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Determining Critical Fall Height for Bermudagrass Grown on Sand and Native Soil Root Zones

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I am submitting herewith a thesis written by Taylor L. Williams entitled "Determining Critical Fall Height for Bermudagrass Grown on Sand and Native Soil Root Zones." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Plant Sciences.

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DETERMINING CRITICAL FALL HEIGHT FOR BERMUDAGRASS GROWN ON SAND AND NATIVE SOIL ROOT ZONES

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DEGREE

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DEDICATION

I would like to dedicate this thesis to my family. They have helped and encouraged me throughout my whole life to finish my time in school. I am lucky to have been given the resources and the opportunity to attend college. I would also like to thank my caring wife, Susie, for her continuous support and understanding. She has been very patient throughout the years it took to get another degree. She has always been there to offer alternative solutions for day-to-day projects. Without this group of people, I would not have pursued college or graduate school.

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ABSTRACT

Surface hardness is typically measured using a Clegg Impact Soil Tester (ASTM F355-D), but recent trends in sports turf are to use the F355-E missile as a potential alternative, because it may provide a more meaningful measurement. Forty traffic events were applied to 'Tifway' bermudagrass grown in an ASTM constructed sand root zone and a silt loam soil on the Center for Athletic Field Safety at the University of Tennessee. An F355-E was used to measure head injury criteria (HIC) for both root zones after every eight traffic events. Head injury criteria values were regressed to varying drop heights to calculate critical fall height (CFH) for both root zones. Critical fall height is the maximum height an athlete can fall from where the surface meets the impact attenuation performance criterium (1000 HIC) established by World Rugby for synthetic turf surfaces. Critical fall height for the ASTM constructed sand root zone was 2.3 m, while CFH for the silt loam soil was 2.0 m. The differences in CFH were due to soil compaction. After 40 traffic events, the average soil bulk density of the ASTM constructed sand root zone was 1.3 g/cm^3, and the silt loam was 1.4 g/cm^3. A 2.3 m CFH of the ASTM root zone occurred during the initial testing, before the loss of green turf cover. A 2.0 m CFH of the silt loam soil was calculated after 40 traffic events. Head injury criteria values for both root zones were significantly influenced as a result of traffic.

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1. Abstract

Surface hardness is typically measured using a Clegg Impact Soil Tester (ASTM F355-D), but recent trends in sports turf are to use the F355-E missile as a potential alternative, because it may provide a more meaningful measurement. Forty traffic events were applied to 'Tifway' bermudagrass grown in an ASTM constructed sand root zone and a silt loam soil on the Center for Athletic Field Safety at the University of Tennessee. An F355-E was used to measure head injury criteria (HIC) for both root zones after every eight traffic events. Head injury criteria values were regressed to varying drop heights to calculate critical fall height (CFH) for both root zones. Critical fall height is the maximum height an athlete can fall from where the surface meets the impact attenuation performance criterium (1000 HIC) established by World Rugby for synthetic turf surfaces. Critical fall height for the ASTM constructed sand root zone was 2.3 m, while CFH for the silt loam soil was 2.0 m. The differences in CFH were due to soil compaction. After 40 traffic events, the average soil bulk density of the ASTM constructed sand root zone was 1.3 g/cm^3, and the silt loam was 1.4 g/cm^3. A 2.3 m CFH of the ASTM root zone occurred during the initial testing, before the loss of green turf cover. A 2.0 m CFH of the silt loam soil was calculated after 40 traffic events. Head injury criteria values for both root zones were significantly influenced as a result of traffic.

1. Introduction

It is estimated that there are 25 million scholastic and 20 million community-based juveniles who participate in sports annually in the United States (Micheli, 2000). Athletic fields must be maintained regularly by alleviating soil compaction to reduce the number of surface-related injuries to this large population. Approximately 10% of sports concussions are related to the athlete's head striking the turf surface (Guskiewicz et al., 2000). In 2004, the Sports Turf Managers Association estimated that over 40,000 sports fields are used every year in the United States (Campbell, 2004). With this many fields, there are a wide variety of management inputs from low resource community/municipal fields to high resource college and professional sports fields. Athletes and coaches constantly demand safe, consistent playing surfaces (Christians, 2004). This creates a challenge for sports field managers to provide consistent and safe playing conditions, regardless of resource inputs. It is often difficult to maintain stringent safety expectations on fields that receive excessive traffic. Excessive traffic can occur on any field used for multiple sporting events.

Traffic reduces playing surface consistency and potentially increases player injury risk (Carrow and Petrovic, 1992). A consistent, uniform surface enhances athlete performance (Cockerham, 1993). Sports such as football, rugby, and soccer are fast-paced making proper maintenance of turfgrass fields important. Turfgrass provides a unique, inexpensive cushioning effect that reduces injuries when compared to worn athletic fields lacking turfgrass cover (Gramckow, 1968). A higher percentage of turfgrass cover usually provides a safer playing surface by reducing the impact force of athletes when they fall to the ground on soils with high clay content. During an athletic event, athletes constantly make dynamic maneuvers, which can impact turfgrass cover. Often, athletes wear cleated footwear, for performance, increasing turfgrass damage compared to shoes with smooth outsoles.

Both warm and cool-season grasses can be used for athletic surfaces in the transition zone. Bermudagrass (*Cynodon* spp.) is the most common turfgrass species used on athletic fields as a result of its superior traffic tolerance and recuperative potential during prolonged periods of summer heat compared to other species (Sever et al., 2020). In the transition zone, bermudagrass athletic fields are often overseeded with perennial ryegrass (*Lolium perenne* L.) during fall, winter, and spring to allow for an actively growing surface with desirable green cover (Ward et al., 1974). Multi-use facilities, such as high school fields, often do not have budgets to overseed perennial ryegrass into bermudagrass, potentially damaging or wearing out the playing surface as a result of excessive use when environmental conditions are not favorable for growth and recovery (Goddard et al., 2008). Excessive soil moisture can also lead to the rapid deterioration of an athletic field. Native soil moisture content should range from 0.07-0.20 $m^3 m^{-3}$, while sand constructed root zones should range from 0.05-0.27 $m^3 m^{-3}$ for maintaining maximum percent green cover when trafficked (Dickson et al, 2018a). Compacted native soil root zones consisting of high percentages of silt and clay limit turfgrass root growth due to the limited availability of oxygen found in the soil (Peterson, 1974). While excessive use decreases turfgrass cover, it also increases soil compaction (Carrow, 1992).

Hybrid bermudagrasses [*Cynodon dactylon* (L.) Pers. x C. *transvaalensis* Burtt-Davy] are preferred for athletic fields due to a fine leaf texture and dense turfgrass canopy (Trenholm et al., 2000; Younger, 1958). 'Tifway' bermudagrass has been shown to have improved simulated athletic traffic tolerance compared to other hybrid and common bermudagrass cultivars (Goddard et al., 2008; Thoms et al., 2011; Haselbauer, 2010; Brosnan and Deputy 2009). Trappe et al.

(2009) reported that 'Riviera', Tift No. 4, and 'Tifway' exhibited the best traffic tolerance in a study of 42 bermudagrasses using the Cady Traffic Simulator (CTS). When comparing varieties of seashore paspalum (*Paspalum vaginatum* Sw.) to hybrid bermudagrass, 'Tifway' bermudagrass provided some of the lowest surface hardness conditions, along with reducing soil compaction the most (Thoms et al., 2011). As a warm-season grass, 'Tifway' provides superior traffic tolerance and is an excellent selection for athletic fields within the transition zone.

Practice fields often receive less attention during design and construction, and are subjected to greater use, generally have lower maintenance, and usually have a harder surface than game fields (Cockerham, 1993). Cockerham (1989) reported during games, the majority of foot traffic on a football field occurs between the 40-yard lines, covering the width of the hash marks [5.7 m for the National Football League and 12.2 m for the National Collegiate Athletic Association (NCAA)]. Athletes spend most of their time during the week on the practice field, which often have lower maintenance inputs compared to the game field.

Athletic field root zones can be comprised of various soil types. Three common root zones are ASTM sand constructed, USGA sand constructed, and native soil. Both the ASTM constructed sand and USGA constructed root zones were designed to facilitate drainage, that is more resistant to soil compaction to maintain a consistent playing surface (ASTM, 2011). The ASTM sand constructed root zone allows more fine gravel (3.4 to 4.75 mm diameter particles) and total fine sized particles (<0.05 mm diameter particles) than root zones constructed to the United States Golf Association construction specifications. Native soil root zones are common in low budget athletic fields due to the costs associated with constructing root zones from sand. Native soil root zones contain high amounts of silt and clay, making them not as consistent as sand constructed root zones due to their lack of drainage ability.

Soil compaction is defined as the pressing together of soil particles and destruction of aggregates by vehicular and foot traffic resulting in a denser soil mass with reduced macroporosity, increased soil bulk density (SBD), and greater soil strength (Topp and Ferré, 2002). Soil compaction is considered a common and consequential problem with recreational sites. Turfgrass growth and development is negatively affected by soil compaction as a result of altering the soil's physical properties (Cockerham and Wiecko, 1989). Compacted soils mechanically impede root penetration. Changes in SBD may explain the increased surface hardness reported with increasing soil compaction (Brosnan et al., 2009). Loss of macropore space, essential for gas exchange, water movement, and root channels, damages root growth and viability, even though soil strength increases (Carrow et al., 2001). Langvad (1968) stated different soil types of athletic fields have more of an effect on ball bounce than mowing height. The soil type in general, and more specifically soil moisture content and water movement, are considered the key variables in determining playability of sports surfaces (Canaway and Baker, 1993).

A modified Cady trafficker (ProCore 648, Toro) was used that was equipped with six spring loaded metal plates with nuts simulating cleats, instead of the original metal tines used to puncture holes in the soil, similar to the Cady traffic simulator described by Kowalewski et al. (2013). One simulated traffic event is equivalent to the same number of cleat marks that occurs between to the hashes, on either 40-yard line during a National Football League or collegiate football game (Cockerham, 1989). This traffic intensity was calculated to be 667 cleat marks per square meter (Cockerham, 1989, Henderson et al., 2005). The traffic simulator is 1.2 m wide, which left 15 cm of non-trafficked bermudagrass along the edges of the 1.5 m x 1.5 m plots.

Ground reaction forces (GRF) are often 2.5 to 3 times greater than an athlete's body mass while performing an athletic motion (Kent et al., 2012). These forces subject an athlete's body to serious injury risk (LaStayo et al., 2003). Playing surface firmness affects GRF and athlete performance (Guise, 1996). An athletic field's condition has the potential to increase risk of injury (Rogers et al., 1994).

Turfgrass cover is a major factor in providing a uniform, smooth, and safe playing surface. Therefore, bermudagrass percent green cover was measured daily using digital image analysis (DIA) (Karcher 2007; Karcher and Richardson, 2003; Richardson et al., 2001). Digital image analysis allows for quantifiable measurements to be taken and eliminates any uncertainty that can come from using visual ratings alone.

Surface hardness is commonly measured using the Clegg Impact Soil Tester (CIST), ASTM F355-A, USGA Turf Firmness Meter, and ASTM 3189. The CIST uses an accelerometer mounted inside a 2.5 kg flat-bottomed missile to measure the duration of impact when released from 46 cm (Clegg, 1976). Test results are displayed as peak deceleration in G_{max} (G_{max} = acceleration due to gravity) (ASTM F1702-96; Clegg, 1976; Rogers and Waddington, 1990). G_{max} values below 30 G_{max} are often considered inadequate for enough traction to perform athletic maneuvers and values above 180 G_{max} are considered to be heavily compacted and dangerous (Aldous, 1999). This is the designated testing method to determine surface hardness used by the National Football League (Mack et al., 2019) and American Society for Testing and Materials (ASTM, 2002). Another device used to measure G_{max} is the ASTM F355-A. This device is the standard test for synthetic turf surfaces according to previous research that indicates the ASTM F355-A is associated with head injury risk (ASTM F1936-10, 2010). The ASTM F355-A measures the impact attenuation of both natural and synthetic turf systems by determining peak impact acceleration. The ASTM F355-A uses an accelerometer mounted inside a 9.1 kg flat-bottomed missile to measure peak impact acceleration (G_{max}) when dropped from 61 cm through a guide tube. The missile is dropped three times in the same location with a 60 second time interval between drops. The average G_{max} of the second and third drops are reported with values greater than 200 G_{max} being associated with increases risk of traumatic brain injury (Gadd, 1966). The USGA Turf Firmness Meter is another device used to measure surface hardness. This device is most commonly used to measure surface firmness of putting greens due to its shape, resembling a golf ball, causing less surface damage than the CIST. A 1.95 kg missile equipped with an accelerometer is dropped from 69 cm through a metal guide tube that measures surface penetration (in) as the missile impacts the surface.

The ASTM 3189 is a mechanical device used in the FIFA quality concept to measure surface firmness characteristics (Fédération Internationale de Football Association, 2015). The device utilizes a 20 kg missile with a helical metal spring dropped from 5.5 cm to measure force reduction, energy restitution, and vertical deformation as the missile impacts the surface. Force reduction is the measure of shock absorption percentage by a surface. Lower percentages are associated with firmer surfaces, due to the surface absorbing less of the impact. Vertical deformation is the distance a foot is expected to deform the surface during a match. Higher numbers are associated with softer surfaces. The drop mechanism utilizes an electromagnet controlled by a remote to consistently drop the missile to the surface. Only force reduction and vertical deformation are included in the standard used for FIFA. Vertical deformation must be between 4 and 11 mm, while force reduction must be between 55% and 77% (Fédération Internationale de Football Association, 2015).

The ASTM F355-E (Figure 1) utilizes a 10.1 kg missile with a hemispherical design to quantify head-related injuries using HIC. The work of Gadd (1966) encouraged the National Highway Traffic Safety Administration to start using HIC. This device is commonly used for testing the hardness of playground surfaces. A CFH can be determined if HIC is known (ASTM, 1999). Critical fall height is correlated with impact attenuation (Mack, et al., 2000) and is the maximum fall height that would not result in a life-threatening head injury. Sixteen percent of the population would suffer a traumatic head injury when HIC reaches 1000 (Torg, 1991). Playgrounds are designed to be safe for children in which they should not be able to fall from a height that would put their health in danger. Head Injury Criteria is derived from the time interval within the acceleration-time history of the impact over which the HIC integral is evaluated (ASTM, 2017).

Injuries to an athlete's head are of great concern during sporting events (Centers for Disease Control and Prevention, 1997). Each year, athletes suffer an estimated 300,000 traumatic brain injuries with concussions occurring during many of these injuries (Sosin et al., 1996). Football players who suffer a concussion are three times more likely to suffer a second concussion in the same season than other players who had not suffered a previous concussion (Guskiewicz et al., 2000). A concussion caused by a sport related incidence is a common type of traumatic brain injury resulting in 200,000 annual emergency room visits in the United States (Sone et al., 2018). Ten percent of all soccer concussions are due to impacts between the head and surface (Boden et al., 1998). Most surface hardness test instruments are not related to field safety, whereas the ASTM F355-E has been shown to provide a measure of field safety as related to critical fall height (CFH).

The objectives of this study were to determine critical fall height (CFH) changes for trafficked bermudagrass athletic fields grown on native soil and a sand root zone meeting ASTM specification root zones and to determine the relationship between changes in percent green turfgrass cover (PGC) and CFH.

1. Materials and Methods

A study to determine the CFH of simulated trafficked bermudagrass athletic fields was conducted at the University of Tennessee Center for Athletic Field Safety (Knoxville, TN) from 2016 to 2018. Testing was performed on each of two 4.6 m x 9.1 m simulated athletic fields established with hybrid bermudagrass (*Cynodon dactylon* x *C. transvaalensis*) var. Tifway, constructed with either an American Standard for Testing Materials (ASTM) sand or a native silt loam soil. One plot of each soil type was used for spring and fall. The native soil root zone was a Sequatchie silt loam soil (fine-loamy, siliceous, semiactive, thermic Humic Hapludult) (28% sand, 48% silt, and 24% clay) with a 6.2 pH, 9 mg Kg^{-1} initial phosphorous, 81 mg kg^{-1} initial potassium, and 25 g kg^{-1} organic matter content (OM).

For both spring test dates (2017 and 2018), the same pair of simulated athletic fields of each root zone was tested, allowing plots to recover during their offseason. Each season, the two soil type treatments were divided into 18 plots, and surface impact characteristics, digital images, and volumetric soil water content were measured. The study design was arranged as a randomized complete block design with three replications with volumetric soil water content as a covariate.

Granular urea fertilizer (46 N-0 P_2O_5-0 K_20-0) was applied monthly at 49 kg N ha^{-1} from May through October during this study. All plots were mown at 2.2 cm three times each week using a triplex reel mower (Jacobsen TriKing 1900D; Textron Inc., Providence, RI), and clippings were returned. Irrigation was applied as necessary to prevent drought stress during the experiment duration.

Two simulated traffic events were applied four times per week for four consecutive weeks during fall (12 September - 13 October 2016 and 18 September – 19 October 2017) and spring (16 May – 15 June 2017 and 16 May – 21 June 2018). Each four-week trafficking period comprised a simulated athletic field season consisting of 40 traffic events. When a season concluded, a recovery process was performed. ASTM sand plots were core aerified, cores were removed, and sand topdressing was applied to fill holes. Native soil plots were core aerified and soil was reincorporated into the surface using a metal drag mat. The same recovery process was performed for both spring and fall plots. Each year, treatments applied to each simulated athletic field were rerandomized to minimize aggregate effects of simulated traffic.

Surface hardness G_{max} was measured after every eight simulated traffic events using a CIST, performing seven drops per plot without testing the same location more than once.

Percent green cover was measured using digital image analysis after every eight simulated traffic events, according to methods described by Karcher and Richardson (2003). Prior to DIA, leaf litter was blown off of each plot using a gas-powered blower (Stihl, Virginia Beach, VA). All DIA pictures were taken using a Canon PowerShot G12 (Canon, Tokyo, Japan). The camera was arranged on top of an enclosed light box with four 40-W spring lamps (TCP, Lighthouse Supply, Bristol, VA), perpendicular to the turf surface that allowed for the same light exposure to be applied to all the pictures taken. Each picture was taken from the same location each day by marking a small white dot on each plot, indicating where the left tire of the light box should rest on the ground. Sigma Scan Pro 5 Software (Systat Software, San Jose, California) was used to count the pixilation of green pixels exhibiting a hue between 45 and 135 and saturation 0 to 100% from the total pixels in each image, to determine the percent green cover of each plot.

Critical fall height was measured prior to treatment initiation and after every eight simulated traffic events. Three drop heights (1.3 m, 1.9 m, and 2.5 m) consisting of three drops per height were tested with the ASTM F355-E. The testing apparatus includes a tripod equipped with a hook on each leg that allows the missile to be accurately dropped in three separate locations within each plot. Due to the mass, hemispherical shape, and drop height of the missile, each drop creates a depression on the playing surface that makes the testing surface uneven. Each drop was marked to avoid dropping the missile or the CIST in the same location during future tests.

When CFH and CIST data was collected, soil volumetric water content was measured using a handheld time domain reflectometer (TDR) using 7.6 cm probes (FieldScout 300 Probe, Spectrum Technologies, Inc. Plainfield, IL). Soil volumetric water content was a covariate of CFH and CIST and analyzed according to Dickson et al., (2018a).

Soil bulk density was measured at the end of the study by collecting 15 undisturbed soil cores each for nontrafficked and trafficked locations within each root zone, using a 5 cm x 5 cm core sampler (Forestry Suppliers, Inc. Jackson MS) for a volume of 98.2 cm^3 according to Topp and Ferré (2002).

A four-way (soil type x simulated traffic event x season x year) analyses of covariance (ANCOVA) was run initially and conducted in SAS (v. 9.4; SAS Institute Inc., Cary, NC). The covariate used in the analysis was volumetric soil water content. Main effects included soil type, simulated traffic events, season, and year. Main effects and interactions for season and year were not significant; therefore, data were pooled and reanalyzed in a two-way ANCOVA (soil type x simulated traffic event) (Table 1). The factors used in the ANCOVA were CFH, CIST, PGC, SBD, and OM (Table 1). Fisher's least significant difference (LSD) was used to separate means at $\alpha = 0.05$.

1. Results and Discussion

There were no significant interactions by year or by season for CFH, surface hardness, PGC, SBD, and OM, respectively (Table 1). The lack of main effect differences in year and season resulted in data being pooled, the following results are discussing pooled data by year and season.

There was a significant CFH difference between ASTM sand and native soil root zones (Figure 2). The CFH for the ASTM sand root zone was 2.53 m, where the native soil root zone was 2.06 m. The higher CFH for the ASTM sand root zone could be due to sand resisting compaction compared to the native soil (higher silt plus clay content). The CFHs for both root zones were nearly 95% higher (ASTM sand root zone) and 58% higher (native soil root zone) than the minimum allowable height (1.3 m) established by World Rugby for synthetic turf (ASTM, 2018).

Traffic significantly increased CFH by 0.1 m from zero (2.24 m) to the eighth (2.34 m) simulated traffic events (Figure 3). Between the 16th (2.38 m) and the 24th (2.25 m) simulated traffic event, CFH significantly decreased to 2.25 m, and was not different from zero simulated traffic events. Critical fall height did not change for the remainder of the study (24th – 40th simulated traffic events). An increase of 0.1 m in CFH is just outside (6%) the 5% sensitivity of the instrument. Thus, this significant effect could mostly be due to instrument sensitivity. Additionally, the biological significance of a 0.1 m increase in CFH is unknown. Irrespective of root zone, the CFH measured in this study was much higher than the allowable 1.3 m CFH established by World Rugby for synthetic turf. This finding indicates that CFHs of turfgrasses are potentially safer than the safety limits imposed by World Rugby. At this time, there is no CFH safety limit established by any sport governing body for a turfgrass surface.

The native soil root zone always generated higher G_{max} values than the sand root zones (Figure 4). An average increase of 6 G_{max} for the native soil root zone (64 G_{max}) was measured when compared to the ASTM sand root zone (58 G_{max}). This comparison suggests native soil root zones can maintain a similar G_{max} as ASTM sand root zones if proper maintenance is performed. However, Dickson et al., (2018a) also found soils with higher silt plus clay content had higher G_{max} values. ASTM sand root zones contain higher macropore space, and are not as conducive to compaction. ASTM sand root zones are used to provide a consistent playing surface, even in inclement weather. The use of sand allows water to drain through the soil profile at a higher rate than root zones containing a high percentage of clay. Measured G_{max} values consistently demonstrated the same relationship that was observed with CFH, mainly that the ASTM sand root zone was more resilient than the native soil root zone.

As simulated traffic events were applied, G_{max} values increased (Figure 5). From 0 to 40 simulated traffic events, surface hardness increased by 24 G_{max}. Under similar management, traffic had a 4x influence on increasing G_{max} compared to soil type. While G_{max} values increased for both root zones with increased simulated traffic events, soil bulk density from 0 – 40 simulated traffic events increased, but was not statistically significant (Table 1). As traffic events increased, G_{max} increased, similar to previous research by Thoms et al., 2011, and Dickson et al., 2018a. In my study, G_{max} values increased after 40 simulated traffic events, but CFH was not different. Using the ASTM F355-E and CIST devices, dissimilarities in results were observed due to surface impact characteristics. Impacts with the two devices differ because of the masses of the missiles, impact velocities, and surface area impact. These results support that the ASTM F355-E and CIST devices are measuring different volumes of a root zone's response to impact.

Percent green cover decreased as a result of traffic (Figure 6). Significant decreases ($R^2 = 0.9954$) in PGC were observed after every 8 simulated traffic events (0 – 40 simulated traffic events). A number of previous studies have shown increasing traffic decreases PGC (Cockerham et al., 1990, Thoms et al., 2008, Trappe et al., 2011, Kowalewski et al., 2015, and Dickson et al., 2018a). Critical fall height significantly increased when PGC was between 86% and 72% after 8 or 16 simulated traffic events (Figures 3 and 6). Prior to 8 and after 16 simulated traffic events, CFH was not significantly different despite a 63% decrease in PGC over the duration of the trial (Figure 6). One possible explanation for this result could be as PGC decreases slightly, the soil surface is exposed and can be displaced more readily due to a lack of vegetative cover. Then, as PGC decreases below 72%, vegetative cover ceases to affect CFH. Conversely, as PGC decreased, the loss of vegetative cover on the surface was a likely reason for higher G_{max} values (Figure 6). This finding supports that the ASTM F355-E and CIST are measuring impact characteristics from different volumes of soil. Previous research by Brosnan et al. (2009) showed surface conditioners of skinned baseball surfaces did not significantly affect baseball impact characteristics, rather the soil moisture of the clay below the treatments was significant.

Testing at various of soil volumetric water contents was outside the scope of this study. Future studies are warranted to understand how CFH is influenced by soil characteristics and volumetric water contents. For example, one study might evaluate the volume or depth of soil that affects CFH as compared to other surface impact devices. Another area of study could be determining optimal combinations of maintenance practices that allow a field manager to maintain PGC as traffic occurs over a season (Figure 6). If PGC were able to be consistently maintained above 72%, one should expect that CFH, G_{max}, and SBD would support an optimal turfgrass sports field.

1. Conclusions

The CFHs identified for natural grass in this study were nearly 95% higher than the minimum height (1.3 m) established by World Rugby for synthetic turf. The CFHs measured on natural grass with an ASTM sand root zone were also high enough to be acceptable for use on playgrounds. These studies found that the ASTM F355-E and the CIST measured different regions of the turfgrass system for surface impact characteristics. It is important that future studies evaluate these differences.

LITERATURE CITED

Aldous, D.E. 1999. International turf management handbook. Dep of Environ. Hortic. And Res Manage., Univ. of Melbourne, VIC, Australia, and CRC Press, Boca Raton, FL.

American Society for Testing and Materials. 2000. Annual book of standards. Vol. 15.07. End use products. Standard test method for shock-attenuation characteristics of natural playing surface systems using a lightweight portable apparatus. F1702-96. Am. Soc. Test. Mater., West Conshohocken, PA.

American Society for Testing and Materials. 2000a. Annual Book of ASTM Standards. Vol. 15.07. End Use Products. Standard Test Method for Shock-Absorbing Properties of Playing Surface Systems and Materials. F355-95 Procedure A. ASTM, West Conshohocken, PA.

American Society for Testing and Materials. 2002. End use products: standard test method for measuring shock-attenuation characteristics of natural playing surface systems using lightweight portable apparatus. *Annual Book of ASTM Standards*; 15(07):F1702-F1796.

American Society for Testing and Materials. 2011. Annual book of standards. Vol. 15.07. End use products. Standard guide for construction of high performance sand-based rootzones for athletic fields. F2396-11. American Society for Testing and Materials, West Conshohocken, PA.

American Society for Testing and Materials. 2016. Annual book of standards. Vol. 15.07. End use products. Standard test method for shock-attenuation characteristics of natural playing surface systems using a lightweight portable apparatus. F1292-13. Am. Soc. Test. Mater., West Conshohocken, PA.

American Society for Testing and Materials. 2017. F1292-17 Standard Specification for Impact Attenuation of Surfacing Materials within the Use of Zone of Playground Equipment; ASTM International: West Conshohocken, PA, USA.

ASTM International. 1999. Standard specification for impact attenuation of surface systems under and around playground equipment, F1292-99.

ASTM F1702-10: Standard Test Method for Measuring Impact-Attenuation of Natural Playing Surface Systems Using a Lightweight Portable Apparatus. 2010., ASTM International, West Conshohocken, PA, www.astm.org.

American Society for Testing and Materials. 2018. *F3146-18 Standard Test Method for Impact Attenuation of Turf Playing Systems Designated for Rugby*; ASTM International: West Conshohocken, PA, USA; doi:10.1520/F1292-17.

ASTM International 2017. F3189-17 Standard Test Method for Measuring Force Reduction, Vertical Deformation, and Energy Restitution of Synthetic Turf Systems Using the Advanced Artificial Athlete. West Conshohocken, PA; ASTM International. doi: https://doi.org/10.1520/F3189-17.

Beard, J.B. 1973. Turfgrass: science and culture. Prentice-Hall, Englewood Cliffs, NJ.

Boden, B. P., Kirkendall, D. T. and Garrett, W. E. J. 1998. Concussion incidence in elite college soccer players. *American Journal of Sports Medicine*, 26: 238–241.

Brosnan, J. T., and Deputy, J. 2009. Preliminary observations on the traffic tolerance of four seashore paspalum cultivars compared to hybrid bermudagrass. HortTech. 19(2): 423-426.

Brosnan, J.T., A.W. Thoms, G.K. Breeden, and J.C. Sorochan. 2010. Effects of various plant growth regulators on the traffic tolerance of 'Riviera' bermudagrass (*Cynodon dactylon* L.). HortScience 45(6):966–970.

Campbell, B. 2004. About the sports turf field and STMA. Retrieved from: http://www.glstma.tripod.com/id19.htm.

Canaway, P.M., S.W. Baker. 1993. Soil and Turf Properties Governing Playing Quality. *International Turfgrass Society*.

Carrow, R. 1980. Influence of Soil Compaction on Three Turfgrass Species1. Agronomy Journal - AGRON J. 72. 10.2134/agronj1980.00021962007200060041x.

Carrow, R.N., R.R. Duncan, J.E. Worley, and R.C. Shearman. 2001. Turfgrass Traffic (Soil Compaction Plus Wear) Simulator: Response of *Paspalum vaginatum* and *Cynodon* spp. *International Turfgrass Society. Vol. 9.*

Carrow, R.N., and A.M. Petrovic. 1992. Effects of traffic on turfgrass. p. 285–330. In D.V. Waddington et al. (ed.) Turfgrass. Agron. Monogr. 32. ASA, CSSA, and SSSA, Madison, WI.

Centers for Disease Control and Prevention (CDC). 1997. "Sports-Related Recurrent Brain Injuries United States," Morb. Mortal Wkly Rpt., Vol. 46, No. 10, pp. 224–227.

Christians, N. 2004. Fundamentals of turfgrass management, 2nd ed. John Wiley & Sons, Hoboken, N.J.

Clegg, B. 1976. An impact testing device for in situ basecourse evaluation. In Proceedings of the Australian Road Research Board (ARRB) Conference, Perth, Australia, 23–27 August.

Cockerham, S.T. 1989. Cleated-shoe traffic concentration on a football field. California Turfgrass Cult. 39:11–12.

Cockerham, S.T.; Brinkman, D.J. 1989. A simulator for cleated-shoe sports traffic on turfgrass research plots. Calif. Turfgrass Culture, 39, 9–10.

Cockerham, S.T., V.A. Gibeault, R.A. Khan. 1993. Alteration of Sports Field Characteristics Using Management. *International Turfgrass Society Journal*: p. 182-191.

Cockerham, S. T., Gibeault, V. A., Van Dam, J., & Leonard, M. K. (1990). Tolerance of several cool-season turfgrasses to simulated sports traffic. In *Natural and artificial playing fields: Characteristics and safety features*. ASTM International.

Cockerham, R.N. and Wiecko, G. 1989. Soil compaction and wear stresses on turfgrass: Future research directions. 6th Intl. Turfgrass Res. Conf., Tokyo. p. 37–42.

Dickson, K.H., J. C. Sorochan, J.T. Brosnan, J.C. Stier, J. Lee, and W.D. Strunk. 2018a. Impact of soil water content on hybrid bermudagrass athletic fields. Crop Sci. May/June. 58(3):1416-1425.

Dickson K, Strunk W, Sorochan J. 2018b. The Effect of Soil Type and Moisture Content on Head Impacts on Natural Grass Athletic Fields. *Proceedings*. 2(6):270.

Fédération Internationale de Football Association (2015) FIFA quality concept for football turf: handbook of test methods. www.FIFA.com.

Gadd, C.W. Use of a weighted—Impulse criterion for estimating injury hazard. In Proceedings of the 10th STAPP Car Crash Conference, Los Angeles, CA, USA, 8–9 November 1966; pp. 164–174.

Goddard, M. J., Sorochan, J. C., McElroy, J. S., Karcher, D. E., & Landreth, J. W. (2008). The effects of crumb rubber topdressing on hybrid Kentucky bluegrass and bermudagrass athletic fields in the transition zone. *Crop science*, *48*(5), 2003-2009.

Grossman, R.B., and T.G. Reinsch. 2002. J.H. Dane and G.C. Topp (ed.) Bulk density and linear extensibility. Methods of soil analysis. Physical methods. SSSA, Madison, WI. 4:201–228.

Guise, S. Playability versus liability. SportsTURF 1996, 12, 16–23.

Guskiewicz, K.M.; Weaver, N.L.; Padua, D.A.; Garrett W.E. 2000. Epidemiology of concussion in collegiate and high school football players. Am. J. Sports Med. 28, 643–650.

Haselbauer, W.D. 2010. Effects of trinexapac-ethyl and winter overseeding on the morphological characteristics and traffic tolerance of bermudagrass cultivars. M.S. thesis. Univ. of Tennessee, Knoxville, TN.

Henderson, J.J., J.L. Lanovaz, J.N. Rogers, III, J.C. Sorochan, and J.T. Vanini. 2005. A new apparatus to simulate athletic field traffic: The cady traffic simulator. Agron. J. 97(4):1153–1157.

Horgan, B.P. and Yelverton, F.H. 2001. Removal of perennial ryegrass from overseeded bermudagrass using cultural methods. Crop Sci. 41:118–126.

Karcher, D. 2007. Digital imaging analysis to assess stress in turfgrass and other crop species. HortScience 42(4):815.

Karcher, D.E. and M.D. Richardson. 2003. Batch analysis of digital images to evaluate turfgrass characteristics. Crop Sci. 45:1536-1539.

Kars, S. 2013. Turfgrass Playing Surface and Injuries. Retrieved from: http://www.turfmate.com.au/article/544/turfgrass-playing-surfaces-injuries.

Kent, R., Crandall, J., Forman, J., Lessley, D., Lau, A., & Garson, C. (2012). Development and assessment of a device and method for studying the mechanical interactions between shoes and playing surfaces in situ at loads and rates generated by elite athletes. *Sports biomechanics*, *11*(3), 414-429.

Kowalewski, A. R., Schwartz, B. M., Grimshaw, A. L., Sullivan, D. G., & Peake, J. B. 2015. Correlations between hybrid bermudagrass morphology and wear tolerance. *Horttechnology*, *25*(6), 725-730.

Kowalewski, A.R., B.M. Schwartz, and A.L. Grimshaw. 2013. Biophysical effects and ground force of the Baldree traffic simulator. Crop Sci. 53:2239–2244. doi:10.2135/cropsci2013.02.0118.

Lafortune, M. A., Lake, M. J. and Hennig, E. M. 1996. Differential shock transmission response of the human body to impact severity and lower limb posture. *Journal of Biomechanics*, 29: 1531–1537.

Langvad, B. 1968. Sambandet mellan fotbollens studshojd och klipphojden pa sportturf. Weibulls Gras-tips 10-11:355-357. "The Connection between the Soccer Ball and the Cutting Edge."

LaStayo, P.C.; Woolf, J.M.; Lewek, M.D.; Synder-Mackler, L; Reich, T; Lindstedt, S.L. 2003. Eccentric muscle contractions: Their contribution to injury, prevention, rehabilitation, and sport. J. Orthop. Sports Ther. 33, 557–571.

Mack, M. G., Sacks, J. J., & Thompson, D. (2000). Testing the impact attenuation of loose-fill playground surfaces. *Injury Prevention*, *6*(2), 141-144.

Mack, Christina D., et al. 2019. "Higher Rates of Lower Extremity Injury on Synthetic Turf Compared With Natural Turf Among National Football League Athletes: Epidemiologic Confirmation of a Biomechanical Hypothesis." *The American Journal of Sports Medicine*, vol. 47, no. 1, Jan. pp. 189–196, doi:10.1177/0363546518808499.

Micheli, L.J., R. Glassman and M. Klein, 2000. The Prevention of Sports Injuries in Children.

McIlvain, Mirar M NM, Fields SK, Comstock RD. 2012. Epidemiology of concussions among United States high school athletes in 20 sports. American Journal of Sports Medicine. 40:747.

O'Kane, J. W., Spieker, A., Levy, M. R., Neradilek, M., Polissar, N. L., & Schiff, M. A. (2014). Concussion among female middle-school soccer players. *JAMA pediatrics*, *168*(3), 258-264.

Peterson M. 1974. Construction of sports grounds based on physical soil characteristics. Proc. of the 2nd Int. Turfgrass Res. Conf. 270-275.

Qu, H., Zhang, S., Sorochan, J. C., Weinhandl, J. T., Thoms, A. W., & Dickson, K. H. (2020). Effects of synthetic turf and shock pad on impact attenuation related biomechanics during drop landing. *Sports biomechanics*, 1–13. Advance online publication. https://doi.org/10.1080/14763141.2019.1690570.

Richardson, M.D., D.E. Karcher, and L.C. Purcell. 2001. Quantifying turfgrass cover using digital image analysis. Crop Sci. 41:1884-1888.

Rogers III, J.N. and D.V. Waddington. 1989. The effect of cutting height and verdure on impact absorption and traction characteristics in tall fescue turf. J. Sports Turf Res. Institute. Vol. 65, p. 80-90.

Saunders, N, Twomey, D, Otago, L. 2011. Clegg hammer measures and human external landing forces: is there a relationship? Int J Sports Sci Eng. 5(4): 231–236.

Sever Mutlu, S., Irkörücü, D., Sancar, B. and Bahar, T. 2020. Evaluation of vegetative bermudagrasses for traffic tolerance. Acta Hortic. 1279, 153-158 DOI: 10.17660/ActaHortic.2020.1279.23.

Sone, J. Y., Courtney-Kay Lamb, S., Techar, K., Dammavalam, V., Uppal, M., Williams, C., Bergman, T., Tupper, D., Ort, P., & Samadani, U. 2018. High prevalence of prior contact sports play and concussion among orthopedic and neurosurgical department chairs. Journal of neurosurgery. Pediatrics, 22(1), 1–8.

Sosin, D. M., Sniezek, J. E., and Thurman, D. J. 1996. "Incidence of Mild and Moderate Brain Injury in the United States in 1991," Brain Injury, Vol. 10, No. 1, pp. 47–54.

Stimmel, S. 1990. Improving sports turf tolerance from the ground up. Lawn and Landscape Maintenance 11(8):28-31.

Thoms, A.W., J.C. Sorochan, J.T. Brosnan, and T.J. Samples. 2011. Perennial ryegrass (Lolium perenne L.) and grooming affect bermudagrass traffic tolerance. Crop Sci. 51:2204-2211.

Topp, G.C., and P.A. Ferré. 2002. Water content. In: J.H. Dane and G.C. Topp, editor, Methods of soil analysis: Part 4. Physi- cal methods. Book Ser. 5.4. SSSA, Madison, WI. p. 241–254. doi:10.2136/sssabookser5.4.c19.

Torg, J.S. 1991. Athletic Injuries to the Head, Neck, and Face (2nd ed.). St. Louis: Mosby.

Trappe, J., Patton, A., Richardson, M. 2009. Bermudagrass cultivars differ in their traffic tolerance. Arkansas Turfgrass Rpt. 2008:137–140.

Trappe, J. M., Patton, A. J., & Richardson, M. D. 2011. Bermudagrass cultivars differ in their summer traffic tolerance and ability to maintain green turf coverage under fall traffic. *Applied Turfgrass Science*, *8*(1), 1-10.

Trenholm, L.E., R.N. Carrow, and R.R. Duncan. 2000. Mechanisms of wear tolerance in seashore paspalum and bermudagrass. Crop Science. 40:1350-1357.

United States Golf Association. 2007. United States Golf Association Recommendations for a Method of Putting Green Construction. Available online:

http://www.usga.org/turf/course_construction/green_articles/putting_green_guidelines.html (accessed on 16 July 2016).

Viano, D.C.; Casson, I.R.; Elliot, J.P.; Zhang, L.; King, A.I.; Yang, K.H. 2005. Concussion in professional football: Brain responses by finite element analysis: Part 9. Neurosurgery 5, 891–916.

Walker, E., & Walker, K. When to Play, When to Postpone? Using Agronomic Measures to Determine Probability of Player Injury. *ESMQ New Researcher Award*, 562.

Younger, V.B. 1958. Bermudagrass for turf in the southwest. California Turfgrass Culture. 8:21-23.

APPENDICES

Appendix A. Tables

Table 1. Partial analysis of variance for soil type, simulated traffic event, season, soil bulk density, and organic matter on hybrid bermudagrass (Cynodon dactylon X C. transvaalensis Burtt Davy), when volumetric water content was included as a covariate, Knoxville, TN, during 12 September – 13 October 2016, 16 May – 15 June 2017, 18 September – 19 October 2017, 16 May – 21 June 2018, respectively.

Treatments	DF	CFH	Clegg	PGC	SBD	OM
Soil type (T)	1	***	**	NS	NS	NS
Simulated Traffic Event (E)	39	**	***	***	NS	NS
Season (S)	1	NS	NS	NS	NS	NS
Year (Y)	1	NS	NS	NS	NS	NS
T*E	39	NS	NS	NS	NS	NS
T*S	1	NS	NS	NS	NS	NS
T*Y	1	NS	NS	NS	NS	NS
E*S	39	NS	NS	NS	NS	NS
E*Y	39	NS	NS	NS	NS	NS
T*E*S	39	NS	NS	NS	NS	NS
T*E*Y	39	NS	NS	NS	NS	NS
T*E*S*Y	39	NS	NS	NS	NS	NS

*, **, ***, significant at the 0.05, 0.01, and 0.001 probability levels, respectively

Appendix B. Figures

Figure 1. ASTM F355-E on hybrid bermudagrass [‘Tifway’ *Cynodon dactylon* (L.) Pers. X *Cynodon transvaalensis*, Burtt-Davy], Knoxville, TN.

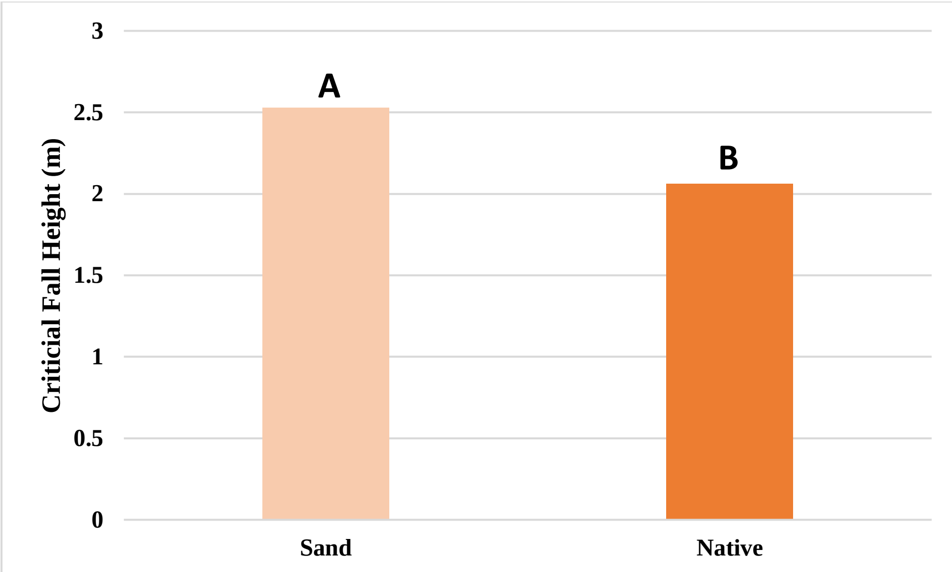

Figure 2. Transformed critical fall height values of an ASTM sand constructed root zone and native soil root zone pooled after 40 simulated traffic events on hybrid bermudagrass ['Tifway' *Cynodon dactylon* (L.) Pers. X *Cynodon transvaalensis*, Burtt-Davy], when volumetric soil water content was included as a covariate, Knoxville, TN. 12 September – 13 October 2016, 16 May – 15 June 2017, 18 September – 19 October 2017, 16 May – 21 June 2018, respectively.

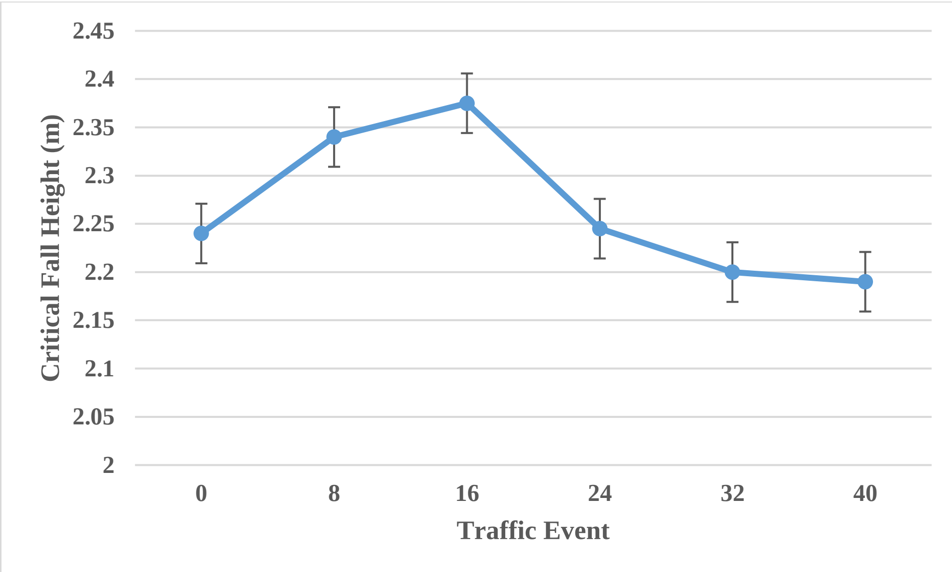

Figure 3. The impacts of simulated traffic events for transformed critical fall height values to determine a critical fall height of 1000 head injury criteria pooled using an ASTM sand constructed root zone and native soil root zone on hybrid bermudagrass [‘Tifway’ *Cynodon dactylon* (L.) Pers. X *Cynodon transvaalensis*, Burtt-Davy], when volumetric soil water content was included as a covariate, Knoxville, TN. 12 September – 13 October 2016, 16 May – 15 June 2017, 18 September – 19 October 2017, 16 May – 21 June 2018, respectively.

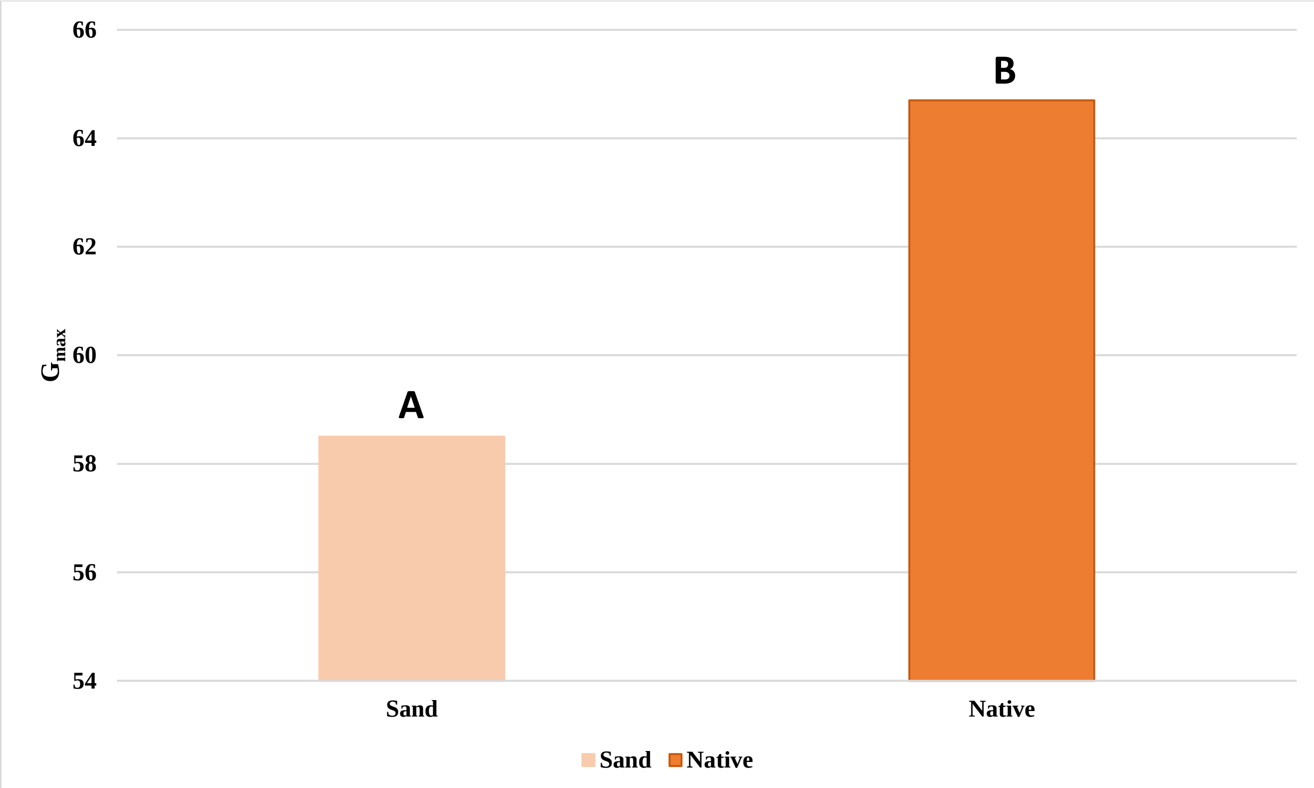

Figure 4. Transformed Surface hardness (G_{max}) of an ASTM sand constructed root zone and native soil root zone pooled over 40 simulated traffic events on hybrid bermudagrass ['Tifway' *Cynodon dactylon* (L.) Pers. X *Cynodon transvaalensis*, Burtt-Davy], when volumetric soil water content was included as a covariate in Knoxville, TN. 12 September – 13 October 2016, 16 May – 15 June 2017, 18 September – 19 October 2017, 16 May – 21 June 2018, respectively.

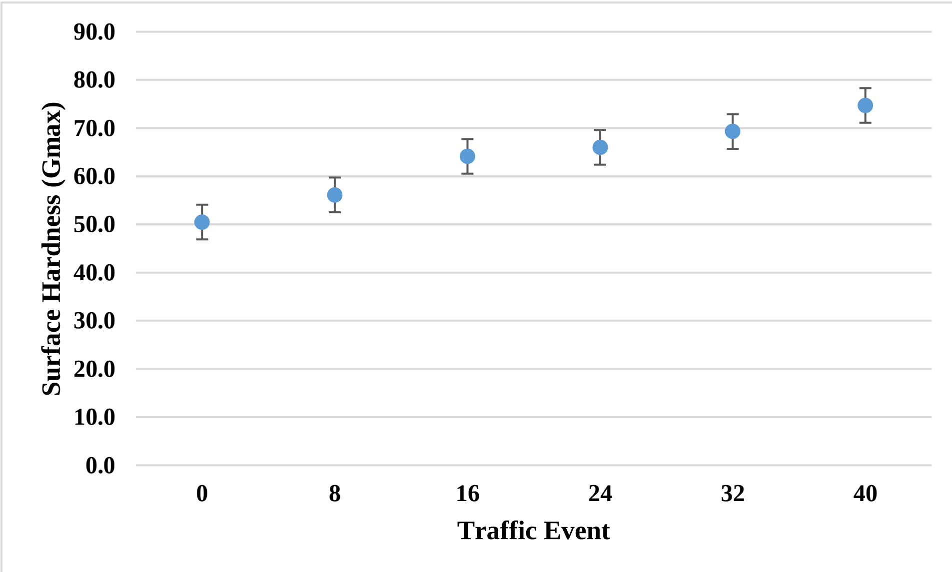

Figure 5. Surface hardness (G_{max}) of an ASTM sand constructed root zone and native soil root zone following 0, 8, 16, 24, 32, and 40 simulated traffic events to hybrid bermudagrass [‘Tifway’ *Cynodon dactylon* (L.) Pers. X *Cynodon transvaalensis,* Burtt-Davy] when volumetric soil water content was included as a covariate in Knoxville, TN. 12 September – 13 October 2016, 16 May – 15 June 2017, 18 September – 19 October 2017, 16 May – 21 June 2018, respectively.

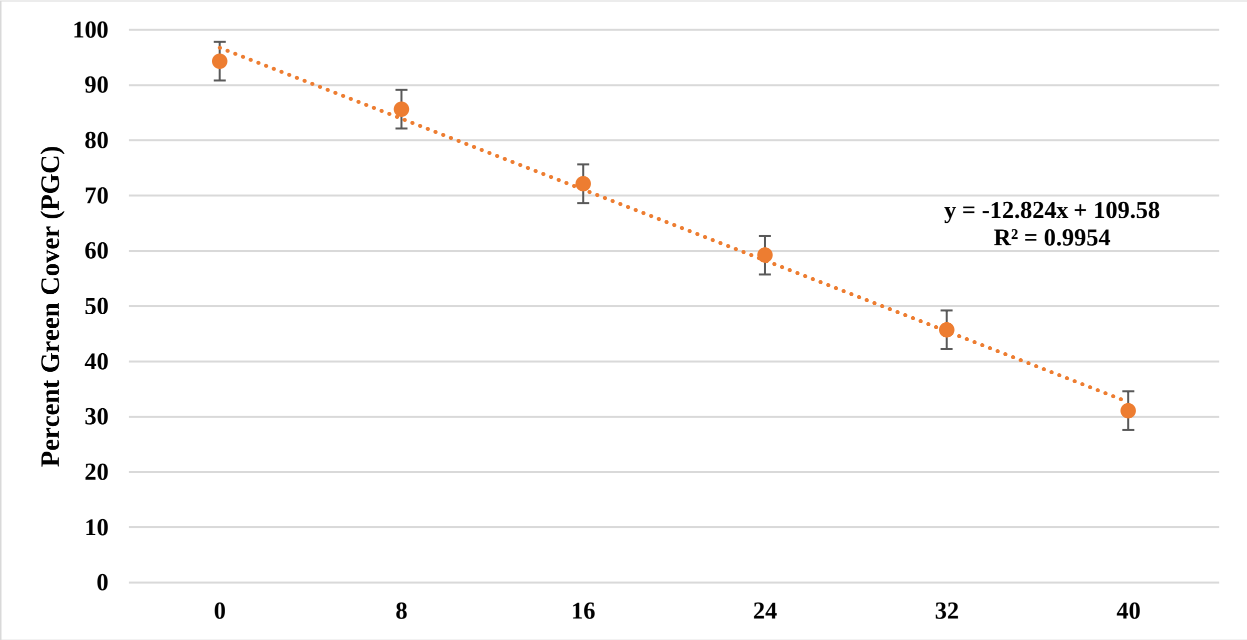

Figure 6. Percent green turfgrass cover of an ASTM sand constructed root zone and native soil root zone following 0, 8, 16, 24, 32, and 40 simulated traffic events to hybrid bermudagrass [‘Tifway’ *Cynodon dactylon* (L.) Pers. X *Cynodon transvaalensis*, Burtt-Davy] when volumetric soil water content was included in a covariate in Knoxville, TN. 12 September – 13 October 2016, 16 May – 15 June 2017, 18 September – 19 October 2017, 16 May – 21 June 2018, respectively.

COMPARING GROUND REACTION FORCES GENERATED USING STANDARD SPORTS TURF SURFACE TESTING DEVICES

Table 2. Summary of ground reaction forces of a human, compared to all devices tested over synthetic turf (AstroTurf Gameday 3D60) on a force platform with various drop heights in a biomechanics laboratory at the University of Tennessee in Knoxville, TN during 6 December, 2017.

Test Drop Height (cm)	**GRF (N) without Shockpad**	**GRF (N) with Shockpad**	**% Change (w/ & w/o Shockpad)**
CIST (46)	2084	1612	23
F355-A (61)	11295	7695	32
TruFirm (69)	781	752	4
F355-E (60)	5517	4223	23
F355-E (100)	8386	6245	26
F355-E (130)	10384	7739	25
AAA (5.5)	2742	2463	10
Human* (60)	1078	1025	5

*Human data obtained from Qu et al., 2020.

Table 3. Summary of ground reaction forces of multiple surface testing devices tested over artificial turf (AstroTurf Gameday 3D60) with and without a pad in a biomechanics laboratory at the University of Tennessee during 6 December 2017 in Knoxville, TN.

Treatments	GRF
Device	***
Pad	***
Device*Pad	***

SUMMARY

There are a variety of testing instruments used to test the performance of turfgrasses. Most of these devices used to evaluate the firmness of playing surfaces use different masses and shapes, and are dropped from varying heights. The CIST, ASTM F355-A, ASTM F355-E, ASTM F3189, and USGA TruFirm Turf Firmness Meter were all tested on synthetic turf over a force platform (1200 HZ, Advanced Mechanical Technologies, Inc., Watertown, MA, USA) to determine the ground reaction forces (Newtons) for each individual testing device (Table 2). A piece of synthetic turf (AstroTurf Gameday 3D60, AstroTurf, Dalton, GA, USA) was cut to fit the force platform (60 cm x 60 cm) and was infilled with sand and rubber according to installer specifications. The GRF of each device was measured over the force platform according to their standard operating procedures.

There were GRF differences between testing devices when dropped over the force platform (Table 3). Therefore, these devices are not recommended to be used to predict athlete performance.

VITA

Taylor Lewis Williams was born in Maryville, TN, on March 8, 1994. He grew up in Lenoir City, TN, and attended Lenoir City High School, graduating in 2012. After graduation, he pursued a Bachelor of Science degree from the University of Tennessee, concentrating primarily on turfgrass management. Taylor was fortunate to take a five-month internship working for the Baltimore Orioles grounds crew. He graduated in the spring of 2016 and accepted a graduate research position at the University of Tennessee in Plant Sciences under Dr. John Sorochan. Upon finishing his thesis, Taylor plans to continue researching all types of turfgrass surfaces at the University of Tennessee.