Drought avoidance of warm-season turfgrasses affected by irrigation system, soil surfactant revolution, and plant growth regulator trinexapac-ethyl

Matteo Serena1 | Marco Schiavon2 | Rossana Sallenave3 | Bernd Leinauer1

1 Dep. of Extension Plant Sciences, New Mexico State Univ., Las Cruces, NM 88003
2 Department of Environmental Horticulture, University of Florida, Davie, FL 33314
3 Dep. of Extension Animal Science and Natural Resources, New Mexico State Univ., Las Cruces, NM 88003

Correspondence
Bernd Leinauer, Dep. of Extension Plant Sciences, New Mexico State Univ., Las Cruces, NM 88003.
Email: leinauer@nmsu.edu

Funding information
New Mexico State University’s Agricultural Experiment Station; Aquatrols Corp.; Seeds West Inc.; Southwest Turfgrass Association; Syngenta AG; The Toro Co.; United States Golf Association

Abstract
A 2-yr study was conducted to investigate the effect of subsurface drip irrigation (SDI), the soil surfactant Revolution (modified methyl-capped block copolymer), and the plant growth regulator PrimoMaxx (a.i. trinexapac-ethyl [TE]), on rooting, stolons, and rhizomes, percentage green turf coverage, and turf quality of ‘Princess 77’ bermudagrass [Cynodon dactylon (L.) Pers.] and ‘Sea Spray’ seashore paspalum (Paspalum vaginatum Sw.). Grasses were grown on a loamy sand and irrigated with potable or saline ground water at 50% of reference evapotranspiration. Stolon and rhizome weight were not affected by water quality, Revolution, or TE, but SDI plots had greater stolon (1.000 vs. 0.627 g m⁻²) and rhizome biomass (0.856 vs. 0.493 g m⁻²) than sprinkler-irrigated plots. Grasses in drip-irrigated control plots showed higher root length density (RLD) at 0–10-cm depth (15.1 vs. 8.3 cm cm⁻³) and 10–40-cm depth (7.2 vs. 4.9 cm cm⁻³) and higher root weight density (RWD) at 0–10-cm depth (3.5 vs. 2.2 g cm⁻³) than their sprinkler-irrigated counterparts. Both RLD and RWD correlated significantly with turfgrass quality (August and September) and green turf cover (July–September). Chemical treatments in combination with irrigation from a sprinkler system resulted in thinner roots and higher RLD at all depths in 2013 when values were compared with the untreated control. Revolution, TE, and SDI all enhanced grasses’ drought avoidance and turf quality, but chemical treatments did not appear to provide additional improvements to grasses in plots irrigated with SDI.

1 | INTRODUCTION

Warm-season grasses, such as bermudagrass [Cynodon dactylon (L.) Pers.] and seashore paspalum (Paspalum vaginatum Sw.) are widely used in warmer, drier parts of the world where heat, drought, and salinity negatively affect the function and aesthetics of turfgrasses. Bermudagrass is one of the most widely used grasses in the southern United States and can be found on golf courses, athletic fields, parks, roadsides, and residential lawns (Emmons, 2000). Seashore paspalum is mostly used along coastlines between 30 and 35° latitude throughout the world, where salinity levels of brackish waters make it difficult to grow other...
grasses (Duncan & Carrow, 2000). Little is known about how seashore paspalum performs at high-altitude arid locations. Like most other turfgrasses in an arid and semi-arid climate, bermudagrass and seashore paspalum require irrigation during the main growing season to provide an aesthetically acceptable turf and a functional playing surface.

The cumulative evapotranspiration (ET) for southwestern areas of the United States can be as high as 1600 mm yr$^{-1}$. However, the historical average precipitation (1981–2010) for southern New Mexico, for instance, was 178.5 mm (NOAA, 2019). The shortfall between natural rainfall and the ET-based water requirement must be provided by irrigation, if plants other than native desert plants are expected to survive. For this reason, >50% of all water consumed during the summer in the southwestern United States goes to irrigation (Devitt & Morris, 2008; Kjelgren, Rupp, & Kilgren, 2000). To conserve water, deficit irrigation is recommended (Feldhake, Danielson, & Butler, 1984) and turfgrass areas are frequently irrigated below replacement levels. Other strategies for water conservation include the use of nonpotable water for irrigation, the use of more efficient irrigation systems such as subsurface drip irrigation (SDI), the use of drought-tolerant species, or a combination of some or all of these strategies (Leinauer & Devitt, 2014).

A variety of nonpotable water sources can be used for turfgrass irrigation if potable water conservation is intended. These sources include recycled water (also referred to as treated effluent or reclaimed water), gray water, coalbed methane-produced water, saline groundwater, brackish surface water or groundwater, surface storm water, and irrigation return water (Duncan, Carrow, & Huck, 2009). Saline groundwater and recycled water are widely used in the southwestern part of the United States. However, these waters can be high in bicarbonates, sodium adsorption ratio (SAR), and Na and other ions detrimental to plants. Using these waters for irrigation can negatively affect plants and the underlying soil due to salt accumulation (Ganjegunte et al., 2017; Magesan, 2001). Remediation strategies such as planting salt-tolerant species and leaching salts from the root zone have been widely suggested (Duncan et al., 2009; Huck, Carrow, & Duncan, 2000). To determine the long-term viability of using nonpotable waters for irrigation, it is important to not only assess the ability of soils and plants to withstand continued salt accumulation, but also whether traditional and required turfgrass maintenance strategies can be combined with the use of saline irrigation water.

Overhead sprinkler irrigation is the most commonly used irrigation system for landscapes and golf courses; however, water application can be inefficient because of losses such as overspray, runoff, wind drift, and evaporation. Subsurface drip irrigation systems, on the other hand, apply water directly to the root zone, thereby avoiding the abovementioned problems (Leinauer & Devitt, 2014). Such systems have been recommended for use on residential lawns (Sevostianova & Leinauer, 2014) and on golf courses (Thompson, 2019) and have been mandated by water agencies (California Department of Water Resources, 2009) as an efficient alternative means of turf irrigation. However, SDI resulted in increased salt concentration in the root zone compared with irrigation with a sprinkler system when used in combination with saline water (Ganjegunte, Leinauer, Schiavon, & Serena, 2013; Schiavon, Leinauer, Serena, Sallenave, & Maier, 2012, 2013; Sevostianova, Leinauer, Sallenave, Karcher, & Maier, 2011a,b), as SDI systems are less effective than sprinkler systems at leaching salts from soils in the absence of adequate rainfall, particularly for root zone depths above the drip lines. Nonetheless, warm-season grasses seashore paspalum, bermudagrass, and inland saltgrass (Distichlis spicata L.) and cool-season tall fescue [Schedonorus arundinaceus (Schreb.) Dum.] did not exhibit a decline in summer quality despite salinity fluctuations in the root zone (Sevostianova et al., 2011a,b).

Irrigating turfgrasses below their water requirement can cause plant stress due to drought, heat, or salt accumulation, which ultimately causes loss in turfgrass quality. As a result, turfgrass managers turn to products designed to help plants cope with the negative effects of deficit irrigation by increasing water use efficiency, or reducing transpiration. Such compounds fall into two classes of chemicals—namely, soil surfactants (or wetting agents) and plant growth regulators (PGRs). Soil surfactants have been used historically in the turfgrass industry to alleviate soil hydrophobicity and improve infiltration and percolation (Cisar, Willimas, Vicas, & Haydu, 2000; Karnok, Xia, & Tucker, 2004; Kostka & Bially, 2005). More recently, studies have documented the role of surfactants in water conservation (Leinauer & Devitt, 2014; Schiavon, Leinauer, Serena, Maier, & Sallenave, 2014; Serena, Sportelli, Sevostianova, Sallenave, & Leinauer, 2018). Another group of chemicals that are marketed to help conserve water are the PGRs. They can be separated into two categories. Type I PGRs reduce plant growth by inhibiting cell division, whereas Type II PGRs inhibit gibberellic acid synthesis (Fry & Huang, 2004). Research has shown that cool-season grasses treated with PGRs, most notably with trinexapac-ethyl (TE), a Type II PGR, exhibit greater turfgrass quality during short periods of drought (Fry & Jiang, 1998; King, Gocal, & Heide, 1997; Marcum & Jiang, 1997). The same beneficial effects have been reported on TE-treated warm-season grasses exposed to drought conditions (Schiavon et al., 2014). The improved drought tolerance exhibited by grasses treated with PGRs and surfactants is thought to be due to changes in root architecture (Schiavon et al., 2014).

Part of an overall drought resistance mechanism in plants involves drought avoidance, and for this to occur, a well-developed root system is needed. Maintaining high visual quality for bermudagrasses during drought has been linked to an effective root system (Brown et al., 1988; Leinauer et al., 2014; Schiavon et al., 2014).
to the ability to develop a more uniform downward root system (Hays, Barber, Kenna, & McCollum, 1991). Zhou, Lambrides, and Fukai (2014) suggested that the survival of bermudagrasses during drought was related to the ability to maintain a vital root system during the stress period. Carrow (1996) documented that bermudagrass and St. Augustinegrass [Stenotaphrum secondatum (Walt.) Kuntze] exposed to drought conditions exhibited greater root biomass and less leaf firing than zoysiagrass (Zoysia spp.) and centipedegrass [Eremochloa ophiuroides (Munro) Hack.], which had shallower roots and showed more leaf firing. Increased root length density (RLD) was also associated with greater recuperative abilities in turfgrasses after a period of drought (Hays et al., 1991; Salaiz, Shearman, Riordan, & Kinbacher, 1991; Sheffer, Dunn, & Minner, 1987). Species with longer roots such as seashore paspalum and bermudagrass recovered faster than zoysiagrass, which had the shortest roots (Huang, Duncan, & Carrow, 1997). Similarly, Qian, Fry, and Upham (1997) reported that the more deeply and densely rooted tall fescue was able to extract 50% more water than the shallower-rooted zoysiagrass during a dry-down period.

Some PGRs have been shown to increase root length in turfgrasses, which could potentially confer greater drought resistance. McCarty, Willis, Toler, and Whitwell (2011) reported that TE increased the root mass of ultradwarf bermudagrass by 45%. McCullough, Liu, and McCarty (2005) documented that root growth responses to TE varied among cultivars, with root mass increases of 23 and 27% observed in treated ‘MiniVerde’ and ‘FloraDwarf’, but no changes in root growth observed in ‘Champion’ ‘MS Supreme’, ‘Tifdwarf’, or ‘TifEagle’. Beasley, Branham, and Ortiz-Ribbing (2005) documented reduced root length and surface area in cool-season Kentucky bluegrass (Poa pratensis L.) treated with TE, although the root diameter (RD) was unchanged. All of the abovementioned studies were conducted in a controlled environment, and grasses were not subjected to deficit irrigation.

Less is known about the effects of soil surfactants on plant root architecture. Karnok and Tucker (2001) reported an increase in root length of creeping bentgrass (Agrostis stolonifera L.) grown on hydrophobic soil when treated with a soil wetting agent. This is in contrast with an earlier study (Cooper, Henderlong, Street, & Karnok, 1987), which reported no significant increase in root elongation of annual bluegrass treated with a wetting agent.

Published results of field studies on the effects of surfactants and PGRs on deficit-irrigated, warm-season turfgrasses are lacking, as are studies examining the efficacy of these chemicals in combination with other water conservation approaches, such as SDI. A 2-yr study was conducted at New Mexico State University to investigate the effect of a PGR and a soil surfactant on drought avoidance of bermudagrass and seashore paspalum. The objective of our research was to compare the effects of repeated applications of TE or the soil surfactant Revolution on rhizome and stolon biomass, and on root diameter, weight, and length of bermudagrass and seashore paspalum plants under deficit irrigation. The grasses were irrigated with potable or saline water using either sprinkler or subsurface-drip irrigation. A second objective of our study was to investigate if untreated turfgrasses irrigated from a subsurface-drip system were as resistant to drought as sprinkler-irrigated grasses treated with either TE or Revolution.

2 | MATERIALS AND METHODS

A 2-yr study (2012–2013) was conducted at New Mexico State University’s Turfgrass Salinity Research Center in Las Cruces, NM (arid, 1265-m elevation) to investigate the effects of a soil surfactant, Revolution (modified methyl-capped block copolymer), and the PGR PrimoMaxx [a.i. TE {4-(cyclopropylhydroxymethylene)-3,5-dioxocyclohexanecarboxylic acid}] against a nontreated control on stolon and rhizome biomass, and on root growth under reduced irrigation of ‘Princess 77’ bermudagrass and ‘Sea Spray’ seashore paspalum. The study area was established in 2009. The soil at the site is classified as a sandy skeletal mixed thermic Typic Torriorthent. Climate data collected by means of a weather station located at the research center are presented in Table 1.

Irrigation was provided from either an overhead sprinkler (Toro MPR) or a subsurface drip-irrigation system (Toro DL2000) (The Toro Company). The Toro pop-up sprinkler heads were placed at the corners and along the sides of each irrigated block. Subsurface drip lines were installed at a depth of 10 cm and spaced 33 cm apart. Emitters were placed at 33-cm intervals along each line. The drip lines were operated at 200 kPa, which assured a delivery rate of 2 L h⁻¹. Irrigation audits of the sprinkler system were conducted twice during each research period (1 May–31 October) to determine application amounts and to assure a minimum distribution uniformity of 70%. Prior to and after the research periods (1 November–30 April), turfgrasses were irrigated once per week at 80% reference ET for short grass (ET⁺o) (Snyder & Eching, 2007). Irrigation volumes were calculated every Monday morning based on the previous week’s ET⁺o, and plots were watered daily receiving the equivalent of 7% of the weekly ET⁺o. Each irrigated block had a separate valve and water meter (Invensys Process Systems), which recorded irrigation water use.

Since establishment, plots were irrigated with either potable (electrical conductivity [EC] = 0.62 dS m⁻¹, pH 7.6, SAR = 1.87) or saline groundwater (EC = 2.33 dS m⁻¹, pH 7.7, SAR = 5.25). Drought stress during the research period was induced by irrigating at 50% ET⁺o. An irrigation amount of 50% ET⁺o was chosen because early signs of drought stress
have been reported on seashore paspalum and bermudagrass when irrigated at 66% ET$_{0,s}$ (Bañuelos, Walworth, Brown, & Kopec, 2011). Therefore, we considered irrigation at 50% ET$_{0,s}$ as adequate to impose moderate stress.

Grasses were mowed twice per week at a height of 1.25 cm by means of a reel mower with clippings collected. The pre-emergence herbicide Pendulum 3.3EC (pendimethalin, BASF Corporation) was applied in mid-March, and Dimension 2EW (dithiopyr, Dow AgroSciences) was applied in mid-June, both at the recommended label rates for bermudagrass to control spring and summer annual weeds. Fertilization consisted of a total of 22.5 g N, 7.5 g P$_2$O$_5$, and 7.5 g K$_2$O m$^{-2}$ applied monthly at 3.5 g N m$^{-2}$ and 1.25 g P$_2$O$_5$ and K$_2$O m$^{-2}$ from April to September. Iron fertilization was applied at a rate of 5 g Fe m$^{-2}$ three times during the growing season by means of foliar chelated Fe.

Revolution and TE were applied every 4 wk from May until October beginning on the last week of May at the recommended label rate of 20 L ha$^{-1}$ mo$^{-1}$ for Revolution, and 1.6 L ha$^{-1}$ mo$^{-1}$ for TE. All treatments were applied in 407 L ha$^{-1}$ of water using a calibrated CO$_2$ backpack sprayer (Bellspray) with a single flat-fan nozzle operated at 241 kPa. Applications were split in half and made in two directions (perpendicular to one another) to assure uniform distribution of the chemicals. Revolution was watered in as part of regular irrigation on the SDI system. Therefore, there was no difference in water applied between the two irrigation systems.

Roots were collected following a procedure similar to that described by Serena, Leinauer, Schiavon, Maier, and Sallenave (2014). Two 53-mm-diam. cores were collected from the center of each plot using a split tube sampler (Eijkelkamp) at the end of each growing season (first week of November). Each sample was separated into four layers (0–5, 5–10, 10–20, and 20–40 cm) and stored at 4°C until further processing. The samples were subsequently washed with a water centrifuge to separate the soil from the roots, then transferred to an ethanol solution (18% v/v) and stored at 4°C. This was followed by additional hand cleaning of each sample to remove any remaining extraneous material such as leaves and pebbles from the samples. Stolons and rhizomes in the samples were separated from the roots, oven dried for 16 h at 105°C, and weighed. Rooting characteristics of composite samples from depths of 0–10 cm and 10–40 cm were analyzed using WinRhizo software (Regent Instrument Canada). After scanning, roots were oven dried for 16 h at 105°C, and weights were recorded. Root weight density (RWD, g cm$^{-3}$) and RLD was calculated by dividing the value (length or weight) by the volume of the sample. This report focuses on RWD (g cm$^{-3}$), RLD (cm cm$^{-3}$), and average RD (mm).

Toro Turf Guard sensors (The Toro Company) were placed in the center of each whole plot, into an area that did not receive any chemical treatment. Volumetric water content at 5- and at 18-cm soil depths were collected every 7 min and averaged over 1 d and over the three replicates (Serena, Leinauer, Sallenave, Schiavon, & Maier, 2012; Sevostianova, Deb, Serena, VanLeeuwen, & Leinauer, 2015).

Turfgrass data were collected bimonthly, 1 and 3 wk after chemical applications. Visual quality was determined on a scale of 1 (worst) to 9 (best) (Krans & Morris, 2007; Leinauer, VanLeeuwen, Serena, Schiavon, & Sevostianova, 2014). Digital image analysis was used to estimate percentage of green turf cover (Richardson, Karcher, & Purcell, 2001). The values for turfgrass quality and green turf cover were subsequently averaged for every month. Turfgrass quality and percentage turf cover for 2012 have already been published by Schiavon et al. (2014), and similar results were determined for 2013. Therefore, these performance parameters are not presented or discussed in detail. However, to explore the relationship between morphological traits and turf quality and percentage turf cover, correlations among stolon and rhizome biomass, RD, RLD, RWD, and monthly turf quality and turf cover from

### TABLE 1 Monthly average air temperatures, precipitation, and reference evapotranspiration for short grass (ET$_{0,s}$) for Las Cruces, NM, historical average (1981–2010) (https://www.noaa.gov/) and for Las Cruces during January 2012 to December 2013

| Parameter | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|-----------|------|------|------|------|-----|------|------|------|-------|------|------|------|
| Avg. air temp. (°C) |     |      |      |      |     |      |      |      |       |      |      |      |
| Historical | 4.0  | 6.3  | 9.7  | 14.4 | 19.5| 24.2 | 26.2 | 25.1 | 21.8  | 15.4 | 8.1  | 3.8 |
| 2012      | 8.0  | 9.3  | 13.9 | 20.2 | 23.3| 29.6 | 27.5 | 28.6 | 23.6  | 19.2 | 13.2 | 7.4 |
| 2013      | 4.8  | 7.7  | 15.1 | 18.8 | 22.9| 29.8 | 26.9 | 27.4 | 24.0  | 17.3 | 11.3 | 6.5 |
| Precipitation (mm) |     |      |      |      |     |      |      |      |       |      |      |      |
| Historical | 13   | 10   | 6    | 7    | 10  | 17   | 39   | 56   | 34    | 24   | 12   | 20  |
| 2012      | 20   | 1    | 0    | 0    | 16  | 1    | 28   | 8    | 45    | 0    | 0    | 3   |
| 2013      | 3    | 2    | 0    | 0    | 16  | 5    | 36   | 24   | 45    | 0    | 5    | 4   |
| ET$_{0,s}$ (mm) |     |      |      |      |     |      |      |      |       |      |      |      |
| Historical | 55   | 78   | 126  | 168  | 197 | 190  | 173  | 142  | 137   | 110  | 69   | 55  |
| 2012      | 63   | 73   | 124  | 159  | 194 | 226  | 192  | 188  | 143   | 117  | 76   | 53  |
| 2013      | 67   | 89   | 157  | 197  | 232 | 264  | 209  | 205  | 162   | 127  | 75   | 50  |
**TABLE 2** Soil analysis results at two depths (0–10 cm and 10–20 cm) of plots irrigated with potable (0.62 dS m$^{-1}$) or saline (2.33 dS m$^{-1}$) water irrigated with sprinkler or subsurface drip

| Month   | Depth | Potable sprinkler | Potable drip | Saline sprinkler | Saline drip |
|---------|-------|-------------------|--------------|------------------|-------------|
|         |       | EC$^a$ (dS m$^{-1}$) | SAR$^b$ (cmol kg$^{-1}$) | Na (cmol kg$^{-1}$) | EC$^a$ (dS m$^{-1}$) | SAR$^b$ (cmol kg$^{-1}$) | Na (cmol kg$^{-1}$) | EC (dS m$^{-1}$) | SAR$^b$ (cmol kg$^{-1}$) | Na (cmol kg$^{-1}$) |
| Mar. 2012 | 0–10  | 0.35              | 0.44         | 1.07             | 0.47         | 0.76         | 1.41         | 1.55         | 1.28         | 2.80             | 0.77         | 2.59         | 3.11         |
|          | 10–20 | 0.41              | 0.54         | 1.18             | 0.46         | 1.44         | 1.56         | 0.83         | 1.60         | 2.55             | 0.84         | 4.13         | 1.11         |
| June 2012 | 0–10  | 1.26              | 1.73         | 3.21             | 1.59         | 3.43         | 5.76         | 3.20         | 5.89         | 14.77            | 3.88         | 4.40         | 14.55        |
|          | 10–20 | 0.99              | 1.94         | 3.00             | 1.02         | 0.90         | 1.64         | 3.13         | 5.79         | 15.00            | 1.28         | 2.68         | 4.63         |
| Nov. 2012 | 0–10  | 1.74              | 2.05         | 4.65             | 1.56         | 1.93         | 3.91         | 4.01         | 5.30         | 16.66            | 7.04         | 6.41         | 29.54        |
|          | 10–20 | 1.52              | 2.73         | 5.26             | 0.74         | 1.84         | 2.43         | 2.67         | 6.58         | 13.54            | 3.95         | 5.47         | 16.94        |
| Mar. 2013 | 0–10  | 0.67              | 1.81         | 2.67             | 0.69         | 1.70         | 2.57         | 0.87         | 1.35         | 2.49             | 3.09         | 5.07         | 14.80        |
|          | 10–20 | 0.64              | 1.34         | 2.12             | 3.48         | 3.83         | 12.76        | 2.28         | 3.22         | 8.61             | 1.63         | 4.98         | 9.54         |
| June 2013 | 0–10  | 0.69              | 2.17         | 2.32             | 1.73         | 4.71         | 8.07         | 1.34         | 3.30         | 5.89             | 3.64         | 6.03         | 18.46        |
|          | 10–20 | 0.76              | 1.59         | 2.19             | 1.60         | 4.29         | 7.48         | 1.45         | 2.95         | 5.46             | 3.74         | 7.33         | 21.46        |
| Nov. 2013 | 0–10  | 1.57              | 1.36         | 3.01             | 2.04         | 1.74         | 4.61         | 4.63         | 5.40         | 18.74            | 6.04         | 7.29         | 30.09        |
|          | 10–20 | 1.15              | 2.46         | 4.26             | 0.49         | 1.08         | 1.54         | 7.22         | 11.18        | 44.17            | 3.66         | 7.66         | 20.89        |

$^a$EC, electrical conductivity.

$^b$SAR, sodium adsorption ratio.

June to October were computed, and if a significant correlation was detected, the corresponding coefficient of determination values ($r$) are reported.

The experimental design was a randomized complete block, with the combination of irrigation system and water quality as whole plots (12 × 6 m), and grass species (6 × 6 m), chemicals (2 × 2 m), and sampling year as split-plot treatments. All treatments were replicated three times. Statistical analyses were performed using SAS proc mixed (version 9.3, SAS Institute). Data were subjected to ANOVA followed by multiple comparisons of means using Fisher’s protected LSD test at the 0.05 probability level.

3 | RESULTS

Initial data analyses revealed that water quality did not affect stolon and rhizome biomass, or any of the measured root variables, despite the differences in soil salinity during the course of the study (Table 2). Therefore, all data were averaged over water quality. Moreover, root data were analyzed separately for the two soil depths, 0–10 cm and 10–40 cm, which correspond to soil layers above (0–10 cm) and below (10–40 cm) the drip line.

3.1 | Stolons and rhizomes

The ANOVA revealed that the type of irrigation system and the sampling year had a significant effect on stolon and rhizome biomass (Table 3). Rhizome but not stolon biomass also differed between grass species (Table 3).

3.2 | Root diameter, root length density, and root weight density

Our analysis focuses on the results of the RD, RWD, and RLD measurements. The ANOVA revealed that the interaction between irrigation systems, chemicals, and year had a

**TABLE 3** Results of ANOVA testing the effects of irrigation system, grass species, chemical treatment, sampling year, and their interactions on stolon and rhizome biomass. Interactions that were not significant are not presented

| Effect     | Stolons | Rhizomes |
|------------|---------|----------|
| Irrigation | *       | *        |
| Species    | NS$^a$  | **       |
| Treatment  | NS      | NS       |
| Year       | ***     | *        |

$^a$NS, not significant at the .05 $P$ level.

*Significant at the .05 probability level.

**Significant at the .01 probability level.

***Significant at the .001 probability level.
significant effect on RD and RLD at both soil depths and on RWD at 0–10-cm depths (Table 4). There was also a significant grass × chemical interaction effect on RD at both soil depths.

Data for RD, RLD, and RWD were averaged over both grasses and are presented separately for each sampling year. Furthermore, RD was averaged over irrigation systems and sampling years, and means are presented for each grass and chemical treatment.

### 3.2.1 Root diameter

With the exception of species receiving Revolution on sprinkler-irrigated plots, chemical treatments had no effect on RD at either depth in 2012, regardless of irrigation system (Figure 1). In 2013, average RD was smallest at 0- to 10-cm depths in plots that were sprinkler-irrigated and treated with TE (0.29 mm), followed by sprinkler-irrigated grasses treated with Revolution (0.33 mm). Average RDs were greatest in untreated grasses, reaching 0.36 mm in length (Figure 1). Chemical treatments also affected roots of sprinkler irrigated grasses at depths of 10–40 cm. Root diameters of the untreated control plots reached 0.39 mm, whereas mean RDs of grasses treated with TE or Revolution were 0.29 and 0.28 mm, respectively (Figure 1). As observed in 2012, chemical treatments had no effect on average RD at either depth when grasses were drip irrigated (Figure 1).

When data were averaged over both sampling years and irrigation systems, RD was greatest in untreated seashore paspalum at both soil depths averaging 0.36 mm at 0–10-cm depths and 0.37 mm at 10–40-cm depths (Figure 2). When compared with the untreated control plots, both TE and surfactant-treated seashore paspalum had significantly smaller RDs at both depths. Trinexapac-ethyl only affected bermudagrass RD at 0–10-cm depths, and the surfactant had no impact on RD at either depth (Figure 2).

### 3.2.2 Root weight density

The ANOVA of RWD revealed differences only at depths of 0–10 cm (Table 3). Chemical treatments significantly affected RWD of species under both irrigation systems in 2013 (Figure 3). When 2012 data were averaged over chemical treatments, RWD of sprinkler- and drip-irrigated species reached 1.9 and 2.0 g cm$^{-3}$, respectively. In 2013, RWD was higher in SDI-irrigated controls (3.5 g cm$^{-3}$) and TE-treated plots (4.8 g cm$^{-3}$) than in their sprinkler-irrigated counterparts (2.2 and 2.9 g cm$^{-3}$) (Figure 3). Revolution did not affect RWD for either irrigation type (Figure 3). Overall, RWD at 10–40-cm depths was greater on SDI plots (1.1 g cm$^{-3}$) than on sprinkler-irrigated plots (0.9 g cm$^{-3}$).

### 3.2.3 Root length density

Root length density at 0- to 10-cm depths did not differ between irrigation systems for the control or the chemical treatments in 2012 (Figure 4). The greatest RLD was observed on plots treated with TE and irrigated with SDI (10.7 cm cm$^{-3}$) or sprinklers (9.2 cm cm$^{-3}$). In 2013, RLD was again highest in plots treated with TE, with higher mean values on SDI plots (20.4 cm cm$^{-3}$) than on sprinkler plots (17.0 cm cm$^{-3}$) (Figure 4). The SDI-irrigated control plots also had greater RLD (15.1 cm cm$^{-3}$) than sprinkler-irrigated control
plots (8.3 cm cm$^{-3}$). Revolution affected RLD differently than TE. Sprinkler irrigation in combination with Revolution resulted in greater RLD (13.7 cm cm$^{-3}$) than SDI combined with Revolution (11.1) (Figure 4).

In 2012, chemical effects on RLD at soil depths of 10–40 cm did not differ between irrigation systems (Figure 4). Turfgrasses treated with TE had the highest RLD (4.9 cm cm$^{-3}$), which was greater than on control plots (2.9 cm cm$^{-3}$).

In 2013, RLD was highest on untreated and TE-treated plots irrigated by SDI, with average densities of 7.2 and 7.5 cm cm$^{-3}$, respectively. Root length densities were lower on SDI-irrigated plots treated with Revolution, averaging 6.5 cm cm$^{-3}$ (Figure 4). The lowest RLD was found on untreated sprinkler irrigated plots (4.9 cm cm$^{-3}$) (Figure 4).

### 3.2.4 Correlation analysis

Stolon dry weight and RLD and RWD at both depths were significantly correlated with visual quality in August and September, and with percentage green turf cover in July, August, and September. Correlation coefficients were highest between stolon dry weight and turfgrass quality (0.54) and between RLD (0–10-cm depth) and visual quality (0.50) in August (Table 5). Root length density also correlated significantly with visual quality in October (0.36). Root weight density at both depths was significantly correlated with visual quality in August and September and with percentage green turf cover in July, August, and September (Table 5). Rhizome production only correlated with turfgrass quality in October.
and had no relationship with percentage green turf cover (Table 5). There was no significant correlation between RD at 0–10-cm depths and visual quality or percentage green turf cover. Root diameter at 10–40-cm depths only showed a significant relationship with turfgrass quality in August (0.33) and with percentage green turf cover in July (0.32) (Table 5).

4 | DISCUSSION

Soil moisture readings were generally higher during summer 2013 compared with 2012 (Figure 5). These differences are due to higher precipitation rates during June to August (Table 1) and to more intense (i.e., greater volume) rainfall events in July, August, and September of 2013 (Figure 5). Moreover, drip-irrigated plots maintained a higher soil moisture at both depths particularly from July to September in 2013, despite equal irrigation and rainfall amounts (Figure 5).

The salt content of the brackish irrigation water was not high enough in soil chemical constituents such as EC, SAR, or Na compared with potable water to affect stolon or rhizome biomass or root architecture (Table 2). The salinity tolerance mechanisms of warm-season bermudagrass and seashore paspalum appeared to cope with the higher soil salinity of plots irrigated with brackish water, resulting in no differences in stolon or rhizome weight or in root measurements between water qualities.

Subsurface drip irrigation had a positive effect on both stolon and rhizome biomass. The greater stolon weight was associated with greater green turfgrass coverage and quality during the summer months (Table 5) and can be most likely attributed to greater soil moisture content (Figure 5). These findings are supported in part by Zhou et al. (2014), who documented a relationship between drought avoidance and rhizome biomass, but not with stolon production on 18 different bermudagrass genotypes. Furthermore, we found higher rhizome biomass in ‘Sea Spray’ seashore paspalum compared with ‘Princess 77’ bermudagrass. These findings are corroborated by Rimi, Macolino, Richardson, Karcher, and Leinauer (2013), who also documented a difference in rhizome but not stolon production between the two species. Lulli et al. (2011) found that seashore paspalum had larger leaves and rhizomes than bermudagrass and zoysiagrass. However, these differences did not affect tensile strength of bermudagrass or seashore paspalum. Our findings show that the differences in rhizome biomass had no effect on green turfgrass cover and little effect on quality. There was no correlation between rhizome biomass and green turfgrass cover and rhizome biomass correlated only with turfgrass quality in October, towards the end of the growing period (Table 5).

Revolution and TE had no effect on stolon or rhizome development during either year of the study. Richardson (2002) also reported that TE applications had no effect on stolon and rhizome dry weight of bermudagrass, but only in the first year of establishment. During the second year, rhizome weight and stolon density were enhanced after TE applications. McCullough, Liu, McCarty, Whitwell, and Toler (2006) also reported a 5% increase in stolon and rhizome weight of TE-treated ultradwarf bermudagrass during the
summer. These findings highlight not only possible species and cultivar differences in rhizome and stolon production but also a difference in TE efficacy between grasses. To our knowledge, no previous research has reported effects of soil surfactants on stolon and rhizome development in turfgrass.

Generally, untreated drip-irrigated control plots showed better drought avoidance characteristics in 2013 than their sprinkler-irrigated counterparts. Root diameter was smaller at 10–40-cm depths, RLD was greater at both depths, and RWD was greater at 0–10-cm depths. Sprinkler irrigation can be affected by wind drift and evaporative losses, reducing the amount of water reaching the root zone when compared with SDI. On turf areas that are irrigated from the subsurface, such losses are avoided, as water is applied directly to the root zone, resulting in higher soil moisture readings and more water available to the plant. Consequently, such improved moisture conditions resulted in better turfgrass performance, which has been reported by other authors (Schiavon, Leinauer, Sevostianova, Serena, & Maier, 2011, 2014; Sevostianova et al., 2011a,b).

Generally, no differences in drought avoidance mechanisms were observed in 2012, during which soil moisture readings at 5 cm were only somewhat higher on drip-irrigated plots during July and August (Figure 5). These soil moisture differences may not have been large enough and long enough to result in improved rooting and drought avoidance; however, they did result in increased quality and green turf cover on plots irrigated with potable water from a drip
system (Schiavon et al., 2014). In 2013, our results show greater turf quality and greater percentage green turf cover on plots irrigated with SDI (data not presented), but also improved drought avoidance characteristics. Grasses on control plots irrigated from a sprinkler system had thicker roots at 10–40-cm depth and lower RLD and RWD throughout the entire measured root zone when compared with SDI plots. Our data support the findings of Zhou et al. (2014), who reported that plants respond to drought with modified root morphology such as increased RD and decreased RLD and RWD. Moreover, our results documented a positive relationship between turfgrass quality and root parameters (Table 5). These findings are corroborated in part by Rimi, Macolino, and Ziliotto (2012), who also found a positive correlation between quality and RLD or RWD of several warm-season turfgrasses at a depth of 25–40 cm.

Trinexapac-ethyl affected root architecture and drought avoidance, particularly on sprinkler-irrigated grasses. Monthly applications of TE in 2013 resulted in thinner roots and higher RLD at all depths and higher RWD at the 0–10-cm depth. Our findings support those of McCullough et al. (2005), who found that root masses of MiniVerde and FloraDwarf cultivars of bermudagrass were enhanced by TE application. However, our findings differ from those of Fagerness and Yelverton (2001), who reported no difference in root biomass between TE-treated and untreated creeping bentgrass.
TABLE 5 Coefficients of determination (r) for the relationship between morphological traits (stolons and rhizomes biomass and root parameters at depths of 0–10 cm and 10–40 cm) and visual turgrass quality or green turf coverage from June to October

| Parameter             | Depth   | Turfgrass quality       |               |               |               | Green turfgrass coverage       |               |               |               |               |               |
|-----------------------|---------|-------------------------|---------------|---------------|---------------|-------------------------|---------------|---------------|---------------|---------------|---------------|
|                       |         | June | July | Aug. | Sept. | Oct. | June | July | Aug. | Sept. | Oct. | June | July | Aug. | Sept. | Oct. |
| Stolons               |         | NS   | NS   | .54*** | .43*** | NS   | NS   | .37*** | .42*** | .40** | NS   | NS   | NS   | NS   | NS   | NS   |
| Rhizomes              |         | NS   | NS   | NS   | NS   | .42*** | NS   | NS   | NS   | NS   | NS   | NS   | NS   | NS   | NS   | NS   |
| Root diameter 0–10 cm | NS      | NS   | NS   | NS   | NS   | NS   | NS   | .32*  | NS   | NS   | NS   | NS   | NS   | NS   | NS   | NS   |
|                       | 10–40 cm| NS   | NS   | .33*  | NS   | NS   | NS   | .32*  | NS   | NS   | NS   | NS   | NS   | NS   | NS   | NS   |
| Root length density   | 0–10 cm | NS   | NS   | .50*** | .46*** | .36*  | NS   | .35*  | .36*** | .40** | NS   | NS   | NS   | NS   | NS   | NS   |
|                       | 10–40 cm| NS   | NS   | .43*** | .46*** | .36*  | NS   | .33*  | .33*  | .32*  | NS   | NS   | NS   | NS   | NS   | NS   |
| Root weight density   | 0–10 cm | NS   | NS   | .42*** | .42*** | NS   | NS   | .35*  | .34*  | .38** | NS   | NS   | NS   | NS   | NS   | NS   |
|                       | 10–40 cm| NS   | .32*  | .45*** | .39**  | NS   | .35*  | .42*** | .38** | NS   | NS   | NS   | NS   | NS   | NS   | NS   |

*NS, not significant at the .05 P level.
**Significant at the .05 probability level.
***Significant at the .01 probability level.

Trinexapac-ethyl also affected root architecture on drip-irrigated grasses, but only at a depth of 0–10 cm. Root length density and RWD were highest for TE treated drip-irrigated grasses. It remains unclear why positive effects of TE did not extend to the deeper profiles. Such findings may indicate that sprinkler irrigation is necessary to extend the benefits of TE on rooting into deeper profiles.

Similar to TE, Revolution had a positive impact on root architecture and drought avoidance in sprinkler-irrigated grasses in 2013. When compared with the untreated controls, plots receiving Revolution had thinner roots, greater RWD at 0–10 cm, and greater RLD at all depths. Karnok and Tucker (2001) demonstrated increased rooting on cool-season creeping bentgrass (Agrostis palustris Huds.) when treated with a surfactant, but no published reports are available on the effects of soil surfactants on root architecture of warm-season turfgrasses.

The surfactant was not effective in improving drought avoidance on SDI plots. When compared with the control plots, Revolution either had no effect (RD at 0–10 cm and at 10–40 cm depths) or reduced root growth (RLD at 0–10 cm and 10–40 cm depths; RWD at 0–10 cm depths). This highlights the importance of watering in a surfactant after application, which cannot be accomplished on a turfgrass area that has SDI installed as the only irrigation system.

Moreover, nontreated seashore paspalum irrigated with potable water had the highest RWD at the depth of 10–40 cm, compared with potable irrigated bermudagrass and saline irrigated bermudagrass and seashore paspalum. Interestingly, at 10–40 cm depths, there appeared to be no difference in RWD between TE or surfactant treated turfgrasses (Figure 3). This would suggest that analyzing for only one parameter (RWD) may not be sufficient to detect treatment effects or document changes resulting from treatment applications.
Improved drought avoidance as affected by increased rooting might be better explained if more than one rooting parameter is measured.

5 | CONCLUSIONS

Our study documented that drought avoidance and green turfgrass cover and quality were enhanced on deficit-irrigated warm-season turfgrasses when SDI, TE, or Revolution were used. Any one of these management strategies can be considered an effective water conservation strategy. Our results support earlier findings on the use of SDI as part of water conservation efforts; however, to the best of our knowledge, our results are the first to document the effects of TE or surfactants on turfgrass drought avoidance of warm-season grasses. All previous research was conducted on cool-season grasses under sufficient irrigation (e.g., Beasley et al., 2005). Generally, the applications of TE and/or Revolution resulted in greater RLD, greater RWD, and thinner roots, particularly in 2013 and on plots irrigated from a sprinkler system. These effects can be all considered as indicators of a healthier turf stand. Additional research is needed to investigate if tank mixing both chemicals would produce a synergistic effect, improving rooting to a greater degree than when each product is applied separately. Serena et al. (2018) documented that tank mixing Revolution and TE resulted in greater turf quality and green turf cover of bermudagrass than applying the products alone, but rooting and physiological data were not investigated. More research is also needed to explore the efficacy of TE in combination with reduced irrigation on stolon or rhizome production. Richardson (2002) and McCullough et al. (2006) documented increased stolon and rhizome production on well-irrigated established bermudagrass after the application of TE. However, our findings were different, as we did not establish a positive effect of TE on stolon or rhizome production on drought-stressed warm-season grasses.

Moreover, the financial implications of using these products need to be considered. Rigorous water restrictions are in effect for turf areas in many communities, but the available budget may preclude the use of such products. Turf managers with a limited budget might want to consider installing SDI rather than monthly applications of surfactants or PGRs to enhance drought avoidance mechanisms in turf stands. Although initial upfront costs may be higher, overall costs in the long term may be less than the cost of monthly applications of chemical products, although no direct cost comparisons have been done. If it comes down to a choice between SDI or monthly chemical applications, SDI appears to have a greater effect on drought avoidance than either TE or the surfactant. In fact, adding chemical treatments to an SDI-irrigated field only had modest additional benefits.

ACKNOWLEDGMENTS

Support of the study was provided by the New Mexico State University’s Agricultural Experiment Station, by Aquatrols Corp., Seeds West Inc., Southwest Turfgrass Association, Syngenta AG, The Toro Co., and United States Golf Association. The authors are further grateful for the donations from Helena Chemical Company and for the help of Karl Olson and Jon Kimmel, golf course superintendents at New Mexico State University’s golf course.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

REFERENCES

Bañuelos, J. B., Walworth, J. L., Brown, P., & Kopec, D. M. (2011). Deficit irrigation of seashore paspalum and bermudagrass. Agronomy Journal, 103, 1567–1577. https://doi.org/10.2134/agronj2011.0127
Beasley, J. S., Branham, B. E., & Ortiz-Ribbing, L. M. (2005). Trinexapac-ethyl affects Kentucky bluegrass root architecture. HortScience, 40, 1539–1542. https://doi.org/10.21273/HORTSCI.40.5.1539
Carrow, R. N. (1996). Drought resistance aspects of turfgrasses in the Southeast: Root-shoot responses. Crop Science, 36, 687–694. https://doi.org/10.2135/cropsci1996.0011183x003600030028x
California Department of Water Resources. (2009). California Code of Regulations, Title 23. Waters, Division 2. Ch. 2.7. Model water efficient landscape ordinance. California Dep. Water Resour. Retrieved from http://www.water.ca.gov/wateruseefficiency/docs/MWELO09-10-09.pdf (accessed 10 Feb. 2019).
Cisar, J. L., Willimas, K. E., Vicas, H. E., & Haydu, J. J. (2000). The occurrence and alleviation by surfactants of soil-water repellency on sand-based turfgrass systems. Journal of Hydrology, 231–232, 352–358. https://doi.org/10.1016/S0022-1694(00)00207-9
Cooper, R. J., Henderlong, P. R., Street, J. R., & Karnok, K. J. (1987). Root growth, seedhead production, and quality of annual bluegrass as affected by mefluidide and a wetting agent. Agronomy Journal, 79, 929–934. https://doi.org/10.2134/agronj1987.00021962007900050035x
Devitt, D. A., & Norris, R. L. (2008). Urban landscape water conservation and the species effect. In J. B. Beard & M. P. Kenna (Eds.), Water quality and quantity issues for turfgrasses in urban landscapes (pp. 171–192). Ames, IA: Counc. Agric. Sci. Technol
Duncan, R. R., & Carrow, R. N. (2000). Seashore paspalum: The environmental turfgrass. Chelsea, MI: John Wiley & Sons.
Duncan, R. R., Carrow, R. N., & Huck, M. T. (2009). Turfgrass and landscape irrigation water quality: Assessment and management. Boca Raton, FL: CRC Press.
Emmons, D. R. (2000). Turfgrass science and management (3rd ed). Albany, NY: Delmar Thompson Learning.
Fagerness, M. J., & Yelverton, F. H. (2001). Plant growth regulator and mowing height effects on seasonal root growth of Penncross creeping bentgrass. Crop Science, 41, 1901–1905. https://doi.org/10.2135/cropsci2001.1901
Fry, J., & Jiang, H. (1998). Plant growth regulators may help reduce water use: Greenhouse research hints that some PGRs can reduce
irrigation needs of perennial ryegrass in cool and transition regions. *Golf Course Manage.*, 66, 58–61.

Fry, J., & Huang, B. (2004). Plant growth regulators and biostimulants. In *Applied turfgrass science and physiology* (pp. 277–298). Hoboken, NJ: John Wiley & Sons.

Feldhake, C. M., Danielson, R. E., & Butler, J. D. (1984). Turfgrass evapotranspiration. 11. Responses to deficit irrigation. *Agronomy Journal*, 76, 85–89. https://doi.org/10.2134/agronj1984.00021962007600010022x

Ganjegunte, G., Leinauer, B., Schiavon, M., & Serena, M. (2013). Using electro-magnetic induction to determine soil salinity and sodicity in turf root zones. *Agronomy Journal*, 105, 836–844. https://doi.org/10.2134/agronj2012.0503

Ganjegunte, G. K., Clark, J. A., Sallenave, R., Sevostianova, E., Serena, M., Alvarez, G., & Leinauer, B. (2017). Soil salinity of an urban park after long-term irrigation with saline ground water. *Agronomy Journal*, 109, 3001–3018. https://doi.org/10.2134/agronj2017.06.0369

Hays, K. L., Barber, J. F., Kenna, M. P., & McCollum, T. G. (1991). Drought avoidance mechanisms of selected bermudagrass genotypes. *HortScience*, 26, 180–182. https://doi.org/10.21273/HORTSCI.26.2.180

Huang, B., Duncan, R. R., & Carrow, R. N. (1997). Drought-resistance mechanisms of seven warm-season turfgrasses under surface soil drying: II. Root aspects. *Crop Science*, 37, 1863–1869. https://doi.org/10.2135/cropsici1997.0011183X003700060033x

Huck, M., Carrow, R. N., & Duncan, R. R. (2000). Effluent water: Nightmare or dream come true? *USGA Green Section Record*, 38, 15–29.

Karnok, K. J., & Tucker, K. A. (2001). Wetting agent treated hydrophobic soil and its effect on color, quality and root growth of creeping bentgrass. *International Turfgrass Society Research Journal*, 9, 537–541.

Karnok, K. J., Xia, K., & Tucker, K. A. (2004). Wetting agents: What are they, and how do they work. *Golf Course Management*, 72, 84–86.

King, R. W., Gocal, G. F. W., & Heide, O. M. (1997). Regulation of leaf growth and flowering of cool season turfgrasses. *Proceedings of International Turfgrass Research Conference*, 8, 565–573.

Kjelgren, R., Rupp, L., & Kilgren, D. (2000). Water conservation in urban landscapes. *HortScience*, 35, 1037–1040. https://doi.org/10.21273/HORTSCI.35.6.1037

Kostka, S. J., & Bially, P. T. (2005). Synergistic surfactant interactions for enhancement of hydrophilicity in water repellent soils. *International Turfgrass Society Research Journal*, 10, 108–114.

Krans, J. V., & Morris, K. (2007). Determining a profile of protocols and standards used in the visual field assessment of turfgrasses: A survey of national turfgrass evaluation program-sponsored university scientists. *Applied Turfgrass Science*, 4(1). https://doi.org/10.1094/ATS-2007-1130-01-TT

Leinauer, B., & Devitt, D. A. (2014). Irrigation science and technology. In J. C. Stier et al. (Eds.), *Turfgrass: Biology, use, and management*, *Agronomy Monographs* (Vol. 56, pp. 1075–1131). Madison, WI: ASA, CSSA, and SSSA. https://doi.org/10.2134/agronomymonogr56.c28

Leinauer, B., VanLeeuwen, D. M., Serena, M., Schiavon, M., & Sevostianova, E. (2014). Digital image analysis and spectral reflectance to determine turfgrass quality. *Agronomy Journal*, 106, 1787–1794. https://doi.org/10.2134/agronj214.0088

Lulli, F., Guglielminetti, L., Grossi, N., Armeni, R., Stefanini, S., & Volterrani, M. (2011). Physiological and morphological factors influencing leaf, rhizome and stolon tensile strength in C₄ turfgrass species. *Functional Plant Biology*, 38, 919–926. https://doi.org/10.1071/FP11070

Magesan, G. N. (2001). Changes in soil physical properties after irrigation of two forested soils with municipal wastewater. *New Zealand Journal of Forestry Science*, 31, 188–195.

Marcum, J. B., & Jiang, H. (1997). Effects of plant growth regulators on tall fescue rooting and water use. *Journal of Turfgrass Management*, 2, 13–27. https://doi.org/10.1301/009v02n02_02

McCarty, L. B., Willis, T. G., Toler, J. E., & Whitwell, T. (2011). ‘TifEagle’ bermudagrass response to plant growth regulators and mowing height. *Agronomy Journal*, 103, 988–994. https://doi.org/10.2134/agronj2010.0467

McCullough, P. E., Liu, H., & McCarty, L. B. (2005). Response of six dwarf-type bermudagrasses to trinexapac-ethyl. *HortScience*, 40, 460–462. https://doi.org/10.21273/HORTSCI.40.2.460

McCullough, P. E., Liu, H., McCarty, L. B., Whitwell, T., & Toler, J. E. (2006). Bermudagrass putting green growth, color, and nutrient partitioning influenced by nitrogen and trinexapac-ethyl. *Crop Science*, 46, 1515–1525. https://doi.org/10.2135/cropsci2005.08.0286

NOAA. (2019). Data tools: 1981–2010 normals. NOAA. Retrieved from https://www.ncdc.noaa.gov/cdo-web/datatools.normals (accessed 15 July 2019)

Qian, Y. L., Fry, J. D., & Upham, W. S. (1997). Rooting and drought avoidance of warm-season turfgrasses and tall fescue in Kansas. *Crop Science*, 37, 905–910. https://doi.org/10.2135/cropsici1997.0011183X003700030034x

Richardson, M. D. (2002). Turf quality and freezing tolerance of ‘Tifway’ bermudagrass as affected by late-season nitrogen and trinexapac-ethyl. *Crop Science*, 42, 1621–1626. https://doi.org/10.2135/cropsci2002.1621

Richardson, M. D., Karcher, D. E., & Purcell, L. C. (2001). Quantifying turfgrass cover using digital image analysis. *Crop Science*, 41, 1884–1888. https://doi.org/10.2135/cropsci2001.1884

Rimi, F., Macolino, S., Richardson, M. D., Karcher, D. E., & Leinauer, B. (2013). Influence of three nitrogen fertilization schedules on bermudagrass and seashore paspalum: II. Carbohydrates and crude protein in stolons. *Crop Science*, 53, 1168–1178. https://doi.org/10.2135/cropsci2012.09.0564

Rimi, F., Macolino, S., & Ziliozio, U. (2012). Rooting characteristics and turfgrass quality of three bermudagrass cultivars and a zoysiagrass. *Acta Agriculturae Scandinavica, Section B – Soil & Plant Science*, 62, 24–31. https://doi.org/10.1080/09064710.2012.673009

Salaiz, T. A., Shearman, R. C., Riordan, T. P., & Kinbacher, E. J. (1991). Creeping bentgrass cultivars water use and rooting responses. *Crop Science*, 31, 1331–1334. https://doi.org/10.2135/cropsici1991.0011183X003100050050x

Schiavon, M., Leinauer, B., Serena, M., Maier, B., & Sallenave, R. (2014). Plant growth regulator and soil surfactants’ effects on saline and deficit irrigated warm-season grasses: I. Turf quality and soil moisture. *Crop Science*, 54, 1–12. https://doi.org/10.2135/cropsci2013.10.0707

Schiavon, M., Leinauer, B., Serena, M., Sallenave, R., & Maier, B. (2012). Bermudagrass and seashore paspalum establishment from seed using different irrigation methods and water qualities. *Agronomy Journal*, 104, 706–714. https://doi.org/10.2134/agronj2011.0390

Schiavon, M., Leinauer, B., Serena, M., Sallenave, R., & Maier, B. (2013). Establishing tall fescue and Kentucky bluegrass using subsurface irrigation and saline water. *Agronomy Journal*, 105, 183–190. https://doi.org/10.2134/agronj2012.0187
Schiavon, M., Leinauer, B., Sevostianova, E., Serena, M., & Maier, B. (2011). Warm season turfgrass quality, spring green-up and fall color retention under drip irrigation. *Applied Turfgrass Science, 8*(1). https://doi.org/10.1094/ATS-2011-0422-01-RS

Sheffer, K. M., Dunn, J. H., & Minner, D. D. (1987). Summer drought response and rooting depth of three cool-season turfgrasses. *HortScience, 22*, 296–297.

Serena, M., Leinauer, B., Sallenave, R., Schiavon, M., & Maier, B. (2012). Turfgrass establishment from polymer coated seed under saline irrigation. *HortScience, 47*, 1789–1794. https://doi.org/10.21273/HORTSCIC.74.12.1789

Serena, M., Leinauer, B., Schiavon, M., Maier, B., & Sallenave, R. (2014). Establishment and rooting responses of bermudagrass propagated with saline water and subsurface irrigation. *Crop Science, 54*, 827–836. https://doi.org/10.2135/cropsci2013.07.0512

Serena, M., Sportelli, M., Sevostianova, E., Sallenave, R., & Leinauer, B. (2018). Combining trinexapac-ethyl with a soil surfactant reduces bermudagrass irrigation requirements. *Agronomy Journal, 110*, 2180–2188. https://doi.org/10.2134/agronj2018.03.0148

Sevostianova, E., Deb, S., Serena, M., VanLeeuwen, D., & Leinauer, B. (2015). Accuracy of two electromagnetic soil water content sensors in saline soils. *Soil Science Society of America Journal, 79*, 1752–1759. https://doi.org/10.2136/sssaj2015.07.0271

Sevostianova, E., & Leinauer, B. (2014). Subsurface-applied tailored water: Combining nutrient benefits with efficient turfgrass irrigation. *Crop Science, 54*, 1926–1938. https://doi.org/10.2135/cropsci2014.01.0014

Sevostianova, E., Leinauer, B., Sallenave, R., Karcher, D. E., & Maier, B. (2011a). Soil salinity and quality of sprinkler and drip irrigated warm-season turfgrasses. *Agronomy Journal, 103*, 1503–1513. https://doi.org/10.2134/agronj2011.0162

Sevostianova, E., Leinauer, B., Sallenave, R., Karcher, D. E., & Maier, B. (2011b). Soil salinity and quality of sprinkler and drip irrigated warm-season turfgrasses. *Agronomy Journal, 103*, 1773–1784. https://doi.org/10.2134/agronj2011.0163

Snyder, R. L., & Eching, S. (2007). PMDay.xls spreadsheet software for estimating daily or hourly reference evapotranspiration using the Penman-Monteith equation. Davis: Univ. California. Retrieved from http://biomet.ucdavis.edu/evapotranspiration/PMdayXLS/PMday.htm (accessed 20 Mar. 2019).

Thompson, C. (2019). Subsurface drip irrigation reduces water use on tees. *US Golf Association Green Section*. Retrieved from http://archive.lib.msu.edu/tic/usgamisc/know/2019-08-02.pdf (accessed 10 Oct. 2019).

Zhou, Y., Lambrides, C. J., & Fukai, S. (2014). Drought resistance and soil water extraction of a perennial C4 grass: Contributions of root and rhizome traits. *Functional Plant Biology, 41*, 505–519. https://doi.org/10.1071/FP13249

---

**How to cite this article:** Serena M, Schiavon M, Sallenave R, Leinauer B. Drought avoidance of warm-season turfgrasses affected by irrigation system, soil surfactant revolution, and plant growth regulator trinexapac-ethyl. *Crop Science*. 2020;60:485–498. https://doi.org/10.1002/csc2.20063