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Hybrid Bermudagrass Responses to Impaired Water Sources

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***Abstract.* Low-quality (i.e., impaired) water sources are commonly used to irrigate warm-season turfgrass landscapes as a result of limited supplies of potable water sources. Currently, there is great need to define the impacts of impaired water sources on turfgrass water consumption, growth, and quality. The objectives of this study were to characterize actual evaporation (ET_a), clipping production, and quality of three hybrid bermudagrass varieties [‘TifTuf’, ‘Tifway’, and ‘Midiron’; *Cynodon dactylon* (L.) Pers. × *C. traansvalensis* Burtt Davy] grown under three water sources [reverse osmosis (RO), local well, and recycled], each supplied at full irrigation levels (1.0 × ET_a) over two 8-week study periods. When pooling across water source and date, TifTuf maintained the highest visual quality and normalized difference vegetation index (NDVI) compared with both Midiron and Tifway. This was accompanied by a greater daily ET_a rate, clipping production, and water use efficiency (WUE) compared with Midiron in both studies. When pooling across variety and date, daily ET_a of turfgrass receiving recycled water was 5% to 10% less than those receiving the local well or RO water. In addition, turfgrasses receiving local well water held the greatest visual quality and NDVI compared with those receiving either RO water in the summer study. Visual quality and NDVI were also less in turfgrasses receiving RO water compared with those receiving local well or recycled water in the fall. Despite turfgrasses having a lower ET_a under recycled water in both study periods, these plants had significantly greater clipping production compared with RO water in the summer. Also, clipping production under recycled water did not differ significantly from the other two sources in the fall study. Furthermoe, in both studies, WUE was similar for turfgrasses receiving recycled water compared with those receiving RO or local well water. Results demonstrated that irrigation water quality influences critical factors for hybrid bermudagrass growth and that considerable variability exists among three commercially available varieties for evapotranspiration rates, quality, and clipping production.**

Diminishing access to potable water sources is a growing concern throughout many regions in the United States. As such, nonpotable alternatives such as recycled (reclaimed) sources are being used to irrigate turfgrass landscapes (Leinauer et al. 2012a; Qian and Lin 2019). As of 2020, recycled water was listed as a major irrigation water source for golf course facilities in the southwestern and southeastern regions, comprising 33% and 28% of reported source, respectively (Shaddox et al. 2022). Although recycled water reduces reliance on potable water sources for turfgrass irrigation, recycled water is often of lower quality as a result of water quality parameters, including salinity, sodium, pH, and bicarbonates (Leinauer et al. 2012a; Marcum 2006). As such, the long-term impacts of its repeated use on soils must be considered. Furthermore, competing demands for recycled water coupled with demands for high-quality turfgrass require a greater understanding of how impaired irrigation sources affect turfgrass growth and quality.

Many chemical factors of irrigation water influence plant growth directly or indirectly, such as elevated salinity, pH, sodium, bicarbonate, and plant essential nutrients (Chang et al. 2020; Harivandi 2004; Porter and Marek 2006; Schiavon et al. 2015; Serba et al. 2022). Salinity is normally expressed as a measurement of electrical conductivity (EC), which is proportional to the concentration of dissolved ions in water or soil. Elevated salinity leads to plant osmotic stress and is expressed within turfgrass shoots and/or roots as diminished capacity to absorb and reallocate water (Marcum 2006). Although recycled water sources do not contain high salt levels inherently, the common use of water softeners in residential communities where recycled water originates can introduce increased levels of sodium and chloride (Tanji et al. 2015). An elevated sodium adsorption ratio (SAR) in soils irrigated with recycled water can also affect soil structure and bicarbonates negatively, because it can cause calcium and magnesium ions in the soil to be replaced with sodium (Marcum 2006). Results from multiple studies have shown that repeated use of recycled water as a turfgrass irrigation source resulted in a greater root zone EC, increased SAR, and increased sodium accumulation in leaf clippings (Lin and Qian 2019; Qian and Mecham 2005; Schuch et al. 2008). Mitigation strategies do exist, such as planting salt-tolerant species, enacting salt leaching, and sand-capping (Carrow et al. 2000; Duncan et al. 2009; Dyer et al. 2020; Hejl et al. 2022); however, the determination of best management strategies could be improved by inclusion of more research parameterizing the impact of water quality on turfgrass water use and quality.

In the US Southwest and Southeast, where climate is characterized as either hot, dry, or both, bermudagrass (*Cynodon* spp.) is an extensively used turfgrass species, resulting, in part, from its hardiness under hot-dry climatic conditions and improved salinity tolerance (Carrow 1996; Marcum and Pessarakli 2006; Serba et al. 2022). Overall, the average evapotranspiration (ET) rate for bermudagrass is 5.51 $mm \cdot d^{-1}$ (Colmer and Barton 2017); however, this value can fluctuate depending on environmental evaporative demand, management practice, soil water availability, and, potentially, chemical properties of irrigation sources (Hejl et al. 2015; Huang and Fry 1999; Romero and Dukes 2016). A previous greenhouse study using lysimeters found that irrigating Tifway bermudagrass [*Cynodon dactylon* (L.) Pers. × *C. traansvalensis* Burtt Davy] with sodic water (elevated sodium) increased actual turfgrass evapotranspiration (ET_a) significantly compared with a saline (elevated EC) or reverse osmosis (RO) irrigation sources, with increases of ≈ 1.1 $mm \cdot d^{-1}$ and ≈ 2 $mm \cdot d^{-1}$, respectively (Hejl et al. 2015). The same study also showed sodic irrigation increased shoot growth significantly relative to the other water sources (Hejl et al. 2015). For recycled water, the presence of plant macro- and micronutrients (Parsons 2018) could also affect turfgrass and

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Table 1. Parameters of water quality for the three irrigation treatments used in both studies, along with their respective classifications.

Parameter	Reverse osmosis	Local well	Recycled
US Salinity Laboratory classification	C1-S1	C4-S2	C3-S2
Salinity hazard	Low	Very high	High
Sodium hazard	Low	Medium	Medium
pH	8.5	7.6	8.1
EC ($dS \cdot m^{-1}$)	0.1	2.4	2.0
Bicarbonate (ppm)	14.0	152.0	196.0
Sodium adsorption ratio	0.9	6.1	8.7
Sodium (ppm)	10.0	330.0	310.0
Calcium (ppm)	8.0	180.0	62.0
Magnesium (ppm)	0.3	24.0	21.0
Potassium (ppm)	<0.0	5.1	20.0
Chlorine (ppm)	9.0	413.0	421.0
Nitrate (ppm)	1.1	13.0	7.4
Sulfate (ppm)	1.2	150.0	36.0
Phosphate (ppm)	0.1	0.0	3.2

ET_a by enhancing leaf transpiration, which impacts photosynthetic carbon gain and plant biomass accumulation directly (Sinclair et al. 1984).

Responsible use of an irrigation source relies on applying water in the right quantities and at the right time. This is often accomplished through reference ET-based irrigation scheduling, where actual turfgrass water use is estimated by calculating potential plant evapotranspiration and then adjusted based upon appropriate crop coefficients (K_c) (Allen et al. 1998, 2005). Numerous consumptive-use studies have evaluated and produced K_c values for a variety of turfgrass species across many different geographic locations (Carrow 1995; Wherley et al. 2015). These values are highly important for water budgeting because they allow the prediction of water needs throughout the year. However, these studies have been conducted in the absence of multiple water sources for which the impact from irrigation-water chemistry on turfgrass ET_a are not accounted in determining reference ET-based irrigation scheduling. This research gap combined with increased utilization of impaired water sources underscore the need for studies to explore the effects of low-quality irrigation on turfgrass growth and water consumption. To address this need, we conducted summer and fall greenhouse studies carried out over 8 weeks to characterize ET_a, growth, and turfgrass quality of three hybrid bermudagrass varieties when irrigated with three irrigation water sources (RO, local well, and recycled) when supplied at full irrigation levels ($1.0 \times ET_a$).

Materials and Methods

Studies were conducted in a greenhouse at the US Arid Land Agricultural Research Center in Maricopa, AZ, USA, over 8-week periods in the summer, and then were repeated in the fall. Summer and fall studies were initiated on 15 Aug 2022 and 14 Nov 2022, respectively. Air temperatures in the greenhouse were set to 33/26 °C (day/night) for both studies. Seven to 8 weeks before each study, 14-cm–diameter washed sod plugs of three bermudagrass varieties (‘TifTuf’, ‘Tifway’, and ‘Midiron’) were established in 27 lysimeters constructed from polyvinylchloride pipe (15.2-cm diameter × 30.5-cm depth). Hybrid bermudagrass cultivars were selected for these experiments because bermudagrass is a predominant species planted in regions where recycled water is used. Tifway has been a widely used variety for decades, whereas TifTuf was recently co-released in 2014 by the University of Georgia and the US Department of Agriculture–Agricultural Research Service and, as a result of improved drought tolerance, has shown enhanced adaptability to water-stressed regions (Guertal and Hicks 2009; Hanna and Schwartz 2016; Schwartz et al. 2018). Midiron is a commonly used general-purpose turfgrass used in lower maintenance scenarios (Kopec 2003; Marcum et al. 2005). Lysimeters were filled with a US Golf Association specification sand [90:10 (vol:vol) sand:peatmoss]. A 10-mm hole was drilled at the bottom of each lysimeter to allow water drainage. A plant and seed guard cloth (DeWitt, Sikeston, MO, USA) was then laid at each base to avoid sand spillage. The second week after planting, fertilizer (21–7–14) (Turf Royale, Yara-Mila, Tampa, FL, USA) was applied at a rate of 2.4 g $N \cdot m^{-2}$. During each establishment period, water was applied as needed to avoid stress and promote successful establishment.

Both studies were arranged in a completely randomized design to support three cultivar- × three water source-level factorial experiments. Immediately before the initiation of studies, all lysimeters were brought to field capacity by fully submerging in water until air bubbles had ceased, indicating saturation had been reached (≈ 4-min submersion). After saturation, lysimeters were allowed to drain freely for 30 to 36 h, at which point field capacity weights were recorded for future reference during weighing and irrigation events. All lysimeters were weighed and irrigated three times weekly during each study period. Within each water source treatment, irrigation was applied at full ET replacement ($1.0 \times ET_a$). Actual turfgrass evapotranspiration was determined by weighing and calculating the mean mass change for each of the 27 lysimeters.

Water source treatments included 1) RO water (generated through an onsite filtration unit), 2) local well water (located onsite), and 3) recycled water (sourced from Neely Wastewater Reclamation Facility, Gilbert, AZ, USA). Pertinent chemical parameters for each water source are summarized in Table 1. These specific impaired sources were chosen because they represent a range of chemical factors and are consistent with sources used by turfgrass practitioners (Shaddox et al. 2022).

Lysimeters were evaluated weekly for turfgrass quality according to a modified National Turfgrass Evaluation Program visual quality ranking system (scale, 1–9 points; minimum quality, 5 points) (Morris and Shearman, 1998). The quality ratings accounted for a combination of color, density, and uniformity of the turfgrass canopy. For reference, a rating of 1 point indicated completely dormant or dead turfgrass and a rating of 9 points represented perfectly green turf

Table 2. Analysis of variance table with *P* values for measuring date, water source, and turfgrass variety effects on evapotranspiration, clipping production, water use efficiency (WUE), normalized difference vegetation index (NDVI), visual quality, and soil electrical conductivity (EC) during the summer and fall studies.

	Evapotranspiration		Clipping production		WUE		NDVI		Visual quality		
Variable	Summer	Fall	Summer	Fall	Summer	Fall	Summer	Fall	Summer	Fall	EC
Date (D)	***	***	***	***	—	—	***	***	***	***	NS
Source (S)	*	***	***	**	*	NS	*	***	*	***	***
Variety (V)	***	**	***	***	***	***	***	***	***	***	NS
D × S	NS	NS	NS	NS	—	—	NS	NS	NS	NS	***
D × S	NS	NS	***	*	—	—	NS	*	NS	NS	NS
S × V	***	*	*	NS	NS	NS	**	NS	NS	NS	NS
D × S × V	NS	NS	*	NS	—	—	NS	NS	NS	NS	NS

Parameters were separated by study where a main study effect was found.

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

Table 3. Daily evapotranspiration of varieties TifTuf, Midiron, and Tifway as affected by water source during the summer and fall experiments.

		Evapotranspiration ($mm \cdot d^{-1}$)	
Variety	Water source	Summer	Fall
TifTuf	Reverse osmosis	6.50 a–c[i]	5.96 a
	Local well	7.26 a	5.56 ab
	Recycled	6.44 a–c	5.18 a–c
Midiron	Reverse osmosis	5.84 cd	5.35 a–c
	Local well	5.32 d	5.30 a–c
	Recycled	6.12 b–d	4.61 c
Tifway	Reverse osmosis	6.92 a–c	4.97 bc
	Local Well	6.70 a–c	5.79 ab
	Recycled	5.79 cd	5.12 bc
P value	—	***	*

[i] Means with the same letter within a given study period are not significantly different based on Tukey's honestly significant difference test at $P \leq 0.05$.

*, *** Significant at $P = 0.05$ or 0.001, respectively.

that is fully dense and dark green. Turfgrass vigor [normalized difference vegetation index (NDVI)] data were also collected weekly using a RapidScan CS-45 NDVI meter (Holland Scientific, Lincoln, NE, USA), which contains an internal light source held 0.7 m above the turf canopy. A trigger activated the targeting lasers to record a single measurement over each lysimeter.

Clipping production was assessed through weekly clipping collections. On each lysimeter, the turfgrass was trimmed to a 2.5-cm height using scissors and a ruler every 7 d. After each collection, the clippings were oven dried for 72 h at 65 °C and weighed to obtain dry weight values. For each period, dry weights were divided by the number of growing days to calculate daily growth for each lysimeter. Water use efficiency (WUE) was calculated by dividing cumulative clipping production by cumulative water use for each lysimeter during each study period (milligrams dry clipping weight per milliliters water used). Soil salinity levels were measured at a 10-cm depth within lysimeters at weeks 0, 3, and 8 using a direct soil EC probe (Spectrum Technologies, Aurora, IL, USA).

Data for all parameters were subjected to analysis of variance (ANOVA) with JMP ver. 15.2.0 (SAS Institute, Cary, NC, USA). When ANOVA indicated a significant study effect, parameters are presented by study. Mean separation procedures were performed using Tukey's honestly significant difference test at the $P \leq 0.05$ level.

Results and Discussion

Effects of variety and water source on ET_a. When pooling across measuring dates, water sources, and varieties, significantly greater ET_a was observed in the summer compared with the fall (6.32 ± 0.07 vs. 5.31 ± 0.09 $mm \cdot d^{-1}$, respectively), with both averages within the typical daily ET range for bermudagrass in well-watered conditions (Colmer and Barton 2017). A greater ET_a in the summer experiment is likely a result of longer days and more intense solar radiation during the summer (data not shown). For this reason, ET_a results are presented separately for each study.

ANOVA of daily ET_a showed highly significant ($P \leq 0.001$) and significant ($P \leq 0.05$) variety × water source interactions in both the summer and THE fall, respectively (Table 2). In both study periods, no significant differences were detected when comparing ET_a rates of varieties within water sources, but significant differences among varieties across water sources were detected (Table 3). In the summer, the ET_a of TifTuf supplied with local well water was significantly greater than Midiron irrigated with RO water, local well water, and recycled water, as well as Tifway irrigated with recycled water, resulting in a 24%, 36%, 18%, and 25% greater ET_a, respectively (Table 3). In the fall, ET_a of RO-irrigated TifTuf was significantly greater than Tifway receiving either RO water or recycled water, and Midiron receiving recycled water, resulting in a 20%, 16%, and 29% greater ET_a, respectively (Table 3). Also in the fall, the ET_a of local well water–irrigated Tifway (5.79 $mm \cdot d^{-1}$) was greater than recycled irrigated Midiron (4.61 $mm \cdot d^{-1}$) (Table 3). These results show the apparent differences in ET_a within bermudagrass varieties as affected by water source. However, because this interaction could be skewed slightly as a result of the overall differences in ET_a between grass varieties, it might not provide the best ability to analyze the effect of water source on ET_a within each variety. As such, the main effect of water source on ET_a was also analyzed individually for each variety.

Overall, a greater ET_a was observed with RO water or local well water sources compared with recycled water within varieties (Fig. 1A–C). Differences within each variety ranged from 11% to 16% in the summer and 13% to 14% in the fall. The one exception was during the summer, when Midiron had a greater ET_a when irrigated with the recycled water source compared with the local well water source (Fig. 1B). Differences in water use among irrigation sources, especially the impaired sources (local well and recycled), validate the need for similar studies to evaluate interactions between water sources and additional turfgrass species or varieties. It should be noted that reduced water use does not correlate directly to being able to survive longer periods without water compared with a greater water-use grass, especially in a restricted root zone where the grass cannot access water at deeper depths (Steinke et al. 2010, 2011). As such, this type of research conducted in field settings would provide important information regarding this concept.

ANOVA for daily ET_a also showed highly significant ($P \leq 0.01$) main effects for variety in both studies (Table 2). Midiron exhibited the lowest daily ET_a in the summer (15% and 11% less compared with TifTuf and Tifway, respectively), and significantly less than TifTuf in the fall (5% less compared with TifTuf) (Table 4). Although information is limited comparing water-use rates of Midiron to other hybrid bermudagrass varieties, Midiron has exhibited lower annual water consumption compared with the common bermudagrass variety Texturf-10 [*Cynodon dactylon* (L.) Pers.] (Garrot and Mancino 1994). For TifTuf, greater ET rates have been observed in nonlimiting soil moisture conditions (unlimited soil profile) compared with seven other turf-type bermudagrasses, including Tifway, pooled across a 3-year period (Amgain et al. 2018). TifTuf was also shown to have used more water compared with Tifway within a soil moisture-limiting root zone (limited soil profile), as 21% more soil water was depleted compared with Tifway in 45-cm–deep lysimeters during a 28-d drought period (Yurisic 2016). In our study, with a soil profile of 30.5 cm, TifTuf had greater ET rates compared with Tifway, although no significant differences were detected in either study when pooling across irrigation source (Table 4).

When pooling across measuring dates and varieties, ANOVA detected a significant ($P \leq 0.05$) main effect for water source in the summer and a highly significant ($P \leq 0.001$) effect in the fall (Table 2). Differences in ET_a among water sources were consistent for both studies, as values for recycled water were less than those for either RO water or local well water (Table 4). In the summer, the average ET_a for plants receiving RO water or local well water was similar (6.42 vs. 6.42 $mm \cdot d^{-1}$), but 5% greater than those receiving the recycled water source (6.12 $mm \cdot d^{-1}$) (Table 4). In the fall, the daily ET_a of turfgrasses receiving irrigation from the local well (5.55 $mm \cdot d^{-1}$) and RO water source (5.43 $mm \cdot d^{-1}$) was 10% and 9% greater, respectively, in daily ET_a compared with recycled water (4.97 $mm \cdot d^{-1}$) (Table 4). Hejl et al. (2015) also found differences in ET_a between turfgrass receiving different water sources; however, both impaired water sources used in that study—sodic-potable water (elevated sodium) and saline water (elevated EC, EC of 7.5 $dS \cdot m^{-1}$)—increased ET_a by ≈ 1.1 $mm \cdot d^{-1}$ and ≈ 2 $mm \cdot d^{-1}$ respectively, compared with RO water (Hejl et al. 2015). Our study showed an increase in daily ET_a when irrigating with RO water compared with one of the impaired water sources (recycled). There are notable differences, however, between the RO sources in both studies in which the RO source in our study had a pH of 8.5 compared with the source used by Hejl et al. (2015) (pH, 5.9) (Table 1). The RO source in our study also had trace levels of bicarbonate, sodium, chlorine, and nitrate-nitrogen, whereas the comparative study (Hejl et al. 2015) did not.

Effects of variety and water source on clipping production, WUE, NDVI, and visual quality. There was a significant ($P \leq 0.05$) three-way date × variety × water source interaction for clipping production in the summer study, and a significant ($P \leq 0.05$) date × variety interaction in the fall study (Table 2).

Table 4. Daily evapotranspiration as affected by either turfgrass variety or water source.

Variety and water source	Evapotranspiration ($mm \cdot d^{-1}$)	
	Summer	Fall
Variety		
TifTuf	6.74 a[i]	5.57 a
Midiron	5.76 b	5.10 b
Tifway	6.47 a	5.30 a
P value	***	**
Water source		
Reverse osmosis	6.42 a	5.43 a
Local well	6.42 a	5.55 a
Recycled	6.12 b	4.97 b
P value	*	***

[i] Means with the same letter within a given study period are not significantly different based on Tukey's honestly significant difference test at $P \leq 0.05$.

*, **, *** Significant at $P = 0.05$, 0.01, or 0.001, respectively.

The three-way date × variety × water source interaction for clipping production in the summer study revealed that, at each date, no significant differences were detected when comparing the clipping production of variety within water sources, but significant differences among varieties across water sources were detected. TifTuf, regardless of water source, maintained similar or greater clipping production compared with other variety × water source combinations in the first 4 weeks of the study period, followed by comparatively lower production and leveling off at weeks 5 through 8 (Fig. 2). Although clipping production for the water source combinations of Tifway was relatively lower in the first 4 weeks, RO-irrigated Tifway maintained relatively greater yields in the later weeks (Fig. 2). All water-source combinations for Midiron remained relatively stable throughout the study (Fig. 2). Dean et al. (1996) reported greater clipping yields for two turfgrasses—Numex Saharah bermudagrass (*Cynodon dactylon* L.) and Monarch tall fescue (*Festuca arundinacea* Schreb.)—when irrigated at full ET replacement with a municipal water source (EC, 1.1 $dS \cdot m^{-1}$) compared with the same grasses receiving a saline water source (EC, 7.65 $dS \cdot m^{-1}$) or a blended source (EC, 5.95 $dS \cdot m^{-1}$) (Dean et al. 1996). Dean et al. (1996) also reported sharp declines in clipping yields for municipal irrigated turfgrass, compared with the saline sources, when initiating soil water deficits, which they attributed to soil water within the municipal treatment being more readily extractable (Dean et al. 1996). These findings highlight the need for further exploration of the tolerance of newer turfgrass varieties (i.e., TifTuf) and other turfgrass species to a broader range of water source treatments and soil water deficits.

Overall, clipping production for Midiron was significantly less compared with the other varieties in both studies (Table 5). In the fall, the variety × date interaction for clipping production showed TifTuf and Tifway maintained greater yields compared with Midiron, excluding the last few rating dates when Midiron clipping yields were less in comparison, but not significantly less (data not shown). This result is consistent with the ET_a differences among varieties, as biomass production is linked to transpiration, and increased shoot growth has been correlated with a greater ET (Bowman and Macaulay 1991; Dean et al. 1996; Hejl et al. 2015; Sinclair et al. 1984).

Zhou et al. (2012) found that turfgrasses with a lower water use also exhibited greater WUE. However, in our study, increased WUE was not achieved by lower water use because WUE was less for Midiron compared with TifTuf in the summer, and with both Tifway and TifTuf in the fall (Table 5). Also, in the summer, WUE was significantly greater for the local well–irrigated turfgrass compared with turfgrasses receiving RO water, whereas no differences were observed among water sources in the fall (Table 5). In the study by Zhou et al. (2012), the included bermudagrasses (*Cynodon dactylon* L.) had the least water use with a corresponding greater WUE compared with Queensland blue couches (*Digitaria didactyla* Willd), seashore paspalums (*Paspalum vaginatum* Swartz.), and St. Augustinegrasses [*Stenotaphrum secundatum* (Walt.) Kuntze]; however, relative ET differences for bermudagrass varieties were not reported (Zhou et al. 2012). In our study, WUE was not reduced significantly for turfgrass receiving recycled water, as the ET_a of turfgrass irrigated with recycled water was less compared with the other water sources in both studies (Tables 4 and 5).

ANOVA of NDVI showed a significant ($P \leq 0.05$) variety × water source interaction in the summer (Table 2). In this study period, no significant differences were detected when comparing NDVI of variety within water sources, but significant differences among varieties across water sources were detected. For all TifTuf water source combinations, NDVI was significantly greater than all other variety × water source combinations, excluding the comparison of TifTuf irrigated with local well water and Tifway irrigated with local well water (Fig. 3). A significant ($P \leq 0.05$) date × variety interaction was also detected for NDVI in the fall (Table 2). This revealed greater NDVI values for TifTuf compared with Midiron at all rating dates, and Tifway at three of the eight rating dates (Fig. 4). During this study period Tifway also had greater NDVI values compared with Midiron at seven of the rating dates and TifTuf at the last rating date (week 8) (Fig. 4).

For visual quality, all three varieties were able to maintain quality above the minimum quality threshold (≥ 5 points) (Table 5). The increased water use of TifTuf compared with Midiron was accompanied by the greatest average visual quality in both the summer and fall (Table 5). The visual quality of Midiron was also significantly greater than Tifway in both studies (Table 5). The effect of variety on NDVI values and turf quality found in this study are consistent with previous findings showing TifTuf had improved quality compared with Tifway in nonstressed conditions (Schwartz et al. 2018). TifTuf has also been a top performer in experiments evaluating the visual

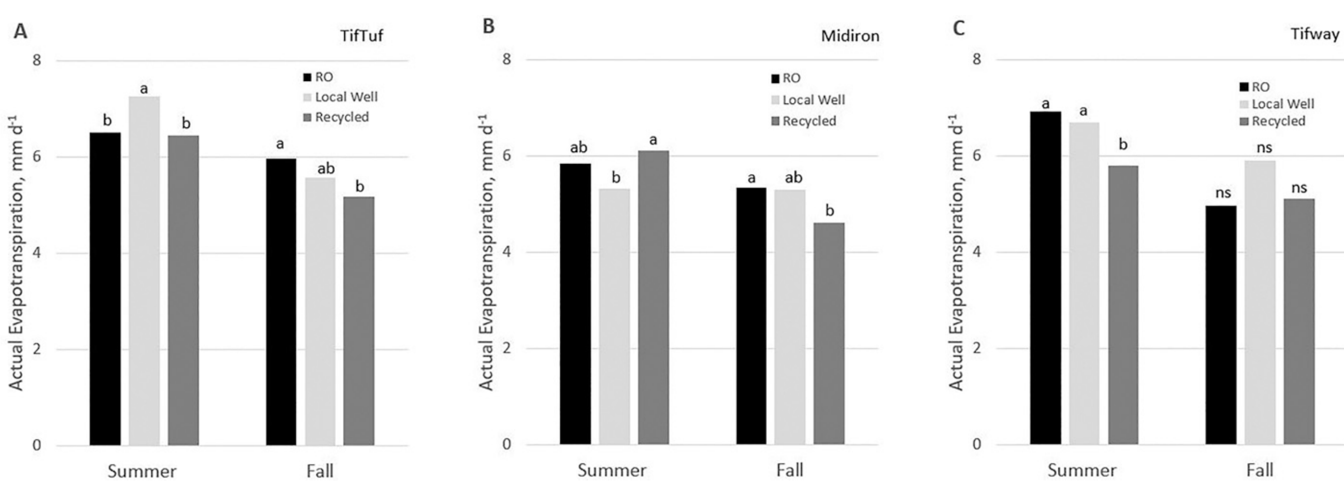

Fig. 1. Daily evapotranspiration (ET_a) of varieties (**A**) TifTuf, (**B**) Midiron, and (**C**) Tifway as affected by water source during the summer and fall experiments. Bars with the same letter within a given variety and study period are not significantly different based on Tukey's honestly significant difference test at $P \leq 0.05$. ns = not significant; RO = reverse osmosis.

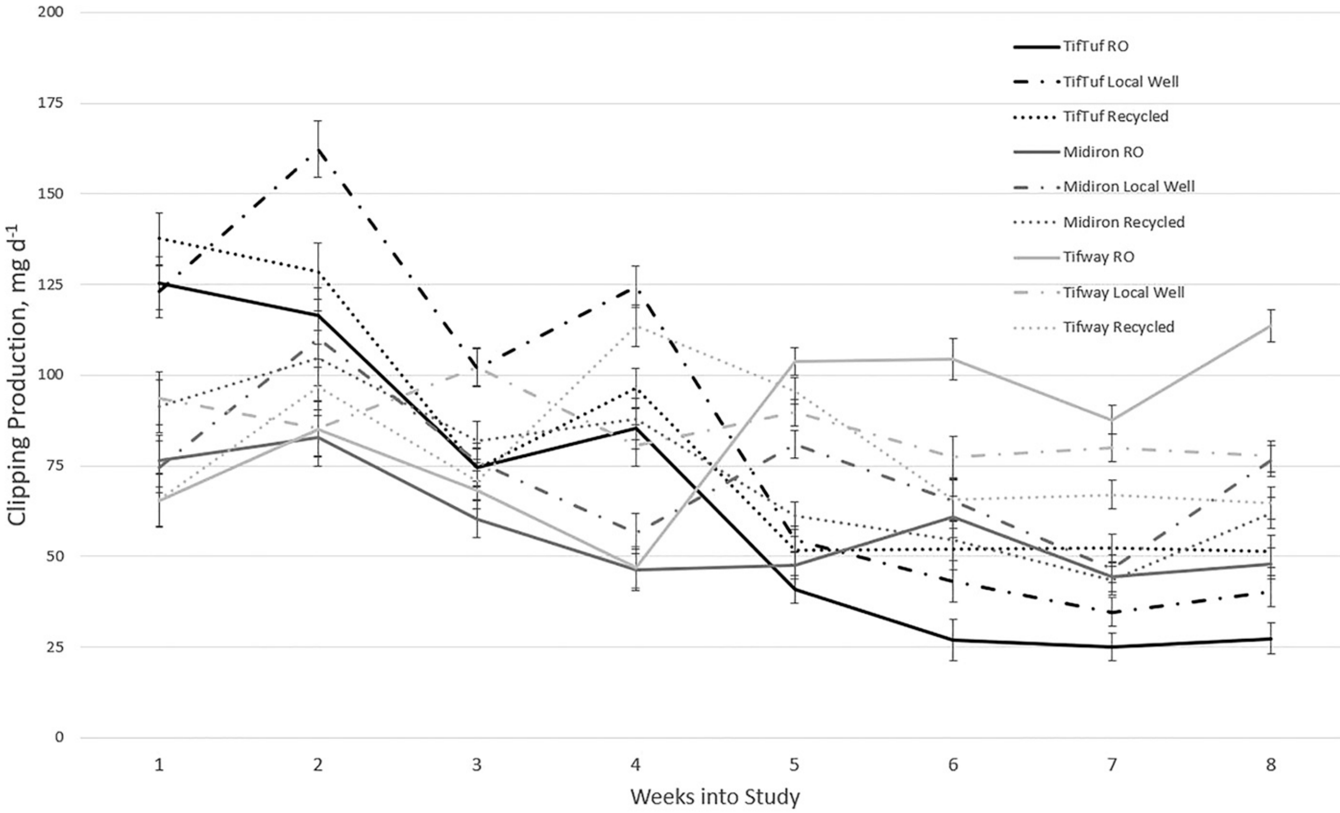

Fig. 2. Clipping production in the summer study as affected by variety and water source. Error bars represent the *SEM*. RO = reverse osmosis.

quality of hybrid bermudagrass in drought or stressed conditions (Jespersen et al. 2019; Katuwal et al. 2020).

For visual quality, there was also a significant ($P \leq 0.05$) main effect for water source detected in the summer and a highly significant ($P \leq 0.001$) effect in the fall (Table 2). The difference in visual quality of recycled water–irrigated turfgrass was nonsignificant compared with the other sources in the summer (Table 5). In the fall, visual quality of recycled water–irrigated turfgrass was significantly greater than RO-irrigated turfgrass and similar to local well water–irrigated turfgrass (Table 5). In a 2012 study, Leinauer et al. (2012b) evaluated the impact of impaired water sources on both warm-season and cool-season turfgrass varieties. That study showed no significant differences in turfgrass quality and NDVI on the warm-season turfgrasses as a result of water quality, but reported a general decline in turfgrass quality on the cool-season grasses as irrigation salinity increased (Leinauer et al. 2012b). In our study, findings could be explained in part by the apparent differences in water chemistries within the potable and recycled sources compared with the RO source (Table 1). Apart from no phosphate-phosphorus detected within the local well source, turfgrasses irrigated with both impaired sources had sustained access to significantly greater levels of macronutrients (nitrogen, phosphorus, and potassium) and secondary nutrients (calcium, magnesium, and sulfur) compared with RO-irrigated turfgrass (Table 1). For example, in the summer study, each lysimeter, on average, irrigated with local well water or recycled water received an additional 79 mg nitrate-nitrogen and 43 mg nitrate-nitrogen, respectively, compared with 6 mg nitrate-nitrogen from RO-irrigated turfgrass.

Effect of water source on soil EC. No study interactions were detected for soil EC, so data were pooled across studies (Table 2). Data were also pooled across turfgrass variety because there was neither a significant main effect of variety nor variety interactions on soil EC. There was a highly significant ($P \leq 0.001$) main effect of water source on soil EC at the 10-cm depth, with values significantly greater for both the local well and

Table 5. Turfgrass daily clipping production, water use efficiency (WUE), normalized difference vegetation index (NDVI), and visual quality as affected by either variety or water source.

	Clipping production ($mg \cdot d^{-1}$)		WUE ($mg \cdot mL^{-1}$)		NDVI[i]		Visual quality[ii]	
Variety and water source	Summer	Fall	Summer	Fall	Summer	Fall	Summer	Fall
Variety								
TifTuf	77.11 a[iii]	60.32 a	1.00 a	0.67 a	0.75 a	0.78 a	7.50 a	7.58 a
Midiron	68.34 b	34.19 b	0.70 b	0.39 b	0.67 b	0.66 c	6.70 b	7.14 b
Tifway	83.39 a	67.02 a	0.71 b	0.79 a	0.66 b	0.74 b	6.40 c	6.84 c
P value	***	***	***	***	***	***	***	***
Water source								
Reverse osmosis	69.32 b	48.15 b	0.69 b	0.54 a	0.67 b	0.70 b	6.74 b	6.88 b
Local well	81.55 a	60.15 a	0.88 a	0.66 a	0.70 a	0.73 a	6.98 a	7.22 a
Recycled	77.97 a	53.10 ab	0.85 ab	0.65 a	0.69 ab	0.74 a	6.94 ab	7.46 a
P value	***	**	*	NS	*	***	*	***

[i] NDVI measured by handheld Holland Scientific RapidScan CS-45 NDVI meter.
[ii] Visual quality was rated on a scale of 1 to 9, where 1 = lowest quality, 5 = minimum acceptable quality, and 9 = excellent quality.
[iii] Means with the same letter within a given study period are not significantly different based on Tukey's honestly significant difference test at $P \leq 0.05$.
NS, *, **, *** Nonsignificant or significant at P = 0.05, 0.01, or 0.001, respectively.

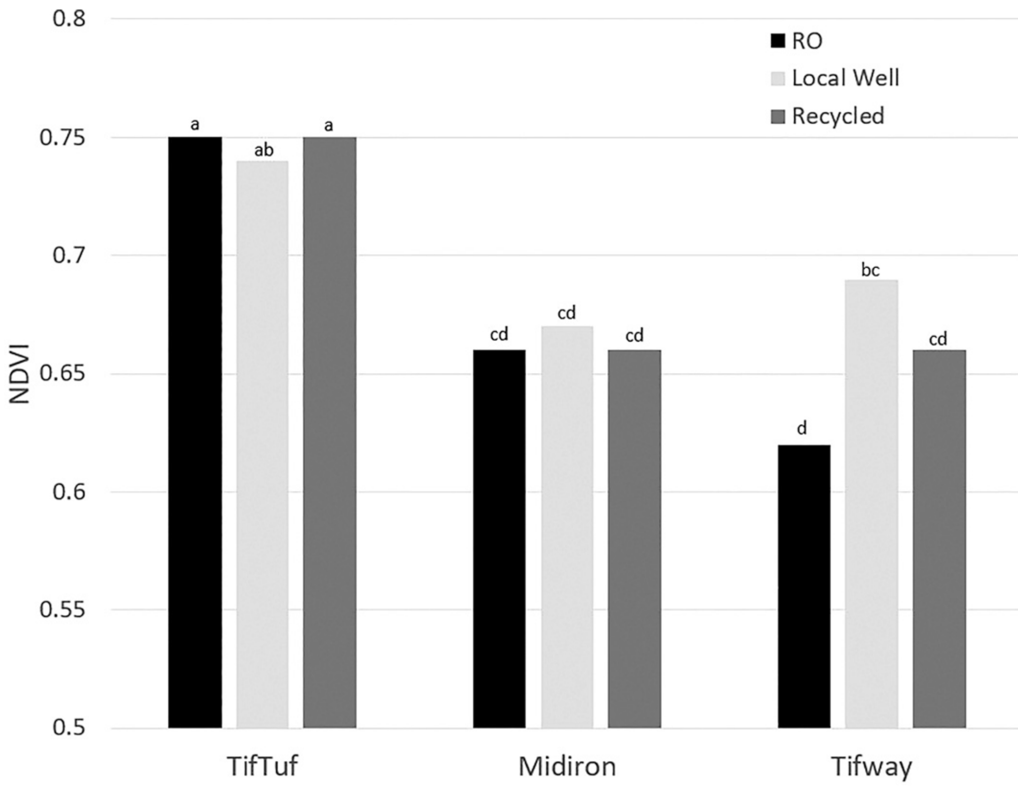

Fig. 3. Normalized difference vegetation index (NDVI) of varieties TifTuf, Midiron, and Tifway as affected by water source during the summer study. Bars with the same letter are not significantly different based on Tukey's honestly significant difference test at $P \leq 0.05$. RO = reverse osmosis.

recycled sources compared with the RO source (Tables 2 and 6). For the significant water source × measuring date interaction, EC was similar at the start of the experiment for each irrigation source because the same water was used during the establishment period. Soil EC levels decreased for the RO source as the study progressed, but increased at weeks 3 and 8 for the local well and recycled sources (Table 6). At weeks 3 and 8, soil EC for the RO-irrigated turfgrass was significantly less compared with local well water– and recycled water–irrigated turfgrasses, whereas no significant differences were observed between the local well and recycled water sources (Table 6). Although these significant differences existed, the soil EC values observed in our experiment with

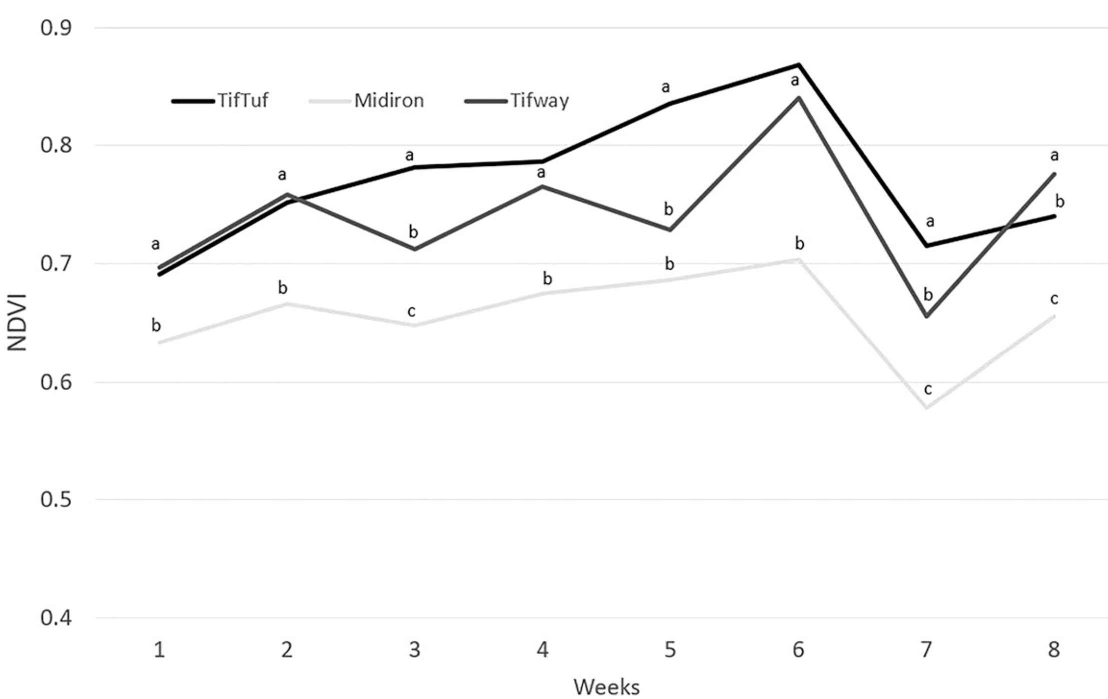

Fig. 4. Normalized difference vegetation index (NDVI) of varieties TifTuf, Midiron, and Tifway in the fall study. Data are pooled across water source. Means with the same letter on a given date are not significantly different based on Tukey's honestly significant difference test at $P \leq 0.05$.

Table 6. Soil electrical conductivity at weeks 0, 3, and 8 as affected by water source.

	Soil electrical conductivity ($dS \cdot m^{-1}$)		
Water Source	Week 0	Week 3	Week 8
Reverse osmosis	0.08 bc[i]	0.04 de	0.03 e
Local well	0.07 cd	0.09 a–c	0.17 ab
Recycled	0.08 bc	0.11 ab	0.12 ab
P value		***	

[i] Means with the same letter are not significantly different based on Tukey's honestly significant difference test at $P \leq 0.05$.

*** Significant at $P = 0.001$.

the recycled and local well sources only approached 0.10 to 0.12 $dS \cdot m^{-1}$ (Table 6), with values that reflect low-saline conditions. Bermudagrass possesses good salinity tolerance and has been shown to withstand salinity levels more than 10 $dS \cdot m^{-1}$ (Harivandi et al. 1992; Xiang et al. 2017).

Conclusions

As low-quality water sources are being used increasingly to irrigate warm-season turfgrasses, it is important to examine how they potentially impact the success of turfgrass varieties. Although prior research has demonstrated that repeated use of impaired water sources impact soil conditions, more information is needed regarding how water quality affects turfgrass ET, quality, and growth. Results from our experiment showed differences in ET rates, clipping production, and quality among three commercially available hybrid bermudagrass cultivars when grown under variable-quality water sources. Midiron bermudagrass maintained significantly lower ET rates, and were accompanied by significantly lower clipping production and WUE compared with TifTuf. In addition, turfgrasses irrigated with the recycled water source had lower ET rates and similar WUE compared with the local well and RO sources, while not reducing visual quality ratings, NDVI, or clipping production. We also found that soil EC levels were increased with both the recycled and local well irrigation sources compared with the RO source, but EC levels never reached damaging levels. Overall, the results showed a nonnegative impact from short-term irrigation with a recycled water source; however, results from previous studies show that issues with long-term use of recycled water are likely to arise if mitigation strategies are not enacted. These results highlight the need for further research addressing irrigation water-quality effects on a broader range of commonly used turfgrass species along with companion studies conducted under field conditions.

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