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Using a soil moisture sensor-based smart controller for autonomous irrigation management of hybrid bermudagrass with recycled water in coastal Southern California

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ABSTRACT

There is a lack of information on the reliability of smart soil moisture sensor-based irrigation controllers for autonomous urban landscape irrigation management using recycled water where water conservation is required, which is the main objective of this study. A three-year turfgrass irrigation research trial (2019–2021) using tertiary-treated recycled water (mean EC = 1.18 dS/m, pH = 7.5) was conducted in Irvine, California, USA. A total of 12 irrigation treatments were designed, including six soil moisture-based thresholds (for triggering and terminating irrigation events) × two irrigation frequency treatments (restricted versus on-demand). Weekly NDVI and canopy temperature data were collected during the summer irrigation season to assess the impact of irrigation treatments on the overall health and quality of 'Tifgreen 328' hybrid bermudagrass. Soil salinity and sodium adsorption ratio (SAR) were measured before and after the summer irrigation seasons. Findings revealed statistically significant effects of irrigation levels and irrigation frequency restrictions on NDVI over the three years. The temperature difference (dT) between turfgrass and air (Tc - Ta) was significantly affected by irrigation levels throughout the three years, while irrigation frequency restrictions showed a significant effect in the years 2021 and 2022. On-demand irrigation resulted in a 10% reduction in temperature difference values during the study period compared to restricted irrigation. Variations in soil salinity levels were observed during the experimental periods; however, both salinity and SAR increased as the study progressed. Results indicate that fully autonomous hybrid bermudagrass irrigation with recycled water, based on recommended soil moisture thresholds of 75% of field capacity over an extended period in a semiarid climate, may lead to unacceptable turfgrass quality.

1. Introduction

With increasing population and urbanization, water scarcity is becoming a pressing issue (Hogue and Pincetl, 2015; Pagán et al., 2016). In the United States, where 80% of the population lives in urban areas (US Census Bureau, 2020), turfgrass landscapes represent a significant component of urbanized land areas that encompass residential, commercial, and institutional lawns, parks, golf courses, and athletic fields that comprise 1.9% of the surface of the continental United States (Milesi et al., 2005). Beyond aesthetic and recreational use, turfgrass provides valuable ecosystem services in high demand by society, such as capturing runoff, mitigating heat islands, reducing dust and noise, and fostering biodiversity (Monteiro, 2017). The presence of well-irrigated lawns on a property is also linked with gains in real estate values (Saphores and Li, 2012), and the appearance of lawns is very important to landowners (Sewell et al., 2010). Bermudagrass (*Cynodon* species) is the most widely used turfgrass species in the nation and made up around 34% of all maintained turfgrass acreage in 2015 (Gelernter et al., 2017). Warm-season grasses such as bermudagrass are also considered the best choice for salinity and drought tolerance (Dean et al., 1996; Manuchehri and Salehi, 2014; Marcum, 2006).

The lack of accessible freshwater resources and the increasing demand for water for urban use have raised the need for more efficient water management strategies. Advancements in irrigation technologies have led to affordable smart irrigation controllers. Homeowners prefer smart irrigation controllers to conventional automated systems due to

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the potential savings in annual water bills associated with these products (Khachatryan et al., 2019). Smart irrigation controllers can be broadly classified into two types: Evapotranspiration (ET)-based and soil moisture sensor (SMS)-based (Davis and Dukes, 2015). ET controllers rely on weather information to determine the irrigation schedule, while SMS controllers bypass/trigger irrigation events when the measured soil moisture reaches threshold levels. SMS-based irrigation is based on the concept of management allowable depletion (MAD, USDA, 1993), which represents the fraction of plant-available water that can be depleted from the soil before plants start to experience stress. This approach involves setting a lower limit, indicating the soil moisture level at which the smart controller triggers irrigation when the moisture level in the root zone falls below this threshold, and an upper limit, indicating the soil moisture level at which irrigation is stopped if the moisture level surpasses this value (Grabow et al., 2013). SMS-based smart irrigation controllers have shown significant water-saving potential in Utah, Florida, and Colorado (Blonquist et al., 2006; Cardenas et al., 2021; Cardenas-Lailhacar and Dukes, 2012; Qualls et al., 2001). For example, SMS-based irrigation controllers reduced irrigation by 11–53% under relatively dry conditions compared to a time-based schedule in Florida (McCready et al., 2009). Cardenas and Dukes (2016) showed 46–78% water savings using SMSs for recycled water irrigation with a salinity of around 0.75 dS/m. Much of the scientific research on the application of SMS-based landscape irrigation scheduling has been done in humid regions, where the focus has been on avoiding overirrigation when rainfall is abundant. Although our recent studies in California showed the efficacy of ET-based smart irrigation scheduling (Haghverdi et al., 2021a–c), information on the use of SMS-based irrigation controllers for landscape irrigation is lacking in the arid/semiarid conditions of southern California.

Alternative irrigation water sources, such as recycled water, can often be successfully used for irrigation without long-term hazardous consequences for crops or soils if proper management strategies are used (Assouline et al., 2015; Rhoades et al., 1989). The availability of recycled water is essential to meet the demand for landscape irrigation in southern California, considering the treatment cost compared to other alternatives, such as seawater desalination and imported surface waters. A state-wide survey in California in 2015 indicated that approximately 31%, 18%, and 8% of the recycled water was utilized for agriculture, landscape, and golf course irrigation, respectively (SWRCB, California State Water Resources Control Board, 2015). There are opportunities to increase the use of recycled water to irrigate urban landscapes, as the proportion of total recycled urban water use in southern California ranged from 26% in Santa Ana, 38% in Los Angeles, to 94% in the San Diego region in 2015. However, high concentrations of salt present in recycled water could negatively impact plant growth and soil health (Gonçalves et al., 2007; Qian and Mecham, 2005). This problem is critical in the arid and semiarid climates of Southern California, where low precipitation may not adequately leach soluble salts from the root zone in some years. Furthermore, a higher concentration of ions such as Na^+ vs Ca^{2+} and Mg^{2+} can increase the sodium adsorption ratio (SAR) in soil, which can cause permeability issues (Gao et al., 2021; Zalacáin et al., 2019).

Currently, information is lacking on the efficacy of smart SMS-based irrigation technologies for autonomous turfgrass deficit irrigation management using recycled water in arid regions such as Southern California, which is the main objective of this study. Other objectives were to (I) determine the impact of different recycled water irrigation strategies on hybrid bermudagrass (*Cynodon dactylon* (L.) Pers. × *C. transvaalensis* Burtt-Davy) quality and (II) determine the effect of recycled water irrigation on soil salinity (EC_e) and sodium adsorption ratio (SAR).

2. Material and methods

2.1. Study site

A three-year (2019–2021) irrigation management research study on ''Tifgreen 328' hybrid bermudagrass was conducted at UC ANR South Coast Research and Extension Center (SCREC) in Irvine, California (33°41'20.9"N 117°43'23.3" W). The soil at the research site was classified as a San Emigdio fine sandy loam with a soil volumetric water content of 18% at 33 kPa (websoilsurvey.sc.egov.usda.gov). The recycled water (pH = 7.5) was supplied by Irvine Ranch Water District. Sewage from the local community is collected and treated to tertiary treatment involving particle removal and disinfection using chlorine or a combination of membrane bioreactor filtration and ultraviolet light.

The daily and monthly averaged reference ET (ET_o), air temperature and precipitation data during the field trial are shown in Fig. 1. Data were obtained from the CIMIS (California Irrigation Management Information System) weather station # 75, which was about 65 m away from the experimental site. The cumulative ET_o in 2017, 2018, and 2019 were 1319, 1427, and 1405 mm, respectively. The cumulative ET_o values in the irrigation season were 765, 768, and 699 mm in 2019, 2020, and 2021, respectively. Throughout the irrigation season, the average daily ET_o was 4.61, 5.44, and 4.89 mm day^{-1} in 2019, 2020, and 2021, respectively. Cumulative precipitation was negligible during the irrigation season, with only 22 mm, 33 mm, and 40 mm in 2019, 2020, and 2021, respectively. In comparison, cumulative precipitation was 423 mm (between experimental seasons 1 and 2) and 164 mm (between experimental seasons 2 and 3) in the non-irrigation seasons. The maximum daily air temperature of 35, 43 and 37 ^oC was recorded in October 2019, Septemeber 2020 and September 2021. The mean maximum daily air temperature during the irrigation season was 27, 28 and 27 ^oC in 2017, 2018 and 2019, respectively.

2.2. Plot instrumentation and maintenance

In July 2018, this study was established as a randomized complete block design with 48 plots, each of dimensions 3.7 m × 3.7 m and approximately 60–90 cm border between the plots. Twelve irrigation treatments based on field capacity (FC) and irrigation frequency were replicated four times. Each plot was irrigated by four quarter-circle pop-up Hunter Pro-Spray PRO12Q sprinkler heads (Hunter Industries, Inc., San Marcos, CA) with an operating pressure range and flow rate of 138–275 kPa and 2.04–2.95 liters per minute, respectively. A solenoid valve equipped each plot for independent irrigation control. A flow meter (Netafim Irrigation, Inc., Fresno, CA) along with an Acclima 2-wire interface module (Acclima, Inc., Idaho, USA) was installed to precisely record irrigation runtimes and water application in each zone.

An Acclima CS3500 smart irrigation controller (Acclima, Inc., Idaho, USA) was installed and all solenoid valves were wired to the controller. A block was instrumented with soil moisture sensors (Acclima TDT sensors) at a depth of approximately 13 cm and was used for irrigation scheduling by connecting the sensors to the controller. The accuracy of TDT sensors was tested in the lab under a wide range of moisture and salinity levels using packed sieved soil samples collected from the experimental field. The sensors performed very well ($R^2 = 0.97$) with universal factory calibration (Fig. 2). Each treatment was equipped with a separate soil moisture sensor and the controller was wired to irrigate all four replications of the treatment at the same time.

The plots were planted with hybrid bermudagrass sod in August 2018 and were under non-limiting irrigation until the deficit irrigation trial began in June 2019 and was terminated in October 2021. A catch can irrigation uniformity test was performed on the plots in February 2019 following the ANSI/ASABE S626 standard method (ANSI/ASABE, 2016). The catch can test performed at the beginning of the experiment resulted in lower half-distribution uniformity (DU_{LH}) and Christiansen uniformity coefficient (CU) values of 0.85 and 85%, respectively. We

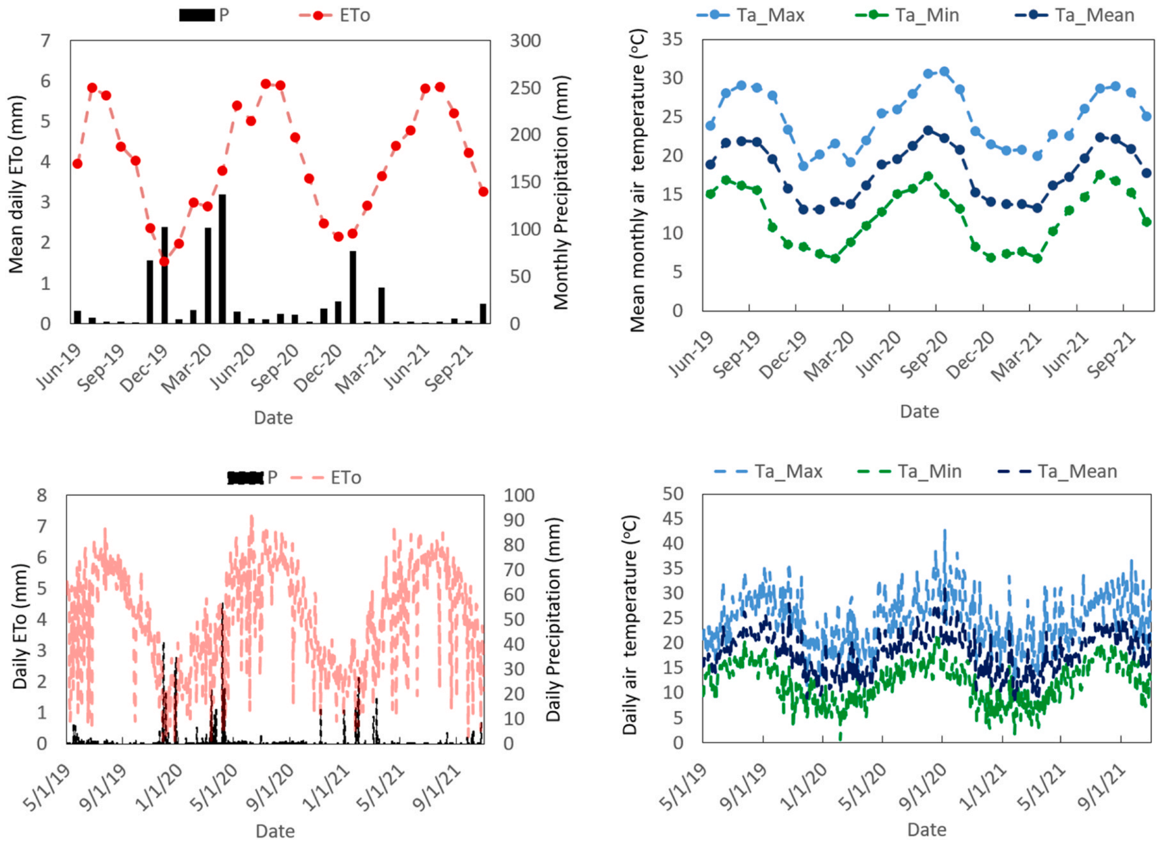

Fig. 1. Reference evapotranspiration (ET_o), precipitation and air temperature variations during the experimental period (May 2019-Septemper 2021) obtained from the CIMIS station #75. Monthly and daily data are shown in the top and bottom panels, respectively.

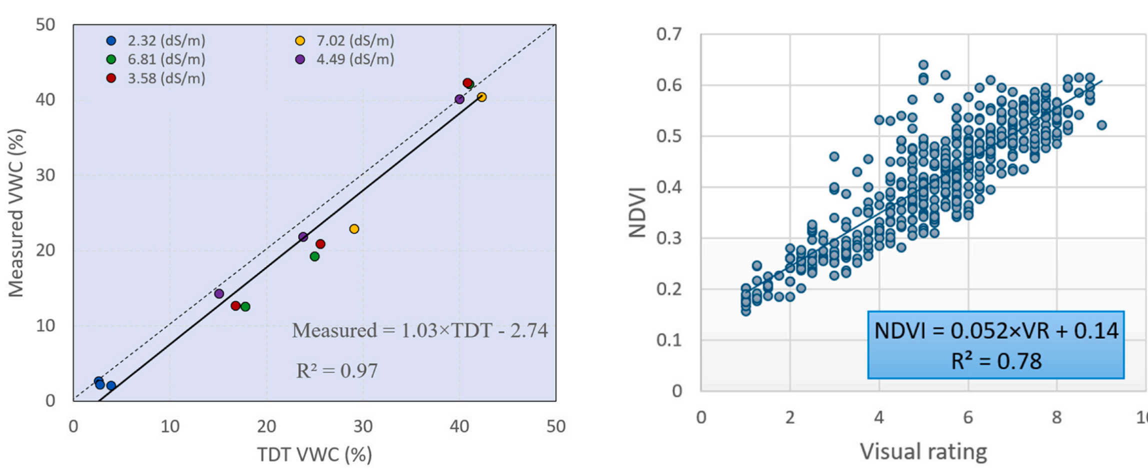

Fig. 2. Left: TDT soil moisture sensor laboratory test results under multiple salinity levels ranging from 2.3 to 7.02 dS/m. **Right:** Relationship between NDVI and visual rating based on data collected in 2019, 2020 and 2021.

followed standard cultural practices to maintain the plots throughout the experimental periods. A reel mower (Evergreen Turf Equipment California Trimmer Model RL257-GX160) was set to mow the plots roughly at the height of 2.54 cm once every week. The fertilizer was applied uniformly to all plots 3–4 times during the active growing season (March to September) at a rate of 0.73 kg/100 m^2, utilizing the UC Guide for Healthy Lawns as a guide. The borders and turfgrass were sprayed, as needed, with Trimec herbicide to control broadleaf weeds in and immediately adjacent to the turfgrass plots.

2.3. *Autonomous irrigation treatments*

Table 1 shows the 12 irrigation treatments implemented in this study consisting of 6 soil moisture thresholds $\times$ 2 irrigation frequencies. The Acclima CS3500 smart irrigation controller required specific lower and upper thresholds for each treatment for irrigation scheduling. The controller triggered irrigation applications when soil moisture was below the lower threshold and ceased watering when it reached the upper threshold or when the maximum watering duration was reached. The manufacturer-recommended levels were FC as the upper limit and soil moisture at 75% of FC (0.75 $\times$ FC) as the lower limit, which results

Table 1
Deficit irrigation treatments based on the soil moisture sensors by setting a lower limit (LL) and upper limit (UL) for allowing and terminating scheduled irrigation events.

Treatment	LL (soil moisture)	UL (soil moisture)	Irrigation Frequency
55–80FC	55%FC (15.0)	FC-20% (21.8)	Restricted
55–100FC	55%FC (16.1)	FC (29.2)	"
65–90FC	65%FC (20.6)	FC-10% (28.6)	"
65–100FC	65%FC (18.8)	FC (28.9)	"
75–100FC	75%FC (24.1)	FC (32.1)	"
75–110FC	75%FC (23.9)	FC+10% (35.0)	"
55–80FC	55%FC (16.6)	FC-20% (24.2)	On-demand
55–100FC	55%FC (17.8)	FC (32.3)	"
65–90FC	65%FC (19.6)	FC-10% (27.1)	"
65–100FC	65%FC (20.0)	FC (30.8)	"
75–100FC	75%FC (19.8)	FC (26.4)	"
75–110FC	75%FC (22.4)	FC+10% (32.9)	"

FC: Field Capacity; LL: Lower limit; UL: upper limit

in a 25% depletion of water holding capacity before the next irrigation event is allowed. Therefore, the soil moisture thresholds were centered around the soil FC, including lower threshold levels of 55, 65 and 75% FC and upper thresholds of 80, 90, and 100% FC. These thresholds were examined to determine the best strategy to reduce irrigation application while maintaining the aesthetic values of turfgrass. The upper threshold for one treatment was set to 110% FC to determine whether such a setting could increase the deep percolation and, therefore, decrease salt accumulation in the root zone. Soil FC was separately determined for each soil moisture sensor. The soil moisture readings 18 hours after heavy rainfall in mid-February 2019 were considered FC for each treatment.

Restricting watering days is a common policy that municipalities in California implement to reduce irrigation applications in urban areas. All irrigation thresholds were implemented for two different irrigation frequency treatments to determine whether watering days restrictions help conserve water without compromising turfgrass quality or if allowing the smart controller to regulate the irrigation frequency based on soil moisture status is more efficient. For restricted irrigation, the maximum frequency was set to 3 days per week, which consisted of three watering windows between 10 pm to 6 am on (I) late night Sunday and early morning Monday, (II) late night Tuesday and early morning Wednesday, and (III) late night Friday and early morning Saturday. This setup prevented the controller from initiating irrigation outside these time frames even if soil moisture was below the lower threshold. The second case was "on-demand" irrigation, in which no restriction on watering days was imposed, and the controller was allowed to initiate and terminate irrigation events (between 10 pm and 6 am) based only on the moisture thresholds. The reason that the controller was programmed to only irrigate overnight was to minimize evaporative water loss and wind drift.

For all irrigation treatments, the controller was preprogrammed with an irrigation schedule consisting of multiple irrigation applications and a maximum watering duration of 5 minutes, followed by an hour of soak time to avoid runoff and allow adequate percolation time. The same irrigation programming was maintained throughout the trial to mimic the real-world irrigation application, i.e., the set-and-forget mentality of the users (Bremer et al., 2013).

2.4. Handheld remote sensing data

The handheld data, including NDVI, turfgrass canopy temperature (T_c), and air temperature (T_a), were collected about once a week close to solar noon on non-cloudy days, 18 times in 2019 (from June 12 to November 15), 20 times in 2020 (from May 4 to September 21), and 21 times in 2021 (from June 7 to October 27). Data were collected by hovering the handheld sensors held at roughly 1 m height over the plots by avoiding the edges, and the average for each plot was recorded. We focused on the summer months since water demand is high due to the high ET demand (Balling et al., 2008) and because hybrid bermudagrass goes dormant over the winter. We used a GreenSeeker (Trimble Inc., Sunnyvale, CA) handheld crop sensor for NDVI measurements, a Fluke 64 Max infrared thermometer (Fluke Corporation, Everett, WA) to measure T_c, and a Fluke 971 Temperature Humidity Meter (Fluke Corporation, Everett, WA, USA) to measure T_a. The NDVI sensor emits brief bursts of red and infrared light and then measures the amount of each type of light that is reflected from the plant. NDVI is sensitive to sparse vegetation, which makes it ideal for use in turfgrass. The data were used to assess the effect of different irrigation scenarios on overall turfgrass health and to monitor water stress.

Visual rating of the plots was performed by an experienced rater using digital photos taken from the plots on the exact dates on which handheld data were collected. The rating was done according to the standards set by the National Turfgrass Evaluation Program (NTEP). In the NTEP standard, scores 1 and 9 are assigned to a brown/dead plot and an ideal turfgrass, respectively. A visual score of six is considered the minimum acceptable threshold for residential areas. (Morris and Shearman, 1998). NDVI equal to 0.45 was established as the minimum threshold to maintain an acceptable quality of hybrid bermudagrass (visual rating $\geq$ 6) for residential areas based on a linear regression equation fitted to the data (Fig. 2).

2.5. Soil sampling

Soil samples were collected biannually, beforeand after the irrigation season, from a depth of 0–60 cm in increments of 15 cm. Samples were collected on May 1 and October 14, 2019, May 6 and October 13, 2020, and April 23 and October 11, 2021. We collected samples from all the plots, and repetitions from the same treatment were mixed to make a composite soil sample before analyzing in the lab. Soil samples were air-dried in the oven at 55 ^{o}C and then sieved through a 2 mm sieve. Saturated soil pastes were prepared with deionized water using ~200 g of air-dried soil and were allowed to stand overnight prior to vacuum filtration (Rhoades, 1982). Soil salinity (EC_e) was measured from the paste extract using Orion Star™ A212 conductivity meter with Orion™ DuraProbe™ 4-Electrode Conductivity Cell (Thermo Fisher Scientific Inc.). The sodium adsorption ratio (SAR) was also measured, providing information on the comparative concentration of Na^+, Ca^{2+}, and Mg^{2+} in the soil solution. It is defined as follows:

$$SAR = \frac{[Na]}{\sqrt{\frac{([Ca]+[Mg])}{2}}} \quad (1)$$

where concentration is expressed in milliequivalents per liter (meq/l).

2.6. Statistical analysis

Data for 2019, 2020, and 2021 were analyzed separately due to significant differences observed in irrigation application and hybrid bermudagrass quality measured by NDVI. Analysis of temperature difference between turfgrass and air (T_c - T_a) and NDVI measurements was performed using repeated-measures ANOVA with spatial power error structure in statistical software 'R' (R Core Team, 2021). For statistical analysis of soil samples, the differences between the means of irrigation frequency were established using a t-test and between different depths, using the one-way ANOVA/one-sample Wilcoxon rank test and Tukey multiple comparison tests at a 0.05 significance level. Normality was assessed by the Shapiro-Wilk normality test, and we used the F-test to test for homogeneity in variances.

3. Results

3.1. Irrigation applications

The daily average EC of irrigation water (ECw) was 1.18 dS/m and ranged from 0.92 to 1.65 dS/m during the experimental period, based on the data recorded by an electrical conductivity sensor, ES-2 (Meter Group Inc., Pullman, WA, USA), installed in the irrigation supply pipe. The maximum reported concentrations in the recycled water were 0.38 mg/L for boron, 168 mg/L for bicarbonate, 165 mg/L for chloride, and 61 mg/L for sodium. These levels indicate no restriction on the use for irrigation for boron and sodium, but slight to moderate restriction for bicarbonate and chloride (Harivandi, 1999). Regularly mowed turfgrass can tolerate moderate levels of chloride since it can be absorbed by turfgrass leaves (Harivandi, 1999). Substantial bicarbonate levels in irrigation water may affect soil permeability, but our infiltration measurements (results not shown here) did not indicate permeability issues on our plots. The concentrations of inorganic chemicals, including heavy metals (e.g., arsenic, copper, lead, mercury, and zinc), were in the microgram per liter range.

Irrigation application and soil moisture fluctuations for all treatments and years are shown in Figs. 3–5. We observed a good response from the smart controller to schedule irrigation based on the implemented thresholds. Analysis of irrigation runtime data showed that actual irrigation frequencies for restricted (3 d/week) irrigation treatments ranged from 2.6 to 4.0 d/week in 2019, 2.4–4.4 d/week in 2020, and 1.7–3.4 d/week in 2021. For on-demand irrigation treatments, the actual irrigation frequencies ranged from 2.6 to 4.0 d/week in 2019, 3.0–4.7 d/week in 2020, and from 2.2 to 3.4 d/week in 2021. The reason for higher than 3d/week averages for restricted irrigation treatments is likely the controller crossing midnight to complete the irrigation cycles since it was programmed to irrigate late at night.

Average soil moisture during 2019 irrigation ranged from 16.0% (55–80FC) to 25.8% (75–110FC) for restricted irrigation and 18.7%

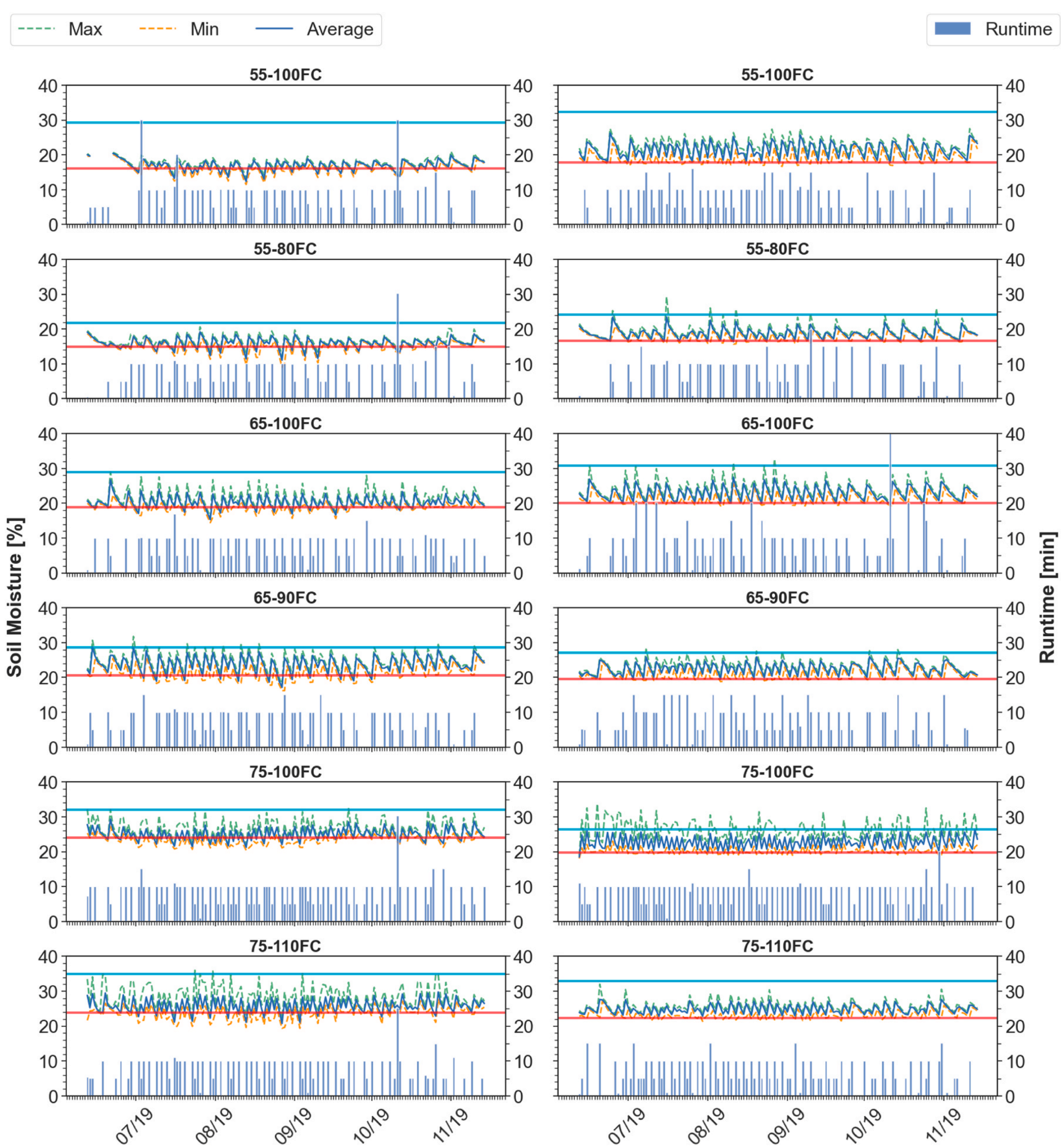

Fig. 3. Soil moisture and irrigation runtime for restricted (3 days/week) and on-demand (7days/week) irrigation treatments implemented in 2019. Solid red and dark blue lines are the lower (LL) and upper (UL) soil moisture threshold levels, respectively.

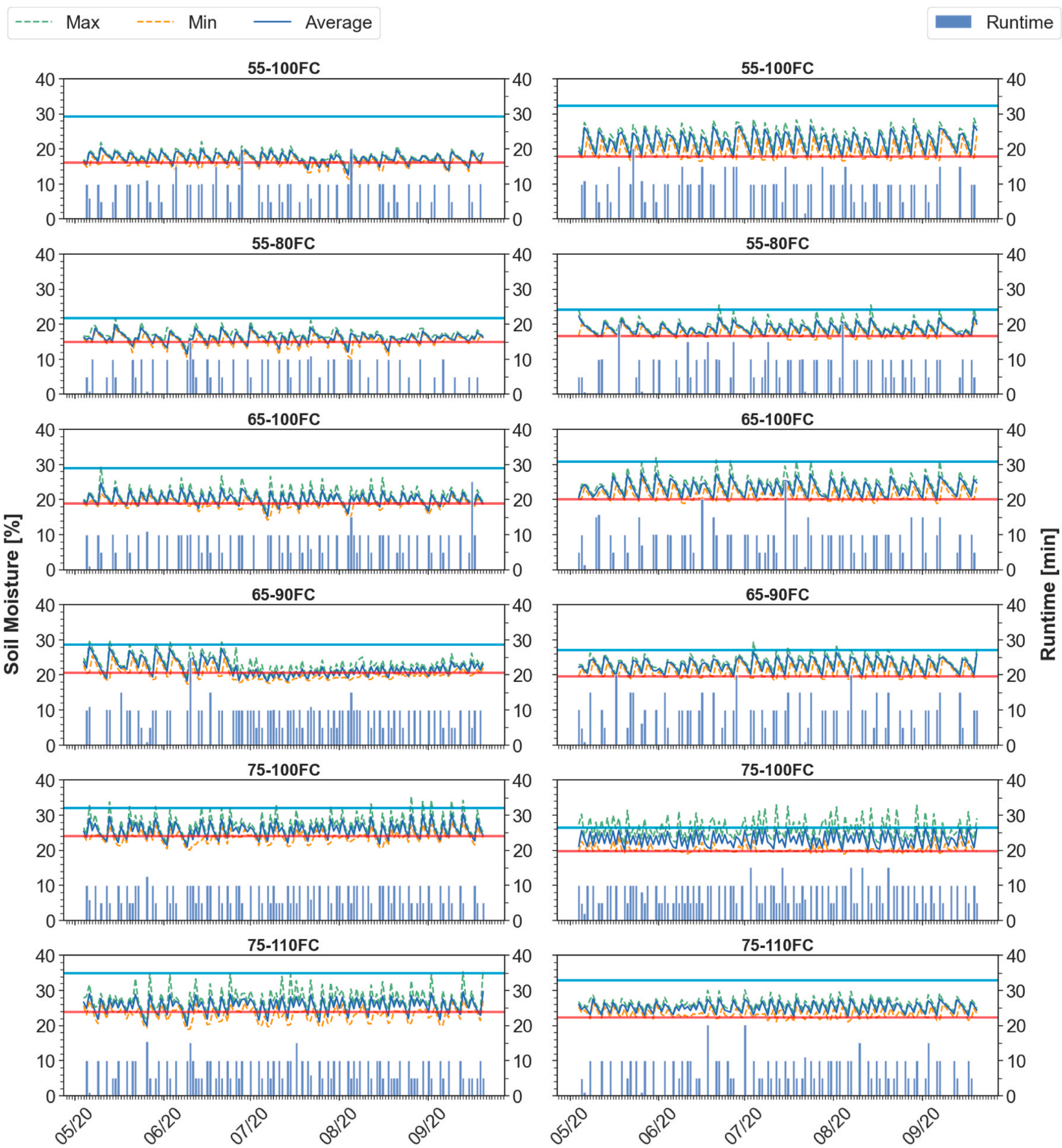

Fig. 4. Soil moisture and irrigation runtime for restricted (3 days/week) and on-demand (7 days/week) irrigation treatments implemented in 2020. Solid red and dark blue lines are the lower (UL) and upper (UL) soil moisture threshold levels, respectively.

(55–80FC) to 24.8% (75–110FC) for on-demand irrigation treatments. In 2020, the average soil moisture ranged from 16.1% (55–80FC) to 25.7% (75–100FC & 75–110FC) for restricted and 18.6 (55–80FC) to 25.2% (75–110FC) for on-demand irrigation treatments. In 2021, soil moisture ranged from 16.6% (55–80FC) to 25.7% (75–100FC) for restricted and 18.6% (55–80FC) to 25.4% (75–100FC) for on-demand irrigation treatments. Overall, on-demand irrigation kept the average soil moisture very stable across years for all the irrigation treatments such that, on average, less than 1% soil moisture difference between years for the same treatments was observed.

Based on the calibrated flow meter readings, the actual applied irrigation varied from 66% to 109% ET_o in 2019 for 55–80FC on-demand and 75–100FC on-demand treatments, respectively. In 2020, irrigation application varied between 51% and 104% ET_o for the 55–80FC restricted and 75–100FC on-demand, respectively. The maximum and minimum water applications were 29% ET_o for 55–80FC restricted and 88% ET_o for 75–100FC on-demand in 2021. Increasing the upper threshold to 110% (75–100FC versus 75–110FC) did not cause additional water application, except in 2021 for restricted frequency. Overall, decreasing the lower irrigation threshold reduced the total water applied, but lowering the upper threshold did not always cause a decrease in irrigation application. For instance, in most cases, the water applied under 65–90FC treatment was the same or more than the irrigation application under 65–100FC treatment.

Table 2 also shows the actual irrigation days for the irrigation season in each year. For 2019, the average number of days when the irrigation was triggered was 71 and 69 for restricted and on-demand irrigation treatments, respectively, out of 156 total irrigation days. For 2020, the average number of days the irrigation was triggered was 70 and 67 for restricted and on-demand irrigation treatments, respectively, out of 140 total irrigation days. For 2021, the average number of days when the irrigation was triggered was 51 and 54 for restricted and on-demand irrigation treatments, respectively, out of 142 total irrigation days. In 2019 and 2020, treatments 55–80FC and 75–100FC had the minimum

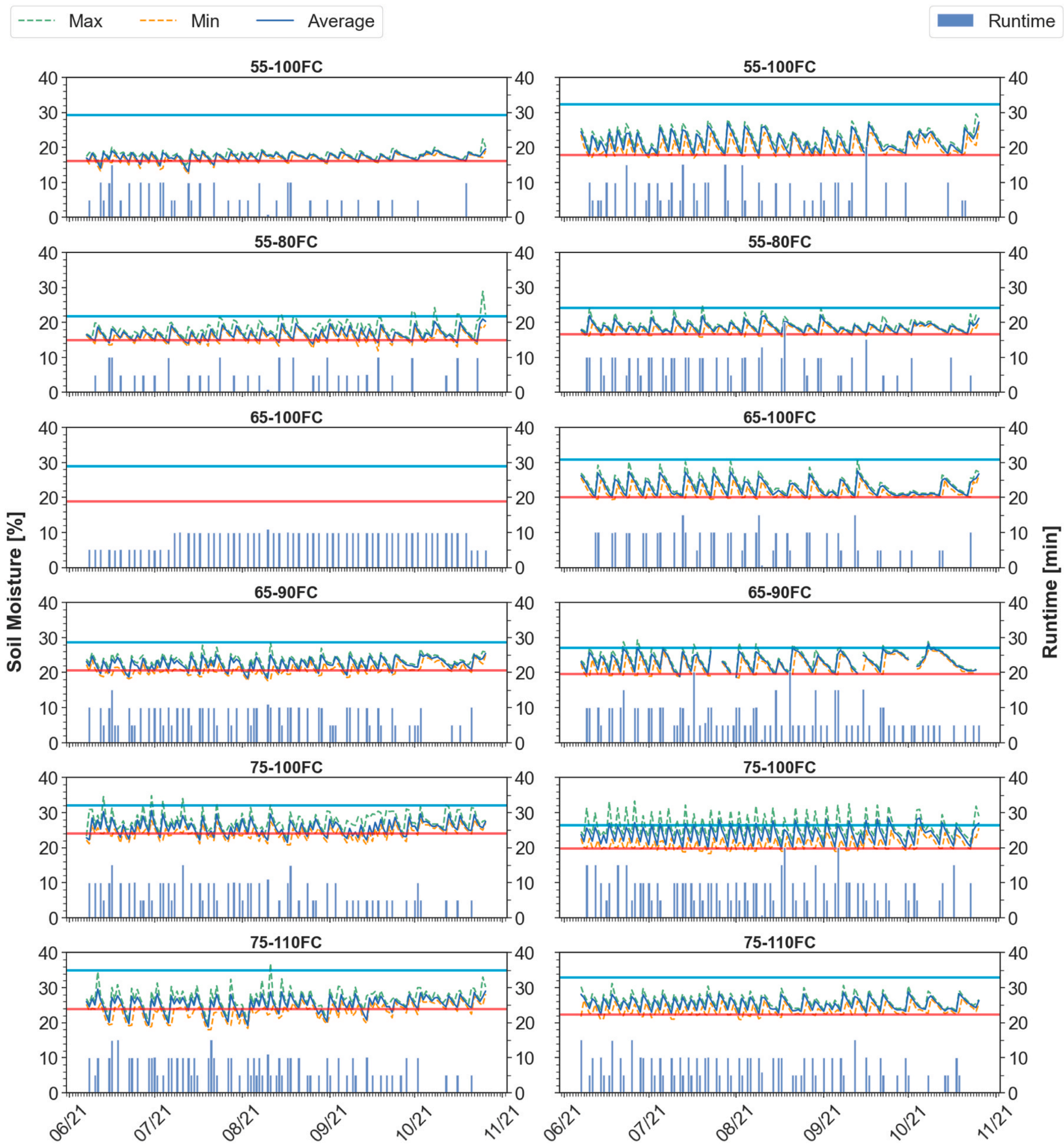

Fig. 5. Soil moisture and irrigation runtime for restricted (3 days/week) and on-demand (7 days/week) irrigation treatments implemented in 2021. Solid red and dark blue lines are the lower (UL) and upper (UL) soil moisture threshold levels, respectively.

and maximum number of irrigation days, respectively, for both restricted and on-demand irrigation scenarios. In 2021, however, the minimum irrigation days were in 55–100FC (restricted frequency) and 65–100FC (on-demand) treatments.

The number of days when the average daily soil moisture was lower than the lower soil moisture threshold for each treatment is also summarized in Table 2. For 2019 (n=156), this ranged from 18 to 49 for the restricted treatment, whereas from 0 to 2 for the on-demand treatments. Treatment 75–100FC (restricted) had the maximum number of days (49) in which soil moisture readings were below the lower threshold in 2019. For 2020 (n=140), the number of days lower than the lower soil moisture threshold ranged from 26 to 47 for restricted and from 0 to 7 for the on-demand irrigation frequency treatments. Treatment 65–90FC (restricted) had the maximum number of days (47) in which soil moisture readings were below the lower threshold in 2020. For 2021 (n= 142), this ranged from 15 to 34 for restricted and from 0 to 3 for the on-demand treatments. In 2021, the maximum number of days (49) in which soil moisture readings were below the lower threshold was for 75–100FC restricted treatment.

3.2. NDVI and Temperature Difference

Table 3 shows the results of the statistical analysis for the NDVI and temperature difference. Treatments 65–100FC are not shown in Table 3 for 2021 because a sensor malfunction impacted the 65–100FC treatment for the restricted irrigation frequency; however, the on-demand irrigation treatment is shown in Fig. 5 for reference. The NDVI values ranged from 0.25 to 0.76 in 2019, 0.19–0.69 in 2020, and 0.15–0.62 in 2021. In the three years, the highest deficit irrigation treatments had the lowest average NDVI, while the lowest deficit irrigation treatments had the highest average NDVI (Table 3). Irrigation levels significantly affected NDVI values in all three years ($p < 0.001$). Irrigation frequency restrictions also showed a significant impact on NDVI in 2019 ($p < 0.05$), 2020 ($p < 0.01$), and 2021 ($p < 0.001$). The interaction of

Table 2
Percent of ET_o applied, irrigation days, and number of days the average soil moisture was lower than the Lower Limit (LL) for each treatment during the experimental period.

	2019 (n=156)		2020 (n=140)		2021(n=142)	
Treatment	**Restricted**	**On-demand**	**Restricted**	**On-demand**	**Restricted**	**On-demand**
55–80FC	69%	66%	51%	71%	29%	46%
55–100FC	77%	76%	70%	82%	37%	51%
65–90FC	82%	81%	103%	82%	75%	76%
65–100FC	82%	81%	74%	78%	-	50%
75–100FC	108%	109%	94%	104%	68%	88%
75–110FC	89%	85%	87%	76%	79%	69%
Irrigation days triggered by Smart Irrigation Controller						
55–80FC	58	50	45	56	30	42
55–100FC	60	67	58	63	32	42
65–90FC	67	65	84	59	62	68
65–100FC	68	61	63	61	-	41
75–100FC	92	91	88	94	57	66
75–110FC	78	78	84	68	63	62
Number of Days the average daily soil moisture was lower than the Lower Limits						
55–80FC	34	2	26	7	25	3
55–100FC	36	0	26	5	15	0
65–90FC	18	1	47	6	24	3
65–100FC	25	2	26	2	-	1
75–100FC	49	1	38	0	34	3
75–110FC	23	0	28	0	33	2

n= total number of irrigation days during each irrigation season. FC= field capacity. Sensor malfunction impacted the 65–100FC treatment for the restricted irrigation frequency in 2021.

Table 3
Statistical analysis of the hybrid bermudagrass response in terms of normalized difference vegetation index (NDVI) and temperature difference between turfgrass and air (dT) to irrigation treatments in years 2019, 2020, and 2021 (each year was analyzed separately).

	2019		2020		2021	
Soil moisture treatments	**NDVI**	**Temperature difference [°C]**	**NDVI**	**Temperature difference [°C]**	**NDVI**	**Temperature difference [°C]**
55–80FC	0.55 a	7.54c	0.41 a	11.8c	0.28 a	18.04 b
55–100FC	0.56 ab	6.88 bc	0.45 b	10.13 bc	0.27 a	16.87 b
65–90FC	0.62 cd	6.42 abc	0.50c	9.29 ab	0.42c	9.84 a
65–100FC	0.59 bc	6.18 abc	0.47 bc	9.38 ab	na	na
75–100FC	0.64 d	5.08 a	0.55 d	7.75 a	0.41c	9.66 a
75–110FC	0.62 cd	5.67 ab	0.49c	8.46 ab	0.37 b	10.94 a
Irrigation Frequency						
Restricted	0.59 a	6.36 a	0.47 a	9.93 b	0.32 a	14.5 b
On-demand	0.60 b	6.23 a	0.49 b	9.00 a	0.38 b	11.7 a
p-value						
I	***	***	***	***	***	***
F	*	NS	**	*	***	***
I x F	NS	NS	***	**	***	***
T	***	NS	***	NS	***	NS
I x T	NS	NS	***	NS	**	NS
F x T	NS	NS	NS	NS	NS	NS
I x F x T	NS	NS	*	NS	***	*

NS, ***, **, and * are non-significant or significant at $p \leq 0.001$, 0.01, and 0.05, respectively. Means sharing a similar letter are not significantly different, based on Tukey's test at significance level (α) = 0.05. I, F, and T in the table refer to irrigation levels, frequency, and time (i.e., repeated measures of NDVI or dT each year over time), respectively. Sensor malfunction impacted the 65–100FC treatment for the restricted irrigation frequency in 2021.

irrigation levels and frequency had no significant effect on NDVI in 2019, while the effect was significant in 2020 ($p < 0.001$) and 2021 ($p < 0.001$).

Fig. 6 shows the dynamics of NDVI values over time across the irrigation treatments for 2019, 2020, and 2021. All treatments showed a steady decline in NDVI during the data collection period in 2019. All treatments, however, stayed above the acceptable quality range, i.e., NDVI of 0.45, except for treatments with 55FC as the lower threshold. In 2020, NDVI remained above the acceptable quality range for the highest irrigated treatment (75–100FC) for both irrigation frequency treatments. Other irrigation treatments saw a steady decline in the NDVI as the summer progressed, and the decline was steeper for the restricted irrigation frequency treatments (Fig. 6). In 2021, NDVI for most treatments dropped below the acceptable quality range except for the on-demand 75–100FC treatment, which maintained NDVI≥0.45 (Fig. 6) until early September. The decline in NDVI values was more evident in 3-day irrigation frequency treatments as the summer progressed.

Fig. 7 shows the dynamics of turfgrass temperature across the irrigation treatments for 2019, 2020, and 2021. The temperature difference values ranged from -2.3–33.9 °C in 2019, from -2.5–36.19 °C in 2020, and from -1.4–34.7 °C in 2021. Irrigation levels showed a significant effect ($p < 0.001$) on the temperature difference in all three years (Table 3). Irrigation frequency restrictions did not have a significant effect on the temperature difference in 2019, while there was a significant effect in 2020 ($p < 0.05$) and 2021 ($p < 0.001$), as the temperature difference was lower for the on-demand treatments than for treatments with restricted irrigation frequency. The on-demand irrigation treatments resulted in a 2, 9, and 19% decrease in temperature difference compared to the restricted irrigation treatments in 2019, 2020, and 2021, respectively. The interaction of irrigation levels and frequency had no significant effect on turfgrass temperature in 2019, while there was a significant effect in 2020 ($p < 0.01$) and 2021 ($p < 0.05$). Overall,

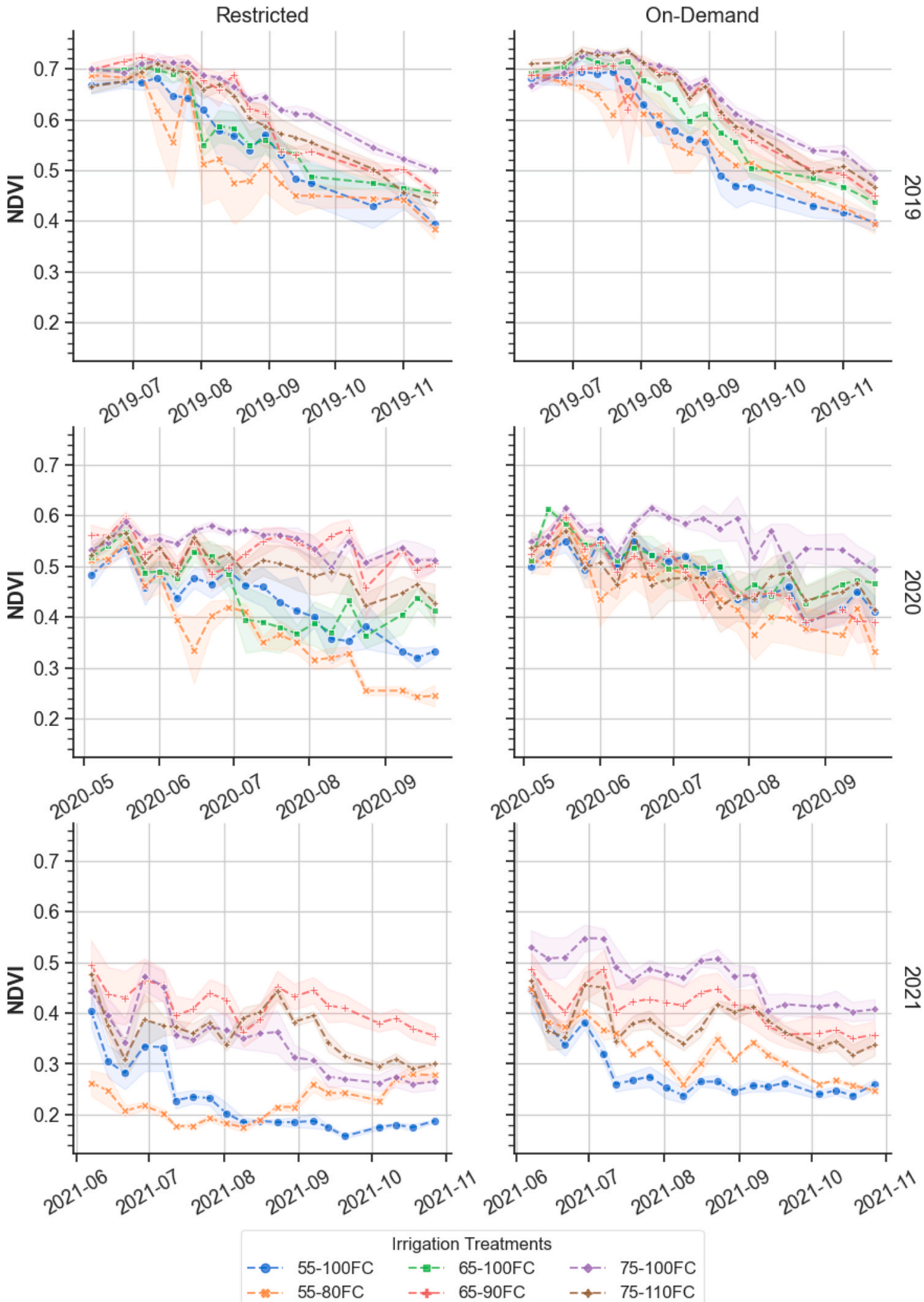

Fig. 6. Changes in normalized difference vegetation index (NDVI) values over time across the irrigation treatments for the restricted (3 days/week) and on-demand (7 days/week) irrigation treatments imposed in 2019, 2020, and 2021. Colored bands represent the standard error for each irrigation treatment.

all treatments showed similar trends during the data collection period in the three years, while fluctuations were more pronounced as the experiment progressed from 2019 to 2021 and were more noticeable in restricted irrigation treatments (3 days/week). Water stress in some plots caused patches of dead turfgrass, which increased the average temperature of the plots to very high values, as is evident in 55–80FC and 55–100FC restricted treatments in 2021.

3.3. Soil salinity

Soil salinity (EC_e) ranged from 0.79 dS/m to 1.66 dS/m in spring 2019 and 0.82–2.98 dS/m in fall 2019. In 2020, soil salinity ranged from 0.45 dS/m to 1.56 dS/m in spring and 0.52–3.90 dS/m in fall. In 2021, soil salinity ranged from 0.73 dS/m to 2.37 dS/m in the spring and from 1.13–4.72 dS/m in the fall. As shown in Fig. 8, soil salinity increased in the fall season, especially in shallow soil depths (0–30 cm), indicating the accumulation of salts due to high ET demand over summer. There was no significant difference between soil moisture threshold-based treatments and irrigation frequencies for soil salinity. Samples collected in spring were associated with lower soil salinity than fall samples. High rainfall before the spring 2020 sampling (Fig. 1) reduced salinity compared to the spring of 2019 and 2021 (Fig. 8). The distribution of soil salinity at different depths varied with the irrigation season since spring samples showed significantly higher accumulation at 0–15 cm depth, while 15–30 cm depth had substantially higher accumulation in fall (Table 4).

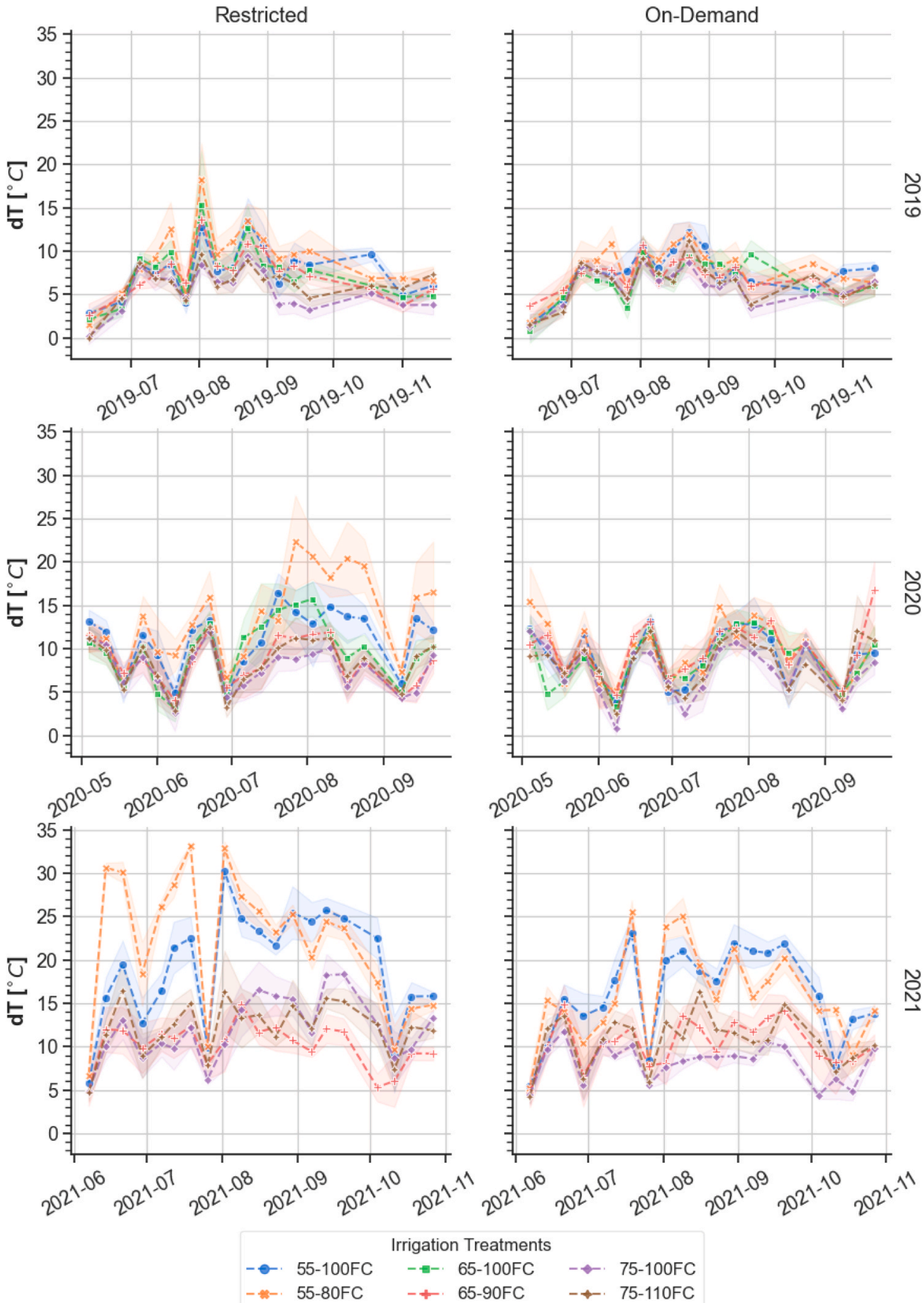

Fig. 7. Changes in temperature difference (*dT*) values over time across the irrigation treatments for the restricted (3 days/week) and on-demand (7 days/week) irrigation treatments imposed in 2019, 2020, and 2021. Colored bands represent the standard error for each irrigation treatment.

The sodium adsorption ratio (SAR) ranged from 1.67 to 4.68 in spring 2020 and 1.68–5.51 in fall 2020. The SAR ranged from 2.89 to 5.68 in the spring and 3.26–7.76 in the fall of 2020. The irrigation frequency did not have a significant effect on SAR, except in spring 2020, as shown in Table 4. SAR distribution at different depths varied with the irrigation season, as spring-collected samples showed significantly higher values at the middle depths (30–45 cm), while shallow depths, particularly 0–30 cm, had significantly higher values in the fall. Overall, the SAR values stayed below the excessive sodium threshold of 13.

4. Discussion

4.1. Autonomous SMS-based irrigation scheduling

On-demand irrigation with proper threshold settings can allow complete irrigation automation and potentially higher water savings. Our recent studies in southern California using ET-based smart controllers revealed that on-demand irrigation is a better option than restricting watering days since it allows the controller to regulate the watering days based on actual atmospheric evaporative demand (Haghverdi et al., 2021C, 2023). Some studies also reported lower irrigation applications by SMS-based irrigation using on-demand irrigation

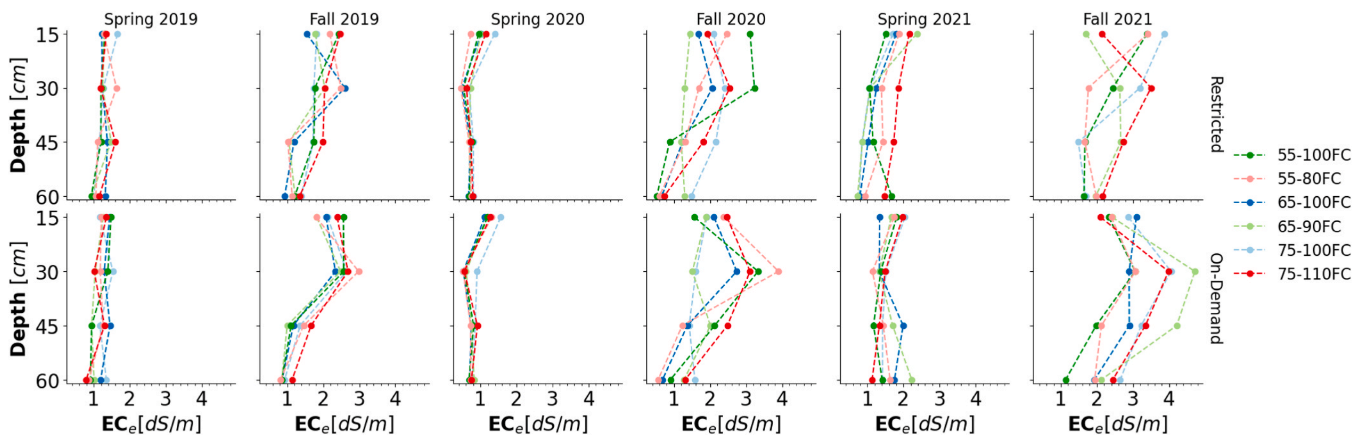

Fig. 8. Soil salinity (EC_e) distribution in the soil profile from soil samples collected before (Spring) and after (Fall) of the summer irrigation seasons for 2019, 2020, and 2021.

Table 4
Statistical analysis of the soil samples collected before (Spring) and after (Fall) the 2019, 2020 and 2021 irrigation seasons.

		Depth (cm)				Irrigation Frequency	
		0–15	15–30	30–45	45–60	3 (days/week)	on-demand
5/1/2019	**ECe**	1.33 b	1.27 b	1.25 b	1.04 a	1.26 a	1.19 a
	SAR						
10/14/2019	**ECe**	2.08 b	2.37 b	1.37 a	1.06 a	1.70 a	1.74 a
	SAR						
5/6/2020	**ECe**	1.16c	0.59 a	0.76 b	0.74 b	0.77 a	0.85 a
	SAR	2.19 a	4.06c	4.09c	3.20 b	3.28 a	3.49 a
10/13/2020	**ECe**	2.09 bc	2.45c	1.60 b	0.97 a	1.66 a	1.89 a
	SAR	4.76 b	4.74 b	4.61 b	2.93 a	4.40 a	4.12 a
4/23/2021	**ECe**	1.83 b	1.32 a	1.34 a	1.33 a	1.36 a	1.56 a
	SAR	3.94 ab	4.8c	4.35 bc	3.61 a	3.76 a	4.59 b
10/11/2021	**ECe**	2.7 ab	3.21 b	2.55 ab	1.97 a	2.39 a	2.79 a
	SAR	6.22 b	6.07 b	5.05 a	4.25 a	5.33 a	5.45 a

Means sharing a similar letter is not significantly different at the significance level (α) = 0.05. Sensor malfunction impacted the 65–100FC treatment for the restricted irrigation frequency in 2021.

scenarios (Cardenas-Lailhacar et al., 2008; Cardenas-Lailhacar and Dukes, 2012). However, we did not observe considerable differences in average irrigation applications between restricted and on-demand irrigation treatments. Nonetheless, on-demand irrigation could be the optimum programming choice during dry months in southern California. Furthermore, allowing SMS to decide when to irrigate results in running the irrigation for shorter periods, thus efficiently maintaining soil moisture between the programmed thresholds. This is evident from Table 2 (and Figs. 3–5), where soil moisture fell below the lower threshold limit several times for restricted treatments during the experiment since the controller was programmed to allow irrigation for only three days a week. In comparison, on-demand irrigation did not irrigate more days or in higher quantities. Still, it kept the soil moisture closer to the lower threshold simply because it was allowed to irrigate as needed with no restrictions on watering days (Table 2).

The importance of understanding the smart controller settings for irrigation scheduling has been emphasized in the literature (Davis and Dukes, 2016). The actual water applied by the irrigation controller in three years of the study was substantially lower than the reference ET_o across all treatments. The applied irrigation water steadily decreased each year, as also shown in Table 2, although the same soil moisture thresholds were maintained throughout the three-year experimental period. A potential reason could be the development of thatch over time, which reduces the demand for ET and thus increases the moisture-holding capacity of the soil (Liang et al., 2017). Furthermore, the relatively lower ET_o and higher precipitation in the 2021 irrigation season may also have been attributed to the reduced irrigation applications. Irrigation water with a high salt content increases the natural salinity of the soil, increases the permittivity of the soil, and affects the estimated dielectric permittivity, especially when EC exceeds a certain threshold (Zemni et al., 2019), which can negatively affect soil moisture readings. However, Our laboratory test revealed a high accuracy level for the TDT sensors used in this study, even at high salinity levels up to 7 dS/m (Fig. 1).

Commercial SMS-based controllers typically use only one soil moisture sensor per hydrozone to regulate irrigation. Our results showed that the controller successfully kept the average soil moisture stable across the years and close to the programmed threshold for on-demand irrigation. But, having only one sensor does not provide enough information about root water uptake patterns and soil moisture status in deeper layers. In addition, soil moisture-based thresholds may be inefficient when soil is relatively wet, yet salinity build-up makes water uptake difficult for plants. Future studies are needed to investigate the possibility of incorporating more than one soil moisture sensor or plant sensor (e.g., NDVI, canopy temperature) in irrigation thresholds.

4.2. *Response of bermudagrass to deficit irrigation with recycled water*

Our recent studies using ET-based irrigation controllers revealed 75% ET_o as the minimum required irrigation application for hybrid bermudagrass in inland southern California (Haghverdi et al., 2021c). We also showed that more severe deficit irrigation levels are only feasible for shorter periods before the quality of hybrid bermudagrass falls below the acceptable level (Haghverdi et al., 2021c). This study also showed that treatments irrigated with more than 75% ET_o resulted in an acceptable quality of hybrid bermudagrass (NDVI $\geq$0.45) for more extended periods during the irrigation season (Fig. 6, Table 3). Our results are consistent with the findings of (Bañuelos et al., 2011), who reported 66–75% actual irrigation application requirement to maintain the acceptable quality of hybrid bermudagrass under deficit recycled water irrigation in Arizona. Crop coefficients of 0.65 and 0.76 have also been reported for deficit and well-watered hybrid bermudagrass, respectively (Colmer et al., 2017). This indicates that further investigations are required to reevaluate under field conditions the commonly accepted 0.6 crop coefficient for hybrid bermudagrass (Dean et al., 1996; Meyer and Gibeault, 1986).

We observed a decline in hybrid bermudagrass quality from year 1 to year 3 of our trial. We attribute this mainly to the fact that damage caused by summer deficit irrigation cannot be completely reversed through soil water recharge over the winter, which agrees with the study by (Bañuelos et al., 2011). The effect of deficit irrigation on the green-up of hybrid bermudagrass in successive years suggests a cumulative effect of drought stress and is also noted in another study (Hejl et al., 2016).

On-demand irrigation resulted in a 10% reduction in temperature difference (*dT*) during the study period while maintaining relatively better turfgrass quality than restricted irrigation. We attribute this to a more pronounced evaporative cooling associated with on-demand irrigation while minimizing runoff and deep percolation. In addition, the irrigated urban landscape can reduce daytime temperatures through ET, thus moderating the climate of urban areas (Shashua-Bar et al., 2009). A previous study in Los Angeles reported that irrigation-induced increases in latent heat flux could lead to land surface temperature reductions in urban parks (Vahmani and Hogue, 2014). Furthermore, (Bonfils and Lobell, 2007) demonstrated the significant cooling effect of irrigation expansion on the summertime average daily daytime temperatures in California.

4.3. Soil salinity and SAR under deficit recycled water irrigation

Deficit irrigation with recycled water increased soil salinity, which oscillated with the rainy season, as precipitation resulted in the leaching of salts. Samples collected after the irrigation season were associated with the highest salinity measurements, while samples collected before the irrigation season had the lowest salinity measurements, which is consistent with the findings of studies utilizing recycled water or deficit irrigation strategies (Aragüés et al., 2014; Lockett et al., 2008). On average, there was a 51% increase in soil salinity in the fall of 2021 compared to the fall of 2019. Lockett et al. (2008) observed the greatest fluctuation in soil salinity at the shallowest depth of 15 cm in golf courses irrigated with recycled water, which agrees with the results observed in our study with the most seasonal fluctuation in soil salinity observed at the 0–30 cm of depth (Fig. 8). Changes in soil EC_e and SAR reflected seasonal changes in irrigation and natural precipitation, as EC_e and SAR values were highest in the fall and lowest in the spring following the precipitation events. The greater accumulation of salts is due to relatively lower irrigation water being applied by the controller as the experiment progressed, thus leaving less remaining water available to leach salts from the root zone. Our results showed that setting the upper threshold above FC did not translate to additional water applications and, therefore did not reduce salinity values compared to other treatments. Therefore, we do not recommended it as an effective strategy to increase leaching.

Sevostianova et al. (2011) noted the acceptable quality of hybrid bermudagrass under saline irrigation (110% ET_o) in New Mexico. On the contrary, we observed a reduction in the turfgrass quality under deficit recycled water irrigation, which could be partly attributed to increased salinity in the rootzone over time despite seasonal leaching by rainfall. Increased salinity is expected to have an osmotic effect and make the water uptake more difficult for turfgrass, exacerbating the water stress symptoms. Based on the extensive literature review conducted by Carrow and Duncan (1998), the salinity threshold (ECe) for hybrid bermudagrass ranged from 0 to 10 dS/m, depending on the cultivar and the average threshold across studies was 3.7 dS/m. Chang et al. (2019) reported a decline in well-watered sand-based 'Tifway' bermudagrass quality to unacceptable levels and also observed a noticeable decrease in nitrogen uptake when soil EC levels at 2.5 cm depth reached 3–5 dS/m. The salinity of our irrigation water was much lower than 10 dS/m used by Chang et al. (2019), yet our soil salinity reached 3.90 and 4.72 dS/m in the fall of 2020 and 2021, respectively. We attribute this to deficit irrigation and our multiyear study, which increased salt accumulation and associated negative impacts on plants (Acosta-Motos et al., 2017).

Recycled water irrigation can increase the SAR of the soil, which can cause infiltration issues. High rainfall enhances the leaching of Na and K more than that of Ca and Mg since these are more soluble cations, which can explain the high SAR at deeper depths after the rainy season. Our study showed an increase in SAR. This agrees with the results from a study in 7 parks in Beijing, China, indicating an increase in soil salinity and SAR with recycled water irrigation compared to tap water (Chen et al., 2015). Aragüés et al. (2014) also highlighted the high transient salinity and sodicity risk under the combined effects of recycled and deficit drip irrigation in Mandarin trees. They concluded that soil water deficits should be avoided whenever saline recycled water is used for irrigation. Although seasonal rainfall reduced the soil salinity (Fig. 8) in our study, a steady increase in salinity and SAR over these cyclic occurrences needs to be further investigated. Adding a leaching fraction to the required irrigation to manage the salinity accumulation (Ayers and Westcot, 1985; Domínguez et al., 2011; Semiz et al., 2022) might be necessary if seasonal rainfall is insufficient to leach down the salts. More studies are needed to investigate whether manual application of additional water for adequate leaching and turfgrass recovery or adjusting irrigation thresholds over time could be effective management strategies to help maintain the quality of turfgrass under autonomous SMS-based irrigation on a long-term basis in a semiarid climate.

5. Conclusion

This study focuses on the performance of the Acclima smart SMS-based irrigation controller for autonomous hybrid bermudagrass deficit recycled water irrigation scheduling. We observed that irrigating with soil moisture thresholds maintained between field capacity and 75% of field capacity results in acceptable visual quality of hybrid bermudagrass, with a minimum NDVI of 0.45 over extended periods. This corresponds to at least 75% ET_o applied for irrigation, a significantly higher rate than the nominal recommended crop coefficient of 60% ET_o for warm-season turfgrass species. On-demand irrigation (without restrictions on watering days) resulted in better quality and lower hybrid bermudagrass temperatures compared to a 3 days/week watering restriction. This was achieved by maintaining soil moisture levels at higher values, which, in turn, reduced the number of days when the soil moisture level dropped below the minimum programmed thresholds. Soil salinity exhibited seasonal oscillations due to rainfall during the non-irrigation season, while there was a steady increase in salinity and SAR as the experiment progressed. The increase in salinity was attributed to the combined effects of deficit irrigation and high ET demands during the summer. Our findings indicate that the natural rainfall during winter in semiarid regions such as southern California might not sufficiently mitigate rootzone salt accumulation and fully resolve the adverse effects of summer deficit irrigation on hybrid bermudagrass. Consequently, the quality of hybrid bermudagrass could suffer over prolonged periods under fully autonomous recycled water deficit irrigation management using SMS-based irrigation controllers.

CRediT authorship contribution statement

Anish Sapkota: Writing – review & editing, Data curation. **Darren Haver:** Writing – review & editing, Resources, Project administration, Investigation, Data curation. **Amir Haghverdi:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Amninder Singh:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Jean Claude Iradukunda:** Writing – review & editing, Data curation.

Declaration of Competing Interest

The authors declare that they have no conflict of interest.

Data Availability

Data will be made available on request.

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