Persistence and Surface Playability of Nine Bermudagrass Cultivars under Simulated Fall Traffic

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KEYWORDS. *Cynodon* spp., normalized difference vegetation index, surface hardness, shear strength

ABSTRACT. Traffic injury caused by foot- or athlete-surface interaction is one of the most critical problems athletic field managers face in maintaining the surface playability and aesthetic quality of athletic fields. Bermudagrass (*Cynodon* spp.) is the most widely used turfgrass species on athletic fields in the transitional climatic zone. A 2-year field study was conducted to evaluate nine bermudagrass cultivars for their persistence and surface playability under simulated fall cleat traffic. The experiment was conducted in Stillwater, OK, on a natural loam soil. Treatments were arranged as a split-block design with three replications. Traffic was applied for 6 weeks in Fall 2019 and 2020 using a Baldree traffic simulator, which generated 10 traffic events per week; each traffic event resulted in 678 cleat marks/m^2. 'Bimini' was generally found to be the most persistent grass under traffic for aesthetic properties, and 'Astro' and 'Tifway' were the least persistent. Surface playability was affected by simulated traffic stress as shear strength (SS) declined and surface hardness (SH) increased, over time. 'Bimini' had greater SS than 'Astro' and 'OKC1131' (Tahoma 31®) by 1.9 and 1.4 N·m, respectively. SS of 'DT-1' (TifTuf®) and Tahoma 31 and SH of 'OKC1134' (NorthBridge®) were least affected by simulated traffic stress. Overall, surface playability characteristics of NorthBridge, 'Bimini', 'OKC1119' (Latitude 36®), TifTuf, Tahoma 31, and 'Riley Riley's Super Sport' (Celebration®) were least affected by traffic. Findings illustrate bermudagrass cultivars can vary in visual persistence and surface playability.

Bermudagrass (*Cynodon* spp.) is the most widely used turfgrass species for athletic fields and golf courses in the southern and transition zones of the United States (Beard 1973). The species are preferred because of excellent traffic tolerance and recuperative potential in comparison with most other turfgrass species (Christians 2011). Traffic is defined as a source of abiotic stress that can cause wear and soil compaction injury to the turfgrass (Trenholm et al. 2000). Athletic field turf may experience continuous and damaging stress caused by foot traffic from wear and soil compaction (Głąb and Szewczyk 2015). Wear is the tearing, scuffing, rubbing, and crushing of turfgrass plant parts, and soil compaction is pressing of soil particles together, both of which can affect the growth and development of bermudagrass (Carrow and Petrovic 1992).

Bermudagrass is generally known for its high traffic tolerance compared with other turfgrass species; however, studies have demonstrated variation within species for this trait (Deaton 2009; Kowalewski et al. 2015; Trappe et al. 2011; Singh et al. 2023). Williams et al. (2010) investigated eight cultivars [common type (*Cynodon dactylon*) and hybrid crosses (*C. dactylon* × *Cynodon transvaalensis*)] for traffic tolerance and reported Riley's Super Sport (hereafter referred to as Celebration™) and ST-5 (Tifgrand®) can better handle traffic stress than Tifway. Kowalewski et al. (2015) determined 'DT-1' (hereafter referred to as TifTuf®) as having greater tolerance to 6 weeks of simulated traffic compared with 'Tifway'. Researchers in Arkansas investigated 42 bermudagrasses and reported that Celebration, 'Premier', 'Contesssa', and 'Barbados' outperformed others in green coverage during summer and fall traffic stress (Trappe et al. 2011). In Tennessee, Thoms et al. (2011) reported 'Tifway' and 'Riviera' had greater traffic tolerance than 'Patriot' on the basis of percent green cover. In Oklahoma, 'Riviera', 'OKC1134' (hereafter referred to as NorthBridge®), 'OKC1119' (hereafter referred to as Latitude 36®), and 'SWI 1057' were reported to have high traffic tolerance among 24 commercial and 16 experimental entries (Segars 2013).

An athletic field's surface quality depends on both aesthetic and surface playability (Brosnan et al. 2014). Surface playability is commonly explained on the basis of surface hardness (SH) and traction. SH is the ability of the surface to absorb the energy generated on impact (Brosnan et al. 2009), which is dependent on various turfgrass and soil parameters, such as soil compaction, soil moisture level, amount of vegetation, and thatch (Rogers and Waddington 1989). Traction is the interaction force between the player and turfgrass surface, often estimated as SS (Canaway and Bell 1986). It allows the player to obtain a secure grip and prevents falls or slips. Wear and soil compaction stress from frequent foot traffic on bermudagrass athletic turfgrass surface can deteriorate the turfgrass quality and surface playability. Frequent traffic stress results in harder playing surfaces and inappropriate footing or traction, which in turn increases the chances of lower extremity injury due to the excessive ground reaction force (Brosnan et al. 2014; Otago et al. 2007).

Bermudagrass cultivars can have different playability characteristics when used as an athletic field surface. Munshaw et al. (2013) evaluated 21 bermudagrass cultivars for SH and Celebration and 'MSChoice' exhibited the lowest SH, whereas 'Midlawn' and Ashmore exhibited the highest SH. Researchers in Australia reported substantial differences among seeded and clonal-type bermudagrasses for rotational traction

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(Roche et al. 2007). Another study in Kentucky reported 'Riviera' and 'Quickstand' having greater SS values compared with 'Tifway' and 'Yukon' (Deaton 2009).

With the advancement in breeding, numerous new bermudagrass cultivars have been developed over the past decade. There are limited studies conducted to investigate the effects of simulated traffic on the persistence and surface playability of these newer cultivars. The objective of this study was to investigate the effect of fall traffic on the persistence and surface playability of bermudagrass cultivars.

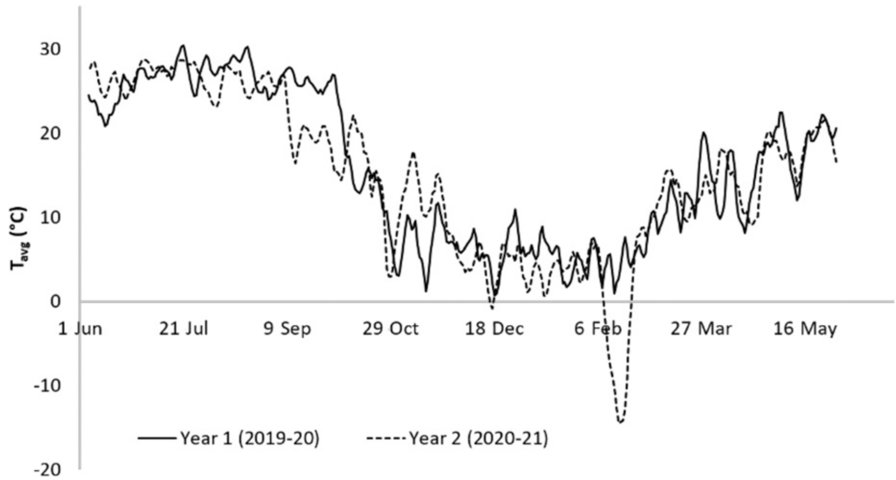

Fig. 1. Five-day running average daily air temperature (T_{avg}) during the experimental period. Data were obtained from the Oklahoma Mesonet–Stillwater site (https://mesonet.org/). (1.8 × °C) + 32 = °F

Materials and methods

Site description and maintenance. A field study was conducted in 2019 and 2020 at the Oklahoma State University Turfgrass Research Center, Stillwater, OK, USA. Nine bermudagrass cultivars were planted in Norge loam soil (fine-silty, mixed, thermic, Udic Paleustoll) on 5 Jun 2019 as 21 1-inch plugs at 1-ft spacing within 8 ft × 4 ft plots. Common types included 'Bimini', Celebration, and 'U-3-SIU' (U-3 obtained from Southern Illinois University, hereafter referred to as U-3). Hybrid types included Latitude 36, NorthBridge, 'OKC1131' (hereafter referred to as Tahoma 31®), TifTuf, 'Tifway', and 'Astro'. Immediately after planting, fertilizer (25N–0P–8.3K) (Agri-Nutrients, Inc., Catoosa, OK, USA) was applied at a rate of 1 lb/1000 sq ft N and oxadiazon pre-emergent herbicide (Ronstar G, Bayer CropScience, Cary, NC, USA) was applied at a rate of 0.045 lb/1000 sq ft a.i. A preliminary soil test (Soil, Water and Forage Analytical Laboratory, Stillwater, OK, USA) demonstrated moderately low soil P (30.5 ppm). To ensure the young plants were not limited by nutrient availability, a complete fertilizer 10N–8.7P–8.3K (1 lb/1000 sq ft N) (Agri-Nutrients, Inc.) was applied on 21 Jun 2019. Thereafter, granular urea (46N–0P–0K) (Agri-Nutrients Inc.) was applied weekly at a rate of 1 lb/1000 sq ft N for 6 weeks from 1 Jul 2019 to 5 Aug 2019 to promote rapid establishment. In 2020, urea (46N–0P–0K) was applied monthly from June to August at a rate of 1 lb/1000 sq ft N. Diammonium phosphate (18N–20P–0K) (Agri-Nutrients Inc.) was applied in May 2020 to ensure sufficient P for optimal plant growth. Oxadiazon pre-emergent herbicide (Ronstar Flo, Bayer Crop Science) was applied on 3 Mar 2020 at a rate of 0.1 lb/1000 sq ft a.i. to control summer annual weeds. Pendimethalin pre-emergence herbicide (Pendulum 3.3 EC; BASF, Research Triangle Park, NC, USA) was applied on 2 Sep 2020 at a rate of 0.14 lb/1000 sq ft a.i. to control winter annual weeds. Irrigation was delivered through in-ground sprinkler systems and applied as necessary to prevent wilt during the study. Plots were mowed at 1 inch using a triplex reel mower (TR330; Jacobsen Corp., Chilton, WI, USA) with clippings returned starting 5 weeks after planting and three times per week during the growing season for the remainder of the study. Five-day running average daily air temperature during the study period is reported in Fig. 1.

Traffic application. Half of each plot was subjected to traffic and the other half was left as a nontreated control. Traffic was applied using a Baldree traffic simulator that was created by modifying a self-propelled core aerifier (ProCore 648; The Toro Company, Bloomington, MN, USA) unit. Coring heads from an aerifier unit were replaced by six spring-loaded metal plates fitted with screw-in plastic cleats of 0.5 inches in size, as described by Kowalewski et al. (2013). At a ground speed of 0.85 mph and a tine spacing of 1 inch, each traffic event resulted in ∼678 cleat marks/m^2. Traffic was applied twice per day from Monday through Friday, totaling 10 traffic events per week from 16 Sep to 26 Oct in 2019 and from 7 Sep to 16 Oct 2020. Each trafficked plot received 60 traffic events each year. During rainy periods, traffic events were delayed by 1 or 2 days to avoid excessive injury to plots while ensuring 10 traffic events per week were applied.

Data collection. The following measurements were conducted for both nontrafficked and trafficked plots at 0, 10, 20, 30, 40, 50, and 60 traffic events (0, 1, 2, 3, 4, 5, and 6 weeks) in Fall 2019 and 2020: SH, SS, and normalized difference vegetation index (NDVI). A Clegg impact tester (Turf-Tec International, Tallahassee, FL, USA) with a 5-lb missile was used to measure SH and the missile was set to drop from 1.5 ft. Impact readings were recorded as the mean of the four randomly selected test locations in each plot based on the ASTM (2018) test methods F1702 with slight modifications to sampling size to improve accuracy. A commercially available shear strength tester (Turf-Tec International) was modified and used to measure SS. As traction force depends on the shoe–surface interaction, the vertical force or loading weight should be comparable to the force applied by the athlete to the point of contact (Nigg 1990). To obtain consistent data, the shear strength tester fitted with the cleated base was modified according to Canaway's trolley mounted rotational device (Canaway and Bell 1986). Briefly, the shear strength tester was loaded with weights, resulting in a total weight of 107.5 lb for the apparatus. This loaded unit was mounted on the four-wheeled wooden trolley structure for transport on research plots. The apparatus was held in place on the wooden trolley by the support of two long iron bars that were fixed on one end and the other end was used to lift and drop the apparatus from the standard height of 2.4 inches. A protractor was fitted on the wooden trolley keeping the shaft of the loaded Turf-Tec unit on its axis and measuring the turning angle throughout the rotation of the loaded unit. The SS values were obtained on all plots using a 40° angle of rotation to obtain the maximum rotational traction (McNitt et al. 1997; Webb et al. 2014). The torque required to tear the turfgrass was measured using the two-handled torque wrench (Turf-Tec International) that was scaled up to 30 N·m. Three random locations were selected in each plot and the average was recorded as the SS for that plot. To measure NDVI, a handheld multispectral crop canopy sensor (CS-45 RapidSCAN; Holland Scientific, Lincoln, NE, USA) was used to scan plots from a height of ~1 m.

Data analysis. The experiment was arranged as a split-block design with three replications. Separate analyses were conducted by year, using statistical software (SAS version 9.4; SAS Institute Inc., Cary, NC, USA). Analysis of variance was performed using PROC GLIMMIX with a repeated measures model for NDVI, SS, and SH. The simple effects of traffic were analyzed by date using "slice (entry × traffic)" statement. Means were separated using the lines statement adjusted for Tukey's test (α = 0.05).

Results and discussion

Surface hardness. Analysis of variance for SH showed a significant traffic × week interaction in 2019 (Table 1) and traffic main effect was observed in 2020 (Table 1). Mean SH of nontrafficked plots ranged from 48.6 to 60.8 Gmax (gravity max) in 2019 (Fig. 2) and ranged from 51.7 to 60.1 Gmax in 2020 (data not presented). Mean SH of trafficked plots ranged from 53.4 to 66.0 Gmax in 2019 and 59.5 to 69.5 Gmax in 2020 (data not presented). Average SH of trafficked plots (pooled across cultivars) was significantly greater than nontrafficked at 30, 40, 50, and 60 traffic events in Fall 2019 by 9.0, 8.5, 8.9, and 6.2 Gmax, respectively (Fig. 2).

Table 1. Summary analysis of variance for shear strength (SS), surface hardness (SH), and normalized difference vegetation index (NDVI) of nine bermudagrass cultivars subjected to 6 weeks of simulated cleat traffic in Fall 2019 and 2020 in Stillwater, OK.

	Fall 2019			Fall 2020		
	SH	SS	NDVI	SH	SS	NDVI
Source	*P* value					
Entry	NS	**[i]	*	NS	***	***
Week	***	***	***	***	***	***
Traffic[ii]	*	**	***	****	**	***
Entry × Week	NS	NS	***	NS	***	NS
Traffic × Week	***	***	***	NS	NS	***
Entry × Traffic	NS	NS	NS	NS	NS	NS
Entry × Traffic × Week	NS	NS	NS	NS	NS	NS

[i] NS, *, **, and *** indicate nonsignificant or significant at $P < 0.05$, 0.01, or 0.001, respectively.
[ii] Traffic was applied using a traffic simulator on half of the plot.

Mean SH (63.6 Gmax) for traffic treatment was significantly greater than the nontraffic treatment (55.5 Gmax) in Fall 2020; however, cultivar under traffic had no significant effect on SH in either year. This finding contradicts Munshaw et al. (2013), who demonstrated variations in SH among cultivars when mowed at a height of 0.5 inches. In addition, SH in the present study was generally less than that reported by Munshaw et al. (2013). These variations were likely due to the higher mowing height (1 inch) in the present study (Rutledge 2005) and a different soil type. Specifically, the present study was conducted on loam soil, which had a greater soil water holding capacity and a high average soil moisture of 35%, compared with the sandy soils reported by Munshaw et al. (2013) (with a high average soil moisture of 16.5%). Although SH generally increased with time, week-to-week spikes (e.g., week 1 in 2019) were likely related to low soil moisture content and illustrates the known negative relationship between SH and soil moisture content (Dickson et al. 2018; Munshaw et al. 2013).

Traffic can lead to soil compaction over time (Dickson et al. 2018; Kowalewski et al. 2013) and can also

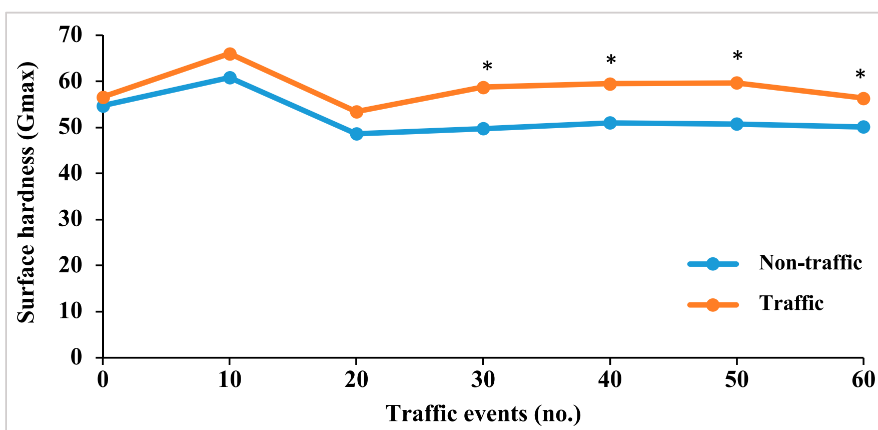

Fig. 2. Effect of traffic on surface hardness (Gmax, gravity max) of nine bermudagrass cultivars over seven rating dates in Fall 2019 in Stillwater, OK (n = 27). Traffic was applied using a traffic simulator on half of the plot. Measurements were made on 15 Sep, 20 Sep, 27 Sep, 4 Oct, 11 Oct, 18 Oct, and 27 Oct in 2019 for 0 to 60 traffic events, and results were pooled across cultivars. Surface hardness measurements were made using an impact soil tester with a 5-lb missile, with four random locations tested per plot, and the average reported in Gmax. * Represents significant difference between nontrafficked and trafficked treatments (*P* < 0.05).

result in increased SH in a relatively short period, particularly on pitches with native soil (Dunn et al. 1994). In the present study, a significant increase in SH was observed after 30 traffic events. Similarly, a traffic study in Knoxville, TN, reported an increase in SH of bermudagrasses after 25 simulated traffic events (NTEP 2016). Excessive SH of an athletic field increases the chance of severe lower extremity or brain injury in athletes (Otago et al. 2007). The industry standard maximum SH for athletic fields is 122.7 Gmax when measured using a 5-lb Clegg soil tester (ASTM 2000; Munshaw et al. 2013). Despite increases in SH, none of the measurements in the present study resulted in SH exceeding maximum safety thresholds.

Differences in SS among cultivars. Analysis of variance for SS showed a significant entry main effect and traffic × week interaction effect in 2019 and entry × week interaction in 2020 (Table 1). In Fall 2019, mean SS of nontrafficked cultivars ranged from 19.0 to 22.3 N·m (Fig. 3) and ranged from 21.3 to 22.2 N·m in Fall 2020 (data not present). In contrast, for trafficked cultivars, mean SS varied from 17.6 to 22.1 N·m in Fall 2019 (Fig. 3) and from 20.0 to 21.2 N·m in Fall 2020. Mean SS for traffic treatment was significantly greater than the nontraffic treatment in most traffic events in 2019 (Fig. 3).

'Bimini' had greater SS than 'Astro' and Tahoma 31 in Fall 2019, whereas no difference in SS was observed among 'Bimini', Celebration, Latitude 36, NorthBridge, TifTuf, 'Tifway', and 'U-3' (Fig. 4). During Fall 2020, significant differences among cultivars (pooled across traffic treatments) for SS were observed at 0, 10, 40, and 50 traffic events (Table 2). 'U-3' and 'Bimini' had greater SS than 'Astro' at 0 and 40 traffic events. After 10 traffic events, 'U-3' exhibited greater SS than 'Astro', NorthBridge, Tahoma 31, and 'Tifway'. In addition, Latitude 36 had greater SS than 'Tifway' at 50 traffic events.

A simple effects analysis of traffic on SS revealed that the SS of 'Astro', 'Bimini', Celebration, NorthBridge, and 'Tifway' was significantly reduced after only 10 traffic events in 2019. However, the reduction in SS occurred after 20 traffic events for Latitude 36 and Tahoma 31, and after 30 traffic events for 'U-3'. Traffic did not reduce the SS of TifTuf before 40 traffic events (Table 3). In total, traffic reduced the SS of 'Bimini' on six rating dates; 'Astro', NorthBridge, and 'Tifway' on five rating dates; Celebration and 'U-3' on four rating dates; 'TifTuf' on three rating dates; and Tahoma 31 on only two rating dates (Table 3). In 2020, traffic reduced the SS of 'Astro', 'Bimini', Latitude 36, Tahoma 31, TifTuf, 'Tifway', and 'U-3' after just 10 traffic events. Celebration demonstrated a reduction of SS after 20 traffic events. In total, 'Astro', 'Tifway', NorthBridge, 'U-3', and Latitude 36 demonstrated a significant traffic effect based on SS reduction on five rating dates, whereas Celebration, Tahoma 31, and TifTuf on four rating dates, and 'Bimini' on three rating dates in 2020 (Table 3).

Excessively high SS can entrap an athlete's foot, whereas too low of an SS contributes to slipping or possible fall (Serensits and McNitt 2014). Dickson et al. (2018) suggested a minimal threshold SS of 18 N·m for acceptable hybrid bermudagrass on a cohesive root zone when measured using a shear tester. Others suggested

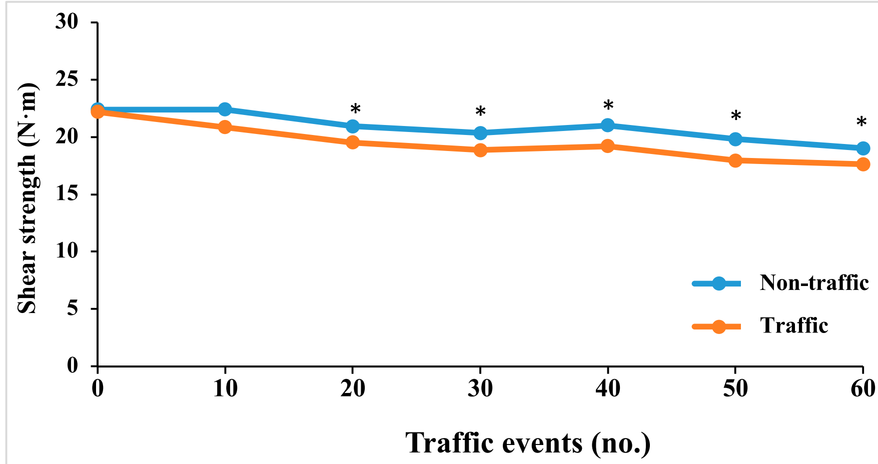

Fig. 3. Effect of traffic on shear strength (SS) of nine bermudagrass cultivars over seven rating dates in Fall 2019 in Stillwater, OK (n = 27). Traffic was applied using a traffic simulator on half of the plot. Measurements were made on 15 Sep, 20 Sep, 27 Sep, 4 Oct, 11 Oct, 18 Oct, and 27 Oct in 2019 for 0 to 60 traffic events, data were pooled across cultivars. SS was measured using a modified shear tester with three random locations tested per plot, and the average was reported in N·m. * Represents significant difference between nontrafficked and trafficked treatments (*P* < 0.05).

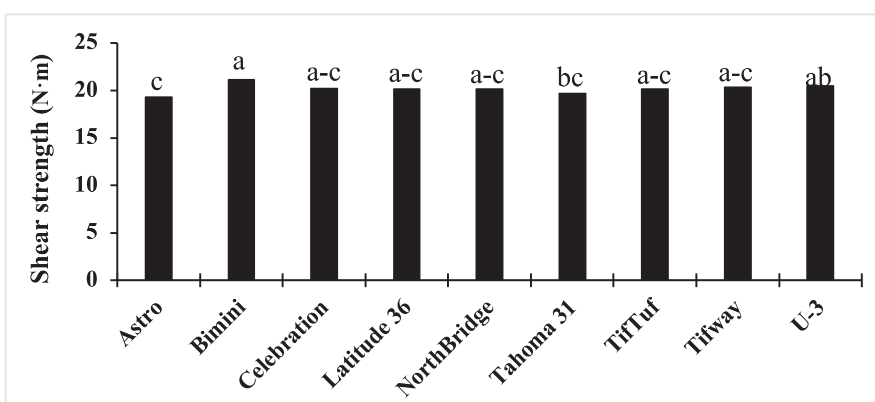

Fig. 4. Shear strength (N·m) for nine bermudagrass cultivars in Fall 2019 in Stillwater, OK. Traffic was applied using a traffic simulator on half of the plot. Data were pooled across trafficked and nontrafficked treatments (n = 6). Bars labeled with the same letters are not statistically different at *P* = 0.05 based on Tukey's honestly significant difference test.

Table 2. Mean shear strength of nine bermudagrass cultivars over seven rating dates in Fall 2020 in Stillwater, OK. Data were pooled across trafficked and nontrafficked treatments (n = 6), with traffic being applied using a traffic simulator on half of the plot.

Cultivar	Week 0[i] (0 events)	Week 1 (10 events)	Week 2 (20 events)	Week 3 (30 events)	Week 4 (40 events)	Week 5 (50 events)	Week 6 (60 events)
Astro	19.6 b[ii]	20.3 b[iii]	20.5	20.6	20.2 b	21.5 a–d	19.9
Bimini	22.7 a	21.5 ab	21.5	22.3	22.1 a	21.7 a–d	20.9
Celebration	21.9 ab	21.4 ab	21.8	22.1	21.6 ab	22.2 ab	20.3
Latitude 36	21.8 ab	20.8 ab	21.4	21.5	21.6 ab	22.5 a	21
NorthBridge	22.4 ab	20.2 b	21.3	21.6	20.8 ab	20.8 cd	20.8
Tahoma 31	21.2 ab	20.5 b	20.8	21.1	21.1 ab	21.2 b–d	21.4
TifTuf	21.6 ab	20.9 ab	20.5	20.7	21.9 a	21.7 a–d	21.2
Tifway	20.6 ab	20.3 b	20.9	20.8	20.6 ab	20.6 d	19.9
U-3	22.8 a	22.2 a	21.5	21.9	22.2 a	21.9 a–c	21.1

[i] Measurements were made on 6 Sep, 11 Sep, 18 Sep, 25 Sep, 2 Oct, 9 Oct, and 16 Oct in 2020 for weeks 0 to 6, respectively.
[ii] Means within columns followed by the same letters are not statistically different at $P = 0.05$ based on Tukey's honestly significant difference test.
[iii] Shear strength was measured using a modified shear tester, selecting three random locations per plot with mean reported in N·m. 1 N·m = 0.7376 lb ft.

SS values of lower than 10 N·m to be considered unacceptable for athletic events (Stier et al. 1999). Traffic is known to reduce SS over time (Dunn et al. 1994; Gibbs et al. 1989; Roche et al. 2007) and results of the present study are in agreement with this general pattern.

When pooled across traffic treatments, differences in SS were evident among bermudagrass cultivars. 'Bimini' and 'U-3' were considered the top-performing cultivars for SS. In contrast, 'Astro' was considered the worst performing cultivar in terms of SS, regardless of traffic conditions. This is in agreement with a previous study conducted in Turkey, where differences in SS among bermudagrasses were reported (Sever Mutlu et al. 2020). The superior performance of 'Bimini' and 'U-3', in terms of turfgrass SS, in comparison with other cultivars is presumably due to their inherent species differences in root and shoot density, and canopy architecture (Lulli et al. 2012; Rutledge 2005; Serensits and McNitt 2014). This variation in cultivar response for SS contrasts with the lack of response observed for SH and suggests that SH may be more related to soil properties and management than cultivar (Sever Mutlu et al. 2020). Similarly, soil properties, such as soil moisture, have been shown to have an impact on SS, as higher soil moisture levels were reported by Dickson et al. (2018) to be associated with increased SS. Nevertheless, whether these differences in cultivar performance would be detectable by athletes is unknown. Similarly, whether increased traffic stress throughout the year or other management factors would influence the magnitude of these differences requires further study.

Canopy health over time. Analysis of variance for NDVI showed significant entry × week interaction and

Table 3. Simple effects of traffic on shear strength of nine bermudagrass cultivars on seven rating dates in Fall 2019 and 2020 in Stillwater, OK. Traffic was applied using a traffic simulator on half of the plot.

Yr	Cultivar	Week 0 (0 events)	Week 1 (10 events)	Week 2 (20 events)	Week 3 (30 events)	Week 4 (40 events)	Week 5 (50 events)	Week 6 (60 events)
		Significance level of F-test						
2019	Astro	NS[i]	*	*	**	*	NS	*
	Bimini	NS	**	***	*	**	**	*
	Celebration	NS	*	**	*	NS	NS	**
	Latitude 36	NS	NS	**	***	*	**	NS
	NorthBridge	NS	***	NS	***	**	*	***
	Tahoma 31	NS	NS	***	**	NS	NS	NS
	TifTuf	NS	NS	NS	NS	**	*	*
	Tifway	NS	*	NS	*	*	*	**
	U-3	NS	NS	NS	*	***	**	***
2020	Astro	NS	**	*	*	**	NS	**
	Bimini	NS	*	NS	NS	**	NS	*
	Celebration	NS	NS	*	*	*	NS	***
	Latitude 36	*	*	NS	**	**	NS	**
	NorthBridge	**	NS	NS	*	*	**	*
	Tahoma 31	NS	*	***	NS	**	**	NS
	TifTuf	NS	*	**	**	***	NS	NS
	Tifway	NS	*	NS	*	**	***	**
	U-3	NS	***	*	NS	**	*	***

[i] NS, *, **, and *** indicate nonsignificant or significant at $P < 0.05$, 0.01, or 0.001, respectively.

traffic × week in Fall 2019 (Table 1). In addition, there was traffic × week and entry main effect in Fall 2020 (Table 1). Mean NDVI of nontrafficked cultivars ranged from 0.748 in the first rating to 0.571 in the final rating of 2019 and from 0.712 in the first rating to 0.665 in the final rating of 2020 (Table 4).

Significant differences on NDVI among nontrafficked cultivars were observed on four rating dates in 2019 and on six rating dates in 2020 (Table 4). In 2019, NorthBridge demonstrated greater NDVI than 'Astro' on three rating dates, and greater than TifTuf, 'Bimini', and 'Tifway' on one rating date. In 2020, 'Bimini' exhibited greater NDVI compared with 'Tifway' and 'Astro' on five rating dates. In addition, it showed greater NDVI than 'U-3' on four rating dates and Celebration, Latitude 36, TifTuf, and Tahoma 31 on the last two rating dates.

The NDVI of trafficked cultivars ranged from 0.429 to 0.784 in Fall 2019 and ranged from 0.520 to 0.759 in Fall 2020 (Table 5). Significant differences among trafficked cultivars were observed on two rating dates in 2019 and all seven rating dates in 2020 (Table 5). In 2019, 'Bimini' had a greater NDVI than 'Astro' and 'U-3' at 40 traffic events and greater NDVI than 'Astro', Celebration, and 'U-3' at 60 traffic events. In 2020, 'Bimini' had a greater NDVI than TifTuf at 0, 10, and 20 traffic events. 'Bimini' demonstrated a greater NDVI than 'Astro' and 'Tifway' on four rating dates. Tahoma 31 showed a lower NDVI than 'Bimini' at 50 and 60 traffic events (Table 5).

In 2019, traffic reduced the NDVI of 'Astro', Celebration, Latitude 36, NorthBridge, Tahoma 31, 'Tifway', and 'U-3' after 50 traffic events (Table 6). No traffic effects on NDVI were observed for 'Bimini' or TifTuf on any rating date in 2019. In 2020, traffic reduced the NDVI of Tahoma 31, TifTuf, and 'Tifway' at as early as 20 events, and 'Astro', Celebration, Latitude 36, and 'U-3' at 30 events. 'Bimini' and NorthBridge did not demonstrate any traffic effect on NDVI before 50 events in 2020.

Visual ratings are commonly used for screening turfgrass traffic tolerance. However, these ratings are subjective and may exhibit variations in consistency between different evaluators. Furthermore, there may be variations from one evaluation event to another, even when evaluated by the same individual. Therefore, NDVI and green coverage are more objective measurements. Both NDVI and green coverage were measured in this study, and a strong correlation was observed. As a result, only NDVI was used to assess turfgrass canopy health in this study. Traffic stress is known to reduce turfgrass canopy health resulting in corresponding declines in NDVI (Trenholm et al. 1999). Kowalewski et al. (2013) reported that 6 weeks of traffic reduced green coverage by nearly 50% compared with the nontreated control. Our findings support the study by Kowalewski et al. (2013), indicating a significant reduction in NDVI for both years. Specifically, we observed a 55% reduction on trafficked bermudagrass and a 31% reduction on nontrafficked bermudagrass from week 0 to week 6 in 2019. In 2020, similar trends were observed, with a 25% reduction on trafficked bermudagrass and a 7% reduction on nontrafficked bermudagrass. Normalizing for the decrease in NDVI induced by seasonal weather patterns (assumed for nontrafficked plots), entries exhibited a 24% and 18% reduction in NDVI due to traffic stress alone in 2019 and 2020, respectively.

In the present study, 'Bimini' was considered to be the most persistent cultivar due to its presence in the top statistical group for NDVI and similarities between trafficked and nontrafficked

Table 4. Normalized difference vegetation index (NDVI) of nine nontrafficked bermudagrass cultivars over seven rating dates in Fall 2019 and 2020 in Stillwater, OK. Traffic was applied using a traffic simulator on half of the plot.

Yr	Cultivar	Week 0[i] (0 events)	Week 1 (10 events)	Week 2 (20 events)	Week 3 (30 events)	Week 4 (40 events)	Week 5 (50 events)	Week 6 (60 events)
2019	Astro	0.740[ii]	0.748 ab	0.661 e	0.666 b	0.604 b	0.620	0.516
	Bimini	0.779	0.762 ab	0.691 b–e	0.717 ab	0.663 ab	0.593	0.587
	Celebration	0.763	0.769 ab	0.736 ab	0.739 a	0.668 ab	0.560	0.548
	Latitude 36	0.769	0.806 a	0.722 a–d	0.729 ab	0.673 ab	0.551	0.592
	NorthBridge	0.780	0.776 ab	0.745 a	0.740 a	0.683 a	0.597	0.572
	Tahoma 31	0.728	0.766 ab	0.731 a–c	0.733 ab	0.686 a	0.595	0.583
	TifTuf	0.720	0.750 ab	0.674 de	0.700 ab	0.666 ab	0.613	0.600
	Tifway	0.756	0.735 b	0.682 b–e	0.686 ab	0.645 ab	0.629	0.570
	U-3	0.745	0.746 ab	0.722 a–d	0.716 ab	0.678 a	0.613	0.608
	Mean	0.753	0.762	0.707	0.714	0.663	0.597	0.575
2020	Astro	0.714	0.720 ab	0.686 b	0.691 b	0.615 c	0.611 d	0.638 c
	Bimini	0.739	0.740 ab	0.741 a	0.742 a	0.685 a	0.710 a	0.734 a
	Celebration	0.739	0.750 a	0.722 ab	0.725 ab	0.674 ab	0.660 b	0.683 b
	Latitude 36	0.732	0.740 a	0.693 ab	0.703 ab	0.644 a–c	0.640 c–d	0.673 b
	NorthBridge	0.684	0.730 ab	0.697 ab	0.696 ab	0.644 a–c	0.630 c–d	0.662 bc
	Tahoma 31	0.747	0.740 ab	0.721 ab	0.724 ab	0.643 a–c	0.620 cd	0.658 bc
	TifTuf	0.709	0.711 ab	0.701 ab	0.698 ab	0.659 a–c	0.650 bc	0.676 b
	Tifway	0.683	0.681 b	0.678 b	0.681 b	0.634 bc	0.630 c–d	0.657 bc
	U-3	0.712	0.713 ab	0.676 b	0.684 b	0.638 a–c	0.620 c–d	0.657 bc
	Mean	0.718	0.725	0.702	0.705	0.648	0.641	0.671

[i] Measurements were made on 15 Sep, 20 Sep, 27 Sep, 4 Oct, 11 Oct, 18 Oct, and 27 Oct in 2019 and 6 Sep, 11 Sep, 18 Sep, 25 Sep, 2 Oct, 9 Oct, and 16 Oct in 2020 for weeks 0–6, respectively.

[ii] Means within columns followed by the same letters are not statistically different at $P = 0.05$ based on Tukey's HSD test in 2019 and 2020.

Table 5. Normalized difference vegetation index (NDVI) of nine trafficked bermudagrass cultivars over seven rating dates in Fall 2019 and 2020 in Stillwater, OK. Traffic was applied using a traffic simulator on half of the plot.

Yr	Cultivar	Week 0[i] (0 events)	Week 1 (10 events)	Week 2 (20 events)	Week 3 (30 events)	Week 4 (40 events)	Week 5 (50 events)	Week 6 (60 events)
2019	Astro	0.741[ii]	0.721	0.688	0.696	0.570 b	0.640	0.429 c
	Bimini	0.779	0.771	0.711	0.720	0.657 a	0.587	0.556 a
	Celebration	0.763	0.733	0.712	0.715	0.625 ab	0.546	0.452 bc
	Latitude 36	0.769	0.790	0.713	0.738	0.681 a	0.555	0.528 ab
	NorthBridge	0.784	0.777	0.742	0.744	0.672 a	0.605	0.480 a–c
	Tahoma 31	0.728	0.730	0.700	0.693	0.623 ab	0.590	0.476 a–c
	TifTuf	0.721	0.711	0.703	0.714	0.652 ab	0.606	0.536 ab
	Tifway	0.756	0.720	0.694	0.680	0.607 ab	0.660	0.486 a–c
	U-3	0.740	0.721	0.688	0.696	0.570 b	0.640	0.429 c
	Mean	0.753	0.741	0.705	0.710	0.629	0.603	0.486
2020	Astro	0.709 a–c	0.686 a–c	0.628 bc	0.608 ab	0.528 b	0.488 b	0.538 b
	Bimini	0.745 ab	0.740 a	0.712 a	0.700 a	0.642 a	0.600 a	0.655 a
	Celebration	0.759 a	0.729 a	0.680 a–c	0.66 ab	0.565 ab	0.528 ab	0.584 ab
	Latitude 36	0.706 a–c	0.705 ab	0.668 a–c	0.620 ab	0.553 ab	0.532 ab	0.559 ab
	NorthBridge	0.757 a	0.721 ab	0.690 ab	0.669 ab	0.592 ab	0.557 ab	0.605 ab
	Tahoma 31	0.732 a–c	0.707 ab	0.653 a–c	0.617 ab	0.544 ab	0.482 b	0.520 b
	TifTuf	0.672 c	0.661 bc	0.627 bc	0.600 ab	0.574 ab	0.514 ab	0.590 ab
	Tifway	0.687 bc	0.638 c	0.605 c	0.577 b	0.524 b	0.516 ab	0.554 ab
	U-3	0.714 a–c	0.704 ab	0.652 a–c	0.607 ab	0.553 ab	0.521 ab	0.578 ab
	Mean	0.720	0.699	0.657	0.629	0.564	0.526	0.576

[i] Measurements were made on 15 Sep, 20 Sep, 27 Sep, 4 Oct, 11 Oct, 18 Oct, and 27 Oct in 2019 and 6 Sep, 11 Sep, 18 Sep, 25 Sep, 2 Oct, 9 Oct, and 16 Oct in 2020 for weeks 0–6 respectively.

[ii] Means within columns followed by the same letters are not statistically different at $P = 0.05$ based on Tukey's HSD test in 2019 and 2020.

plots before 50 events in either year (data not presented). 'U-3', Celebration, and Tahoma 31 were identified as having moderate persistence under traffic. Although most cultivars showed relatively similar results from year 1 to year 2, TifTuf surprisingly went from a top performer in year 1 to showing the effects of traffic after just 10 events in year 2. These findings contradict prior reports of TifTuf having excellent traffic tolerance (NTEP 2013; Kowalewski et al. 2015) and may be influenced by the greater intensity of traffic stress applied in the present study. In addition, the relatively tall mowing height (1 inch or 2.54 cm) used in the present study may have influenced results for particularly dwarf turfgrasses (e.g., Tahoma 31), causing traffic patterns to be more visible in a "puffier" canopy (Sancar et al. 2023). The poorest performing cultivars ('Astro' and 'Tifway') were among the oldest cultivars tested in this study. Their poor

Table 6. Simple effects of traffic on normalized difference vegetation index (NDVI) of nine bermudagrass cultivars on seven rating dates in Fall 2019 and 2020 in Stillwater, OK. Traffic was applied using a traffic simulator on half of the plot.

		Week 0 (0 events)	Week 1 (10 events)	Week 2 (20 events)	Week 3 (30 events)	Week 4 (40 events)	Week 5 (50 events)	Week 6 (60 events)
Yr	Cultivar	Significance level of F-test						
2019	Astro	NS	NS	NS	NS	NS	NS	* [i]
	Bimini	NS	NS	NS	NS	NS	NS	NS
	Celebration	NS	NS	NS	NS	NS	NS	**
	Latitude 36	NS	NS	NS	NS	NS	NS	NS
	NorthBridge	NS	NS	NS	NS	NS	NS	**
	Tahoma 31	NS	NS	NS	NS	NS	NS	**
	TifTuf	NS	NS	NS	NS	NS	NS	NS
	Tifway	NS	NS	NS	NS	NS	NS	**
	U-3	NS	NS	NS	NS	NS	NS	**
2020	Astro	NS	NS	NS	*	**	***	**
	Bimini	NS	NS	NS	NS	NS	***	**
	Celebration	NS	NS	NS	*	***	***	**
	Latitude 36	NS	NS	NS	*	***	***	***
	NorthBridge	NS	NS	NS	NS	NS	*	NS
	Tahoma 31	NS	NS	***	***	***	***	***
	TifTuf	NS	NS	**	**	*	***	**
	Tifway	NS	NS	**	**	**	***	**
	U-3	NS	NS	NS	*	*	*	*

[i] NS, *, **, and *** indicate nonsignificant or significant at $P < 0.05$, 0.01, or 0.001, respectively.

performance is consistent with several previous studies (Kowalewski et al. 2015; Segars 2013; Williams et al. 2010) and illustrates the advancement in bermudagrass breeding over the past several decades.

Conclusion

Bermudagrass has been widely used on athletic fields throughout the transition zone and beyond, due to its tolerance to heat, drought, disease, and wear. With the increasing demand and use of athletic fields, the evaluation and selection of cultivars for traffic tolerance has become increasingly crucial. The present study provides one of the more exhaustive lists of modern bermudagrass cultivars tested for traffic tolerance. Moreover, it is the first peer-reviewed source to report the traffic tolerance of 'Bimini', a cultivar developed from southern Florida, in the transition zone. Simulated traffic stress reduced bermudagrass NDVI and affected playability parameters by decreasing SS while increasing the SH. Older cultivars such as 'Astro' and 'Tifway' were more sensitive to traffic than newer releases. This study contributes to the understanding of how bermudagrasses perform in various environments and can provide guidance to practitioners selecting a cultivar for their facility.

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