SIMULATING AND ASSESSING THE EFFECTS OF TRAFFIC ASSOCIATED WITH MODERN GOLF FOOTWEAR ON PUTTING SURFACE PERFORMANCE

A Thesis

Presented to the Faculty of the Graduate School

of Cornell University

In Partial Fulfillment of the Requirements for the Degree of

Master of Science

by

Alec Hunter Moore

December 2018

ABSTRACT

Concentrated foot traffic is a significant source of stress for natural turfgrass systems. Downward foot pressure can increase soil bulk density and reduce turfgrass shoot density. Golf putting surface traffic has attempted to be simulated using specialized equipment or with humans moving in a linear walking path or side-stepping. These methods often disregard the unique movement associated with actual traffic patterns, especially localized around the hole location. Concern regarding traffic stress associated with specific golf footwear has increased due to dramatic design changes made to increase traction and stability during a golf swing. An unintended consequence of increasing golf footwear traction and stability has been a perceived increase in foot traffic stress and disruption of playing conditions on putting surfaces. Studies were conducted in 2016 and 2017 to develop a standard method of applying a known volume of foot traffic associated with playing golf and utilize this method to assess performance of two golf playing surfaces. To achieve a rapid, uniform, quantifiable rate of traffic a walking pattern designed to impose concentrated foot traffic at known rates and volumes was investigated during the 2016 and 2017 growing seasons. Data collected on key surface performance parameters at the hole location indicated differences between playing surface types. Golf footwear traffic resulted in a significant increase in clipping yield independent of playing surface type. Putting surface performance declined proportionally with traffic volume as a result of reductions in fractional green canopy cover, ball roll distance, and visual turf quality.

BIOGRAPHICAL SKETCH

Alec Moore completed his AS in 2014 at Corning Community College majoring in Liberal Arts and Sciences and a Bachelor of Technology at the State University of New York at Cobleskill in May 2016 majoring in Plant Sciences. Alec grew up working in Horticulture, specifically Orchard Management where he was mentored by Rick Reisinger who helped build a foundation in plant health management. Alec did his internship at The Los Angeles Country Club in 2016, joined the Turfgrass Program at Cornell University as a summer intern in 2015 and now as an MS candidate.

ACKNOWLEDGMENTS

I would like to thank everyone that has helped me throughout completing my master's thesis. First, I would like to express my thanks to the financial support provided through a Cornell University teaching assistantship that supported my education and FootJoy (Acushnet Holdings Corp.) that provided operating funds to conduct this research.

I would next like to thank Professor Frank Rossi for his guidance and knowledge making me a better scientist and turf manager. I would also like to recognize members of my program, staff of the Robert Trent Jones golf course at Cornell University, and other volunteers without whom the research could not have been completed. I would like to extend my gratitude to the Cornell University Statistical Consulting Unit for being an asset in data analysis.

I would especially like to thank my parents. My mother and father (Shari and Dennis) have always supported me, pushing me to be the best I can be, instilling in me a strong work ethic, and providing me endless opportunities to grow and do what I love; without them this would not have been possible.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

Ball Roll Distance, BRD; Brinkman Traffic Simulator, BTS; Cady Traffic Simulator, CTS; Centimeter, cm; Days After Traffic, DAT; Days Before Traffic, DBT; grams dry weight, gDw; Eighteen-hole equivalent, EHE; Fractional Green Canopy Cover, FGCC; Grams per Cubic Centimeter, g/cc; Hectare, ha^{-1}; Height of Cut, HOC; Kilogram, Kg; Kilopascal, kPa; Liter, L; Meter, m; Millimeter, mm; National Turfgrass Evaluation Program, NTEP; Ounce; oz; Putting Surface Performance, PSP; Sand Amended Native Soil, SANS; Sand Amended Native Soil Predominantly Annual bluegrass, SANSPAB; Sand Based, SB; Sand Based Predominantly Creeping bentgrass, SBPCB

LITERATURE REVIEW

Mechanical Traffic Simulations

Devices used in traffic simulations have varied widely from modified greens mowers, power brooms, rollers, and core cultivation units. The Brinkman Traffic Simulator (BTS) is a towed unit utilizing connected studded drums that spin differentially, providing wear realistic to that of a football game (Vanini et al., 2007). The Cady Traffic Simulator (CTS) is a modified core cultivation unit where each head unit is outfitted with a rubber foot fixed with spikes. The feet alternately impact the ground during operation creating three directional dynamic forces. The BTS and CTS apply identical traffic rates, but the CTS produces greater reaction forces causing greater damage (Henderson et al., 2005). A modified power sweeper outfitted with rubber paddles has been used to simulate wear stress without the added soil compaction of other devices (Bonos et al., 2001)

Putting surface trafficking machines apply uniform replicable traffic but do not provide effective simulation of rotational forces from turning (Green et al., 2013; Samaranayake et al., 2008). These mechanical devices have been widely used in studying turf establishment, wear tolerance/ response, and impact on soil physical properties. Capturing the finer impacts of golfer traffic on putting surface performance can’t be accurately identified by these mechanical simulators. The turning, focused foot pressure, known rate of traffic and the increased traffic density at the hole location are not captured.

Human Participants Simulating Traffic

Studies employing human subjects wearing golf shoes to apply traffic are improvements over mechanically imposed traffic but still lack a known and repeatable traffic rate (Ferguson, 1958; Hamilton et al., 1999). Gibeault et al. (1983) did accurately simulate traffic by having golfers walk and putt in plots but has concerns with application repeatability and applying a known rate of play.

Golf participation measured as the average rate of rounds in the U.S. was 92 rounds per eighteen-hole equivalent per day (Pellucid & Edgehill, 2017). The number of rounds a golf course receives is an important determinant on the wear occurring throughout the day on a putting surface. More importantly knowing the rate of applied traffic during footwear testing is key accurately simulating golf course conditions. For this reason, quantifying the round rate in a research setting is crucial. Previous studies have not quantified traffic in units of rounds, instead stating traffic in terms of pattern traverses (Ferguson, 1958) or by time trafficking (Young et al., 2010). Therefore, these studies do not accurately reflect realistic and relatable golf course round velocities.

To more realistically simulate golfer traffic, Nikolai and Hathaway (2005) observed golfers during several rounds and counted number of steps per round of golf in a known area. This work provided researchers with a method to precisely apply traffic to research plots and emphasized the importance of a pin rotation on managing traffic.

Preliminary observations at Cornell University (unpublished field data, 2016) indicate biometric variability of the human subjects applying traffic, i.e. body type, shoe size, weight, and walking mechanics vary among individuals and can affect the impact they have on a putting surface. For example, individuals golf swings generate different amounts of torque at the shoe ground interface (Worsfold et al., 2008); indicating variability among humans.

Few studies have attempted to account for the inherent biometric variability of human participants. Ferguson (1958) rotated participants, Nikolai (2003) had all participants with size 11 shoe traffic in each footwear type. Hamilton et al. (1999) used participants of similar biometric measures (height, weight and shoe size). However, the lack of uniform biometric reporting in studies limits repeatability in a variety of climates, with different surfaces.

Traffic Effects on Putting Surface Performance

Putting surface firmness is an important performance characteristic as it influences the bounce and roll when a ball strikes the surface. Firm surfaces require more skill from players to hit more lofted shots. In comparison, soft greens reward poorly executed shots and eliminate the need for strategic play, making play easier (Whitlark & Pringle, 2012).

Studies have considered impacts of traffic on firmness measuring soil physical properties such as bulk density. Roberts et al. (2013) developed a method that simulated 50 rounds of golf through foot traffic and measured soil bulk density with a portable surface moisture-density gauge. They measured significant increases in bulk density in the second and third weeks of traffic. Samaranayake et al. (2008) measured soil bulk density of plots receiving mechanical traffic and compaction treatments concluding that bulk density was numerically higher (not significant) compared to the control (no traffic/ compaction) plots.

BRD measures the distance a ball rolls on a putting surface when released from a standard position with uniform energy in a lateral motion. BRD is traditionally measured with a Stimpmeter, where typical BRD range from 2.1m – 3.7m depending on the golf course (Happ, 2003). However, it has been reported that golfers do not easily identify BRD, especially differences less than 15.2 cm, and are satisfied with a wide range BRD if the greens are uniform and consistent (Karcher et al., 2001).

Traffic studies measuring BRD have shown conflicting results on the influence of traffic on BRD. Hamilton et al. (1999) studied golf shoe tread type effects on ball roll and concluded that golf footwear did significantly reduce BRD. Morrow and Dannenberger (1995) concluded that golf footwear traffic caused increased BRD over non-trafficked plots, stating the traffic provided the turf a “light rolling”.

Increasing attention is being paid to measuring surface smoothness and trueness of roll. There is some evidence to suggest surface smoothness may be as critical as ball roll distance in determining the outcome of a well struck putt. The Sports Turf Research Institute trueness meter, ParryMeter, and Sphero turf research software devices are attempting to quantify surface smoothness and trueness digitally measuring lateral [x-axis] and vertical [z-axis] movement.

Previous research has developed simpler methods for measuring surface trueness and smoothness. Recently, surface trueness was measured over a variety of disrupted surfaces using the hole out test, concluding that despite appearance of a surface when struck on the proper line and speed putts will still be holed (Linde et al., 2017). Hamilton et al. (1997) measured change in ball roll dispersion before and after traffic applications. Results revealed differences in ball roll deflection caused by different traffic intensities.

Visual quality of putting surfaces is the aggregate of subjective measures of color, texture, density, and uniformity (Emmons & Rossi, 2016). Color is the amount of green light reflected by the turf, in which darker green turf is favorable. Density is the number of shoots per area, where high shoot density is considered favorable. Texture is a measure of leaf blade width, generally finer-textured leaves are preferable to coarse-textured (wider blade). Uniformity is a subjective aggregate measure of the previously discussed parameters.

Many golf footwear studies have focused on assessing the impacts on turf quality, specifically rating damage and/or wear tolerance of the turf. Nikolai (2003) had PGA pros rate plots for damage level caused by various spike and outsole combinations, concluding this influence's the amount of turf damage produced. Gibeault et al. (1983) and Roberts et al. (2013) among other studies have rated turf quality and/or turf wear caused by foot traffic.

Putting surfaces must tolerate regular and often very focused foot traffic imposed by golfers, caddies, and maintenance activities. Traffic tolerance is related to turf density, growth habit, and firmness. A firm dense turf often withstands significant amounts of foot traffic with minimal surface disruption. However, studies have shown that high rates of golf traffic or aggressive maintenance practices can significantly alter surface performance.

Putting surface performance is an aggregate measure of traffic tolerance, BRD, surface trueness, and firmness that are influenced by rounds velocity, climate, plant species, soil physical properties and surface preparation. Assuming the economic goal is to maximize play, climate and plant species are fixed and soils can be modified overtime but are mostly fixed. Therefore, only daily surface preparation is under the complete control of the course management staff.

Modern putting surfaces grow in sand dominated rootzones designed to be firm and permeable to maximize drainage and provide stable footing. Early 1900's putting surfaces were constructed from native soils with higher percentages of fine soil particles and prone to compaction (Hummel, 1993). Consequently, the USGA developed putting green specification's in 1960 and revised in 1995 (Moore, 2005). Additionally, existing native soil rootzones were improved with frequent sand topdressing and cultivation (Hurdzan, 2004).

Hamilton et al. (1997) measured the impact of golf shoes on turf wear, ball roll, and ball roll deflection on a sand based rootzone and a modified soil rootzone. Turf wear measured qualitatively on a scale (0-5) was dependent on rootzone composition. However, there was no significant difference in ball roll deflection among the different rootzones.

The turf species on a putting surface will influence putting surface performance. Species with more upright growth like annual bluegrass (*Poa annua reptans*) and newer creeping bentgrass (*Agrostis* stolonifera) varieties offer the ability for closer mowing (Happ, 2003). Studies have shown that at several mowing heights creeping bentgrass maintains consistently longer ball roll distances over annual bluegrass but creeping bentgrass turf quality declines more quickly (Lulis & Kaminski, 2016).

Researchers have identified differences in wear tolerance among different species and cultivars. Laskowski et al. (2014) assessed impact of traffic on creeping bentgrass and annual bluegrass physiological response and visual quality. Under simulated traffic stress creeping bentgrass had better turf quality than annual bluegrass maintained at multiple soil moisture levels.

Putting surfaces are closely mown daily between 2 mm – 4 mm to reduce surface friction and maximize ball roll distance (White, 2011). Closely mown turf at 2 mm or less creates significant turf stress that often leads to thinning (Smith, 2016). Lulis and Kaminski (2016) reported that as height of cut went down ball roll distance went up, but turf quality declined. Therefore, it is not uncommon for putting surfaces to be regularly stressed from low mowing.

As the demand for faster putting surfaces has risen, rolling has gained popularity since the 1990's (Nikolai, 2002). Ball roll distance increases 10 - 15 percent immediately after rolling (Hartwiger, 1996). Richards et al. (2008) concluded that rolling could reduce turf stress by raising mowing heights or decreasing mowing frequency, maintaining acceptable BRD.

The practices of mowing and rolling need to be applied carefully as when combined with foot traffic can negatively impact putting surface quality. Young et al. (2010) found that under foot traffic stress lower mowing heights and higher rolling frequency lead to reductions in turf quality.

Most studies of putting surface performance have concluded that weather imposes great influence. Fluctuations in soil/air temperature, relative humidity, wind, soil moisture and precipitation impact daily putting surface performance and turf growth. Hot and humid conditions can result in reduced green speed; while dry and windy conditions can increase green speed (Oatis, 2016). Similarly, wet weather (increased soil moisture) will soften greens decreasing firmness, reducing BRD (Oatis, 1990). It is important that putting surfaces be frequently monitored for moisture and selectively hand watered to maintain consistent quality conditions (Winter, 2002).

Gibeault et al. (1983) considered the effects of surface/soil moisture effects on traffic damage by heavily watering plots prior to trafficking, demonstrating increased moisture caused increased traffic damage. Clearly temperature and moisture extremes will exacerbate damage from footwear traffic, however little research has correlated these factors.

INTRODUCTION

Human and vehicular traffic on a golf or sports playing surface creates turf wear stress. Wear stress to a natural turfgrass system is defined as the *immediate* damage to tissue through tearing, abrasion, shear, or pressure caused by repeated concentrated traffic, twisting, turning, and slippage (Carrow, 1995). Methods have been developed to simulate traffic stress on golf and sports turf. Accurate simulation of traffic must provide wear analogous to normal wear, apply traffic in a uniform and repeatable manner, and the magnitude of the simulated traffic must be greater than the normal rate of traffic to minimize required traverses of the simulation (Younger, 1961). Therefore, assessing the specific impact of modern golf footwear on playing surface performance will require a rapid, effective and realistic method for simulating wear stress. The current methodology used in turfgrass research imposes wear stress however little evidence exists of the realistic traffic required to assess surface performance. An improved method would apply traffic over time at a known and realistic rate, imposing the twisting and slippage concentrated in the area around the hole location followed by rapid assessment for immediate visual and functional performance.

Mechanical simulators like the BTS and the CTS have been used to apply traffic to sports turf. The equipment was designed to simulate traffic from a single American Football match in the concentrated surface areas down the center line between the hash marks (Vanini et al., 2007). Other mechanical methods of foot traffic using rollers, studded rollers and modified power brooms are useful for studying soil characteristics, turfgrass species and cultivar assessments but not for determining subtle impacts of the human surface interaction (Bonos et al., 2001; Canaway, 1975; Shearman et al., 2001). The PENNFOOT device was designed to evaluate the human foot and playing surface interaction by measuring lateral and rotational traction (McNitt & Waddington, 1997).

The simulation of golf vehicular and human-imposed traffic has been performed successfully for general turfgrass wear stress and soil physical properties (Samaranayake et al., 2008; Cattani & Clark, 1991). Mechanical units, modified pedestrian putting surface mowers, and human linear walking methods have been used to simulate general wear stress on golf playing surfaces (Green et al., 2013). These methods focus generally on wear, not subtleties of human-imposed traffic and have not addressed comprehensive assessment of playing surface performance.

Human-imposed methods have been used to simulate and assess golf footwear traffic using straight line walking or in small plots taking one or two steps (Nikolai & Karcher, 2006; Roberts et al., 2013). However, these simulations lack the twisting, turning, and slippage of traffic around a measurable playing area at the hole location. This area is exposed to unique wear stress associated with modern golf footwear, playing surface management and modern performance expectations.

The game of golf and associated playing equipment has evolved since the 1400’s with specialized footwear beginning in the 1850’s by advising novice golfers to wear shoes “roughed with small nails or sprigs” for traction (Farnie, 1857). Modern golf footwear is engineered for visual (comfort and style) and functional performance, i.e. for traction designed to increase player swing speed. Increasing or alteration of traction elements has been reported to impact the visual quality (Nikolai, 2003) and performance of the putting surfaces (Gibeault et al., 1983).

The average golfer takes 48 percent of all strokes on the putting surface in a regulation round of golf (MYGOLFSPY, 2016). Putting surfaces account for 3.4 percent of the managed land of a typical EHE golf course yet consume the highest rate of maintenance inputs per unit land area (GCSAA, 2017). Golf turf maintenance standards have increased at playing establishments that value functional performance while maintaining high visual quality (White, 2011). Consequently, any perceptible alteration of the immediate area around the hole location could significantly influence putting surface performance.

An improved method of simulating and assessing the influence of turfgrass wear stress from human-imposed golf footwear traffic on measurable visual and functional putting surface performance would be uniform, reproducible, and accurately represent realistic known rates of play.

The objective of this study is to simulate and assess known rates and volumes of foot traffic with modern golf footwear at the hole location. Assessments conducted on different putting surface types include influence on playing surface performance using aggregate measures of surface performance (firmness, turfgrass density, ball roll distance, and visual turfgrass quality).

MATERIALS AND METHODS

Human-imposed golf footwear-traffic studies were conducted for seven-day periods from June to October 2017 on two cool-season turfgrass putting surface types found in Ithaca, NY, USA (42°27'34" N, 76°27'38" W). The 2017 growing season was mild with adequate moisture until late summer and especially into autumn. Very little heat stress was experienced during the season until above average warm temperatures and humidity during studies conducted in late September and early October. Throughout the season temperatures were similar to the 30-year average temperatures while October temperatures were 4°C above average (Table 1). Overall, precipitation was below the 30-year average for July, August, and September; while July and October were above average precipitation (Table 2).

Table 1. 2017 temperature compared to average temperature from 1981-2010. Information provided by the Northeast Regional Climate Center.

Month	Actual Temperature	Average temperature	Difference
	————	°C	————
June	18	18	0
July	20	21	-1
August	19	20	-1
September	16	16	0
October †	15	11	4

† only includes the 1st – 16th

Table 2. 2017 precipitation compared to average precipitation from 1981-2010. Information provided by the Northeast Regional Climate Center.

Month	Actual Precipitation	Average precipitation	Precipitation departure
	————	mm ————	%
June	3.1	3.4	-8
July	5.4	3.1	26
August	2.1	3.0	-30
September	1.9	3.1	-40
October †	3.1	2.8	91

† only includes the 1st – 16th

Experimental Putting Surfaces

An engineered sand-based putting surface rootzone (SB) and an engineered sand amended native soil rootzone (SANS) were assessed for physical properties (Table 3 & 4). Initial annual bluegrass population levels were determined using total plant counts in gridded digital images by using the digital grid overlay method (Booth et al., 2006). The initial annual bluegrass population in the SB rootzone was approximately three percent and is 97 percent creeping bentgrass (planted to A1/A4 in 2012) (SBPCB). The initial annual bluegrass population of the SANS putting surface is approximately 60 percent in a polystand with 40 percent of several creeping bentgrass varieties (SANSPAB). The SANSPAB was established in 1996 using aeration plugs on a uniform native soil rootzone, where the 0-3 cm depth is defined as sand and from 3-12 cm is a sandy loam soil. SANSPAB and SBPCB have a similar rootzone makeup to a 3 cm depth and both have infiltration rates that meet USGA standards from 0-7.5 cm.

Table 3. Putting surface rootzone particle size and shape analysis. Measurements taken in 3 cm increments. Testing conducted by Turf and Soil Diagnostics.

Putting surface	Sample depth	Particle size			Sieve size/ sand particle diameter (mm)							Uniformity Coefficient	Organic Matter Dry Wt.
		Sand	Silt	Clay	No. 5 Grave l 4.0	No. 10 Gravel 2.0	No. 18 Very Coarse 1.0	No. 35 Coarse 0.50	No. 60 Medium 0.25	No. 100 Fine 0.15	No. 270 Very Fine 0.05		
	Cm	%										Cu	%
Sand based	0-3	92.3	5.7	1.8	0	0.2	1.4	16.7	51.5	17.4	5.4	3.5	4.51
	3-6	87.7	8.5	3.3	0.2	0.2	7.5	21.5	36	14.6	7.7	16.9	1.87
	6-9	89.9	7	2.8	0.1	0.2	13.7	25.5	31	12.4	7.4	9.3	0.8
	9-12	91.7	6	1.9	0	0.4	10.5	23.5	32.2	15.5	9.9	9.3	0.46
Sand amended native soil	0-3	92.5	6.6	< 1.0	0	0.2	1.8	21.6	51.4	13.3	4.2	3.4	5.05
	3-6	73.9	18.2	7.3	0	0.6	2.8	17.9	35.3	11.9	5.9	110	2.32
	6-9	63.4	22.6	9.1	1.9	3	6.2	14.6	27.3	9.4	5.9	151	2.27
	9-12	55.2	27.2	10.3	3.1	4.3	6.2	12	22.3	8.4	6.2	163	2.37
USGA Recommendations		≥ 92	≤ 5	≤ 3	≤ 3 gravel, ≤ 10 combined			≥ 60 combined		≤ 20	≤ 5	2.0 – 3.5	< 4†

† recommended < 4% at a 5.7 - 7.6 cm depth (Moeller and Lowe, 2016)

Table 4. Putting surface root zone physical properties. Measurements taken in 7.5 cm increments. Testing conducted by Turf and Soil Diagnostics.

Putting surface	Sample depth	Infiltration Rate	Bulk Density	Total Pore Space
	cm	cm/hr.	g/cc	%
Sand based	0-7.5	20.8	1.6	41.6
	7.5-15	28.2	1.7	38.8
	15-22.5	42.7	1.6	39.8
Sand amended native soil	0-7.5	16.8	1.5	44.9
	7.5-15	3.0	1.6	41.4
	15-22.5	3.0	1.6	41.4
USGA Recommendations		≥ 15.3	1.2-1.6	35- 55

Putting Surface Management

Both putting surfaces were managed to provide what can be described casually as "firm and fast" tournament ready conditions. Measurement parameters for tournament-ready conditions are, minimum 3.2 m BRD, exceptional (>7 NTEP scale) visual turfgrass quality and close to maximum turfgrass density using digital imagery, is free of obvious abiotic and biotic stress. Data were collected on these parameters for two days prior to commencing assessment. Plots receive no other traffic prior to assessment beyond required maintenance.

Golf course design and maintenance are critical to sustainable high-quality playing surfaces. Modern golf turf maintenance practices have the capacity to significantly constrain classic course design that maintained BRD less than 183 cm (Beard & Beard, 2005; Stimpson, 1935). Therefore, providing tournament-ready conditions is readily achievable for today's average golf course with slight modifications of the target values.

Nitrogen and potassium are managed in a 1.5:1 ratio from water soluble sources; urea, ammonium sulfate and sulfate of potash (Table 5). In July 2017 SBPCB fertilization with ammonium sulfate continued but the SANSPAB surfaces were switched over to urea nitrogen source. Iron is applied in a six percent liquid iron (iron glucoheptonate chelate) (Plant Food Company, Inc.; Cranbury, NJ)

Table 5. Total fertilizer applied to putting surfaces in 2017

Putting Surface	Nitrogen	Potassium	Iron
	kg ha^{-1}		
SBPCB	199	147	15
SANSPAB	221	153	15
Median use †	152	142	N/A

† Median use per hectare on putting surfaces in the Northeast United States (GCSAA et al., 2015)

Both surfaces were maintained to tournament-ready standards, this included daily mowing at 3.05 mm bench-set HOC and daily rolling that applies 28.9kPa of ground pressure based on surface area calculations (Salsco Inc., 2018). Sand meeting USGA specifications (Table 6) was applied to a depth of 2.3 mm in April and five more times from May to October 2017 at 1.5 mm depth.

Table 6. Putting surface silica sand topdressing particle size and shape analysis. Testing conducted by Turf and Soil Diagnostics.

	Particle size										Uniformity Coefficient
				Sieve size/ sand particle diameter							
	Sand	Silt	Clay	No. 5 Gravel 4.0	No. 10 Gravel 2.0	No. 18 Very Coarse 1.0	No. 35 Coarse 0.50	No. 60 Medium 0.25	No. 100 Fine 0.15	No. 270 Very Fine 0.05	
	%										Cu
Sureplay Topdressing 310	99.8	<1.0	<1.0	0	0	0.1	13.2	73.9	11.6	1	1.8
USGA Recommendations	≥ 92	≤ 5	≤ 3	≤ 3 Gravel, ≤ 10 Combined			≥ 60 combined		≤ 20	≤ 5	2.0 - 3.5

Zeta-Cypermethrin ((*S*)-α-cyano-3-phenoxybenzyl (1*RS*,3*RS*;1*RS*,3*SR*)-3-(2,2-dichlorovinyl)-2,2-dimethylcyclopropanecarboxylate), bifenthrin (cyclopropanecarboxylic acid, 3-[(IZ)-2-chloro-3,3,3-trifluoro-1-propenyl]-2,2-dimethyl-,(2-methyl[1,1'biphenyl]-3-yl)methyl ester), imidacloprid (1-(2-Chloro-pyridinylmethyl-5-yl)-2-nitroamino-imidazoline) (FMC Corporation, Philadelphia, PA) were applied on a curative basis for ants (*Lasius spp.*) at 1.9 L/ha^{-1}. A preventative disease control program was implemented during the study periods and curative between trafficking events. Specifically, chlorothalonil (2,4,5,6-tetrachloroisophthalonitrile) (Primera Inc., Cleveland Heights, Ohio) at 12.1 L/ha^{-1} and a combination fungicide azoxystrobin (Methyl (2*E*)-2-(2-{[6-(2-cyanophenoxy)pyrimidin-4-yl]oxy}phenyl)-3-methoxyacrylate) and propiconazole (1-[[2-(2,4-dichlorophenyl)-4-propyl-1,3-dioxolan-2-yl]methyl]-1,2,4-triazole) (Syngenta, Greensboro, NC) at 6.4 L/ha with aluminum tris (0-ehtyl phosphonate) (Bayer CropScience, Greensboro, NC) at 12.7 L/ha^{-1}.

Water management is a significant aspect of playing surface performance and hence why the rootzones are sand dominated. An unpublished study conducted on the sand-based rootzone experimental area suggested the use of wetting agents for prevention of hydrophobic conditions that can emerge during periods of dry weather. A monthly application of a modified alkylated polyol wetting agent (Aquatrols, Paulsboro, NJ) was applied at 19.1 L/ha^{-1}. Soil moisture driven site-specific hand-watering occurred to prevent surface hydrophobicity. Irrigation was applied to remove dew from plants prior to mowing during September and October.

Human-imposed Traffic

The design objectives of the method were that it be realistic, rapid, repeatable, and uniform traffic resulting in a measurable putting surface performance response. Additionally, the use of human subjects has inherent variability that must be addressed. In fact, several initial golf footwear assessments conducted prior to the project (data not shown) suggested a strong human influence on putting surface performance.

Individual experimental units were established at 3.05 m by 3.05 m to rapidly traffic an area suitable for measuring putting surface performance at rates calculated from actual observations of modern play (Hathaway & Nikolai, 2005). This system also allows subjects reasonable time commitments from participants to simulate wear and reduces time to immediately assess surface performance.

Actual daily play rates of 140 rounds per day were imposed by humans on a 1.17 m^2 area around the hole location per day. Currently the average play rate or round velocity is approximately 100 rounds per day per EHE (Pellucid, 2016) with exceptional traffic events occurring on weekends, holidays or special events.

Video analysis of walking patterns of each human subject insured integrity of treatments through coaching and timing. Ultimately it was confirmed that human subjects must apply 800 steps in a 9.3 m^2 area to apply 140 rounds in a 1.17 m^2 circle around the hole location. Again, visual confirmation of these walking patterns (Figure 1) was conducted on a variety of walking surfaces (cement and close-cut turf) (Figure 2).

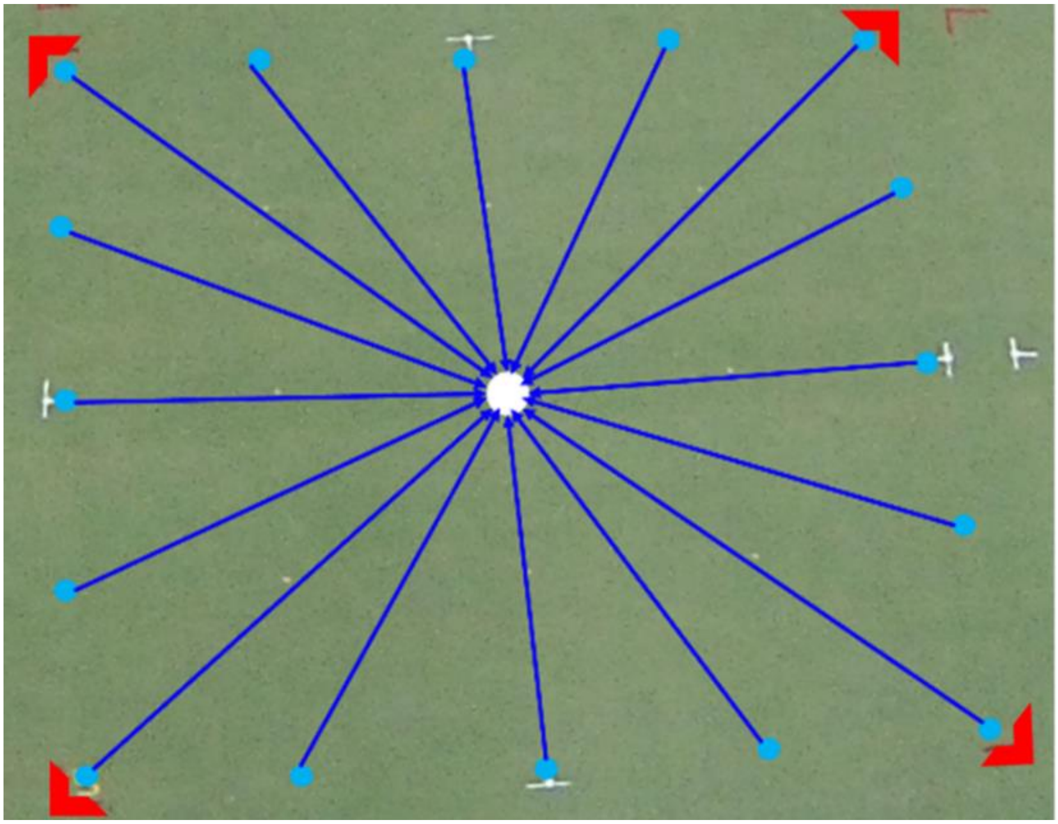

Figure 1. Trafficking pattern around central hole location. Participants walk to and from the hole location moving from one-point perimeter location to the next.

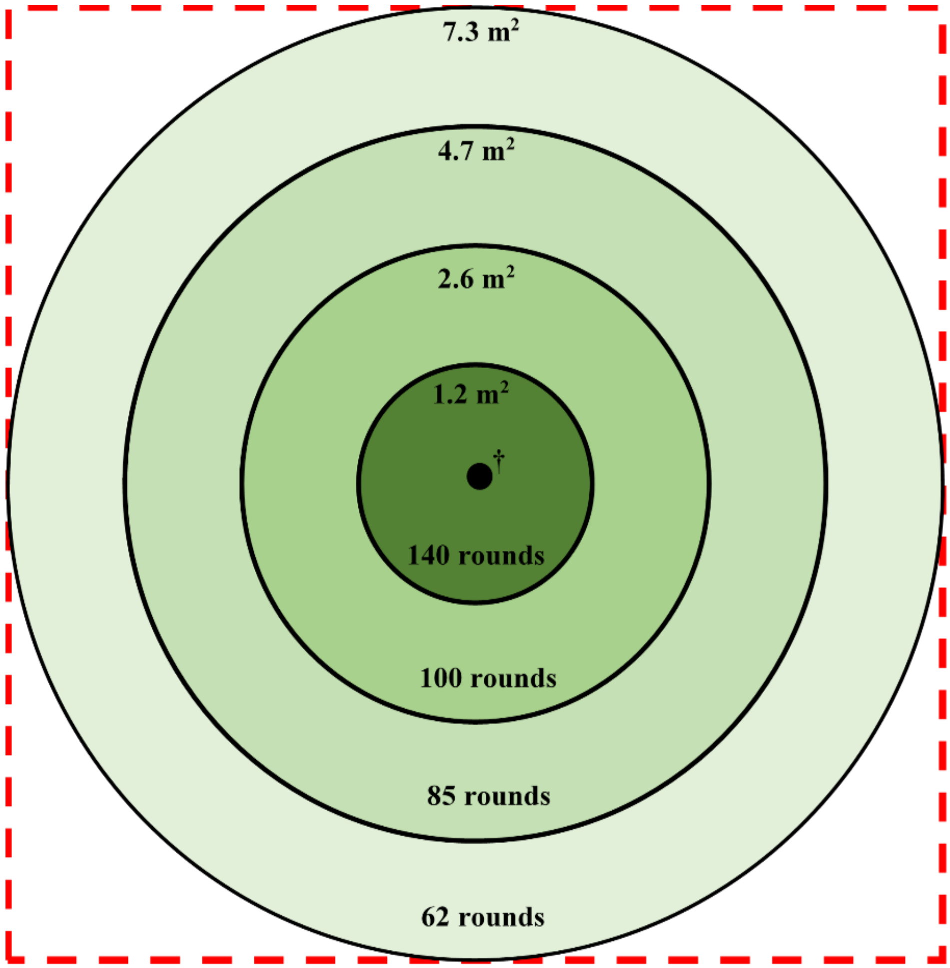

Figure 2. Simulated round volume per day at varying distance from the hole location based on measured rates in a typical round of golf. Dotted line represents the plot perimeter. Shaded rings represent measured areas around the hole location, denoted with the number of rounds within measured area.

† hole location at center of the plot

Assessing finer impacts of specific golf footwear designs on putting surface performance proved challenging. Human participants have inherent biometric differences that could bias the response data and/or if properly controlled could indicate potential shoe design or maintenance practice adjustments required. Significant differences between humans was observed in preliminary footwear studies with six participants fitted with the same design. Putting surface performance response was significantly altered by human participant (data not shown). Specific golf footwear traffic was rotated daily to minimize this influence and data reported here are for investigating golf traffic not specifically for footwear design assessment.

Trafficking Method

Traffic treatments for each seven-day experiment took 30 minutes to apply, starting between 0715 and 0800 immediately after maintenance practices were performed. Traffic simulated 140 rounds at the hole location per day for a total of 980 rounds at the hole location per experimental unit per experiment.

Putting Surface Performance Measurements

Playing surface performance factors for tournament-ready conditions are minimum 3.2 m BRD, exceptional (>7 NTEP scale) visual turfgrass quality and close to maximum turfgrass density using digital imagery, is free of obvious abiotic and biotic stress. Additional measures could be established for firmness and smoothness. Firmness and soil moisture data are monitored as well during the experiment. Data are collected on these parameters for two days prior to commencing assessment. Plots receive no other traffic prior to and during assessments beyond maintenance needs and data collection. During experiments data were collected within 45 minutes following traffic treatments.

Average daily percent volumetric water content was calculated from three measurements on each experimental unit at two depths (3.8 cm and 7.6 cm) using Spectrum Technologies Field Scout Time Domain Reflectometry 300 calibrated for sand and probe lengths, this measures the reflection of electromagnetic pulse to determine volumetric water content (Reeves and Smith, 1992)

Surface firmness is a measure of the resistance of the putting surface to an incoming shot measured in rate of deceleration of a moving body and resulting in a calculated penetration value, a unitless measure (Brame, 2008). The Tru-firm developed by the United States Golf Association measures putting surface firmness as it relates to turf penetration depth following weighted missile release. Average surface firmness was calculated from three daily measures on each experimental unit.

BRD is the distance a golf ball rolls when released from an inclined plane (Richards et al., 2009). Daily ball roll measures were collected across the diagonal of the plot through the most heavily trafficked area using the Pelz meter. The Pelz meter reduces influence of some confounding effects associated with the use of the traditional stimpmeter, such as providing a consistent release point and the ability to level the device before releasing balls. A reduction in BRD of less than 15.2 cm is considered undetectable by golfers (Karcher et al., 2001).

FGCC image analysis is used to assess precise alteration of the playing surface in the area with the highest traffic rate. Images are taken using a Canon PowerShot SX110 digital camera (9.0 mega pixels) under a $0.31m^2$ light box to eliminate natural light and ensure consistent light. Batch analysis of images is conducted in MATLAB using Canopeo to calculate FGCC. This application more effectively and rapidly identifies the pixel ratios when compared to SigmaScan and SamplePoint (Patrignani & Ochsner, 2015). These data are collected for the duration of traffic treatments and for 14 days following traffic completion, monitoring progression of turf damage and recovery.

Daily visual turfgrass quality ratings were collected in a 3.05 m diameter around the hole location as a subjective aggregate measure of color, density, and uniformity following traffic applications. Visual quality ratings use the NTEP rating guidelines (Morris & Shearman, 2011). Plots are rated on a 1-9 scale, using quarter increments, based on 9 being best and a rating greater than 6 is considered acceptable.

Daily clipping yields were collected during each experiment for seven days prior to traffic, during traffic treatments, and for seven days after traffic. Clippings were harvested in a single pass down the center line of each unit after dew removal. Clippings from each unit were brushed into paper bags, dried in an oven at 60°C for three days, cleaned of sand, and weighed.

Study Design and Statistical Analysis

Experimental units within experimental runs were completely randomized including non-trafficked control plots. Multiple experiments were conducted on each putting surface type during the season. Data from these runs were assessed for influence of putting surface and run, then data pooled to explore golf footwear traffic independent of footwear design, human participants, and under seasonal growing conditions in the Northeastern United States.

Data were analyzed using JMP pro 13 from SAS (SAS Institute Inc., Cary, NC). A mixed model (fixed and random effects) was used to analyze differences in traffic and non-traffic treatments, and differences between SBPCB and SANSPAB surfaces at the 0.05 probability level. Data used in assessing differences in putting surface types were normalized to non-traffic treatments before analysis. Significance testing was conducted using the student's t Test post HOC analysis at the 0.05 probability level. Data collected prior to assessment commencement were included in the model as a co-variate for each experimental unit to account for unit to unit variability before treatment application.

RESULTS AND DISCUSSION

Traffic Assessment

Visual assessment of wear from the designed traffic pattern revealed a gradient of stress. As distance from hole location increased wear stress decreased (Figure 3). The wear stress caused by this pattern simulates high intensity traffic at the hole location, decreasing in intensity as distance from the hole location increases. This method improves upon methods that did not employ turning or increased traffic at the hole location (Roberts et al., 2013; Hamilton et al, 1999). The measurable rounds velocity and associated known step counts are repeatable and allows for rapid adjustment of desired rounds rate, where other research has relied on time trafficking or traverses of a pattern to quantify the traffic rate (Ferguson, 1958; Young et al., 2010).

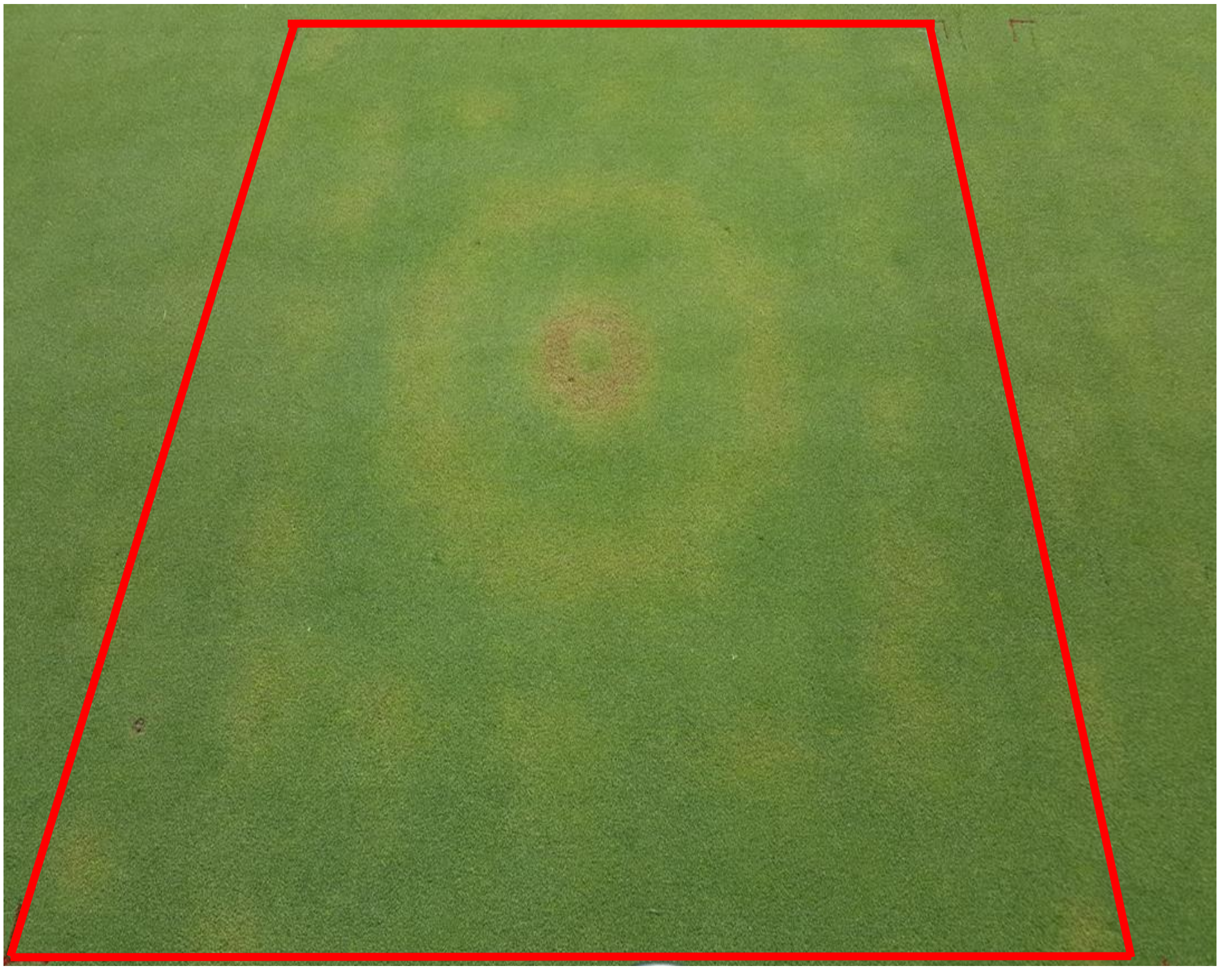

Figure 3. Damage caused to putting surface by traffic pattern after 980 rounds of golf. The center and most damage part of the traffic area is where the rate 140 rounds of traffic occurs daily.

Human participants trained and coached in the Moore method during preliminary studies were able to maintain a natural, comfortable pace when imposing traffic. One random check on step numbers performed live during experiments monitored departure from the original calibration. Overall separation from desired steps was less than five percent error on average for eight of ten participants (data not shown). An accurate and replicable application of golfer traffic was achieved but any gap in desired and actual steps applied need to be diminished to further increase precision.

Consistent human-imposed traffic with modern footwear designs at known rates and volumes over time led to significant declines in visual quality. The immediate collection of functional data associated with PSP assessment method were also significantly altered by traffic. Generally, across both putting surface types significant reductions in PSP were observed. Traffic did not cause significant differences among 3.8 cm volumetric soil moisture or surface firmness after 140 rounds (Table 7 & 8)

Table 7. Influence of traffic on 3.8 cm volumetric soil moisture

Rounds at hole location	Traffic †	Non-traffic ‡
	——%——	
140	20	20
280	19	19
420	15	15
560	18	18
700	23	22
840	22	22
980	22	22

† n = 144 at each rounds volume
‡ n = 24 at each rounds volume

Table 8. Influence of traffic on putting surface firmness

Rounds at hole location	Traffic †	Non-traffic ‡	
	——unitless——		
140	0.38	0.40	*
280	0.38	0.38	
420	0.37	0.37	
560	0.38	0.39	
700	0.41	0.40	
840	0.40	0.40	
980	0.40	0.40	

*Significant at the 0.05 probability level
† n = 144 at each rounds volume, except n= 143 at 700 rounds
‡ n = 24 at each rounds volume, except n= 23 at 700 rounds

Overall, BRD measured across the hole location was significantly reduced (Table 9). A reduction in BRD greater than 15 cm is noticeable by golfers (Karcher et al., 2001). BRD was significantly reduced greater than 15 cm at all rates and volumes of traffic. Interestingly, BRD did not gradually decline but declined immediately after 140 rounds and remained consistent through 980 rounds. The decline in BRD observed in the current study is consistent with Hamilton et al. (1999) and in contrast to Morrow and Dannenberger (1995) who reported increased ball roll distance in trafficked areas. However, in both studies traffic rate and volume was not reported.

Table 9. Influence of traffic on ball roll distance

Rounds at hole location	Traffic †	Non-traffic ‡	Reduction in BRD§	
	———	cm	———	
140	304	329	25	*
280	300	328	27	*
420	298	325	27	*
560	294	325	31	*
700	290	319	29	*
840	291	318	27	*
980	289	319	30	*

*Significant at the 0.05 probability level
† n = 144 at each rounds volume, except n= 143 at 700 and 980 rounds
‡ n = 24 at each rounds volume
§ reductions in BRD > 15.2cm are noticeable by golfers

FGCC is a quantitative measure of green canopy cover designed was utilized to quantify damage from traffic stress. FGCC at the hole location declined 11 percent following 980 rounds of traffic, however a significant difference between treatments was not evident until 840 rounds were applied demonstrating the value of testing known round rates and volumes (Table 10). Ferguson (1958) quantified surface density using the double quadrat method and found a decline in surface density over time however, traffic volumes were not reported.

Table 10. Influence of traffic on Fractional Green Canopy Cover

Rounds at hole location	Traffic †	Non-traffic ‡	
	——————%—————		
140	87.0	86.6	
280	88.1	87.8	
420	84.1	87.7	
560	81.9	85.4	
700	80.6	87.2	*
840	80.4	88.2	*
980	79.5	90.9	*
2 DAT §	73.8	89.8	*
3 DAT	75.0	88.8	*
4 DAT	75.0	90.0	*
5 DAT	78.9	93.1	*
6 DAT	82.0	93.9	*
7 DAT	83.7	93.9	*
8 DAT	88.6	96.8	*
9 DAT	89.9	97.1	*
10 DAT	89.5	95.7	*
11 DAT	85.0	94.1	*
12 DAT	86.9	94.3	*
13 DAT	87.5	95.0	*
14 DAT	87.6	94.4	*

*Significant at the 0.05 probability level

† n = 144 at each rounds volume

‡ n = 24 at each rounds volume

§ DAT- days after traffic

Visual turfgrass quality ratings decline with increasing round velocity, however, were never rated un-acceptable (Table 11). Significant reductions in turfgrass visual quality were observed associated with golfer traffic, though the traffic rate did not reduce visual quality below an acceptable level. Roberts et al. (2013) reported similar findings when applying human traffic equivalent to 1,015 rounds per week. Visual quality is a combined rating of turf quality and traffic damage, measured in quarter increments on a one to nine scale. These should have been rated as separate measures of visual turf quality and turf damage, measured in whole numbers on a one to nine scale.

Table 11. Influence of traffic on visual turf quality

Rounds at hole location	Traffic †	Non-traffic ‡	
140	6.9	7.1	*
280	6.9	7.1	*
420	6.8	7.1	*
560	6.6	7.0	*
700	6.6	7.1	*
840	6.4	7.1	*
980	6.4	7.3	*

*Significant at the 0.05 probability level
† n = 144 at each rounds volume
‡ n = 24 at each rounds volume

Clipping yield increased on trafficked turf (Table 12). Trafficked plots produced greater clipping yield immediately upon commencement of traffic and persisted significantly greater than non-trafficked plots through 700 rounds and numerically greater through 980 rounds. Theoretically increased clipping yield in response to traffic suggests a growth response to stress or a physical disruption of the canopy from golf footwear.

Table 12. Influence of traffic on clipping yield

Rounds at hole location	Traffic †	Non-traffic ‡	
	———gDw———		
1 DBT §	1.3	1.3	
140	2.0	1.7	*
280	1.4	1.1	*
420	1.8	1.6	*
560	2.6	2.2	*
700	1.9	1.7	*
840	1.7	1.4	
980	3.0	2.8	
1 DAT ¶	2.4	2.3	
2 DAT	2.0	2.1	
3 DAT	1.2	1.2	
4 DAT	2.4	2.5	
5 DAT	1.6	1.8	
6 DAT	1.8	1.9	

*Significant at the 0.05 probability level
† n = 72 at each rounds volume
‡ n = 12 at each rounds volume
§ Days before traffic
¶ Days after traffic

Figure 4 is the standing up of turf on the surface associated with traffic, causing scalping following mowing (Figure 5). Clipping yields were similar between the surface types though alteration of SANSPAB surfaces did not appear as severe as SBPCB surface, indicating a potential growth response associated with traffic.

Figure 4. Disrupted turf on SBPCB putting surface as a result of traffic pictured through a prism gauge. Showing turf plants stood up to 22mm height, HOC is 3.05mm

Figure 5. Scalping effect of mowing stood up turf on SBPCB. Left image shows trafficked turf before mowing and the right image is the scalping of turf following mowing

Many of the responses observed in this research were consistent with previous studies investigating the influence of traffic stress on golf playing surface performance. However, the Moore method characterizes playing surface performance as influenced by known rates and volumes of traffic associated with modern golf footwear. Furthermore, the walking pattern utilized in the Moore method offers traffic rate gradients in the 3 m diameter across the hole location consistent with established traffic rates (Hathaway & Nikolai, 2005).

Traffic Effect on Playing Surface

The Moore method was utilized to assess differences in playing surface performance as influenced by putting surface type. Results of this assessment indicates significant differences based on putting surface as determined by rootzone and predominate surface vegetation. Soil moisture and surface firmness measurements were not different between the two putting surface types suggesting no difference in surface response (Appendix A & B).

In general, the SBPCB surface experienced greater decline than the SANSPAB surface as measured by BRD, FGCC, and visual turf quality (Tables 13, 14, & 15).

Table 13. Influence of traffic on the reduction of ball roll distance between two putting surfaces

Rounds at hole location	SBPCB †	SANSPAB ‡	
	———% §———		
140	8	6	
280	8	7	
420	10	5	*
560	12	6	*
700	12	5	*
840	8	7	
980	11	8	*

*Significant at the 0.05 probability level
† n = 72 at each rounds volume
‡ n = 72 at each rounds volume
§ percentage reduction from non-trafficked treatment

Table 14. Influence of traffic on the reduction of visual turf quality between two putting surfaces

Rounds at hole location	SBPCB †	SANSPAB ‡	
	———% §———		
140	4	2	
280	5	2	*
420	7	4	*
560	8	4	*
700	9	5	*
840	11	7	*
980	15	9	*

*Significant at the 0.05 probability level
† n = 72 at each rounds volume
‡ n = 72 at each rounds volume
§ percent reduction from non-trafficked treatment

Table 15. Influence of traffic on the reduction of Fractional Green Canopy Cover between two putting surfaces

Rounds at hole location	SBPCB †	SANSPAB ‡	
	———% §———		
140	1	-5	
280	1	-5	
420	6	0	
560	7	0	
700	11	2	
840	14	3	*
980	18	5	*
2 DAT ¶	26	10	*
3 DAT	24	8	*
4 DAT	24	9	*
5 DAT	22	7	*
6 DAT	17	7	
7 DAT	16	4	*
8 DAT	13	2	*
9 DAT	11	2	
10 DAT	10	1	
11 DAT	15	3	*
12 DAT	12	1	*
13 DAT	11	2	
14 DAT	11	2	

*Significant at the 0.05 probability level
† n = 72 at each rounds volume
‡ n = 72 at each rounds volume
§ percent reduction from non-trafficked treatment
¶ Days after traffic

Specifically; BRD, FGCC, and visual turf quality declined to a greater extent on SBPCB, however significant differences in FGCC were not evident until 840 rounds. In contrast Laskowski et al. (2014) concluded that creeping bentgrass maintained higher visual quality ratings than annual bluegrass. However, traffic rates were reported as “low and moderate” using a traffic simulator not human imposed traffic. The lack of quantifiable traffic rates and volumes in Laskowski et al. (2014) could explain this inconsistency. Interestingly, putting surface types evaluated using the Moore method did not show differences under lower volumes of traffic.

This study demonstrates the value of applying a rapid, uniform, quantifiable rate of traffic for assessing playing surface performance as influenced by traffic associated with modern golf footwear. Additionally, this method distinguished between playing surface performance on putting surface types. Clipping yield response to traffic warrants additional study to more fully explore canopy alteration and growth response.

REFERENCES

Beard, J. B., & Beard, H. J. (2005). Turfgrass Culture Evolution at the St. Andrews Golf Links. *International Turfgrass Society*, *10*, 70–79.

Bonos, S. A., Watkins, E., Honig, J. A., Sosa, M., Molnar, T., Murphy, J. A., & Meyer, W. A. (2001). BREEDING COOL-SEASON TURFGRASSES FOR WEAR TOLERANCE USING A WEAR SIMULATOR. *International Turfgrass Society*, *9*, 137–145.

Brame, B. (2008). Affirming Firmness. *USGA Green Section Record*, (March-April), 17–20.

Canaway, P. M. (1975). *A Differential Slip Wear Machine (D.S.I) For The Artificial Simulation of Turfgrass Wear*.

Carrow, R. N. (1995, September). Wear stress on turfgrass: This common malady comes with the territory on golf courses because of the significant impact of foot and vehicular traffic. *Golf Course Management*, *63*(9), 49–53. Retrieved from http://tic.lib.msu.edu/tgif/flink?recno=35130

Cattani, D. J., & Clark, K. W. (1991). Influence of wear-stress on turfgrass growth components and visual density ratings. *Canadian Journal of Plant Science*, *71*(1), 305–308. Retrieved from http://tic.lib.msu.edu/tgif/flink?recno=20185

Corp, P., & Advisors, E. G. (2017). 2016 State of the Industry.

Farnie, H. B. (1857). *The Golfer's Manual*.

Ferguson, M. H. (1958). Effects of Golf-Shoe Soles On Putting Green Turf. *USGA Journal and Turf Management*, *11*(5), 25–28. Retrieved from http://tic.lib.msu.edu/tgif/flink?recno=36745

GCSAA. (2017). *Golf Course Environmental Profile Phase II* (Vol. IV). Retrieved from https://www.gcsaa.org/environment/golf-course-environmental-profile

GCSAA, USGA, & EIFG. (2015). *Golf Course Environmental Profile* (Vol. IlI).

Gibeault, Victor A.; Youngner, Victor B.; Bengeyfield, W. H. (1983). Golf Shoe Study II. *USGA Green Section Record*, *25*(5), 1–7.

Green, T. O., Rogers, J. N., & Chestnut, E. C. (2013). *Effects of Creeping Bentgrass Seeding Rates and Traffic on Establishment of Putting Greens during Renovation*.

Hamilton, G. W.; Gregos, J. S.; Sinkus, D. S.; Tredway, L. P.; Gover, A. E. (1999). The effects of golf shoe tread types on putting green quality. In A. J. Farrally, M. R. and Cochran (Ed.), *Science and Golf III* (pp. 576–580). Human Kinetics, Inc., for the World Scientific Congress of Golf Trust.

Hamilton, G. W. Jr.; Gregos, J. S.; Gean, D. R.; Gover, A. E. (1997, April). Golf shoe treads affect putting green quality: Spikeless shoes cause least wear on turf; metal spikes wear hardest on sand-based greens. *Golf Course Management*, *65*(4), 53–56. Retrieved from http://tic.lib.msu.edu/tgif/flink?recno=39897

Han, K. M., Kaminski, J. E., & Lulis, T. T. (2017). Influence of Nitrogen, Plant Growth Regulators, and Iron Sulfate on Annual Bluegrass Populations on a Golf Green. *International Turfgrass Society Research Journal*, *13*, 661–669. https://doi.org/10.2134/itsrj2016.05.0402

Happ, B. Y. K. (2003). Putting surface pace. *USGA Green Section Record*, *41*(4), 16–20. Retrieved from http://tic.lib.msu.edu/tgif/flink?recno=89518

Hathaway, A. D.; Nikolai, T. A. (2005). *A putting green traffic methodology for research applications established by in situ modeling*. Aberystywth, Ceredigion, UK. Retrieved

from http://tic.lib.msu.edu/tgif/flink?recno=105363
Henderson, J. J., Lanovaz, J. L., Rogers, J. N., Sorochan, J. C., & Vanini, J. T. (2005). A New Apparatus To Simulate Athletic Field Traffic: The Cady Traffic Simulator. *Agronomy Journal*, *97*(4), 1153–1157. https://doi.org/10.2134/agronj2004.0083N
Hummel, N. W. (1993). Rationale for the Revisions of the USGA Green Construction Specifications. *USGA Green Section Record*, *31*(2), 15. Retrieved from http://tic.lib.msu.edu/tgif/flink?recno=26679
Hurdzan, M. J. (2004). *Golf Greens: History, Design, and Construction*. Hoboken, New Jersey: John Wiley & Sons, Inc.
Karcher, D., Nikolai, T., & Calhoun, R. (2001). Golfer's perceptions of greens speeds vary: Over typical Stimpmeter distances, golfers are only guessing when ball-roll differences are less than 6 inches. *Golf Course Management*, *69*(3), 57–60. Retrieved from http://tic.lib.msu.edu/tgif/flink?recno=72405
Laskowski, K., Merewitz, E. B., & Frank, K. W. (2014). Effects of Drought and Traffic Stresses on Physiological Responses and Water Use Characteristics of Creeping bentgrass (Agrostis stolonifera) and Annual bluegrass (Poa annua). In *Graduate Student Oral Competiton: Golf Course Management - Cultural Practices, Stress Tolerance, and Pest Management*. Retrieved from https://scisoc.confex.com/crops/2014am/webprogram/Paper86325.html
Linde, D. T., Mitchell, A. D., & Hannan, B. (2017). Comparing Three Methods to Measure Putting Green Trueness. *ITSRJ*, *13*, 264–274. https://doi.org/10.2134/itsrj2016.05.0332
McNitt, A. S., Middour, R. O., & Waddington, D. V. (1997). Development and Evaluation of a Method to Measure Traction on Turfgrass Surfaces. *American Society for Testing and Materials*, *25*. https://doi.org/10.1520/JTE11329J
Moore, J. F. (2005). A true team effort: Guidelines for putting green construction. *GreenMaster*, *40*(4), 4. Retrieved from http://tic.lib.msu.edu/tgif/flink?recno=112098
Morris, K. N., & Shearman, R. C. (2011). NTEP Turfgrass Evaluation Guidelines Prepared by. Retrieved from www.ntep.org/pdf/ratings.pdf
Morrow, J., & Dannenberger, K. (1995). Ball Roll Comparison : Traditional Metal Spikes Hanley ' s of Sun Prairie, 38–39.
MYGOLFSPY. (2016). 2016 Report: Overall Golfer Performance By Handicap. Retrieved from https://www.mygolfspy.com/2016-report-overall-golfer-performance-by-handicap/
Nikolai, Thomas A.; Karcher, Douglas E.; Sorochan, J. C. (2006). Professional Golfers Conclude that Spike Design Affects Putting Green Quality. *Applied Turfgrass Science*, (November 27), 1–2. https://doi.org/10.1094/ATS-2005-1127-01-BR.The
Nikolai, T. A. (2003). PGA touring pros evaluate putting greens for spike damage: Researchers seize an opportunity to learn about the performance of spikes. *USGA Green Section Record*, *41*(5), 7–9. Retrieved from http://tic.lib.msu.edu/tgif/flink?recno=91350
Patrignani, A., & Ochsner, T. E. (2015). Canopeo: A Powerful New Tool for Measuring Fractional Green Canopy Cover. *Agronomy Journal*, *107*(6), 2312–2320. https://doi.org/10.2134/agronj15.0150
Reeves, T. I., & Smith, M. A. (1992). Time domain reflectometry for measuring soil water content in range surveys. *Journal of Range Management*, *45*(4), 412–414.
Robert, E., & Frank, R. (2016). *Turfgrass Science & Management* (5th ed.). Stamford, CT: Cengage Learning.

Roberts, J. A.; Inguagiato, J. C.; Murphy, J. A. (2013). A method to evenly apply foot traffic to turf plots. *International Turfgrass Society Research Journal*, *12*, 743–746. Retrieved from http://tic.lib.msu.edu/tgif/flink?recno=223375

Samaranayake, H., Lawson, T. J., & Murphy, J. A. (2008). Traffic stress effects on bentgrass putting green and fairway turf. *Crop Science*, *48*(3), 1193–1202. https://doi.org/10.2135/cropsci2006.09.0613

Shearman, R. C., Carrow, R. N., Wit, L. A., Duncan, R. R., Trenhold, 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*, *9*(13248), 347–352.

Smith, L. (2016). Green Speed: The need for speed? *Pitchcare*, *69*(October/ November), 38–41.

Stimpson, E. (1935). Introducing the Stimp. *The Business Journal of Golf*, (February), 2–4.

Vanini, J. T., Henderson, J. J., Sorochan, J. C., & Rogers, J. N. (2007). Evaluating Traffic Stress by the Brinkman Traffic Simulator and Cady Traffi c Simulator on a Kentucky Bluegrass Stand. *Crop Science*, *47*(2), 782–786. https://doi.org/10.2135/cropsci2006.07.0500

White, C. (2011). The cutting height dilemma: Finding the right balance. *USGA Green Section Record*, *49*(17), 1. Retrieved from http://tic.lib.msu.edu/tgif/flink?recno=179733

Whitlark, B. Y. B., & Pringle, M. (2012). Can’t Stop Your Ball on the Green ?: Are the greens to blame or is it your game?, *50*(25), 1–3. Retrieved from http://tic.lib.msu.edu/tgif/flink?recno=213468

Worsfold, P., Smith, N. A., & Dyson, R. J. (2008). Low handicap golfers generate more torque at the shoe-natural grass interface when using a driver. *Journal of Sports Science and Medicine*, *7*(3), 408–414.

Young, J., Richardson, M., & Karcher, D. (2010). Mowing and Rolling Affect Wear Injury from Foot Traffic on Creeping Bentgrass Putting Greens. *Arkansas Turfgrass Report*, 88–93.

Younger, V. B. (1961). Accelerated Wear Tests on Turfgrasses. *Agronomy Journal*, *53*(4), 217–218. Retrieved from http://agron.scijournals.org/cgi/abstract/53/4/217

APPENDIX

Appendix A. Influence of traffic on 3.8cm soil volumetric water content between two putting surfaces

Rounds at hole location	SBPCB †	SANSPAB ‡
	——————%——————	
140	21	19
280	20	18
420	16	14
560	18	19
700	23	22
840	22	22
980	22	22

*Significant at the 0.05 probability level
† n = 72 at each rounds volume
‡ n = 72 at each rounds volume

Appendix B. Influence of traffic on surface firmness between two putting surfaces

Rounds at hole location	SBPCB †	SANSPAB ‡
	———unitless—————	
140	0.40	0.39
280	0.37	0.39
420	0.37	0.37
560	0.38	0.39
700	0.39	0.42
840	0.38	0.42
980	0.38	0.42

*Significant at the 0.05 probability level
† n = 84 at each rounds volume
‡ n = 84 at each rounds volume