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Environmental Impacts and Runoff Dynamics Associated with Urban Landscape Conversions

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Introduction

As rapid population growth continues in urban areas, water conservation has become a key priority for many municipalities. In many regions of the U.S. and world, more than 50% of domestic water usage is attributed to residential landscape irrigation (Mayer et al., 1999; Degen 2007; Haley et al., 2007). While homeowners have traditionally installed and appreciated landscapes comprised predominantly of natural turfgrass; in recent years many municipalities have incentivized removal of turfgrass areas and conversion to alternative 'water-efficient' landscapes with the goal of reducing outdoor water use (Addink, 2005; Zhang and Khachatryan, 2018; Pincetl et al., 2019; Chesnutt, 2020). As a component of these programs, homeowners are often encouraged or required to adopt specific landscape designs and planting materials, presumably with good adaptation to the region.

While water efficient landscape conversions should presumably result in reduced outdoor water use, this is not always the case. Furthermore, there has been little research examining the long-term environmental consequences and ecosystem services resulting from these landscape changes following lawn removal. Turfgrass lawns have been shown to provide an array of benefits both to the environment and to humans (Beard and Green, 1994; Bolund and Hunhammar, 1999; Monteiro, 2017).

Therefore, the objectives of this research were to 1) examine runoff dynamics including flow rates, volumes, and chemistries associated with urban landscape conversions, 2) monitor seasonal changes in surface temperatures of several residential landscapes types, and 3) document the maintenance requirements of each landscape in terms of weed pressure.

Material and Methods

This on-going study is being conducted at the Urban Landscape Runoff Facility located at the Texas A&M University Soil and Crop Sciences Field Research Laboratory, College Station, TX. The facility previously comprised 24 individually irrigated 4.1 m × 8.2 m plots established with 6-yr old 'Raleigh' St. Augustinegrass established on an average 3.7 % slope atop of a fine sandy loam soil. Each plot has its own irrigation control and runoff collection system composed of an ISCO flow meter ((ISCO 4210, Teledyne Isco, Lincoln NE)) and auto-sampler (ISCO 6712, Teledyne Isco, Lincoln NE). This provides full documentation of the runoff dynamics including flow patterns and runoff water volumes from irrigation and rainfall events, and also collects 1 L samples (maximum of 24) from these events for subsequent chemical analysis.

Landscape conversions were initiated during August 2018. For all treatments where grass needed to be removed, sod was stripped to a depth of 1" using a sod cutter. Additional layers of topsoil were subsequently removed corresponding to the final subgrade depth needed to accommodate the new infill material for each treatment. By August 15, 2018, all treatments were completed. The five landscape treatments were arranged in a randomized complete block design with 4 replicate plots per treatment for all treatments except artificial turf and sand-capped lawn, which had 3 replicates per treatment. The treatments used in the study are shown in Figure 1, and included:

1. **St. Augustinegrass Lawn:** The original eight-year-old Raleigh St. Augustinegrass (*Stenotaphrum secundatum*) lawn established in 2012 atop of native fine sandy-loam soil and irrigated 2x weekly at 60% reference evapotranspiration levels (60% ET_o).

2. **Water Efficient Landscape- Xeriscaping:** Native, water conserving plants comprising 50% of the total plot area including Red Yucca (*Hesperaloe parviflora*), Texas sage (*Leucophyllum frutescens*), Muhly grass (*Muhlenbergia capillaris*), and Dwarf yaupon holly (*Ilex vomitoria*) established in 3" of compacted decomposed granite. Plants are irrigated via drip irrigation twice weekly at a rate of 0.8 L, according to a recommended rate of 0.23 L per day.

3. **Water Efficient Landscape-Mulch:** Native, water conserving plants comprising 50% of total plot area including Red Yucca (*Hesperaloe parviflora*), Texas sage (*Leucophyllum frutescens*), Muhly grass (*Muhlenbergia capillaris*), and Dwarf yaupon holly (*Ilex vomitoria*) grown in native fine sandy-loam soil and mulched with 2" of dark hardwood mulch (New Earth Compost, San Antonio, TX). Plants are irrigated twice weekly at a rate of 0.8 L, according to a recommended rate of 0.23 L per day.

4. **Artificial Turf:** Premium II (EPS Turf, Ewing Irrigation and Landscape Supply, Phoenix, AZ) unirrigated synthetic turf was installed atop of 2 inches of compacted decomposed granite. Grit silica sand infill (Ewing irrigation and landscape supply, Phoenix, AZ) was incorporated into the base of the turf at a rate of 9.76 kg m^{-2}. The resulting sand infill layer is approximately 1" in depth.

5. **Sand-Capped Lawn:** Washed Raleigh St. Augustinegrass sod laid atop of 4" sand-cap layer (medium-coarse concrete sand (Knife River Corp. Bryan, TX) plated over native fine-sandy loam soil. Irrigated 2 times weekly at 60% ET_o.

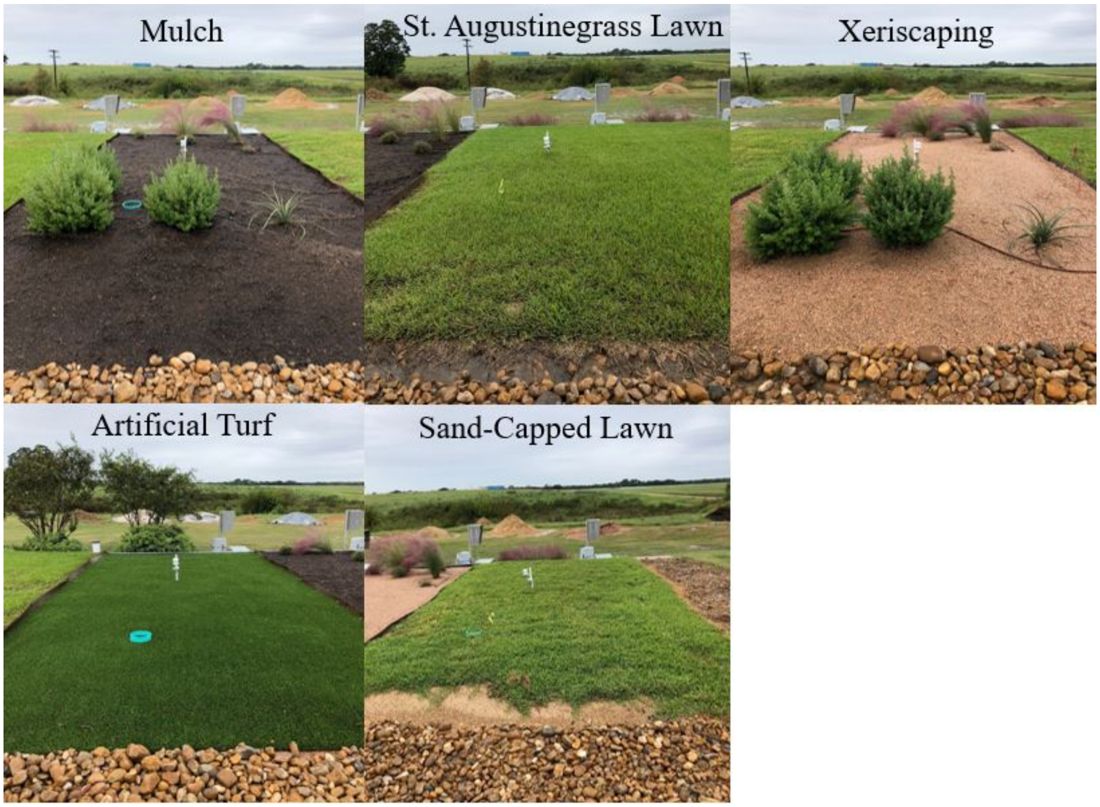

Figure 1. Natural turfgrass lawn and alternative 'water-efficient' landscape treatments being tested at the Urban Landscape Runoff Facility at Texas A&M University. Image was taken during fall 2018, two months after landscape conversions were made.

Table 1. Fertilizer applications applied during the study period (August 2018 through December 2019).

Treatment	Fertilizer analysis	Date applied	Rate
St.Augustinegrass Lawn	Sulfur Coated Urea (21-7-14)	8/27/2018	4.88 g N per m^2
	Turfbuilder (32-0-10)	4/23/2019	4.88 g N per m^2
	Turfbuilder (32-0-10)	7/10/2019	4.88 g N per m^2
	Turfbuilder (32-0-10)	8/27/2019	4.88 g N per m^2
Sand-capped Lawn	Bumper Crop (13-13-13)	8/15/2018	6.34 g N per m^2
	Sulfur Coated Urea (21-7-14)	8/27/2018	4.88 g N per m^2
	Turfbuilder (32-0-10)	4/23/2019	4.88 g N per m^2
	Turfbuilder (32-0-10)	7/10/2019	4.88 g N per m^2
	Turfbuilder (32-0-10)	8/27/2019	4.88 g N per m^2
Xeriscaping	Miracle-Gro All Purpose Plant Food (24-8-16)	10/29/2018	1 g N per m^2 planted area
Mulch	Miracle-Gro All Purpose Plant Food (24-8-16)	10/29/2018	1 g N per m^2 planted area
Artificial Turf	No Fertilizer Applied		

The two water-efficient landscapes were drip-irrigated, while the St. Augustinegrass plots were overhead irrigated to meet plant demand based on 60% of reference ET from an onsite weather station. Synthetic turf received no irrigation. Fertilizer was applied by drop spreader for turfgrass plots, while fertilizer was mixed in a watering can and applied to Texas sedge and dwarf yaupon holly only for xeriscaping and mulch. A fertilization plan for all treatments is presented in Table 1.

Rainfall volumes (mm) were obtained from an onsite tipping rain gauge (Isco 647, Teledyne Isco, Lincoln, NE) at a two-minute temporal resolution as well as from an on-site weather station that was registered in Texas ET Network, with a station name of TAMU Turf Lab.

Pre-emergence herbicides were applied to all treatments (except artificial turf plots) during February 2019 using oxadiazon (Ronstar G, Bayer Environmental Sciences) at a rate of 2.25 kg ha^{-1} active ingredient.

Soil Moisture Content

Soil volumetric moisture content was measured once weekly for all landscapes beginning 10/11/2018. A handheld moisture meter (HH2, Delta-T Devices Ltd., Cambridge, UK) was used for measurement of St. Augustinegrass lawn, Sand-capped Lawn, and Mulch treatments, while a different soil moisture meter with more robust 7.6 cm probes (FieldScout TDR 350, Spectrum Technologies, Aurora, IL) was used for measuring decomposed granite-based Artificial turf and Xeriscaping treatments. For each measurement, the average of 4 random readings taken at four locations within each plot was recorded. For St. Augustinegrass lawn, sand-capped lawn, artificial turf, and sand-capped lawn readings were taken in one of each of the four quadrants of the plot. For water efficient mulch and xeriscaping treatments, all 4 readings were obtained at four random points in the center potion of planted areas of plots, in order to avoid any damage of the plants.

Runoff Dynamics

Runoff characteristics were evaluated for all naturally occurring rainfall event from throughout the study. Peak flow rates (L s^{-1}) as well as total runoff volumes from each landscape type were compared to determine influence of landscapes on runoff characteristics. Flow rates were downloaded from ISCO 4210 flow meter (Teledyne Isco, Lincoln, NE), and total runoff volumes were determined by multiplying the 2-minute recorded runoff flow rates for the duration of the event. Total runoff volume data were analyzed for all rain events. Hydrographs were created for each treatment by plotting flow rate of runoff along with precipitation for a typical rainfall event in order to characterize the response of each landscape treatment to precipitation.

Runoff samples were collected by an ISCO 6712 autosampler (Teledyne Isco, Lincoln, NE) with the sampling interval set at every 150 L of runoff water. Samples were collected the day after a rainfall event. If intermittent rainfall lasting several days occurred, then sample collection occurred after the event was completed.

Parameters including pH, electrical conductivity, and total suspend solids (TSS) were measured for raw runoff samples on the day of sample collection. Only the first sample and the last sample of each plot were analyzed for TSS (labeled as TSS (First) and TSS (Last), respectively). This was meant to test the first-flush phenomenon of runoff. After TSS determination, all runoff samples were filtered through the same type of filter paper used for TSS determination. Nutrients for filtered samples included: Total dissolved N (TDN), nitrate-N (NO_3-N), ammonium-N (NH_4-N), orthophosphate-P (PO_4-P) and dissolved organic Carbon (DOC). Dissolved organic nitrogen (DON) was estimated by deducting NO_3-N and NH_4-N from TDN.

Total nutrient exports from each landscape for each runoff event were calculated using the following equation:

$$\text{Export (mg m}^{-2}\text{)} = \frac{\text{Average concentration for rain event (mg L}^{-1}\text{)} \times \text{Total runoff volume (L)}}{\text{Plot size (m}^{2}\text{)}}$$

Landscape Surface Temperatures

Reflective surface temperatures were measured once a week for each landscape on a clear day with an infrared thermometer (E6-XT, FLIR, Wilsonville, OR). Measurements were taken during the early afternoon hours (1200 to 1400 hours) on each measuring day in order to minimize the influence of the diurnal change of solar radiation. The thermometer was aimed perpendicular to the center of the plot at a height of 1 m, and the median number of a temperature range that was measured for a detectable area by the thermometer was recorded as the surface temperature for the plot. If there was no clear day for weeks during the study period, measurements were not taken.

Weed Pressure and Weed Control

Weed pressure was used as an indicator of maintenance requirement of each landscape, with total amount of weeds, no matter what species, counted on a weekly basis. Once the number of weeds was recorded, all weeds were removed from each plot to avoid repetitive counting over time. Large weeds were hand-pulled and small weeds were controlled by point spraying post-emergent herbicide (Roundup, Bayer, Leverkusen, Germany) within xeriscaping, mulch, and artificial turf treatments, while weeds were only removed by hand pulling for two the two lawns. Sometimes, mushrooms thrived, especially for mulch during the rainy season of late fall and winter. However, since they normally die off relatively quickly, they were not closely monitored.

Landscape Aesthetics

Since there is no existing evaluation mechanism for comparing the quality of water efficient landscapes and home lawns, a scoring system commonly used for the turfgrass industry developed by the National Turfgrass Evaluation Program (NTEP) was adapted and used for this study. The NTEP system, while somewhat subjective, evaluates turfgrass quality based on visual rating integrating density, color, and uniformity of turfgrass, with a scale of 1 (totally brown) to 9 (perfect), with a rating of 6 or greater denoting acceptable quality. This system has considered the complexity and difficulty of quality evaluation for different turfgrasses, given the diversity of morphology of different species and cultivars, and thus was used for this study, as all plants selected in this study were mainly for aesthetics. A single rating was given to sand-capped lawn, St. Augustinegrass lawn, and artificial turf treatments, while all plants grown in xeriscaping and mulch treatments received a score and the average of those scores used as the overall score of landscape quality.

Statistical Analyses

All data including runoff volume, pH, EC, nutrient concentration, and nutrient export, surface temperature, weed density, and aesthetics were analyzed as a single continuous experiment over one year (Sept. 2018 to Sept. 2019) using two factor ANOVA repeated measures, with date as the repeated measures. Date and landscapes were considered two major factors. Both main factor date, landscapes and their interactions were considered fixed effects. Where significant main effects or interactions were detected, treatments means were compared by using Tukey's HSD at $P = 0.05$. Correlation was also conducted using SAS for most of the runoff parameters using Pearson correlation analyses.

Results and Discussion

Runoff Events

During the one-year study period (September 2018 – September 2019), 24 runoff events from naturally occurring rainfall occurred (Figure 2). The magnitude of runoff volume was closely related to the intensity of rainfall, and runoff was only detected when rainfall was greater than 12 mm for the majority of events and treatments. Most runoff events occurred during fall and winter (late September 2018 to March 2019) when turfgrasses were dormant and native plants had stopped growing. Significant differences in runoff volume among treatments began to develop within 4 months following installation of alternative landscapes (Figure 2).

No significant differences in runoff volumes were found among landscape treatments during the first five months of the study (September 2018 – January 2019) (Figure 2). The lack of effect of landscape treatment observed for this earlier period is likely due to newly constructed landscapes taking time to settle, with their water holding capacities being higher after construction compared to after settling and compaction. For example, the newly applied mulch was able to hold more water after it was laid compared to later in the study when it had settled and compacted somewhat. This likely resulted in a larger soil water pool that released more water over a longer period of time, as the results demonstrated for the first two dates 9/13/2018 and 9/24/2018, where an abnormally high total volume of runoff was found for mulch (Figure 2).

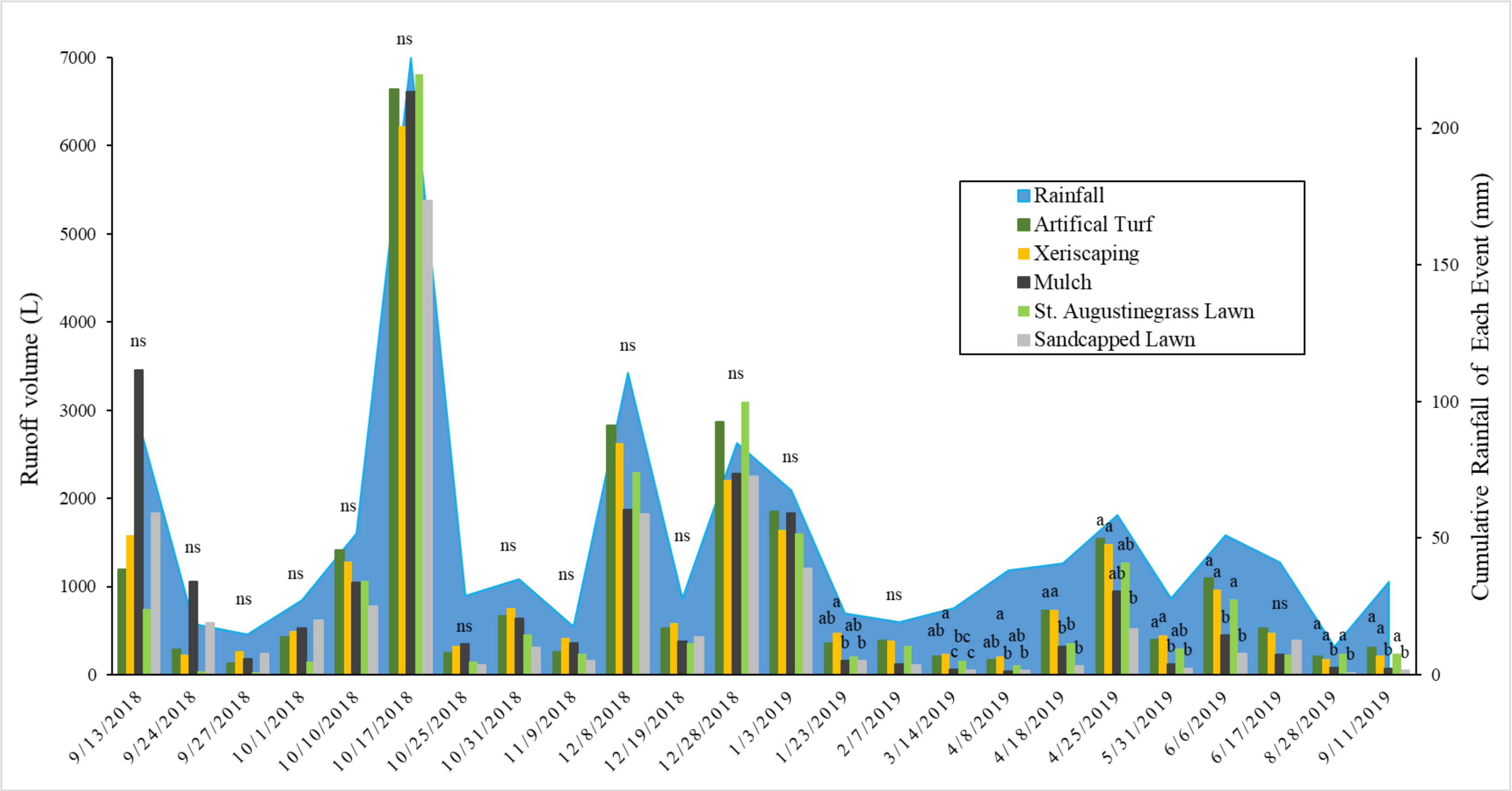

Figure 2. Cumulative rainfall of each runoff event and total runoff volume of all landscapes for each runoff event during the study period. Different lower case letters signify a significant difference within each runoff event, while ns indicates no significant difference.

This same phenomenon is applicable to sand-capped lawns since 10 cm coarse sand was placed on top of the native soil on August 2018 and likely took time to settle and compact. Secondly, the effect of landscape type on runoff volume was generally diluted when rainfall received was higher than 60 mm, which was the case for many of the fall 2018 rainfall events (10/17/2018, 12/8/2018, 12/28/2018, and 1/3/2019) (Figure 2). Thirdly, turfgrass was either newly established (sand-capped lawn), or under dormancy (6-year-old St. Augustinegrass), so the overall water requirement for the turfgrass treatments was low during fall and winter of the first season, which again diminished the advantage of turfgrasses in reducing runoff volumes through uptake and evapotranspiration. While these explanations help to explain the lack of significant differences in runoff volume between treatments early in the study, it should be noted that the St. Augustinegrass lawn treatment generated the lowest runoff volumes for most events during the initial months of the study (Figure 2).

During the first full growing season (March – September 2019), a significant effect of landscape on runoff volumes was observed for most runoff events (Figure 2). During this period, the cumulative rainfall of each event was less than 60 mm and turfgrasses took up more water to fulfill growth. Overall, the sand-capped lawn had significantly lower runoff volume than other landscapes (Figure 2). Mulch and St. Augustinegrass lawn maintained a medium runoff volume, while xeriscaping and artificial turf showed the highest runoff volume which was significantly higher than the other landscapes, especially when compared to sand-capped lawns for most events (Figure 2).

Landscape Effects on Runoff Volumes, pH and EC and Suspended solids

Significantly different runoff volumes were observed due to landscape treatments (Table 2) as well as date of rain event (Table 2). There was also a significant interaction effect on runoff volume of date of rain event × landscape treatment (Table 2). All variables measured (pH, EC and TSS) showed a significant effect of rain event date, landscape treatment and an interaction between rain date and landscape treatment (Table 2).

Table 2. ANOVA for effect of landscape treatment and date of rain event on runoff volume and quality during the study period. TSS (first) is the total suspended solids of first runoff sample. TSS (last) is the total suspended solids of last runoff sample.

	Runoff Volume and Quality				
Source	Volume	pH	EC	TSS (First)	TSS (Last)
Replication	NS	*	NS	NS	NS
Date (D)	***	***	***	***	***
Landscape (L)	***	***	***	***	***
D x L	***	**	***	***	*

ns, ***, **, *; Not significant, significant at P=0.001, 0.01, and 0.05, respectively

Runoff Flow Rates

In order to fully understand the runoff dynamics of all landscapes, hydrographs were created for all landscapes for two representative runoff events, one occurring during the first month, and the other occurring during summer of the first full growing season (10/10/2018 and 6/6/2019, respectively) (Figure 3 and 4).

For the 10/10/2018 event (Figure 3), on each graph, flow rate (y-axis) was plotted along with precipitation (z-axis), and the runoff event timing (x-axis) can be divided into two phases, during rainfall and after rainfall. The flow rate of runoff mirrored the pattern of precipitation during rainfall, and the peak of flow rate and peak of precipitation coincided. Among all landscapes, xeriscaping, artificial turf and St. Augustinegrass lawn had a relatively larger peaks compared to sand-capped lawn and mulch. In addition, there was another small peak found for artificial turf and xeriscaping, following the first peak of precipitation, which was not observed for other three landscapes. Thus, it can be concluded that water infiltration rate was relatively low for the relatively impervious landscapes artificial turf and xeriscaping, which both displayed an early peak in runoff after rainfall initially commences, and this contributes to the overall high runoff volume. Another notable result was during the after-rainfall period, where the flow rate of artificial turf, mulch, xeriscaping, and sand-capped lawn were around 5 to 10 times higher than St. Augustinegrass, which suggests that the native soil had a better water holding capacity than mulch, coarse sand, and decomposed granite at the early stage of landscape conversion. As such, the flow rate of after rainfall period ranged between 0.001 to 0.002, 0.003 to 0.005, 0.07 to 0.01, 0.01 to 0.017, and 0.015 to 0.025 L s^{-1} for St. Augustinegrass lawn, xeriscaping, artificial turf, sand capped lawn, and mulch, respectively. Thus, it can be seen that after rainfall, runoff was detected from all newly constructed landscapes, which attributed at least partially to their total runoff volume.

Runoff dynamics of all landscapes are again shown for later on during the first full growing season on 6/6/2019 (Figure 4). During this event, the highest flow rates were still found for artificial turf and xeriscaping. For St. Augustinegrass lawn, the actively growing grasses pulled more water out of soil through evapotranspiration resulting in a lower soil moisture content. This combined with deep rooting and soil structure that is receptive to rapid infiltration allowed more rainfall to be captured in the soil, which resulted in the lower flow rate when comparing to artificial turf and xeriscaping. The lowest peak of flow rate was detected from sand-capped lawn and mulch, and no peak was detected at 7:00 AM for those two landscapes, which confirmed the high soil infiltration rate of sand-capped lawn and mulch. In addition, water was held more tightly by sand-capped lawn and mulch when comparing to 10/10/2018 event, as coarse sand and hard wood mulch likely settled in by 6/6/2019. The overall greater infiltration rate and water holding capacity of sand-capped lawn and mulch appeared to offer good absorption of rainfall resulting in good runoff control.

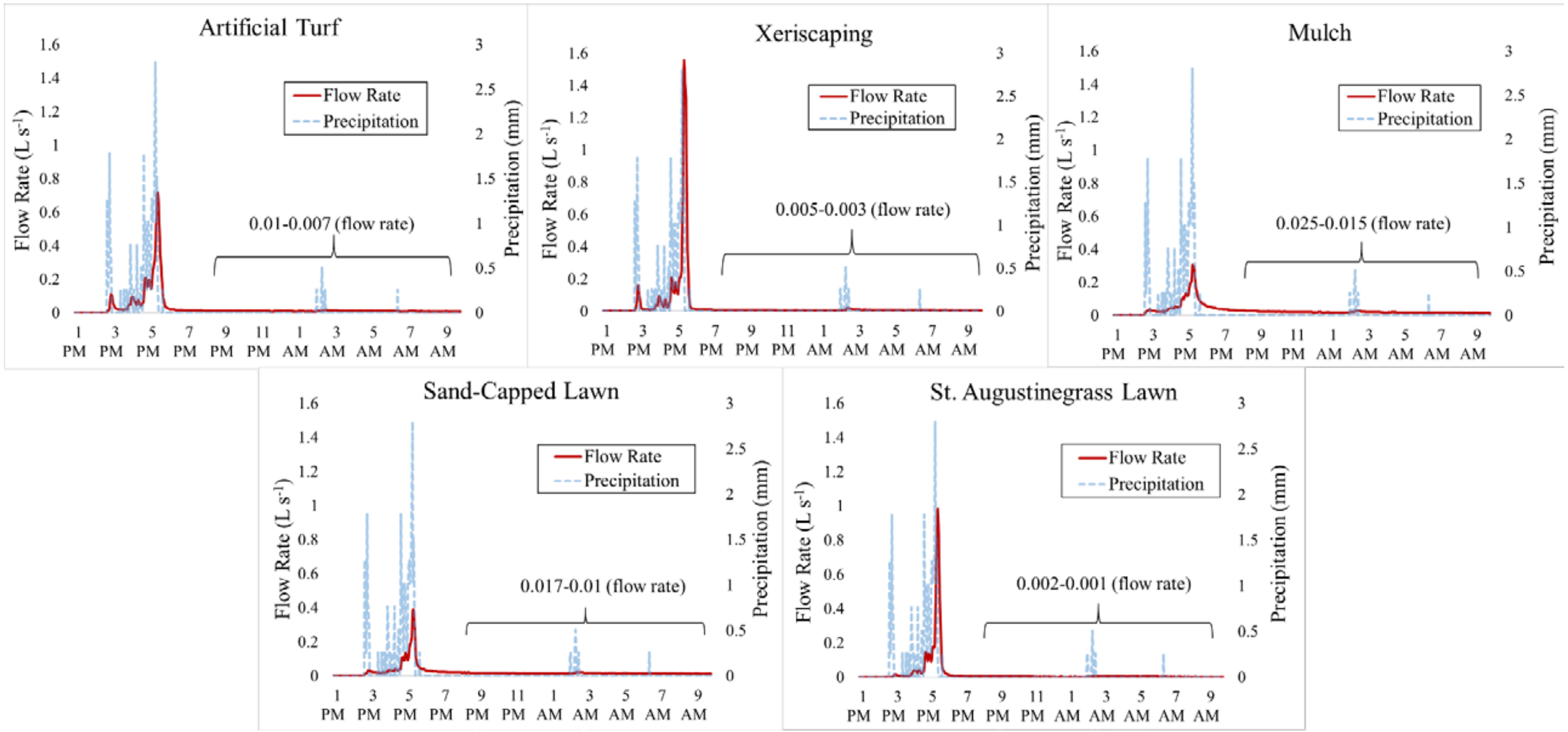

Figure 3. Runoff flow rates occurring from each landscape during 10/10/2018 rain event. Flow rate and precipitation were measured on 2-minute intervals.

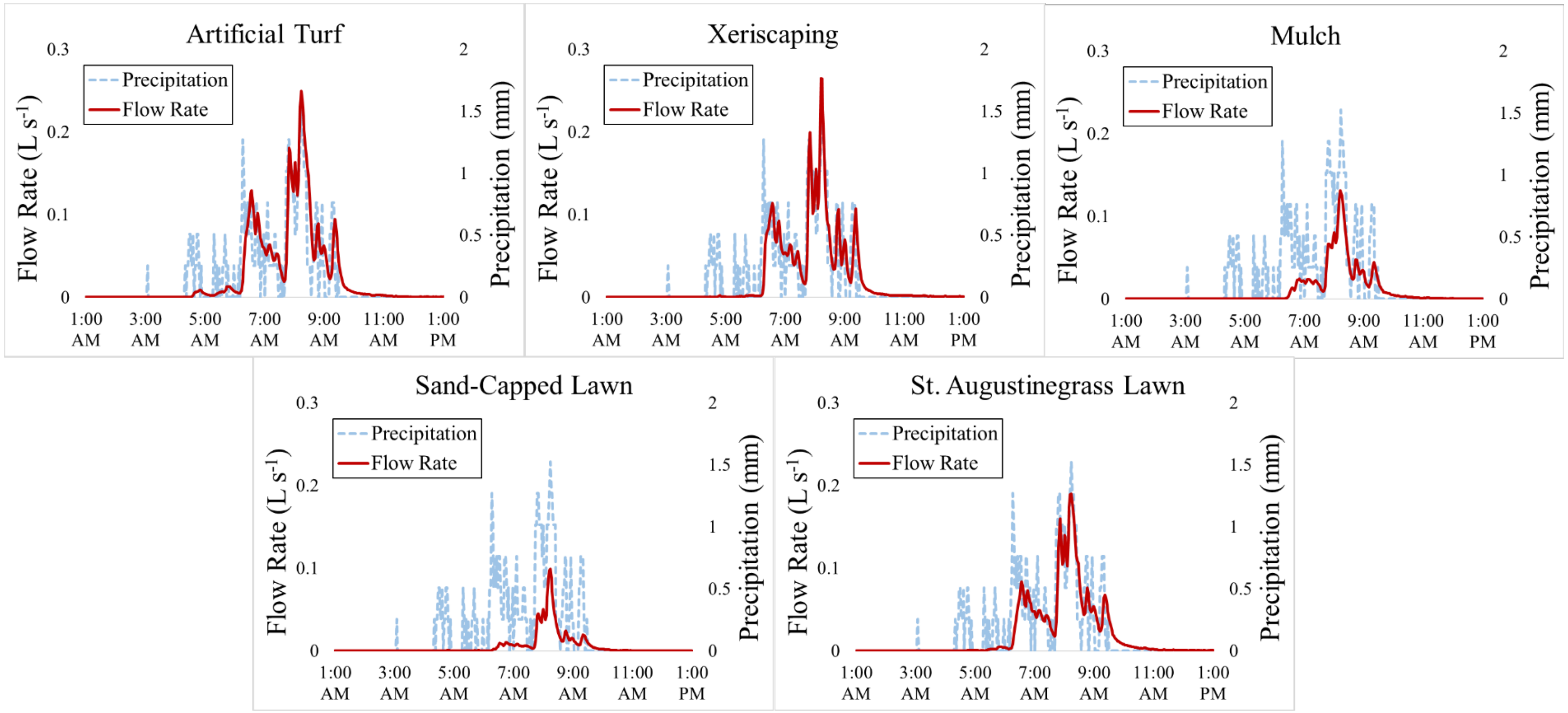

Figure 4. Runoff flow rates occurring from each landscape during 6/6/2019 rain event. Flow rate and precipitation were measured on 2-minute intervals.

Soil Moisture Content

A significant interaction between rain date and landscape treatment was observed for soil moisture content (Table 3).

Table 3. ANOVA table of plot quality, weed pressure, surface temperature, and soil moisture content of landscapes on different measuring dates.

Source	Plot Quality	Weed Pressure	Surface Temperature	Soil Moisture Content
Replication	NS	***	NS	NS
Date (D)	***	***	***	***
Landscape (L)	***	***	***	***
D x L	***	***	***	***

ns, ***, **, *; not significant, significant at *P*=0.001, 0.01, and 0.05, respectively

During the winter or dormant season, when irrigation was turned off, the effect of landscape on soil moisture content was highly significant (Figure 5). More specifically, St. Augustinegrass lawn had the highest soil moisture content, followed by mulch. Sand-capped lawn and xeriscaping soil moisture content were lower, ranging between 15 to 20%. The lowest soil moisture content was found for artificial turf (below 10%), and it was consistent during the entire year. During the growing season, soil moisture content of turfgrass dropped, except for several peaks that were measured after a rainfall event, such as 4/26/2019, 6/4/2019, 6/25/2019, and 9/13/2019 (Figure 5). Mulch surpassed St. Augustinegrass lawn in soil moisture content during 4/26/2019 to 7/9/2019 when several rainfalls were experienced during that period. During 7/17/2019 to the end of the study, soil moisture content was highest for St. Augustinegrass, followed by sand-capped lawn, which was likely due to these treatments receiving irrigation twice weekly. Although minimal amounts of water were applied to plants in the mulch treatment from drip irrigation, its captured rainwater kept its soil moisture content consistently higher than 20%. The same drip irrigation and irrigation plan was used for xeriscaping as mulch, but the soil moisture content of xeriscaping was significantly lower. No irrigation was provided to artificial turf, which resulted in the lowest soil moisture content (less than 10%), and it was significantly lower than that of other landscapes. To conclude, the soil moisture content reflected the nature of different landscapes in response to water input. In brief, mulch and lawns demonstrated the best ability to hold water within the system for an extended time period, however, the soil moisture content of artificial turf and xeriscaping was not sensitive to water input, thus a higher potential for water losses through runoff may be expected for those two landscapes.

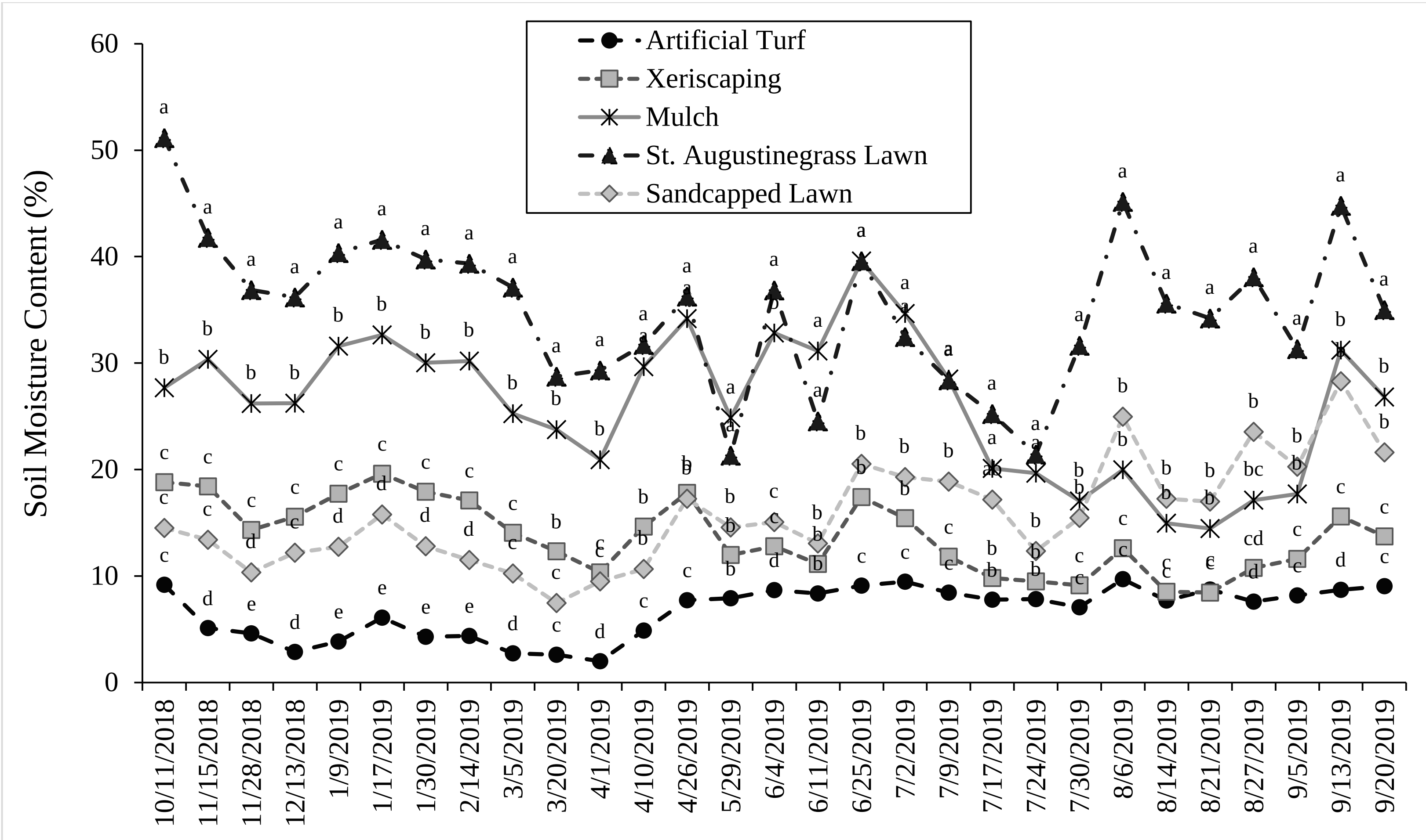

Figure 5. Soil moisture content of all landscapes. Means with the same letter in a given date are not significantly different based on Tukey's HSD at P = 0.05.

Runoff Quality

For each runoff event detected during the study period, runoff water quality was analyzed for several parameters, including pH, EC, TSS, and concentration of NO_3-N, NH_4-N, PO_4-P, TDN, DON, and DOC. There was a significant interaction between landscape and date on all parameters measured (Tables 2 and 4).

Table 4. ANOVA for effect of landscape and date on nutrient concentration.

	Nutrient Concentration (mg L^{-1})					
Source	NO_3-N	NH_4-N	PO_4-P	TDN	DON	DOC
Replication	**	NS	NS	NS	NS	NS
Date (D)	***	***	***	***	***	***
Landscape (L)	***	***	***	***	***	***
D x L	***	***	***	***	***	***

ns, ***, **, *; not significant, significant at P=0.001, 0.01, and 0.05, respectively

pH

Runoff pH for all landscapes over the study period, dropped slightly; the range of runoff pH dropped from 7.5 - 8.5 in fall and winter months to a pH range of 7 - 8 (except for a couple outliers) during early spring and summer (Figure 6). Effect of landscape was not significant for most runoff events (Figure 6). Mulch always had the lowest pH, especially for those dates that a significant effect of landscape was found, such as 10/10/2018, 10/31/2018, 12/19/2018, 3/14/2019, 6/6/2019, 8/28/2019, and 9/11/2019 (Figure 6).

Fertilization sometimes also has an influence on runoff pH. Fertilizer influence on runoff pH likely explains the pH outliers occurring on 8/28/2019 and 9/11/2019 a couple days after fertilization applied on 8/27/2019. This suggests that avoiding fertilization before rainfall can reduce potential environment impact resulting from turfgrass management.

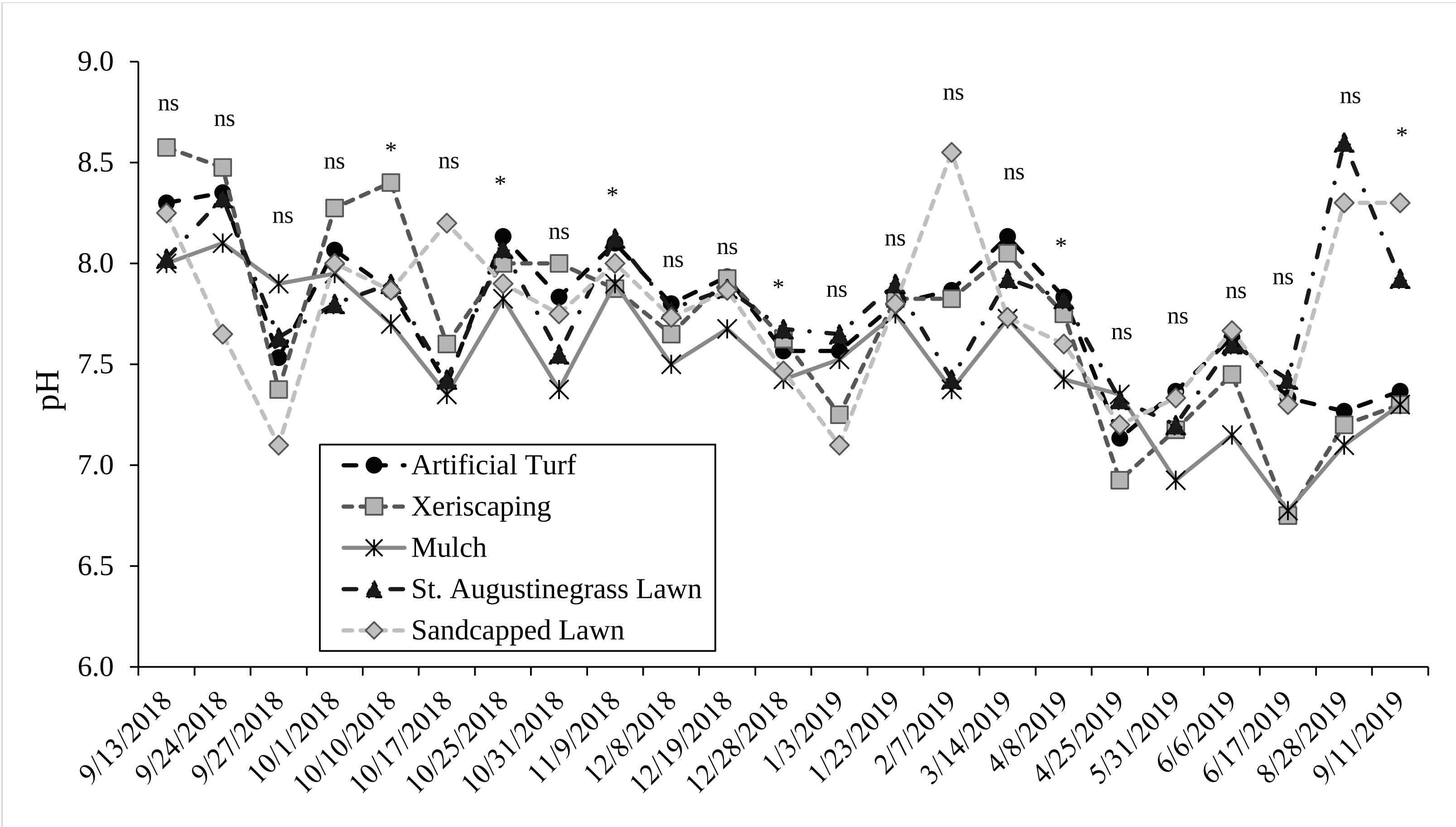

Figure 6. Effect of landscape and date on runoff pH. ns indicates no significant difference and * indicates significant differences on each date, based on Tukey's HSD at P = 0.05.

Electrical conductivity (EC)

Electrical conductivity (EC) has been used as an indicator of water quality, as it is affected by the presence of organic and inorganic dissolved solids. Thus, water with high EC contain high concentrations of cations, anions and other solutes. Effect of landscapes on runoff EC was significant during the study period (Table 2), and a seasonal pattern was also observed (Figure 7). The highest runoff EC was observed on 9/24/2018. Runoff EC values then dropped to below 400 µS cm^{-1}) until a second peak was observed on 8/28/2019. During the entire study period, xeriscaping and artificial turf displayed a significantly lower EC than other three landscape treatments, and the largest difference among treatments was observed on 9/24/2018 (500 µS cm^{-1} for xeriscaping and artificial turf vs.1000+ µS cm^{-1} for the other three landscapes). The low EC value of xeriscaping and artificial turf is related to low nutrients in the runoff, which will be discussed later. In addition, a significant negative correlation was observed between EC and runoff volume, (Table 5, Figure 7). For example, several EC peaks occurred on 9/24/2018, 9/27/2018, 10/25/2018, 11/9/2018, 4/8/2019, and 8/28/2019, and comparing to Figure 2, on these dates, landscapes also had the lowest runoff volume that derived from a low rainfall event. The negative correlation illustrates that “dilution is the solution” in terms of runoff. These results also suggest that most nutrients stored in the soil could be moving out of systems with a small fraction of runoff, which is sometimes referred to as the first flush. A significantly elevated EC can be tested in runoff when soils have not been flushed by water for an extended period of time, as the peak shown on 8/28/2019 when the last runoff was 2 months earlier.

Table 5. Correlation of parameters measured for runoff samples. All nutrient parameters presented here are concentrations (mg L^{-1}).

Parameter	pH		EC		NO_3-N		NH_4-N		PO_4-P		TDN		DON		DOC		TSS (First)		TSS (Last)	
Volume	-0.10	*	-0.17	**	-0.02	ns	-0.01	ns	-0.07	ns	-0.07	ns	-0.03	ns	-0.05	ns				
pH			0.31	***	0.12	*	0.10	ns	0.10	*	0.12	*	0.10	*	-0.02	ns				
EC					0.23	***	0.30	***	**0.70**	***	0.60	***	0.37	***	0.54	***				
NO_3-N							0.15	**	0.06	ns	0.32	***	0.18	***	-0.12	*	-0.05	ns	0.09	ns
NH_4-N									0.27	***	**0.78**	***	0.31	***	0.18	***	-0.02	ns	-0.02	ns
PO_4-P											0.59	***	0.32	***	**0.72**	***	-0.06	ns	-0.05	ns
TDN													0.46	***	0.54	***	-0.09	ns	-0.05	ns
DON															0.31	***	-0.09	ns	-0.08	ns
DOC																	-0.05	ns	-0.09	ns

ns, ***, **, *; not significant, significant at P=0.001, 0.01, and 0.05, respectively

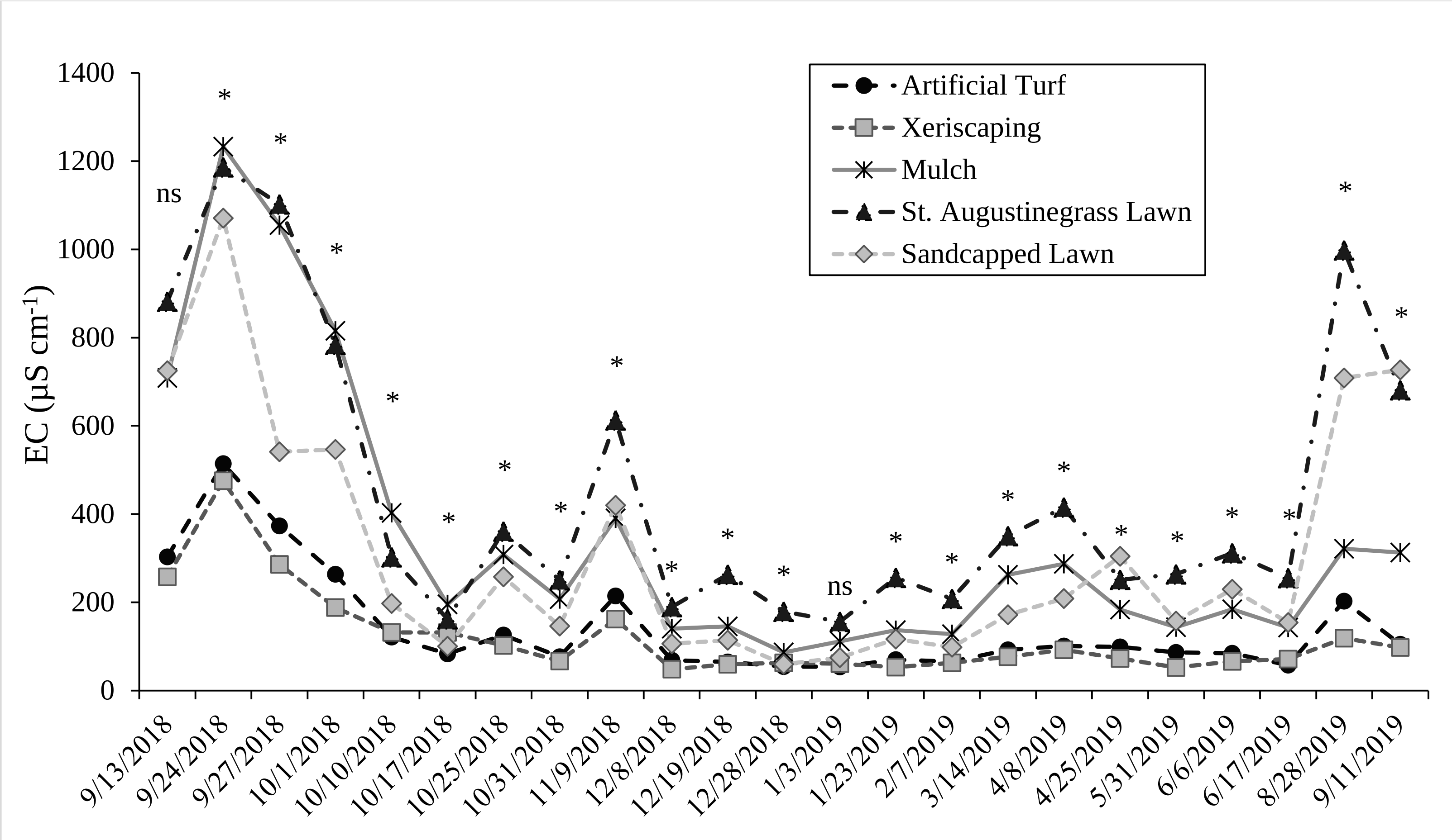

Figure 7. Effect of landscape and date on runoff electrical conductivity (EC). ns and *, respectively, indicate that no significant difference and significant difference were detected between treatments on each date, based on Tukey's HSD at P = 0.05.

TSS

Total suspend solids were analyzed by separating the first runoff samples and last runoff samples for each landscape treatment. A significant interaction between date × landscape was found for both the first and last runoff samples (Table 2). Higher concentrations of TSS were always carried by the first sample of runoff than the last sample of runoff (Figure 8) TSS was first measured on 10/10/2018, almost two months after the landscape conversion was initiated. However, the TSS losses for newly constructed landscapes, especially for xeriscaping were still extremely high, even though all decomposed granite used for this landscape was compacted using a plat compacter. This suggests that TSS loses must be considered in a higher priority for new construction where surface was covered by decomposed granite. TSS losses from xeriscaping were significantly higher for both the first sample and last sample when compared to other landscape treatment. The magnitude of TSS (first) of xeriscaping was 5 to 10 times higher than other landscapes for several runoff events, such 10/10/2018, 10/17/2018, 11/9/2018, and 4/8/2019 (Figure 8). Although decomposed granite was also used for beneath artificial turf, the synthetic turf mat that was installed appears to have secured and protected against TSS loss resulting in the lowest TSS concentration (Figure 8). Moreover, the raw runoff samples received from artificial turf were clear whereas samples from xeriscaping were always turbid (picture not shown). High TSS concentrations in runoff water, specifically of decomposed granite high in iron and aluminum can serve as carriers of negatively charged potentially toxic elements (PTE's) and other negatively charged compounds of herbicides and pesticides. Furthermore, irrigation systems or surface waters can be clogged by these solids.

'First flush' of TSS is believed important by researchers, which is that the initial portion of the runoff always carries more TSS than the reminder portion due to the washout of deposited pollutants by rainfall. Our result confirmed the importance of this concept on surface water quality evaluation.

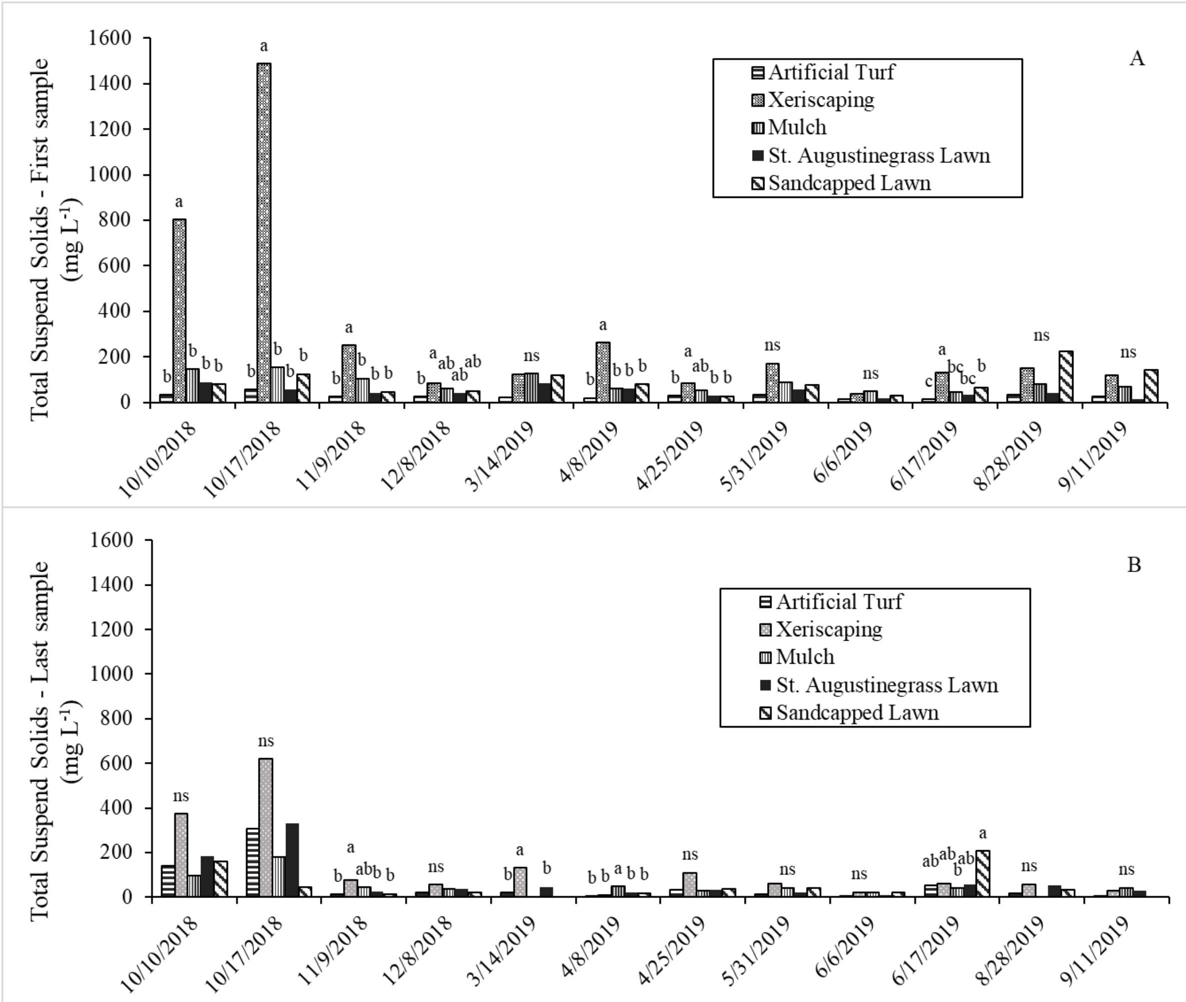

Figure 8. Total suspend solids of the first runoff sample (A) and the last runoff sample (B) for all landscapes. Means with the same letter in the same date are not significantly different based on Tukey's HSD at P = 0.05.

NO_3-N

Runoff NO_3-N concentrations ranged from 0.1 to 2.6 mg L^{-1} for all landscapes during the study periods, which are well below the standard of maximum contaminant level (10 mg L^{-1}) for drinking water developed by EPA (Figure 9).

The highest NO_3-N concentration was observed for artificial turf and St. Augustinegrass lawn for most events (Figure 9). A significant difference was observed between mulch and artificial plots for several runoff events, with a range of 0.03 to 0.5 mg L^{-1} and 0.5 to 2.6 mg L^{-1} for mulch and artificial turf, respectively (Figure 9). The unexpected high NO_3-N runoff concentrations of artificial turf could be related to animal activities, as it has been found that several wild animals have shown up on those plots at night, leaving behind feces or urine in plots while they were there. However, even though animal urine can increase N between 20 to 80 g N m^{-2}, over 70% of the N is present as urea. Thus, the high NO_3-N runoff may be due to soil aeration from ground disturbance from wildlife. Concentrations of NO_3-N in runoff from artificial turf could also be due to mineralization within underlying soil below the decomposed granite layer, which may accumulate and not be assimilated due to lack of plant roots for taking up NO_3-N.

The NO_3-N concentrations of St. Augustinegrass appeared to be correlated with fertilization events. As such, a significant difference between St. Augustinegrass lawn and xeriscaping, mulch, and sand-capped lawn was observed on 4/25/2019 and 8/28/2019, in the days following fertilizer applications to the lawn plots (Table 1; Figure 9).

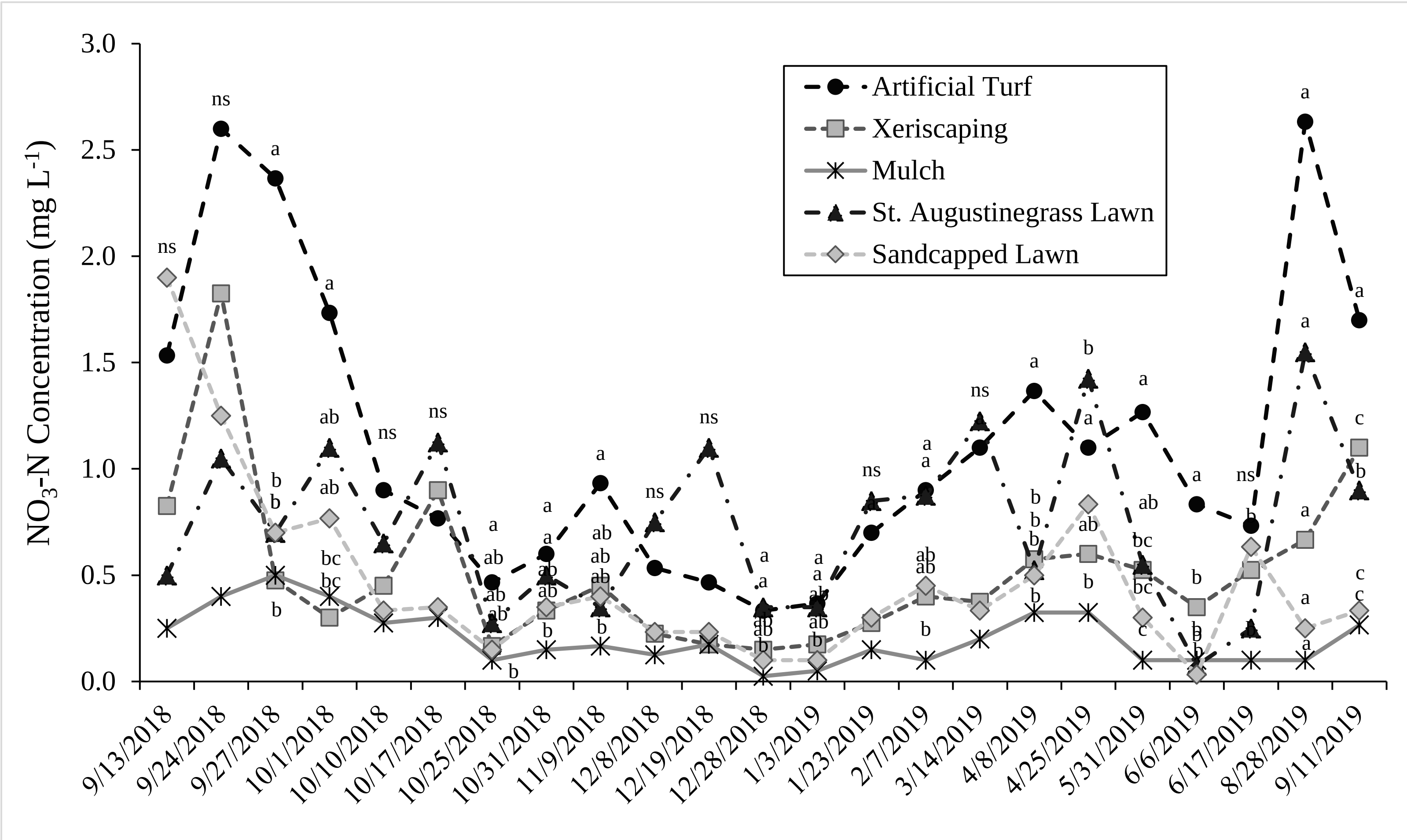

Figure 9. NO_3-N concentration as affected by landscapes and date. Means with the same letter on the same date are not significantly different based on Tukey's HSD at $P = 0.05$

NH_4-N

Runoff NH_4-N concentration was relatively stable for all landscape treatments and stayed at a lower concentration for xeriscaping and artificial turf over the entire study period, with a range from 0.1 to 0.6 mg L^{-1} (Figure 10). There was an exception of three peaks of NH_4-N during the study period when runoff concentrations exceeded 2 mg L^{-1}.

All three dates where peaks and significant differences for NH_4-N were noted (10/31/2018, 4/25/2019, and 8/28/2019) appeared to be related to fertilization. As such, on 10/31/18, two days after mulch were fertilized, NH_4-N concentration was significantly higher for mulch when comparing to unfertilized artificial turf. Similarly, significantly higher concentration was found for sand-capped lawn and St. Augustinegrass lawn on 4/25/2019, and 8/28/2019 due to fertilization that was applied 2 days before a rainfall (Table 1 and Figure 10). These observations highlight the importance of monitoring the weather forecast and avoiding fertilization before a rain event in order to minimize the NH_4-N losses through runoff, regardless of landscape type.

It should be noted that in this study, fertilization of landscape treatments were based on published recommendations, with turfgrass plots receiving the highest fertilization rates (~14.7 g N m^{-2} yr^{-1}), while alternative landscapes received fertilization only once during the establishment period. Thus, the efficiency of using applied N by lawns and alternative landscapes is not able to be compared in this study.

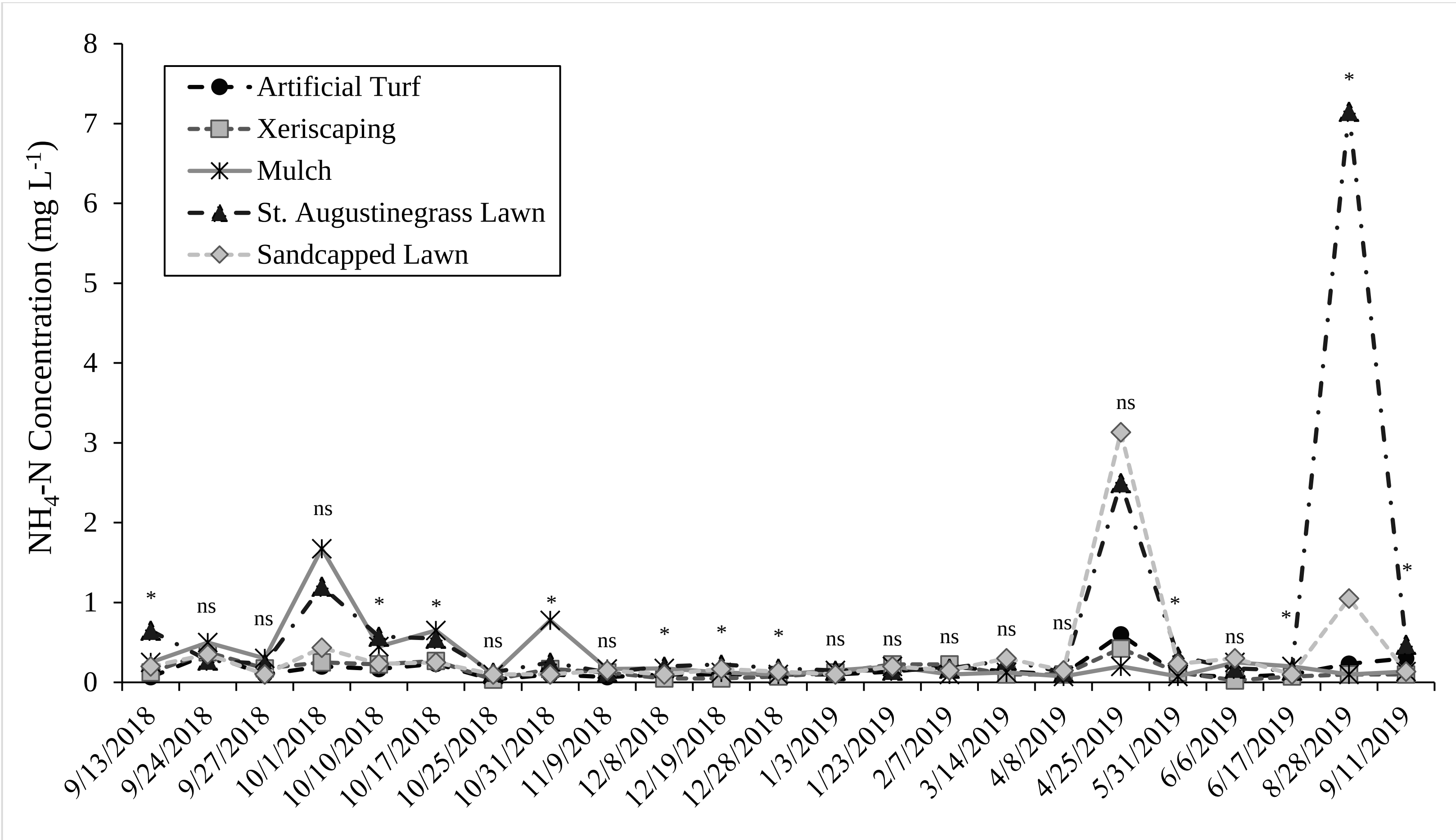

Figure 10. NH_4-N concentration of runoff water for all landscapes. ns indicates no statistically significant difference and *statistically significant difference were detected between treatments on each date, based on Tukey's HSD at P = 0.05.

TDN, DON, and DOC

According to ANOVA table (Table 4), significant interactions between landscapes and runoff events were found for TDN (total dissolved nitrogen), DON (dissolved organic nitrogen), and DOC (dissolved organic carbon). Most N in runoff was derived from organic N, around 70 to 90% for mulch and St. Augustinegrass lawn, and thus the total dissolved N (TDN) concentration followed a similar pattern to dissolved organic N (DON) concentration (Figures 11 and 12).

For TDN and DON, the highest concentrations were found for mulch plots, which were followed by St. Augustinegrass lawns during the growing season (9/13/2018 – 10/31/2018) after landscape installation. During this period, DON concentration of mulch and St. Augustinegrass lawns were always significantly higher than other three landscapes, and the runoff DON concentration of mulch was significantly higher than all other landscapes, with a range of 4 to 11 mg L^{-1}. Starting from 11/9/2018, the difference of TDN and DON among landscapes were reduced, and St. Augustinegrass started showing the highest concentration for most of the dates (Figures 11 and 12). In comparison, DON concentration was relatively stable and almost negligible for xeriscaping, artificial turf and sand-capped lawn (less than 2 mg L^{-1} for most cases), except for two peaks found for sand-capped lawn, which were due to fertilization (Figure 12). TDN of xeriscaping and artificial turf was dominated by inorganic N (more than 50%), and their trend was discussed in previous sections on NO_3-N and NH_4-N.

Means separation were clear among landscapes for DOC concentration during the study period, with a seasonal pattern presented. Basically, DOC in runoff water was dependent upon the organic carbon pool of each landscape) For example, mulch, 5 cm of shredded dark wood was used as infill material and contributed a large amount of organic carbon to the landscape. This organic carbon was leached into the plot water after rain and left plot with runoff water when during high rainfall events which resulted in the highest DOC concentration in runoff during the entire study period. A warmer environment seems facilitated the wood breakdown, releasing organic C, as peaks found on dates within April to October 2019 (Figure 13). This breakdown is likely linked to the fungal growth reported earlier.

Turfgrass biomass was the major organic C source for St. Augustinegrass lawn and sand-capped lawn, and the organic carbon pool was large when more biomass was produced during growing season, which directly impacted the DOC concentration in runoff. Two major DOC peaks were found for St. Augustinegrass lawns both years, while there was only one peak found in 2019 for sand-capped lawn, likely because not much biomass was produced by newly sodded sand-capped lawn in 2018. This is also likely the reason why St. Augustinegrass had higher DOC concentration than sand-capped lawn, as 6-year-old turfgrasses should have produced more biomass and hence thatch than less than 1-year old turfgrasses. DOC concentration of xeriscaping and artificial turf was less than 20 mg L^{-1} for most runoff events, likely because there was little to no above-ground organic input for these two landscapes.

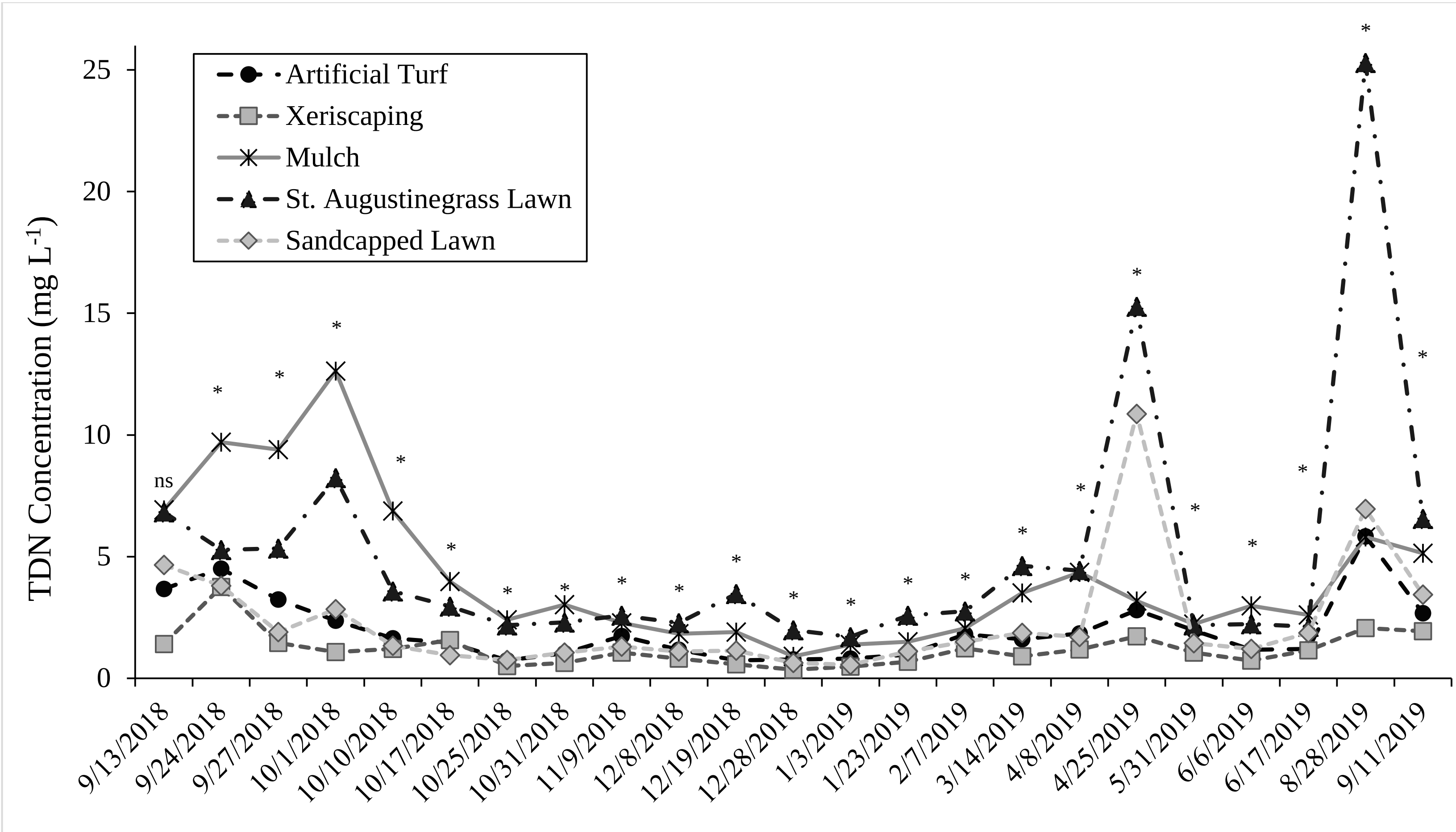

Figure 11. Total dissolved nitrogen (TDN) concentration of runoff water for all landscapes. ns and *, respectively, indicate no statistical difference and statistical difference between treatments on each date, based on Tukey's HSD at P = 0.05.

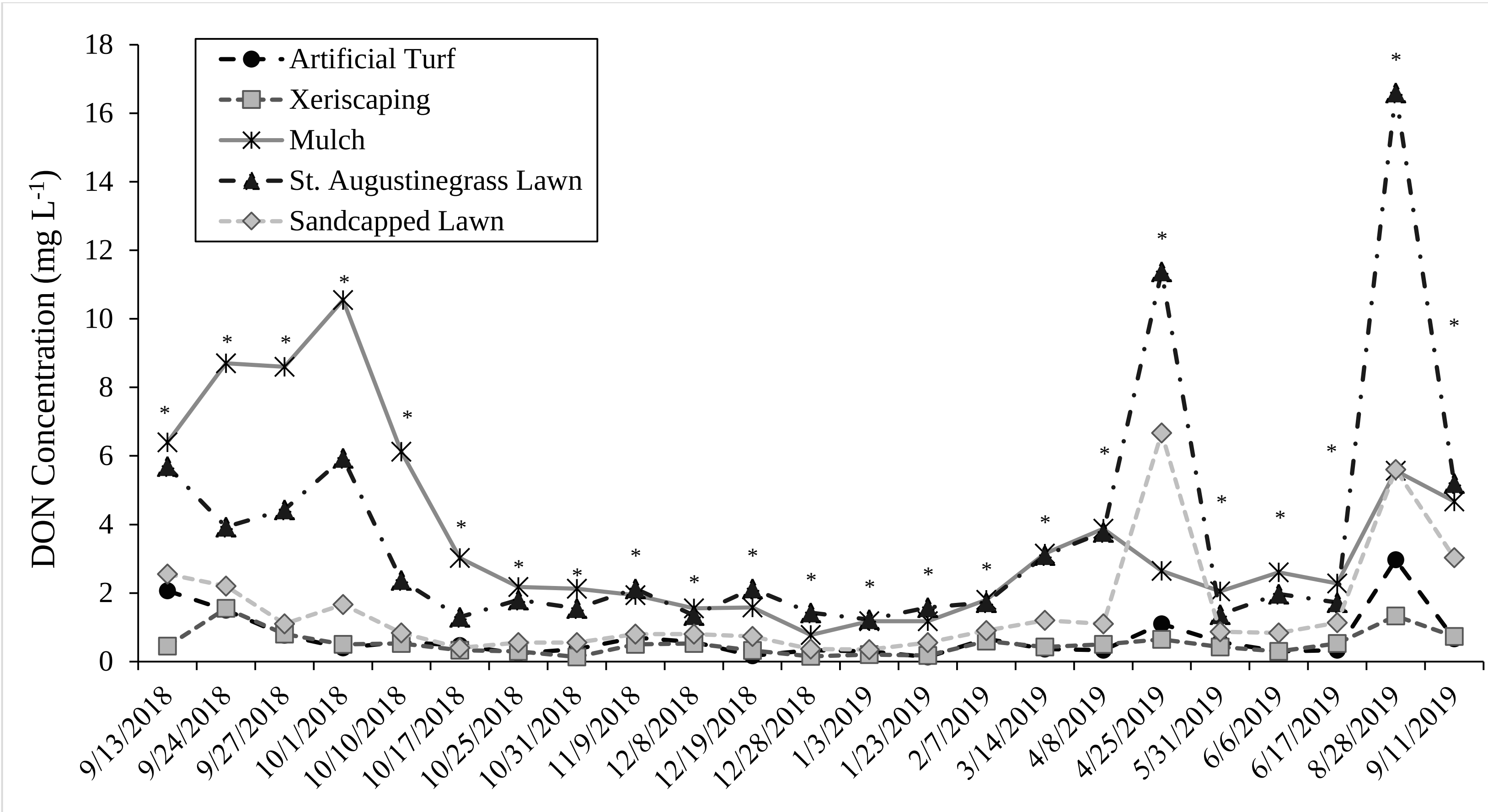

Figure 12. Dissolved organic nitrogen (DON) concentration of runoff water for all landscapes. ns and *, respectively, indicate no statistical difference and statistical difference between treatments on each date, based on Tukey's HSD at P = 0.05.

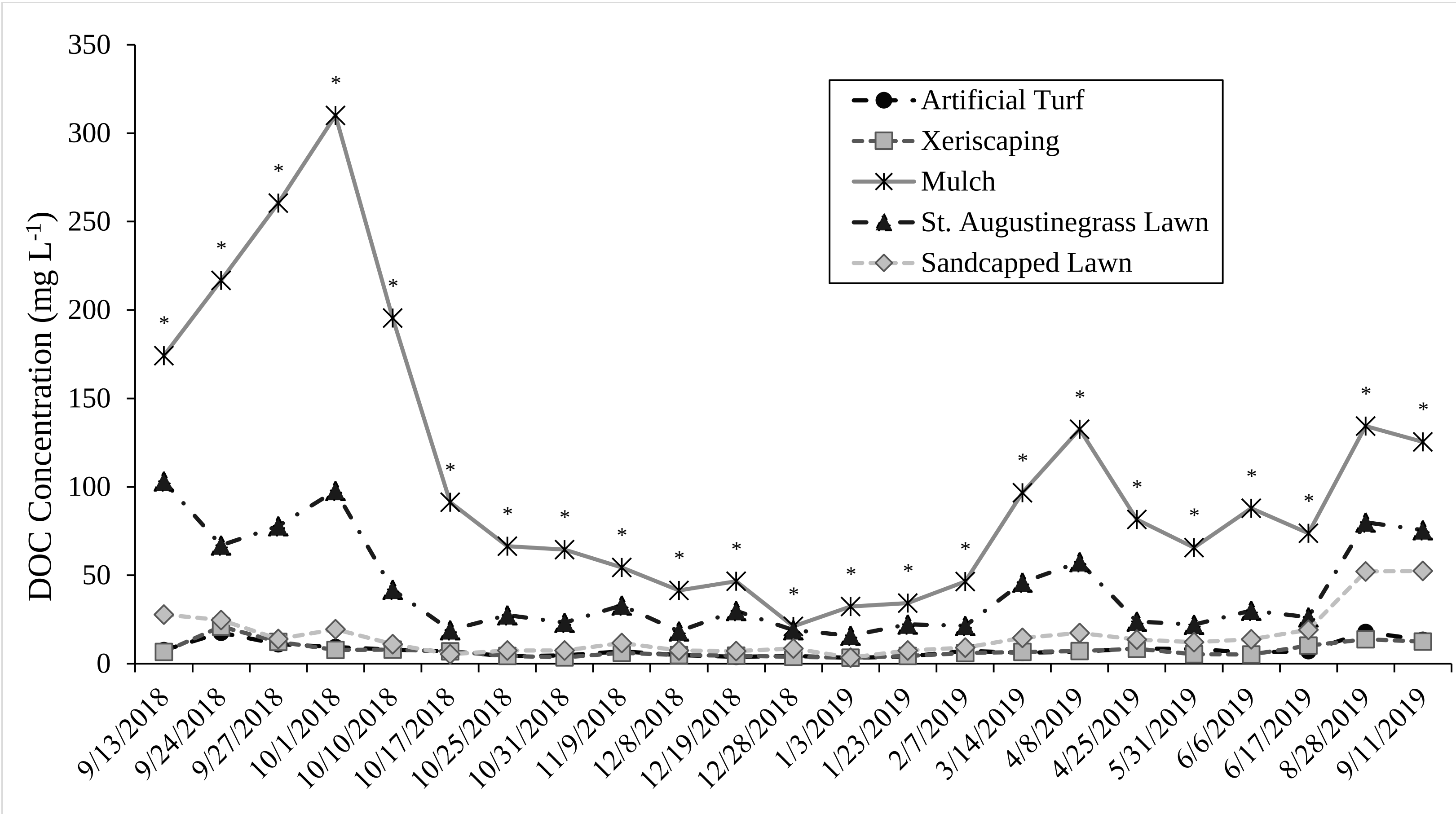

Figure 13. DOC (dissolved organic carbon) concentration of runoff water for all landscapes. ns and * respectively indicate that no statistically different and statistically different were detected between treatments on each date, based on Tukey's HSD at P = 0.05.

PO_4-P

Significant differences in runoff PO_4-P concentration was observed among landscape treatments. The location of the runoff facility was previously used for dairy animals. Therefore, the soil at the study site has a high PO_4-P content (legacy PO_4-P). High PO_4-P concentrations in runoff samples have been detected before starting this project when all plots were still covered by St. Augustinegrass. The high concentrations of PO_4-P in the native soil still existed in this study, as evidenced by significantly higher PO4-P in St. Augustinegrass lawn when compared to the three newly constructed landscapes, xeriscaping, artificial turf and sand-capped lawn. (Figure 14).

Mulch showed the same concentration of PO_4-P concentration as St. Augustinegrass between 9/14/2018 to 10/10/2018 with a range of 4 to 10 mg L^{-1}, then dropped to a stable range of 1.3 to 2.3 mg L^{-1} that was not significantly higher than other three newly established landscape anymore. However, PO_4-P concentration was relatively stable for sand-capped lawn, xeriscaping, and artificial turf over the entire study period, with a range of 0.2 to 1.5 mg L^{-1} (Figure 14). These results suggest that putting an additional layer on top of native soil could help reduce PO_4-P losses through runoff. One possible reason of the function of PO_4-P control provided by newly established plots is that PO_4-P is adsorbed with the infill materials, such as coarse sand, decomposed granite than native soils due to the presence of iron and aluminum oxides, thus, less PO_4-P would be leaving the system. However, according to a Pearson correlation test, a relationship with TSS and PO_4-P was only observed for mulch (Table 6).

The second theory is that an additional layer on top of native soil protected the PO_4-P from leaving the system in runoff. If the second theory is correct, it helps to explain the unique performance of mulch that large amount of PO_4-P was lost only in the beginning of the study similar to St. Augustinegrass and then it was reduced significantly due perhaps to compaction and hydrophobicity. In the beginning of the study, native soil was not covered very well by the new shredded dark wood mulch, and PO_4-P was still leaving the soil easily when native soils along with mulch materials were flushed by runoff, however, once mulch materials have become compacted over time, a better protection was given and less native soil can be flushed by runoff, which resulted in a lower PO_4-P loss.

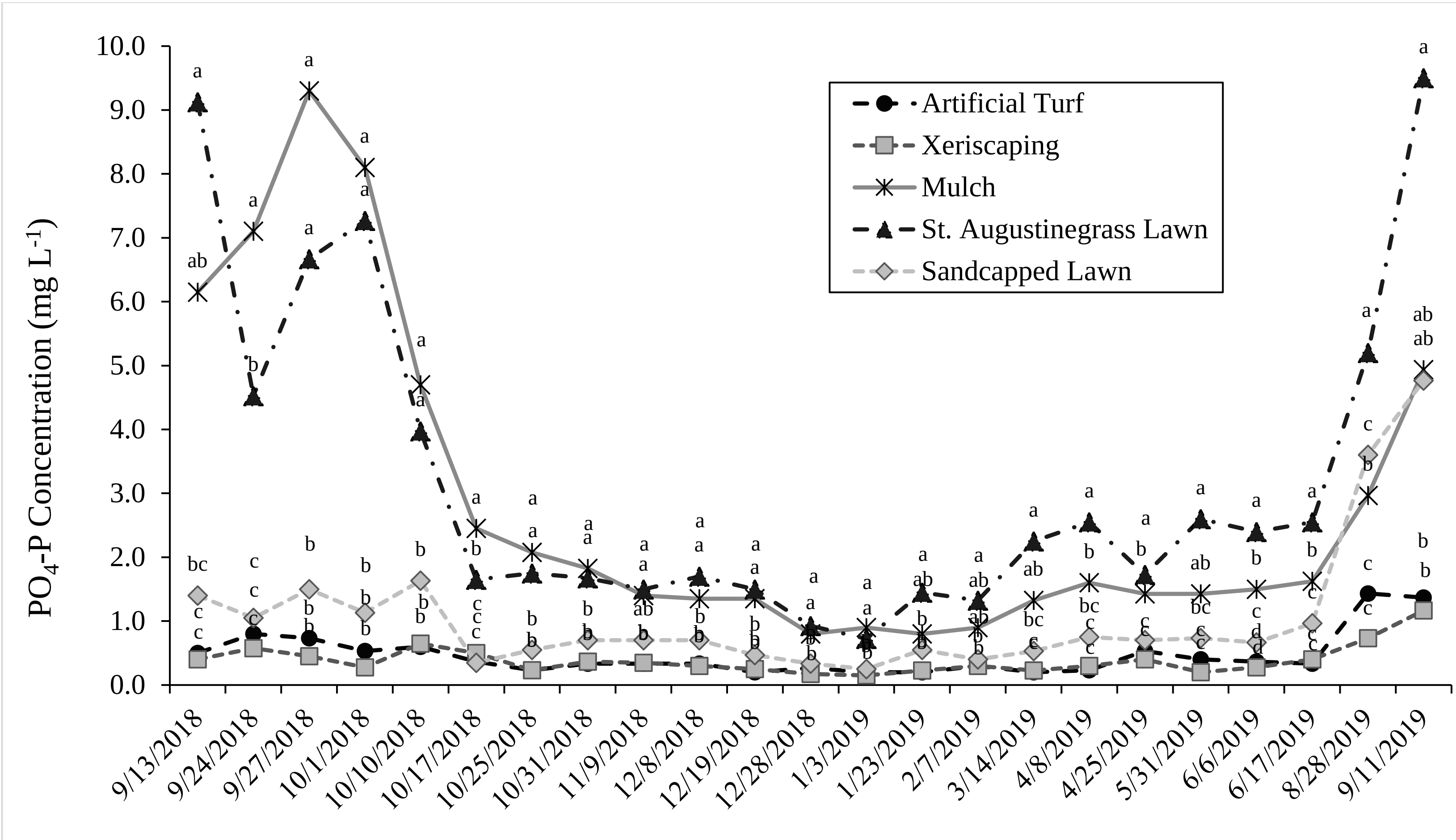

Figure 14. PO_4-P concentration of runoff water for all landscapes. Means with the same letter at the same date are not statistically different based on Tukey's HSD at P = 0.05.

Table 6. Correlation of TSS with parameters of runoff quality measured for runoff samples. All nutrient parameters presented here are concentrations (mg L^{-1}).

	St.Augstinegrass Lawn				Sand-capped Lawn				Xeriscaping				Mulch				Artificial Turf			
	TSS (First)		TSS (Last)		TSS (First)		TSS (Last)		TSS (First)		TSS (Last)		TSS (First)		TSS (Last)		TSS (First)		TSS (Last)	
NO_3-N	0.08	ns	0.23	ns	0.00	ns	0.35	ns	0.12	ns	0.24	ns	0.30	*	0.40	*	0.15	ns	-0.12	ns
NH_4-N	-0.09	ns	-0.04	ns	-0.12	ns	-0.14	ns	0.56	***	0.37	*	0.54	***	0.51	**	0.26	ns	0.15	ns
PO_4-P	0.13	ns	-0.12	ns	0.33	ns	0.19	ns	0.23	ns	0.18	ns	0.36	*	0.64	***	0.16	ns	0.10	ns
TDN	-0.01	ns	-0.09	ns	-0.03	ns	-0.03	ns	0.23	ns	0.16	ns	0.48	***	0.69	***	0.22	ns	-0.02	ns
DON	-0.01	ns	-0.12	ns	0.00	ns	-0.03	ns	0.10	ns	-0.03	ns	0.44	**	0.64	***	0.19	ns	0.05	ns
DOC	0.39	**	-0.22	ns	0.42	*	0.25	ns	0.24	ns	0.03	ns	0.46	**	0.65	***	0.11	ns	0.04	ns

ns, ***, **, *; not significant, significant at *P*=0.001, 0.01, and 0.05, respectively

Nutrient Export

Nutrient export was calculated by multiplying nutrient concentration by runoff volumes and divided by the size of plot. As shown in table 7, there was a significant landscape main effect on all nutrient export measured in this study. In addition, there were significant interactions between landscape and date on all nutrient export as well.

Table 7. ANOVA for effect of landscape and date on nutrient export.

	Total Nutrient Export (mg m^{-2})					
Source	NO_3-N	NH_4-N	PO_4-P	TDN	DON	DOC
Replication	NS	NS	NS	NS	NS	NS
Date (D)	***	***	***	***	***	***
Landscape (L)	***	***	***	***	***	***
D x L	*	***	***	***	***	***

ns, ***, **, *; not significant, significant at P=0.001, 0.01, and 0.05, respectively

NO_3-N Export

While the graphs were similar between runoff volume and NO_3-N export as nutrient export were highly affected by runoff volume, landscape treatment affected NO_3-N export differently when comparing to their effect on runoff volume. As such, during the study period, no significant differences were observed for landscape treatment for almost half of the rain events, no matter if the rain event was high or low (Figure 15). However, when a significant difference was detected, it tended to be observed when export was less than 50 mg m^{-2}. Artificial turf always had the highest NO_3-N export, and it was significantly greater than all other landscape treatments (Figure 15). The high NO_3-N exports observed in the turfgrass treatment may be related to the potential disturbance of the plot by wildlife.

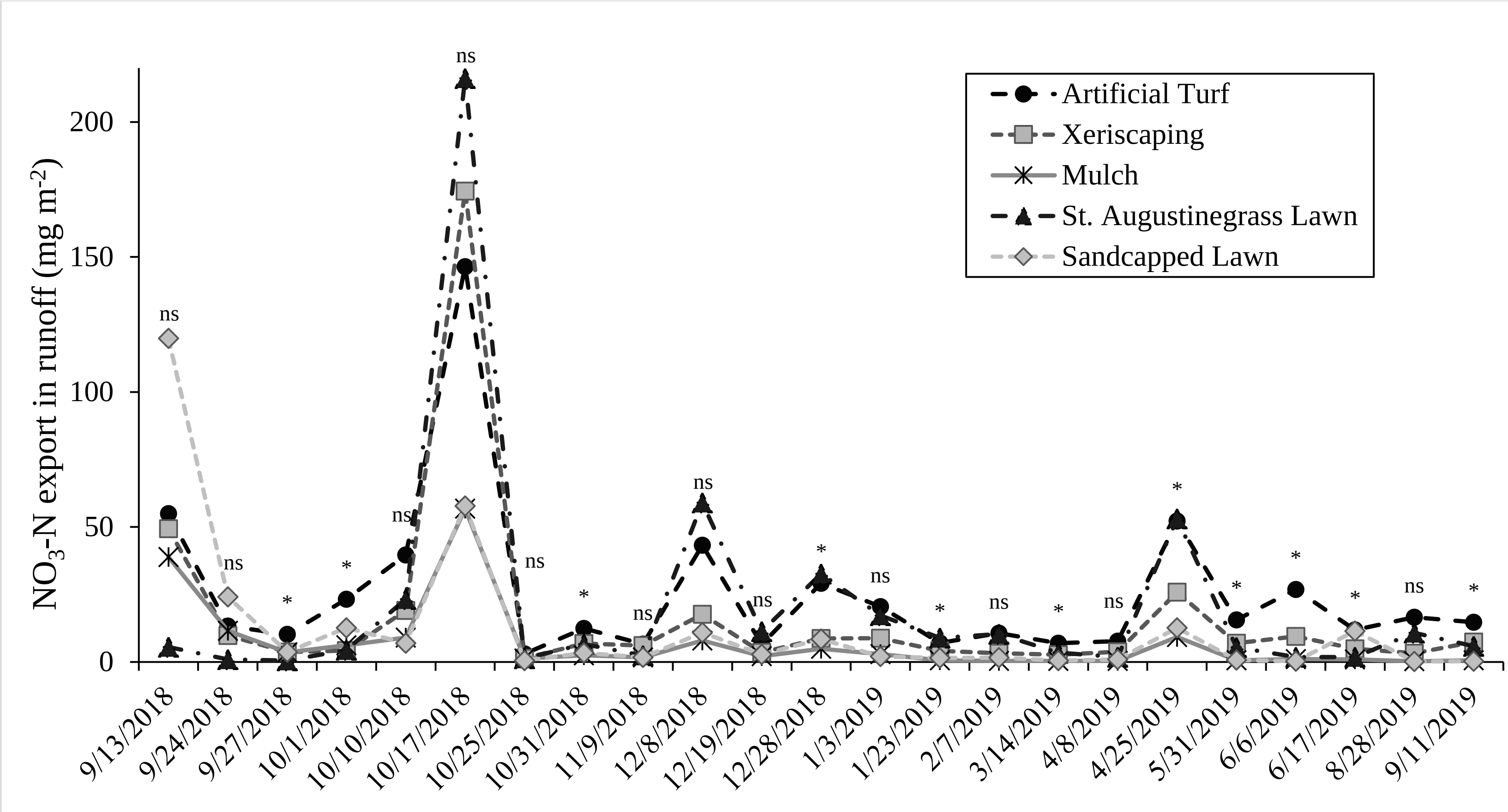

Figure 15. Effect of landscape and date on runoff NO_3-N export per event (mg m^{-2}). ns and * respectively indicate that no statistically different and statistically different were detected between treatments on each date, based on Tukey's HSD at P = 0.05.

NH_4-N Export

NH_4-N export was significantly higher for mulch for the first few events such as 9/13/2018, 9/24/2018, 9/27/2018, and 10/17/2018 (Figure 16). Export ofNH_4-N then declined to a stable level (below 20 mg m^{-2}) and no effect of landscape was observed. The landscape treatments with decomposed granite and sandcap tended to hold steady over the study period. One large peak was observed on 8/28/2019 when NH_4-N export was extremely high for St. Augustinegrass lawn compared to other landscapes; this was likely due to the high NH_4-N concentration in runoff that was derived from previous fertilization. It is interesting to note that the NH_4-N export on the same date for sand-capped lawn was low, although the same fertilization was applied. This should give the credit to the great runoff volume control of the sand-capped lawn treatment. Similarly, another peak was also found on 4/25/2019, but the overall NH_4-N export was not significantly higher for St. Augustinegrass lawn and sand-capped lawn. Likely because more of the applied fertilizer was taken up by the turfgrasses two days after fertilization. In contrast, runoff occurred 1 day after fertilization (8/27/2019) on 8/28/2019. These results suggested that NH_4-N losses through runoff from lawns can be avoided if a better nutrient management is adhered to and a rule of thumb is that never spray fertilizers ahead of a rain event.

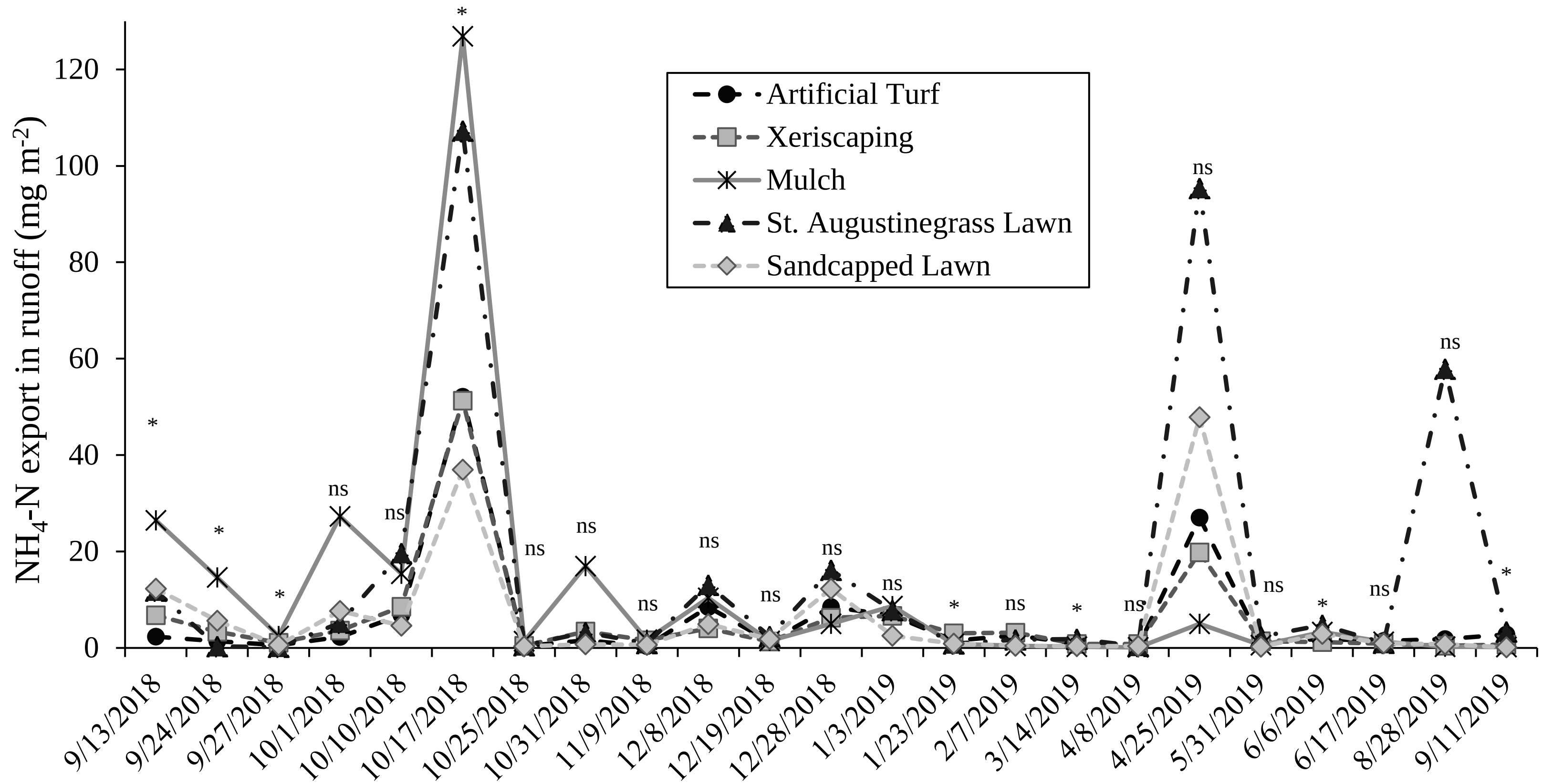

Figure 16. Effect of landscape and date on runoff NH_4-N export per event (mg m^{-2}). ns and * respectively indicate that no statistically different and statistically different were detected between treatments on each date, based on Tukey's HSD at P = 0.05.

TDN, DON, and DOC Export

DON is the largest portion of TDN export (around 60 to 80%, depending on the runoff event). A significant effect of landscape and date, and their interaction were also found for TDN and DON export (Table 7). On the early stage of the study, mulch showed a significantly higher TDN and DON export, followed by either sand-capped lawn, or St. Augustinegrass lawn. However, as mulch was rinsed by rainfall over time, TDN and DON export dropped significantly (less than 100 mg m^{-2}). Starting from winter until the second summer, whenever there was a heavy rain (greater than 50 mm), such as 12/8/2018, 12/28/2018, and 4/25/2019, or a runoff event occurred after fertilization, such as 8/2/2019, the greatest peak for TDN and DON was found for St. Augustinegrass lawn (Figures 17 and 18).

Because DON is a subset of DOC (a DOC molecule with an amino group), the effect of landscape on DOC export over time was expected. Surprisingly, their patterns were only comparable for the early stage of the study. As such, the DOC export was significantly greater for mulch plots during the first growing period (9/14/2018-10/31/2018) when comparing to other landscapes (Figure 19). However, not like TDN and DON, St. Augustinegrass lawn dominated for several runoff events during winter to the second growing season. Few to no significant differences among landscapes were observed during spring, and when there was a significant difference among landscape treatments, the highest export was still found for mulch plots (Figure 19). St. Augustinegrass only showed significantly higher DOC export on 8/28/2019 and 9/11/2019, when turfgrass were actively growing, returning decent amount of Carbon to the plots through clippings.

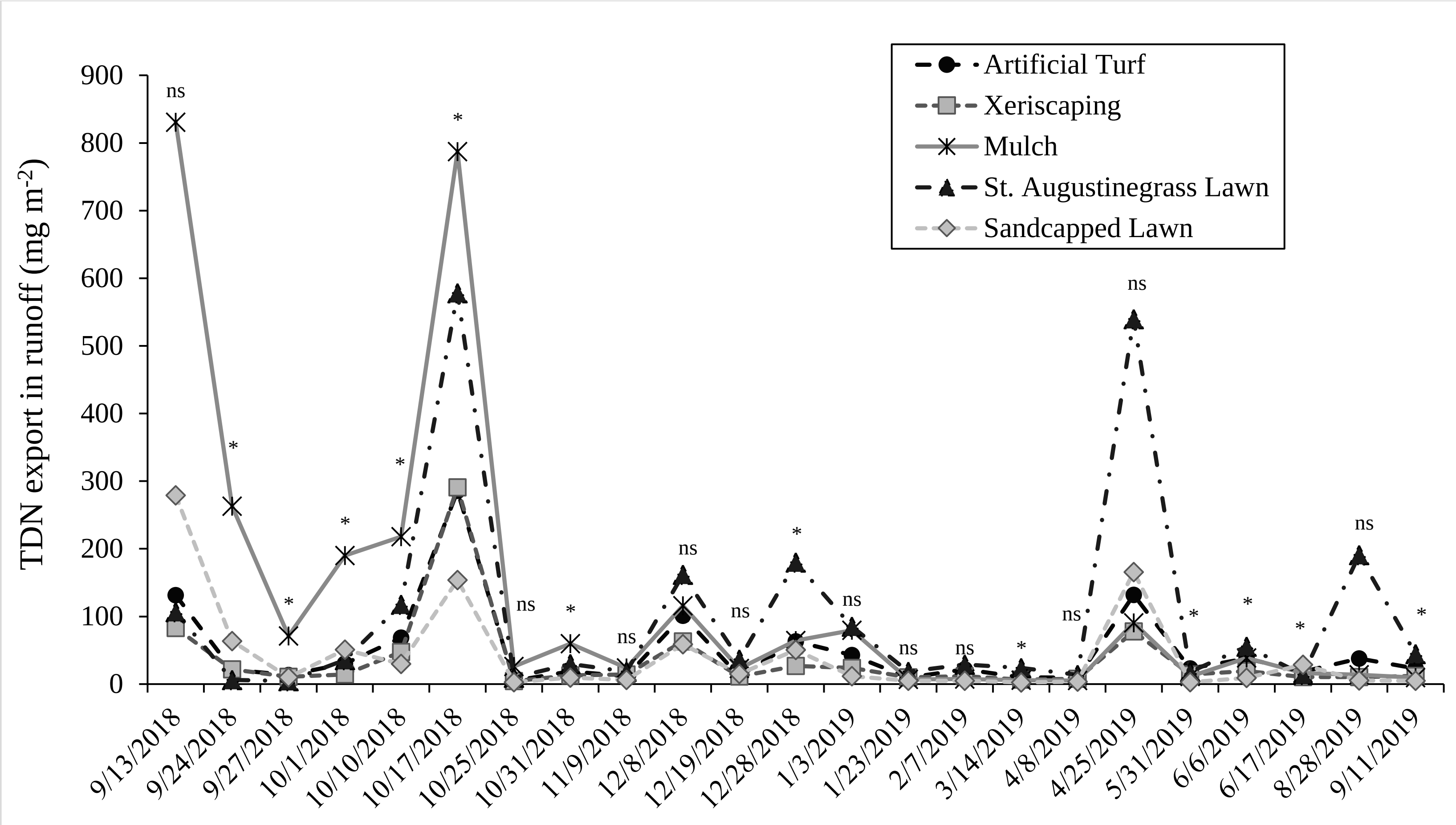

Figure 17. Effect of landscape and date on runoff TDN (total dissolved nitrogen) export per event (mg m^{-2}). ns and * respectively indicate that no statistically different and statistically different were detected between treatments on each date, based on Tukey's HSD at P = 0.05.

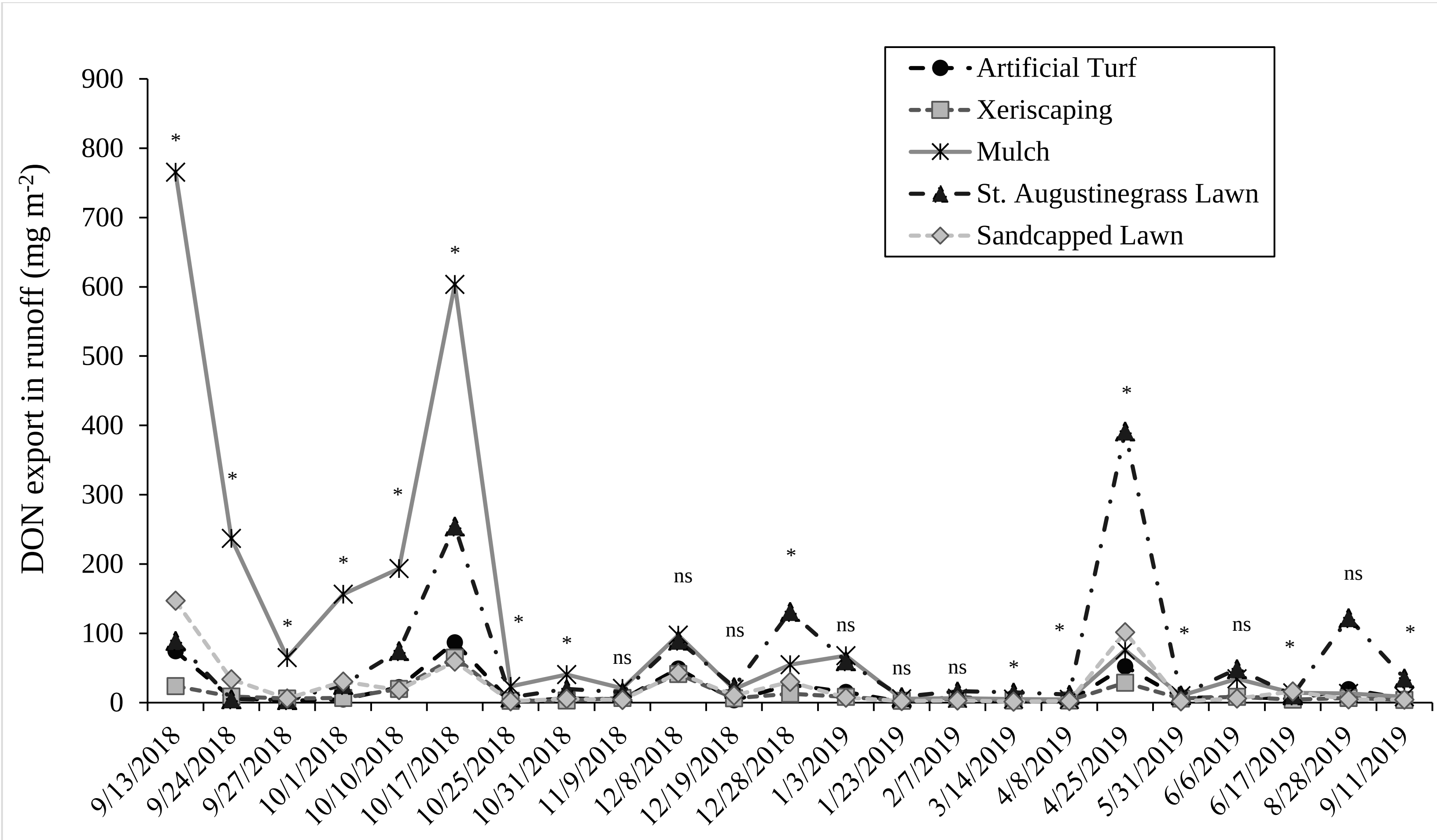

Figure 18. Effect of landscape and date on runoff DON (dissolved organic nitrogen) export per event (mg m^{-2}). ns and * respectively indicate that no statistically different and statistically different were detected between treatments on each date, based on Tukey's HSD at P = 0.05.

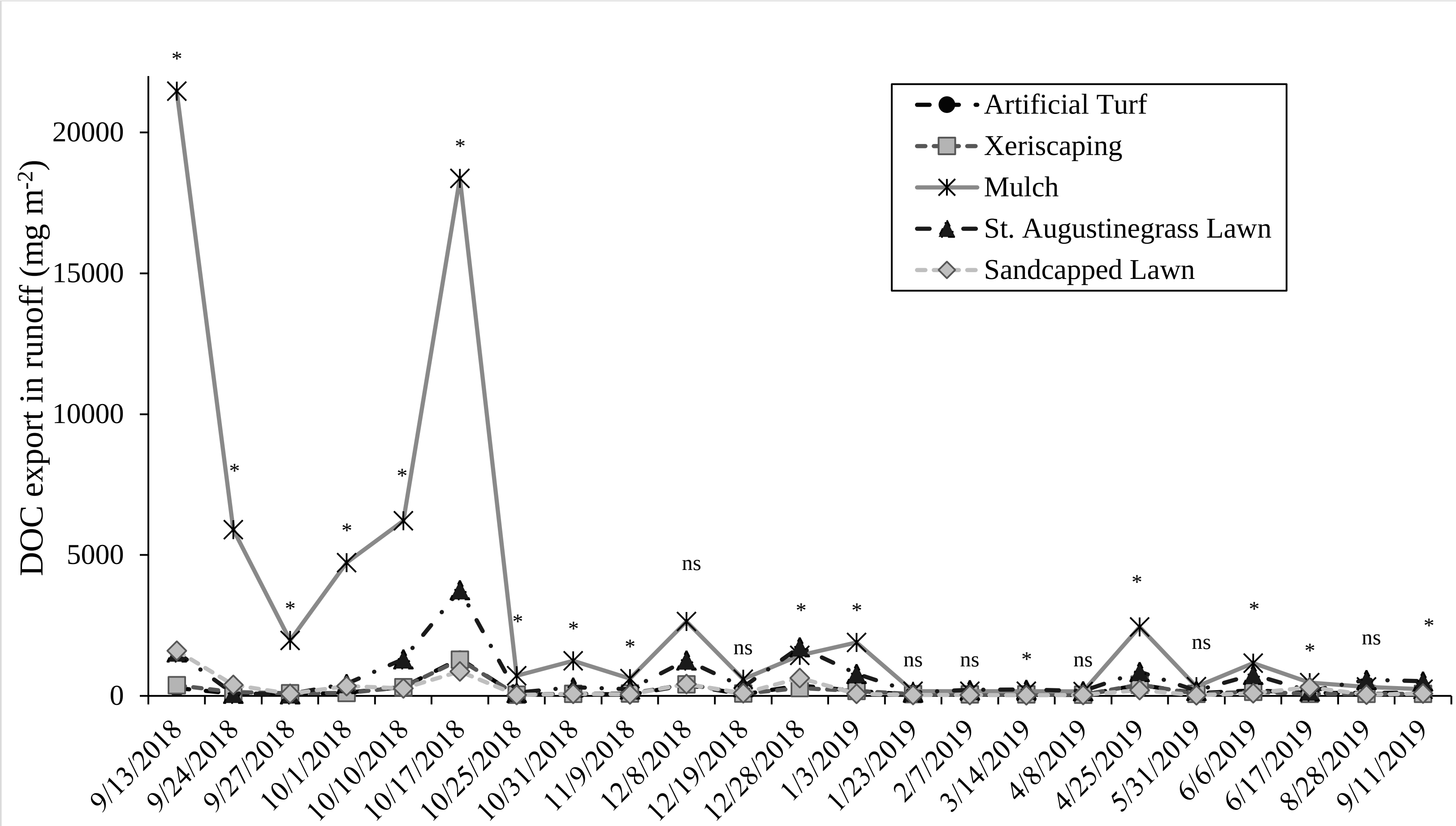

Figure 19. Effect of landscape and date on runoff DOC (dissolved organic carbon) export per event (mg m^{-2}). ns and * respectively indicate that no statistically different and statistically different were detected between treatments on each date, based on Tukey's HSD at P = 0.05.

PO_4-P Export

Unlike PO_4-P concentration, which was relatively stable effect from landscape treatments over the study period, the effect of landscapes on PO_4-P export was varied (Table 7; Figure 20). The highest export was detected for mulch during September 2018 to November 2018, as both its concentration and runoff volume were high. Although concentration was also high for St. Augustinegrass lawn during this period as shown in Figure 14, export of St. Augustinegrass lawn was not significantly higher than that of xeriscaping, sand-capped lawn, and artificial turf due to the lower runoff volume. For the rest of the study period (staring from November 2018), while concentration of PO_4-P for mulch was still significantly higher than other three landscapes for most cases (Figure 14), export of mulch dropped to the lowest level as xeriscaping, artificial turf, and sand-capped lawn due to its great runoff volume control.. In the meantime, St. Augustinegrass lawn stand-alone released significantly greater amount of PO_4-P than other landscapes mainly due to the high PO_4-P concentration.

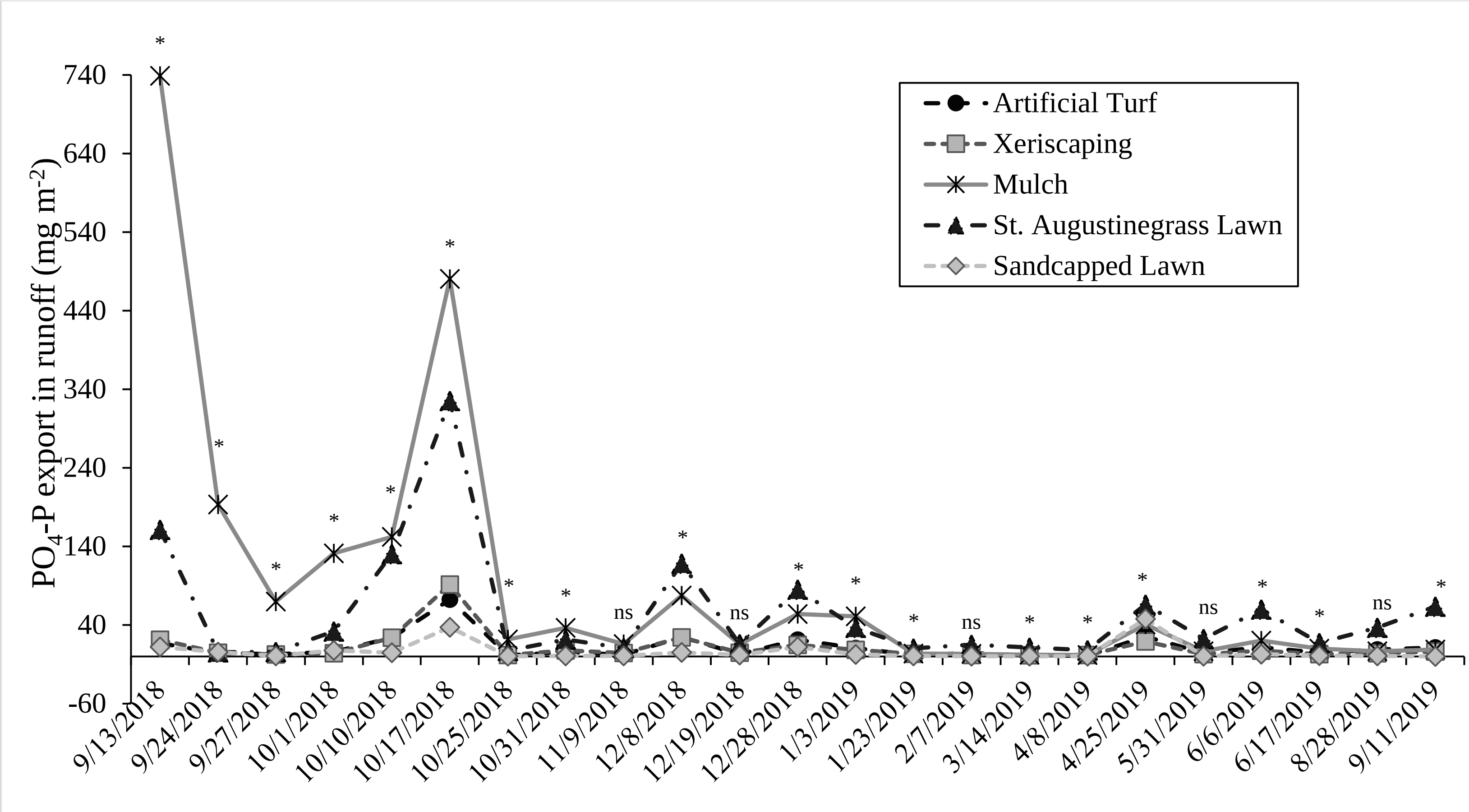

Figure 20. Effect of landscape and date on runoff PO_4-P export per event (mg m^{-2}). ns and * respectively indicate that no statistically different and statistically different were detected between treatments on each date, based on Tukey's HSD at P = 0.05.

The effect of landscape treatment on runoff water quality and quantity can be used as a useful reference for landscape design that can be used for both municipal purpose and watershed management. The performance of each landscape tested in this study were significantly different on different nutrient parameters. Thus, this study illustrated that there is no specific landscape to be used under all scenarios for mitigating runoff volumes and quality and alternative landscapes should be selecting based on environmental needs. For example, artificial turf and xeriscaping could be a better choice for a watershed where concern of river or stream contamination that was derived from the chemical offload of shoreside soil. On the contrary, if flood is a major concern, these two relatively impervious landscapes turn out to be unwise choice. Instead, lawn systems are more effective on flood water control.

Surface Temperatures

Surface temperature was significantly different among landscapes over the study period, and an interaction of landscape and date was also observed (Table 3). Overall, the surface temperature was always highest for artificial turf, followed by mulch for most of the dates (Figure 21).

A seasonal variation of difference of surface temperature among landscapes is observed during growing season (April to October) and non-growing season (November to March). As such, during the growing season, St. Augustinegrass lawn and sand-capped lawn maintained the lowest surface temperature (35 ± 4^{o} C), which was significantly lower than that of xeriscaping, mulch and artificial turf. This may be partially due to the energy liberation by turfgrasses through transpiration and high reflection of solar radiation. Surface temperature of xeriscaping was also significantly lower than that of mulch and artificial turf during the growing season, mainly because of its highest reflected solar radiation or in other words, highest albedo. However, limited energy losses through transpiration of native water efficient plants still result in a higher surface temperature when compare to lawns. Extremely high surface temperature was measured for mulch and artificial turf during the growing season, with a range of 44 to 70^{o}C for both landscapes. Radiation measurements revealed that this was because the relatively high net radiation and low reflected solar radiation of these two landscapes, especially for artificial turf (data not shown). During non-growing seasons, transpiration of turfgrasses was limited, and thus the surface temperature of St. Augustinegrass lawn and sand-capped lawn was within the similar range as xeriscaping (between 10 to 30^{o} C). In addition, when air temperature was low, the lowest surface temperature was found for xeriscaping due to the highest albedo, and it was sometimes significantly lower than that of St. Augustinegrass lawn and sand-capped lawn, such as for dates 10/26/2018, 12/3/2019, and 2/28/2020. A similar effect was found for mulch and artificial turf during the non-growing season when compared to the growing season, as the highest surface temperature was always found for between these two landscapes, with a range of 15 to 45^{o} C.

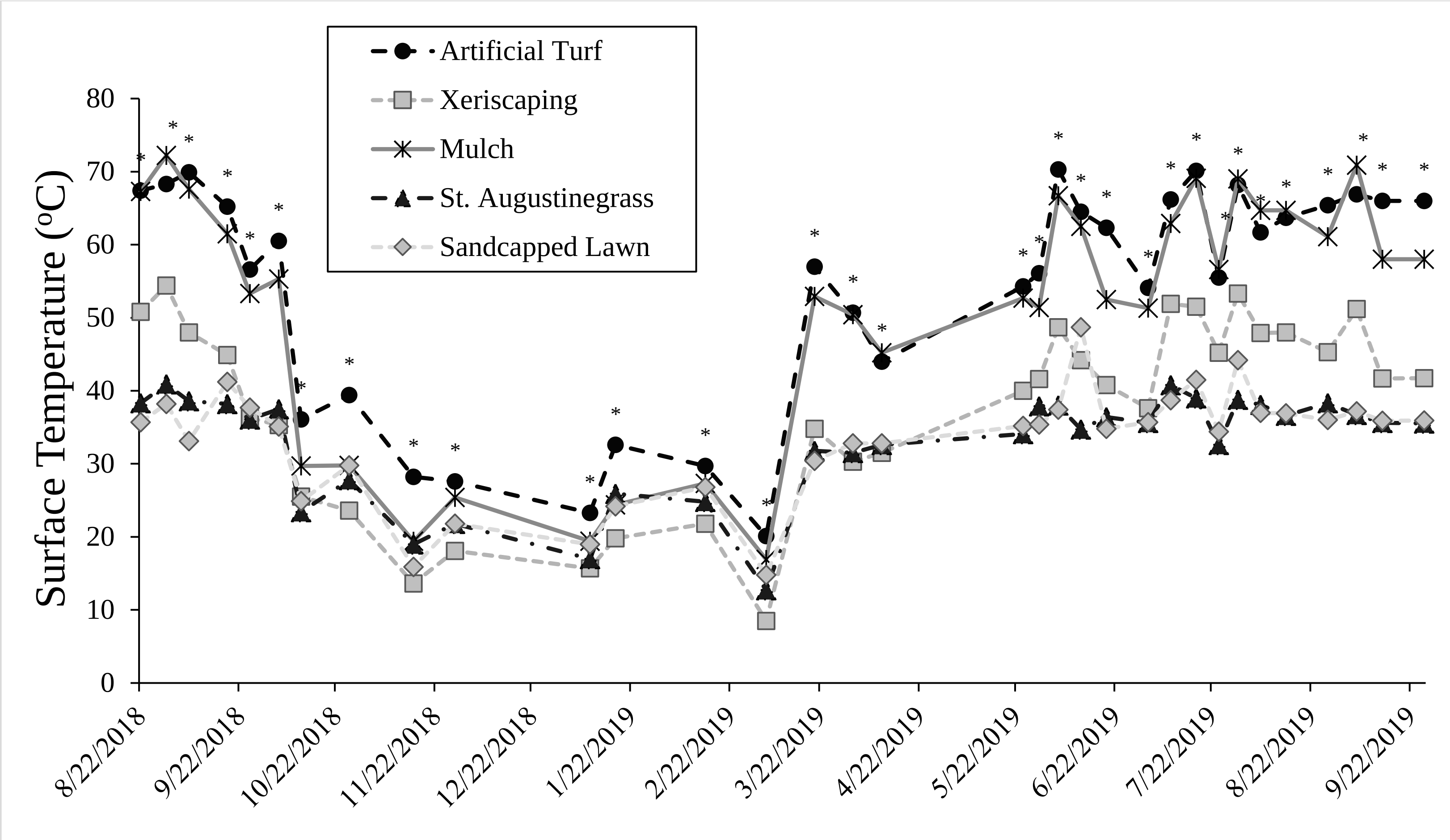

Figure 21. Infrared reflected surface temperature of all landscapes over the study period. Measurements were taken once a week during 12:00 pm to 2:00 pm on each measuring day. ns and * respectively indicate that no statistically different and statistically different were detected between treatments on each date, based on Tukey's HSD at P = 0.05.

Weed Density

It is a preconceived idea that alternative landscapes required less maintenance than turfgrasses. Regular maintenance such as mowing and fertilization of turfgrass are not necessary for xeriscaping, artificial turf and other alternative landscapes. However, some maintenance is always overlooked. For example, refilling infill material and straightening leaf blades are needed for artificial turf, but not required by natural turfgrass lawns. No matter if mowing or fertilization is needed, weed control is related to most residential landscapes, and thus weed density was measured to document the maintenance requirement for all landscapes included in this study. Total amount of weeds, no matter what species grew in the plots were measured weekly were found to be significantly affected by date, landscape, and their interaction (Table 3). The worst weed problem was observed for xeriscaping and mulch, and there was a wide-ranging fluctuation of weekly weed counts for the entire study period, with a range of 10 to 400 and 5 to 125 for xeriscaping and mulch, respectively (Figure 22).

The fluctuation of weed numbers during the study was related to the growing pattern of different weed species, as certain weed species only thrive in summer, while others only emerge when temperature was low. For example, the most common weeds found in summer include Horsenettle (*Solanum carolinense L.*), purple nutsedge (*Cyperus rotundus L.*), and spotted spurge (*Euphorbia maculata L.*). Bristly mallow (*Modiola caroliniana (L.) G. Don*) and annual ryegrass (*Lolium perenne L. ssp. multiflorum*) were found in fall, and bur clover (*Medicago polymorpha L.*), annual bluegrass (*Poa annua L.*), and henbit (*Lamium amplexicaule L.*) were found in winter. Weed problem was almost nonexistent for St. Augustinegrass lawn, sand-capped lawn, and artificial lawn, during the study period, especially when grasses were actively growing. When turfgrasses were dormant, the competition between turfgrass and weed for nutrient and water was low, and thus a mild weed emergence was found for sand-capped lawn, as shown on date 1/3/2019 to 3/20/2019 (Figure 22). Few weeds were found for sand-capped lawn on the late summer of 2018, and those weeds were introduced to the plot with sod that were purchased from a sod farm, used to cover the plots after the construction.

Our results confirmed the high requirement of herbicides for weed control for water efficient landscapes. This revealed that less maintenance requirement should not be advertised as an advantage of water efficient landscapes. Also, the higher dose of herbicides required for alternative landscapes could cause potential water contamination and concomitant safety issues.

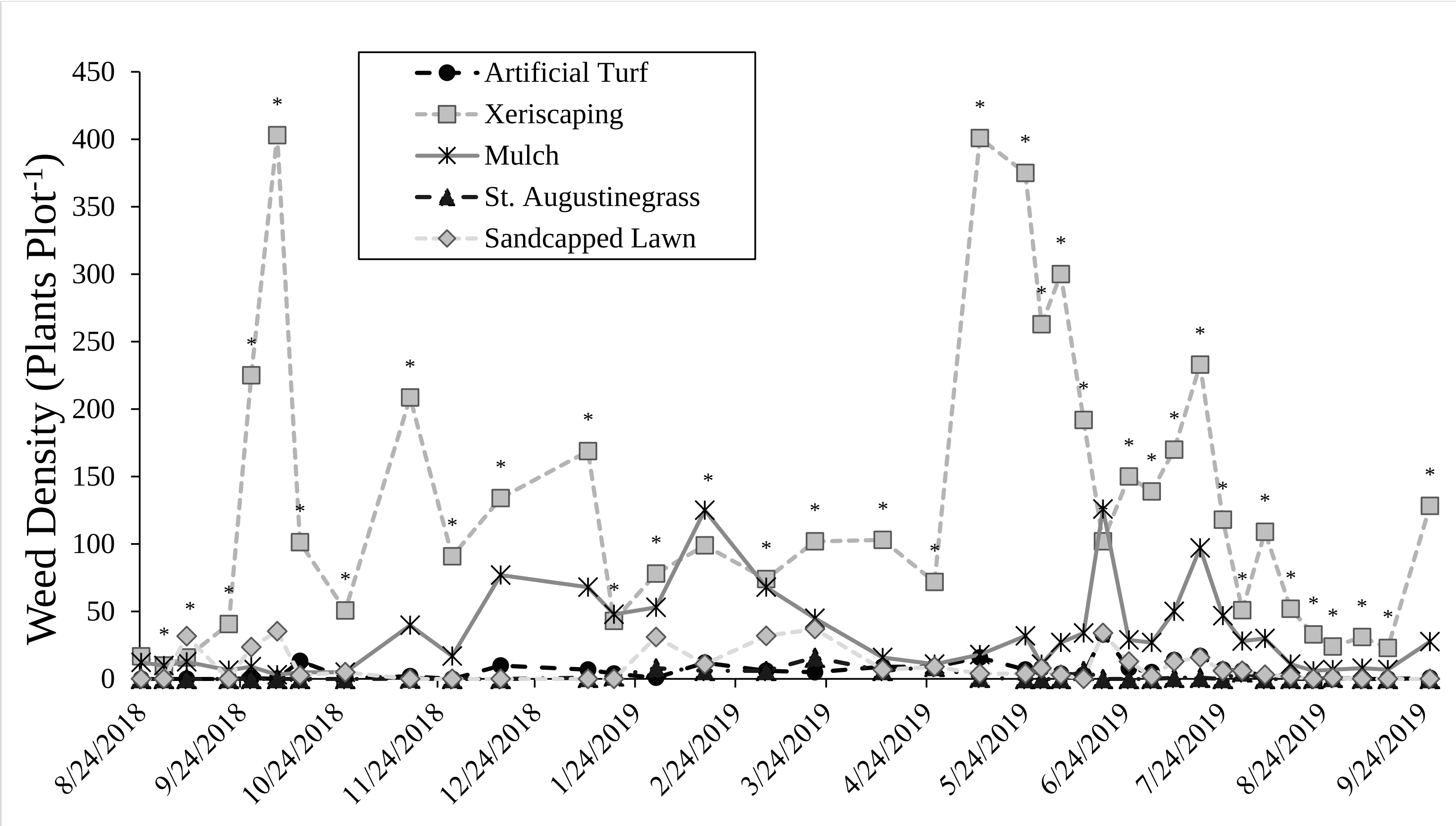

Figure 22. Weed pressure of each landscape during the study period, evaluated as cumulative weekly weed account. ns and * respectively indicate that no statistically different and statistically different were detected between treatments on each date, based on Tukey's HSD at P = 0.05.

Landscape Aesthetics

Landscape aesthetics were evaluated with a modified visual quality rating system. Based on the results, the visual quality score was significantly affected by landscape, date, and their interaction (Table 3). Not surprisingly, artificial turf maintained a high score of 9 for the entire study period, as it was unaffected by the seasonal climate change, which provided a benefit of providing a favorable green color all season long, even during the non-growing season (Figure 23).

A seasonal pattern was found for St. Augustinegrass lawn and sand-capped lawn as expected. Under appropriate management including recommended fertilization and irrigation, a great visual quality (7 to 9) can be obtained for St. Augustinegrass lawn and sand-capped lawn during the growing season. However, the plot quality was significantly lower for lawns when comparing to other alternative landscapes during the non-growing season (Figure 23). When just comparing two lawns, sometimes St. Augustinegrass had a greater quality than sand-capped lawn when temperature was high, which is because that sand-capped lawn might show symptoms of drought as a result of higher water shortage due to greater drainage. However, a greater quality was found for sand-capped lawn over St. Augustinegrass lawn during the non-growing season, which is also might be due to the better drainage of sand-capped lawn. Fungal related disease could be less likely under a lower soil moisture content. A similar pattern was found for xeriscaping and mulch in terms of plot visual quality rate as plot quality reached to the same level as artificial turf during the growing season and dropped during the non-growing season. Their quality plunged to an unacceptable level in the winter is because that during the acclimation period when native water efficient plants were just transferred to the plots, an extended raining season was experienced (referring to figure 2), and Texas sage (*Leucophyllum frutescens*) was sensitive to high water input, and thus pulled down the average of the plot quality for xeriscaping and mulch.

In this study, aesthetic is mainly evaluated by plants growth condition, and it serve as a supportive information to show the quality of eco-service provided by plants of each landscape during different seasons. As such, based on the results, turfgrass lawns offer the most eco-benefits during their growing seasons, and the impact of 3 alternative landscapes on environment is relatively stable over the year.

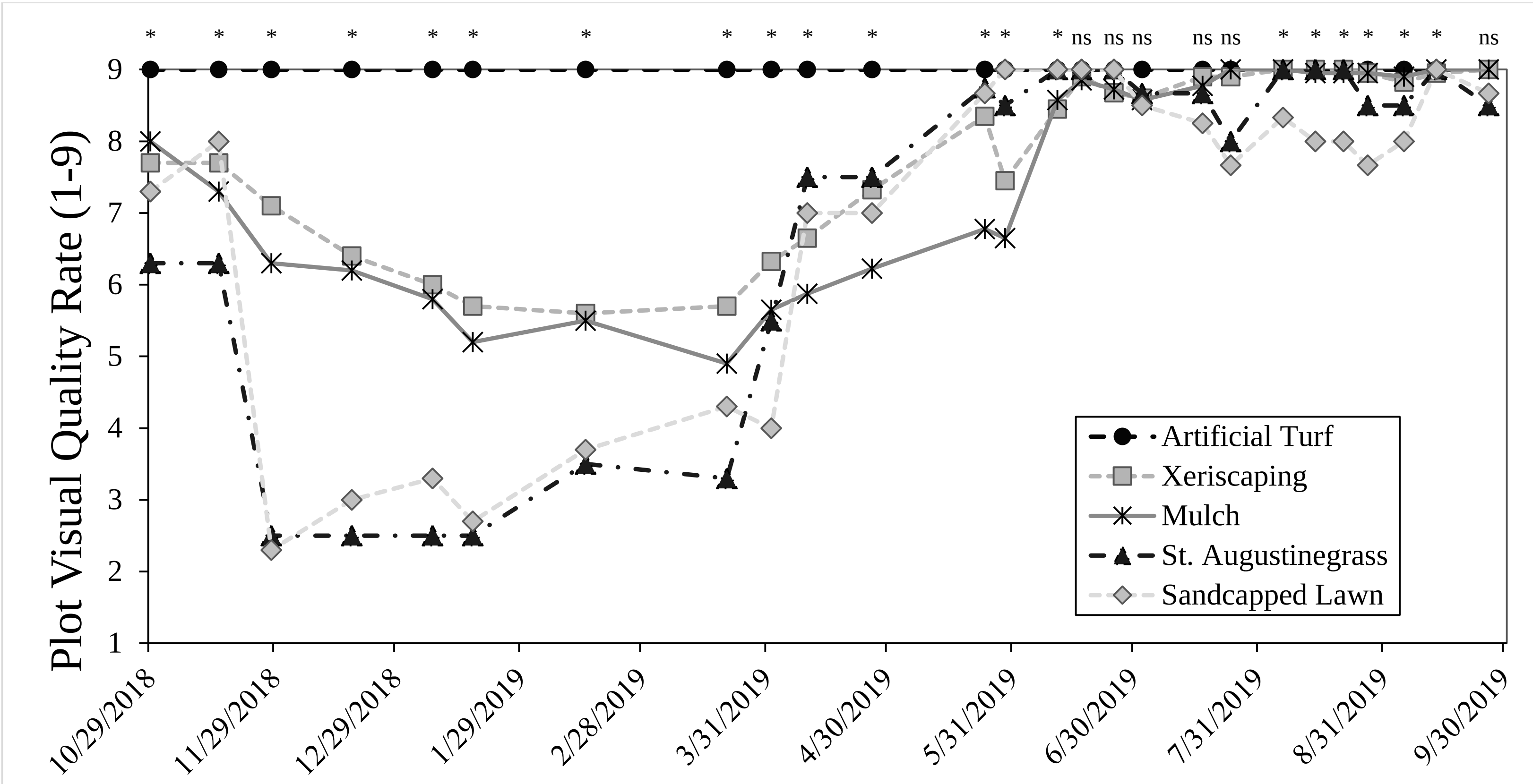

Figure 23. Visual grade of plant quality over the study period as an evaluation of landscape aesthetics. The grading standard was revised based on a commonly used scoring system for turfgrass science, with a scale of 1 to 9, and 6 as the minimal acceptable quality. For artificial turf and two lawns, rating was given to turfgrass, while the final score was an average of four plants that was grown in the plot for xeriscaping and mulch. ns and * respectively indicate that no statistically different and statistically different were detected between treatments on each date, based on Tukey's HSD at P = 0.05.

Conclusions

This study evaluated the environmental impacts and ecosystem services associated with turfgrass lawns and alternative ‘water-efficient’ landscapes in Texas. Collectively, the findings demonstrate that while xeriscaping and water efficient landscape could reduce irrigation cost, their impacts on surface runoff and higher maintenance requirements must also be considered. Artificial turf provided year-long green color and low maintenance requirements, but the extremely high surface temperatures compared to other landscapes appear to make it a poor choice for warmer climates, especially where home cooling costs must be considered during the summer months. Traditional home lawn and sand-capped lawn treatmetns were generally most effective at capturing rainwater and reducing runoff and weed emergence. These landscapes also moderated surface temperatures compared to mulch and artificial turf during the summer. So long as a proper management can be given, the data from this study highlight the functional importance of lawns to the urban ecosystem. More studies are still needed to investigate the real role of such landscapes at different locations, as climate and concerns are varied significantly in different regions. Overall, the information gained from this research will benefit municipalities, water purveyors, and homeowner associations as they weigh the long-term consequences and impacts of lawn removal and landscape conversion programs.

References:

Addink, S., 2005. Cash for Grass-A Cost Effective Method to Conserve Landscape Water? Turfgrass Research Facility, University of California, Riverside, available online at: https://turfgrass.ucr.edu/reports/topics/Cash-for-Grass.pdf (accessed 21 April 2020)

Beard, J.B. and Green, R.L., 1994. The role of turfgrasses in environmental protection and their benefits to humans. Journal of Environmental Quality, 23:452-460.

Bolund, P. and Hunhammar, S., 1999. Ecosystem services in urban areas. Ecological economics, 29:293-301.

Chesnutt, T.W., 2020. Statistical estimates of water savings from landscape transformation programs. AWWA Water Science, 2:e1167.

Degen, D., 2007. Water Sustainability: City of Kelowna Water Utility. Presentation for Okanagan Water Stewardship Council.

Haley, M.B., Dukes, M.D. and Miller, G.L., 2007. Residential irrigation water use in Central Florida. Journal of Irrigation and Drainage Engineering, 133:427-434.

Mayer, P.W., DeOreo, W.B., Opitz, E.M., Kiefer, J.C., Davis, W.Y., Dziegielewski, B., Nelson, J.O., 1999. Residential End Uses of Water. AWWA Research Foundation, Denver, CO.

Monteiro, J.A., 2017. Ecosystem services from turfgrass landscapes. Urban Forestry & Urban Greening, 26:151-157.

Pincetl, S., Gillespie, T.W., Pataki, D.E., Porse, E., Jia, S., Kidera, E., Nobles, N., Rodriguez, J. and Choi, D.A., 2019. Evaluating the effects of turf-replacement programs in Los Angeles. Landscape and urban planning, 185:210-221.

Zhang, X. and Khachatryan, H., 2018. Monetary Incentives and Eco-friendly Residential Landscape Preferences for Florida Friendly Landscaping. Invited presentation at the 2018 Southern Agricultural Economics Association Annual Meeting, Jacksonville, Florida