2020

Interspecific comparisons of C_3 turfgrass for tennis use: I. Wear tolerance and carrying capacity under actual match play

Jeffrey S. Ebdon

I. James

Michelle DaCosta

J. Lu

Received: 6 April 2020 | Accepted: 7 July 2020 | Published online: 24 August 2020

DOI: 10.1002/csc2.20270

Crop Science

ORIGINAL RESEARCH ARTICLE

Turfgrass Science

Interspecific comparisons of C_3 turfgrass for tennis use: I. Wear tolerance and carrying capacity under actual match play

J. S. Ebdon[1] | **I. James**[1,2] | **M. DaCosta**[1] | **J. Lu**[1]

[1] Stockbridge School of Agriculture, Univ. of Massachusetts, 415 Paige Lab., Amherst, MA 01301, USA

[2] TGMS, Ampthill, Bedford MK45 2ND, UK

Correspondence
J. S. Ebdon, Stockbridge School of Agriculture, Univ. of Massachusetts, 415 Paige Lab., Amherst, MA 01301, USA.
Email: sebdon@pssci.umass.edu

Assigned to Associate Editor Nathan Walker.

Abstract

Previous studies in the evaluation of wear tolerance have been conducted using wear simulators. Research to investigate wear tolerance of C_3 turfgrasses under actual playing conditions and their carrying capacity is limited. Three grass tennis courts (replicates) maintained as official size (single) courts were constructed. Eight species and cultivars were randomized within the three courts (blocks): (1) 'Keeneland' Kentucky bluegrass (KB, *Poa pratensis* L.), (2) 'Rubix' KB, (3) 'Villa' velvet bentgrass (VBG, *Agrostis canina* L.), (4) 'Puritan' colonial bentgrass (CL, *Agrostis capillaris* L.), (5) '007' creeping bentgrass (CB, *Agrostis stolonifera* L.), (6) fine fescue (FF, *Festuca* spp.) mixture, (7) 'Karma' perennial ryegrass (PR, *Lolium perenne* L.), and (8) 'Wicked' PR. Injury at the baseline was measured by counting healthy grass on four dates in 2017 and 2019 using an intersect grid. Carrying capacity at the baseline was derived as hours of play to sustain 90, 80, 70, and 60% grass cover. After 6 wk of actual tennis play involving >120 participating players in 2017 and 2019, KB and PR were superior to other C_3 turfgrass for wear tolerance and carrying capacity. These two species exhibited four times the carrying capacity of FF species and nearly 60% more carrying capacity than bentgrass (BG) species. Species of BG afforded higher shoot density and better traction than KB and PR, with VBG exhibiting the best traction, and FF and PR exhibiting the poorest traction. In 2017, greater cell wall content increased wear tolerance and carrying capacity. Velvet bentgrass was as good as KB and PR in overall wear tolerance and carrying capacity under actual match play.

1 | INTRODUCTION

Research specific to sporting activities and associated traffic injury to turfgrass from wear (abrasion to aerial shoots) and soil compaction (increase soil bulk density) are investigated using simulators. There are numerous scientific reviews available in the literature on the subject of traffic

Abbreviations: ADF, acid detergent fiber; CB, creeping bentgrass; CL, colonial bentgrass; FF, fine fescue; hemi, hemicellulose; HOC, height of cut; ITF, International Tennis Federation; KB, Kentucky bluegrass; ligno, lignocellulose; NDF, neutral detergent fiber; PR, perennial ryegrass; TCW, total cell wall content; VBG, velvet bentgrass.

stress (Aldahir & McElroy, 2014; Bell, Baker, & Canaway, 1985; Canaway, 1975; Carrow & Petrovic, 1992; Murphy & Ebdon, 2013) in which wear simulators of various types are the sole source of wear for research investigations. Wear simulation in the field to match actual sports activities can be difficult to replicate because of the numerous factors that affect traffic stress such as the type, intensity, and season of traffic, turfgrass species and cultivar, soil type, root zone construction and design, plant and soil water content at the time of traffic, and maintenance practices (Murphy & Ebdon, 2013). To that end, several types of traffic simulators have been developed in the attempt to mimic actual sports activity by applying injury to the shoots of turfgrass and compaction to soil (Bourgoin & Mansat, 1981; Canaway, 1976; Carrow, Duncan, Worley, & Shearman, 2001; Cockerham & Brinkman, 1989; Evans, 1988; Henderson, Lanovaz, Rogers, Sorochan, & Vanini, 2005; Shearman et al., 2001; Youngner, 1961). The use of simulators affords a control that cannot be achieved using human subjects (variation in body mass, sport-specific movements, and intensity of use), but it also allows acceleration of wear in the research environment, and this can be a limitation of such simulators.

Injury to turfgrass from wear is not uniformly distributed in its intensity and varies with the sporting event (Puhalla, Krans, & Goatley, 1999). Many sports turf facilities are subjected to more than one type of sporting activity in addition to nonsporting uses (Aldahir & McElroy, 2014). One possible exception is grass tennis courts because the sole source from wear is from tennis play and wear is principally concentrated along the court baselines (Holmes & Bell, 1986), especially in the case of single courts. Grass courts in the United States make up <1% (TIA, 2019) of all outdoor court surfaces combined (125,000 as acrylic, asphalt, and clay), whereas 7% of the tennis courts in the United Kingdom are planted to grass (James, 2015). Although difficult to quantify, grass courts are preferred by players (Thorpe & Canaway, 1986). Their lower use as a surface in tennis is the result of their higher maintenance requirements and costs, as well as the sensitivity of turfgrass to weather conditions that affect player use, traction, wear tolerance, ball-to-surface friction, and ball bounce (James, 2015). Grass tennis courts as a matter of their smaller dimensions are a more practical sports surface for study in replicated experiments to investigate turfgrass response to wear under actual player traffic; single courts are only 195.731 m^2, and doubles are 260.872 m^2 (ITF, 2019; CS 04/02).

Critical thresholds or sustainable carrying capacity for the number of sporting events or hours of play that can be safely conducted on a sports turf are difficult to quantify because of the numerous factors that affect the durability of turfgrass to traffic stress. For example, periodic assessment or survey of field conditions are needed to measure associated wear, traction, hardness, resiliency, and recovery time for individual fields (Minner, 1999). In one rare survey conducted by Gibbs, Adams, and Baker (1993), they reported that carrying capacity of soccer pitches ranged from <50 to 125–180 adult games per season, equating to 3.5–8.5 h of play per week depending on the drainage used during construction. Additional research is needed to estimate carrying capacity under more uniform experimental conditions; this is currently lacking in the scientific literature.

Comprehensive interspecific comparisons among cool-season turfgrass is limited to the work by Shearman and Beard (1975a, 1975b, 1975c) in their evaluation of the wear tolerance of seven cool-season turfgrass species. In their study, three *Festuca* spp. (coarse and fine textured), Kentucky bluegrass (KB, *Poa pratensis* L.), perennial ryegrass (PR, *Lolium perenne* L.), annual ryegrass (*Lolium multiflorum* Lam.), and rough bluegrass (*Poa trivialis* L.) were evaluated under simulated wear at 5-cm height of cut (HOC). Perennial ryegrass ranked at the top in wear tolerance, and tall fescue (*Schedonorus arundinaceus* Schreb.) and KB ranked second, with annual ryegrass and creeping red fescue (*Festuca rubra* L. ssp. *rubra*) ranking as intermediate, and Chewing's fescue (*Festuca rubra* var. *commutate* Gaudin) and rough bluegrass ranking as low. They were the first to report a thorough examination of plant factors related to wear tolerance, including the effect of total cell wall (TCW) content measured using neutral detergent fiber (NDF), cellulose and lignin measured using acid detergent fiber (ADF), and hemicellulose (hemi, NDF − ADF), which were associated with improved interspecies tolerance to wear. Other research in wear tolerance has also been conducted to investigate wear mechanisms at the interspecific level, but these studies have been limited to only two species in C_4 turfgrass (Trenholm, Carrow, & Duncan, 2000) and two C_3 *Agrostis* species (Dowgiewicz, Ebdon, DaCosta, & Dest, 2011). Greater levels of TCW, lignocellulose (ligno), and hemi measured on a dry mass basis were associated with the greater wear tolerance of velvet bentgrass (VBG, *Agrostis canina* L.) compared with creeping bentgrass (CB, *A. stolonifera* L.) (Dowgiewicz et al., 2011). Additional research similar to Shearman and Beard's early interspecific comparisons are needed for evaluating wear tolerance and associated wear mechanisms.

Interspecific comparison of C_3 turfgrass wear tolerance for tennis use was evaluated in the United Kingdom by Newell and Jones (1995). Their research focused on overall wear tolerance under simulated traffic and not plant mechanisms. They reported that the more wear-tolerant cultivars of PR and KB performed well under simulated traffic, whereas most fine fescue (FF, *Festuca* spp.) species (with the exception of slender creeping red fescue, *Festuca* *rubra* ssp. *litoralis* Vasey ex Beal) and *Agrostis* species (*A capillaris* and *A stolonifera*) performed poorly. For championship tennis, cool-season turfgrass are generally mowed at a HOC of ~8 mm (Newell, Crossley, & Jones, 1996; Newell & Jones, 1995; Newell & Wood, 2000; Puhalla et al., 1999). Interspecific comparisons under tennis match play in the evaluation of C_3 turfgrass have applications to golf course turf because they are maintained under similar HOC.

The overall objective of this study was to compare six different turfgrass species (eight turfgrass species–cultivar combinations) at the interspecies level for their tolerance to wear and carrying capacity under actual match play. Associated cell wall components, shoot density, and tennis shoe traction were also investigated at the interspecific level. This current study is Part 1 of a companion study, whereas Part 2 investigates ball–surface interactions (Ebdon, James, DaCosta, & Lu, 2020).

2 | MATERIALS AND METHODS

2.1 | Treatments and grass court setup

Three official size single courts (i.e., replications) were constructed at the Joseph Troll Turf Research and Education Center, South Deerfield, MA. The latitude and longitude of the site is 42.49 °N and 72.59 °W, respectively, located 86.9 m asl. Grass tennis courts were established on Hadley silt-loam (coarse-silty, mixed, superactive, nonacid, mesic, Typic Udifluents) and planted to eight different species and cultivars on 17 May 2016. The Hadley silt-loam is characterized as 23.5% sand, 63.8% silt, and 12.7% clay. Soil test K and P in 2016 averaged 106 mg K kg^{-1} (medium high) and 21 mg P kg^{-1} (high), with a soil pH of 6.3. By the last year of the test in 2019, soil test K and P averaged 89 mg K kg^{-1} (medium) and 23 mg P kg^{-1} (high), with a soil pH of 6.0.

Single courts were established that followed International Tennis Federation (ITF, 2019) recommended court dimensions (ITF CS 04/02: 23.77 × 8.23 m, length × width, respectively). Eight main plots were planted in each court with four main plots on each side of the net. All main plots extended 1.52 m beyond the baseline so that each main plot measured 13.41 by 2.06 m. The area was constructed with a 0.3% slope side line-to-side line for surface drainage (ITF CS 03/03). Each main plot was sufficient in length to capture wear at the baseline and with sufficient grass area between the service line and net for measurements to be taken in the service box (i.e., the minimal-wear service area). The service area of each main plot measured 6.40 by 2.06 m (13.17 m^2). Individual courts were separated by at least 6.1 m in all directions to allow for sufficient space for match play to occur on all three courts at the same time.

The following eight species and cultivars were randomized within the three courts (replicates): (1) 'Keeneland' KB, (2) 'Rubix' KB, (3) 'Villa' VBG, (4) 'Puritan' colonial bentgrass (*Agrostis capillaris* L., CL), (5) '007' CB, (6) FF mixture consisting of approximately 60–40% by weight 'Bridgeport II' Chewing's fescue (*Festuca rubra* var. *commutata*) and 'Barcrown' slender creeping red fescue (*Festuca rubra* ssp. *litoralis*), (7) 'Karma' PR, and (8) 'Wicked' PR. Seeding rates used at planting and renovation of baselines were as follow: 49 kg ha^{-1} (VBG), 98 kg ha^{-1} (CL and CB), 245 kg ha^{-1} (KB), 490 kg ha^{-1} (FF), and 980 kg ha^{-1} (PR). Turfgrass cultivars of KB, PR, VBG, CL, and CB species were selected based on their superior wear tolerance in National Turfgrass Evaluation Program (NTEP) wear trails conducted at the University of Massachusetts Amherst (unpublished). Cultivars of FF were selected as a control, with some *Festuca* species and cultivars showing potential for wear tolerance under simulated wear for tennis use (Newell & Jones, 1995; Newell & Wood, 2000).

2.2 | Grass court maintenance

After the establishment year in 2016, grass courts were mowed at 8-mm HOC with clippings collected. Courts were mowed once daily before play and scheduled measurements. Beginning in 2017, courts were rolled three to four times per week using a 1,000-kg roller (3.05-m length and 0.254-m diam.) (Smithco, Fairway Roller) to maintain uniform ball bounce and firmness.

Grass courts were fertilized with foliar fertilizer (4.9–9.8 kg N ha^{-1}) using various N forms and sources on a 2- to 3-wk interval. Total N applied per year was 166.5, 162, and 102 kg ha^{-1} in 2017, 2018, and 2019, respectively. In 2017 and 2018, fertilization ended in November, whereas during the last year of the test in 2019, fertilization ended on 1 August. Primo (trinexapac-ethyl) was applied with all foliar N applications at 0.40 L product ha^{-1}.

During the growing season in 2017–2019, preventative fungicides were applied on a 21-d interval from May through September along with preventative fungicides for snow mold (*Typhula* species) applied in November of 2017 and 2018. Siduron [1-(2-methylcyclohexyl)-3-phenylurea] was applied each year at a total rate of 488 kg a.i. ha^{-1} as a split application in mid-May and reapplied in late June for preventative annual grass weed control. Carbaryl insecticide (1-naphthyl N-methylcarbamate) was applied in June and July of each year for curative control of cutworm (*Agrotis ipsilon*) on *Agrostis* species. All products were applied using a calibrated boom sprayer and a spray

TABLE 1 Summary statistics for grass tennis court playing hours and use per court during the experimental period. The cumulative hours in each period indicate the hours of play when grass cover at the baselines was measured on tennis courts in 2017 and 2019

Date	Hours per court	Cumulative hours	Avg. hours per week	Players Total	Players Avg. per week
	h			no.	
2017			12.8	130	21.7
2–16 July	28.9	28.9			
17–22 July	12.8	41.7			
25–31 July	14.0	55.7			
1–12 Aug.	20.0	75.7			
2019			13.3	125	20.8
8–12 June	13.5	13.5			
15 June–7 July	33.0	46.5			
8–21 July	24.3	70.8			
23 July–2 Aug.	22.2	93.0			

volume of 813 L ha^{-1}. All plots and border areas were treated uniformly with preventative fungicides, insecticides, and herbicides to maintain uniform and actively growing turf for optimum wear tolerance during tennis match play. Irrigation was applied to prevent wilt as evapotranspiration replacement calculated using the FAO-56 Penman–Monteith reference evapotranspiration (Allen, Pereira, Raes, & Smith, 1998) and adjusted using the appropriate crop coefficient of 0.90 (Poro, Ebdon, Dacosta, & Brown, 2017).

Reseeding along baselines was conducted in mid-August in 2017 at termination of tennis play and reseeded again in early May of 2018 in order to reestablish baselines and other areas worn from traffic caused by tennis play. Tennis play was not initiated again until 2019 to allow sufficient time for reestablishment of grass court baselines. As such, tennis play and associated wear injuries and their assessment were only conducted in 2017 and 2019. In 2018 and 2019, other measurements related to tennis pace (speed of play) such as surface hardness, soil moisture, ball bounce, and ball-to-surface friction were measured in the service area and are presented in a companion paper (Ebdon et al., 2020).

2.3 | Player wear injury and carrying capacity

Tennis match play was conducted on all three courts in 2017 and 2019. The duration of each playing season was ~6 wk, but the start and end dates for play varied (Table 1). Hours of play was monitored and recorded daily to ensure that playing hours and use on all (three) courts was distributed evenly across courts. Injury and damage from tennis play was assessed four times in 2017 and 2019 (Table 1). Injury increased with hours of play and progressed along the baseline over the 6-wk period. Players were required to wear tennis shoes, and no bare feet and no doubles play was allowed on the singles courts.

Injury at the baseline was measured by counting healthy grass vs. injured or damaged grass or bare soil using an intersect grid. The length of the grid measured the same as the width of the main plots (2.06 m), with the width of the grid measuring 1.03 m. Grid intersect strings were equally spaced every 14.7 cm and formed 98 (7 × 14) intersects. The intersect grids' center string along the long side was centered on the painted (white marked) baselines of each main plot; the center string was not used for assessing grass cover. Therefore, counts for percentage grass cover were based on a total number of 84 intersects with percentage green cover calculated as (number of intersects of healthy uninjured grass/84) × 100.

Carrying capacity at the baseline was expressed as hours of play to sustain 90, 80, 70, and 60% grass cover. Carrying capacity was derived by curve fitting using a four-parameter sigmoid model (Sigma Plot, SPSS), which conformed closely to the relationship between grass cover and hours of play at the baseline. Carrying capacity was derived by curve fitting each individual main plot (replicate) using Y as the percentage grass cover measured at X cumulative hours as shown in Table 1 for each year (2017 and 2019). In the analysis, grass cover at the baseline for each replicated main plot was at 100% grass cover corresponding to 0 h of play. After curve fitting, parameter estimates were substituted back into the nonlinear equation to estimate hours of play to achieve 90, 80, 70, and 60% grass cover.

2.4 | Traction and friction

Rotational traction was measured by a device similar to that described by Canaway and Bell (1986). The torque required for the device's shoe to shear or tear the turf surface is measured and reported in N m (newton meters). The surface area of the shoe and weight on the shoe can vary (Bell et al., 1985). Our device was modified using the outsole an of Asics grass court tennis shoe (Men's Gel-Solution Speed 3 Grass). Although our shoe had the same surface area (0.0177 m^2), the shoe was weighted with 34 kg, compared with the 45-kg weight used by Canaway and Bell (1986).

From the observed values of torque applied, traction or friction coefficients were calculated to allow for comparisons with other studies when weights (kg) and surface area (m^2) of the device vary. Friction coefficient for traction was calculated as

$$\mathrm{COF_T} = [(3T)/(2Wr)]\ (1/g) \quad (1)$$

where T is torque (N m), W is the weight (kg) on the disc, r (m) is the radius of the disc (0.075 m), and g is acceleration due to gravity (9.81 N kg^{-1} force) (Bell et al., 1985; Canaway, 1975). Earlier research has shown that a coefficient of friction (COF) for traction <1.0 can indicate that slips or falls may occur because the forces required to start motion are less than the normal force (N) on the shoe (van Gheluwe, Deporte, & Hebbelink, 1983). Traction measurements are static forces required to start motion, and therefore static traction coefficients in the current study are denoted as (COF_T). Although standards for rotational traction have been developed for some sport surfaces, no standards for traction or grip have been developed for tennis (Fleming, Young, & Carré, 2015). In our study, three measurements of traction (and COF_T, Equation 1) were taken in the afternoon on dry grass surfaces from the service area. Traction was measured in each main plot in August of both years (2017 and 2019) after play was terminated.

2.5 | Cell wall fractions and shoot density

Three 2.25-cm-diam. plugs were taken from each main plot in August of each year (2017, 2018, and 2019). Counts of aerial shoots (tillers) were made and are reported as shoots per square centimeter. Leaf fiber analysis was used to assess the TCW content (entire fibrous portion) and ligno and hemi fractions as described by Goering and Van Soest (1970). The NDF procedure was used to determine the percentage TCW on a dry-weight basis. Lignocellulose content was determined on a dry-weight basis using the ADF method. The difference between the quantity of NDF and ADF served to estimate the percentage hemi fraction (NDF − ADF). Leaf fiber analysis was performed by Cumberland Valley Analytical SVCS. Leaf fiber analysis was measured on leaf tissues (clippings) collected after a mowing event within the service area of each main plot during August of each year (2017, 2018, and 2019). Cell wall fractions measured in 2017 and 2019 were used in this current study to investigate the relationship between cell wall components (TCW, hemi, and ligno) and wear tolerance (percentage grass cover), carrying capacity, and traction. In addition, leaf fiber analysis measured in 2018 and 2019 was used to correlate cell wall components with ball friction and ball bounce (discussed in Ebdon et al., 2020).

2.6 | Statistical analysis

Eight species and associated cultivars were randomized within the three individual grass courts (replicates) and analyzed as randomized complete blocks. The three subsamples that were taken for traction and shoot density on species and cultivar main plots were averaged, and ANOVA was performed on those averages using Minitab. The sum of squares for all reported data including cell wall components, shoot density, baseline grass cover, and baseline carrying capacity were partitioned into single-df, orthogonal contrasts to test for interspecific difference between the combined means of various species.

Seven single-df orthogonal contrasts were computed and are reported in tables as follow: Contrast 1: FF mixture vs. all other species (KB +VB + CL+ CB + PR); Contrast 2: KB + PR vs. all *Agrostis* (BG) species (VB + CL + CB); Contrast 3: between *Agrostis* species (CB vs. VB + CL); Contrast 4: between *Agrostis* species (VB vs. CL); Contrast 5: KB vs. PR; Contrast 6: within KB (Keeneland vs. Rubix); Contrast 7: within PR (Karma vs. Wicked). Results and associated contrasts computed for carrying capacity and grass cover measured at the baseline were analyzed and reported by individual dates and year because of the different hours of play that were observed between playing periods (Table 1). In addition, interactions were detected between year (2017 and 2019) and treatment main effect and associated contrasts for measured response variables. Treatment means were separated using Fishers protected LSD at the .05 level when significant main effect (7 df) for treatment and associated contrasts (1 df) were observed. Correlation coefficients (r values) were computed between various anatomical and morphological characteristics and their relationship with wear tolerance measured as a percentage grass cover and carrying capacity at the baseline. No serious departures from the assumptions of ANOVA were detected in homogeneity of variance or normality.

TABLE 2 Results from ANOVA of wear tolerance measured as percentage[a] green coverage along the tennis court baselines in 2017 and 2019 for eight turfgrass species and cultivars

		Green cover at the baseline							
		2017				2019			
Cultivar and species	**df**	**17 July**	**23 July**	**30 July**	**12 Aug.**	**17 June**	**8 July**	**23 July**	**3 Aug.**
		%							
Keeneland, Kentucky bluegrass (KB)		76.7ab[b]	80.7ab	72.7ab	72.7ab	95.3abc	90.3a	80.7a	57.3a
Rubix, KB		92.3ab	78.3ab	69.3abc	70.3ab	95.0abc	83.7ab	80.7a	61.3a
Villa, velvet bentgrass (VBG)		73.7ab	62.3bc	61.0abc	65.0abc	95.7abc	78.3ab	73.7ab	54.0a
Puritan, colonial bentgrass (CL)		69.0b	58.0bc	44.7bcd	39.3bcd	92.3bc	73.7ab	52.0c	31.3b
007, creeping bentgrass (CB)		68.0b	54.7c	39.0cd	35.3cd	90.3c	65.3b	54.7c	28.3b
Bridgeport II + Barcrown, fine fescue mixture (FF)		32.0c	21.7d	17.3d	10.7d	78.0d	64.3b	59.7bc	39.0b
Karma, perennial ryegrass (PG)		95.0ab	80.7ab	77.7ab	73.7ab	100.0a	90.0a	82.0a	61.0a
Wicked, PG		99.3a	89.7a	84.7a	80.3a	98.3ab	91.3a	87.3a	65.0a
Hours of match play, h		28.9	41.7	55.7	75.7	13.5	46.5	70.8	93.0
		ANOVA							
Source of variation									
Species and cultivars	7	**	***	**	**	***	†	***	***
Orthogonal contrasts[c]									
1. FF vs. all	1	***	***	**	***	***	*	*	*
2. BG vs. KB + PR	1	*	***	**	**	**	**	***	***
3. CB vs other	1	NS‡	NS	NS	NS	NS	NS	NS	*
4. VBG vs. CL	1	NS	NS	NS	NS	NS	NS	**	**
5. KB vs. PR	1	NS	NS	NS	NS	†	NS	NS	NS
6. Among KB	1	NS	NS	NS	NS	NS	NS	NS	NS
7. Among PR	1	NS	NS	NS	NS	NS	NS	NS	NS

[a] Derived using the intersect method by counts of green uninjured grass.
[b] Values followed by a common letter are not statistically different at the $\alpha = .05$ level according to Fishers protected LSD.
[c] Contrasts: (1) fine fescue vs. all other species and cultivars; (2) all bentgrass species vs. the combined mean of Kentucky bluegrass and perennial ryegrass cultivars; (3) creeping bentgrass vs. the combined mean of velvet bentgrass and colonial bentgrass; (4) velvet bentgrass vs. colonial bentgrass; (5) combined mean of Kentucky bluegrass cultivars vs. perennial ryegrass cultivars; (6) contrast comparing between cultivars of Kentucky bluegrass; (7) contrast comparing between cultivars of perennial ryegrass.
*Significant at the .05 probability level. **Significant at the .01 probability level. *** Significant at the .001 probability level. †Significant at the .10 probability level.
‡NS, nonsignificant.

3 | RESULTS AND DISCUSSION

During both years of tennis play, the average hours of play per week, total number of players or participants over the playing season and the average number of players per week were similar (Table 1). The cumulative hours of play and the number of hours of play during the four evaluations periods when percentage green cover was determined at the baselines varied with the year. The cumulative hours of play in 2017 when play was terminated was 75.7 h, whereas in 2019, play was terminated at 93.0 h (Table 1). As such, greater wear injury (less green cover) was observed at termination of the study in 2019 at 93.0 h compared with that observed in 2017 after 75.7 h of match play (Table 2).

3.1 | Wear tolerance under match play

According to preplanned contrast, the FF mixture (Bridgeport II + Barcrown) performed poorly compared with all other species in 2017 and 2019 (Table 2). In 2017 at the termination of the study (75.7 h), percentage green cover averaged only 10.7% for the FF mixture, whereas KB + PR averaged 74.3% green cover. At all evaluation periods and years, BG species (VBG + CL + CB) did not provide as high a level of green cover at the baselines as KB + PR species afforded (Table 2). In 2019 after 70.8 and 93.0 h of play, VBG provided better green cover along the baselines under match play than other BG species (CL and CB) (Table 2). Additionally, VBG provided similar wear tolerance to KB and PR in both 2017 and 2019. Previous studies also demonstrated VBG to have superior wear tolerance to CB under simulated traffic (Cashel, Samaranayake, Lawson, Honig, & Murphy, 2005; Dowgiewicz et al., 2011; Newell, Crossley, Hart-Woods, Richards, & Wood, 1997; Samaranayake, Lawson, & Murphy, 2008).

Kentucky bluegrass and PR were similar in wear tolerance during most evaluation periods, with the exception of 2019 at 13.5 h of play when PR was superior in green cover to KB ($\alpha = .10$ level, Table 2). Among the species evaluated, PR and KB were the best on average in overall wear tolerance under actual match play. Little to no difference in green cover was observed between the different cultivars evaluated within the various KB and PR species.

Minner and Valverde (2005) found that the relative traffic tolerance ranking under simulated traffic of six cool-season grasses was KB = PR > tall fescue = supina bluegrass (*Poa supina* Schrad.) > CB > FF, which was similar to our study under actual match play. Newell and Jones (1995) reported KB and PR cultivars performed best under simulated tennis traffic, whereas BG and FF species performed very poorly. These same authors noted that percentage green cover for Chewing's fescue and strong creeping red fescue declined rapidly under simulated traffic. These results were similar to our results under actual match play when FF green cover declined rapidly to 32% after 28.9 h of play in 2017 (Table 2). In 2017, KB + PR exhibited 2.8 times as much green cover as the FF mixture during the first evaluation period (28.9 h). Newell and Wood (2000) suggested that FF and BG mixtures may be more appropriate for lawn tennis use receiving occasional play, rather than grass courts intended for elite tournament play. The FF mix used in our study is similar to mixtures planted for use on golf greens (Aamlid, Molteberg, Enger, Steensohn, & Susort, 2006). As pointed out by Newell and Jones (1995), practitioners often underestimate the level of wear that tennis courts endure during actual match play.

3.2 | Carrying capacity

The number of hours of play to sustain 90, 80, 70, and 60% grass cover are reported in Table 3 for 2017 and 2019. Results from carrying capacity at the interspecies level (Table 3) are similar to those observed for wear tolerance (Table 2) for various preplanned contrasts. Correlations (*r* values) between carrying capacity to sustain 60% green cover (Table 2) and wear tolerance measured as percentage green cover (Table 3) near termination of the study were .94 ($p \leq .001$, $n = 24$) in 2017 and .74 ($p \leq .001$, $n = 24$) in 2019. More hours of play indicate greater carrying capacity for a species and more sustainable playing surfaces under the uniform maintenance conditions and costs used in this study. As suggested by Gibbs et al. (1993), if play is limited because of a turf's poor carrying capacity, the cost of maintenance can be a disproportionate burden on financial resources.

The FF mixture, for example, was at 60% grass cover after only 16.2 h of match play in 2017, compared with PR + KB, which averaged 70.3 h in 2017. Therefore, KB and PR afforded over four times the carrying capacity in 2017 and more than two times the carrying capacity in 2019 compared with the FF mixture. The FF mixture was inferior to all other species on average according to preplanned contrasts. Similarly, BG species were inferior to the combined mean for KB + PR. Tennis main plots generally exhibited 36% greater carrying capacity near termination of play (60% grass cover) in 2019 (average = 73.7 h) compared with 2017 (average = 54.4 h). This greater carrying capacity observed in 2019 is most likely the result of the almost 60% greater shoot density (Table 4) observed in 2019 (average = 13.9 shoots cm^{-2}) compared with 2017 (average = 8.9 shoots cm^{-2}). Aggressive reseeding in early May of 2018 in order to reestablish baselines and other areas worn from traffic caused by tennis play may have contributed to the higher densities observed in 2019. In addition, the potential for more thatch and mat to develop may have contributed to greater wear tolerance in 2019 compared with 2017.

3.3 | Traction and shoot density

A coefficient of static friction for traction <1 indicates that the horizontal force (N) to start motion (i.e., slip) is less than the normal force (N) on the shoe and suggests that slip is more likely to occur. For example, the weighted shoe fitted with the outsole of the grass court shoe had a COF_T on smooth concrete of only 1.04, whereas dead grass exhibited a traction coefficient of 1.74 (Table 4). Clearly the grass court shoe is more likely to slip on smooth concrete than dead grass because of the near 70% lower COF_T observed for the tennis shoe on smooth concrete compared with dead grass. Similarly, PR in 2017 exhibited a traction coefficient equivalent to dead grass (Table 4). The COF_T was 20% higher in 2019 (average = 2.30) than in 2017 (average = 1.91), which is likely due to the greater shoot densities

TABLE 3 Results from ANOVA of carrying capacity[a] along the tennis court baselines in 2017 and 2019 for eight turfgrass species and cultivars

		Fitted hours of play at the baselines							
		2017				2019			
		Percentage grass cover							
Cultivar and species	df	90%	80%	70%	60%	90%	80%	70%	60%
		h							
Keeneland, Kentucky bluegrass (KB)		12.6d[b]	57.4abc	61.5ab	66.4a	46.8a	65.9a	79.8a	91.9a
Rubix, KB		34.9abc	60.6ab	62.1ab	63.6a	38.2ab	61.6ab	77.7a	91.7a
Villa, velvet bentgrass (VBG)		21.0bcd	24.1bcd	52.9ab	54.1a	43.0a	55.2ab	62.1ab	67.0ab
Puritan, colonial bentgrass (CL)		17.6cd	22.3d	26.9bc	43.4ab	15.8bc	29.8bc	42.7bc	54.9b
007, creeping bentgrass (CB)		15.1cd	23.2bcd	30.7bc	39.9ab	11.6bc	25.0c	38.6bc	53.1b
Bridgeport II + Barcrown, fine fescue mixture (FF)		7.1d	10.4d	13.3c	16.2b	5.9c	15.6c	27.0c	42.2b
Karma, perennial ryegrass (PG)		39.7ab	53.6abc	62.8ab	75.6a	46.1a	68.4a	85.5a	93.0a
Wicked, PG		47.5a	65.1a	75.6a	75.6a	59.7a	80.3a	91.2a	93.0a
		ANOVA							
Source of variation									
Species and cultivars	7	**	*	*	*	**	**	**	**
Orthogonal contrasts[c]									
1. FF vs. all	1	*	*	**	***	**	**	**	**
2. BG vs. KB + PR	1	**	**	*	**	**	**	***	***
3. CB vs other	1	NS[†]	NS	NS	NS	NS	NS	NS	NS
4. VBG vs. CL	1	NS	NS	NS	NS	‡	NS	NS	NS
5. KB vs. PR	1	**	NS	NS	NS	NS	NS	NS	NS
6. Among KB	1	*	NS	NS	NS	NS	NS	NS	NS
7. Among PR	1	NS	NS	NS	NS	NS	NS	NS	NS

[a] Calculated hours as carrying capacity derived using curve fitting to achieve 90, 80, 70, and 60% green cover at the baselines.
[b] Values followed by a common letter are not statistically different at the $\alpha = .05$ level according to Fishers protected LSD.
[c] Contrasts: (1) fine fescue vs. all other species and cultivars; (2) all bentgrass species vs. the combined mean of Kentucky bluegrass and perennial ryegrass cultivars; (3) creeping bentgrass vs. the combined mean of velvet bentgrass and colonial bentgrass; (4) velvet bentgrass vs. colonial bentgrass; (5) combined mean of Kentucky bluegrass cultivars vs. perennial ryegrass cultivars; (6) contrast comparing between cultivars of Kentucky bluegrass; (7) contrast comparing between cultivars of perennial ryegrass.
*Significant at the .05 probability level. **Significant at the .01 probability level. *** Significant at the .001 probability level. †NS, nonsignificant. ‡Significant at the .10 probability level.

observed in 2019 vs. 2017 (Table 4). Traction and associated traction coefficient increased with increasing shoot densities in 2017 and 2019 (Table 5). Canaway (1985) and Bell et al. (1985) reported traction coefficients on PR slightly above or below 1 when maintained under 0 N, and higher traction coefficients >2 were observed when maintained under higher N (200 kg ha^{-1}), which is likely the result of greater verdure with increasing N.

In 2017 and 2019, traction and the associated traffic coefficient of BG was higher than that of PR + KB (Table 4), which is likely due to BG species having greater shoot densities than PR and KB (Table 4). The grip of grass tennis shoes on KB was significantly greater (15% higher, on average) than the grip afforded by the grass court shoe on PR (Table 4). Canaway (1979) reported similar results for grip (traction, N m) with KB, which exhibited greater traction and friction coefficients than PR. Static friction coefficients for traction ranged from 1.2 (11.8 N m) for PR to 1.6 (15.4 N m) for KB (Canaway, 1979). Canaway concluded that PR and FF were most slippery, whereas KB gave the best grip. In this study, it was found that immature turf (new plantings) did not afford the traction of mature turf because of the greater ground cover of mature turf. Interestingly, Canaway (1979) used the outsole of a climbing

TABLE 4 Results from ANOVA of traction and shoot density[a] measured in the service area (nonwear areas). Traction was measured using the Canaway device fitted with grass court shoe outsoles. The coefficients of static friction for traction (COF_T)[b] were derived directly from traction measurements. Means are reported for eight turfgrass species and cultivars evaluated in 2017 and 2019 maintained as tennis courts

Cultivar and species	df	Traction 2017	Traction 2019	COF_T 2017	COF_T 2019	Shoot density 2017	Shoot density 2019
		N m				shoots cm^{-2}	
Keeneland, Kentucky bluegrass (KB)		32.6bc[c]	40.6a	1.96bc	2.43a	3.9c	6.3d
Rubix, KB		33.9ab	38.4bc	2.03ab	2.30bc	4.2c	6.7d
Villa, velvet bentgrass (VBG)		35.0a	40.5a	2.10a	2.43a	21.6a	28.9a
Puritan, colonial bentgrass (CL)		31.6cd	40.7a	1.89cd	2.44a	14.1b	18.3b
007, creeping bentgrass (CB)		32.8bc	39.9ab	1.97bc	2.39ab	13.6b	17.8b
Bridgeport II + Barcrown, fine fescue mixture (FF)		30.1de	37.8c	1.80de	2.27c	5.2c	10.3c
Karma, perennial ryegrass (PG)		29.4de	34.4d	1.76de	2.06d	4.2c	11.5c
Wicked, PG		29.1e	34.4d	1.74e	2.06d	4.0c	11.0c
Dead grass (± SE)		–	29.1 ± 0.6	–	1.74 ± 0.03	–	–
Smooth concrete (± SE)		–	17.3 ± 0.3	–	1.04 ± 0.01	–	–
		ANOVA					
Source of variation							
Species and cultivars	7	***	***	***	***	***	***
Orthogonal contrasts[d]							
1. FF vs. all	1	*	NS†	*	NS	***	***
2. BG vs. KB + PR	1	**	***	**	***	***	***
3. CB vs other	1	NS	NS	NS	NS	***	***
4. VBG vs. CL	1	**	NS	**	NS	***	***
5. KB vs. PR	1	***	***	***	***	NS	***
6. Among KB	1	NS	*	NS	*	NS	NS
7. Among PR	1	NS	NS	NS	NS	NS	NS

[a] Traction and shoot density were measured in mid-August of each year.
[b] Static COF of the shoe-to-surface is calculated directly from traction measurements where N m is adjusted to account for different weights placed on the devices' shoes (Canaway used 45 kg, current study used 34 kg) and to adjust for different devices' shoe surface areas in contact with the interacting surface.
[c] Values followed by a common letter are not statistically different at the $\alpha = .05$ level according to Fishers protected LSD.
[d] Contrasts: (1) fine fescue vs. all other species and cultivars; (2) all bentgrass species vs. the combined mean of Kentucky bluegrass and perennial ryegrass cultivars; (3) creeping bentgrass vs. the combined mean of velvet bentgrass and colonial bentgrass; (4) velvet bentgrass vs. colonial bentgrass; (5) combined mean of Kentucky bluegrass cultivars vs. perennial ryegrass cultivars; (6) contrast comparing between cultivars of Kentucky bluegrass; (7) contrast comparing between cultivars of perennial ryegrass.
*Significant at the .05 probability level. **Significant at the .01 probability level. *** Significant at the .001 probability level. †NS, nonsignificant.

TABLE 5 Correlation (*r*) values between traction, wear tolerance measured at the tennis court baselines as percentage green cover at termination of the study, and carrying capacity (hours of play) to achieve 60% green cover, shoot density, and cell wall components (percentage dry matter) including total cell wall content (TCW), hemicellulose (hemi), and lignocellulose (ligno) measured on various grass surfaces in 2017 and 2019 ($n = 24$)

Response variable	Green cover 2017	Green cover 2019	Carrying capacity 2017	Carrying capacity 2019	Traction 2017	Traction 2019
TCW	.643***	.049	.498*	−.215	.301	−.069
Hemi	.492*	.092	.366†	.066	.361†	.078
Ligno	.319	−.046	.281	−.317	−.132	−.064
Shoot density	−.204	−.287	−.257	−.401*	.470*	.385†

*Significant at the .05 probability level. *** Significant at the .001 probability level. †Significant at the .10 probability level.

TABLE 6 Results from ANOVA of cell wall components including total cell wall content (TCW), hemicellulose (hemi), and lignocellulose (ligno) fractions measured in eight turfgrass species and cultivars maintained as tennis courts

Cultivar and species	df	Percentage dry matter								
		2017			2018			2019		
		TCW	Hemi	Ligno	TCW	Hemi	Ligno	TCW	Hemi	Ligno
		%								
Keeneland, Kentucky bluegrass (KB)		58.3a[a]	36.7ab	21.6a	55.1b	32.0b	23.1b	51.7	30.9c	20.8bcd
Rubix, KB		58.7a	37.2a	21.5a	55.1b	34.3ab	20.8c	52.9	32.1bc	20.8bcd
Villa, velvet bentgrass (VBG)		57.0ab	37.5a	19.4b	57.6ab	37.3a	20.3c	55.5	35.5a	20.0cd
Puritan, colonial bentgrass (CL)		51.8d	33.9b	18.0c	56.1b	35.4ab	20.7c	54.5	34.0ab	20.4bcd
007, creeping bentgrass (CB)		53.5cd	35.6a	18.0c	55.4b	35.1ab	20.2c	52.8	32.9bc	19.9d
Bridgeport II + Barcrown, fine fescue mixture (FF)		48.6e	27.4c	21.2a	60.7a	31.4b	29.3a	55.2	28.9d	26.3a
Karma, perennial ryegrass (PG)		54.6bc	33.7b	20.9a	57.3ab	34.3ab	23.0b	53.9	32.5bc	21.3bc
Wicked, PG		55.6bc	34.1b	21.5a	58.0ab	35.6ab	22.4bc	53.4	31.9bc	21.5b
		ANOVA								
Source of variation										
Species and cultivars	7	***	***	***	NS[†]	NS	***	NS	**	***
Orthogonal contrasts[b]										
1. FF vs. all	1	***	***	*	**	*	***	NS	***	***
2. BG vs. KB + PR	1	***	NS	***	NS	NS	**	NS	**	**
3. CB vs other	1	NS	NS	NS	NS	NS	NS	NS	‡	NS
4. VBG vs. CL	1	***	*	*	NS	NS	NS	NS	NS	NS
5. KB vs. PR	1	**	*	NS	‡	NS	NS	NS	NS	NS
6. Among KB	1	NS	NS	NS	NS	NS	*	NS	NS	NS
7. Among PR	1	NS	NS	NS	NS	NS	NS	NS	NS	NS

[a] Values followed by a common letter are not statistically different at the $\alpha = .05$ level according to Fishers protected LSD.
[b] Contrasts: (1) fine fescue vs. all other species and cultivars; (2) all bentgrass species vs. the combined mean of Kentucky bluegrass and perennial ryegrass cultivars; (3) creeping bentgrass vs. the combined mean of velvet bentgrass and colonial bentgrass; (4) velvet bentgrass vs. colonial bentgrass; (5) combined mean of Kentucky bluegrass cultivars vs. perennial ryegrass cultivars; (6) contrast comparing between cultivars of Kentucky bluegrass; (7) contrast comparing between cultivars of perennial ryegrass.
*Significant at the .05 probability level. **Significant at the .01 probability level. *** Significant at the .001 probability level. †NS, nonsignificant. ‡Significant at the .10 probability level.

boot weighted with 45 kg, whereas in the current study, the outsole of the grass tennis shoe was used, and it was only weighted with 34 kg. Resistance to sliding (traction) between the shoe and surface increases with the weight (normal load) on the shoe and the contact area and varies with the configuration pattern of the shoe outsole (van Gheluwe et al., 1983). Traction (N m) adjusted for weight (45 vs. 34 kg) using Equation 1 indicated the Canaway climbing boot COF_T averaged 1.42, whereas the tennis shoe outsole COF_T averaged 1.91 (2017) and 2.30 (2019) (Table 4).

The grass court outsole provided 35–62% greater traction than the climbing boot. With the exception of the Wimbledon Championship and all professional grass court tournaments played on grass in the United Kingdom, grass court tennis shoes are generally banned from recreational tennis in the United States (Mike Buras, Director of Grounds at Longwood Cricket Club personal communication, 2018) because of the additional wear caused by aggressive (pimpled) shoes (Hall, Gibbs, Munro, Hannan, & McAuliffe, 2001; Nikolai, Karcher, & Sorochan, 2005). Equation 1 can correct for weight on the shoe and for surface area but does not adjust for the shoe configuration or outsole pattern. It should be noted that the climbing boot outsole is not an appropriate shoe for measuring traction in tennis. Alternatively, the outsole of the grass court shoe may overestimate the wear injury and traction compared with flat-soled tennis shoes on grass (as per the majority of subjects in this study).

Although KB and PR were similar in their wear tolerance (Table 2) and carrying capacity (Table 3), the greater grip of the grass court shoe when tennis is played on KB is one advantage of planting KB over PR. Perennial ryegrass cultivars in our study provided nearly two times the shoot density of KB in 2019, but this greater PR shoot density did not promote greater traction or grip. Aboveground plant material does not necessarily improve surface traction (Rogers & Waddington, 1989). Traction is a function of soil type, soil density, grass root density, soil moisture content, and shoe-to-surface interaction (influenced by the choice of stud pattern) (Stiles, Guisaola, James, & Dixon, 2011). For example, bermudagrass offers greater shoe-to-surface traction than PR (Orchard, 2001; Richardson et al., 2019). Like bermudagrass, KB exhibits a spreading type growth habit due to the horizontal growth habit of rhizomes, which increases traction compared with nonspreading PR.

3.4 | Cell wall components

Total cell wall content (TCW) was correlated with green cover at the baselines and carrying capacity to sustain 60% grass cover in 2017 (Table 5). Greater TCW provided better wear tolerance and carrying capacity. No significant correlation was observed in 2019. In most years and for most cell wall fractions (ligno and hemi) significant differences were observed except for TCW measured in 2019 (Table 6). Differences in cell wall components for the contrast comparing BG vs. KB + PR were observed at five different times across the 3 yr (2017, 2018, and 2019) of evaluation and indicated that BG species generally exhibited lower cell wall fractions than KB and PR, with the exception of hemi fractions in 2019. These results correlate with the superior wear tolerance (Table 2) and carrying capacity (Table 3) observed with KB and PR compared with BG species.

Greater levels of TCW, ligno, and hemi measured on a dry mass basis have been associated with the greater wear tolerance of VBG compared with CB (Dowgiewicz et al., 2011). Although differences among bentgrass species were observed in cell wall components in 2017, these BG species were not different in wear tolerance (Table 2) and carrying capacity (Table 3). As such, no association between wear tolerance and carrying capacity with cell wall fractions was observed among BG species in the current study. Canaway (1981) found leaf fiber analysis to be an unreliable predictor of wear tolerance because the relationship reported in the literature fluctuated between positive and negative correlation. Additionally, there are numerous factors that can influence leaf fiber content such as age of the tissue, stem vs. leaf tissue, leaf blade vs. sheath, and growing season (Shearman & Beard, 1975b). Therefore, leaf fiber analysis and interpretation of the data can be highly variable.

4 | CONCLUSIONS

Actual tennis play indicated that KB and PR were observed to exhibit superior wear tolerance and carrying capacity to other C_3 turfgrasses. These two species afforded as much as four times the carrying capacity of FF species and nearly 60% more carrying capacity than BG species. Velvet bentgrass was as good as KB and PR in overall wear tolerance and carrying capacity. Traction measurements were superior with KB compared with PR. Results also indicated that BG species afforded higher shoot density and better traction than KB + PR, with VBG exhibiting the best traction and FF and PR the poorest traction. In some years greater cell wall content was associated with better wear tolerance and carrying capacity. Wear tolerance and carrying capacity were highly correlated. As such, along with appropriate species and cultivar selection, maintenance practices associated with improved wear tolerance will promote greater carrying capacity. Future research should evaluate traction coefficients comparing different shoe outsoles (flat vs. pimpled outsoles) on C_3 species and cultivars.

ACKNOWLEDGMENTS

Special thanks to the New England Regional Turfgrass Foundation for funding this research. We also acknowledge the technical support of Mike Buras and his crew at Longwood Cricket Club.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest.

ORCID

J. S. Ebdon https://orcid.org/0000-0002-2611-4693

REFERENCES

Aamlid, T. S., Molteberg, B., Enger, F., Steensohn, A. A., & Susort, A. (2006). Evaluation of *Agrostis* and *Festuca* varieties for use on Scandinavian golf greens. *Bioforsk Reports*, *1*, 1–35.

Aldahir, P. C. F., & McElroy, J. S. (2014). A review of sport turf research techniques related to playability and safety standards. *Agronomy Journal*, *106*, 1297–1308. https://doi.org/10.2134/agronj13.0489

Allen, R. G., Pereira, L. S., Raes, D., & Smith, M. (1998). *Crop evapotranspiration: Guidelines for computing water requirements*. Rome: FAO.

Bell, M. J., Baker, S. W., & Canaway, P. M. (1985). Playing quality of sports surfaces: A review. *Journal of the Sports Turf Research Institute*, *61*, 26–45.

Bourgoin, B., & Mansat, P. (1981). Artificial trampling and players traffic on turfgrass cultivars. In R. W. Sheard (Ed.) *Proceedings of the 4th International Turfgrass Research Conference* (pp. 55–63). Guelph, ON, Canada: International Turfgrass Society, Ontario Agricultural College and the University of Guelph.

Canaway, P. M. (1975). Fundamental techniques in the study of turfgrass wear: An advance report on research. *Journal of the Sports Turf Research Institute*, *51*, 104–115.

Canaway, P. M. (1976). A differential slip wear machine (D.S.1.) for the artificial simulation of turfgrass wear. *Journal of the Sports Turf Research Institute*, *52*, 82–99.

Canaway, P. M. (1979). Studies on turfgrass abrasion. *Journal of the Sports Turf Research Institute*, *55*, 107–120.

Canaway, P. M. (1981). Wear tolerance of turfgrass species. *Journal of the Sports Turf Research Institute*, *57*, 65–83.

Canaway, P. M. (1985). The response of renovated turf of *Lolium perenne* (perennial ryegrass) to fertilizer nitrogen III. Ball bounce resilience and traction. *Journal of the Sports Turf Research Institute*, *61*, 104–110.

Canaway, P. M., & Bell, M. J. (1986). Technical note: An apparatus for measuring traction and friction on natural and artificial playing surfaces. *Journal of the Sports Turf Research Institute*, *62*, 211–214.

Carrow, R. N., Duncan, R. R., Worley, E., & Shearman, R. C. (2001). Turfgrass traffic (soil compaction plus wear) simulator: Response of *Paspalum vaginatum* and *Cynodon* spp. *International Turfgrass Society Research Journal*, *9*, 253–258.

Carrow, R. N., & Petrovic, A. M. (1992). Effects of traffic on turfgrass. In D. V. Waddington, R. N. Carrow, & R. C. Shearman (Eds.), *Turfgrass* (Vol. 32, pp. 285–330). Madison, WI: ASA, CSSA, and SSSA. https://doi.org/10.2134/agronmonogr32.c9

Cashel, R. H., Samaranayake, H., Lawson, T. J., Honig, J. A., & Murphy, J. A. (2005). Traffic tolerance of bentgrass cultivars grown on a sand-based rootzone. *International Turfgrass Society Research Journal*, *10*, 531–537.

Cockerham, S. T., & Brinkman, D. J. (1989). A simulator for cleated-shoe sports traffic on turfgrass research plots. *California Turfgrass Culture*, *39*, 9–10.

Dowgiewicz, J., Ebdon, J. S., DaCosta, M., & Dest, W. M. (2011). Wear tolerance mechanisms in *Agrostis* species and cultivars. *Crop Science*, *51*, 1232–1243. https://doi.org/10.2135/cropsci2010.07.0395

Ebdon, J. S., James, I., DaCosta, M., & Lu, J. (2020). Interspecific comparisons of C_3 turfgrass for tennis use: II. Investigation of ball friction, ball bounce, and associated factors in replicated grass courts. *Crop Science*. https://doi.org/10.1002/csc2.20277

Evans, G. E. (1988). Tolerance of selected bluegrass and fescue taxa to simulated human foot traffic. *Journal of Environmental Horticulture*, *6*, 10–14. https://doi.org/10.24266/0738-2898-6.1.10

Fleming, P., Young, C., & Carré, M. (2015). Mechanical testing and characterisation of sports surfaces. In S. Dixon, P. Fleming, I. James, & M. Carré (Eds.), *The science and engineering of sports surfaces* (pp. 26–69). New York: Routledge.

Gibbs, R. J., Adams, W. A., & Baker, S. W. (1993). Playing quality, performance, and cost-effectiveness of soccer pitches in the UK. *International Turfgrass Society Research Journal*, *7*, 212–221.

Goering, H. K., & Van Soest, P. J. (1970). *Forage fiber analysis (apparatus, reagents, procedures, and some applications)*. Washington, DC: U.S. Government Printing Office.

Hall, E. J. G., Gibbs, R. J., Munro, P. R., Hannan, B. K., & McAuliffe, K. W. (2001). Evaluation of golf footwear for New Zealand golf course conditions. *International Turfgrass Society Research Journal*, *9*, 875–881.

Henderson, J. J., Lanovaz, J. L., Rogers, J. N., III, Sorochan, J. C., & Vanini, J. T. (2005). A new apparatus to simulate athletic field traffic: The Cady Traffic Simulator. *Agronomy Journal*, *97*, 1153–1157. https://doi.org/10.2134/agronj2004.0083

Holmes, G., & Bell, M. J. (1986). Technical note: Playing surface hardness and tennis rebound resilience. *Journal of the Sports Turf Research Institute*, *62*, 207–210.

ITF. (2019). *Approved tennis balls, classified surfaces and recognised courts 2018: A guide to products and test methods*. International Tennis Federation. Retrieved from www.itftennis.com/technical/home.aspex

James, I. (2015). Surface classification, function, construction and maintenance. In S. Dixon, P. Fleming, I. James, & M. Carré (Eds.), *The science and engineering of sports surfaces* (pp. 9–25). New York: Routledge.

Minner, D. (1999). How much is too much… Round II. *SportsTURF*, *15*(1), 46.

Minner, D. D., & Valverde, F. J. (2005). Performance of established cool-season grass species under simulated traffic. *International Turfgrass Society Research Journal*, *10*, 393–397.

Murphy, J. A., & Ebdon, J. S. (2013). Study and management of turfgrass traffic stress. In J. C. Stier, B. P. Horgan, & S. A. Bonos (Eds.), *Turfgrass: Biology, use, and management* (pp. 1029–1074). Madison, WI: ASA, CSSA, and SSSA. https://doi.org/10.2134/agronmonogr56.c27

Newell, A. J., Crossley, F. M. E., Hart-Woods, J. C., Richards, C. E., & Wood, A. D. (1997). *STRI report to turfgrass breeders 1997*. Bingley, UK: Sports Turf Research Institute.

Newell, A. J., Crossley, F. E. M., & Jones, A. C. (1996). Selection of grass species, cultivars, and mixture for lawn tennis. *Journal of the Sports Turf Research Institute*, *72*, 42–60.

Newell, A. J., & Jones, A. C. (1995). Comparison of grass species and cultivars for use in lawn tennis courts. *Journal of the Sports Turf Research Institute*, *71*, 99–106.

Newell, A. J., & Wood, A. D. (2000). Selection of grass species, cultivars and mixtures for lawn tennis. *Journal of Turfgrass Science*, *76*, 53–65.

Nikolai, T. A., Karcher, D. E., & Sorochan, J. C. (2005). Professional golfers conclude that spike design affects putting green quality. *Applied Turfgrass Science*, *3*(1). https://doi.org/10.1094/ATS-2006-1127-01-BR

Puhalla, J. C., Krans, J. V., & Goatley, J. M. (1999). *Sports fields: Design, construction and maintenance* (2nd ed.). Hoboken, NJ: John Wiley & Sons.

Poro, J., Ebdon, J. S., Dacosta, M., & Brown, P. W. (2017). Effects of mowing height and nitrogen on FAO-56 PM crop coefficients for recreational turf in the cool-humid region. *Crop Science*, *57*, 119–129. https://doi.org/10.2135/cropsci2016.05.0363

Orchard, J. (2001). The AFL penetrometer study: Work in progress. *Journal of Science and Medicine in Sports*, *4*, 220–232. https://doi.org/10.1016/S1440-2440(01)80032-3

Richardson, M. D., Mattina, G., Sarno, M., McCalla, J. H., Karcher, D. E., Thoms, A. W., … Sorochan, J. C. (2019). Shade effects on overseeded bermudagrass athletic fields: II. Rooting, species composition, and traction. *Crop Science*, *59*, 2856–2865. https://doi.org/10.2135/cropsci2019.05.0311

Rogers, J. N. III, & Waddington, D. V. (1989). The effect of cutting height and verdure on impact absorption and traction characteristics in tall fescue turf. *Journal of the Sports Turf Research Institute*, *65*, 80–90.

Samaranayake, H., Lawson, T. J., & Murphy, J. A. (2008). Traffic stress effects on bentgrass putting green and fairway turf. *Crop Science*, *48*, 1193–1202. https://doi.org/10.2135/cropsci2006.09.0613

Shearman, R. C., & Beard, J. B. (1975a). Turfgrass wear mechanisms: I. Wear tolerance of seven turfgrass species and quantitative methods for determining wear injury. *Agronomy Journal*, *67*, 208–211. https://doi.org/10.2134/agronj1975.00021962006700020009x

Shearman, R. C., & Beard, J. B. (1975b). Turfgrass wear mechanisms: II. Effects of cell constituents on turfgrass wear tolerance. *Agronomy Journal*, *67*, 211–215. https://doi.org/10.2134/agronj1975.00021962006700020010x

Shearman, R. C., & Beard, J. B. (1975c). Turfgrass wear mechanisms: III. Physiological, morphological, and anatomical characteristics associated with turfgrass wear tolerance. *Agronomy Journal*, *67*, 215–218. https://doi.org/10.2134/agronj1975.00021962006700020011x

Shearman, R. C., Carrow, R. N., Wit, L. A., Duncan, R. R., Trenholm, L. E., & Worley, J. E. (2001). Turfgrass traffic simulators: A description of two self-propelled devices simulating wear and compaction stress injury. *International Turfgrass Society Research Journal*, *9*, 347–352.

Stiles, V. H., Guisaola, I. N., James, I. T., & Dixon, S. J. (2011). Biomechanical response to changes in natural turf during running and turning. *Journal of Applied Biomechanics*, *27*, 54–63. https://doi.org/10.1123/jab.27.1.54

Thorpe, J. D., & Canaway, P. M. (1986). The performance of tennis court surfaces I. General principles and test methods. *Journal of the Sports Turf Research Institute*, *62*, 92–100.

TIA. (2019). *Tennis industry association: National database court report*. Tennis Industry Association. Retrieved from https://www.tennisindustry.org/page/research_general

Trenholm, L. E., Carrow, R. N., & Duncan, R. R. (2000). Mechanisms of wear tolerance in seashore paspalum and bermudagrass. *Crop Science*, *40*, 1350–1357. https://doi.org/10.2135/cropsci2000.4051350x

van Gheluwe, B., Deporte, E., & Hebbelink, M. (1983). Frictional forces and torques of soccer shoes on artificial turf. In B. M. Nigg & B. A. Kerr (Eds.), *Proceedings of the international symposium on biomechanical aspects of sport shoes and playing surfaces*. Calgary, AB, Canada: University of Calgary.

Youngner, V. B. (1961). Accelerated wear tests on turfgrasses. *Agronomy Journal*, *53*, 217–218. https://doi.org/10.2134/agronj1961.00021962005300040003x

How to cite this article: Ebdon JS, James I, DaCosta M, Lu J. Interspecific comparisons of C_3 turfgrass for tennis use: I. Wear tolerance and carrying capacity under actual match play. *Crop Science*. 2021;61:750–762. https://doi.org/10.1002/csc2.20270