring green-up for inland saltgrass and greatest fall color retention for seashore paspalum when compared to several other warm-season grasses. Among bermudagrass cultivars, Princess 77, Riviera, and Transcontinental had greater fall color retention than NuMex Sahara. These results are in the agreement with findings of Rodgers and Baltensperger (2004), who also found better fall color retention in Princess 77 than in NuMex Sahara.

Table 7. Spring green-up and fall color retention (from 1=complete dormancy to 9=plot entirely green) of nine warm-season turfgrasses in 2005, 2006, and 2007. Data for spring green-up are pooled over three water qualities (potable, moderately saline, and saline) and listed separately for drip and sprinkler irrigation. Values represent an average of nine readings (three water qualities and three replications). Data for fall color retention are pooled over three water qualities (potable, moderately saline, and saline) and two irrigation systems (drip and sprinkler irrigation). Values represent an average of 18 readings (three water qualities, two irrigation systems, and three replications).

	Spring Green-Up							Fall Color Retention			
Cultivar	2005		2006		2007		Mean	2005	2006	2007	Mean
	Drip	Sprinkler	Drip	Sprinkler	Drip	Sprinkler					
A138	5.1a[‡]	5.4a	2.8b	2.7a	1.0	1.0b	3.0ab	2.9e	5.4d	4.3e	4.2e
De Anza	3.7bA[†]	2.9cB	2.3cA	1.6cB	1.0B	1.6aA	2.2c	3.1e	5.4d	4.4de	4.3e
DT16	5.4a	5.7a	3.4aA	2.9aB	1.0	1.0b	3.2a	5.6ab	6.8c	5.9a	6.1b
Princess 77	5.3aA	4.2bB	2.1c	1.8bc	1.0	1.0b	2.6bc	5.0cd	7.6b	5.1b	5.9bc
NuMex Sahara	3.7bA	2.7cB	2.1c	2.1b	1.0	1.0b	2.1c	4.7d	6.7c	4.7bc	5.4d
Sea Spray	5.2aA	4.3bB	1.7dA	1.1dB	1.0	1.0b	2.4bc	5.9a	8.3a	5.7a	6.7a
SeaDwarf	5.0aA	4.2bB	1.4d	1.2cd	1.0	1.0b	2.3c	5.3bc	8.6a	5.8a	6.6a
Transcontinental	3.2b	2.7c	2.3c	2.1b	1.0	1.0b	2.1c	4.9cd	6.8c	4.5cde	5.4cd
Mean	4.5A	3.9B	2.3A	1.9B	1.0	1.1					

[‡,†] Values followed by the same letter are not significantly different from one another (Fisher's protected LSD, α=0.05). [‡]Lower case letters denote differences between cultivars separately for each year (in columns), [†] Upper case letters denote differences between drip and sprinkler irrigation separately for each cultivar and year.

Correlations between turf quality, NDVI and salinity

The correlation between visual turfgrass quality and NDVI was significant ($P<0.001$), yielding a correlation coefficient of $r=0.51$. When correlations were run separately for each cultivar, Sea Spray and SeaDwarf had the highest coefficients, with 0.64 and 0.59, respectively. The correlation between quality and NDVI was poorest for the three bermudagrasses, yielding 0.34 for Princess 77 and Riviera, and 0.35 for Transcontinental. Even though a significant relationship between NDVI and turf quality was revealed, the two variables were not always affected in the same way by the different treatments. For example, the interaction between irrigation, water quality, and sampling date had a highly significant ($P<0.001$) effect on NDVI, but not on visual quality (Table 5).

Stepwise linear regression revealed that summer values of EC, Na, and SAR in the top 10 cm of the rootzone were not good predictors of summer quality. No significant relationship between any of the salinity parameters and turf quality could be established for saltgrasses A138, DT16, or seashore paspalum SeaDwarf and Sea Spray. While there was a significant regression between soil EC and quality of De Anza and Princess 77, the regression coefficients were very low (0.18 and 0.30), indicating that little of the variation in quality could be explained by variation in soil EC. There was also a significant relationship between electrical conductivity and Na content and summer quality of Riviera and Transcontinental, but regression coefficients were equally low (0.33 and 0.28, respectively).

Cool-Season Grasses

Rootzone salinity at depths of 0-20 cm

The analysis of variance (ANOVA) (Table 8) revealed that the three-way interaction between type of irrigation, sampling depth, and sampling date had a significant effect on Na content. The ANOVA further revealed that the two-way interaction between water quality and sampling date had a significant effect on EC, Na content, and SAR, and the interactions between irrigation type and sampling date, and between irrigation type and sampling depth had significant effects on EC and SAR, and on EC, respectively (Table 8). Rootzone EC, Na, and SAR data were subsequently pooled over sampling depths and irrigation systems and are displayed separately for each water quality at each sampling date (Figure 9). Data were also pooled over depths and are shown separately for each irrigation system at each sampling date for EC and SAR (Figure 10).

When data were pooled over both sampling depths and irrigation systems, soil salinity, Na content, and SAR values exhibited a peak-and-decline pattern during 2005 and 2006. Peaks in June reflected salt accumulation from March to June from irrigation and minimal natural precipitation, and declines in salinity values in late summer and early fall were due to leaching of salts from the rootzone as a result of the rainy season (Table 8, Figure 9). A similar trend was observed for EC in plots that were irrigated with potable water (Figure 9) and plots irrigated with saline water between June and November 2007. Over the three-year research period, rootzone salinity was at its highest in June 2006, with EC, Na, and SAR values reaching 4.8 dS m^{-1}, 1247 ppm and 20.7, respectively. Salinity values did not change between November 2006 and November 2007 on plots irrigated with potable or moderately saline water. Salinity values within the rootzone generally reflected the values of the irrigation water, with highest values measured in plots irrigated with saline water and lowest values in plots irrigated with potable water (Figure 9). Sodium and SAR values of plots irrigated with moderately saline water fell between those measured in potable and saline irrigated plots from June 2005 to June 2006 but dropped to levels observed in plots irrigated with potable water from November 2006 to November 2007 (Figure 9). EC values did not differ between plots irrigated with moderately saline water and those irrigated with potable water on four out of six sampling dates. High amounts of precipitation during spring and summer 2007 (Table 1) resulted in lower peaks of EC, Na, and SAR in summer 2007, and none of the three measured parameters differed over time on plots irrigated with potable or moderately saline water.

Table 8. Results of analysis of variance testing the effects of water quality, irrigation systems, sampling times, and their interactions on rootzone salinity (EC, Na, and SAR) at soil depths of 0-20 cm (in 10 cm increments hence depth as additional treatment) and 50-60 cm under cool-season turfgrasses.

	Soil depth					
	0-20 cm			50-60 cm		
	EC	Na	SAR	EC	Na	SAR
Irrigation (I)	*	n.s.‡	n.s.	n.s.	n.s.	**
Water Quality (W)	***	***	***	***	**	***
I*W	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Sampling Date (S)	***	***	***	***	***	***
I*S	*	n.s.	*	n.s.	n.s.	*
W*S	***	***	***	n.s.	n.s.	***
I*W*S	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Depth (D)	***	***	n.s.			
I*D	***	***	**			
W*D	n.s.	n.s.	n.s.			
I*W*D	n.s.	n.s.	n.s.			
D*S	n.s.	*	*			
I*D*S	n.s.	*	n.s.			
W*D*S	n.s.	n.s.	n.s.			
I*W*D*S	n.s.	n.s.	n.s.			

*	Significant F test at the 0.05 level of probability
**	Significant F test at the 0.01 level of probability
***	Significant F test at the 0.001 level of probability
‡n.s.	Not significant at the 0.05 probability level

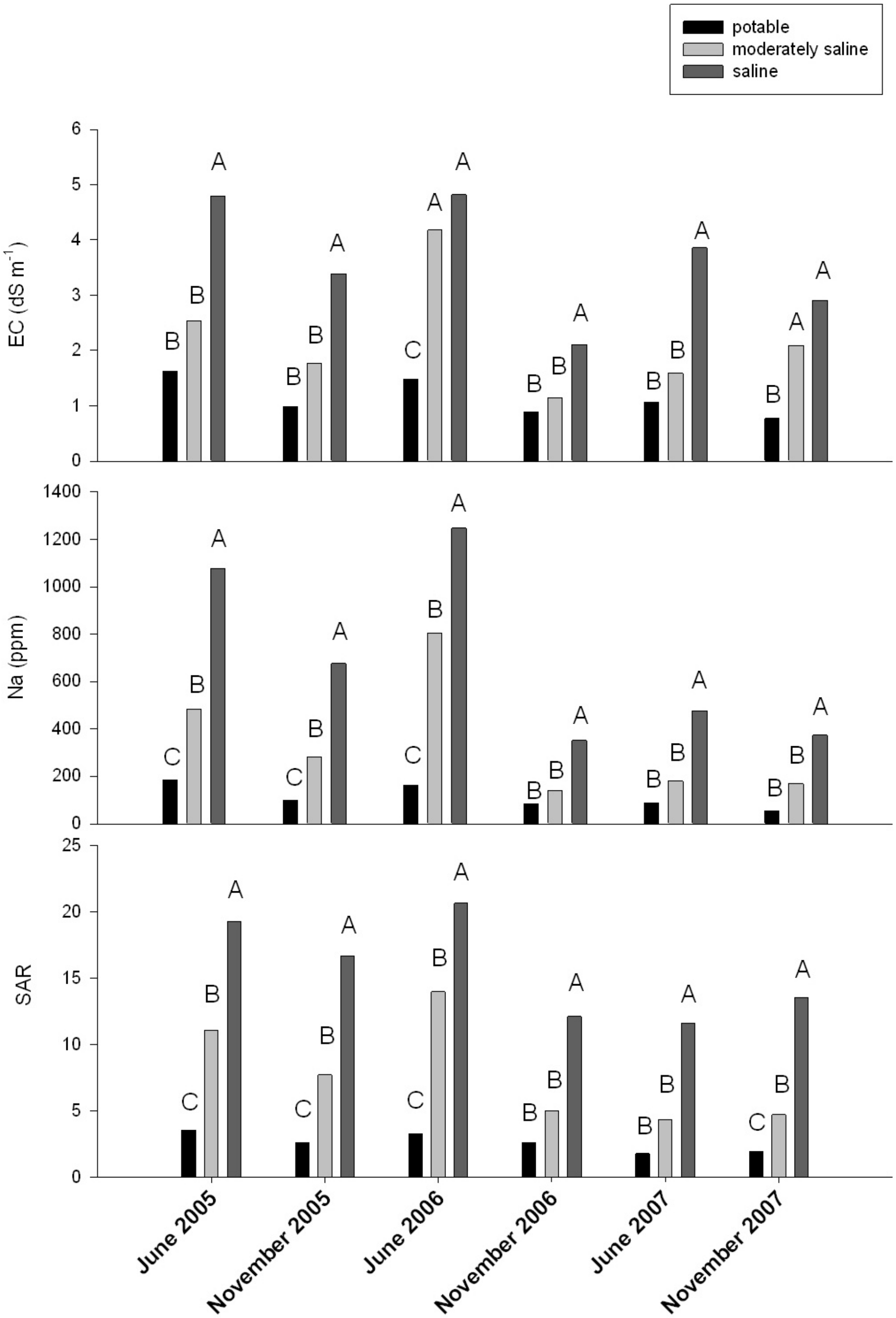

Figure 9. Electrical conductivity (EC, dS m^{-1}), sodium content (Na, ppm), and sodium adsorption ratio (SAR) in soil at 0-20 cm depths irrigated with potable, moderately saline, or saline water. Data are pooled over two irrigation systems (subsurface drip and sprinkler) and two depths (0-10 cm and 10-20 cm). Letters denote the differences ($P<0.05$) in EC, Na, and SAR between the three water qualities separately for each sampling date.

When EC and SAR data were pooled over all water qualities and depths but analyzed separately for sampling dates and irrigation types, EC was highest in drip irrigated plots on four of the six sampling dates (Figure 10). Type of irrigation system did not affect EC in June 2005 or November 2006. Sodium adsorption ratio values were higher in sprinkler irrigated plots than drip irrigated plots on the first sampling date but did not differ between the two irrigation systems from November 2005 to November 2007. When data were averaged over all water qualities and sampling dates and analyzed separately for the two depths and irrigation systems, EC was highest at depths of 0-10 cm under drip irrigation compared to sprinkler irrigation. At a depth of 10-20 cm, EC did not differ between sprinkler and drip irrigated plots (Figure 11). In contrast, irrigation system did not affect SAR at 0-10 cm, but at 10-20 cm depths values were higher on sprinkler irrigated plots than on drip irrigated plots (Figure 11).

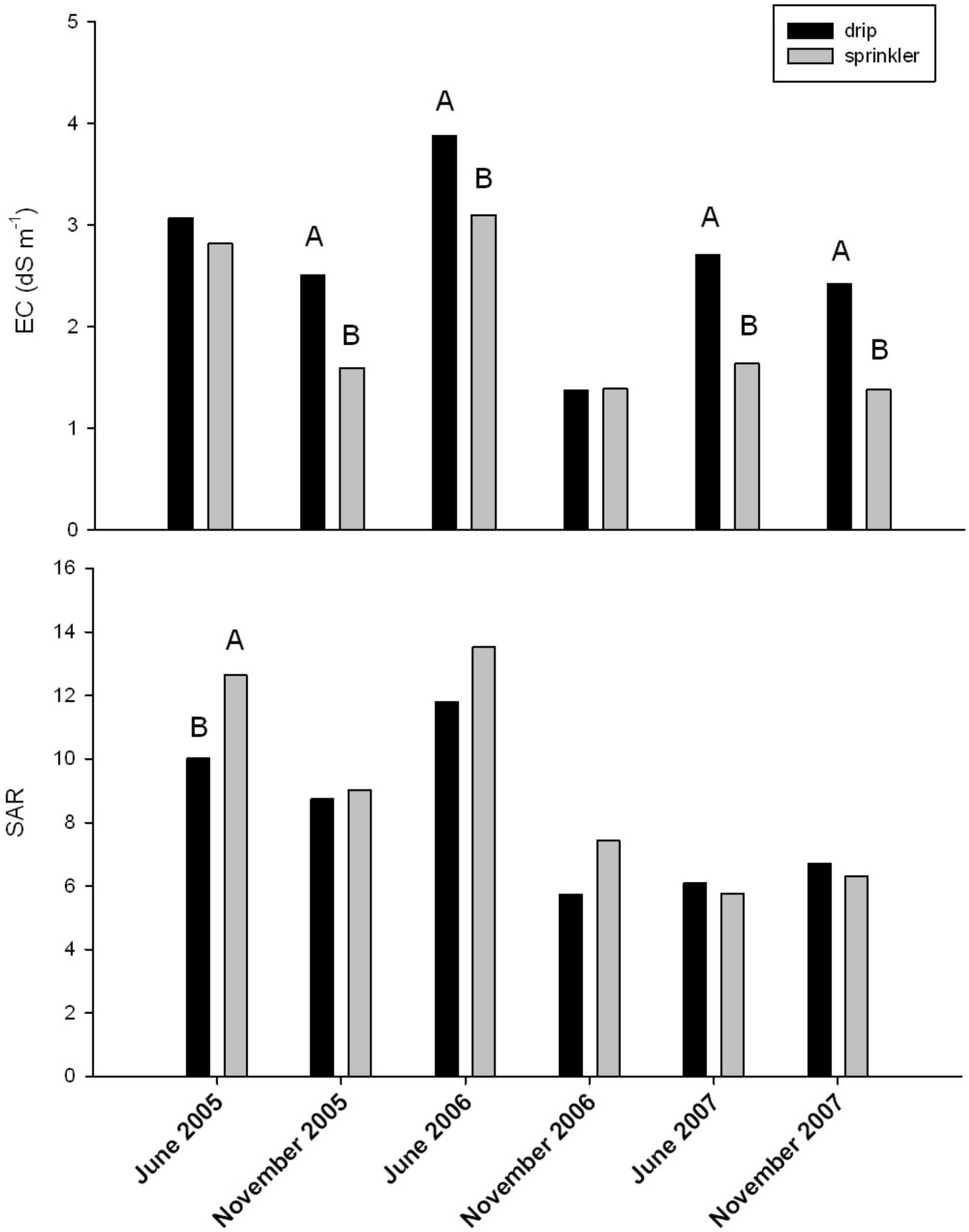

Figure 10. Electrical conductivity (EC, dS m^{-1}) and sodium adsorption ratio (SAR) in soil at 0-20 cm depths irrigated from a subsurface drip or sprinkler system. Data are pooled over three water qualities (potable, moderately saline, and saline) and two depths (0-10 cm and 10-20 cm). Letters denote the differences ($P<0.05$) in EC and SAR between the two irrigation systems separately for each sampling date.

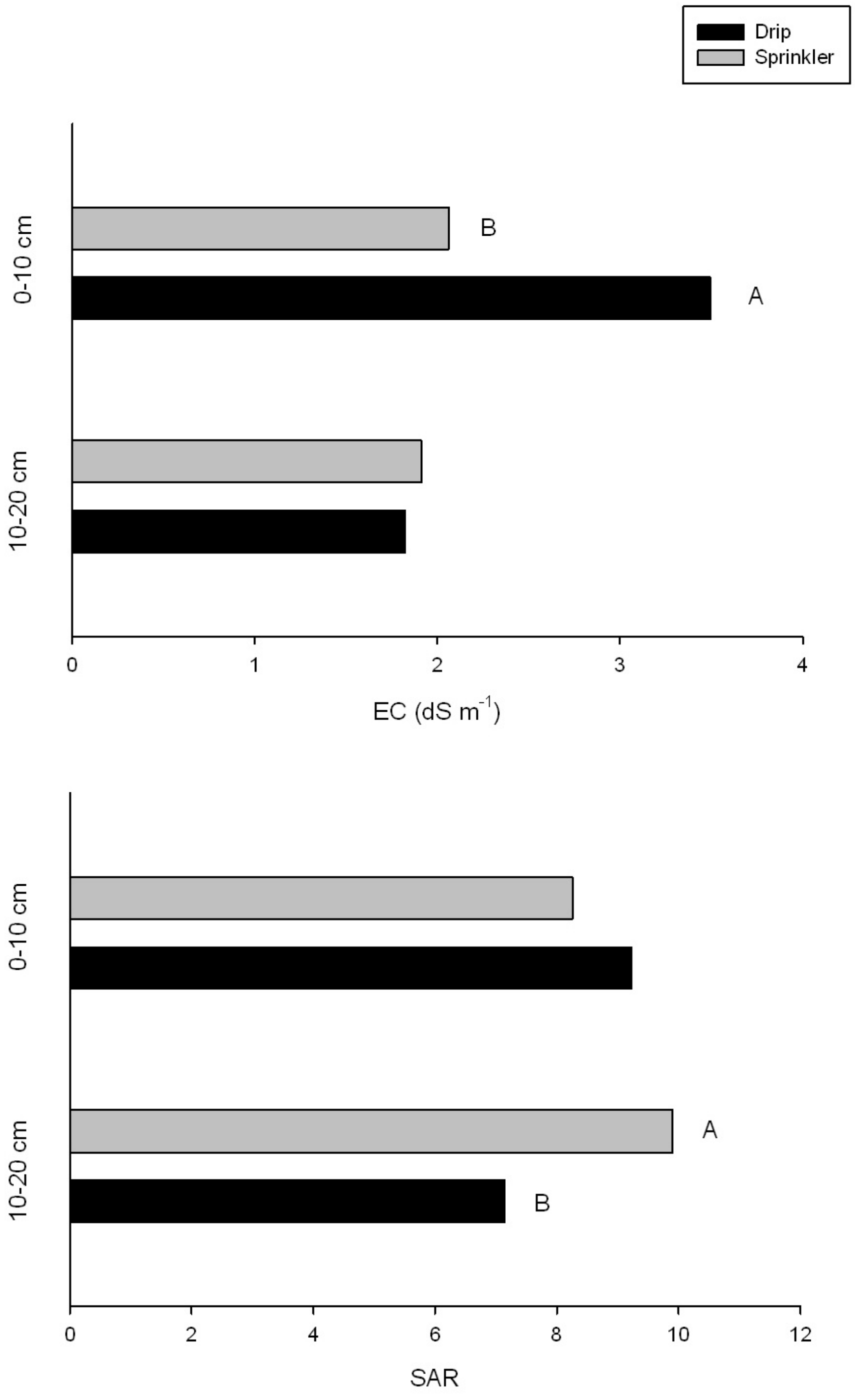

Figure 11. Electrical conductivity (EC, dS m^{-1}) and sodium adsorption ratio (SAR) in soil at 0-10 cm and 10-20 cm depth. Data are pooled over three water qualities (potable, moderately saline, and saline) and six sampling dates. Letters denote the differences ($P<0.05$) in EC and SAR between the two irrigation systems depths separately for each sampling depth.

Water quality and type of irrigation system affected Na content in the top 20 cm of the rootzone differently than for SAR and EC (Table 8, Figures 12). When Na data were pooled over all three water qualities and analyzed separately for rootzone depths, irrigation systems, and sampling dates, Na values were highest in drip irrigated plots at 0-10 cm in June and November of 2005 and in June of 2006. Sodium levels in the 10-20 cm depths of drip-irrigated plots were either equal (November 2005 and June 2006) or lower (June 2005) than those observed in sprinkler-irrigated plots. Soil depth did not affect Na content in sprinkler irrigated plots throughout the research period or in plots irrigated with a drip system from November 2006 to November 2007.

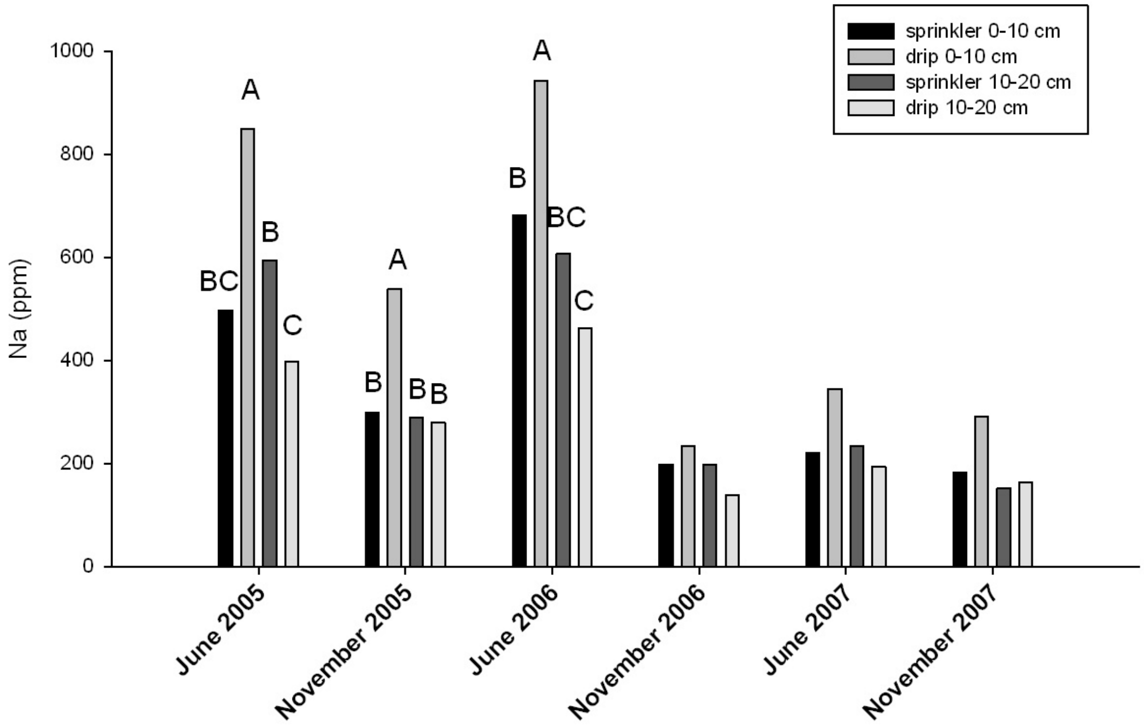

Figure 12. Sodium content (Na, ppm) in soil at 0-10 cm and 10-20 cm depths irrigated from a subsurface drip or sprinkler system. Data are pooled over three water qualities (potable, moderately saline, and saline). Letters denote the differences ($P<0.05$) in Na content between the two irrigation systems and two depths separately for each sampling date.

Rootzone salinity at depths of 50-60 cm

The analysis of variance (Table 8) revealed that the two-way interactions between water quality and sampling date and between type of irrigation and sampling date had a significant effect on SAR. Interactions between sampling date and water quality did not significantly affect EC or Na content. Sodium adsorption values were therefore pooled over irrigation systems and are presented separately for each water quality (Figure 14), and pooled over water qualities and presented separately for each irrigation type (Figure 15) at each sampling date. Electrical conductivity and Na content were not affected by irrigation type, but differed significantly among sampling dates and water quality (Table 8). Generally, changes in EC and Na values at 50-60 cm depths followed the same irrigation and precipitation pattern as changes at 0-20 cm depths. Electrical conductivity and Na was highest in June of 2005 and 2006 and dropped to lower levels in November of both years. Salinity levels (EC and Na) stayed consistently low from November 2006 to November 2007 (Figure 13). When EC and Na values were pooled over irrigation systems and sampling dates, the highest EC and Na content were measured in plots irrigated with saline water (Table 9). Electrical conductivity and Na did not differ between plots irrigated with potable and moderately saline water (Table 9).

Table 9. Soil electrical conductivity (dS m^{-1}) and sodium content (ppm) for the 50-60 cm soil depth irrigated with moderately saline, saline, and potable water. Data are pooled over irrigation systems (drip and sprinkler) and values represent an average of six readings (two irrigation systems and three replications).

Water quality	EC (dS m^{-1})	Na (ppm)
Moderately saline	1.7b†	275.3b
Potable	0.9b	86.5b
Saline	2.8a	503.9a

† Values followed by the same letter are not significantly different from one another (Fisher's protected LSD, α=0.05). Letters denote differences between three water qualities separately for electrical conductivity and sodium content (in columns).

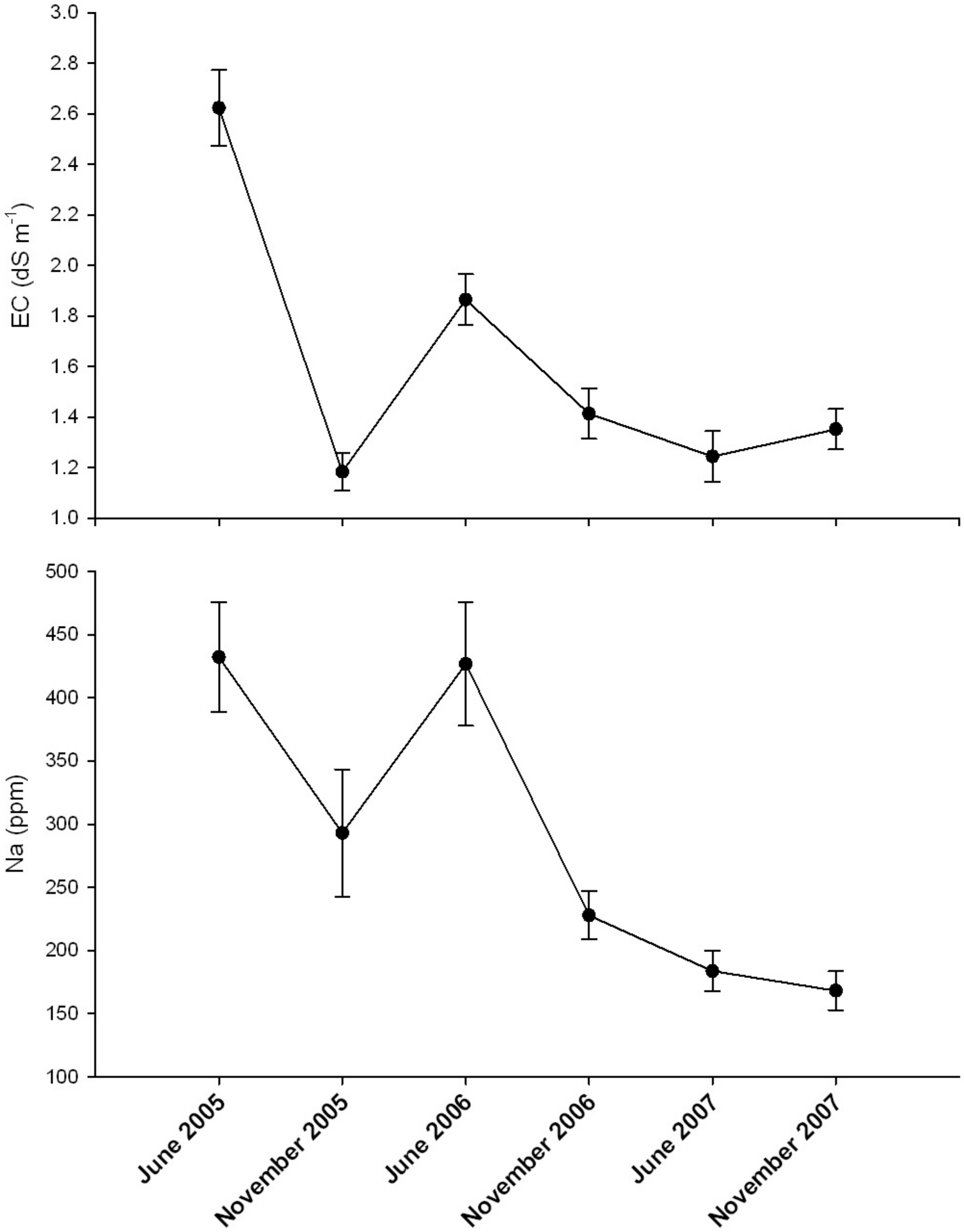

Figure 13. Electrical conductivity (EC, dS m^{-1}) and sodium content (Na, ppm) in soil at 50-60 cm depths. Data are pooled over three water qualities (potable, moderately saline, and saline) and two irrigation systems (subsurface drip and sprinkler). Error bars indicate the standard error of the mean.

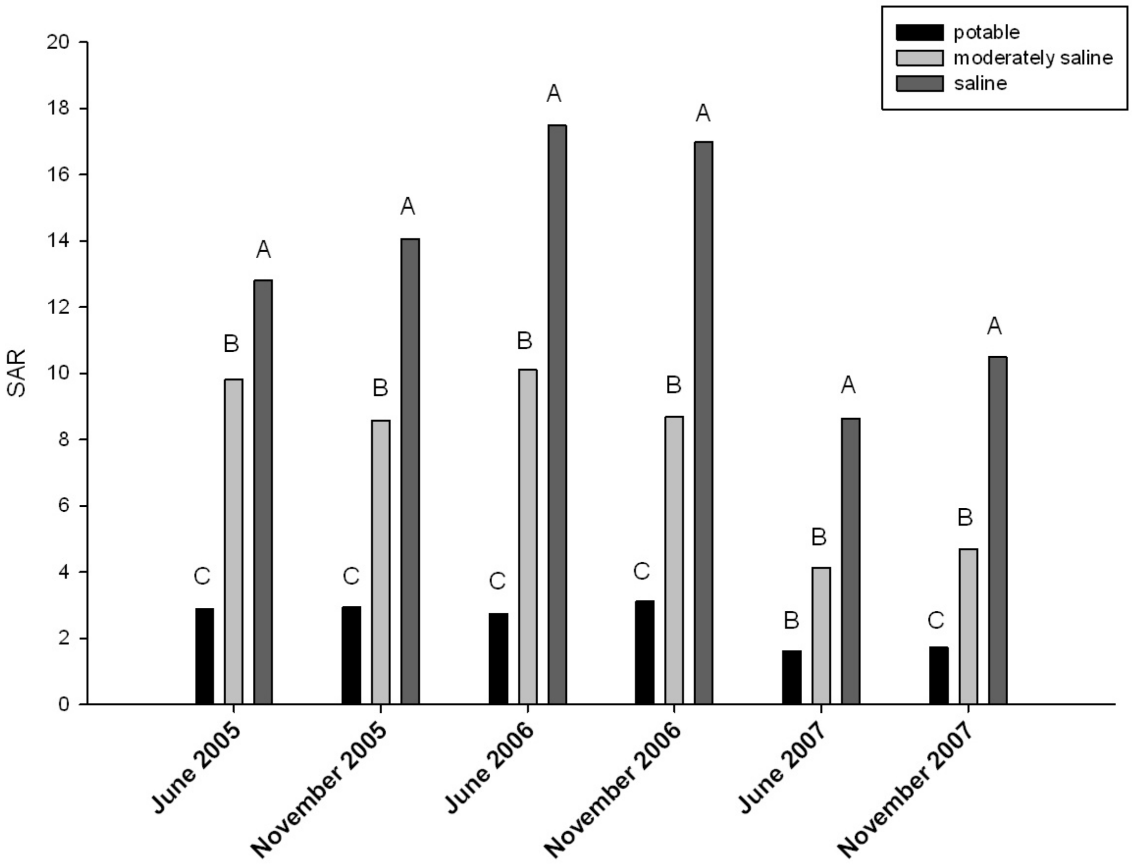

Figure 14. Sodium adsorption ratio (SAR) in soil at 50-60 cm depth. Data are pooled over two irrigation systems (subsurface drip and sprinkler). Letters denote the differences ($P<0.05$) in EC between the three water qualities separately for each sampling depth.

Soil SAR at soil depths of 50-60 cm mirrored the SAR of the irrigation water on each of the sampling dates (Figure 9). The values were greatest in plots irrigated with saline water, and lowest in plots irrigated with potable water. With the exception of June 2007, SAR in plots irrigated with moderately saline water fell between those measured in plots irrigated with saline and potable water on all other sampling dates (Figure 11). When SAR data were averaged over water qualities and displayed separately for each sampling date and irrigation system, sprinkler irrigation resulted in higher SAR than drip irrigation on all but the last sampling date (Figure 15). Moreover, changes in SAR did not follow the same seasonal peak-and-decline pattern that was observed for EC or Na. Under plots that received sprinkler irrigation, SAR was highest in November 2006 and lowest in June and November 2007 (Figure 15). June and November SAR values in drip irrigated plots did not differ in 2005 and 2007, but lower levels were found in November of 2006 when compared to June measurements (Figure 15).

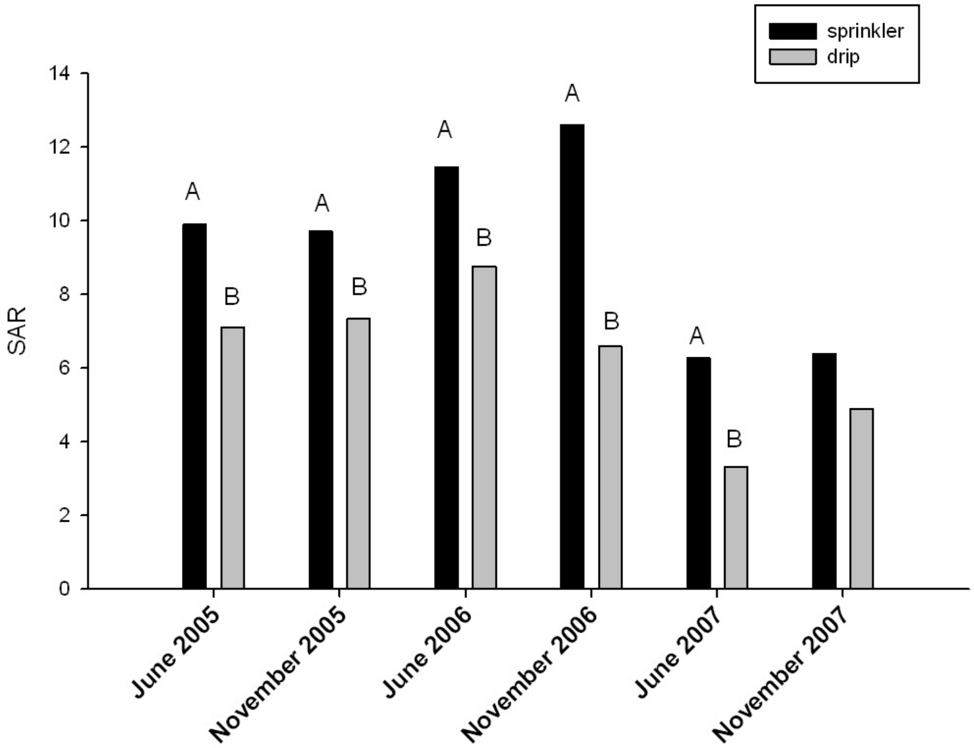

Figure 15. Sodium adsorption ratio (SAR) in soil at 50-60 cm depths. Data are pooled over three water qualities (potable, moderately saline, and saline). Letters denote the differences ($P<0.05$) in SAR between the two irrigation systems separately for each sampling date.

Turf quality

The analysis of variance revealed that the three way interaction between irrigation type, water quality, and sampling date and the two way interactions between cultivar and water quality and between cultivar and sampling date significantly affected turf quality (Table 10). Data were subsequently pooled over irrigation systems and water qualities and are presented separately for each sampling date (Table 11). Turf quality data were also pooled over irrigation systems and are presented separately for each cultivar for the three water qualities (Table 12).

Table 10. Results of analysis of variance testing the effects of water quality, irrigation systems, sampling dates, and their interactions on quality, cover, and NDVI of seven cool-season turfgrasses.

Effect	Quality	Cover	Quality 2007	NDVI
Cultivar (C)	***	***	***	**
Irrigation (I)	n.s.[‡]	n.s.	n.s.	**
C*I	n.s.	n.s.	n.s.	n.s.
Water Quality (W)	***	n.s.	**	**
C*W	***	n.s.	*	n.s.
I*W	n.s.	n.s.	n.s.	n.s.
C*I*W	n.s.	n.s.	n.s.	n.s.
Sampling Date (S)[†]	***	***	***	***
C*S	***	***	*	n.s.
I*S	***	*	***	***
C*I*S	n.s.	n.s.	n.s.	n.s.
W*S	***	***	n.s.	***
C*W*S	n.s.	n.s.	n.s.	n.s.
I*W*S	***	*	***	**
C*I*W*S	n.s.	n.s.	n.s.	n.s.

*	Significant F test at the 0.05 level of probability
**	Significant F test at the 0.01 level of probability
***	Significant F test at the 0.001 level of probability
[‡]n.s.	Not significant at the 0.05 probability level
[†]	Sampling date for ‘Quality’ and ‘Cover’ indicates monthly visual ratings that were averaged for seasons spring, summer, and fall throughout the research period (2005 to 2007). Sampling date for Quality 2007 and NDVI indicates monthly ratings and measurements from March 2007 to October 2007 only.

Turfgrasses tested in this study exhibited highest quality during 2005 and in spring and summer 2006. From fall 2006 until the end of the investigative period in 2007 overall quality declined to an average of 4.7 when data were pooled over all grasses (Table 11). During spring of 2005, five grasses out of seven performed equally well, while at the end of the 2007 growing season only tall fescue cultivars Tar Heel II and Southeast exhibited highest quality ratings. Alkaligrass Fults was among the grasses displaying poorest quality throughout the research period. When data were averaged over all sampling dates, Tar Heel II and Southeast performed best and Salty and Fults poorest. Turf quality of Brightstar SLT, Dawson, and Catalina fell between those of tall fescue and alkaligrasses (Table 11).

Table 11. Quality (from 1=worst to 9=best) of seven cool-season turfgrasses during spring, summer, and fall of 2005, 2006, and 2007. Data are pooled over three water qualities (potable, moderately saline, and saline) and two irrigation systems (sprinkler and drip) and represent an average of 18 readings (three water qualities, two irrigation systems, and three replications).

		2005			2006			2007		
Cultivar	Spring	Summer	Fall	Spring	Summer	Fall	Spring	Summer	Fall	Mean
Brightstar SLT	5.4ab[‡]	5.3c	5.2cd	5.6bc	5.5b	5.3cd	4.5bc	4.1bc	4.5b	5.1cd
Catalina	5.0c	5.1cd	5.2cd	5.0cd	5.4b	4.8de	4.2c	4.1bc	4.4bc	4.8de
Dawson	5.6a	6.1ab	6.1b	5.8ab	5.8b	5.5bc	4.7b	4.2b	4.0bc	5.3c
Fults	5.0bc	4.7d	4.3e	4.1e	4.0d	3.9f	3.8c	3.4d	3.8c	4.1f
Salty	5.5a	5.1cd	4.7de	4.9d	4.9c	4.4ef	4.2c	3.7cd	4.2bc	4.6e
Tar Heel II	5.6a	6.6a	7.3a	6.3a	6.8a	7.2a	5.8a	5.9a	6.0a	6.4a
Mean	5.4ABC[†]	5.5A	5.5AB	5.3BC	5.5ABC	5.3C	4.7D	4.5E	4.7D	

[‡,†] Values followed by the same letter are not significantly different from one another (Fisher's protected LSD, α=0.05). [‡]Lower case letters denote differences between cultivars separately for each season (in columns), [†] Upper case letters denote differences of the mean values between seasons during three years (in row).

When data were pooled over irrigation systems and analyzed separately for three water qualities, overall turfgrass quality was lowest under saline irrigation and highest under irrigation with potable and moderately saline water (Table 12). Four grasses, Tar Heel II, Fults, Salty, and Brightstar SLT, exhibited the same quality under potable and moderately saline water, while the performance of Catalina and Dawson was affected by moderately saline irrigation water. Turf quality of Catalina declined further with increasing salinity in the irrigation water (Table 12). Salinity did not affect performance of Salty or Fults but both grasses rated lowest in quality for each of the three water qualities (Table 12). Tar Heel II averaged a rating of 6.7 for quality under irrigation with potable water, followed by Brightstar SLT, Catalina, Dawson, and Southeast, with ratings of 5.8, 5.7, 5.9, and 5.7, respectively (Table 12). Fults displayed the poorest visual quality under irrigation with potable water averaging 4.3. Tar Heel II and Southeast had the highest quality under saline irrigation during the investigative period, averaging 5.7 and 5.2, respectively. Brightstar SLT, Catalina, and Fults exhibited poorest quality under saline irrigation. Type of irrigation system had no influence on turfgrasses quality on plots irrigated with potable water or on those irrigated with moderately saline or saline water for most dates (Figure 16). Plots irrigated from a drip system with moderately saline water rated lower in quality in summer and fall of 2007 and drip irrigated plots irrigated with saline water exhibited lower quality in spring and summer of 2006 (Figure 16).

Table 12. Quality (from 1=worst to 9=best) of seven cool-season turfgrasses irrigated with potable, moderately saline, and saline water. Data are pooled over two irrigation systems (sprinkler and drip) and values represent an average of six readings (two irrigation systems and three replications).

Cultivar	Potable	Moderately saline	Saline
Brightstar LST	5.8b[‡]A[†]	5.4cA	3.9cB
Catalina	5.7bA	4.9cB	3.8cC
Dawson	5.9bA	5.1cB	5.0bB
Fults	4.3d	4.2d	3.9c
Salty	4.9c	4.5d	4.5b
Southeast	5.7bA	6.1bA	5.2aB
Tar Heel II	6.7aA	6.8aA	5.7aB
Mean	5.6A	5.3A	4.6B

[‡,†] Values followed by the same letter are not significantly different from one another (Fisher's protected LSD, α=0.05). [‡]Lower case letters denote differences between cultivars separately for each water quality (in columns), [†] Upper case letters denote differences between three water qualities (in rows).

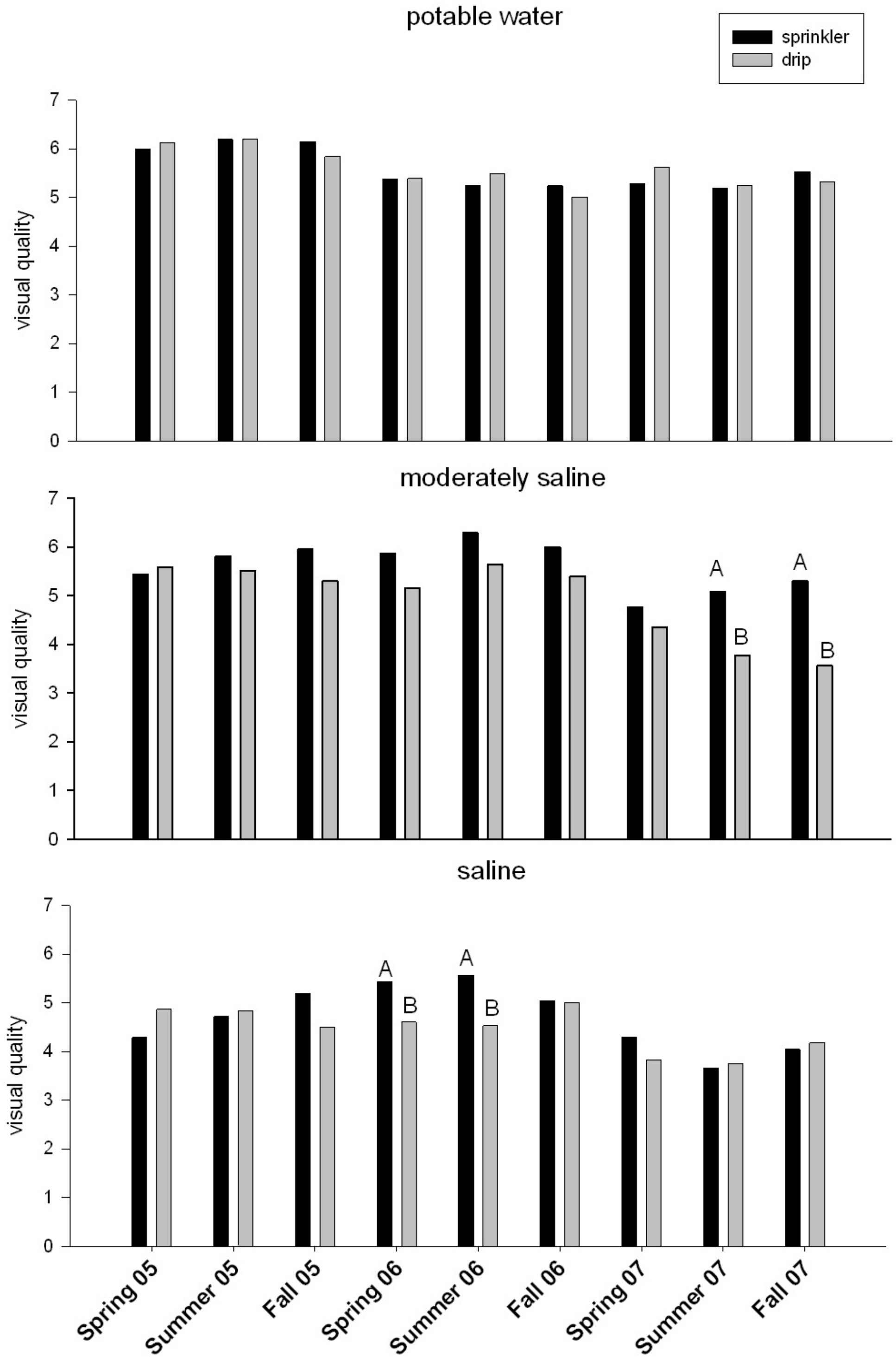

Figure 16. Visual quality of cool-season turfgrasses during spring, summer, and fall in 2005, 2006, and 2007 irrigated with potable, moderately saline, or saline water. Data are pooled over nine cultivars. Letters denote the differences ($P<0.05$) in quality between the two irrigation systems separately for each sampling date.

Correlations between turf quality, cover, NDVI and salinity

The correlation between visual turfgrass quality and NDVI was significant ($P<0.001$) yielding a correlation coefficient of $r=0.57$. When correlations were run separately for each cultivar, Dawson and Tar Heel II were most strongly associated with NDVI, yielding coefficients of 0.71 and 0.60, respectively. The correlation between quality and NDVI was poorest for Southeast, yielding a coefficient of 0.41. Despite the significant correlation between NDVI and turf quality, the different treatments did not always affect the two variables similarly. For example, the interactions between water quality and sampling date had a highly significant ($P<0.001$) effect on NDVI, but not on visual quality (Table 6). Furthermore, the interactions between cultivar and sampling date and between cultivar and water quality affected significantly turf quality but not NDVI.

Stepwise linear regression revealed that summer and fall values of EC, Na, and SAR in the top 10 cm of the rootzone were predictors of turf quality of Brightstar SLT, Catalina, Fults, and Tar Heel II significantly ($P<0.05$), although coefficients of determination were low, ranging from 0.27 (Catalina) to 0.18 (Tar Heel II). No significant relationship between any of the salinity parameters and turf quality could be established for Dawson, Salty, and Southeast. Generally, these results indicate that little variation in quality could be explained by variation in soil EC, Na, or SAR.

Whether pooled over all cultivars or analyzed separately, the linear regression between cover and quality revealed a significant relationship between the two variables ($P<0.001$). High coefficients of determination ranging from 0.66 (Southeast) to 0.82 (Brightstar SLT) indicate that between 66% and 82% of the variation in quality could be explained by the variation in coverage. Despite a strong relationship between turf cover and visual quality, analysis of variances revealed that water quality and the interaction between cultivar and water quality affected turf quality differently than turf cover (Table 10).

DISCUSSION

Warm-Season Grasses

Irrigating turfgrasses with saline waters requires careful rootzone management to prevent detrimental levels of salt accumulation. Adding a leaching fraction to the required irrigation amount, blending irrigation water, or alternating sources of irrigation water have all been suggested as strategies to manage salinity accumulation (Ayers and Westcot, 1985; Dean et al., 1996; Schaan et al., 2003, Rhoades, 1989). In this study we added a leaching fraction (irrigation was applied at 110% ET_o) and relied on natural precipitation to manage salinity in the top 20 cm of the rootzone. Consequently, seasonal changes in soil EC and Na content followed the irrigation and natural precipitation pattern, with higher values during the dry periods of the summer followed by lower values after the summer rains. During the three-year investigative period, EC and Na content were highest in summer of 2005 and 2006 when rainfall accumulated from March to end of June amounted to only 21 and 16 mm, respectively. Electrical conductivity and Na content in the rootzone in summer of 2007 were lower due to 103 mm of precipitation during the same time period. While the frequency of cyclic irrigation in this study was less than that of Schaan and others (2003), who reported no salt accumulation when multiple saline irrigation cycles were followed by a single cycle of potable water, the natural precipitation received by our test plots during the second half of the growing period was sufficient to leach salts from the rootzone. The highly permeable coarse-textured sandy soils of our test plots also contributed to the successful leaching of salts from the rootzone. Our findings are corroborated by Choi and Suarez-Rey (2003) who found for Tucson (AZ) that successful leaching can be accomplished in a desert environment through a typical rainy season despite a low overall annual precipitation. For most of the grasses tested, EC, Na content, or SAR values in the summer showed no significant relationship with turf quality during our three-year research period. During spring and summer of 2005 and 2006, EC and Na content were greatest for drip irrigated plots at a depth of 0-10 cm. Hoffman (1975) demonstrated that drip irrigation with saline water can result in a non-uniform distribution of salts with an accumulation of salts both at the surface and the periphery of the wetting front. In point source emitters, the water distribution into the soil follows a three-dimension infiltration pattern, which differs from the vertical, or one-dimensional infiltration pattern resulting from sprinkler irrigation (Bresler, 1977). In the case of very closely spaced emitters or porous pipes (used in our study) infiltration processes follow a two-dimensional distribution pattern and dissolved salts tend to also accumulate at the perimeter of the wetted zone, where the water content of the soil is lower (Bresler, 1977). Cote and others (2003) showed that in drip irrigated highly permeable sand, the wetted depth is larger than the wetted radius, which results in more water below than above the emitter plane. In our study, soil salinity at 0-10 cm depths did not exceed 3.8 dS m^{-1} in 2005 or 4.2 dS m^{-1} in 2006 in plots irrigated with saline water. These relatively low salinity levels can be attributed to little upward movement of water in sandy soils resulting in little salt accumulation and values at which acceptable turfgrass quality could be maintained.

At soil depths of 50-60 cm irrigation type did not affect the three salinity parameters measured. Results indicate that differences in water flow patterns between irrigation systems only affected salinity in depths immediately surrounding the drip lines. Salinity at depths well below the soil surface and drip lines was affected by the salinity of the irrigation water and by the amount of precipitation but not by the type of irrigation system. At soil depths of 50-60 cm, seasonal changes in salinity did not consistently follow the pattern observed at depths of 0-20 cm. For example, the decline in EC between summer and fall 2006 at depths of 0-20 cm (Figure 1) reported for plots irrigated with saline water, was not observed at 50-60 cm depths. To better understand changes in salinity at depths greater than 20 cm, additional sampling at depths between 20 cm and 50 cm would be needed. More studies are necessary to investigate changes in salinity at greater soil depths and whether or not groundwater or low lying aquifers are affected by turfgrass irrigation with saline water.

Visual quality of warm-season turfgrasses was neither affected by type of irrigation system nor by the quality of the irrigation water and generally responded only to seasonal changes. Lower summer quality in 2005 may be attributed to a reduced coverage compared to 2006 or 2007. Plots were established in 2004 with some grasses having not reached full coverage by the end of the 2004 growing season (Johnson, 2007).

Among all cultivars studied, seashore paspalum exhibited the best visual quality during all three growing seasons, while saltgrass had the lowest quality (Table 6). Our findings support those of Duncan and Carrow (2000), Berndt (2007), and Lee and others (2005) who reported a high salinity tolerance in seashore paspalum and consequently a high turf quality in saline soils. Low quality ratings for inland saltgrass could not be attributed to salt stress, as water quality had no effect on turf performance in our study (Table 5). Moreover, the salt tolerance of saltgrasses has been demonstrated in past studies (Pasternak et al., 1993; Marcum, 2005). Both studies used dry matter yield or relative live shoot and root weight as indicators of salt tolerance but not visual quality as applied in the study. Saltgrass exhibits a low stand density and light green color regardless of the level of salinity applied (Pessarakli et al., 2009), which resulted in a lower visual quality compared to other grasses used in our study. Schiavon and others (2011) also reported low turf quality on inland saltgrass plots when compared to other warm-season turfgrasses. In spite of a low visual quality during summer and fall, inland saltgrass showed higher quality in spring due to an early spring green-up (Table 7).

The salinity tolerance of zoysiagrass has been ranked as similar to that of seashore paspalum (Duncan et al., 2009; Harivandi et al., 2008) or in the range of bermudagrass (Carrow and Duncan, 1998);

but a broad range exists among varieties (Marcum, 1999b). Qian and others (2000) identified De Anza as the cultivar with the best ability to concentrate and exclude Na^+ from the shoots, resulting in greater tolerance of high salinity levels than other cultivars. In our study, mean summer and fall quality of De Anza was lower than most other grasses tested (Table 6), but rated higher for sprinkler than drip irrigated plots. Riviera bermudagrass was the only bermudagrass cultivar that exhibited higher summer quality under sprinkler irrigation than under drip irrigation. Irrigation system had no effect on summer quality for all other bermudagrasses. These findings are in part supported by Gibeault and others (1985) who found drip irrigated zoysiagrass and seashore paspalum lower in quality than sprinkler irrigated and no effect of irrigation system on bermudagrass quality. More research is needed to understand how differences in canopy temperature between sprinkler and drip irrigation affect summer turf quality of warm-season grasses. Sprinkler irrigation has been shown to cool the canopy and may provide a more favorable microclimate for grasses that are less heat tolerant that could result in higher turf quality.

Among the four cultivars of bermudagrass, Princess 77 exhibited highest summer and fall quality (Table 6). In a comparison of salinity tolerances of 35 bermudagrasses, Marcum and Pessarakli (2006) reported similar EC thresholds for 50% growth reduction in Princess 77 and Riviera. These results, coupled with our findings that neither EC nor Na content accurately predicted summer quality of Princess 77 and Riviera suggest that factors other than irrigation water quality may be responsible for the differences in turf quality we observed.

When comparing the effect of irrigation systems on turf quality, seven out of nine grasses showed no difference in quality during the first two years and eight out of nine grasses did not differ in fall quality for all three years. These findings are supported by Choi and Suarez-Rey (2003), who reported that visual quality of bermudagrass was not affected by type of irrigation system used when recycled water was applied. Devitt and Miller (1988) have demonstrated that bermudagrass can be grown with acceptable quality using irrigation water with EC levels as high as 6.0 dS m^{-1}. In summer of 2007, four of the nine grasses showed reduced quality on drip irrigated plots compared to sprinkler irrigated ones. The reasons for this drop in quality remain unclear and did not lead to a reduction in fall quality. Further investigations are necessary to explore whether or not short-term clogging occurs in emitterless porous pipes and affects water application and turf quality. Contrary to our findings, Schiavon and others (2011) reported a steady and high performance of subsurface drip irrigated warm-season turfgrasses over a four-year period, when potable water was applied by means of emitters from point sources.

One of the limitations of growing warm-season turfgrasses in the transition zone is the long dormancy period during which turfgrasses have reduced or no color for up to five months. Any treatment that could reduce this dormancy period would help improve the acceptability of warm-season grasses in transition zone climates. Water quality did not affect spring green-up but in 2005 and 2006 drip irrigated plots showed earlier green-up than sprinkler irrigated plots (Table 7). Faster green-up of turfgrasses under drip irrigation could be a result of higher night canopy temperatures due to a lack of cooling from irrigation water applied by above ground sprinkler heads. However, additional research is needed to investigate potential differences in canopy temperature between the two irrigation systems.

The significant but weak correlation we observed between visual turfgrass quality and NDVI was consistent with findings of Ghali (2011), Haendel and Wissemeier (2008), and Schiavon et al. (2011). Our results show a wide spread of NDVI values for each visual quality rating value, which has also been reported by Bunderson and others (2009), Haendel and Wissemeier (2008), and Schiavon and others (2011). Ghali (2011) suggested that such a weak correlation is the result of comparing discrete (quality ratings) to continuous variables (spectral reflectance values). Schiavon and others (2011) concluded that the weak correlation between visual quality and NDVI could be due to differences in color and canopy structure between species that are detected by spectral reflectance but are not as noticeable when visually assessing plots. If NDVI measurements are to replace visual and subjective quality ratings, more research is needed to investigate this variability.

Our results indicate that most of the warm-season grasses included in this study can be maintained at an acceptable quality level when irrigated with saline water from a subsurface drip system. Salinity levels in our irrigation water were higher than those found in recycled water currently used in the Southwest to irrigate lawn and turf areas and long-term exposure to salinity levels used in our study are considered deleterious to plant growth and soil structure. Nevertheless, our results indicate that over the course of the three-year study, warm-season turfgrasses maintained acceptable quality and were not affected by these soil salinities when these high levels were reached in a cyclic pattern followed by leaching. In order to determine the long-term viability of using saline waters for irrigation, more research is needed to assess the ability of soils and plants to withstand continued salt accumulation, and to also determine any detrimental effects on aquifers and groundwater.

Cool-Season Grasses

Irrigating cool-season turfgrasses with saline waters in a climate with limited rainfall necessitates adding a leaching fraction to the required irrigation amount to prevent detrimental levels of salt accumulation (Ayers and Westcot, 1985). In this study plots were irrigated at 120% ET_o and relied on natural precipitation during the rainy season (June to September) to manage salinity in the top 20 cm of the rootzone. Generally, changes in soil EC, Na content, and SAR reflected seasonal changes in irrigation and natural precipitation. Higher values for EC, Na content, and SAR were measured in summer of 2005 and 2006 prior to the onset of the monsoon season. These peak salinity levels were followed by lower values in the fall, following the rainy season, which typically begins in early July and continues into early fall (Figures 9 and 10). These findings are in agreement with results of Choi and Suarez-Rey (2003), who demonstrated successful salt leaching in a desert Arizonan soil with the help of monsoon rains. These findings are also similar to results obtained in a parallel study conducted by the authors on warm-season grasses, where seasonal changes in soil salinity concomitant with changes in natural precipitation were observed (Sevostianova et al., 2011).

Type of irrigation systems had a greater impact on Na content during the drier, first half of the study period (June 2005 to June 2006) than during the wetter, second half (Figures 10 and 11). Similarly, EC was affected by irrigation systems in November 2005 and June 2006. Turf plots irrigated from a drip system exhibited greater Na content at a soil depth of 0-10 cm from June 2005 to June 2006 and greater EC on November 2005 and June 2006 than turf plots irrigated from a sprinkler system (Figures 10 and 11). These findings corroborate our hypothesis that drip irrigation is less successful in leaching salts from depths above the drip lines than sprinkler systems at similar depths. However, at depths below the drip lines (10-20 cm), EC, Na, and SAR were either lower or similar to values measured on sprinkler irrigated plots (Figures 10, 11, 12) throughout the study period. Findings confirm those of Cote and others (2003), who demonstrated that more water is distributed below than above the emitter plane in highly permeable sand that is drip irrigated. Similarly, Hoffman (1975) reported a non-uniform distribution of salts from drip irrigation with saline water with an accumulation of salts both at the surface and on the periphery of the wetting front. Precipitation during 2007 appeared to be responsible for a successful leaching of Na from both drip and sprinkler irrigated plots. However, precipitation did not affect total salinity, as EC was again higher in drip irrigated plots than in those that were sprinkler irrigated.

During the course of the investigative period, highest EC and Na values (6.1 dS m^{-1} and 943 ppm, respectively) were measured on drip irrigated plots at depths of 0-10 cm in June of 2006. Highest values recorded on warm-season grasses subjected to the same salinity treatments but irrigated at 110% ET_o were 4.3 dS m^{-1} and 793 ppm, respectively (Sevostianova et al., 2011). Electrical conductivity and Na were approximately 30% and 20% lower on warm-season grasses compared to cool-season. A longer growing period with a correspondingly longer irrigation period and higher total irrigation amounts contributed to greater salt inputs from the irrigation water into the rootzone on cool-season turf. However, a higher leaching fraction on cool-season grasses should have compensated for the greater salinity input. The greater accumulation of salts at depths of 0-20 cm in cool-season grasses could be due to their higher ET rates compared to warm-season grasses, which results in less remaining water available to leach salts from the rootzone.

Irrigation type and water quality did not affect EC and Na at soil depths of 50-60 cm on any of the sampling dates. These results differ from our findings on warm-season grasses (Sevostianova et al., 2011) which suggested that water quality affected EC and Na at these depths. However, both irrigation type and water quality affected SAR values. As was observed at rootzone depths of 0-20 cm, SAR values reflected the quality of the irrigation water at 50-60 cm. It remains unclear why water quality influenced all measured salinity parameters at depths 0-20 cm but not at 50-60 cm. Non-uniform water distribution in drip irrigated plots, as indicated by slightly greener plants on top of the drip lines compared to between the lines, may have affected water movement into deeper profiles. Layering of different soil types at the research site could also have affected water movement and salt accumulation and may have contributed to the results. Further research that includes salinity measurements at depths throughout the soil profile might help elucidate these differences in salt accumulation.

Among all cultivars included in our study, both tall fescue cultivars exhibited highest visual quality, while alkaligrasses had the lowest quality (Tables 11 and 12). These results differ from those of Lunt (1961), Butler (1972), Torello and Symington (1984), and Alshammary and others (2004), who all reported the superior salinity tolerance of alkaligrass compared to other cool-season grasses. The low quality ratings of alkaligrasses in this study may not be due to salt stress, as it was lowest even when irrigated with potable water (Table 12). Schiavon and others (2010) and Leinauer (unpublished data) reported low turf quality of alkaligrass during summer months in southern New Mexico, even when irrigated with potable water in sufficient amounts to avoid drought stress. Therefore, a poor performance of alkaligrass during the three-year research period appears to be the result of inadequate heat tolerance and not necessarily due to salt stress.

Tall fescue provided the highest quality among the cool-season grasses in our study. These findings support those of Lunt and others (1961) and Harivandi and others (1992), who rated tall fescue either moderately tolerant or tolerant to salinity. Superior salinity tolerance of tall fescue compared to other cool-season grasses may be the result of salinity avoidance that is achieved by developing a deep root system that remains viable at depths below those at which salt accumulates. Although rooting depth was not measured in this study, tall fescue has been reported to be an excellent drought avoider by other authors based on a deep and extensive root system (Juang and Huang, 2001; Qian et al., 1997). Moreover, Alshammary and others (2004) observed a high root to shoot ratio in salt-stressed tall fescue. Moreover, Jiang and Huang (2001) found that tall fescue maintained a high root viability at depths of 20-40 cm and 40-60 cm under heat stress. In our study, tall fescue quality received an average rating of either six or seven when irrigated with saline or moderately saline water (Table 12). Similar turf quality was observed by Sevostianova and others (2011) for inland saltgrasses A138 and DT16 and bermudagrasses NuMex Sahara and Transcontinental, both of which are generally considered more salt tolerant than cool-season tall fescue. However, more research is necessary to determine whether quality of tall fescue grown in a saline environment can remain as high as that of salt tolerant warm-season grasses on a long term basis.

Visual quality ratings of Brightstar SLT, Catalina, and Dawson support findings of Carrow and Duncan (1998) and Harivandi and others (1992) who ranked salinity tolerance of perennial ryegrass as similar to that of slender creeping red fescue cultivars. However, these findings do not concur with those of Schaan and others (2003). The authors reported no significant loss in quality of perennial ryegrass cv. Champion during a two-year period of alternating irrigation between potable and saline water of 3.3 dS m^{-1}. In this study, perennial ryegrasses Brightstar SLT and Catalina only maintained acceptable quality under irrigation with potable water (Table 12). Irrigation with moderately saline and saline water resulted in turf quality below an acceptable minimum of six. In this study, the quality of Dawson under saline irrigation was higher than that of both cultivars of perennial ryegrass. These findings are in agreement with those of Marcum (1999) who reported greater salinity tolerance in accessions of strong and slender creeping red fescue compared to perennial ryegrass. Torello and Symington (1984) reported higher NaCl tolerance in Dawson than Fults. As in alkaligrasses, the low quality we observed in both perennial ryegrasses and creeping red fescue may have been due to high summer temperatures and not salinity stress. This would explain why quality ratings for these three grasses never exceeded six, even under potable irrigation (Table 8). Other studies have also found perennial ryegrass and creeping red fescue to be heat sensitive species (McCarty 2010, Christians 2007). Moreover, no recovery was observed for Catalina plots after the summer of 2006, or for Dawson and Brightstar after winter of 2006, despite lower salinity levels in the rootzone compared to previous years (Table 12, Figure 9). Simultaneous heat and salt stress may have been detrimental to both species resulting in little or no recovery. In contrast, tall fescue successfully recovered to acceptable quality levels at the end of the research period. Linear regression between salinity and turf quality further supports our hypothesis that more than one stressor affected visual quality of cool-season grasses in our study. Despite a wide range of salinities measured over the three-year research period, quality could only be significantly predicted from soil salinity for four cultivars. Furthermore, low regression coefficients indicated that only between 18 and 27% of the variations in quality can be explained by soil salinity. Further research in cooler climate zones is needed to investigate the role of temperature and salinity on turf quality of cool-season grasses.

Visual quality of turfgrasses was not affected by the type of irrigation when potable water was used (Figure 16). These results differ from those of Gibeault and others (1985) who reported a significant reduction in quality of Kentucky bluegrass, perennial ryegrass, and tall fescue when drip irrigated as opposed to sprinkler irrigated. However, the results are in agreement with those of Schiavon and others (2010) and Sevostianova and others (2011) who reported no decline in turf quality of subsurface irrigated cool-season grasses during a four-year research period and no difference in quality between sprinkler and drip irrigated plots of several warm-season cultivars. Cool-season turfgrass plots irrigated with saline water from a sprinkler system exhibited higher quality than plots irrigated from the drip systems in spring and summer of 2006. The higher turf quality of sprinkler irrigated plots may be due to lower EC and Na content at rootzone depths of 0-10 cm (Figures 11 and 12) compared to drip irrigated plots. During summer and fall of 2007, grasses drip irrigated with moderately saline water exhibited lower quality than those that were sprinkler-irrigated. By the end of the research period, turf quality of plots both sprinkler and drip irrigated with moderately saline and saline water was below the acceptable minimum rating of six (Figure 8), suggesting that cool-season grasses generally do not perform well when irrigated with more saline water on a long-term basis in a transitional desert climate. The high correlation between percent ground cover and quality suggests that reduced turf quality is mainly due to lack of green cover. However, loss of green cover may not necessarily be attributed to a complete loss of plants, as leaf firing and loss of pigmentation during the early stages of salinity and heat stress has been reported by several researchers as a result in cool-season turfgrasses (Harivandi et al., 1992; Nabati et al., 1994; Suplick-Ploense et al., 2002).

The weak correlation between visual turfgrass quality and NDVI is the result of a wide spread of NDVI values for each visual quality rating. Similar results have been reported for both cool and warm-season grasses by Bunderson and others (2009), Ghali (2011), Haendel and Wissemeier (2008), and Schiavon and others (2010, 2011). Schiavon and others (2011) suggested that differences in color and canopy structure between grasses that are readily detected by spectral reflectance may be less noticeable and of lesser importance to assessing overall quality to the person visually rating the plots. Ghali (2011) noted that comparing discrete (quality ratings) with continuous variables (spectral reflectance values) results in a weak correlation. Further research is required to investigate the weak correlation if NDVI measurements are to replace visual and subjective quality ratings.

These results indicate that most of the cool-season grasses included in this study could not be maintained at an acceptable quality level in a transition zone climate when irrigated with saline water regardless of irrigation system. Salinity levels in the irrigation water were either higher or matched those found in recycled water currently used in the Southwest to irrigate turf areas. Summer heat and exposure to salinity build-up in the rootzone were deleterious to growth and quality of all grasses but tall fescue. Over the course of the three-year study, quality was affected by both soil salinities and high temperatures, despite a semi-annual cyclic leaching pattern that reduced soil salinity in the second half of the calendar year. Based on these and earlier findings, with the exception of tall fescue, warm-season grasses appear to be the logical choice for turf areas irrigated with saline water from either a drip or a sprinkler system in transitional semi-arid or arid climate zones.

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