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Water Conservation Practices and Nitrogen Fertility for the Reduction of Greenhouse Gas Emissions from Creeping Bentgrass Putting Greens

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Abstract: Irrigation practices that conserve water use have the potential to reduce greenhouse gas (GHG) emissions but may adversely affect turfgrass appearance. The purpose of this study was to identify irrigation practices and N fertilizers that will decrease carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emissions while evaluating turfgrass color and quality. In both years, supplemental rainfall (SRF) soil moisture content was higher than business as usual (BAU) irrigation and syringing (SYR). Higher soil moisture led to increased fluxes in both soil CO_2 and soil N_2O. In 2017, the SRF fluxed lower soil CO_2 as soil moisture reached levels that restricted respiration. Soil moisture was also an important predictor of soil N_2O flux with BAU and SRF having higher soil N_2O fluxes. SRF produced the greenest turf from May to July, whereas SRY and SRF produced the greenest turf from August to October in 2016. Both BAU and SRF had the greenest turf in 2017. BAU had the highest turfgrass quality ratings in 2016 followed by SRF and SRY, respectively, whereas in 2017 SRF and SRY had higher turfgrass quality ratings. When adopting water conservation practices to reduce GHG emissions, soil moisture content and site-specific rainfall should be closely monitored to prevent overwatering.

Keywords: greenhouse gas; carbon dioxide; methane; nitrous oxide; nitrogen; irrigation; turfgrass color; turfgrass quality

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1. Introduction

Low-input cultural management strategies (mowing, irrigation, fertilization, and pesticide use) have been developed in turfgrass systems to reduce the environmental impacts of nutrient and pesticide movement in soils [1]. Future sustainability initiatives need to focus on cultural management strategies that will also reduce greenhouse gas (GHG) emissions while still providing the optimum aesthetic characteristics. Golf courses are commonly irrigated and receive a nitrogen (N) fertilizer to improve turfgrass color and quality, and thus may contribute significantly to GHG emissions [2]. Developing best management practices that can also reduce GHG emissions from turfgrass systems can go a long way to mitigating climate change.

Due to limited water supply and water shortages, research into water conservation management practices continues to be a top priority in the turfgrass industry. Irrigation is the process of applying supplemental water when rainfall is insufficient to meet the needs of the plant [3]. Irrigation needs vary with environmental conditions, rooting, turfgrass species/cultivar, and soil conditions. Established cool-season turfgrass requires 25 to 38 mm of water per week (1 to 1.5 inches/week). The plant water requirements can come from natural rainfall, irrigation, or a combination of the two. Irrigation is needed to supplement natural rainfall even in humid regions (high air temperatures and low humidity) where high quality turfgrass is desired. Irrigation systems are required for golf courses, athletic fields, and other intensively managed turfgrass areas to maintain turfgrass aesthetics. When water is limited, the environmentally responsible use of irrigation should be implemented by turfgrass managers [4]. Therefore, there is an urgent need to continue developing management strategies that improve irrigation efficiency and reduce water use.

The water needs of turfgrass plants are dependent on one key factor, evapotranspiration (ET), which is the process of water loss from the soil's surface (evaporation) and the loss of water from the plant (transpiration). Turfgrass managers can use ET rates to better inform irrigation decisions [2]. Gelernter et al. [4] found that 94% of golf courses surveyed in 2013 used turf observation and 56% used short-term weather forecasts as a means for determining irrigation scheduling. Only 13% of courses used ET monitoring from the weather service and 18% used ET monitoring from a weather station. In addition, cultural management practices can be employed to reduce water use rates. Species and cultivar selection, mowing height, fertilization, cultivation, and chemical use can affect ET rates and are, therefore, important considerations when the goal is to conserve water [5]. Several conditions, such as air temperature, wind speed, humidity, and solar radiation, affect ET [3]. All of these environmental factors not only impact ET rates but are elevated by climate change [6].

Little research has been conducted to identify irrigation levels and N fertilization practices that reduce the flux of GHGs (CO_2, CH_4, and N_2O). Previous research has included carbon sequestration from irrigated turfgrass. Qian et al. [7] found that carbon sequestration was greater in irrigated than non-irrigated fine fescue (*Festuca* spp.) and creeping bentgrass (*Agrostis stolonifera* L.). The understanding of the stability of that stored carbon is important as we look to turfgrass areas as one of the solutions to combat climate change [8–10]. It is well established that soil temperature and soil moisture are significant factors in the gaseous losses of soil CO_2 [11], and thus understanding how irrigation practices impact greenhouse gas loss is of interest. Nitrous oxide emissions are influenced in turfgrass systems by irrigation, precipitation, and soil moisture [2,12]. Higher soil water content can increase denitrification, thereby potentially releasing N_2O in larger quantities to the atmosphere. Nitrous oxide emissions on 'Meyer' zoysiagrass (*Zoysia japonica* Steud.) have been evaluated under varying regimes of irrigation and N fertility. Braun and Bremer [2] found that lower irrigation (54% ET replacement) and the use of controlled-release fertilizer (polymer-coated urea, 98 kg N ha^{-1} yr^{-1}) reduced N_2O emissions. In a later study, Braun and Bremer [13] found that higher irrigation amounts (66% reference ET replacement) and urea resulted in higher N_2O emissions. Neither irrigation regimes nor water conservation strategies on cool-season turfgrasses have been evaluated. Methane can act as a potential sink rather than a source in grasslands [14] and urban soils [15] but has not been studied in turfgrass systems. Methane needs to be further studied to determine the influence of irrigation and N fertilization to develop more comprehensive cultural management practices to reduce GHG emissions [1]. Reducing greenhouse gas emissions while maintaining the quality of turfgrass is an important strategy in mitigating climate change as our society strives for a more sustainable world.

The fertilizer source influences the fate of the applied fertilizer [1]. Slow-release fertilizers can reduce N leaching losses in the soil compared to fast-release N fertilizers. Nitrification and denitrification can naturally generate N_2O [16]. When turfgrass is fertilized with N, available N increases in soil solution and, therefore, the potential for N_2O emissions also increases [12]. Fast-release N fertilizers can increase N_2O emissions as much as 15 times as compared to unfertilized turfgrass [2,17–19]. When considering the influence that irrigation and N fertilization have on GHGs, there is an urgent need to continue developing irrigation and fertilization strategies that conserve water [1] and utilize slow-release N fertilizers [18].

Cultural turfgrass management practices implementing slow-release N fertilizers combined with water conservation techniques may reduce GHG emissions [2]. The development of the best management practices that reduce GHGs from turf may help to mitigate climate change. The purpose of this study was to identify irrigation practices [Business As Usual (BAU), Supplemental Rainfall (SRF), and Syringing (SYR)] and N fertilizer practices [urea (147 and 294 kg N ha^{-1} yr^{-1}; UREL and UREH), milorganite (147 and 294 kg N ha^{-1} yr^{-1}; MILL and MILH), and an unfertilized control (0 kg N ha^{-1} yr^{-1}; UNTC)] that could decrease GHG (CO_2, CH_4, and N_2O) emissions. Because turfgrass appearance is important to turfgrass managers, the effects of water conservation techniques and N fertilizer on turfgrass color and quality were also evaluated. The information gained from this study will add to the knowledge around irrigation practices and N fertilizers' impact on GHG flux while also providing turfgrass managers with cultural strategies to manage turfgrasses sustainably.

2. Materials and Methods

2.1. Site Description

This two-year field study was conducted from May 2016 to October 2017 at Lincoln Golf Course in Grand Forks, ND, USA (47°53′57.79″ N 97°01′30.92″ W). The golf course was built in 1909 and is located on the west bank of the Red River of the North. Two putting greens (#1 and a practice putting green) were used to implement the various irrigation practices. Each putting green consisted of 80% 'Penncross' creeping bentgrass (*Agrostis stolonifera* L.) and 20% annual bluegrass (*Poa annua* L.) grown on a sand-based root zone (90:10 sand/organic matter). The putting greens were constructed as native soil-based push-up greens. They have been modified over the years with the addition of topdressing (90:10 sand/organic matter). The putting green profile consists of a 1.91 cm organic layer over 10.2 cm of sand (90:10 sand/organic matter). The underlying native soil is a fine-silty, mixed, superactive, frigid Cumulic Hapludoll.

Fifteen soil subsamples (10.2 cm depth) were randomly taken and combined into one composite soil sample per location at the beginning of this study and sent to AgVise (Harwood, ND, USA) for analysis. The putting green (#1) had a pH of 7.5, 45 kg ha^{-1} P, 215 kg ha^{-1} K, and 55 g kg^{-1} organic matter. The practice green had a pH of 7.5, 39 kg ha^{-1} P, 178 kg ha^{-1} K, and 57 g kg^{-1} organic matter.

2.2. Irrigation Practices

Three irrigation practices were evaluated during this study: supplemental rainfall (SRF), syringing (SYR), and business as usual (BAU). The golf course superintendent applied all irrigation practices during the study. The superintendent used turf observations and area weather forecasts to determine irrigation scheduling. In the absence of significant rainfall, irrigation was supplementally (SRF) applied at night using the in-ground irrigation system each week (0.38 cm) to the putting greens to promote growth and maintain the soil at or near field capacity during the growing season (Apr–Oct). SYR (hand watering) using a hose attached to the irrigation head using a quick coupler was applied to the green each day. SYR involves applying a small volume of water (0.13 cm) to moisten/mist the uppermost region of the turfgrass canopy. SYR occurred during the early afternoon hours during the hottest part of the day. BAU refers to relying on the irrigation system to water the greens. Irrigation was applied using an in-ground irrigation system (Rainbird, 700 Series) overnight at 0.64 cm per day. Both the SRF and SYR irrigation treatments were considered water conservation practices the superintendent could employ as compared to the typical BAU irrigation application.

2.3. Fertilizers Evaluated

Turfgrass plots were fertilized from May to October with an annual N rate of 147 or 294 kg N ha^{-1} yr^{-1}. Two sources of granular fertilizers were used to supply N: urea (URE) (46% N) and milorganite (MIL) (5% N). Urea is a fast-release N source whereas MIL (natural organic) is a slow-release N source. There were five fertilizer treatments: unfertilized control (UNTC, 0 kg N ha^{-1} yr^{-1}), urea low (UREL, 147 kg N ha^{-1} yr^{-1}), urea high (UREH, 294 kg N ha^{-1} yr^{-1}), milorganite low (MILL, 147 kg N ha^{-1} yr^{-1}), and milorganite high (MILH, 294 kg N ha^{-1} yr^{-1}). For the low fertilizer treatments (UREL and MILL, 147 kg N ha^{-1} yr^{-1}), a rate of 24.5 kg N ha^{-1} was applied to each plot in May, June, July, August, September, and October. For the high fertilizer treatments (UREH and MILH, 294 kg N ha^{-1} yr^{-1}), a rate of 49 kg N ha^{-1} was applied to each plot in May, June, July, August, September, and October. Monthly applications were applied on the first week of each month throughout the growing season.

2.4. Experimental Design

The plot size was 0.61 m × 0.61 m. Each fertilizer treatment was replicated four times and plots were arranged in a randomized, complete-block design. Each experimental site (irrigation regime) was treated as a block. Each block contained four replications and five fertilizer treatments for a total of twenty plots per block and a total of sixty plots in the experiment.

2.5. Greenhouse Gas Analysis

Gas samples were taken weekly during the growing season (May–October) at midday following the protocols of the United States Department of Agriculture-Agriculture Research Service Greenhouse Gas Reduction through Agricultural Carbon Enhancement Network [20,21]. Briefly, a polyvinyl chloride pipe (0.152 m diameter × 0.114 m height) was tamped into the ground until it was flush with the soil surface following cultivation. The bases remained in the soil until cultivation treatments were re-applied and then immediately replaced. Gas samples were taken by tamping a vented closed gas chamber covered in reflective tape (no light penetration) over the base in the ground for the sampling period. Gas samples were taken at chamber closure and at 20 and 40 min post chamber closure. The samples were placed into gas-tight vials using a 10 mL syringe.

These samples were analyzed using a gas chromatograph to determine the concentration of CO_2, CH_4, and N_2O in each sample. The gas chromatograph used was a Varian 350 equipped with a thermal conductivity detector for CH_4, an electron capture detector for N_2O, and a flame ionization detector for CO_2. Concentrations were determined by interpolation using gas standards obtained from Scott Specialty Gases (Air Liquide). Standard curves were used if they had an r^2 value of 0.99 or greater. The concentrations of the samples collected were then used to determine a change in concentration (flux rate) during the 40 min sampling period using linear regression.

2.6. Turfgrass Color and Quality

Turfgrass appearance was evaluated by quantifying canopy greenness and using visual turfgrass quality ratings. Turfgrass greenness was determined weekly using a chlorophyll meter that measured the normalized difference vegetation index (NDVI) of the turfgrass stand (FieldScout CM 1000 NDVI from Spectrum Technologies, Inc., Aurora, IL, USA). Three measurements were taken from approximately 90 cm above the turfgrass canopy using a diagonal grid pattern, which measured the back, center, and front of each plot. The three measurements were averaged to produce a single plot rating and were reported as NDVI (−1 to 1). Turfgrass quality was visually rated (per plot) weekly throughout the growing season using a 1 to 9 scale, where 1 = completely brown dead turf, 6 = minimally acceptable turf, and 9 = optimum uniformity, density, and greenness [22]. Although many studies have correlated NDVI and turfgrass visual quality [23–28], Leinauer et al. [29] found it valuable to include both visual turfgrass quality and turfgrass color (NDVI scale) to characterize the aesthetic appeal of turfgrass accurately.

2.7. Environmental Conditions

The total rainfall (mm) and mean air temperatures (°C) were recorded during the growing season (May–October) of 2016 and 2017 (Figure 1). Weather data were collected by the Grand Forks International Airport (Grand Forks, ND, USA). Canopy temperature, soil temperature, and soil moisture were recorded weekly synchronously with greenhouse gas collection during the growing season using an infrared temperature meter (Spectrum Technologies, Inc.), an HM digital TM-1 industrial grade digital thermometer, and a Dynamax TH300 TDR soil moisture probe, which takes the average soil moisture in the top 60 mm of soil.

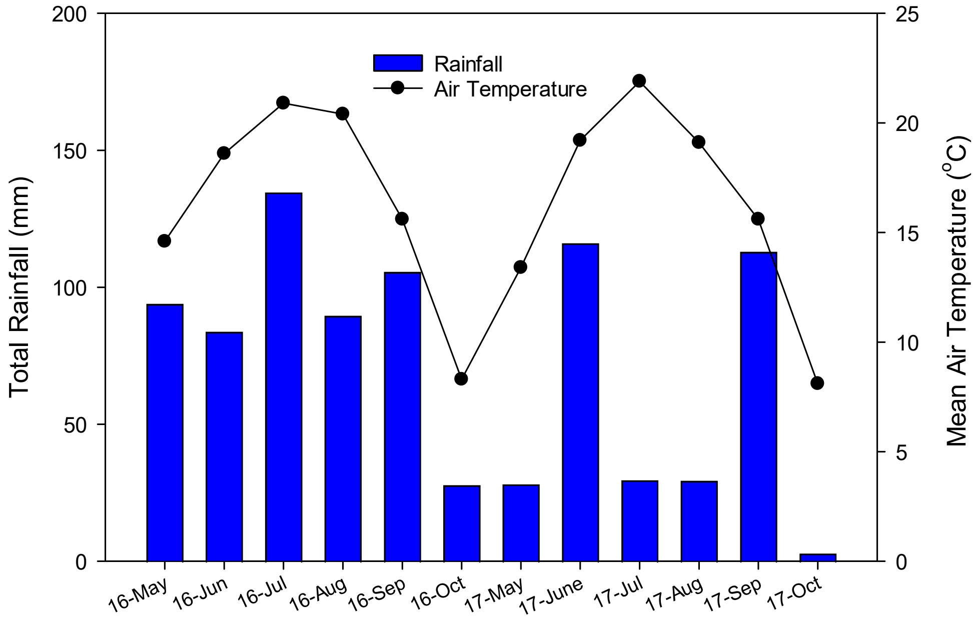


Figure 1. Total rainfall (mm) and mean air temperatures (°C) during the growing season (May–October) of 2016 and 2017. Total rainfall is indicated by a bar chart (left axis) and mean air temperature is indicated by a line graph (right axis). Weather data were collected by the Grand Forks International Airport (Grand Forks, ND, USA).

2.8. General Plot Maintenance

The putting greens were mowed at 0.36 cm. The putting greens did not receive any additional fertilization other than the fertilizer treatments during this two-year study. The research plots were not aerated for the duration of this study due to ring location in the soil. Four applications of topdressing [United States Golf Association (USGA) rootzone mixture, 0.65 cm/application] were applied to the green during the growing period to maintain putting green uniformity. Herbicides and fungicides were not applied over the research plots for the duration of this study.

2.9. Statistical Analysis

Statistical analysis was conducted using a general linear model (GLM) for GHG data and turfgrass data and a regression model (REG) for moisture and temperature as predictors of greenhouse gas flux using SAS version 9.4. Data points more than two standard deviations from the mean were identified as outliers and removed from the dataset. The assumptions of these models were checked, and appropriate transformations were applied as needed. The CO_2 data were transformed using a λ of 0.5, CH_4 was transformed using a λ of -0.1, and N_2O data were transformed using a λ equal to the inverse of the square. No transformation was necessary for the turfgrass data. Treatment means were separated using Fisher's protected LSD, and a significance level of $\alpha = 0.05$ was established a priori. Figures and tables represent back-transformed means.

3. Results and Discussion

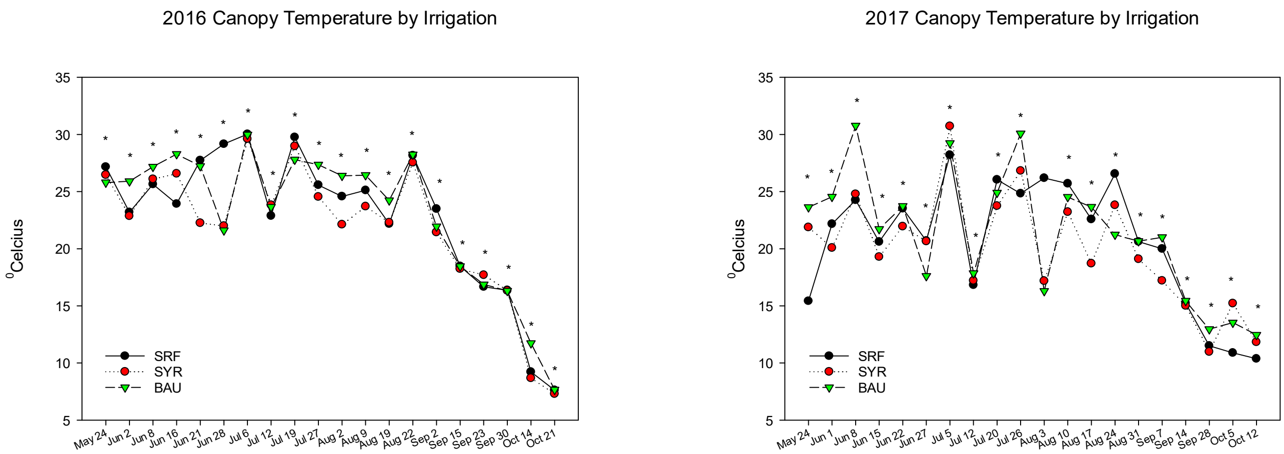
3.1. Canopy Temperature, Soil Temperature, and Soil Moisture

The irrigation regime (Table 1) was the only treatment that resulted in significant ($p < 0.001$) differences for canopy temperature and soil moisture (2016). In 2016, canopy temperature was significantly ($p < 0.001$) higher for the BAU irrigation treatment. The SRF irrigation treatment was significantly ($p < 0.001$) higher for soil moisture followed by the BAU treatment. The lowest canopy temperature and soil moisture (Figures 2a and 3a) was found in the SYR treatment. In 2017, significant ($p < 0.001$) differences were observed for all environmental conditions measured (Table 1). Canopy temperature was significantly ($p < 0.001$) higher for BAU treatment than either of the SRF and SYR treatments. Soil temperature was the highest for SRF, followed by BAU with SYR showing the lowest soil temperature across the 2017 season. Soil moisture followed the same trend observed in 2016 where SRF had significantly ($p < 0.001$) higher soil moisture than either the BAU or SYR treatments (Figure 3b).

Table 1. Mean and median canopy temperature, soil temperature, and soil moisture by year, irrigation treatment, and fertilizer.

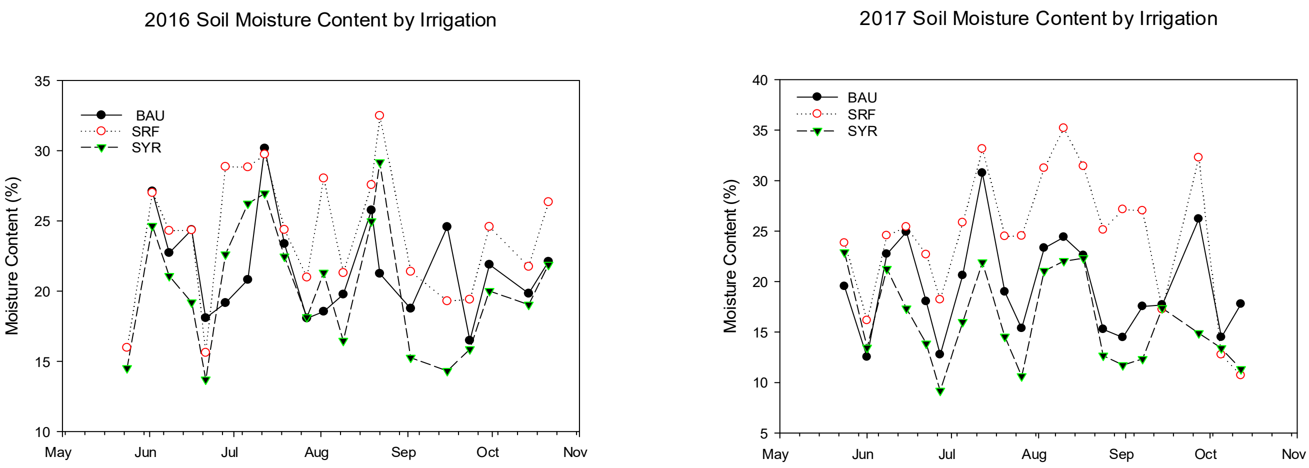
		Canopy Temperature		Soil Temperature		Soil Moisture	
Year	**Treatment**	**Mean**	**Median**	**Mean**	**Median**	**Mean**	**Median**
2016		°C		°C		%	
	BAU	23.2 a	23.2	22.0 a	24.4	21.7 b	20.8
	SRF	22.9 b	22.9	21.6 a	23.4	24.1 a	24.5
	SYR	21.9 c	21.9	21.3 a	23.9	20.4 c	20.3
Source of Variation							
Irrigation		***		NS		***	
Fertilizer		NS		NS		NS	
Irrigation × Fertilizer		NS		NS		NS	
2017							
	BAU	21.3 a	21.2	21.0 b	21.5	19.5 b	18.9
	SRF	20.6 b	20.2	21.7 a	21.4	24.4 a	24.8
	SYR	20.0 b	20.0	20.0 c	21.2	16.0 c	14.9
Source of Variation							
Irrigation		***		***		***	
Fertilizer		NS		NS		NS	
Irrigation × Fertilizer		NS		NS		NS	

Within columns, means followed by a different letter are significantly different according to Fisher's protected LSD *t*-test (0.05). *** Significant at the 0.001 probability level; NS, nonsignificant.



(**a**) (**b**)

Figure 2. Canopy temperature by irrigation regime (SRF = supplemental rainfall, SYR = syringing, and BAU = business as usual) in 2016 (**a**) and 2017 (**b**). * Means are significantly different at the 0.05 level according to Fisher's protected LSD *t*-test.



(**a**) (**b**)

Figure 3. Soil moisture content (%) by irrigation treatment in the 2016 (**a**) and 2017 (**b**) growing seasons. BAU, business as usual; SRF, supplemental rainfall; SYR, syringing.

Both SYR and SRF are considered water conservation practices [3]; however, our results show that the SRF consistently resulted in a higher soil moisture content than the BAU (Table 1). The problem with using SRF as a water conservation practice comes when trying to determine how much water is needed to supplement natural precipitation. Using only weather forecasts to estimate irrigation needs led to overwatering in this study. Overwatering for SRF was more pronounced in 2017 (Table 1), when the rainfall for the year was less consistent (Figure 1). To decrease water use, strategies need to be developed that improve irrigation efficiency [1]. There has been a concerted effort by US golf courses and the green industry as a whole to educate and implement strategies to improve irrigation efficiency and reduce water use [4]. Monitoring technology that incorporates soil moisture sensors and ET data can make irrigation scheduling decisions easier for the turfgrass manager and prevent over-irrigation. The use of soil moisture sensors on golf courses to determine irrigation scheduling has led to a 22% decrease in water usage [4]. Weather stations can also aid in scheduling irrigation using ET-based controllers. Future directions for determining irrigation amounts should utilize novel technologies including remote sensing ET estimates and soil water content estimates as utilized in precision agriculture to avoid over-irrigation [30]. This technique is beginning to gain traction within row cropping systems and would likely benefit turfgrass systems as well. Golf course superintendents should adopt tools that improve irrigation system efficiency that will lead to water use reductions.

3.2. GHG Emissions

3.2.1. CO_2 Emissions

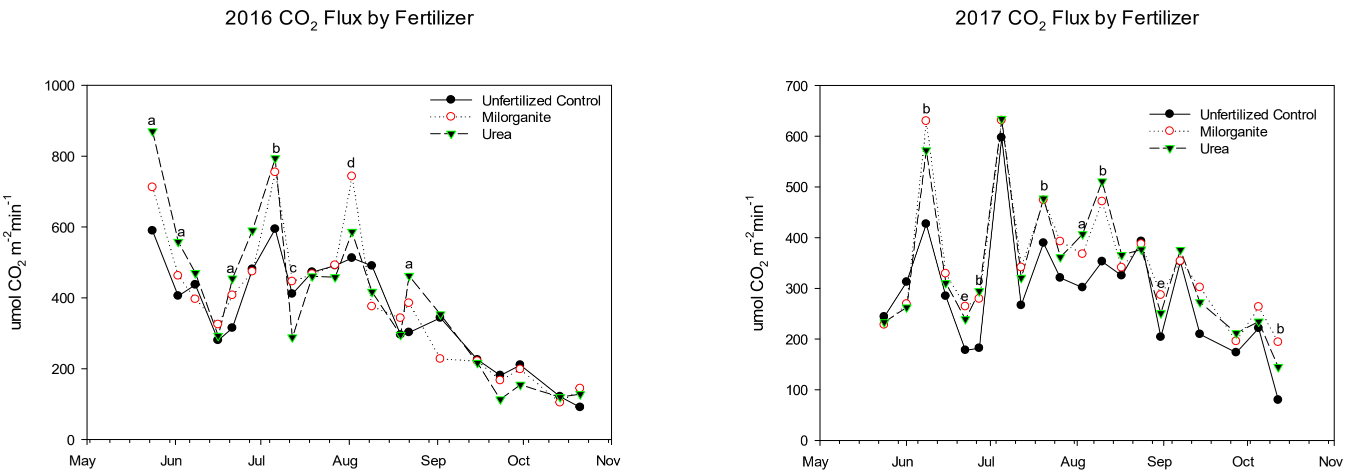
In 2016, the fertilizer source did not result in any significant ($p < 0.05$) differences in soil CO_2 flux, whereas in 2017 the fertilized plots showed significantly higher soil CO_2 flux than the UNTC (Table 2). Although there are several dates with significant differences between fertilizer treatments, there is no consistent trend in which the fertilizer source is fluxing more or less across the growing season (Figure 4a). Similarly in 2016, the rate of N showed no significant differences in soil CO_2 flux, whereas in 2017 both fertilizer rates (147 and 294 kg N ha^{-1} yr^{-1}) fluxed significantly ($p < 0.05$) more than the UNTC (Table 2). Across the growing season (2017), it was evident that the fertilized treatments were fluxing more soil CO_2 than the UNTC (Figure 4b). Also, the higher rate (294 kg N ha^{-1} yr^{-1}) of N (Figure 5) was fluxing significantly more soil CO_2 (five out of ten dates). Fertilization has been shown to increase soil respiration rates by providing nutrients to enhance the growth of microorganisms [17,31,32]. The effects observed in 2017 consistently demonstrated that the presence of N fertilizer increased the soil respiration rate and in both years, the rate (147 and 294 kg N ha^{-1} yr^{-1}) and source of N (milorganite and urea) were not significantly different from each other (Table 2).

Table 2. Back-transformed mean and median soil CO_2, N_2O, and CH_4 flux by year, fertilizer source, fertilizer rate, and irrigation treatment.

		CO_2		N_2O		CH_4	
Year	**Treatment**	**Mean**	**Median**	**Mean**	**Median**	**Mean**	**Median**
2016		g CO_2-C m^{-2} h^{-1}		μg N_2O-N m^{-2} h^{-1}		μg CH_4-C m^{-2} h^{-1}	
	Milorganite	0.43 a	0.43	46.44 a	27.55	−78.13 a	−3.42
	Urea	0.44 a	0.44	40.75 a	23.87	−72.20 a	−1.53
	Control	0.40 a	0.42	12.31 b	7.12	−98.78 a	−3.97
	147 kg N	0.43 a	0.44	30.91 b	19.33	−87.09 a	−6.25
	294 kg N	0.43 a	0.43	56.66 a	36.25	−63.22 a	−1.30
	BAU	0.35 c	0.36	33.99 a	18.70	−158.84 b	−12.05
	SRF	0.51 a	0.51	51.02 a	27.54	−185.61 b	−4.02
	SYR	0.43 b	0.45	26.38 b	14.62	112.73 a	4.59
Source of Variation							
	Irrigation (I)	***		***		***	
	Rate (R)	NS		***		NS	
	Fertilizer (F)	NS		***		NS	
	I × R	NS		NS		NS	
	I × F	NS		NS		NS	
	R × F	NS		NS		NS	
	I × R × F	NS		NS		NS	
2017							
	Milorganite	0.40 a	0.41	27.11 a	16.37	−97.33 a	−26.50
	Urea	0.39 a	0.38	33.97 a	18.31	30.14 a	−24.27
	Control	0.33 b	0.34	7.97 b	5.08	−109.59 a	−39.96
	147 kg N	0.38 a	0.38	15.90 b	11.92	49.87 a	−15.20
	294 kg N	0.41 a	0.41	45.50 a	29.93	−116.03 a	−35.08
	BAU	0.44 a	0.45	35.45 a	21.19	−101.3 a	−43.40
	SRF	0.34 c	0.33	26.88 a	14.85	15.55 a	−6.21
	SYR	0.37 b	0.39	15.74 b	9.17	−62.07 a	−34.46
Source of Variation							
	Irrigation (I)	***		***		NS	
	Rate (R)	*		***		NS	
	Fertilizer (F)	**		***		NS	
	I × R	NS		NS		NS	
	I × F	NS		NS		NS	
	R × F	NS		NS		NS	
	I × R × F	NS		NS		NS	

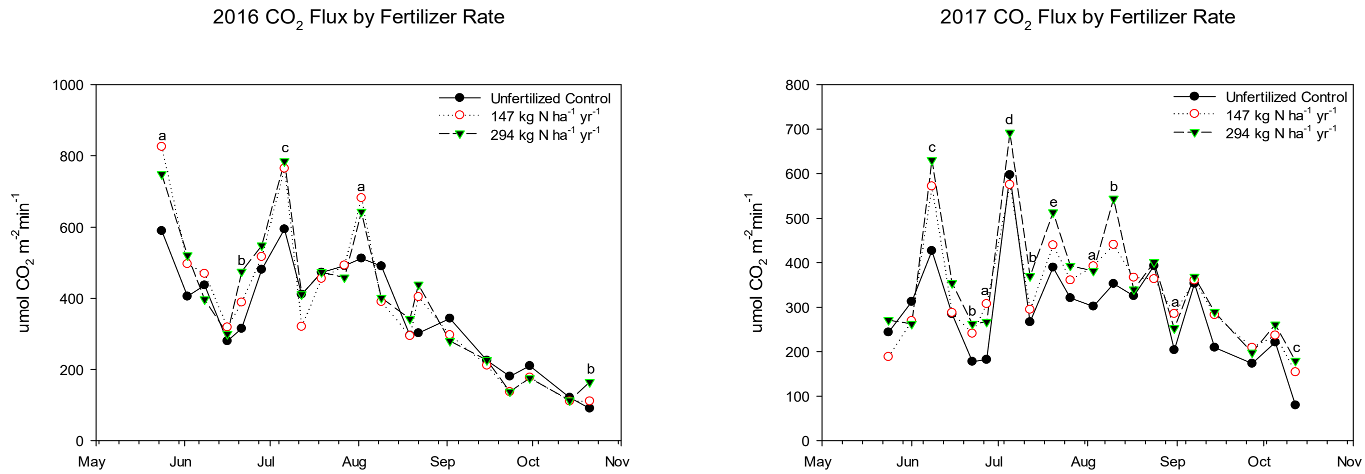
Milorganite = milorganite fertilizer, urea = urea fertilizer, and control = unfertilized control represents the fertilizer sources; 147 kg N ha^{-1} yr^{-1} and 294 kg N ha^{-1} yr^{-1} was the rate of fertilizer applied per year; BAU = business as usual, SRF = supplemental rainfall, and SYR = syringing represent the irrigation regimes. Within columns, means followed by a different letter are significantly different according to Fisher's protected LSD *t*-test (0.05). * Significant at the 0.05 probability level; ** Significant at the 0.01 probability level; *** Significant at the 0.001 probability level; NS, nonsignificant.

The irrigation regime showed significant ($p < 0.05$) differences in soil CO_2 flux in both 2016 and 2017. In 2016, SRF fluxed significantly more than SYR, which fluxed significantly more than BAU (Table 1). This is likely a result of the overwatering that occurred in the SRF treatment (Figure 3). Increased aerobic organic carbon respiration is associated with an increased soil moisture content of soils [33]. Whereas in 2017, BAU fluxed significantly ($p < 0.05$) more than SYR, which fluxed significantly more than SRF (Table 2). SRF demonstrated a significantly ($p < 0.05$) higher soil moisture content (Table 1) across both years of this study. The magnitude of the difference in soil moisture content was smaller in 2016 compared to 2017. The higher CO_2 emissions observed in 2016 are likely a result of the consistently higher soil moisture content observed in SRF throughout the growing season as soil moisture has a significant impact on microbial respiration [34–36]. In 2017, the flux of CO_2 from SRF was significantly lower (Figure 6) than the other irrigation treatments despite having a significantly higher soil moisture content (Figure 3). The moisture contents observed in the later part of 2017 (Figure 3) for the SRF irrigation treatment reached the degree of saturation for which there is a lack of oxygen for aerobic respiration [37]. This is evidenced by the dramatic decrease in soil CO_2 (Figure 5), and thus explaining the dramatic reduction in soil CO_2 flux from SRF (Figure 6).



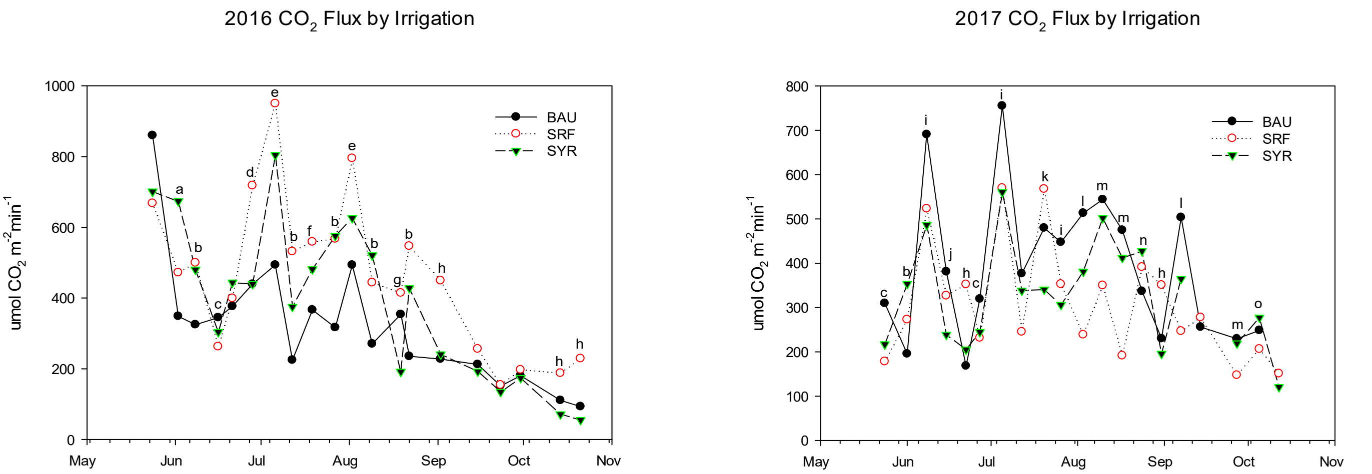
(**a**) (**b**)

Figure 4. Carbon dioxide (CO_2) emissions by fertilizer source in 2016 (**a**) and 2017 (**b**). Notes: a = urea > unfertilized control; b = milorganite and urea > unfertilized control; c = milorganite > urea; d = milorganite > urea and unfertilized control; e = milorganite > unfertilized control. Means are significantly different at the 0.05 level according to Fisher's protected LSD *t*-test.



(**a**) (**b**)

Figure 5. Carbon dioxide (CO_2) emissions by fertilizer rate in 2016 (**a**) and 2017 (**b**). Notes: a = 147 kg N ha^{-1} yr^{-1} > unfertilized control (0 kg N ha^{-1} yr^{-1}); b = 294 kg N ha^{-1} yr^{-1} > unfertilized control (0 kg N ha^{-1} yr^{-1}); c = 147 and 294 kg N ha^{-1} yr^{-1} > unfertilized control (0 kg N ha^{-1} yr^{-1}); d = 294 kg N ha^{-1} yr^{-1} > 147 kg N ha^{-1} yr^{-1}; e = 294 kg N ha^{-1} yr^{-1} > 147 kg N ha^{-1} yr^{-1} and unfertilized control (0 kg N ha^{-1} yr^{-1}). Means are significantly different at the 0.05 level according to Fisher's protected LSD *t*-test.



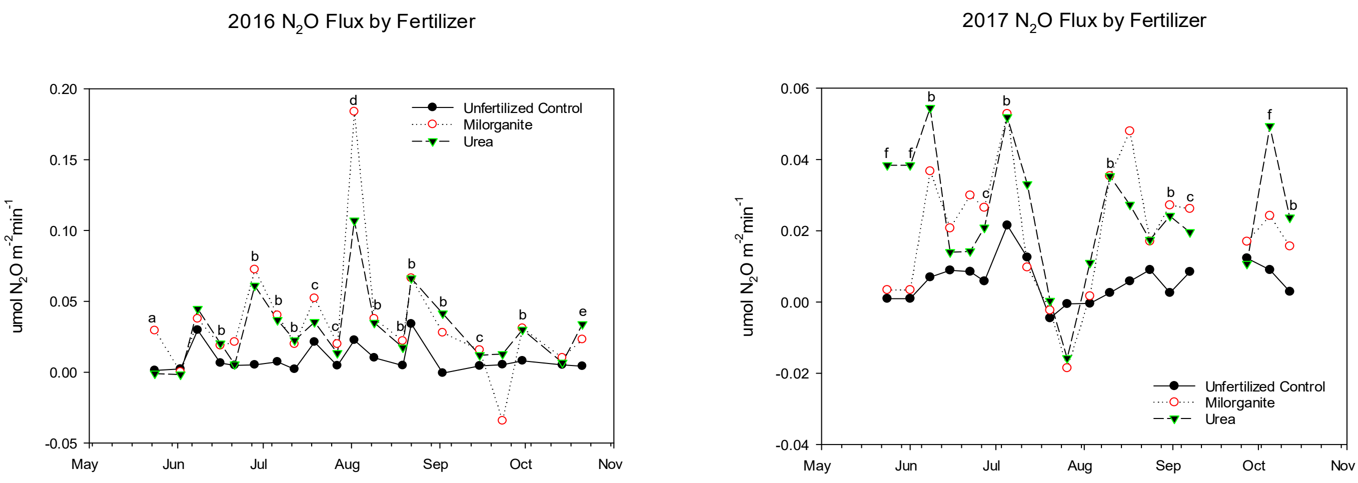
(**a**) (**b**)

Figure 6. Carbon dioxide (CO_2) emissions by irrigation regime in 2016 (**a**) and 2017 (**b**). Notes: a = SYR > SRF > BAU; b = SYR and SRF > BAU; c = BAU > SRF; d = SRF > SYR > BAU; e = SRF > SYR > BAU; f = SRF > BAU; g = BAU and SRF > SYR; h = SRF > SYR and BAU; i = BAU > SRF and SYR; j = BAU > SRF; k = SRF > BAU > SYR; l = BAU > SYR > SRF; m = BAU and SYR > SRF; n = SYR > BAU; o = SYR > SRF. Means are significantly different at the 0.05 level according to Fisher's protected LSD *t*-test.

The SYR treatment consistently fluxed higher CO_2 emissions than the lowest irrigation treatment (BAU in 2016 and SRF in 2017) and lower than the highest irrigation treatment (SRF in 2016 and BAU in 2017). The soil moisture content of the SYR treatment was the lowest (Table 1) across both years of this study. Based on moisture content, it was expected that SYR would flux the lowest soil CO_2 across both years of this study, but this was not the case. This is likely a result of the Birch effect [38,39] in which a large pulse of CO_2 is released from soils that are rewetted, which can last for a few days. SYR involved adding water during the hottest part of the day, and thus the soil was much drier (Table 1) as no other irrigation was applied. Additionally, the regression analysis revealed that both soil temperature ($p < 0.001$) and soil moisture ($p < 0.001$) are significant predictors of soil CO_2 flux. Soil temperature is much more influential with a parameter estimate of 22.6 vs. 4.7 for soil moisture indicating while both are important, soil temperature is more influential. Therefore, applying water during the hottest part of the day (vs. at night for the other two irrigation practices) may also promote the loss of soil CO_2. While SYR is a great water conservation practice, it appears to be promoting the loss of soil CO_2, and thus may not be a great strategy for reducing gaseous losses of soil CO_2. None of the interactions were significant (Table 2).

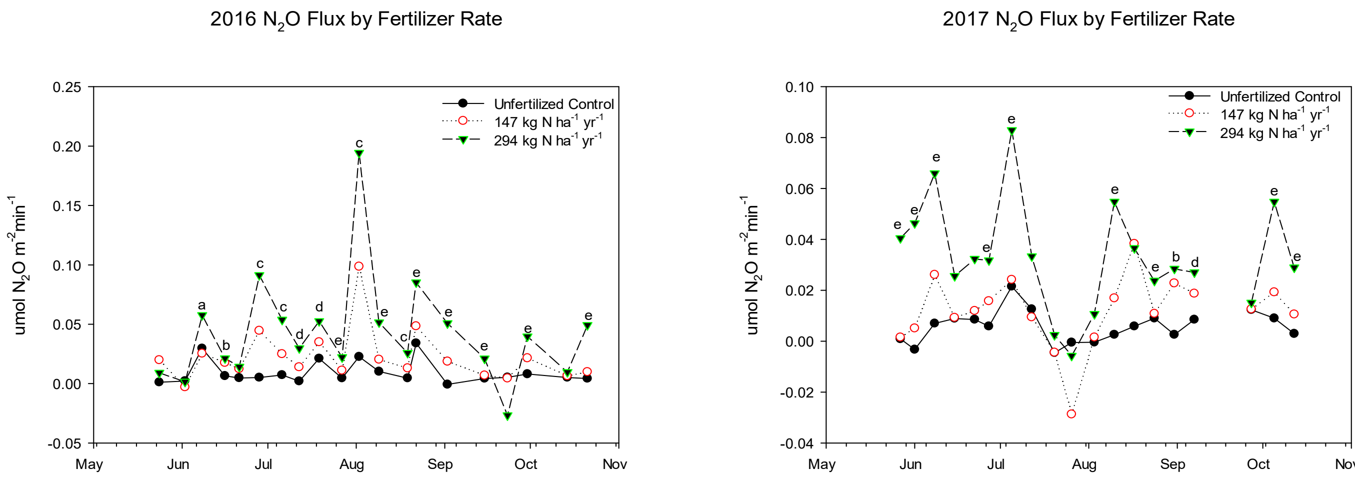
3.2.2. N_2O Emissions

In both 2016 and 2017, both fertilizer treatments (milorganite and urea) fluxed significantly ($p < 0.001$) more soil N_2O than UNTC (Figure 7, Table 2). Also, the 294 kg N ha^{-1} yr^{-1} rate fluxed significantly ($p < 0.001$) more soil N_2O than UNTC in both 2016 and 2017 (Figure 7, Table 2). In 2016, the 294 kg N ha^{-1} yr^{-1} rate fluxed significantly more than the 147 kg N ha^{-1} yr^{-1} rate, and the 147 kg N ha^{-1} yr^{-1} rate fluxed significantly ($p < 0.001$) more than UNTC (Table 2). These results are consistent with the published literature in which a meta-analysis of N_2O emissions from turfgrass lawns showed that N_2O emissions from fertilized plots are significant and on average 41% higher than control plots [40]. In contrast to the meta-analysis, this current study found increased soil N_2O emissions associated with higher rates (294 kg N ha^{-1} yr^{-1}) of N fertilizer (Table 2, Figure 8). The meta-analysis noted that the effect of soil N_2O was higher for low N (<150 kg N ha^{-1} yr^{-1}) applications and lower for high N (>150 kg N ha^{-1} yr^{-1}) applications across the 27 studies examined [40]. Dutt and Tanwar [31] hypothesized that this was due to the tendency of the fertilizer to get washed away for higher fertilizer inputs after rainfall events and the association of higher fertilizer rates with higher irrigation rates. In the current study, both rates of fertilizer received identical rainfall/irrigation rates and were associated with relatively flat putting greens where the risk for runoff is reduced, and thus this may explain why our results show increased soil N_2O emissions associated with the higher (294 kg N ha^{-1} yr^{-1}) fertilizer rate.



(**a**) (**b**)

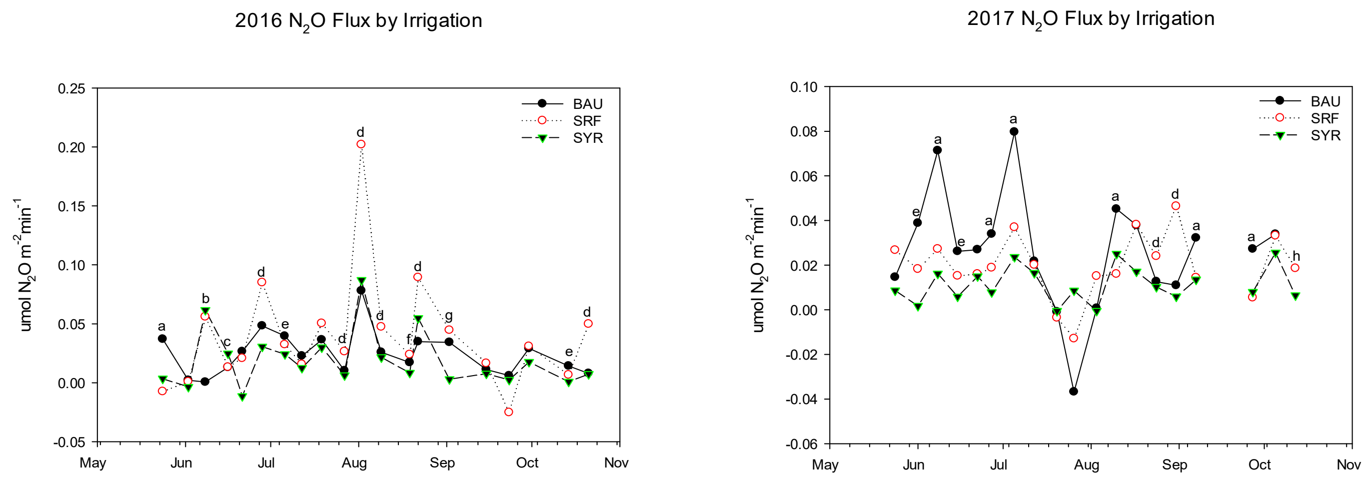
Figure 7. Nitrous oxide (N_2O) emissions by fertilizer source in 2016 (**a**) and 2017 (**b**). Notes: a = milorganite > urea; b = milorganite and urea > unfertilized control; c = milorganite > unfertilized control; d = milorganite > urea > unfertilized control; e = urea > unfertilized control; f = urea > milorganite and unfertilized control. Means are significantly different at the 0.05 level according to Fisher's protected LSD *t*-test.



(**a**) (**b**)

Figure 8. Nitrous oxide (N_2O) emissions by fertilizer rate in 2016 (**a**) and 2017 (**b**). Notes: a = 294 kg N ha^{-1} yr^{-1} > 147 kg N ha^{-1} yr^{-1}; b = 294 kg N ha^{-1} yr^{-1} and 147 kg N ha^{-1} yr^{-1} > unfertilized control (0 kg N ha^{-1} yr^{-1}); c = 294 kg N ha^{-1} yr^{-1} > 147 kg N ha^{-1} yr^{-1} > unfertilized control (0 kg N ha^{-1} yr^{-1}); d = 294 kg N ha^{-1} yr^{-1} > unfertilized control (0 kg N ha^{-1} yr^{-1}); e = 294 kg N ha^{-1} yr^{-1} > 147 kg N ha^{-1} yr^{-1} and unfertilized control (0 kg N ha^{-1} yr^{-1}). Means are significantly different at the 0.05 level according to Fisher's protected LSD *t*-test.

In both 2016 and 2017, BAU and SRF fluxed significantly ($p < 0.001$) more soil N_2O than SYR (Figure 9, Table 2). Both of these resulted in a significantly ($p < 0.05$) higher soil moisture content (Figure 3, Table 1) when compared to SYR. It is well established that higher soil moisture contents [2,12] are associated with higher fluxes of soil N_2O due to the increased denitrification that occurs under anoxic conditions [41,42]. Therefore, these results are consistent with previous studies in which soils with a higher soil moisture content exhibit higher soil N_2O flux. None of the interactions were significant (Table 2).



(**a**) (**b**)

Figure 9. Nitrous oxide (N_2O) emissions by irrigation regime in 2016 (**a**) and 2017 (**b**). Notes: a = BAU > SYR and SRF; b = SYR and SRF > BAU; c = SYR > SRF and BAU; d = SRF > SYR and BAU; e = BAU > SYR; f = SRF > BAU > SYR; g = SRF and BAU > SYR; h = SRF > SYR. Means are significantly different at the 0.05 level according to Fisher's protected LSD *t*-test.

3.2.3. CH_4 Emissions

Across both growing seasons, very little soil CH_4 flux was observed. In 2016, SYR showed significantly ($p < 0.001$) higher soil CH_4 flux than BAU and SRF (Table 2). However, this trend was inconsistent and was not considered an important finding. No other significant differences were observed between irrigation treatments, fertilizer treatments, or fertilizer rates across either study year. While terrestrial ecosystems can serve as both a source and a sink of atmospheric CH_4, terrestrial ecosystems rarely result in significant fluxes of soil CH_4 due to their lack of anoxic conditions. Therefore, these results demonstrated mostly insignificant ($p > 0.05$) differences and small positive and negative fluxes of soil CH_4 (Table 2). This was consistent with the published literature [11,15]. None of the interactions were significant (Table 2).

3.3. Turfgrass Color and Turfgrass Quality

For turfgrass color, the irrigation regime and N fertilizer treatment were not significant in 2016 when averaged across the year (Table 3). However, when statistically analyzed by date, the irrigation regime was significant ($p < 0.05$) in 14 out of 18 sampling dates (77%) for turfgrass color (Figure 10a). Nitrogen fertilizer treatment was significant ($p < 0.05$) in 12 out of 18 sampling dates (67%) for turfgrass color (Figure 10c). SRF produced the greenest turf from May to July, whereas SRY and SRF produced the greenest turf from August to October. BAU produced the greenest turf on August 22 and October 21 of 2016. The high rate of urea (294 kg N ha^{-1} yr^{-1}) produced the greenest turf from May to mid-July and from September to October, followed by the UREL (147 kg N ha^{-1} yr^{-1}) treatment. The UNTC (0 kg N ha^{-1} yr^{-1}) consistently produced the poorest turfgrass color throughout the growing season.

Table 3. The Effects of Irrigation and N Fertilizer Treatment on Mean Annual Turfgrass Color and Turfgrass Quality.

	Treatment	Turfgrass Color		Turfgrass Quality	
		2016	**2017**	**2016**	**2017**
		NDVI		Visual Rating (1–9 Scale)	
Irrigation					
	BAU	0.83 A	0.86 A	7.3 A	7.2 A
	SRF	0.90 A	0.85 A	7.0 B	7.3 A
	SRY	0.83 A	0.84 B	6.9 B	7.2 A
Fertilizer					
	MILH	0.83 a	0.86 a	7.5 a	7.8 a
	MILL	0.83 a	0.85 ab	7.2 b	7.5 b
	UREH	0.85 a	0.86 ab	6.9 c	7.2 c
	UREL	0.84 a	0.86 ab	6.9 bc	7.2 c
	UNTC	0.92 a	0.84 c	6.9 bc	6.6 d
Source of Variation					
Irrigation (I)		NS	***	***	NS
Fertilizer (F)		NS	***	***	***
I × F		NS	NS	***	NS

Turfgrass color. The normalized difference vegetation index (NDVI) measurements can range from −1 to 1, with higher values indicating greater plant health. Turfgrass quality is a visual rating of 1–9; where 1 = completely brown dead turf, 6 = minimally acceptable turf, and 9 = optimum uniformity, density, and greenness. Means in the same column for each irrigation regime (BAU = business as usual, SRF = supplemental rainfall, and SRY = syringing) followed by the same uppercase letter are not significantly different according to Fisher's protected LSD *t*-test (p = 0.05). Means in the same column for each fertilizer treatment (MILH = milorganite, 294 kg N ha^{-1} yr^{-1}, MILL = milorganite, 147 kg N ha^{-1} yr^{-1}, UREH = urea, 294 kg N ha^{-1} yr^{-1}, UREL = urea, 147 kg N ha^{-1} yr^{-1}, UNTC = unfertilized control, 0 kg N ha^{-1} yr^{-1}) followed by the same lowercase letter are not significantly different according to Fisher's protected LSD *t*-test (p = 0.05). *** and NS refer to significance at 0.001 and nonsignificant, respectively.

In 2017, both the irrigation regimes and N fertilizer treatment were significant ($p < 0.001$) when averaged across the year (Table 3). The BAU and SRF irrigation regimes produced the best turfgrass color. This trend was observed throughout the growing season of 2017. Both the irrigation regime and N fertilizer treatment were significant ($p < 0.05$) on 17 out of 19 dates (89%) for turfgrass color (Figure 10b,d). BAU and SRF produced the greenest turf followed by SRY. The MILH (294 kg N ha^{-1} yr^{-1}) produced the greenest turf followed by UREH (294 kg N ha^{-1} yr^{-1}) and UREL (147 kg N ha^{-1} yr^{-1}) and the MILL (147 kg N ha^{-1} yr^{-1}) N treatments. The UNTC (0 kg N ha^{-1} yr^{-1}) produced the poorest turfgrass color.

Supplemental irrigation is applied to greens during periods of low rainfall to maintain the quality of play and aesthetics [43]. The water conservation practice of SRF, and to some extent SYR (only in 2016), produced the greenest turfgrass color. In 2017, SRF along with BAU had the highest turfgrass color. These results suggest that supplementing natural rainfall can produce the same turfgrass color while conserving water than irrigating daily. However, the soil moisture content for SRF was higher than BAU throughout the study period (Table 1, Figure 3). SYR had better or similar turfgrass color as SRF from August to October in 2016 (Figure 10a). Therefore, SRY could be an option for irrigation when there is ample precipitation in the fall. Our results also indicate that SYR can be used as a water conservation practice in years with sufficient natural rainfall to meet the plant's water needs (Figure 1). SYR has been shown to also decrease canopy temperature through the evaporation of water from the leaf surface, preventing wilt [44]. In 2016, SYR decreased canopy temperature (Table 1), whereas in 2017 SRF and SYR decreased canopy temperature. By date, SYR decreased canopy temperatures from July to September in 2016 (Figure 2a), whereas in 2017 (Figure 2b) SYR decreased canopy temperatures only on a few dates each month throughout the growing season. There is a potential that SYR can aid in water stress during the summer months [45]. Even though soil moisture was lowest for SYR in 2016 and 2017, SYR with the addition of natural rainfall kept the soil moisture at field capacity, preventing water stress.

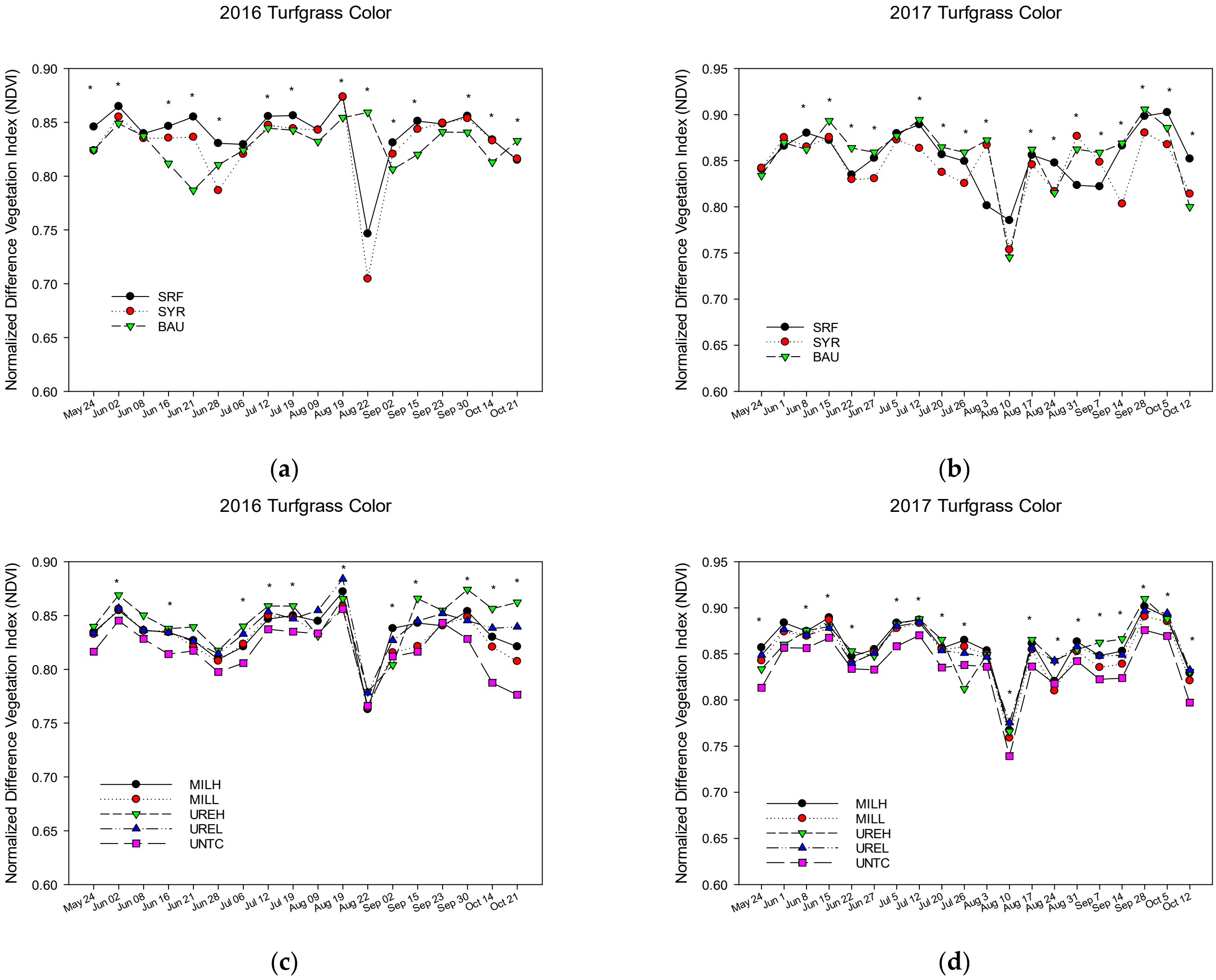


Figure 10. The effects of the irrigation regime ((**a**,**b**); SRF = supplemental rainfall, SYR = syringing, BAU = business as usual) and fertilizer ((**c**,**d**); MILH = milorganite high, 294 kg N ha^{-1} yr^{-1}, MILL = milorganite mow, 147 kg N ha^{-1} yr^{-1}, UREH = urea high, 294 kg N ha^{-1} yr^{-1}, UREL = urea low, 147 kg N ha^{-1} yr^{-1}, UNTC = unfertilized control, 0 kg N ha^{-1} yr^{-1}) on turfgrass color (NDVI = normalized difference vegetation index, −1 to 1) in 2016 and 2017. Datapoints on the graphs represent means by date. * Means are significantly different at the 0.05 level according to Fisher's protected LSD *t*-test. Plots were fertilized the first week of every month from May to October with a high N rate of 49 kg N ha^{-1}, a low N rate 24.5 kg N ha^{-1}, or an unfertilized control of 0 kg N ha^{-1} per application.

For turfgrass quality, the irrigation regime and N fertilizer treatment was significant ($p < 0.0001$) in 2016 when averaged across the year (Table 3). There was also an irrigation regime by N fertilizer interaction. BAU treatment had the highest turfgrass quality ratings followed by SRF and SRY treatments, respectively. The MILH (294 kg N ha^{-1} yr^{-1}) produced the highest turfgrass quality ratings followed by the MILL (147 kg N ha^{-1} yr^{-1}) treatment. When statistically analyzed by date, the irrigation regime was significant ($p < 0.05$) in five out of twenty sampling dates (25%) where SRF and SRY treatments had better turfgrass quality (Figure 11a). Nitrogen fertilizer treatment was significant ($p < 0.05$) in 12 out of 20 sampling dates (60%) for turfgrass quality (Figure 11c). The UREH (294 kg N ha^{-1} yr^{-1}) treatment had the poorest turfgrass quality ratings from the end of

June to September. During this same time period, MILH (294 kg N ha^{-1} yr^{-1}) produced the highest quality of turf.

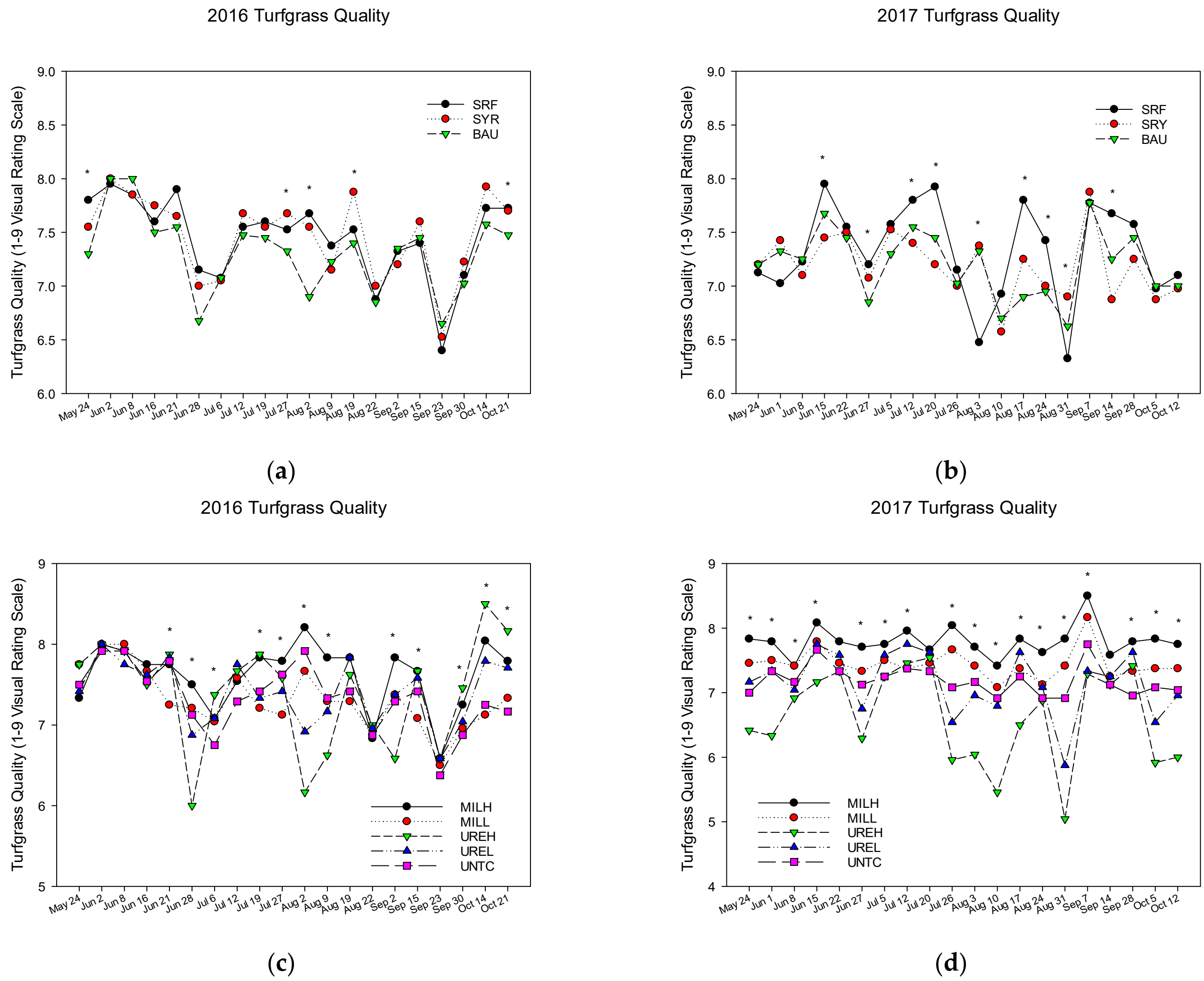


Figure 11. The effects of irrigation regime ((**a**,**b**); SRF = supplemental rainfall, SYR = syringing, BAU = business as usual) and fertilizer ((**c**,**d**); MILH = milorganite high, 294 kg N ha^{-1} yr^{-1}, MILL = milorganite low, 147 kg N ha^{-1} yr^{-1}, UREH = urea high, 294 kg N ha^{-1} yr^{-1}, UREL = urea low, 147 kg N ha^{-1} yr^{-1}, UNTC = unfertilized control, 0 kg N ha^{-1} yr^{-1}) on turfgrass quality (1–9 visual scale; where 1 = completely brown dead turf, 6 = minimally acceptable turf, and 9 = optimum uniformity, density, and greenness) in 2016 and 2017. Datapoints on the graphs represent means by date. * Means are significantly different at the 0.05 level according to Fisher's protected LSD *t*-test. Plots were fertilized the first week of every month from May to October with a high N rate of 49 kg N ha^{-1}, a low N rate 24.5 kg N ha^{-1}, or an unfertilized control of 0 kg N ha^{-1} per application.

The irrigation regime was not significant in 2017 when averaged across the year (Table 3). Nitrogen fertilizer treatment was significant ($p < 0.001$) where the MILH (294 kg N ha^{-1} yr^{-1}) had the highest turfgrass quality ratings followed by the MILL (147 kg N ha^{-1} yr^{-1}) and both the UREH (294 kg N ha^{-1} yr^{-1}) and UREL (147 kg N ha^{-1} yr^{-1}) treatments. The irrigation regime was significant ($p < 0.05$) in nine out of twenty sampling dates (40%) where SRF and SRY treatments had better turfgrass quality (Figure 11b). Nitrogen fertilizer treatment was significant ($p < 0.05$) in 17 out of 20 sampling dates (85%) for turfgrass quality (Figure 11d). The MILH (294 kg N ha^{-1} yr^{-1}) had the highest turfgrass quality ratings followed by the MILL (147 kg N ha^{-1} yr^{-1}) treatment. The UREH (294 kg N ha^{-1} yr^{-1}) resulted in the lowest turfgrass quality ratings in 14 out of 17 dates (82%) in 2017.

Although BAU produced the highest quality of turf in 2016, the water conservation practices, SRF and SRY, had acceptable turfgrass quality ratings (≥6.0) throughout the growing season. This indicates that water conservation practices, SRF and SYR, have the potential to achieve the desired aesthetics when aided by natural rainfall. However, soil moisture was higher for SRF than BAU and SYR in both years of this study (Table 1). For N fertility, MILH had the highest ratings for turfgrass quality in both years. This is promising as milorganite is a slow-release fertilizer source of N and is considered more environmentally friendly (less leaching) than a fast-release source like urea [46]. Urea can cause fertilizer burn to creeping bentgrass putting greens, reducing turfgrass quality below acceptable values [18]. These results demonstrate that fertilizer burn due to the UREH treatment caused turfgrass quality ratings to fall below acceptable values (<6.0) five out of seventeen times (29%) in 2017 from July to October. Additionally, MILH had the highest turfgrass color in 2017. Milorganite is not only a sustainable N fertility option but also can produce the desired appearance of turfgrass that superintendents require on golf course putting greens.

3.4. Global Warming Potential Contributions

In both 2016 and 2017, the global warming potential (GWP) for each fertilizer and irrigation treatment was largely driven by soil CO_2 emissions (Table 4). Across fertilizer and irrigation practices the percent contribution of CO_2 to the total GWP ranged from 97–99% with the soil N_2O emissions being the second most important in contributing to GWP with its contributions ranging from 1–3% (Table 4). Soil CH_4 emissions never reached a level to which they significantly contributed to the overall GWP coming from the soils. Thus, when managing soils for reduction of GWP, it is best to select land management practices that reduce soil CO_2 emissions because they drive the majority of the GWP for any given management practice.

Table 4. Percent Global Warming Potential (GWP) contributions of CO_2, N_2O, CH_4 flux by year, fertilizers, fertilizer rates, and irrigation treatments.

		CO_2	N_2O	CH_4
Year	**Treatment**	**GWP**	**Mean**	**Mean**
2016				
	Fertilizer			
	Control	99%	1%	0
	Milorganite	98%	2%	0
	Urea	98%	2%	0
	Fertilizer Rate			
	147 kg N	98%	2%	0
	294 kg N	97%	3%	0
	Irrigation			
	BAU	99%	1%	0
	SRF	97%	3%	0
	SYR	98%	2%	0
2017				
	Fertilizer			
	Control	99.9%	0.1%	0
	Milorganite	98.5%	2%	0
	Urea	99.9%	0.1%	0
	Fertilizer Rate			
	147 kg N	99.1%	0.9%	0
	294 kg N	99.1%	0.9%	0
	Irrigation			
	BAU	98%	2%	0
	SRF	98%	2%	0
	SYR	99%	1%	0

Control = unfertilized control, milorganite = milorganite fertilizer, and urea = urea fertilizer represent the fertilizer sources; 147 kg N ha^{-1} yr^{-1} and 294 kg N ha^{-1} yr^{-1} were the rate of fertilizers applied per year; BAU = business as usual, SRF = supplemental rainfall, and SYR = syringing represent the irrigation regimes.

4. Conclusions

The irrigation regime significantly impacted soil CO_2 emissions. The irrigation regimes with higher moisture content, SRF, and BAU, resulted in higher soil CO_2 flux. The exception to this was the SRF treatment in 2017 in which the soil CO_2 flux dropped drastically at higher soil moisture contents. This is likely a result of overwatering in the SRF irrigation treatment causing the conditions of the soil to no longer be suitable for soil respiration. Nitrogen fertilizer treatment also impacted soil CO_2 emissions in that the presence of any N fertilizer (2017) increased soil CO_2 emissions. Soil N_2O emissions were also impacted by the irrigation regime and N fertilizers. SYR had the lowest soil moisture content (SYR) resulting in the lowest soil N_2O emissions. Additionally, while no difference was observed between the two N fertilizer sources, the higher rate (294 kg N ha^{-1} yr^{-1}) of N fertilizer did result in higher soil N_2O emissions. Soil CO_2 emissions drove the global warming potential (Table 4); focusing on cultural management practices that reduce soil CO_2 emissions will reduce the global warming potential of turfgrass. Irrigation practices that result in lower soil moisture content generally flux smaller amounts of soil CO_2 with the exception of SYR due to the observed Birch effect and the application of water during the hottest part of the day. The SRF treatment resulted in overwatering during this study, which increased soil CO_2 emissions over the BAU treatment. Further research into the impacts of irrigation practices on GHG emissions is needed to clarify which water-reduction irrigation practices can be used to reduce the global warming potential of GHGs fluxing from the soil.

The water conservation practice of SRF, and to some extent SYR, produced similar turfgrass color to the BAU treatment. Although not observed in this study, SRF has the potential to conserve water if applied using ET-based irrigation management and/or soil moisture sensors to reduce overall water use. SYR is a water conservation practice that can be implemented when there is ample precipitation in the growing season. SYR can also decrease canopy temperature through the evaporation of water from the leaf surface, preventing wilt and water stress, especially during the summer months. Both water conservation practices, SRF and SRY, had acceptable turfgrass quality (>6.0) in 2016. For N fertility, MILH had the highest ratings for turfgrass quality in both years and the highest turfgrass color in 2017. Urea caused fertilizer burn on the putting greens, which resulted in turfgrass quality ratings falling below acceptable levels (<6.0). Therefore, milorganite is not only a sustainable N fertility option but also can produce the desired appearance turfgrass that superintendents require on golf course putting greens. Golf course superintendents can improve irrigation system efficiency when soil moisture sensors and ET-based irrigation management are incorporated into their cultural management strategies, which can assist them in reducing their overall water use. Trying to conserve water without the adoption of monitoring technology by turfgrass managers is ineffective. This was apparent during this study for SRF when only turf observations and area weather forecasts were used to schedule irrigation. This led to over-irrigation rather than conserving water. Further research is needed to better understand the relationship between irrigation practices and GHG emissions.

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