Utilization of 'TifGrand' Bermudagrass for Sports Turf: Wear Tolerance, Shade Response, and Quality Improvement

by

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Abstract

'TifGrand' is a relatively new, reportedly wear-, shade-, and drought-tolerant bermudagrass cultivar. TifGrand is similar to other bermudagrasses such as 'Tifway' and 'TifSport', and yet, displays some unique features, uncommon to its family. Studies were conducted to evaluate and compare TifGrand to other bermudagrass cultivars for wear tolerance, as influenced by increasing levels of simulated wear applied with a Cady Traffic Simulator, similarly to American-football wear. Wear tolerance was investigated as in fall durability during simulation of wear, and spring response following fall wear-simulation. TifGrand consistently resulted in equal or greater fall durability, green cover, traction, and spring recovery, compared to other cultivars. Whereas some differences were noticed under light traffic, pronounced cultivar differences were noticed under higher frequencies of uninterrupted simulated wear. Studies were also conducted to evaluate and compare TifGrand to other bermudagrass cultivars as influenced by different shade regimes. Diurnal shade regimes, as well as continuous, increasing shade levels were simulated and turfgrass responses analyzed. TifGrand resulted in superior performance under moderate shade when compared to full-sun. Etiolation was a key factor in bermudagrass shade tolerance: cultivars with decreased etiolation (TifGrand and 'TifSport') resulted in superior quality. Physiological adaptations were also noticed, however, as a response to shading rather than as a tolerance mechanism. Additionally, herbicides and PGRs were applied attempting to suppress TifGrand seedhead formation, and to increase aesthetic

quality. Flucarbazone plus trinexapac-ethyl and imazethapyr successfully suppressed TifGrand seedheads safely, resulting in quality improvement.

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List of Abbreviations

A	absorbance
ACL	anterior cruciate ligament
AFL	Australian Football League
AL	Alabama
am	*ante meridiem* (before noon)
ANOVA	analysis of variance
ASTM	American Society for Testing and Materials
bar	refers to unit of pressure 1 bar = 100 kPa
BCS	Bowl Championship Series
BS	British Standards Institution
BTS	Brinkman Traffic Simulator
C	Celsius
c	coefficient of restitution
CA	California
CD	coefficient of durability
CF	coefficient of sliding friction
Chl *a*	chlorophyll *a*
Chl *b*	chlorophyll *b*
CO	Colorado
Co.	Company

CTS	Cady Traffic Simulator
cm	centimeter
DAI	days after initiation
DAIA	days after initial application
DE	Delaware
e.g.	*exempli gratia* (for example)
FL	Florida
FIFA	Fédération Internationale de Football Association
FIH	Fédération Internationale de Hockey
g	grams
g	acceleration due to gravity
$g\ cm^{-3}$	grams per cubic centimeter
GA	Georgia
GCI	green cover index
G_{max}	maximum gravity (weight per unit mass)
h	height
ha	hectare
HSB	hue, saturation, and brightness
IA	Iowa
IL	Illinois
IN	Indiana
Inc.	Incorporated
K	potassium

kg	kilogram
kg cm^{-1}	kilograms per centimeter
kPA	kilopascal
L	liters
LSD	least significant difference
m	meter
m	mass
µg	microgram
MA	Maryland
MLS	Major League Soccer
mL	mililiter
mm	millimeter
MN	Minnesota
MO	Missouri
mol	mole
MPA	megaPascal
N	nitrogen
N	normal
NC	North Carolina
NCAA	National Collegiate Athletic Association
NDVI	normalized difference vegetation index
NE	Nebraska
NFL	National Football League

NGC	non-green turfgrass cover
NJ	New Jersey
NTEP	National Turfgrass Evaluation Program
NY	New York
N m	Newton meter
OH	Ohio
P	phosphorous
PA	Pennsylvania
PAR	photosynthetically active radiation
PEP	phosphoenolpyruvate carboxylase
PGR	plant growth regulator
PVC	polyvinyl chloride
r	coefficient of correlation
RCB	randomized complete block
RGB	red, green, and blue color model
ROS	reactive oxygen species
RuBP	ribulose-1,5-biphosphate carboxylase
SAS	Statistical Analysis Software
spp.	species
STRI	Sports Turf Research Institute
TGC	turfgrass green cover
TNC	total nonstructural carbohydrates
TQ	turfgrass quality

TTC	total turfgrass cover
U.S.	United States
USGA	United States Golf Association
UV-B	ultraviolet B
V	volt
vol vol^{-1}	volume per volume
v	linear velocity
W	watt
WAI	weeks after initiation
°	degree of arc

LITERATURE REVIEW

[Aldahir, P.C.F. and J.S. McElroy. 2014. A review of sports turf research techniques related to playability and safety standards. Agron. J. 106:1297-1308]

Sports turf and sports fields

Sports turf can be defined as the turfgrass and soil environment managed for fast and aggressive sporting events such as American football and soccer. Sports turf must offer a safe playing surface for the athletes, and must obey a determined sport's regulations. It is desirable that the turfgrass be durable enough to resist and quickly overcome the stress caused by sporting events (Pu halla et al., 1999). It is important to separate the terms *turf* and *turfgrass,* and *sports turf* from *sports field* or *pitch*. While turfgrass only refers to the plant community, turf includes a portion of the turfgrass-growing medium (Turgeon, 2011). Sports turf refers to turf related management practices that prepare the turfgrass and soil components for sporting events. Sports field or pitch refers to the construction and implementation of layouts and designs necessary for specific sporting events. Sports turf, in terms of this review, does not include golf course turf as the majority of playing related damage to golf course turf is done by golf clubs or ball marks, not by shearing or friction caused by athlete movements (Fry et al., 2008; Kane, 2004; McMahon et al., 1993; Orchard, 2003). In fact, Ferguson, (1959) and Evans (1988) concluded that, with proper golf course management, abrasion from foot and vehicular traffic is not enough to damage the plant crown, and turf recovery is rather quick. In turn, sports turf wear is by nature more aggressive, often resulting in damage to the plant crown as one detrimental effect (Puhalla et al. 1999).

According to the American Society for Testing and Materials (ASTM; ASTM, 2011), an ideal sports turf "should consist of a dense, uniform, smooth, and vigorous natural turfgrass, which also increases safety providing the athletes stable footing, cushioning for impacts, falls, slides and/or tackles, and cooling the surface during hot weather". This ASTM definition, however, only mentions the term turfgrass, leaving unclear to the reader if the soil component was not considered, or if by turfgrass, the ASTM also meant to include it. If the soil component is considered, turf would be a more appropriate term. Semantic differences aside, the ASTM definition points out two key aspects related to the ideal sports turf: the properties of the turf and/or turfgrass and their impact on sports and players. Quantification of turf properties and their impact on player performance and safety has varied widely. Herein, we provide a review of sports turf research techniques, playability standards and their interaction with safety; as well as ideas regarding the future of sports turf research.

History

According to Escritt (1969), the turfgrass industry in the United States was more developed by the 1960's compared to the rest of the world. Also in the 1960's, Britain, home of the Sports Turf Research Institute (STRI), became a standard for European sports turf research. The United States was the most organized country in the world regarding sports turf research, not only with a well specialized industry divided into utility, aesthetics, and recreation (Nutter, 1965), but also the research was done mostly by public institutions and universities, differing from others. In fact, the interest in turfgrass research in the U.S. started in the late 1800's to the early 1900's in Connecticut, Rhode Island, and Virginia, including the allocation of funds for turfgrass research by the federal government through the Agricultural Appropriations Act in 1901 (Seagle and Iverson, 2002). Most agricultural experiment stations started turfgrass research after World War II (Huffine and Grau, 1969) allowing the information to be divided into five regions: Northeast, Southeast, Midwest, Central Plains, and West Coast. These efforts allowed a substantial amount of information to be generated for these very ecologically and climatologically different regions containing diverse grass types and management techniques (Cornman, 1969; Gilbert, 1969; Daniel, 1969; Keen, 1969; Bengeyfield, 1969). Despite the importance of soil factors for turf playability, early research focused on ball/surface interactions governed by plant factors (Canaway, 1985; Bell et al. 1985; Canaway and Baker, 1993; Baker and Canaway, 1993).

Outside of the United States and the United Kingdom, sports turf research began in earnest in the late 1960's (STRI, 1969). The first report of a full time turfgrass researcher in Canada dates back to 1968 (Switzer, 1969). In Germany, initial reports clarified the state of the turfgrass industry as unsatisfactory, but promising due to the development of the economy at the time (Boeker, 1969). In the Netherlands, agriculture, and therefore turfgrass, faced a lack of physical space for sports turf areas, contributing to below average maintenance standards (STRI, 1969). Lack of space in cities generated a need for multiuse sports facilities, which propelled research in the wear tolerance of turfgrass species, due to heavy use (Ruychaver, 1969). Early research in sports turf focused on very basic factors such as turfgrass species adaptability to diverse climates, and identification of troublesome weeds and diseases, while little attention was dedicated to the quality and playability of the fields (STRI, 1969). In the last 20 years, research in Australia focused on playing surface properties and correlation with player injury (Orchard, 2001). In Brazil, the first turfgrass research projects were initiated in 2000, focusing on sod production, and little or no attention was given to sports turf research, a scenario that is slowly changing (Godoy et al., 2012).

Sports turf playability and wear

Sports turf *playability* is a term referring to how a given sports field plays allowing for successful, uninhibited execution of a given sport. Key components of playability include how the athlete and the ball (or object played) interact with the sports turf. Playability is a multifaceted, subjective factor. Researchers must attempt to translate a subjective idea of "how the field plays" into an objective, quantifiable measurement (Baker and Canaway, 1993). Playability of a field is, as suggested by Canaway and Baker (1993), a result of plant and soil factors as influenced by the environment and their interaction with the ball/object played and player movements (Figure 1). These interactions result in turf sporting wear. *Wear* is the result of the forces applied to the turf during usage, causing soil compaction, turfgrass tearing, crushing and scuffing, with occasional plant disruption and burying (Beard, 1973). *Wear tolerance*, also referred to as *durability*, is the ability of a field to resist and overcome wear, maintaining adequate playability (Canaway, 1975). The concept of wear tolerance by turf managers is composed by the actual turfgrass tolerance to wear (turfgrass durability), and turfgrass *recuperative ability* (or recovery ability) (Beard, 1973). Wear includes turf stress caused by playing action, playing equipment and apparel, and maintenance practices (Canaway and Baker, 1993). Nowadays, game operations and setup also contribute to wear, as well as non-sporting events that may take place on a sports field such as concerts, ceremonies, and social gatherings. Wear tolerance research is most often focused on maintaining adequate playability of a sports field throughout a season, but it can also refer to short term, within-game tolerance to wear.

Quantifying Sports Turf Playability and Wear: Common Research Techniques

Both plant and soil influence sports turf wear. Plant factors that directly influence wear tolerance and playability are turfgrass species, cultivar, biomass, density, ground cover, height of cut and root biomass (Canaway and Baker, 1993). Canaway (1981) measured wear tolerance as percent ground cover after simulated wear. After 56 passes of a wear machine, annual bluegrass (*Poa annua* L.) was shown to be the most wear tolerant species remaining at 71% ground cover, followed by perennial ryegrass (*Lolium perenne* L.) 'Aberystwyth S.23' (38%), Timothy-grass (*Phleum pratense* L.) 'Aberystwyth S.48' (28%), Kentucky bluegrass (*Poa pratensis* L.) 'Baron' (19%), highland bentgrass (*Agrostis castellana* Boiss. & Reut.*)* 'Highland' (6%), chewing's fescue (*Festuca rubra* L. *ssp. Commutata* Gaud.) 'Highlight' (6%), and red fescue (*Festuca rubra* L. *ssp. rubra*) 'Borcal' (3%). As this study evaluated wear tolerance by measuring percent ground cover, it is possible that the top ranked annual bluegrass did overcome wear by successive germination, and not by actually tolerating wear damage. In fact, a later study by Canaway (1984) found annual bluegrass to have the least shear strength among eight cool season grass species and cultivars. *Shear strength* is another way to measure turf and turfgrass wear tolerance by measuring *torque*. In turf, shear strength can be measured by the rotational force applied by a cleated plate promoting complete turf shearing (Canaway and Bell, 1986). Roche et al. (2008) noticed differences in turf shear strength within the warm season grasses: swazigrass (*Digitaria didactyla* Willd) (82 N m) and bermudagrass (*Cynodon dactylon* L. Pers) (76 N m) showed highest traction readings, whereas *Zoysia* species (*Zoysia matrella* L.: 60 N m; *Zoysia japonica* Steud: 65 N m) and Kikuyugrass (*Pennisetum clandestinum* Hochst. ex Chiov.) (56 N m) revealed to have easily breakable stolons, falling on the lower end of traction values. St. Augustinegrass (*Stenotaphrum secundatum* (Walter) Kuntze) (62 N m) and seashore paspalum (*Paspalum vaginatum* Sw.) (65 N m) had roughly the same traction readings between the highest and lowest traction groups above cited. Park et al. (2010), assessed wear tolerance as loss or recovery of canopy density, and found seasonal differences for wear tolerance in Kentucky bluegrass. Most reduction in density occurred in the fall, whereas greater recovery potential was noticed during fall and spring. According to Park et al. (2010), verdure of Kentucky bluegrass submitted to wear was greater in the spring. *Verdure* is another plant factor influencing sports turf playability. Verdure refers to the remaining living grass above the ground after mowing. It is an adequate characteristic to evaluate in sports turf, as it plays a key role in cushioning, wearability, and rapid recovery of the turf. Soil bulk density was another factor reported to be associated with traction. Zebarth and Sheard (1985) found increased traction (greater shear strength) with increasing bulk density values for bare-soil. In the same study, turf shear strength was increased by three-fold in soils with a root system compared to soil only systems.

Lastly, digital image analysis for turfgrass cover can be performed to measure wear. Recently, this technique has been used to quantify percent ground cover and turfgrass genetic color with relative consistency, turning subjective visual ratings into an objective measurement (Karcher and Richardson, 2005). The analysis often utilizes an automated macro for SigmaScan Pro software (Systat Software Inc., San Jose, CA) to sequentially analyze pictures taken with the "light box" apparatus, however, other software can be used if setup properly. Sequential evaluation doesn't require manual labor after the macro is setup. The light box provides a constant environment for all pictures across the experimental area, and across data collections at different timings. Absolute levels of red, green, and blue (RGB) are converted to a hue, saturation, and brightness (HSB) color scale through an appropriated algorithm. Beyond the fact the RGB scale can confound the analysis due to interference of the intensity of red and blue with levels of green of a green image, the HSB scale is based on the human perception of color, which justifies a scale conversion. In HSB scale, hue represents the angle on a continuous circle from 0 to 360˚, saturation represents the purity of the color from 0 (gray) to 100% (fully saturated), and brightness represents the level of lightness or darkness of the image (0% = black, 100% = white) (Karcher and Richardson, 2005). Digital image analysis performed by Karcher and Richardson (2003) was able to identify differences in zoysiagrass, bermudagrass, and creeping bentgrass (*Agrostis palustris* Huds.) color due to various fertility treatments, similarly to the differences found through visual assessment of turfgrass color. The study also reaffirmed the validity of visual ratings for turfgrass color, especially when performed by a single evaluator.

Wear sources

A given sports field or pitch may host more than one type of events. Events that may take place on the sports turf can be *sporting* and *non-sporting events*. Sporting events include matches and games, scrimmages, practices, walkthrough routines, and physical fitness sessions. Non-sporting events include social and community gatherings such as dinners, graduation ceremonies, charity events, cheerleading/band practices, and fairs. Also, events regarding complex structure and logistics such as concerts may take place on sports fields, greatly contributing to wear damage.

Sporting wear is the wear damage directly resultant from game/practice action. Sporting wear varies according to the type of sport played, level of competitiveness, frequency, and intensity (Puhalla et al., 1999). For example, in American football, sporting wear damage is concentrated between the hash marks and caused by athletes' abrupt movements associated with changes in direction and speed, and by falls caused by tackles. In soccer, sporting wear injury is more evenly distributed throughout the field; however, it is caused by less intense movements and a sliding motion-like type of tackle. Baseball sporting wear occurs mainly in the skinned infield, and it is concentrated on the base paths, pitcher's mound, home plate and batters' boxes. On the grassed area, baseball sporting wear is concentrated at the outfielders position spots, on the coaches' position spots, and on the path between the home plate and the pitcher's mound.

Non-sporting wear results from non-sporting events or game operations that take place in the game setup process. Non-sporting wear is caused mainly by excessive foot traffic and turfgrass stresses caused by apparatus placed on the turf, which can include compression/abrasion of the turf, darkness, and increased humidity and temperature resultant from temporary "flooring" systems, tarps, stages, tables, tents, and benches. Non-sporting wear in American football occurs on the sidelines due to placement of tarps, benches, coolers/heaters, trainers, and other apparati; and on areas reserved for staff, media, and cheerleading personnel. Soccer non-sporting wear also occurs on the field's surroundings, similarly to American football. Non-sporting wear on baseball fields occurs at the field's accesses from the teams' dugouts.

Youth, junior, community and recreational, college, and professional sports also vary in regard to wear intensity. As is expected, wear damage is minimal for youth sports, and increasing along increasing levels of competitiveness, up to intense wear in professional sports. An easy way to identify sporting wear is by assuring that wear damage is caused by the athletes/players, coaches (especially in baseball), or referees (Figure 2).

Assessment of non-sporting wear is very important, as non-sporting events are becoming more frequent, and game setup has become more elaborated, attempting to enhance the "gameday experience" to live and broadcast viewers. Another significant change in the modern era of sports is that stadia conformation and design has changed to taller and roofed venues, providing a more difficult environment for turfgrass growth and recovery (Beard, 1973; Baker, 1995, Kuhn and Hayden, 2012). Kuhn and Hayden (2012), considering the challenges of preparing soccer fields for the 2014 World Cup in Brazil, stated that sports field management within a modern stadium is more complex than in a small stadium or open practice field. In fact, a field survey conducted by Baker (1995) on 28 fields found that shade caused by stadia design and construction resulted in decreased turfgrass cover, soil temperature, and traction; and increased weed cover, and divots removed. Thus, the need not only for more wear-tolerant sports turf, but also the need for better wear management in such complex venues, in- and off-season.

Sporting wear simulation

Practical difficulties researching turf wear in actual field usage situations result in the need for artificial *wear simulation*. Ideal wear simulation replicates the horizontal and vertical forces that affect both the soil and the turfgrass, in a quick and reproducible manner. Ideal athletic-wear simulation can be difficult to achieve. The vertical component of wear is responsible for soil compaction, and it is dependent on the pressure produced. In turn, pressure is dependent on the type of footwear used and the area of contact through which the forces interact with the turf (Soane, 1970). For cleated footwear, the contact area is reduced and the pressure is increased. Beard (1973) reported that soccer shoes with seven cleats with diameter of 0.9 cm would be enough for a 91 kg man to produce a pressure of 10.57 kg cm^{-1} when standing and up to three times this value when running, however this value was underestimated. Studies utilizing force plates showed that the pressure caused by the same type of shoes and cleats would be actually of 61.3 kg cm^{-1}, enough to cause complete cleat penetration (Canaway, 1975). In sporting situations, the horizontal forces caused by the players' footwear may rise from 25 to 87% of the player's body weight for walking and running/sprinting, respectively. When caused by cleated shoes, both vertical and horizontal forces result in compression, compaction, disruption, and shearing of the turf (Harper et al., 1961). Where cleats are not present in the shoe, the force is translated into friction, causing turfgrass abrasion (Ferguson, 1959; Canaway, 1975). Equipment utilized for this purpose includes modified turf management equipment, studded rollers and drums, and machines specifically developed for wear simulation. “Wear machines” have one or a combination of the following characteristics: turf compaction, abrasion, shearing, and tearing (Canaway, 1975; 1982).

Simulated wear is often imposed on turfgrass by trafficking machines that attempt to mimic wear reproducing vertical forces to cause soil compaction as well as horizontal forces to cause tissue tearing (Henderson et al., 2005). A variety of machines were developed overtime consisting basically of a pair of cleated or smooth drums/rollers, with different rolling speeds to create the tearing effect on the turf, while causing a rolling-type compaction effect (Canaway, 1976; Cockerham and Brinkman, 1989; Shearman et al., 2001). The Brinkman Traffic Simulator (BTS) uniformly reproduces both vertical and horizontal forces, and it is calibrated so that 2 passes of the BTS create the same number of cleat marks per square meter that one National Football League (NFL) game produces between the hash-marks at the 40-yard line (Cockerham and Brinkman, 1989). Despite advantages of the BTS, it does not reproduce accurately the highly variable forces at the playing surface during athletic competition. The Cady Traffic Simulator (CTS) was developed from adaptations of a walk-behind core aerifier to produce more realistic sporting wear simulation, becoming an alternative to the roller-type machines (Henderson et al., 2005). A cleated foot substitutes each of the four coring head units so that it strikes the ground as the machine moves. The CTS is calibrated to make 2 passes obtaining 667 cleat marks m^{-2} similar to an NFL game, but creating more turfgrass wear than the BTS (Henderson et al., 2005). Modifications on the CTS include (i) a metal spacer system added to control the height of operation, (ii) a crank arm adjustment to promote more lateral motion, and (iii) simulated cleated feet: a cushioning system utilizing looped tires and a metal plate attached to the bottom with 7 cleats. Testing the machine with force plates revealed that the machine produced vertical (*compressive force*) and horizontal components (front to back and side to side forces). The horizontal forces were combined into *net shear force* using Pythagorean theorem ($c^2 = a^2 + b^2$). When driving the machine forward, the compressive force was over 5 times greater than the horizontal forces and more variable forces were produced with this sense of motion. On reverse, the magnitude of the forces decreased greatly while the angle of impact increased, resulting in more turf shearing. One game of American football type wear is mimicked by this machine by combining one pass forward (compaction effect) and one pass reverse (tearing effect) over a turfgrass area (Henderson et al., 2005).

Turf research measurements

Measurements commonly utilized to quantify sports turf characteristics can be divided into turf quality and turf playability measurements. Turfgrass quality (TQ) is often evaluated through subjective measurements; however, objective measurements can also be used. In the U.S., subjective measurements often follow the National Turfgrass Evaluation Program (NTEP) guidelines (Morris and Shearman, 1998). Turfgrass quality combines turf characteristics such as color, density, texture, and stress caused by pests or the environment; and can be rated as overall quality or as individual ratings of the measurements cited above. Landschoot and Mancino (2000) compared visual and instrumental color measurements in 10 bentgrass cultivars, finding inconsistency among different evaluators in regard to visual assessment of color in a 1-9 scale. Visual estimates are commonly measured as a percentage (McElroy et al., 2005; Flessner et al., 2011; Settle et al., 2001). Percentage ratings are commonly used for measuring turfgrass damage due to wear, environmental stress, pathogens and pests, and weed infestation. Percentages can also be performed as objective measurements through counts (e.g. percent seed germination). Another objective measurement often performed in turfgrass and sports turf science is weight (e.g. clippings or root dry weight) (Morris and Shearman, 1998). Such measurements are extensively discussed in previous literature.

Specific research techniques to sports turf

Ball rebound resilience. Ball rebound resilience is the ratio of height bounced versus height dropped, and this vertical drop test does not take into account spin or angled ball behavior (Baker and Canaway, 1993). The height of drop varies widely (Langvard, 1968; FIH, 1988) and recording of the bounced height can be recorded by eye or by video with slow motion replay for cases where the ball is small and the bounce height is low (Colclough, 1989). This test can be correlated to surface hardness (Holmes and Bell, 1985; Baker and Isaac, 1987), using an Impact Soil Tester, often referred to as “Clegg hammer” or “Clegg meter” to determine the correlation of surface hardness on ball rebound resilience (Clegg, 1976). Regardless, ball rebound resilience is measured as follows:

$$ball\ rebound\ resilience = \frac{height\ bounced}{height\ dropped}\ x\ 100$$

Ball standardization is a factor affecting consistency of these measurements (Baker, 1989) as found by Holmes and Bell (1985): ball rebound resilience on concrete increased 5.1% across the pressure range of 60 to 110 kPa, the acceptable pressure range by the Football Association. For the Fédération Internationale de Football Association (FIFA) approved balls at any given pressure, maximum variation on ball rebound resilience was 14% (Baker and Canaway, 1993). Acceptable ball bounce resilience values for different sports were proposed by Dury and Dury (1983) and Sports Council (1984a, b), regardless of the lack of ball standardization. Values for tennis ranged from 25-36% (Dury and Dury, 1983). Soccer ball rebound resilience values ranged roughly from 20 to 40% according to both sources. For field hockey, the range was from 20 to 40% according to the Sports Council (1984a), which differed from 8-12% reported by Dury and Dury (1983). A difference was also noticed for cricket: 20 to 34% according to the Sports Council (1984b), and 12 to 19% according to Dury and Dury (1983). Ball rebound resilience is also affected by the sports field construction method. Magni et al. (2004) found that higher rebound values are associated with native soil type fields (76%), whereas lowest rebound values are associated with sandy fields (68%). The same study also revealed a significant interaction between fields built on a sandy profile and the turfgrass choice: tall fescue (*Lolium arundinaceum* (Schreb.) Darbysh.) established in a sandy field provided 67% rebound. For perennial ryegrass the values were higher and also affected by the physical properties of sand: 75% rebound on non-porous and 83% on porous sand. The relationship between ball pressure (inflation) and ball rebound resilience was assessed by Holmes and Bell (1985) for seventeen different soccer ball types, revealing a proportional decrease in ball rebound following a decrease in ball inflation. Ball rebound values ranged from 54 to 69% at an inflation pressure of 1.1 bar, whereas at 0.6 bar rebound values ranged from 49 to 64% (Holmes and Bell, 1985). Soccer ball inflation regulations were changed by FIFA after the 1982 World Cup in Spain: until then, maximum inflation was only 0.7 bar (Holmes and Bell, 1985).

Coefficient of restitution. Coefficient of restitution is the ratio of the differences in velocities of colliding objects before and after the collision. It does not differ from ball rebound resilience, as it is only another way to express the relationship between a bouncing ball and the surface (Zeller, 2008). A totally elastic collision has a coefficient of restitution of 1, meaning that all kinetic energy remains in the system after the collision instead of being converted into other types of energy such as heat or sound (Chau et al., 2002). It can be measured by utilizing the following formula:

$$c = \frac{v_{2a} - v_{1a}}{v_{1b} - v_{2b}}$$

where c = coefficient of restitution

v_{1b} = linear velocity of object 1 before impact

v_{2b} linear velocity of object 2 before impact (negative if opposite direction to object 1)

v_{1a} = linear velocity of object 1 after impact

v_{2a} = linear velocity of object 2 after impact

Through the relationship between kinetic energy and potential energy, one can say that ball rebound resilience is equal to the coefficient of restitution squared (Zeller, 2008; Wadhwa, 2012):

$$\frac{mv^2}{2} = mgh$$

where m = mass

v = linear velocity of object

g = acceleration due to gravity

h = height

Therefore

$$v = \sqrt{2gh}$$

The velocity after rebounding v_1 due to the coefficient of restitution c is

$$v_1 = cv = c\sqrt{2gh}$$

The ball reaches a $height\ bounced$of

$$height\ bounced = \frac{v_1^2}{2g} = \frac{c^2(2gh)}{2g} = c^2(height\ dropped)$$

Resulting in

$$c = \sqrt{\frac{height\ bounced}{height\ dropped}}$$

Or, when related to the ball rebound resilience:

$$ball\ rebound\ resillience = \frac{height\ bounced}{height\ dropped} = c^2$$

Ball roll. Ball roll is also referred to as ball speed, and it is the distance rolled by the ball while in contact with the playing surface (Bell and Holmes, 1988). It is particularly important for soccer, field hockey, and golf (Canaway and Baker, 1993). It is measured by propelling the ball with a standard blow, or releasing the ball from a ramp. The recommended ramp design for soccer and field hockey has a 45˚ slope and 1 m of release height (BS 7044, 1989). When the ball can suffer variances due to external sources such as wind (e.g., soccer) or in small area restricting the measurement (e.g., experimental plots) measurement of ball roll can be done through ball deceleration or velocity change (Holmes and Bell, 1986). Deceleration is attributed to the ball/surface dynamic friction (Holmes and Bell, 1986), and it is the negative of the rate of change in speed in a certain period of time (Lehrman, 1998). Velocity accounts for the rate of change of the object's position (Wilson, 1901). In natural turf surfaces, a good correlation is found between velocity change and distance rolled (r = -0.88), deceleration and distance rolled (r = -0.86), and velocity change and deceleration (r = 0.92) (Baker, 1989).

Magni et al. (2004) found a significant interaction between construction method and sand type/turfgrass mix affecting the distance rolled by the ball. Rolling distance after releasing the ball from a height of 1 m utilizing a standard ramp (BS 7044, 1989) ranged from 6.1 m on a silt loam rootzone with gravel backfilled pipe drainage system to 8.0 m on native soil without drainage. Rolling distance values in tall fescue were affected by sand type and higher than in perennial ryegrass (7.3 m): 6.9 m for non-porous sand and 6.5 m for porous sand.

Construction method for sports turf rootzones also affects moisture characteristics. Ball rolling distance was reported by Langvard (1968) to be more influenced by surface moisture than by mowing height: 13 m for dry grass and 10 m for wet grass mowed at 20 mm; 12 m (dry) and 9 m (wet) at 30 mm; 11 m (dry) and 8 m (wet) at 40 mm.

Spin and Friction. A non-spinning ball contacting the playing surface will acquire forward spin if both the frictional force and the angle of impact are large enough, meaning that the ball will start spinning while still in contact with the ground. Otherwise, the ball will skid or slide without gaining any spinning motion (Brody, 1984). The coefficient of sliding friction calculates the topspin gained on impact (Thorpe and Canway, 1986):

$$CF = \frac{horizontal\ force\ to\ maintain\ motion}{vertical\ force}$$

where $CF =$ coefficient of sliding friction

Due to complex interactions between horizontal velocity and bounce and friction, this can only be studied with high-speed video recording or electronic detecting equipment, as theorized by Canaway (1985).

Friction and traction. Friction and traction enable the athletes to execute sporting movements and motions without falling or slipping excessively (Canaway, 1985). Research has approached this aspect from the medical and biomechanical standpoint, as well as in turf science studies. However, the majority of turf studies have focused on synthetic turf instead of natural turf. A number of other methods have been used attempting to measure friction and traction, despite the presence of many forces and external variables involved such as type of footwear sole, and type and practicality of equipment (Baker and Canaway, 1993). These methods include pendulum tests for translational friction mostly in artificial surfaces (Lloyd and Stevenson, 1990), towed sledges to measure friction properties (Schlaepfer et al., 1983; Thorpe and Canaway, 1986), trolleys mounted with a test foot released from a ramp for sliding distance properties (Winterbottom, 1985; Baker, 1990), force platforms for measurement of vertical and horizontal forces involved in the athletes' biomechanics (Valiant, 1988; Adrian and Xu, 1990), rotational friction and traction assessed for turf shear strength (Canaway, 1975; Canaway and Bell, 1986). Many of these methods encountered interpretation problems. The most widely utilized device by sports turf managers is the rotational device by Canaway and Bell (1986) that measures the torque required to achieve complete surface disruption. However, this device produces high variability due to variances in: (i) cleat penetration depth; (ii) the effect that variation of rotational speed may have on traction measurement; and (iii) the resulting errors due to variance in vertical forces potentially applied by the operator (Zeller, 2008). The "Pennfoot" device developed by McNitt et al. (1997) quantifies linear and rotational traction by measuring the hydraulic pressure applied to a strike plate attached to a football shoe. A combined error, however, arises in the "Pennfoot" due to changes in length of the moment arm and changes in direction of the applied force, which does not remain perpendicular to the strike plate (Zeller, 2008). Nigg (1990) found variances in shoe sole type, lack of correlation between translational and rotational movement, and the fact that normal force may play a key role in test results. Furthermore, players can make adjustments for body weight distribution and foot position in response to the level of traction needed for a particular situation (Baker and Canaway, 1993).

Canaway (1975) utilized the rotational device with a studded disc to reveal that the end point of the measurement - point where the turf completely shears or breaks free - could be used as a measure of the intrinsic turf shear strength. In this study, Kentucky bluegrass (76 N m) and perennial ryegrass (68 N m) resulted in greater shear strength than Timothy-grass (61 N m), Common bentgrass (*Agrostis capillaris* L.) (58 N m), and red fescue (53 N m). Magni et al. (2004) found significant differences in traction utilizing an apparatus similar to Canaway and Bell (1986). Differences were due the interaction between construction method and turfgrass type: native soils resulted in lower values (37 N m), whereas sandy soils resulted in higher values (66 N m) (Canaway, 1975). Tall fescue/Kentucky bluegrass mixtures resulted in higher traction values than perennial ryegrass/Kentucky bluegrass mixtures on amended soils (sand/native soil mixture up to 80:20 vol vol^{-1}) constructed with close spacing slit drainage (Canaway, 1975). Lower shear strength was attributed to easily breakable stolons by Roche et al. (2008). In the same study, swazigrass and bermudagrass offer greater shear strength, followed by St. Augustinegrass and seashore paspalum, and lastly by Kikuyugrass and Zoysia species.

Hardness. Hardness relates to the interaction between the player and the surface and the injury potential. Hardness can be divided into 2 components: (i) Stiffness is the ratio between the force applied to the surface and its deflection (Canaway, 1985); (ii) Resilience is the ratio between the energy returned to player after contact and the energy applied before contact (Baker and Canaway, 1993). Hardness is assessed through a wide range of tests and can vary depending on the object's mass, drop height, the area of contact with the surface, and variances due to field interactions (Nigg and Yeadon, 1987). Soil penetrometers measure *soil strength*, or in sports turf research, the *turf strength* (resistance to penetration). Such devices have been used in the past (Boekel, 1980; van Wijk, 1980), however, penetrometer studies are weakly correlated to ball bounce resilience tests (r = 0.35) and are not correlated with Clegg Impact measurements (Clegg, 1976). Several other devices were developed for surface hardness measurements. Drop weights equipped with an accelerometer have been widely used in artificial surfaces, while the Clegg Impact Soil Tester has been used for natural turf surfaces (Canaway, 1985; Baker and Isaac, 1987; Rogers and Waddington, 1990). Peak deceleration values using the Clegg Soil Impact Tester with a 0.5 kg hammer and drop height of 0.3 m were found by Canaway et al. (1990) to be closely correlated with players' perceptions of surface hardness for running and also falling or diving onto the surface.

Holmes and Bell (1986) also used penetrometers to measure soccer field penetration resistance. The researchers reported at least 1.4 MPa for areas of intense use and at least 1.0 MPa for areas of moderated use. Also utilizing a penetrometer, Magni et al. (2004) found higher penetration resistance in sand-based rootzone profiles (2.5 MPa) compared to native rootzone profiles featuring different drainage systems: undrained (1.5 MPa), amended topsoil (1.7 MPa), pipe drained (1.6 MPa), and slit drained (1.7 MPa). Moisture was shown by Baker (1991) to be the major factor controlling surface hardness for native soils, with hardness failing to reach the lower preferable limit of 20 G_{max} when soil moisture is in the 34-39% range. The maximum *gravity*, or G_{max} refers to the peak value for a "weight per unit mass" measurement, where acceleration is perceived as weight by an accelerometer in the impact-testing device (Clegg, 1976). On the contrary, sandy rootzone profiles altered little with moisture content variation. Moisture content was also shown to control ball rebound resilience (closely correlated to surface hardness), whereas player traction was controlled mainly due to grass ground cover (Baker and Gibbs, 1989).

Safety of Sports Fields

The goal for many sports turf complexes is to sustain playing with a reasonable maintenance budget, while maintaining safety standards (Baker and Canaway, 1993). ASTM provides safety general guidelines for football facilities in regard to few aspects including space, surface, and playing preferences; however, these guidelines do not take into consideration agronomic details that will ultimately result in field playability and safety (Mittelstaedt, 1996). Injuries are common in sports and can result from inadequate preparation, interaction with other players and equipment, or interaction between players and the playing surface. Data from 1997 to 2002 showed that 47% of significant injuries in the Australian Football League (AFL) are most likely due to the playing surface (Orchard 2001). A study with elite soccer teams showed that playing-related injury is the major single factor affecting player availability, surpassing suspension, illness, and other factors. These injuries account for 7 out of 10 players absent from the first team and training routines (Parry and Drust, 2006). Furthermore, up to 24% of soccer injuries are directly correlated with the playing surface (DPI, 2004; Ekstrand, 1982; Nigg and Yeadon, 1987).

Knee cruciate ligament injuries, especially anterior cruciate ligament (ACL) injuries, are major sporting injuries and, in most cases, need ligament reconstruction in order to rehabilitate the athlete for playing (Orchard, 2003). ACL rupture affects 1 out of 3000 people in the U.S. (Feagin et al., 1987; Miyasaka, et al., 1991). Approximately 70% of these injuries occur in recreational and sporting activities, especially in activities including pivoting and sudden stopping tasks (Hewett, 2000). In the AFL, a sport where tackling is allowed only in the upper body, more than 95% of the ACL injuries are severe, needing ligament reconstruction. Most of these injuries are classified as non-contact injury, commonly characterized by a player being tackled in the upper body with the foot fixed in the turf. In this scenario, ACL injury is triggered by a combination of indirect forces (Orchard, 2003; Zeller, 2008). Both the anterior and posterior cruciate ligaments limit the forward and backward sliding of two bones (femur and tibia) at the joint of the knee, during knee flexion and extension. These ligaments also limit knee extension. In high stress situations (such as in competitive sports), the knee ligaments (high in collagen rather than in elastin) have elasticity of only 3 to 4% of its elongation, and final rupture occurs at 7 to 8% (Zeller, 2008).

Recovering from injury can also represent a threat to the player's health and can be affected by the playing surface. When returning from ACL injury, for instance, a player's fitness is tested in matches of reduced importance or impact (often called "lower grade matches"), which concerns the AFL in regard to exposing a returning player from injury to a non-elite sports field (Zeller, 2008). As a matter of fact, the chance of a recurring ACL injury is 10-times greater for a returning player from the same injury, and 4-times greater of occurring in the opposite knee ACL during the following months after their return (Orchard et al. 2001). Other factors such as higher match grade, high evapotranspiration rate in the previous 28 days prior the match, and low rainfall in the previous year were reported by Orchard et al. (1999) and Orchard et al. (2001) to contribute to ACL injury in the AFL. Orchard (2003) also reported in the AFL injury report that ACL injuries are most likely due to the amount of traction the surface provides the athletes, rather than the surface hardness alone. Although hardness could not be correlated with risk of injury, the fields sampled for hardness with a Clegg hammer in this study ranged from 40 to 120 G_{max}. Surface hardness may be a relevant factor assessing ACL injury incidence for sports or leagues where hardness extrapolates this range of values (Orchard and Powell, 2003). Surface hardness was described by McMahon et al. (1993) to promote higher incidence of injury early in the season in the AFL, concluding that injuries on harder surfaces are more likely to be fractures associated with ground contact.

Cleat configuration of sporting footwear and its effect on shoe-surface traction (torque) is potentially the most reversible risk factor for knee injury and ACL injury incidence (Orchard, 2002). McNitt et al. (1997) reported greater safety on perennial ryegrass sports turf compared to Kentucky bluegrass and bermudagrass sports turf, three of the most widely utilized turfgrass species for sports fields. Greater safety was associated with a lower shoe-surface traction. Perennial ryegrass was reported to be safer due to less thatch production than Kentucky bluegrass, and bermudagrass – a warm season turfgrass with potential for excessive thatch accumulation (White and Dickens, 1984). Excessive thatch formation can cause "trapping" of the players' footwear, preventing free rotation of the foot and causing more stress on knee ligaments (Orchard et al., 2001). The same rationale can be applied to explain the incidence of more ACL injuries early in the season, when thatch accumulation is greater due to less traffic on the fields (Orchard et al., 2005).

Sporting footwear sole configuration and traction provided by the turf are important factors for player safety and playability (Newdwideck, 1969; Mueller, 1974). The dilemma is whether reducing the traction provided by the surface is a suitable alternative in modern sports, as they become more physical and competitive. Will the players agree and enjoy playing on a surface that offers less traction or will they wear lower traction footwear attempting to reduce injury risk? In the 2010 college football season, a nationwide watched event, the decisive game (or BCS Championship Bowl) ended with a surprisingly low score, as opposed to the high scoring nature of both competitor teams. The fact was attributed to the slippery field. In January 2011, O'Toole's (2011) online feature stated: "Auburn's 22-19 victory over Oregon in the BCS title game was much more low-scoring than expected, considering the teams averaged a combined 92 points a game. Maybe the footing had something to do with it. Players from both teams seemed to have trouble all game with the grass", showing that playing surfaces are not only an important factor for safety, but also for playability, and can impact the scoring outcome. Furthermore, the lack of a published, well documented randomized trial on athlete footwear including a control treatment with shorter cleats, and a treatment with longer cleats, is a barrier to a deeper understanding on this subject. Players would have trouble being randomly assigned into one of the above described treatment groups, as for performance reasons they would prefer longer cleats providing more traction rather than risk playing a slippery match (Orchard, 2001; Yu et al., 2002).

Injury assessment in sports turf

The two components of the sports turf, the turfgrass sward and the soil, have different but interacting properties (Canaway and Baker, 1993). Both systems – aboveground and belowground - are of major importance for playability, safety, and quality of sports fields. Traction will depend on shoe type and on the cleats or studs, and their interaction with the playing surface (Zeller, 2008). Traction is positively correlated with turfgrass root density, ground hardness, grass type and density, and negatively correlated with soil moisture content (Holmes and Bell, 1986; McNitt et al., 1997; Orchard, 2002). As soil moisture content influences surface hardness (Baker, 1991), altering irrigation management practices to soften the surface may reduce hardness, traction, and ACL injury incidence (Orchard et al., 1999; Orchard and Finch, 2002). Irrigation management will also alter the perception of "speed" of the field, and tends to reduce ball rebound (Holmes and Bell, 1986), and increases ball roll (Langvard, 1968; Magni et al., 2004).

The early season injury bias. Most competitive sports around the world are played from early fall through the winter. Injury reports from soccer, rugby, American football, Australian football, and Gaelic football have repeatedly shown an increased incidence of injuries early in the season. The same has not been noticed in summer sports played outdoors nor for indoor sports (Orchard, 2002). Two factors serve as possible explanation for the injury early-season bias: the variation in weather and ground conditions (resulting in increased shoe-surface interaction), and player fitness and conditioning. However, serial fitness evaluations over the period of a season have not been evaluated thus far (Dalley et al.,1989; Hughes and Fricker, 1994; Orchard et al., 1999; Durie and Munroe, 2000; Roux et al., 1987; Hawkings and Fuller, 1999; Alsop et al., 2000).

Only natural fields and synthetic fields exposed to weathering revealed an early season bias for ACL injuries in the NFL, especially due to temperature changes (Orchard and Powell, 2003). More shoe-surface traction in warmer synthetic fields combined with findings by Orchard (2002) and Torg et al. (1996), suggest that increased shoe-surface traction leads to an increased ACL injury risk. Also in the NFL, the lack of correlation between natural fields in warmer temperatures and the risk of ACL injuries indicates that grass type is by itself a greater factor for playing safety than climate factors, especially temperature (Orchard, et al. 2005). The NFL is played mainly on synthetic fields and/or natural fields with cool season grasses. Few venues contain bermudagrass and are usually overseeded with perennial ryegrass for winter color and playability. Furthermore, density and health of the warm season species stand may decrease depending on the overseeding establishment and following management practices. Therefore, the higher incidence of injury associated with warmer temperatures, southern geography, or warm season turfgrass is confounded among other factors. Freezing of the fields in the northern USA can also be a confounding factor for the warmer temperature (or southern) bias for ACL injuries (Orchard and Powell, 2003).

Winter sports such as rugby or the NFL revealed to have an early-season bias for injury, with injury incidence declining throughout the season (Orchard, 2002). Differently, research by Hawkins and Fuller (1999) study reported a “U” shaped curve for injury incidence in professional soccer, (played from August to May), with injury peaks early and late in the season, although the study could not determine whether the high incidence of injury during late season was due to the excessive load of games or to increased surface hardness. Major League Soccer (MLS), a summer sport played from April to September in the U.S., also revealed a late-season bias rather than early-season injury bias (Morgan and Oberlander, 2001). The early season bias was accounted for by changing ground conditions, as observed by Andersen et al. (1989) in a study showing that injuries on muddy or wet natural grass surfaces were less frequent than on drier, firmer surfaces in Wisconsin. In the NFL, the majority of non-contact ACL injuries occurred on surfaces described as good or dry and the early-season injury bias was present only in games played on natural or artificial turf in the open air, not on indoor artificial fields (Scranton et al., 1997).

Injuries may also result from the athlete’s health and fitness, and not necessarily be associated with the turf. Overuse or chronic injuries resultant form cumulative trauma or repetitive use and stress were found by Yang et al. (2012) to account for 30% of 1317 reported injuries in 573 males and females. These athletes were exposed to a total of 208,666 athlete-exposure events (AEs) - coach-directed session(s) or game(s) or practice(s) – over a 3-year period in one NCAA Division I institution within the Big Ten Athletic Conference. Acute injuries, defined as “trauma caused by a specific and identifiable event”, accounted for 70% of the total. Over 50% of the athletes evaluated in this study reported more than one injury, with women’s rowing, men’s cross country, and track and field athletes of both sex reporting the greatest number of overuse injuries. On the other end, football players and wrestlers were the subjects with highest number of acute injury. Most common overuse injuries were classified and quantified as general stress (27%), inflammation (21%), and tendinitis (15%).

Knowledge gaps

Quantification of non-sporting wear. Non-sporting wear has become a major issue for sports fields. Non-sporting wear damage from social and community events, concerts, ceremonies, and television commercial shootings have become common, especially in famous, high-capacity stadia. These events often take place on the playing field (turf or skinned area in baseball) and may require advanced setup regarding logistics and engineering. Stages, benches, sound systems, dinning furniture, heavy trucks, loading/unloading equipment, and excessive foot traffic account for wear in these cases. Non-sporting wear damage will vary depending on size, type, and engineering level of the event. Smaller social gatherings such as gala dinners, or fairs may not cause as much wear damage as big concerts or graduation ceremonies. Furthermore, for such big events, tarps and temporary flooring systems may be installed. Regardless of the type and size of event, a method for quantifying non-sporting wear has yet to be developed, which would help turf managers to be prepared to host such events, and deal with the post-event management of the fields.

Recent trends. In the U.S., at the collegiate level, recruiting student-athletes has become a year-round process for many schools within NCAA division one. Coaches, athletic administrators, and boosters demand for green, “perfect” fields everyday, regardless of the agronomic conditions for turfgrass growth and turf management. This expectation may lead to game-type management of fields everyday even during the off-season, increasing the non-sporting wear stress through recruiting events hosted on the fields, and to management practices such as painting (lines and logos), or such as management practices dependent on equipment and machinery (mowing, fertilizing, topdressing, spraying, etc.). Turf managers are realizing that the growing or turf recovery season has shortened or disappeared in some cases. This issue leads to a recent trend for resodding sports fields every year during the off-season, which demands high amounts of resources. The problem may further compromise the need for turf agronomists and increase the demand for turf engineers. Sports turf builders and "renovators" are available on the market; however, little or no research has been conducted in such resodding operations, especially the ones most commonly used by professional leagues and NCAA schools.

Sports turf research techniques and methods. Many different methods and measurements have been used to quantify sports turf properties, with a wide variety of equipment and procedures. Standardization of methods and equipment should be pursued, facilitating the interpretation of results, and broadening sports turf studies' scope of inference. Furthermore, more universal and straightforward research techniques may also result in a stimulus for turf managers to read more turfgrass scientific literature, reducing the gap between sports turf science and management.

It is known that traction provided by a sports field is resultant from properties of the soil and the turfgrass (Baker and Canaway, 1993). However, little is known about the level of contribution provided by each individual turfgrass part such as leaves, stolons, and rhizomes. Anatomical and morphological variations between and within turfgrass species could contribute differently for the traction provided by the turfgrass component.

Playability and safety of sports fields. An association between playability and surface properties has not yet been well defined for most sports through surveys with the athletes and participants. In surveys that have been conducted, the concept of "playability" is related to the management style of turf managers. Playability should actually rely on the players' perceptions about the field. Although turfgrass science and sports medicine science are individually well defined, their interaction has not yet been studied enough, especially in regard to the relationship between sports surfaces and injuries for players (Chivers and Orchard, 2008). The majority of the studies published in the last 10 years were related to football (mostly AFL) and little research focused in other types of sport (Orchard, 2002; Chivers and Orchard, 2008). It is ethically unfeasible to conduct randomized experiments on the matter, which reduces the scope of inference of published articles, and therefore injury reports have been used to correlate surface properties and field safety. Establishing a correlation between the sports turf and player injury depends on collecting and analyzing ground conditions and weather data over a long period of time; most of the published studies in this area were not able to determine causality between sports turf injury and playing surface due to lack of data (van Mechelen et al., 1992). Alsop et al. (2000) were one of the few to consider sporting injuries at non-elite competition levels. Their study supported the early season bias for injury, and reported that injury decreased over time across all types of athletes. However, decrease in injury rate was significantly different between specific player grades (competitiveness level).

It is important to make a distinction between the surface type elite athletes play versus the surfaces available for community and junior sporting events. It is also important to notice the difference in competitiveness and speed in different levels of sport (Chivers and Orchard, 2008). Both of these factors can influence player/surface interaction and injury risk potential. Several studies showed that the early season bias was the main trigger for sports injuries and playing surface research (Ekstrand and Nigg, 1989; Blaser and Aeschlimann, 1992; Armour et al., 1997; Hawkins and Fuller, 1999; Alsop et al., 2000; Lee and Garraway, 2000; Orchard, 2002), and therefore, an investigation including the sports turf surface, injury reports, pre-season fitness, and conditioning of athletes could help understand the issue more thoroughly.

Finally, research in sporting footwear is lacking, even though it may be the most important factor associated with risk injury that can be easily controlled (Orchard, 2002). A reduction in shoe-traction provided by all fields through sports field construction and management practices may not be appropriated due to the level of competition of modern sports, therefore, the role played by sporting footwear in shoe-surface traction will increase in importance in the future (Newdwideck, 1969; Mueller and Blyth, 1974). Injury risk as influenced by turf management practices should also be investigated, as many fields are prepared for a season or a game according to the turf manager's preferences.

Future of Sports Turf Research. Sports turf research has evolved from basic turfgrass investigations initiated in the mid 1900's to specific techniques regarding turf components - soil and turfgrass, and also in regard to players. A variety of specific tests for sports turf were developed, as well as equipment and apparati. Also, research efforts allowed for a better understanding of sports' dynamics and interactions between the field, the ball, and the players. It is complicated to provide a "one-system fits all" for sports field construction and maintenance, as the field quality is influenced by type of sport, competitiveness level of sports, budget, and many local trends. Regardless, future research should focus in (i) safety, (ii) playability, and (iii) aesthetics of sports fields.

Studies such as Canaway et al. (1990) and Canaway and Baker (1993) demonstrated that it is of great importance to correlate the data from research on playing quality with players' perception of the field through questionnaires and surveys with large number of responses. This type of research would help control quality for construction and maintenance operations, quantify sports fields' quality parameters, and establish parameters indicating if a determined field is ready for play.

Although future research should keep focusing on field measurements in order to obtain surface parameters for comparison means, it is crucial to associate information obtained through injury reports from leagues and sports organizations with players' expectations and evaluations of the playing fields, linking playability from the players' perspective, with playability from the turf manager's perception, and safety through injury reports.

Also, standardizing surface tests by utilizing similar equipment and measurements, as well as obtaining repeatable and accurate measurements, will bring a more universal and complete meaning to sports turf testing. Combined, this would elucidate a range of playing parameters that is safe for players, agreeable to players' perceptions, and convenient to modern competition standards.

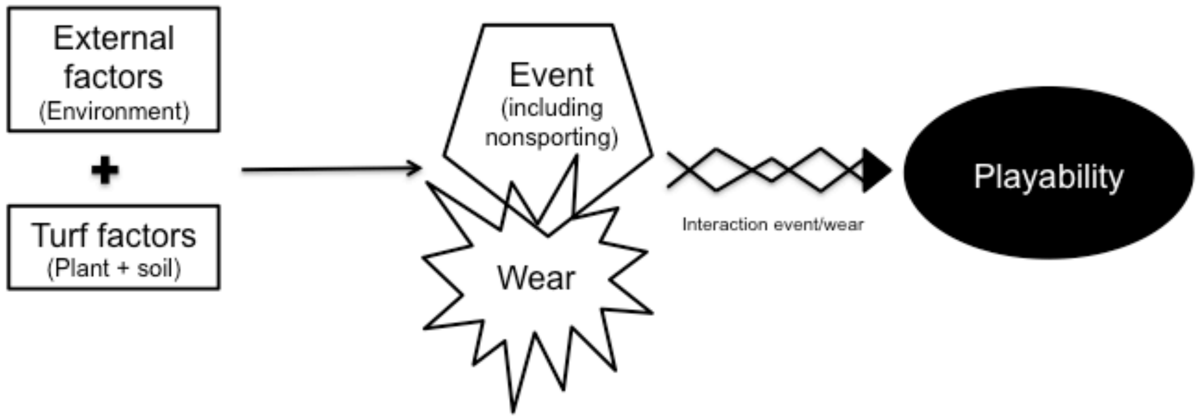

Figure 1. Conceptual model for playability (adapted from Canaway and Baker, 1993).

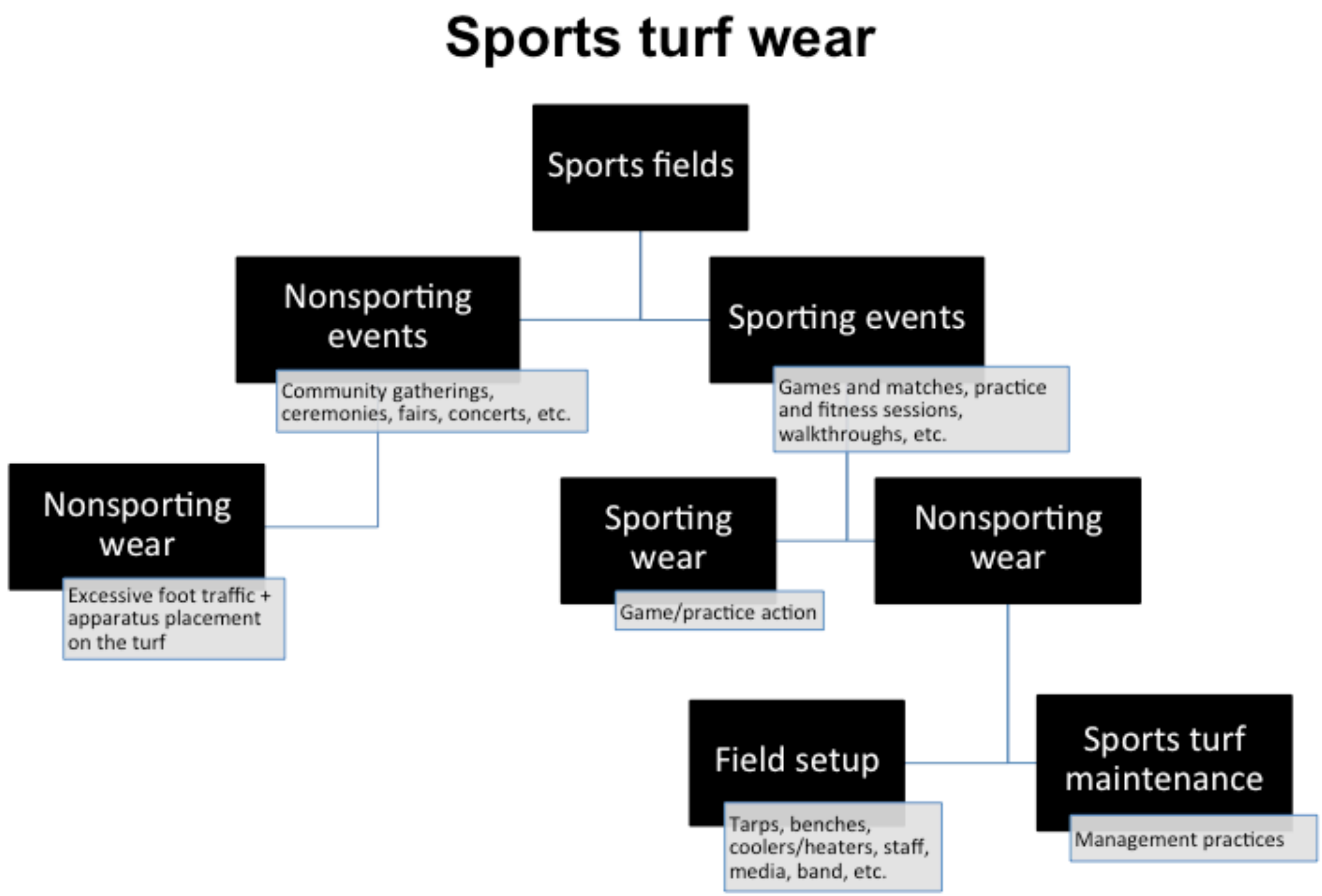

Figure 2. Sports turf wear as a function of type of event (Aldahir and McElroy, 2014).

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Dissertation objectives

Research was conducted to investigate the suitability of TifGrand bermudagrass for use as a sports turf cultivar for shaded environments. Specific objectives were:

1) Examine fall durability and spring response of TifGrand amongst other bermudagrass cultivars. Bermudagrass is often chosen as a sports turf species, despite its winter dormancy. Research was conducted on aesthetics and playability parameters related to fall durability of five bermudagrass cultivars submitted to increasing levels of American football-type, simulated wear. Other agronomic parameters were additionally evaluated in the following spring, as indicators of turfgrass recovery to simulated fall wear.

2) Determine shade adaptation and response of bermudagrass cultivars, including TifGrand. Bermudagrass has low shade tolerance amongst the warm-season turfgrass species; however, relative shade tolerance is found within bermudagrass cultivars. Research was conducted to investigate impact of different shade regimes on bermudagrass quality, performance, and morphological and physiological responses. In addition to turfgrass responses to shade, characterization of the shaded microenvironment was also performed.

3) Investigate TifGrand seedhead suppression and quality improvement with use of herbicides and plant growth regulators (PGRs). Bermudagrass, especially TifGrand, have proliferous seedhead formation, especially late spring through the summer, which decreases turf aesthetic and functional quality. Several herbicides and PGRs were applied to mature stands of TifGrand, and seedhead suppression and quality improvement were evaluated.

FALL DURABILITY AND SPRING RESPONSE OF BERMUDAGRASS SPORTS FIELDS SUBJECTED TO AMERICAN FOOTBALL-TYPE WEAR.

Introduction

Sports turf wear is the damage caused to the turfgrass and the soil through vertical and horizontal forces applied to the turf (Soane, 1970; Beard, 1973; Canaway, 1975; Carrow and Petrovic, 1992). These forces may result from playing action, equipment, apparel, apparatus, and maintenance practices (Canaway and Baker, 1993; Aldahir and McElroy, 2014). Sports turf wear, caused by playing action and playing-related operations (Aldahir and McElroy, 2014), is dependent on the sport played, level of competitiveness, frequency and intensity of play (Puhalla et al., 1999), and is characterized by severe damage to the plant crown in addition to the abrasion common in golf course wear (Ferguson, 1959; Evans, 1988). Ball- and player-field interactions are key components in playability, and contribute to sports turf wear. Sports turf wear is, then, closely related to playability (Canaway and Baker, 1993). Sports turf wear is an issue for both low and high-end fields. Low-end sports fields, such as those of municipal recreation and secondary education facilities, have limited maintenance and excessive number of events, compared to high-end. High-end sports fields, such as in college and professional stadia, require higher turfgrass quality and performance, support fewer events, but are subjected to more intense wear from larger, higher performance athletes.

Bermudagrass (*Cynodon* spp.) is widely adopted for sports turf use due to its wear tolerance, amongst other characteristics (Beard, 1973; Christians, 2004; Thoms et al., 2011). In addition to its use in the southeastern U.S., more than half of the pitches in Australian football league are established with bermudagrass (Orchard, 2001), and in the 2014 World Cup in Brazil, most of the 12 game pitches were also established with ‘Tifway’, ‘Celebration’, and a relatively new, reportedly wear and shade-tolerant cultivar for sports turf use, ‘TifGrand’ (Roche et al., 2009; Hanna and Bramam, 2010; Melancon, 2014; Novak, 2014). Also, bermudagrass use is no longer limited to the Southern U.S., once more winter-hardy cultivars such as ‘Patriot’ and ‘Latitude 36’ have successfully increased their northern limit beyond the U.S. turfgrass transition zone (Taliaferro et al., 2006; Marshall, 2007; Morris, 2008; Wu et al., 2012).

TifSport, Tifway, Princess 77, and ‘Riviera’ bermudagrass under traffic remained at superior green cover compared to Patriot (Trappe et al., 2011b). Turf shear strength is related to playability and may also be used to measure wear tolerance by measuring the surface traction at its maximum torque (Aldahir and McElroy, 2014). Roche et al. (2008) found differences in the shear strength of warm season grasses maintained without wear: swazigrass (*Digitaria didactyla* Willd) and bermudagrass (*Cynodon dactylon* L. Pers) had the highest shear strength values, 82 and 76 N m, respectively; while *Zoysia* species and Kikuyugrass (*Pennisetum clandestinum* Horchst. ex Chiov.) had the lowest readings, from 65 to 56 N m. Bermudagrass intraspecific differences for wear tolerance has been reported mostly as percent ground cover, percent green cover, or verdure (Trenholm et al., 2000; Thoms et al., 2011; Deaton and Williams, 2014). Although, for trafficked turf, limited information is available on bermudagrass intraspecific differences regarding playability parameters such as turf shear strength.

Wear tolerance of turfgrass can vary seasonally. Bermudagrass when submitted to fall and winter play relies mostly on its durability rather than its recuperative potential due to less than ideal growing conditions for recovery (Roche and Loch, 2005). Trappe et al. (2011a) reported differences in green cover among 42 bermudagrass cultivars under summer and fall wear. In addition, spring quality of sports fields following fall-wear (e.g. after the American football season) is also crucial, considering that the growing (or recovery) season has shortened or even ceased in some cases (Aldahir and McElroy, 2014). Park et al. (2010) reported that Kentucky bluegrass (*Poa pratensis* L.) took longer than 185 days to achieve 33% recovery from fall wear. Furthermore, trafficked turfgrass spring quality and recovery has become important, due to a nationwide trend of higher expectations and maintenance standards, even during the of-season (Aldahir and McElroy, 2014).

Wear tolerance is, therefore, the ability of a field to remain at adequate playability and aesthetic quality when submitted to sports turf wear, by both mechanisms: durability (wear tolerance) and recovery (recuperative potential) (Beard, 1973; Canaway, 1975). We hypothesize that more wear-tolerant, durable bermudagrass cultivars would be able to withstand aggressive fall playing such as in American football, maintaining higher aesthetics and playability standards; and resulting in superior quality in the following spring. The objectives of this research are (i) to evaluate the response of 5 bermudagrass cultivars commonly used as sports turfgrasses under various levels of simulated football-type wear during the fall, when American football is mostly played; and (ii) to investigate the effects that fall wear may cause on bermudagrass sports fields in the following spring.

Materials and methods

A two-year study (2011-2013) was conducted to evaluate the effect of fall durability and spring quality of bermudagrass cultivars subjected to football-type wear at the Auburn University Turfgrass Research and Education Center in Auburn, AL (32.58° N, 85.50° W). Soil type was a Marvyn loamy sand soil (fine-loamy, kaolinitic, thermic, Typic Kanhapludult) with pH 5.9 and 2.1% organic matter. Five locally sourced bermudagrass cultivars (Celebration, Patriot, TifGrand, ‘TifSport’, and ‘Tifway’) were sprigged on June 15, 2011 and June 12, 2012. Each individual cultivar was sprigged at 13.5 m^3 fresh sprigs ha^{-1} in 15 m^2 blocks (3 m width by 5 m length). During the first four weeks, sprigs were irrigated five to six times daily for three to five minutes to maintain adequate surface moisture and prevent sprig desiccation. Cultivar treatments were randomized and replicated 3 times. Lime, P, and K were applied according to recommendations from the Soil Testing Laboratory at Auburn University. All cultivars were fully established 10 weeks after planting. Following turfgrass establishment, N was applied at 49 kg ha^{-1} per month during active bermudagrass growth (May-August), and at 25 kg ha^{-1} after bermudagrass dormancy through April of the following year.

The experimental design was a randomized complete block with a strip plot arrangement of treatments. Main plots were bermudagrass cultivars. Strip plots were 0.7 m-wide simulated wear applied across cultivars. Simulated wear was applied with a Cady Traffic Simulator (CTS), simulating American football games according to Henderson et al. (2005), at 1, 3, and 5 games $week^{-1}$. A non-treated control with no simulated games was also included. Wear simulation started in August 22 and September 4 for 2011 and 2012, respectively, and followed for 10 weeks. In order to limit bermudagrass recovery, simulated games were applied in the following fashion: one game on Mondays only, for 1 game $week^{-1}$; one game on Mondays, Wednesdays, and Fridays, for 3 games $week^{-1}$; and 2 games on Mondays and Wednesdays, and one game on Fridays, for 5 games $week^{-1}$. Simulated wear was not applied under or after heavy rain events until the soil moisture reached approximate field capacity again. Individual, adjacent areas were established for each experimental run in 2011-12 and 2012-13, avoiding turfgrass and soil damage that could possibly remain from a previous run.

Data Collection. Data were taken on aesthetics and playability parameters. Bermudagrass durability was assessed 2 (September), 6 (October), and 10 (November) weeks after initiation (WAI) of fall simulated wear and included measurements for total turfgrass cover (TTC) and turfgrass green cover (TGC) as aesthetics measurements. Non-green turfgrass cover (NGC) was obtained by subtracting turfgrass green cover from total turfgrass cover, indicating the amount of brown turfgrass cover, contributing for playability parameters only. Turfgrass cover parameters were measured on a percent basis, using batch analysis of digital images. Digital images were taken using Canon Power Shot G9 (Canon Inc., Tokyo, Japan), mounted on a 0.28 m^2 light box apparatus equipped with four 43 W Reveal® energy efficient lamps (General Electric. Fairfield, CT), and powered by a 1000 W, 12 V generator (American Honda Power Equipment. Alpharetta, GA). Excess debris resulting from simulated wear damage were removed prior to picture collection using a common leaf blower. All images were resized to 480 x 640 pixels. Hue and saturation values were standardized to 50 to 92 and 25 to 94, respectively, for analysis of all images. Turf shear strength and soil volumetric water content were also measured at 2, 6, and 10 WAI of simulated wear. Turf shear strength used a rotational torque device developed by Canaway and Bell (1986) to measure playability as in surface rotational traction. The device weighed approximately 50 kg, and was dropped from a 6 cm height for each measurement. Turf shear strength was measured 3 times on each experimental unit, accounting for 3 subsamples. Rotational force was applied to a 90˚ angle, or until complete shearing of the turf, and a torque reading in N m was recorded. Soil volumetric water content was measured using a FieldScout TDR 300 moisture meter (Spectrum Technologies, Inc., Aurora IL) equipped with 7.5 cm rods, with 3 subsamples.

Bermudagrass spring recovery was assessed in late March and early April in 2011 and 2012, respectively. Spring recovery evaluated turfgrass and soil parameters, and included bermudagrass shoot density, surface hardness, above and belowground dry-biomass, thatch depth, and bulk density. Shoot density was measured by counting the number of living shoots in 5.6 cm diameter plugs, and converted to shoots 100 cm^{-2}. Surface hardness was measured in G_{max} and used a Clegg impact soil tester (Turf-Tec International. Tallahasse, FL) equipped with a 2.25 kg hammer, dropped 4 times from a 45 cm height, and included 3 measurements (subsamples) per plot. Above and belowground dry-biomass were measured in g. Plugs were collected with a standard 10.8 cm diameter golf cup-cutter, and cut with a knife to separate aboveground from belowground tissue. Excess soil was washed off and plant tissue was allowed to dry in a forced air, mechanical convection oven (VWR International. Radnor, PA), at 80˚ C (± 4˚ C), until constant weight was reached. Soil cores were collected with a Giddings soil probe (Giddings Machine Co. Inc., Windsor, CO) equipped with a cylinder 5.6 cm diameter by 10 cm depth. Thatch depth was measured in mm before soil cores were analyzed for bulk density separately at 0-5 cm and 5-10 cm soil depths. Bulk density determination used the oven dry mass of the soil and the volume of the cores.

Figure 3. Equipment and apparatus used for data collection.

a) Light box apparatus and batch analysis of digital images. b) Rotational device for turf shear strength. c) Soil moisture probe. d) Shoots separation and counting. e) Clegg Impact Soil Tester for surface hardness. f) Giddings probe for collection of soil cores.

Statistical Analysis. Data analysis was conducted in SAS 9.2 (SAS Institute. Cary, NC) using analysis of variance (ANOVA). Significant year × simulated games × weeks, and year × cultivars x weeks were found for turfgrass green cover and turf shear strength in the fall (Table 1), and therefore, data were analyzed separately. Treatment means were separated using PROC GLM, by Fisher's protected LSD test at the probability level $\alpha = 0.05$. Regression analysis was performed in PROC GLM for turfgrass green cover over weeks, resulting in quadratic functions for cultivar changes in green color under each level of simulated wear for 2011 and 2012. Means and fitted regression curves were plotted in SigmaPlot 11.2 (Systat Software Inc. San Jose, CA). Analysis of bermudagrass spring response was performed similarly to fall durability parameters, resulting in many significant interactions, and therefore, data are presented separately.

Calculation of Green Cover Index (GCI) and coefficient of durability (CD). A GCI was calculated for each cultivar under each level of wear, using the quadratic equation parameters found in regression analysis. The graphical representation of the quadratic formula below results in a curve (Washington, 1999):

$$y = y_0 + ax + bx^2$$

where y is the solution(s), y_0 is the constant term, and a and b are, respectively, the quadratic and linear coefficient;. The solution(s) of the quadratic equation are graphically represented by the point(s) where the curve crosses the x axis (Noble and Daniel, 1988). The integral of a function, also referred to as "area under the curve", results in the area measurement for the function, and could be used in our case to compare turfgrass green cover amongst cultivar for different traffic levels (Siauw and Bayen, 2014). Such integrations, however, require either advanced algebraic knowledge or advanced computational software, and often need a graphical representation in order to be fully understood (Siauw and Bayen, 2014). Alternatively, the two equation solutions and the point where the curve's tangents cross, form a triangle of height:

$$height = -\frac{b^2}{2a}$$

where $-\frac{b^2}{2a}$ is the one and only real solution for the equation, if its discriminant equals zero (McConnell et al., 1998). The height of the triangle, herein called GCI, could be used as a comparative mean between cultivars for variations in green cover throughout the simulated wear season.

A CD for each bermudagrass cultivar was further calculated relative to the wear-free treatment by adding the constant (y_0) and the GCI for each cultivar under each level of simulated wear, and dividing the result over the cultivar's y_0 for the wear-free, accounting for the natural dormancy of bermudagrass cultivars:

$$CD_{cultivar} = \frac{y_0 + GCI}{y_{0\ no\ wear}}$$

A cultivar's durability decreases with decreasing *CD* values, and increases with increasing *CD* values. A CD value of 1 represents no change in durability accounted by simulated wear.

Results and discussion

Total turfgrass cover, turfgrass green cover, and non-green turfgrass cover. The number of simulated games per week affected all turfgrass cover parameters at all dates in 2011 and 2012 ($P < 0.0001$), except for turfgrass green cover on November 1, 2011, when high variability was observed. In general, total turfgrass cover and turfgrass green cover values decreased with increasing number of simulated games, in most cases with distinct differences between 0, 1, 3, and 5 games week^{-1} (Table 2). In all rating dates in 2011, non-green turfgrass cover decreased as number of games increased, which could be related to the decrease in total turfgrass cover, or simply more turfgrass complete shearing. In 2012, non-green turfgrass cover increased with increasing simulated games, except for 10 WAI when 5 games week^{-1} were applied, indicating less turfgrass shearing. In 2012, greater total turfgrass cover 2 WAI could be related to less turfgrass shearing, providing a cushioning effect, and preventing complete cleat penetration that could result in turf shearing (Canaway, 1981; Canaway and Baker, 1993) throughout the wear season.

Though resulting in a significant interaction, total turfgrass cover varied due to cultivar only 6 WAI of wear simulation in 2011 (Table 3). At this date, TifGrand, Celebration, and TifSport had the greatest total turfgrass cover: 80, 79, and 75%, respectively. Tifway (73%) and Patriot (70%) resulted in lower turfgrass total cover. Our findings agree with Thoms et al. (2008) and Trappe et al. (2011b) in which Patriot and TifSport are reported to have low, and high wear tolerance, respectively. Our research differs from Trappe et al. (2011a) on the measurement of total turfgrass cover in addition to turfgrass green cover. His study did not consider total turfgrass cover as in green plus dormant turfgrass. Bermudagrass dormancy may be a complication in the study of wear tolerance in the fall, once both green and dormant turfgrass can withstand some level of wear and provide traction (Trappe et al., 2011a; Schmidt, 1980). Both turfgrass green cover and non-green turfgrass cover varied due to cultivar in all rating dates in 2011 and 2012 (Table 3). In general, cultivars with greater green cover values resulted in lower non-green cover values (e.g. TifGrand) and vice-versa (e.g. Patriot).

In both years, when comparing October (6 WAI) to November (10 WAI) cover values, turfgrass green cover values decreased, while non-green turfgrass cover values increased, likely due to bermudagrass natural dormancy, in addition to simulated wear. The effect of dormancy on bermudagrass green cover reduction throughout the fall is shown in Figure 4ab. In 2011, Celebration bermudagrass had greater loss of green cover than other cultivars due to dormancy, decreasing from 60% 2 WAI to 30% 10 WAI. In 2012, while Celebration had greater green cover throughout the fall than other cultivars, Patriot bermudagrass green cover reduction was the greatest: from 80 to 10%. Lower initial green cover for non-trafficked plots could have an influence on the effect of natural dormancy on bermudagrass green cover, as noticed 2 WAI for Celebration in 2011 (60%), and Patriot in 2012 (80%). Other cultivars with greater initial green cover 2 WAI, resulted in superior green cover (reduced green cover loss) 10 WAI, despite natural dormancy.

In regard to trafficked bermudagrass, green cover reduction was greater in 2012 than in 2011. Cultivars with greater green cover after 10 weeks of simulated wear in 2011 were TifSport and TifGrand, maintaining green cover of approximately 70, 60, and 40-45%, for 1, 3, and 5 simulated games week^{-1}, respectively. Greater green cover in 2011 for TifSport and TifGrand could be associated with their recovery ability due to temporary interruption of wear. Tifway had inconsistent green cover, with green cover similar to TifSport and TifGrand when maintained without wear (62%), and at 3 simulated games week^{-1} (50%), but reduced green cover under 1 (40%) and 5 (25%) simulated games week^{-1}. Celebration and Patriot resulted in intermediate to lower green cover in 2011, compared to other cultivars at all simulated game frequencies.

Greater green cover reduction occurred in 2012: from 90 to 50% for Celebration, TifSport, and Tifway, 40% for TifGrand, and 20% for Patriot under 1 simulated game week^{-1}. Increasing wear (3 and 5 simulated games week^{-1}) further decreased green cover of all cultivars, and despite the lower green cover of Patriot, separation amongst other cultivars was not always possible.

From Table 4, positive GCI values representing recuperative potential can be found for 3 simulated games week^{-1} in 2011 for TifSport (0.23), along with near-zero values for Tifway (0.01) and TifGrand (-0.04), indicating an increase in tufgrass green cover for TifSport and Tifway, and very limited reduction in TifGrand green cover, compared to the nontreated. In 2012, a positive GCI could only be observed for TifGrand under 5 simulated games week^{-1} (0.18). According to the coefficients of durability listed for 2011, Celebration was the cultivar more prone to loss of green cover due to dormancy (0.6), however, recuperative ability was noticed when under 5 simulated games week^{-1} (1.33). Patriot was the less durable tested cultivar, as indicated by CDs. TifGrand and TifSport were the most durable cultivars in 2011. In 2012, with uninterrupted simulation of games, Celebration, TifGrand, TifSport and Tifway were more durable when wear-free, however, only TifGrand was able to maintain greater CD values with increasing number of simulated games week^{-1}. Patriot was the least durable cultivar under no simulated wear, but similar to Celebration, TifSport, and Tifway as number of weekly simulated games increased.

These data provide additional insight on the durability of bermudagrass cultivars in the fall, for non-trafficked and trafficked turf, accounting for the natural dormancy that results in loss of green cover even without sporting wear, or for non-sporting wear (Aldahir and McElroy, 2014). Weekly assessment of turfgrass durability is important from the spots turf manager perspective, once in-season sports turf management, especially for American football, is based on a weekly basis, according to teams' schedules. Although the CD was based on loss of bermudagrass green cover, total turfgrass cover is still important as a playability parameter, associated with ball-field interactions (ball roll, ball bounce), and player-field interactions (surface hardness, traction) (Trappe et al., 2011a; Schmidt, 1980).

Turf Shear strength. Turf shear strength, also referred to as traction (Baker, 1995; Lulli et al., 2010; Serensits and McNitt, 2014), initially decreased 2 WAI for increasing number of simulated games week^{-1} (Table 5). At 6 WAI, for 1 and 3 simulated games week^{-1} in 2011, and 1 game week^{-1} in 2012, turf shear strength was equal or greater than for non-trafficked bermudagrass. On both years, wear-free, and 1 game week^{-1} treated plots resulted in similar turf shear strength 10 WAI, with decreasing values for 3, and 5 simulated games week^{-1}. Greater initial turfgrass cover in addition to more actively growing bermudagrass could have resulted in greater traction (Baker and Gibbs, 1989; Schmidt, 1980). Additionally, other soil properties could have further influenced the reduction of traction values with increasing number of simulated games. Previous literature reports increasing soil strength values with decreasing soil moisture (van Wijk and Beuving, 1980), as well as the contrary: increased traction as water content increased (Winterbottom, 1985). In our research, soil volumetric water during application of simulated wear did not change consistently with increasing simulated games (Table 6). Instead, thatch depth in the following spring after a wear season was greater for 0 and 1 simulated games week^{-1} (19 mm) compared to 3 (14 mm), and 5 (9 mm) games week^{-1} (Table 7).

Increased traction has been associated with increasing belowground biomass (Rogers, 1988), however, in our research, a distinction between above- and belowground biomass in the following spring was not noticed for increasing simulated wear ($P < 0.8753$). In our study, greater traction could be associated with greater thatch depth, according to Barton et al. (2009)

and Li et al. (2009), regardless of the bermudagrass cultivar ($P < 0.6091$). Soil bulk density differences were found only in April 2013, and only for the 0-5 cm soil layer. Bulk density differences were inversely related to to thatch depth, where increasing thatch depth resulted in decreasing bulk density (Table 7), suggesting that simulated, football-type wear is enough to partially eliminate the superficial thatch layer by physical disruption, yet resulting in soil compaction. Non-trafficked bermudagrass, and 1 simulated game week^{-1} resulted in similar, lower bulk density: 1.50 and 1.54 g cm^{-3}, respectively. Wear simulation of 3 games week^{-1} resulted in an increase in bulk density (1.61 g cm^{-3}), whereas 5 games week^{-1} resulted in the greatest bulk density value (1.69 g cm^{-3}). Simulated wear also affected surface hardness, a playability parameter dependent on the turfgrass and soil parameters, including soil moisture, compaction, and thatch (Rogers et al. 1988; Rogers and Waddington, 1989). Non-trafficked bermudagrass had the softest surface (50 G_{max}), 1 and 3 simulated games week^{-1} resulted in increased hardness (62 and 63 G_{max}, respectively), whereas 5 games week^{-1} resulted in the hardest turf surface (72 G_{max}). A reduction in surface hardness was noticed for 3 weekly simulated games in 2012 (Figure 8b), likely due to greater turfgrass shearing, and direct contact between the wear simulator's cleated feet and the soil, causing a "spiking effect". Increased thatch depth, and lower bulk density and surface hardness values for non-trafficked and lightly trafficked bermudagrass could further explain increased traction due to more cleat penetration in the soil/thatch layer (Zebarth and Shear, 1985; Rogers et al., 1988).

Regarding turf shear strength, TifGrand was the only cultivar to maintain greater traction at all rating dates (Table 8), which is consistent to its aesthetic fall durability. Celebration (58 N m) provided similar traction to TifGrand (60 N m) 2 WAI in 2011. Celebration and TifGrand also resulted in similar traction values at 2 and 10 WAI in 2012 (62 and 47 N m for TifGrand, 60 and 49 N m for Celebration; 2 and 10 WAI, respectively). TifSport provided similar traction to TifGrand 6 (58 N m) and 10 WAI (56 N m) in 2011. TifGrand and Tifway resulted in similar traction at 6 WAI in 2011 (57 N m), and 10 WAI in 2012 (49 N m). Patriot had lowest traction at all statistically significant rating dates. Traction amongst cultivars varied less between rating dates in 2011 than in 2012. More initial turfgrass shearing and bermudagrass recovery due to interruption of wear simulation could have maintained similar turf shear strength values throughout the simulated wear season in 2011. Shear strength values for 2012 were not only greater 2 WAI (Table 8), but were reduced to a greater degree at 6 and 10 WAI. Shear strength values ranged from 44 to 60 N m in 2011, and from 43 to 62 N m in 2012. Despite the differences in traction, it is difficult to associate the results with a playability-relevant perspective in sports turf management, due to the lack of objective data correlating sports field traction, and player safety and performance (Aldahir and McElroy, 2014). Furthermore, athletic footwear configuration, considerably different from the traction measurement device developed by Canaway and Bell (1986), has been reported to be the main factor affecting rotational traction (Serensits and McNitt, 2014).

Spring response. Spring growth response parameters were quantified to determine how cultivars recovered from fall trafficking. Dried biomass of bermudagrass cultivars following simulated wear in 2012 was greater for TifGrand (6.7 g) and TifSport (6.0 g), intermediate for Tifway (5.0 g) and lower for Celebration (4.5 g) and Patriot (4.5 g) (Table 9). In 2013, Tifway (6.2 g) resulted in dried biomass similar to TifGrand (5.5 g) and TifSport (6.2), whereas Patriot (5.2 g) resulted in intermediate biomass. Celebration (3.8 g) had the least dried biomass. A similar effect for shoot density is also noticed in the data (Table 9). Although no differences were found on both years for non-trafficked bermudagrass, TifGrand and TifSport resulted in greater shoot density, followed by Tifway, Patriot, and Celebration. Traction has been previously associated with biomass belowground biomass (Gibbs et al. 1989), shoot density, and verdure biomass (Shildrick and Peel, 1984), which is in accordance to our results, even though dried biomass results in our study was analyzed across above- and belowground tissues ($P < 0.8753$). According to Duble (1995), spring recovery is a function of viable propagules present during spring, or in our case, number of living shoots per area. Another study found most cultivars with higher shoot density under non-wear conditions to have greater wear tolerance (Trenholm et al., 1999). Spring et al. (2007) noticed that grass cover is greater at the beginning of the playing season, declining over the winter, and recovering again during spring. We noticed more wear damage and decreased grass cover when initial bermudagrass green cover was lower, such as in 2011. In our study, more durable (greater CD) cultivars resulted in greater number of living shoots in the spring. Despite lower fall aesthetic durability and lower spring shoot density and biomass, Celebration bermudagrass provided intermediate to high traction by its turf shear strength, in agreement previous literature, that reported ‘Conquest’ bermudagrass to maintain greater wear tolerance compared to ‘Princess 77’, despite its lower dry biomass yield (Roche et al., 2009). Hence, playing traction provided by Celebration during the fall could be associated with brown (dead or dormant) tissue, especially considering the decrease in durability and turfgrass green cover noticed in 2011.

Surface hardness in the following spring was greater for cultivars with lower biomass and shoot density, or cultivars with reduced CD (Figure 8ab). Assessment of surface hardness after fall-wear is important in case a determined sports field remains open for spring play, hosting practices, spring football, or youth sporting events. Nonetheless, from the sports turf manager standpoint, a quick spring recovery is important in order to enable proper summer management attempting to achieve highest possible turfgrass cover at the beginning of the next playing season, in the following fall.

Conclusions

Lower simulated wear intensities did not significantly reduced soil or bermudagrass quality. In fact, compared to non-trafficked bermudagrass, stimulation and growth was noticed under 1 simulated game $week^{-1}$ for some cultivars. Severe, frequent simulated wear further decreased bermudagrass green cover compounded by natural fall dormancy. Patriot bermudagrass performed the poorest for most of the parameters tested: turfgrass green cover, turfgrass total cover, turf shear strength, durability, spring biomass, and shoot density were reduced by simulated wear. Despite inconsistency between years in regard to fall durability, Celebration was able to maintain adequate traction even under severe simulated wear, justifying its use as sports turf for playability reasons. Celebration spring response, however, was poor, resulting in low biomass and shoot density. Tifway, utilized as a standard bermudagrasses cultivar, resulted in intermediate durability and spring response to fall, simulated wear. TifSport and TifGrand resulted in greater fall durability, including greater turfgrass green cover, lower green cover loss due to dormancy, and greater durability. Both cultivars also resulted in greater shoot density and biomass in the following spring. In addition to the turfgrass, severe wear also affected soil and playability parameters by decreasing thatch depth, and increasing soil bulk density and surface hardness. Soil parameters can affect sports field playability, and impact turfgrass growth and recovery from a wear season. Sports turf managers may use these results in the choice of the bermudagrass cultivar that best suit their needs.

Table 1. Analysis of variance (ANOVA) for effects of bermudagrass cultivar†, number of simulated games per week‡, date, year, and their interactions on percent green cover§, and turf shear strength¶ in Auburn, AL, for 2011 and 2012.

Source of variation	df	Percent green cover	Turf shear strength
Cultivar (C)	4	***	***
Games week^{-1} (G)	3	***	***
C x G	12	NS#	NS
Week (W)	2	***	***
C x W	8	*	***
G x W	6	**	***
C x G x W	24	NS	NS
YEAR (Y)	1	NS	***
C x Y	4	***	***
G x Y	3	***	***
C x G x Y	12	NS	NS
W x Y	2	***	***
C x W x Y	8	**	***
G x W x Y	6	**	***
C x G x W x Y	24	NS	NS

*Significant at the 0.05 probability level.

**Significant at the 0.01 probability level.

***Significant at the 0.001 probability level.

#NS, not significant at the α = 0.05 level.

†Cultivars evaluated were Celebration, Patriot, TifGrand, TifSport, and Tifway. Cultivars were established via sprigs on 15 Jun 2011 and 12 Jun 2012. Sprigging rate was 13 m^3 ha^{-1}.

‡Wear simulation was done with a Cady Traffic Simulator (CTS) at 0, 1, 3, and 5 simulated games week per week, from 22 Aug. to 1 Nov. 2011, and 4 Sept. to 12 Nov. 2012.

§Percent green cover determined via batch analysis of digital images.

¶Turf shear strength was measured in Newton meters (N m), on 3 subsamples per experimental unit, using a rotational device developed by Canaway and Bell (1986).

Table 2. Influence of number of simulated games per week[†] on percent bermudagrass total turfgrass cover (TTC)[‡], turfgrass green cover (TGC)[§], and non-green turfgrass cover (NGC)[¶] in Auburn, AL, in 2011 and 2012.

	-----%-----								
	TTC	TGC	NGC	TTC	TGC	NGC	TTC	TGC	NGC
Games week^{-1}	5 Sept. 2011			3 Oct. 2011			1 Nov. 2011		
0	99a[#]	68a	31a	100a	74a	26a	100a	53a	47a
1	87b	65a	22b	87b	71a	16b	82b	51a	31b
3	74c	59b	15c	68c	55b	14b	62c	47a	14c
5	68d	53c	15c	45d	39c	6c	54d	43a	10c
P value	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	NS[††]	< 0.0001
LSD (0.05)	5.0	3.9	6.1	5.1	3.4	4.2	7.9	14.2	11.9
Games week^{-1}	18 Sept. 2012			16 Oct. 2012			13 Nov. 2012		
0	100a	91a	10c	100a	89a	11c	100a	60a	40b
1	95b	82b	13c	95b	80b	16b	87b	36b	52a
3	85c	60c	25b	79c	56c	23a	61c	14c	46ab
5	79d	46d	33a	69d	41d	28a	32d	5d	27c
P value	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
LSD (0.05)	4.6	5.4	5.5	3.4	5.0	4.4	5.8	4.4	7.6

[†] Wear simulation was done with a Cady Traffic Simulator (CTS) at 0, 1, 3, and 5 simulated games week per week, from 22 Aug. to 1 Nov. 2011, and 4 Sept. to 12 Nov. 2012.

[‡] Percent total turfgrass cover was rated visually on a 0-100 scale.

[§] Percent turfgrass green cover means obtained on a 0-100 scale via batch analysis of digital images. Hue values were standardized from 50 to 92, and saturation values from 25 to 94.

[¶] Percent non-green turfgrass cover means obtained by subtracting the percent turf green cover means from the percent turf cover means.

[#] Within each column, and for each year, means sharing the same letter are not statistically different according to Fisher's protected test ($\alpha = 0.05$).

[††] NS, not significant at the $\alpha = 0.05$ level.

Table 3. Percent total turfgrass cover (TTC)[†], turfgrass green cover (TGC)[‡], and non-green turfgrass cover (NCG)[§] of bermudagrass cultivars[¶] subjected to fall, football-type wear in Auburn, AL, in 2011 and 2012.

	--------	--------	--------	--------	%	--------	--------	--------	--------
	TTC	TGC	NGC	TTC	TGC	NGC	TTC	TGC	NGC
Cultivar	5 Sept. 2011			3 Oct. 2011			1 Nov. 2011		
Celebration	82a[#]	55b	26a	79ab	60b	24a	74a	20c	42a
Patriot	81a	51b	29a	70c	58b	12c	72a	46b	26b
TifGrand	84a	66a	19b	80a	63a	17b	82a	60a	22b
TifSport	79a	67a	12b	75a-c	62a	13bc	75a	61a	15b
Tifway	84a	67a	17b	73c	62a	11c	69a	45b	24b
P value	NS[††]	< 0.0001	< 0.0001	0.0064	0.0006	< 0.0001	NS	< 0.0001	0.031
LSD (0.05)	5.6	4.4	6.8	5.8	3.8	4.7	7.8	12.6	13.3
Cultivar	18 Sept. 2012			16 Oct. 2012			13 Nov. 2012		
Celebration	93a	72b	21b	88a	72a	16cd	73a	34a	39b
Patriot	88a	59c	30a	83a	58c	25a	68a	13b	54a
TifGrand	91a	80a	11c	87a	73a	13d	68a	30a	37b
TifSport	90a	70b	20b	86a	66b	20bc	71a	34a	37b
Tifway	87a	68b	19b	87a	63b	23ab	72a	32a	40b
P value	NS	< 0.0001	< 0.0001	NS	< 0.0001	< 0.0001	NS	< 0.0001	0.0006
LSD (0.05)	5.1	6.0	6.1	3.8	5.6	5.0	6.5	4.9	8.5

[†]Percent total turfgrass cover was visually rated on a 0-100 scale.
[‡]Percent turfgrass green cover means obtained on a 0-100 scale via batch analysis of digital images. Hue values were standardized from 50 to 92, and saturation values from 25 to 94.
[§]Percent non-green turfgrass cover means obtained by subtracting the percent turf green cover means from the percent turf cover means.
[¶]Cultivars were established from sprigs on 15 Jun. 2011 and 12 Jun. 2012. Sprigging rate for both years was 13.5 m^3 ha^{-1}.
[#]Within each column, and for each year means sharing the same letter are not statistically different according to Fisher's protected test ($\alpha = 0.05$).
[††]NS, not significant at the $\alpha = 0.05$ level.

Table 4. Bermudagrass green cover quadratic regression parameters† ($y = y_0 + ax + bx^2$), green cover index (GCI)‡, and bermudagrass coefficient of durability (CD)§ obtained by calculating the the height of the triangle formed by the equations'roots, and the point where the equations' tangents intercept, when touching the equations'roots; in Auburn, AL, in 2011 and 2012.

	Simulated games week^{-1}	Cultivar	y_0	a	b	GCI	CD	R^2	*P* value
2011	0	Celebration	36.747	13.748	-1.393	-13.34	0.6	0.59	0.0047
		Patriot	43.992	11.081	-1.010	-5.66	0.87	0.47	0.0234
		TifGrand	60.318	5.407	-0.520	-0.73	0.99	0.20	NS¶
		TifSport	62.667	6.402	-0.676	-1.46	0.98	0.60	0.0042
		Tifway	59.483	7.147	-0.712	-1.81	0.97	0.23	NS
	1	Celebration	38.897	10.795	-1.046	-5.90	1.03	0.28	NS
		Patriot	30.790	14.382	-1.315	-12.44	0.67	0.64	0.0023
		TifGrand	64.333	1.924	-0.129	-0.02	1.06	0.04	NS
		TifSport	60.595	4.634	-0.372	-0.32	0.96	0.41	0.041
		Tifway	55.705	9.109	-1.070	-5.22	0.92	0.71	0.0006
	3	Celebration	32.862	9.741	-0.985	-4.72	0.77	0.40	0.0463
		Patriot	34.108	4.717	-0.658	-1.02	0.75	0.25	NS
		TifGrand	57.991	1.638	-0.209	-0.04	0.96	0.08	NS
		TifSport	70.280	-4.158	0.331	0.23	1.13	0.06	NS
		Tifway	63.517	-1.889	-0.108	0.01	1.07	0.02	NS
	5	Celebration	48.733	-1.556	0.063	0.00	1.33	0.03	NS
		Patriot	38.239	-1.653	0.079	0.01	0.87	0.18	NS
		TifGrand	58.470	-3.567	0.279	0.14	0.97	0.11	NS
		TifSport	61.499	-5.663	0.315	0.28	0.99	0.22	NS
		Tifway	55.610	-1.231	0.091	0.01	0.94	0.16	NS
2012	0	Celebration	85.853	4.756	-0.570	-0.77	0.99	0.94	< 0.0001
		Patriot	64.515	11.663	-1.538	-13.80	0.79	0.96	< 0.0001
		TifGrand	84.871	6.941	-0.913	-2.90	0.97	0.95	< 0.0001

	TifSport	89.145	2.538	-0.448	-0.25	1.00	0.91	< 0.0001
	Tifway	84.544	4.272	-0.613	-0.80	0.99	0.67	0.0014
1	Celebration	77.945	7.548	-1.085	-4.44	0.86	0.97	< 0.0001
	Patriot	50.417	14.437	-1.842	-24.49	0.40	0.83	< 0.0001
	TifGrand	82.181	7.458	-1.249	-5.82	0.90	0.93	< 0.0001
	TifSport	80.180	5.218	-0.876	-2.00	0.88	0.85	< 0.0001
	Tifway	78.415	4.693	-0.853	-1.71	0.91		
3	Celebration	52.302	10.378	-1.394	-10.09	0.49	0.95	< 0.0001
	Patriot	46.969	6.803	-1.154	-4.53	0.66	0.77	< 0.0001
	TifGrand	64.484	5.264	-1.081	-3.08	0.72	0.92	< 0.0001
	TifSport	52.025	6.099	-0.997	-3.03	0.55	0.94	< 0.0001
	Tifway	51.983	5.846	-0.986	-2.84	0.58	0.83	< 0.0001
5	Celebration	46.776	5.966	-1.051	-3.30	0.51	0.92	< 0.0001
	Patriot	39.202	3.166	-0.743	-0.87	0.59	0.70	0.0007
	TifGrand	65.015	-1.597	-0.480	0.18	0.77	0.91	< 0.0001
	TifSport	40.273	5.117	-0.895	-2.05	0.43	0.93	< 0.0001
	Tifway	32.543	6.427	-0.949	-2.89	0.35	0.90	< 0.0001

[†]Regression analysis parameters for turfgrass green cover (TGC) were obtained in SAS 9.2 (SAS Institute. Cary, NC) using PROC GLM at probability level of α = 0.05, following batch analysis of digital images. TGC was regressed over weeks and it is presented for each level of simulated wear and for each bermudagrass cultivar, in 2011 and 2012, satisfying the significant interactions year by simulated wear by weeks ($P < 0.0004$), and year by cultivar by weeks ($P < 0.0006$).

[‡]Green cover index was calculated as the height of the triangle formed by the two roots of the quadratic equation and the point where the curves' tangents intercept when touching each individual equation root. Applicably, the green cover index represents the change in a cultivar's TGC. Negative values indicate loss of TGC, whereas positive values indicate increase in TGC.

[§]Coefficient of durability obtained as the difference between the initial constant green cover within each simulated wear level and green cover loss, over the initial constant green cover for the nontreated. Diminishing values from 1 indicate loss of green cover, or less durability of a cultivar. Increasing values from one indicate greater durability than the nontreated for a specific cultivar.

[¶]NS, not significant at the α = 0.05 level.

Table 5. Influence of number of simulated games† on turf shear strength‡ of bermudagrass sports fields in Auburn, AL, in 2011 and 2012.

	--- N m ---					
		2011			2012	
Simulated games $week^{-1}$	5 Sept.	3 Oct.	1 Nov.	18 Sept.	16 Oct.	13 Nov.
0	61.6a§	53.2b	59.6a	61.2ab	46.9a	50.2a
1	59.1b	56.2a	60.2a	62.7a	45.9ab	50.1a
3	53.5c	56.9a	54.6b	59.5bc	44.8b	45.9b
5	46.6d	49.8c	43.8c	58.5c	42.1c	38.1c
P value	0.0001	0.0001	0.0001	0.0005	0.0001	0.0001
LSD (0.05)	2.3	2.7	2.2	2.1	1.6	2.9

†Wear simulation was done with a Cady Traffic Simulator (CTS) at 0, 1, 3, and 5 simulated games week per week, from 22 Aug. to 1 Nov. 2011, and 4 Sept. to 12 Nov. 2012.

‡Turf shear strength was measured in Newton meters (N m), on 3 subsamples per experimental unit, using a rotational device developed by Canaway and Bell (1986).

§Within each column, means sharing the same letter are not statistically different according to Fisher's protected test ($\alpha = 0.05$).

Table 6. Soil volumetric water content[†] under increasing number of simulated games[‡] in Auburn, AL, in 2011 and 2012.

		Volumetric water content (%)		
2011	Simulated games week^{-1}	5-Sep	3-Oct	1-Nov
	0	23.4 a[§]	32.1 ab	28.8 b
	1	22.6 a	32.8 a	31.4 a
	3	21.8 a	30.0 b	27.6 b
	5	22.7 a	29.9 b	28.2 b
	P value	NS[¶]	0.0206	0.0155
	LSD	2.2	2.3	2.5
2012	Simulated games week^{-1}	18-Sep	16-Oct	13-Nov
	0	26.9 a	23.5 a	19.6 a
	1	24.6 b	21.9 b	18.1 b
	3	23.7 b	20.6 c	18.3 b
	5	24.4 b	20.4 c	19.1 ab
	P value	< 0.0001	< 0.0001	0.0457
	LSD	1.2	1.1	1.2

[†]Measured with a FieldScout TDR 300 (Spectrum Technologies Inc. Aurora, IL) hand-held moisture probe equipped with 7.5 cm rods, with 3 subsamples per experimental unit.

[‡]Wear simulation was done with a Cady Traffic Simulator (CTS) at 0, 1, 3, and 5 simulated games week per week, from 22 Aug to 1 Nov 2011, and 4 Sep to 12 Nov 2012.

[§]Within each column, means sharing the same letter are not statistically different according to Fisher's protected test (α = 0.05).

[¶]NS, not significant at the α = 0.05 level.

Table 7. Game simulation effects on thatch depth[†], bulk density[‡], and surface hardness[§] of bermudagrass cultivars subjected to fall, football-type wear[¶] in 2012 and 2013, in Auburn, AL.

Games week^{-1}	Thatch depth (mm)	Bulk density (g cm^{-3})	Surface hardness (G_{max})
0	19 a[#]	1.50 c	50 c
1	19 a	1.54 c	62 b
3	14 b	1.61 b	63 b
5	9 c	1.69 a	72 a
P value	< 0.0001	< 0.0001	0.0002
LSD (0.05)	2	0.07	6.96

[†]Thatch depth measured in mm.
[‡]Bulk density refers to April 5, 2013. No significant differences were found for bulk density in the spring 2012. Measured within 0-5 cm soil layer, obtained from 5.6 cm diameter cores collected with a Giddings soil probe (Giddings Machine Co. Windsor, CO).
[§]Surface hardness measured with a Clegg impact soil tester (Turf-Tec International, Tallahassee, FL) using a 2.25 kg hammer, with 4 drops from a 45 cm height. Measurements included 3 subsamples per experimental unit.
[¶]Wear simulation was done with a Cady Traffic Simulator (CTS) at 0, 1, 3, and 5 simulated games week per week, from 22 Aug. to 1 Nov. 2011, and 4 Sept. to 12 Nov. 2012.
[#]Within each column, means sharing the same letter are not statistically different according to Fisher's protected test (α = 0.05).

Table 8. Turf shear strength† of different bermudagrass cultivars‡ subjected to fall, football-type simulated wear§ in Auburn, AL, in 2011 and 2012.

	---------- N m ----------					
	2011			2012		
Cultivar	5-Sep	3-Oct	1-Nov	18-Sep	16-Oct	13-Nov
Celebration	58 ab#	52 b	55 b	60 ab	45 a	49 a
Patriot	44 c	48 c	48 c	59 b	45 a	43 b
TifGrand	60 a	57 a	59 a	62 a	45 a	47 a
TifSport	57 b	58 a	56 ab	62 a	46 a	43 b
Tifway	57 b	56 a	55 b	58 b	44 a	49 a
P value	0.0001	0.0001	0.0001	0.0018	NS¶	0.0001
LSD (0.05)	2.6	3.0	2.5	2.3	1.8	3.2

†Turf shear strength was measured in Newton meters (N m), on 3 subsamples per experimental unit, using a rotational device developed by Canaway and Bell (1986).

‡Cultivars evaluated were Celebration, Patriot, TifGrand, TifSport, and Tifway. Cultivars were established via sprigs on 15 Jun. 2011 and 12 Jun. 2012. Sprigging rate was 13 m^3 ha^{-1}.

§Wear simulation was done with a Cady Traffic Simulator (CTS) at 0, 1, 3, and 5 simulated games per week, from 22 Aug. to 1 Nov. 2011, and 4 Sept. to 12 Nov. 2012.

#Within each column, means sharing the same letter are not statistically different according to Fisher's protected test ($\alpha = 0.05$).

¶NS, not significant at the $\alpha = 0.05$ level.

Table 9. Spring response of bermudagrass cultivars† following fall, football-type simulated wear‡ in Auburn, AL in 2012, and 2013: dried biomass§ and shoot density#.

Cultivar	------- Dried biomass (g) -------		---------------------- Shoot density (number of living shoots 100 cm^{-2}) ----------------------			
	27 Mar 2012	5 Apr 2013	27 Mar 2012		5 Apr 2013	
			No simulated wear	Simulated wear	No simulated wear	Simulated wear
Celebration	4.5 c¶	3.8 c	694 a	422 c	596 a	236 b
Patriot	4.7 c	5.2 b	845 a	460 c	456 a	312 ab
TifGrand	6.7 a	5.5 ab	966 a	908 a	682 a	411 a
TifSport	6.0 ab	6.4 a	1112 a	755 ab	718 a	428 a
Tifway	5.0 bc	6.2 ab	1117 a	669 b	529 a	351 ab
P value	0.0001	< 0.0001	NS††	< 0.0001	NS	0.0281
LSD (0.05)	1.1	1.1	332	197	260	128

†Cultivars were established via sprigs on 15 Jun. 2011 and 12 Jun. 2012. Sprigging rate for both years was 13.5 m^3 ha^{-1}.

‡Wear simulation was applied with a Cady Traffic Simulator (CTS) at 0, 1, 3, and 5 simulated games week per week, from 22 Aug. to 1 Nov. 2011, and 4 Sept. to 12 Nov. 2012.

§Biomass measured by weighing oven-dried samples collected with a standard golf cup cutter with 10.8 cm diameter.

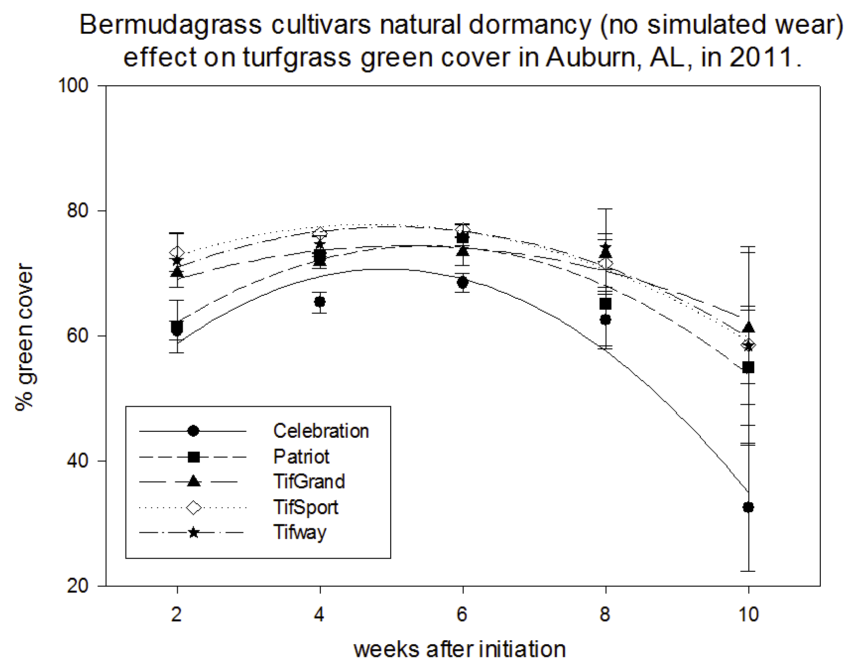
#Shoot density measured by counting number of living shoots from a 5.6 cm diamater plug, and converted to number of shoots per 100 cm^2.

¶Within each column, means sharing the same letter are not statistically different according to Fisher's protected test ($\alpha = 0.05$).

††NS, not significant at the $\alpha = 0.05$ level.

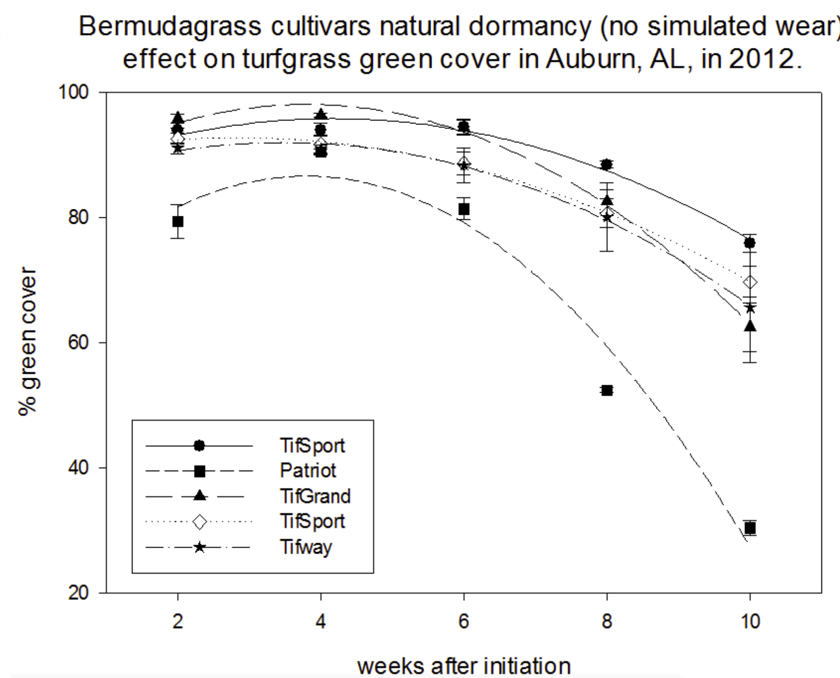
Figure 4.

a)



Bermudagrass cultivars natural dormancy (no simulated wear) effect on turfgrass green cover in Auburn, AL, in 2011.
% green cover
weeks after initiation
100
80
60
40
20
2
4
6
8
10
Celebration
Patriot
TifGrand
TifSport
Tifway

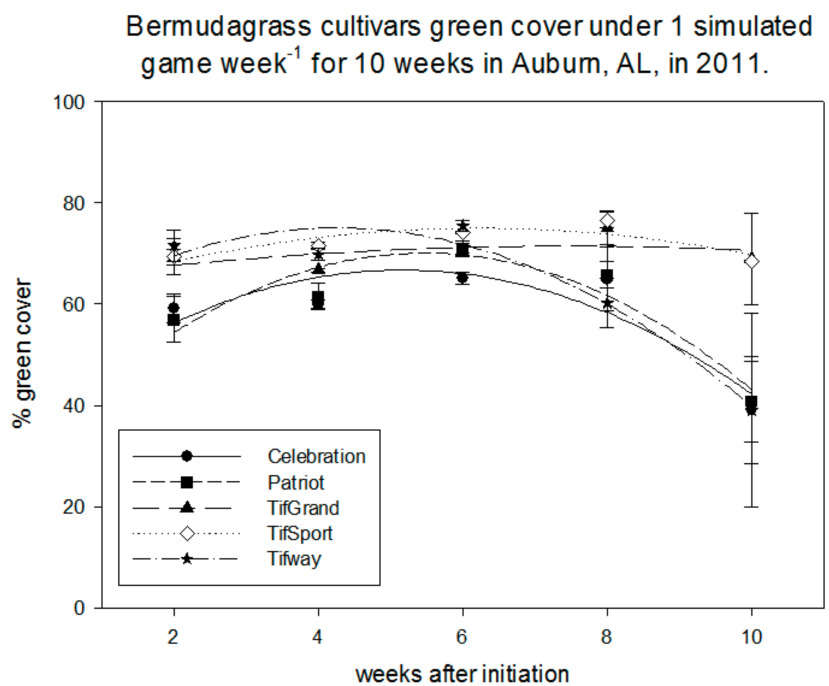
b)



Bermudagrass cultivars natural dormancy (no simulated wear) effect on turfgrass green cover in Auburn, AL, in 2012.
% green cover
weeks after initiation
100
80
60
40
20
2
4
6
8
10
TifSport
Patriot
TifGrand
TifSport
Tifway

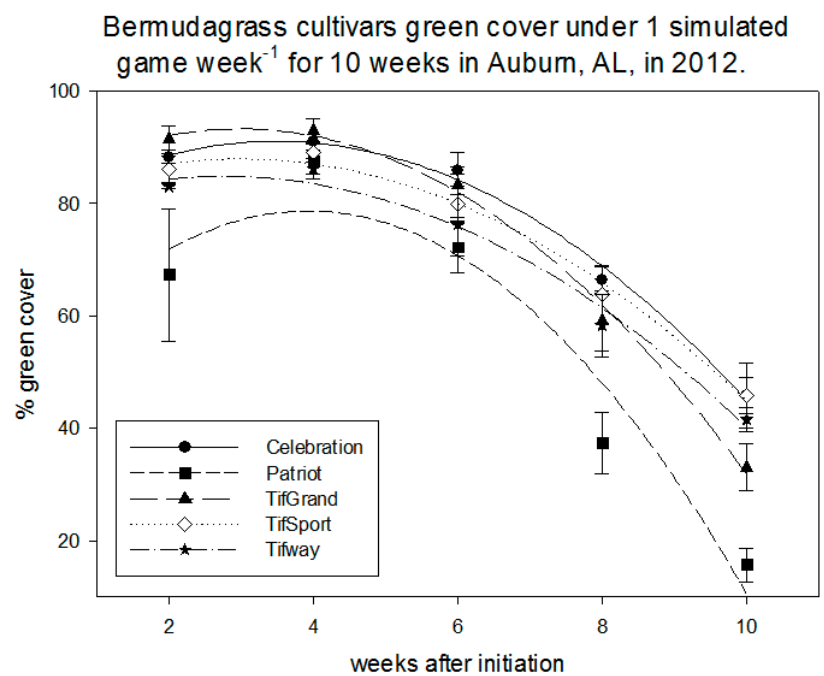
Figure 5.

a)



Bermudagrass cultivars green cover under 1 simulated game week^{-1} for 10 weeks in Auburn, AL, in 2011.
% green cover
weeks after initiation
Celebration
Patriot
TifGrand
TifSport
Tifway

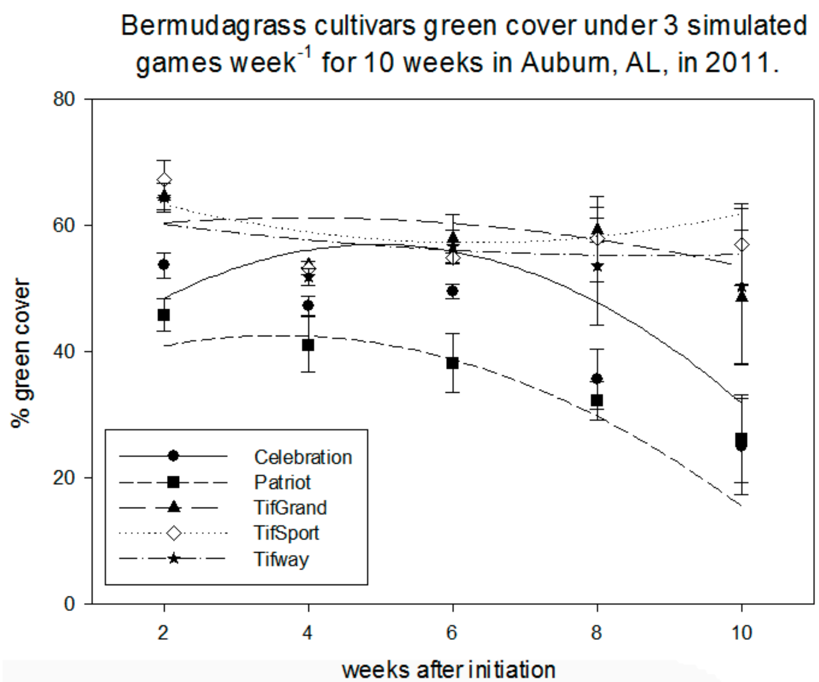
b)



Bermudagrass cultivars green cover under 1 simulated game week^{-1} for 10 weeks in Auburn, AL, in 2012.
% green cover
weeks after initiation
Celebration
Patriot
TifGrand
TifSport
Tifway

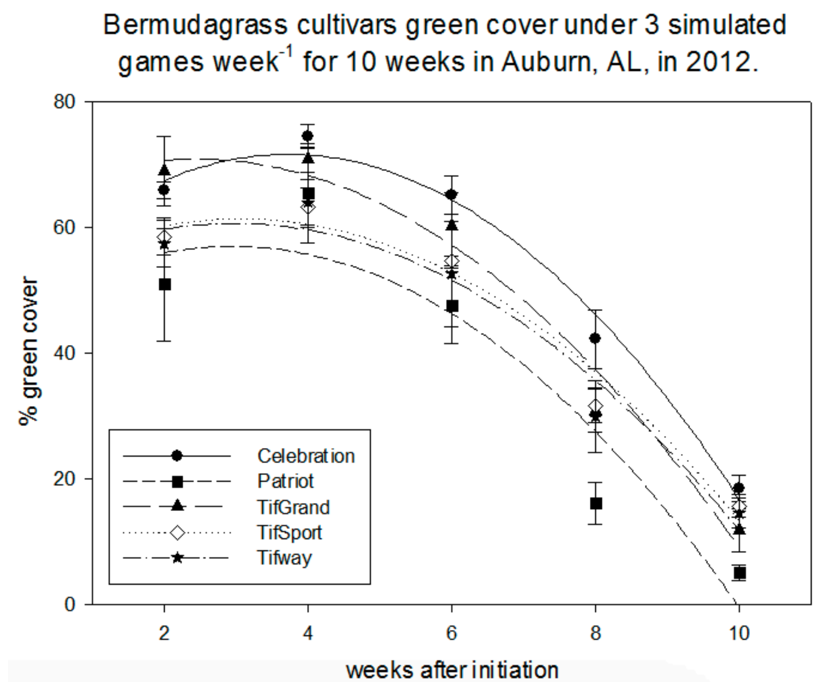
Figure 6.

a)



Bermudagrass cultivars green cover under 3 simulated games week-1 for 10 weeks in Auburn, AL, in 2011.
% green cover
weeks after initiation
0
20
40
60
80
2
4
6
8
10
Celebration
Patriot
TifGrand
TifSport
Tifway

b)



Bermudagrass cultivars green cover under 3 simulated games week-1 for 10 weeks in Auburn, AL, in 2012.
% green cover
weeks after initiation
0
20
40
60
80
2
4
6
8
10
Celebration
Patriot
TifGrand
TifSport
Tifway

Figure 7.

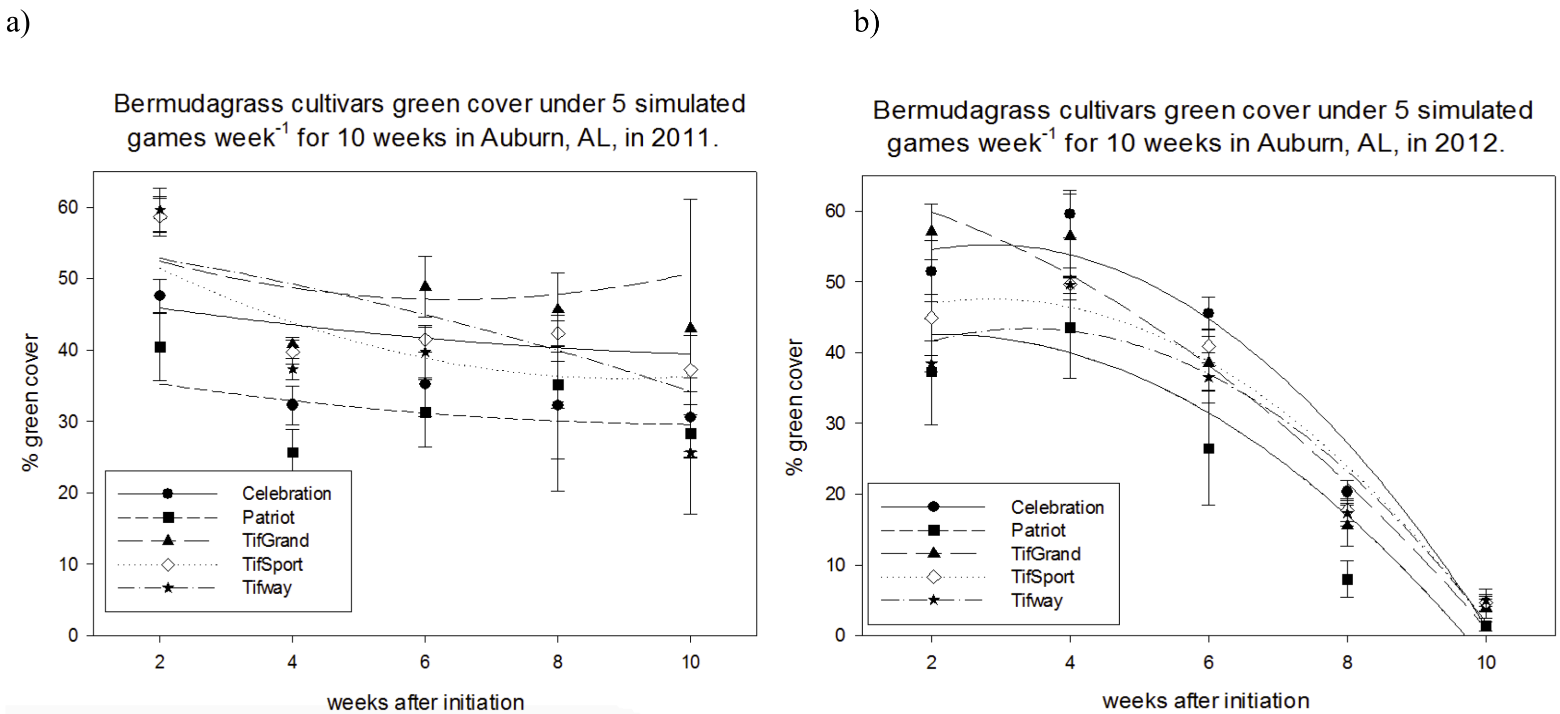
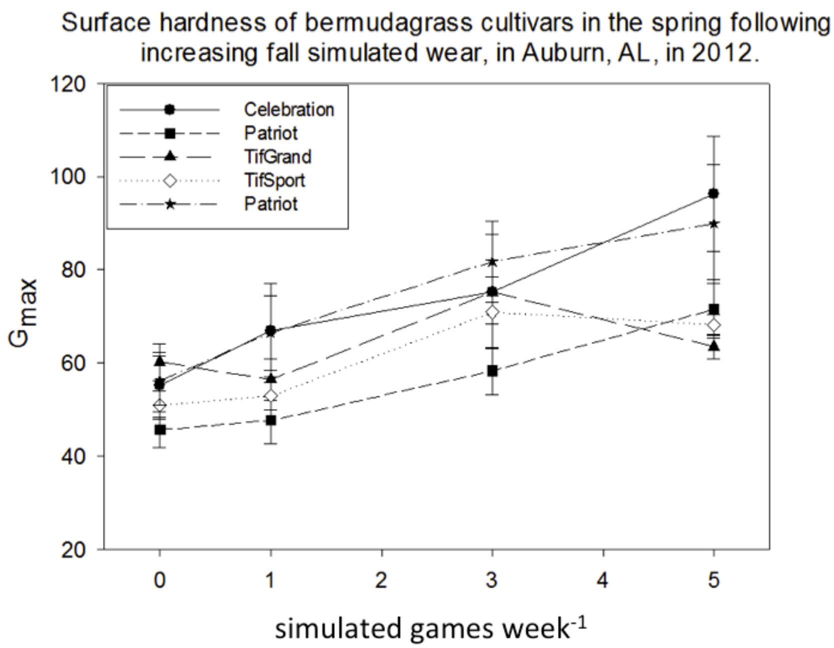

a)
Bermudagrass cultivars green cover under 5 simulated games week-1 for 10 weeks in Auburn, AL, in 2011.
% green cover
weeks after initiation
Celebration
Patriot
TifGrand
TifSport
Tifway
b)
Bermudagrass cultivars green cover under 5 simulated games week-1 for 10 weeks in Auburn, AL, in 2012.
% green cover
weeks after initiation
Celebration
Patriot
TifGrand
TifSport
Tifway

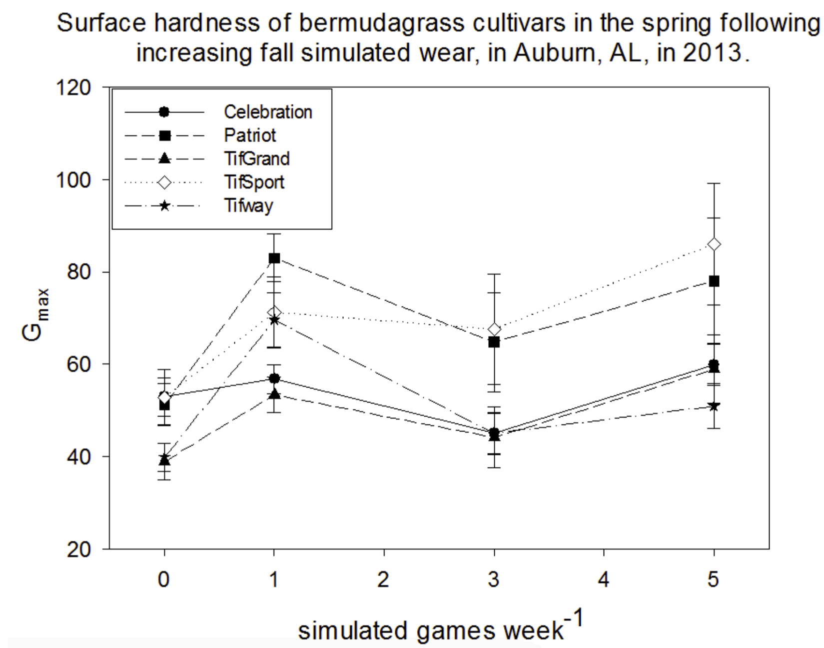
Figure 8.

a)



Surface hardness of bermudagrass cultivars in the spring following increasing fall simulated wear, in Auburn, AL, in 2012.
Celebration
Patriot
TifGrand
TifSport
Patriot
G_{max}
simulated games week^{-1}

b)



Surface hardness of bermudagrass cultivars in the spring following increasing fall simulated wear, in Auburn, AL, in 2013.
Celebration
Patriot
TifGrand
TifSport
Tifway
G_{max}
simulated games week^{-1}

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BERMUDAGRASS RESPONSE, ADAPTATION, AND TOLERANCE TO SIMULATED SHADE.

Introduction

A reduced light environment, or simply shade, negatively impacts turfgrass species inducing morphological and physiological changes (Beard, 1965; Wilkinson and Beard, 1974). Shaded plants have larger, but thinner leaves (Corre, 1983; Allard et al., 1991; Wherley et al., 2005), and more vertical growth, but at the expense of lateral growth and root biomass (Henry and Aarssen, 1997; Hebert et al., 2001; Huber and Wiggerman, 1997). Additionally, shaded turfgrass leaves develop higher levels of chlorophyll per unit of fresh mass, but reduced chlorophyll a to b ratio (Beard, 1973; Lambers et al., 2008). While the described shade acclimation response can allow for possible plant survival in natural ecosystems, such adaptations can be highly undesirable in maintained turfgrass, resulting in excessive foliage loss by frequent mowing, decreased photosynthetic capacity, poor turfgrass quality, and reduced ability to recover from wear (Studzinska, 2011). Baker (1995) reported decreased turfgrass cover, soil temperature, traction, and increased weed cover, and divot removal in a survey including 28 shaded stadiums. Research on shaded turfgrass is often done by applying continuous shade to the turfgrass (Gaussion et al., 1988; Ervin et al., 2002), despite the existence of diurnal variances in the shaded environment (Bunnell et al., 2005a). Bunnell et al. (2005a) quantified the light requirement of 'TifEagle' bermudagrass putting green applying periodic, diurnal shade. Yet, limited information is available on the behavior of periodically shaded bermudagrass cultivars for use in sports fields.

Bermudagrass (*Cynodon dactylon* (L.) Pers. X *C. transvaalensis* Burtt-Davy) is the turfgrass of choice for sports fields in the Southern U.S., the U.S. turfgrass transition zone, and possibly north of the transition zone (McBee and Holt, 1966; Taliaferro et al., 2006; Marshall, 2007; Morris, 2008; Wu et al., 2011; Thoms et al., 2011). Despite many desirable characteristics such as wear tolerance, aggressive growth, and summer heat tolerance, (Gibeault et al., 1992; Christians, 2004; Roche et al., 2009), bermudagrass growth is limited under shaded environments (Beard, 1997; Gaussoin et al., 1988). Shaded bermudagrass undergoes reductions in density, chlorophyll content, root biomass, carbohydrate production, and canopy photosynthetic rates (Jiang et al., 2004, Bunnell et al., 2005a, b, c; Baldwin et al., 2009b). Shade has also been reported to reduce yield, stands, roots, and rhizomes of 'Coastal' bermudagrass (*Cynodon dactylon* L. Pers. x *C. dactylon* L. Pers.) (Burton et al., 1959). McBee and Holt (1966), while studying the effect of shade on bermudagrasses amongst other species, reported that ground cover and type of growth were the most noticeable effects of shade on turfgrass plants. Such changes were less noticeable in bahiagrass (*Paspalum notatum* Flüggé), a warm-season turfgrass species with bunch-type growth habit.

Poor shade adaptation of bermudagrass is partially attributed to its C_4 photosynthetic pathway. While plants with C_3 photosynthesis require minimal tissue coordination under stresses such as shade due to simpler photosynthetic machinery, C_4 photosynthesis is a complex, space-partitioned process yielding greater photosynthetic efficiency under ideal conditions (Sage and McKown, 2006). Greater efficiency of C_4 photosynthesis is attributed to a more efficient carbon-fixing enzyme, phosphoenolpyruvate (PEP) carboxylase, compared to C_3 enzyme ribulose-1,5-biphosphate (RuBP) carboxylase (Taiz and Zeiger, 2006), and also to a unique anatomical configuration, the so-called Kranz anatomy, confering C_4 two distinct photosynthetic pathways:

in the mesophyll and in the bundle sheath (Taiz and Zeiger, 2006). As a result, adaptation to changes in the environment (such as low light) for C_4 plants requires advanced coordination between the two photosynthetic tissues, which is often not timely achieved (Horton and Neufeld, 1998; Sage and McKown, 2006).

Previous research indicates that there is variation for shade response within bermudagrass cultivars. 'No-Mow' bermudagrass (*Cynodon* spp.), suggesting a slow-growing cultivar with reduced vertical growth, was more shade tolerant than 'Tifway', based on turfgrass density and prostrate-growth type (McBee and Holt, 1966). The same study hypothesized that shade increased internode length and reduced internode diameter, resulting in turfgrass elongation, and decline in turfgrass quality (TQ). Other studies have reported total non-structural carbohydrate (TNC) content to vary under simulated shade (Gaussoin et al., 1988; Ervin et al., 2002), and greater TNC content differences between full-sun and shaded plants with increasing shade intensity: Tifway bermudagrass under 41% simulated, continuous shade, had similar TNC content to a full-sun plant, whereas 'TifSport' bermudagrass under 58% continuous shade maintained greater TNC than other cultivars. Excessive, continuous shade (71%), however, resulted in similar decline for grasses mowed at the same height (Bunnell et al., 2005c). 'Celebration' bermudagrass has been reported to maintain TQ ≤ 7 under 58% continuous shade, while TifSport and Tifway failed to maintain TQ ≤ 7 under 41% or less continuous shade (Bunnell et al., 2005c). In addition, Celebration maintained greater TQ under 64% continuous shade, followed by TifSport, Tifway, and Patriot (Baldwin et al., 2008), but a reduction in root biomass was noticed with increasing shading time. The same study reported an initial increase on chlorophyll content, however, after 8 weeks under shade, chlorophyll content declined (Baldwin et al., 2008).

‘TifGrand’, a relatively new hybrid bermudagrass, is a triploid genetically similar to other cultivars such as Tifway, Tifway II and TifSport (Chen et al., 2009; Harris et al., 2010). TifGrand, however, contains some unique alleles, uncommon to its “family” (Harris et al., 2010). Such unique differences could be associated with TifGrand’s differentiated performance compared to other bermudagrasses alike. TifGrand, also referred to as ‘ST-5’, has been reported to be more shade tolerant than other bermudagrass cultivars, performing “well under full-sun and under 70% continuous shade”, superior to Tifway and TifSport (Hanna et al., 2010). Haselbauer et al. (2012) reported similar or greater wear tolerance for TifGrand, compared to other bermudagrass cultivars including Tifway. In another study, TifGrand was a top performer for drought tolerance amongst others including Tifway, TifSport, and Celebration (Thapa, 2011).

Altogether, we hypothesize that TifGrand bermudagrass could be used as a sports turfgrass for shaded environments. Therefore, the objectives of this study are (i) to investigate the effect of diurnal shade regimes on Tifway and TifGrand bermudagrass maintained as sports turf, and (ii) investigate the response of 5 bermudagrass cultivars, including TifGrand, under increasing levels of continuous shade.

Materials and Methods

Two research projects were conducted for 12 weeks during the summers of 2012 and 2013, to evaluate the effects of simulated shade on bermudagrass cultivars commonly used as sports turf. Research was located at the Auburn University Turfgrass Research and Education Center in Auburn, AL (32.58° N, 85.50° W). The first project was conducted to evaluate established field plots of Tifway and TifGrand bermudagrass submitted to different diurnal simulated shade regimes. Project one will be referred to as the “Diurnal Shade Regimes”. The second project evaluated five bermudagrass cultivars grown in pots and acclimated in a greenhouse, to continuous, increasing simulated shade levels on an open field. Project two will be referred to as “Increasing Shade Intensities”.

Diurnal Shade Regimes. Mature stands of Tifway and TifGrand bermudagrass established on a Marvyn sandy loam (fine-loamy, kaolinitic, thermic, Typic Kanhapludult) with pH 6.2 and 2.1% organic matter, were submitted to diurnal simulated shade regimes from May 24 to August 17 in 2012, and June 5 to August 28 in 2013. Shade treatments included continuous shade, morning-only shade, afternoon-only shade, and a non-shaded, full-sun control. Shade was applied artificially, using a custom-made, neutral density, poly-fiber black shade cloth (International Greenhouse Co., Sidel IL) supported 30 cm above the turfgrass by a 2 by 2 m PVC structure. Shade level was 70%, allowing 30% incident light. To prevent low angle incident sunlight in the early and late hours of the day, 2 m by 25 cm shade cloth curtains were attached to 3 sides of each shade tent with no curtain attached on the north facing side. A 10 cm gap was maintained between the bottom of the curtain and the turf surface, to minimize changes in the microenvironment while still maintaining shade treatment levels. Shade tents were manually moved daily for morning-only and afternoon-only treatments. Bermudagrass was fertilized monthly during the duration of the experiment with polyon® (43-0-0, Harrell’s Fertilizer Inc., Sylacauga AL) slow release fertilizer at 49 kg N ha^{-1}, watered using an automated irrigation system to prevent plant wilting, and mowed 2-3 times weekly at approximately 1.8 cm with a reel mower (The Toro Company, Bloomington MN). Shade tents were momentarily removed for mowing for approximately five minutes every Monday, Wednesday, and Friday at approximately 9 am.

Light reduction, air temperature and relative humidity, cloud cover, soil volumetric water content, leaf temperature, and soil temperature were measured weekly at solar noon to quantify the shaded microenvironment. Light was measured as in photosynthetically active radiation (PAR), using a LI-250A hand-held spectroradiometer (LI-COR Inc., Lincoln NE). Air temperature and relative humidity were measured using a Kestrel 3000 pocket weather meter (Nielsen-Kellerman Inc., Boothwyn PA). Soil water was volumetrically measured using a FieldScout TDR 300 moisture meter (Spectrum Technologies, Inc., Aurora IL) equipped with 7.5 cm rods, with 3 subsamples. Soil and leaf temperature were measured with an IR2-S infrared thermometer with probe (Turf-Tec International, Tallahassee FL). Cloud cover was assessed visually on a percent basis, where 0 represents clear sky with no clouds and 100 represents complete cloud cover. Turfgrass data were also collected and included weekly ratings for turfgrass cover and quality, weekly measurements for normalized difference vegetation index (NDVI), seedhead production whenever noticed, pigment concentration at 4, 8, and 12 WAI, and above- and below ground fresh biomass of harvested samples at the end of the study. Turfgrass cover was rated visually on a percent scale where 0 represented bare ground with no turfgrass and 100 represented full turfgrass coverage with no visible soil. Turfgrass quality was also rated visually, on a 1-9 scale, following NTEP guidelines (Morris and Shearman, 1998), and considered turfgrass cover and turf density of green, actively growing bermudagrass. A TQ rating of 6 or above was considered acceptable. NDVI measurements used a FieldScout TCM 500 NDVI color meter (Spectrum Technologies Inc., Aurora IL), placed directly on the turf surface, including 3 subsamples. Seedheads were counted within a 0.02 m^2 frame and converted to number of seedheads per square meter.

Pigments were extracted for quantification according to Lictenthaler (1987), and included chlorophyll *a* (Chl *a)*, chlorophyll *b* (Chl *b*), and total carotenoids (β-carotene and xanthophylls). Bermudagrass leaves were homogenized in liquid nitrogen using a mortar and pestle. Approximately 0.05 g of the homogenized tissue was grinded in a 15 mL Potter-Elvehjem tissue grinder tube (Wheaton Science Products, Milville NJ) containing 10 mL of 99.5% acetone (dimethyl ketone; CH_3COCH_3) (Thermo Fisher Scientific Inc., Waltham MA). The supernatant was then centrifuged in a Clinical 200 large capacity centrifuge (VWR International LLC, Radnor PA) for 10 min at 2700 *g*. After centrifuging, an aliquot was transferred to a quartz spectrophotometer cell (VWR International LLC, Radnor PA) and analyzed spectrophotometrically using a Genesys 10S UV-Vis spectrophotometer (Thermo Fisher Scientific Inc., Waltham MA) at absorbance spectra of 661.6 ($A_{661.6}$), 644.8 ($A_{644.8}$), and 470.0 (A_{470}), respectively for Chl *a*, Chl *b*, and carotenoids. Pigment concentrations were calculated using the following formulae (Lictenthaler, 1987):

$$\text{Chl } a = 11.24A_{661.6} - 2.04A_{644.8}$$

$$\text{Chl } b = 20.13A_{644.8} - 4.19A_{661.6}$$

$$Carotenoids = \frac{1000A_{644.8} - 1.90(\text{Chl } a) - 63.14\ (\text{Chl } b)}{214}$$

where the pigment concentrations are in $\mu g\ mL^{-1}$, and *A* is the absorbance value at 661.6, 644.8, or 470.0 nm. Pigment concentration data were further converted to mg 100 g^{-1} on a bermudagrass fresh tissue weight basis, similarly to McCurdy et al. (2008).

Finally, Plugs were collected with a standard 10.8 cm diameter golf cup cutter, separated into above- and belowground tissue at the thatch/soil interface, and had excess soil washed off. Fresh biomass was measured for above- and belowground tissue by weighing the samples after excess water was dried off with a paper towel.

The experimental design was a randomized complete block, with a two-by-four factorial arrangement (two bermudagrass cultivars by four diurnal shade treatments). Data were collected at 4, 8 and 12 weeks after initiation (WAI), and analyzed in SAS 9.2 (SAS Institute. Cary, NC), using PROC GLIMMIX and PROC GLM. All data were subjected to analysis of variance (ANOVA) and separated by Fisher's protected LSD at $\alpha = 0.05$ level.

Increasing Shade Intensities. Five bermudagrass cultivars: Celebration, Patriot, TifGrand, TifSport, and Tifway, were investigated under increasing levels of simulated shade from May 23 to August 17 in 2012, and June 5 to August 28 in 2013, in Auburn, AL. Turfgrass plugs were collected in March 27, 2012, and April 7, 2013, using a 10.8 cm diameter standard golf cup cutter, and transplanted into 15 cm diameter pots after excess soil was washed off and roots were trimmed to approximately 15 cm length. Thirty cm-tall pots contained a 10 cm gravel layer, and 20 cm USGA soil mix (90:10 sand:peat vol vol^{-1}) profile. Pots were fertilized weekly with Miracle-Gro® (24-8-16, The Scotts Miracle-Gro® Company, Marisville OH) water soluble, all purpose plant food, providing 12.2 kg N ha^{-1}. Shade treatments included 30, 60, and 90% continuous shade, allowing 60, 40, and 10% incident light respectively (International Greenhouse, Sidel IL). A non-shaded, full-sun control treatment was also included. Artificial shade was applied similarly to the previous study, using a neutral density, black shade cloth attached to a 2 by 2 m PVC frame. Shade tents were 45 cm tall in order to accommodate the pots under them. Similarly to the previous study, 3 sides of each shade tent were enclosed using 2 m by 50 cm strips of the treatment-designated shade cloth. The north-facing side of the tents remained open. An automated sprinkler head was placed under each shade tent to provide adequate water and prevent plant wilting. After complete establishment of bermudagrass cultivars in a greenhouse, pots were placed on the field under shade treatments on May 23 in 2012 and June 5 in 2013.

Shade treatments were replicated 3 times, resulting in a randomized complete block experimental design with a four-by-five (four shade treatments by five bermudagrass cultivars) factorial arrangement. A total of 120 pots, two for each cultivar, were subjected to experimental treatments, to be analyzed separately. Turfgrass ratings, green cover analysis, and clipping yield were assessed weekly on pots under a weekly mowing schedule. Morphological parameters were assessed weekly on the duplicated set of pots. In order to measure etiolation parameters, plants in those pots were allowed to grow for 4 weeks, when plant harvest occurred for pigment and total TNC laboratory analysis at 4, 8, and 12 WAI, ensuring collection of enough plant material. Plant harvest was done by manually clipping plants at a 2 cm height, with plants allowed to grow until the next harvesting event.

Similarly to the previous study, light intensity, air temperature, and air relative humidity were measured to quantify the shaded microenvironment. Turfgrass data included bermudagrass green cover and quality, biomass, and morphological and physiological characteristics. Bermudagrass was rated for TQ similarly to the previous study, following NTEP guidelines (Morris and Shearman, 1998). Bermudagrass green cover was measured on a percent basis, using batch analysis of digital images (Karcher and Richardson, 2005). Digital images were taken using Canon Power Shot G9 (Canon Inc., Tokyo, Japan), mounted on a 0.07 m^2 light box apparatus equipped with two 43 W Reveal® energy efficient lamps (General Electric, Fairfield CT), and powered by a 1000 W, 12 V generator (American Honda Power Equipment, Alpharetta GA). Total biomass was measured by the cumulative dried clippings yield throughout 12 weeks. Clippings were collected weekly using a wooden rack with a reel mower set approximately at 1.8 cm mowing height. Individual tissue material for each pot was collected, and dried in a forced air, mechanical convection oven (VWR International, Radnor PA) at 80˚ Celsius (± 4˚ C) until constant weight was reached. Weight values in grams were added throughout the 12 weeks, representing total dried biomass. In addition to dried clipping biomass, fresh root biomass was measured at the end of the study. Morphological parameters included leaf length and width, and internode distance, measured at 4, 8, and 12 WAI using an electronic caliper (Mitutoyo America Corporation, Aurora IL), with 3 subsamples per pot. Plant shoots were harvested at 4, 8, and 12 WAI, immediately frozen in liquid nitrogen, then placed on ice for transfer to storage at -80˚ C for posterior analysis for pigment concentration. Chl *a* and *b*, and total carotenoids were analyzed similarly to the previous Diurnal Shade Regimes project as described above.

In addition to carotenoids, TNC was also analyzed according to this harvest schedule via the Shaffer-Hartmann (1921) iodometric titration of cuprous oxide, modified as described by Shaffer-Somogyi (1933). Analysis of TNC used frozen, field-collected samples, freeze-dried in a Freezone 6 Plus freeze-drier (Labconco, Kansas City MO), to avoid degradation of carbohydrates via the Maillard reaction (Van Soest, 1994). Freeze-dried samples were ground in a Tecator Cyclotec sample mill (Thermo Fisher Scientific Inc., Waltham MA) to pass a 1-mm screen. Samples weighing approximately 0.25 g were boiled in 50 mL of 0.05 *N* sulfuric acid (H_2SO_4) for 1 hour and placed in a shallow ice bath. The pH was adjusted to 4.5 using sodium hydroxide (NaOH) prior to addition of 0.1 mL of G-Zyme 480 amyloglucosidase solution (Batch

1662330935, DuPont Industrial Biosciences, Cedar Rapids IA), and then covered samples were incubated at 60˚ C for 1 hour. Preliminary analysis were performed to ensure the amount of amyloclugosidase was sufficient to completely digest expected amounts of starch into glucose. After incubation, samples were filtered and brought to volume with 2 mL 0.1 *N* NaOH and deionized water (H_2O) in a 250-mL volumetric flask. Ten mL of Shaffer-Somogyi (1995) reagent was added to a 10-mL aliquot of sample in a 25 x 200 mm capped test tube, and boiled for 15 min. After boiling, tubes were placed in an ice bath to cool, and 2 mL of a 2.5%, 100 mL solution containing potassium iodide (KI) and potassium oxalate [$(COOK)_2$] was added to each tube. Prior to titration, 10 mL of 1.0 *N* H_2SO_4 and 1 mL of gelatinized starch solution were added to each tube. Samples were titrated with 0.02 *N* sodium thiosulfate ($Na_2S_2O_3$) until the solution turned light blue. Along with sample preparation, 6 standards were prepared and included in each titration batch: corn stover (low TNC), winter annual crop mixture (high TNC), glucose TNC recovery, amylopectin TNC recovery, enzyme TNC recovery, and a water-only (blank) were added to ensure accuracy of the methodology. Concentration of TNC was calculated as the amount of reducing sugar in the sample, indicated by the amount of iodine used to reoxidize the copper (Cu^{+2}), multiplied by the dilution factor x 100, divided over the sample weight.

Treatment factors consisted of a split-plot within a RCB design, with a four-by-five (four shade treatments by five bermudagrass cultivars) factorial arrangement. Treatment means were submitted to ANOVA in SAS 9.2 (SAS Institute, Cary NC) for assessment of interactions, with α level = 0.05. Data residual analysis for normality used PROC GLIMMIX. Analysis of treatment means used Fisher's Protected LSD test at $\alpha = 0.05$, and regression analysis, in PROC GLM. Means and curves were plotted in SigmaPlot (Systat Software Inc., San Jose CA).

Results and discussion

Diurnal Shade Regimes. Significant interactions were found between year and several microenvironmental parameters, therefore, data are presented for 2012 and 2013 separately (Table 10). Light reduction was 70 and 73% for 2012 and 2013, respectively. Slightly more intense shading in 2013 could be associated with increased cloud cover ($P = 0.0248$) (Bell and Danneberger, 1999). No differences for air temperature and air humidity were found between full-sun and shade, suggesting that air flow was enough to avoid a shading-related effect for air temperature and relative humidity, partially contradicting Busey (1991) and Beard (1997). In agreement with Baker (1995) and Beard (1997), however, soil temperature was lower under shade compared to full-sun in both years. Soil volumetric water content also decreased under shade by 3.4 and 1.2%, for 2012 and 2013, respectively. Our soil moisture results contradicts Busey (1991), who hypothesized that shaded turfgrass should receive less irrigation than under full-sun due to less evapotranspiration (Feldhake et al., 1983), which would result in increased soil moisture content. Average bermudagrass leaf temperature also decreased under shade compared to full-sun by 5.2 and 4.3˚ C, respectively in 2012, and 2013. Such a cooling effect is significantly less pronounced than that found in the literature for cool season turfgrasses: 27 to 34˚ C reduction when air temperature was 40˚ C or above (Lee et al., 2001).

Multiple interactions were found for turfgrass parameters; therefore, data are presented separately for 2012 and 2013. Continuous 70% shade reduced total turfgrass cover 4, 8, and 12 WAI, most pronounced for Tifway compared to Tifgrand (Table 11). Continuous shade reduced Tifway cover from 100 to 47-68%. Periodic, diurnal shade was less detrimental to Tifway. Morning shade reduced Tifway cover to 90 and 87% for 2012 and 2013, respectively, whereas afternoon shade reduced Tifway cover to 80 and 77% in 2012 and 2013, respectively. TifGrand cover under continuous shade ranged 71-100% whereas morning- and afternoon-only shade did not reduce TifGrand cover, compared to full-sun. Shade regimes affected TQ of both cultivars in 2012 and 2013 (Table 12). In both years, continuous shade significantly reduced TQ for Tifway compared to full-sun. Reduction of TQ by morning- or afternoon-only shade was noted to a lesser extent. Tifway TQ scores 12 WAI in 2012 (6.3) indicate recovery and adaptation to shade. According to Busey (1991), "shade conditioning" or acclimation could play a role in turfgrass shade tolerance. Increased cloud cover could have impacted Tifway adaptation to shade in 2013. TifGrand had lowest TQ under full-sun in 2012, due to excessive seedhead production ($P <$ 0.0001), as shown on Table 13. Proliferous seedhead production has been previously noticed for TifGrand by Hanna et al. (2010). Seedhead production was lower in 2013 compared to 2012, likely due to increased cloud cover in 2013, preventing excessive radiation stress (Asada, 2006), resulting in greater TQ scores under full-sun. Excessive light can lead to formation of reactive oxygen species (ROS), resulting in photo-oxidative damages (Lambers et al., 2008; Xu et al., 2010). Possibly for TifGrand bermudagrass, a *sun plant* with reported shade acclimation, stresses resulting in excessive seedhead formation may be also associated with diurnal light variation leading to disturbances in its steady-state response to shade. Steady state response is achieved when plant responses are constant to an environmental change (irradiation in our case) after some time of exposure. Disturbances in the environment lead to dynamic responses, already mentioned slower to be achieved by bermudagrass relative to *shade plants* (Horton and Neufeld, 1998; Sage and McKown, 2006; Lambers et al., 2008).

Similarly to Tifway, continuous shade resulted in lowest TQ scores for TifGrand in 2013, which could be associated with reduced PAR by clouding. Under morning- and afternoon-only shade in 2013, however, TifGrand had maximum TQ 8 WAI, but only morning shade was able to sustain maximum TQ scores 12 WAI, contradicting the perception of morning shade as being more detrimental to turfgrass (Baldwin et al., 2009a). Previous literature reports that neither morning nor afternoon shade resulted in differences for creeping bentgrass (*Agrostis palustris* Huds.) growth (Bell and Danneberger, 1999), though Jiang et al. (2003) suggested afternoon shade could be more detrimental to trafficked seashore paspalum (*Paspalum* vaginatum Swartz) sports turf, agreeing with our results for periodically shaded bermudagrass. It seems self-evident that afternoon shade would be more detrimental for C_4 grasses as this is the greatest concentration of solar irradiance due to lower humidity in the atmosphere allowing for greater light concentration to the surface.

Significant differences for fresh tissue biomass by shade regime by cultivar were found for TifGrand only in 2012 (Table 14). Both cultivars had significantly greater belowground tissue production in 2013 (regardless of light level), which could be related to reduced light and heat stress, and less energy remobilization due to energy balance relationships between roots and shoots (Hull, 1992). Crafts and Crisp (1971) and Nyahoza (1973) have reported that shoots are strong sinks, depleting root energy content. In 2012, above- and belowground biomass of Tifway was lower than TifGrand, when there was no differences between shade regimes. TifGrand aboveground fresh biomass was mostly reduced by continuous shade (34 g) and afternoon shade (26 g). Full-sun and morning shade yielded similar aboveground biomass for TifGrand, 43 and 41 g, respectively. Similar results were noticed for TifGrand belowground fresh biomass, also in agreement with Hanna et al., (2010).

Overall, NDVI values were greater for TifGrand compared to Tifway (Table 15), similarly to TQ results (Trenholm et al., 1999). Little differences were found between full sun and shade treatments for TifGrand in 2012 and 2013, but generally, greater NDVI values ranked full sun ≥ morning shade > afternoon shade ≥ continuous shade. Tifway under morning shade resulted in greater NDVI values, followed by full sun, afternoon shade, and continuous shade. Multispectral radiometry analysis is associated to numerous plant stresses (including shade), and is strongly correlated with leaf chlorophyll concentrations (Carter, 1993; Carter et al., 1996). Therefore, pigment concentration results are discussed below.

Due to a significant shade treatment by cultivar by WAI by year interaction (multiple significant *P* values for Chl *b*, Chl *a* / Chl *b* ratio, and total carotenoids), pigment concentration is reported 6 and 12 WAI to assess possible physiological adaptation, which was not the case (Table 16). In general, Chl *a* and Chl *b* concentration for shaded TifGrand were greater than for Tifway. No differences were found between TifGrand and Tifway under full sun for Chl *a* and Chl *b*. Tifway Chl *a* concentrations were lower under continuous shade and afternoon shade. TifGrand greatest Chl *a* concentration resulted from continuous shade and afternoon shade. Chl *b* differences were noticed only in 2012, with greater concentrations for TifGrand compared to Tifway, especially when under shade. Previous research failed to report differences for Chl *a* to Chl *b* ratio under varying light regimes (Peacock and Dundeck, 1981; Miller et al., 2005). In our study, whereas TifGrand Chl *a* to Chl *b* ratio was not changed by shading regimes, Tifway under full sun had reduced Chl *a* to Chl *b* ratio compared to shaded treatments, suggesting summer stress to some degree. Chlorophyll degradation is reportedly accelerated when exposed to PAR at 1000 μ mol m^{-2} s^{-1} (Aro et al., 1993), and has also been associated with the lack of light in combination with high UV-B (Cen and Bornman, 1990; Nangle et al., 2015), though light quality was not measured in our study.

Total carotenoids concentration was also greater for TifGrand compared to Tifway, however, differences were only noticed in 2012. Tifway under full sun, and continuous shade resulted in lowest carotenoid concentrations 6 WAI, however, same treatments resulted in greater carotenoid concentrations 12 WAI. Conversely, no differences were found for TifGrand carotenoid concentrations 6 WAI, whereas full sun and continuous shade resulted in lower carotenoid concentrations 12 WAI (Table 7). Besides harvesting unabsorbed photons by chlorophyll (Niyogi, 1999), carotenoids also protect plants from high light intensity by changing its composition in response to high and low light conditions (Bell and Danneberger, 1999; McElroy et al., 2006). Our results suggest excessive light and excessive shading reduced carotenoid concentration (Xu et al., 2010), as seen in 2012. Similar decrease in total carotenoids was not noticed in 2013, likely due to increased cloud cover throughout the experiment.

Increasing shade intensities. PAR was reduced ($P < 0.0001$) to 33, 63, and 87 % relative to full-sun, respectively for 30, 60, and 90 % shade according manufacturer specifications (Data not shown). No differences between treatments were found for relative humidity (63-64%; $P = 0.99$) and air temperature (33-34˚ C; $P = 0.74$), thus our data assessment is solely based on light intensity reduction. Patriot, TifSport, and Tifway had greater TQ scores under full sun, while TifGrand and TifSport had greater TQ under increasing shade (Table 17). No differences were found for TQ under 90% simulated shade, likely due to excessive light reduction (Van Huylenbroeck and Van Bockstaele, 2001). Only TifGrand remained at acceptable minimum TQ under 60% shade, in agreement with Hanna et al. (2010), but contrary to Baldwin et al. (2008), who reported Celebration as being relatively shade tolerant. Increasing simulated shade decreased percent green cover of all cultivars, especially in 2013 (Figures 9a, b). Celebration and TifGrand maintained greater green cover, whereas Patriot, TifSport, and Tifway resulted in least green cover. Excessive shade (90%), however, eliminated some intraspecific differences for green cover.

Contrary to green cover, Chl *a* and *b* concentration increased with increasing simulated shade levels (Figures 10a, b). TifGrand had greatest Chl *a* and Chl *b* concentrations, whereas Patriot had the least Chl *a* and Chl *b* concentrations. Celebration, TifSport, and Tifway were intermediate for Chl *a* concentration, whereas for Chl *b,* intraspecific differences were reduced due to greater data variability. Similarly to Miller et al. (2005), no general trends for the ratio of Chl *a*:*b* were noted for increasing shade, despite cultivar differences (Figure 11). In fact, no change of the Chl *a*:*b* ratio for TifGrand and Celebration with increasing shade could be associated with more shade-stress adaptation (Busey, 1991). Total carotenoids concentration resulted in similar results, with a slight, steady concentration increase for TifGrand (Figure 12). Similarly to chlorophyll *a*:*b* ratio, Patriot, TifSport and Tifway greatly oscillated for carotenoid concentration with increasing shade levels. No differences in total carotenoids were noted for Celebration with increasing shade. Although previous research report both, increase and decrease in pigment concentration of shade-grown grasses, shade-adapted plants often result in greater pigment concentrations (Allard et al., 1991; Bell and Danneberger, 1999).

Total biomass accumulation decreased with increasing shade for all cultivars (Figure 13), in agreement with Beard (1997). TifGrand resulted in greater biomass under full-sun and 30% simulated shade, whereas Celebration resulted in greatest biomass under 90% shade. Baldwin et al. (2008; 2009b) reported greater Celebration root biomass relative to other bermudagrass cultivars. In our research, Celebration also had greater root fresh biomass under full-sun and 30% shade. However, as simulated shade increased, no differences between cultivars were found (Figure 14). Greater Celebration initial root biomass could be related to greater clipping yield 12

WAI. Roots could have become a major source of energy, once shoots have priority over roots in energy partitioning relationships (Hull, 1992; Krans and Beard, 1980). Furthermore, a major contributor for increased biomass could have been leaf etiolation. Leaf length was increased by increasing shades in 2012 and 2013, contrary to previous research with cool season grasses (Wilkinson and Beard, 1974) (Figures 15a, b). TifGrand had the least leaf etiolation in both years. Leaf etiolation was greater for Tifway, Celebration, and Patriot in 2012, and for Celebration in 2013. Leaf width also increased under moderate shade, but decreased with excessive shade (Figure 15c), which could be partially caused by overall turfgrass decline (Gaussoin et al., 1988). Internode distance under increasing shade was greater for Patriot, Celebration and Tifway, whereas TifGrand and TifSport resulted in least internode distance (Figure 15d). Whereas etiolation is desirable in some native ecosystems, it is detrimental to close-mowed turfgrass, resulting in more vertical growth, tissue removal, and decline in root biomass (Allard et al., 1991; Hebert et al., 2001; Studzinska, 2011). Finally, despite the possible energy translocation from roots to shoots (Hull, 1982; Krans and Beard, 1980), TNC content of shoots also decreased under increasing shade, indicating that energy remobilization is a turfgrass response in shaded environments, rather than a tolerance mechanism. Patriot and Celebration resulted in greater shoot TNC content, whereas TifGrand, Tifway, and TifSport resulted in lower TNC content. Intraspecific differences for TNC content, however, decreased as simulated shade increased (Figure 16).

Conclusions

TifGrand consistently had superior TQ, turfgrass cover, and greater pigment concentration than Tifway, when shaded. Full-sun and morning shade resulted in greater

TifGrand biomass, although there was excessive seedhead formation under full-sun. Morning shade for 12 weeks resulted in TifGrand maximum TQ, whereas maximum TQ of Tifway was noticed only under full-sun. Cloud cover could have influenced results for 2013, enlightening the need for research on management practices that could impact bermudagrass growth under such conditions. Differences in soil parameters under shade also bring to light potential for future research focusing on root stress and water relationships such as evapotranspiration of shaded bermudagrasses. Evidently, TifGrand seedhead suppression is another potential area for future research.

Under increasing simulated shade levels, TifSport and TifGrand had superior TQ compared to Patriot, Tifway, and Celebration. Celebration had greater biomass when grown under shade, however, etiolation played a role in greater biomass, contributing to Celebration decline. Cultivars more tolerant to etiolation under shade (e.g. TifGrand and TifSport) resulted in greater quality, and therefore, shade tolerance of bermudagrasses appears to rely on morphological parameters rather than physiological parameters. Physiological parameters such as pigment concentration and TNC varied under increasing shade, seemingly as response mechanisms to other bermudagrass adaptations. No general trend could be detected, except for the fact that shade-adapted turfgrasses were less affected by increasing shade, showing little to no oscillation for such parameters. Because of etiolation, there is great potential for the use of herbicides and plant growth regulators for shaded bermudagrass quality improvement.

Table 10. Influence of simulated shade on microenvironmental parameters for 2012 and 2013, in Auburn, AL.

	2012				2013			
	Full sun		70% shade		Full sun		70% shade	
PAR[a] (µmol m^{-2} sec^{-1})	1042	a[f]	327	b	666	a	179	b
LSD (0.05)	168				107			
P value	< 0.0001				< 0.0001			
Air temperature[b] (°C)	31.7	a	31.4	a	32.0	a	31.5	a
LSD (0.05)	1.2				1.1			
P value	NS[g]				NS			
Air relative humidity[b] (%)	67.3	a	66.6	a	75.8	a	75.0	a
LSD (0.05)	3.8				4.7			
P value	NS				NS			
Soil temperature[c] (°C)	27.6	a	25.5	b	28.6	a	26.9	b
LSD (0.05)	0.6				0.6			
P value	< 0.0001				< 0.0001			
Leaf temperature[c] (°C)	32.2	a	27.0	b	31.6	a	27.3	b
LSD (0.05)	1.7				1.3			
P value	< 0.0001				< 0.0001			
Volumetric water content[d] (%)	36.2	a	32.8	b	36.6	a	35.4	b
LSD (0.05)	1.0				0.9			
P value	< 0.0001				< 0.0001			

	2012			2013		
	Mean	Min	Max	Mean	Min	Max
Cloud cover[e] (%)	40	0	100	69	50	100

[a]Measured weekly, at mid-day, using a LI-250A hand held light meter (Li-Cor, Inc. Lincoln, NE).

[b]Measured weekly, at mid-day, using a Ketrel 3000 pocket weather meter (Nielsen-Kellerman, Boothwyn, PA).

[c]Measured weekly, using an IR2-S infrared thermometer with probe (Turf-Tec International, Tallahassee FL).

[d]Measured weekly, at mid-day, with 3 subsamples per experimental unit, using a FieldScout TDR 300 soil moisture meter (Spectrum Technologies, Inc., Aurora, IL) equipped with 7.5 cm rods.

[e]Assessed visually, weekly, on a percent scale.

[f]Within each column, means sharing the same letter are not statistically different according to Fisher's protected test (α = 0.05).

[g]NS, not significant at the α = 0.05 level.

Table 11. Bermudagrass cultivars visual ratings[a] for total turfgrass cover under different shade regimes[b], 4, 8, and 12 weeks after shade initiation[c] (WAI), for 2012 and 2013, in Auburn, AL.

		--------% turfgrass cover--------											
		4 WAI				8 WAI				12 WAI			
		Tifway		TifGrand		Tifway		TifGrand		Tifway		TifGrand	
2012	Full sun	97	a[d]	93	ab	100	a	100	a	100	a	100	a
	Continuous shade	57	c	57	c	68	c	97	ab	53	e	73	d
	AM only shade	87	ab	90	ab	100	a	100	a	90	bc	93	ab
	PM only shade	80	b	90	ab	93	b	100	a	83	c	97	ab
	LSD (0.05)	15				5				8			
	P value	< 0.0001				< 0.0001				< 0.0001			
		4 WAI				8 WAI				12 WAI			
		Tifway		TifGrand		Tifway		TifGrand		Tifway		TifGrand	
2013	Full sun	100	a	100	a	97	a	100	a	90	a-c	100	a
	Continuous shade	57	c	100	a	73	b	77	b	47	d	83	bc
	AM only shade	87	b	100	a	97	a	100	a	97	ab	100	a
	PM only shade	80	b	100	a	97	a	100	a	77	c	93	ab
	LSD (0.05)	8				8				16			
	P value	< 0.0001				< 0.0001				< 0.0001			

[a]Visual ratings on a percent basis.

[b]Shade regimes consistent of a non-treated, full sun treatment, and 70 % continuous artificial shade, 70 % in the morning only, and 70 % shade in the afternoon only. Duration of treatments were from May 24 to August 17 in 2012, and June 5 to August 28 in 2013.

[c]Shade initiation ocurred on May 24 2012, and June 5, 2013.

[d]Within each column, means sharing the same letter are not statistically different according to Fisher's protected test (α = 0.05).

Table 12. Visual ratings[a] for turfgrass quality scores under different shade regimes[b], 4, 8, and 12 weeks after shade initiation[c] (WAI), for 2012 and 2013, in Auburn, AL.

		TQ (1-9)											
		4 WAI				8 WAI				12 WAI			
		Tifway		TifGrand		Tifway		TifGrand		Tifway		TifGrand	
2012	Full sun	8.3	a[e]	6.7	a	9	a	4.3	c	9	a	6	cd
	Continuous shade	7.7	a	7.7	a	4.3	c	8.7	a	6.7	bc	6.3	cd
	AM only shade	7.7	a	6.7	a	6.7	b	6	b	5	d	7	bc
	PM only shade	8.3	a	8.7	a	6.3	b	5.7	bc	3	e	8	ab
	LSD (0.05)	2.1				1.4				1.6			
	P value	NS[d]				< 0.0001				< 0.0001			
		4 WAI				8 WAI				12 WAI			
		Tifway		TifGrand		Tifway		TifGrand		Tifway		TifGrand	
2013	Full sun	9	a	7.3	b	7	b	8	ab	6.3	cd	6.7	bc
	Continuous shade	4.7	d	6	c	4.7	c	5	c	3.7	e	4.7	e
	AM only shade	7.3	b	9	a	7	b	9	a	8	ab	9	a
	PM only shade	6.7	bc	7.3	b	7.3	b	9	a	5	de	6.3	cd
	LSD (0.05)	0.8				1.2				1.5			
	P value	< 0.0001				< 0.0001				< 0.0001			

[a]Visual ratings on a 1-9 scale, where 1 represents brow/dead, thin turfgrass, and 9 represents dark green, dense turfgrass. A rating of 6 or above was considered acceptable.

[b]Shade regimes consistent of a non-treated, full sun treatment, and 70 % conyinuous artificial shade, 70 % in the morning only, and 70 % shade in the afternoon only. Duration of treatments were from May 24 to August 17 in 2012, and June 5 to August 28 in 2013.

[c]Shade treatments intiated on 31 May 2012, and 12 Jun 2013.

[d]NS, not significant at the $\alpha = 0.05$ level.

[e]Within each column, means sharing the same letter are not statistically different according to Fisher's protected test ($\alpha = 0.05$).

Table 13. Total seedhead production[a] for TifGrand bermudagrass under to different shade regimes[b], for 2012 and 2013, in Auburn, AL.

	------- Total number of seedheads m-2 -------	
Shade regime	2012	2013
Full sun	2516 a[c]	399 b
Continuous shade	1 c	154 c
AM only shade	615 b	225 c
PM only shade	490 b	619 a
LSD (0.05)	279	143
R^2	0.92	0.62

[a]Total seedhead production measured by counting seedheads weekly, within a 0.02 m^2 frame and converted to number of seedheads per square meter. Weekly counts for individual treatments were added throughout 12 weeks.

[b]Shade regimes consistent of a non-treated, full sun treatment, and 70 % conyinuous artificial shade, 70 % in the morning only, and 70 % shade in the afternoon only. Duration of treatments was from May 24 to August 17 in 2012, and June 5 to August 28 in 2013.

[c]Within each column, means sharing the same letter are not statistically different according to Fisher's protected test (α = 0.05).

Table 14. Fresh biomass[a] of Tifway and TifGrand bermudagrass under different shade regimes[b], in Auburn AL, in 2012 and 2013.

	g fresh tissue plug^{-1}							
	2012				2013			
	Aboveground		Belowground		Aboveground		Belowground	
Shade regime	Tifway	TifGrand	Tifway	TifGrand	Tifway	TifGrand	Tifway	TifGrand
Full-sun	33 a-c[c]	43 a	25 b	31 ab	20 b	83 a	116 a	118 a
Continuous shade	22 c	34 a-c	19 b	20 b	36 ab	23 ab	102 a	117 a
AM only shade	27 bc	41 ab	27 b	45 a	23 ab	44 ab	78 a	66 a
PM only shade	23 c	26 c	14 b	27 b	26 ab	47 ab	94 a	101 a
LSD (0.05)	16		18		60		66	

[a]Measured on separated turfgrass sections from samples collected with a 10.8 diameter golf cup cutter.

[b]Shade regimes consistent of a non-treated, full sun treatment, and 70 % conyinuous artificial shade, 70 % in the morning only, and 70 % shade in the afternoon only. Duration of treatments was from May 24 to August 17 in 2012, and June 5 to August 28 in 2013.

[c]Within each column, means sharing the same letter are not statistically different according to Fisher's protected test ($\alpha = 0.05$).

Table 15. Normalized difference vegetation index[a] (NDVI) for Tifway and TifGrand bermudagrass under different shade regimes[b], 4, 8, and 12 weeks after initiation (WAI), for 2012 and 2013, in Auburn, AL.

		---- NDVI ----											
		4 WAI				8 WAI				12 WAI			
	Shade regime	Tifway		TifGrand		Tifway		TifGrand		Tifway		TifGrand	
	Full sun	0.756	c[c]	0.75689	bc	0.795	b	0.800	b	0.742	a	0.705	ab
	Continuous shade	0.773	abc	0.769	abc	0.717	c	0.797	b	0.495	d	0.621	c
2012	AM only shade	0.796	a	0.799	a	0.790	b	0.833	a	0.709	a	0.717	a
	PM only shade	0.744	c	0.78689	ab	0.791	b	0.828	a	0.658	bc	0.706	ab
	LSD (0.05)	0.031				0.017				0.049			
	P value	0.0038				< 0.0001				< 0.0001			
	R^2	0.27				0.8				0.7			
		4 WAI				8 WAI				12 WAI			
	Shade regime	Tifway		TifGrand		Tifway		TifGrand		Tifway		TifGrand	
	Full sun	0.728	bc	0.781	a	0.606	c	0.738	a	0.623	bc	0.681	ab
	Continuous shade	0.563	e	0.747	ab	0.566	d	0.652	b	0.476	c	0.68433	a
2013	AM only shade	0.693	cd	0.777	a	0.655	b	0.727	a	0.688	a	0.720	a
	PM only shade	0.684	d	0.781	a	0.582	cd	0.686	b	0.531	c	0.675	ab
	LSD (0.05)	0.035				0.036				0.067			
	P value	< 0.0001				< 0.0001				< 0.0001			
	R^2	0.79				0.74				0.64			

[a]NDVI measured using a FieldScout TCM 500 NDVI turf color meter (Spectrum Technologies Inc. Aurora, IL), including 3 subsamples.

[b]Shade regimes consistent of a non-treated, full sun treatment, and 70 % conyinuous artificial shade, 70 % in the morning only, and 70 % shade in the afternoon only. Duration of treatments was from May 24 to August 17 in 2012, and June 5 to August 28 in 2013.

[c]For each rating timing and year, means sharing the same letter are not statistically different according to Fisher's protected test (α = 0.05).

Table 16. Spectral determination[a] of shaded[b] Tifway and TifGrand bermudagrass pigments for 2012 and 2013, in Auburn, AL.

			---------------------------- g 100 g^{-1} of fresh plant material ----------------------------							
			Chlorophyl A		Chlorophyl B		Chlorophyl A/B ratio		Total carotenoids	
2012	6 WAI	Shade regime	Tifway	TifGrand	Tifway	TifGrand	Tifway	TifGrand	Tifway	TifGrand
		Full sun	21.6 cd[c]	29.1 ab	6.1 d	9.8 ab	3.5 a	3.0 b	9.2 d	12.7 ab
		Continuous shade	21.1 d	34.3 a	6.1 d	10.6 a	3.5 a	3.3 ab	9.1 d	14.5 a
		AM only shade	26.9 bc	27.6 b	7.7 cd	8.2 bc	3.5 a	3.4 a	11.8 bc	12.6 ab
		PM only shade	23.8 b-d	28.9 b	6.8 cd	8.4 bc	3.5 a	3.4 a	10.3 cd	12.8 ab
		LSD (0.05)	5.2		1.6		0.3		1.9	
		P value	< 0.0001		< 0.0001		0.0318		< 0.0001	
		R^2	0.50		0.60		0.30		0.58	
	12 WAI		Chlorophyl A		Chlorophyl B		Chlorophyl A/B ratio		Total carotenoids	
		Shade regime	Tifway	TifGrand	Tifway	TifGrand	Tifway	TifGrand	Tifway	TifGrand
		Full sun	18.2 a-c	17.7 bc	6.4 a	6.2 ab	2.9 cd	2.6 d	8.2 bc	7.2 c-e
		Continuous shade	15.3 d	17.6 bc	5.8 a-c	5.9 a-c	3.2 a-c	3.0 b-d	8.1 b-d	7.7 b-e
		AM only shade	16.8 b-d	18.7 ab	4.8 bc	7.0 a	3.5 a	2.7 d	7.1 de	8.6 ab
		PM only shade	16.3 cd	20.1 a	4.6 c	7.0 a	3.5 ab	2.9 cd	7.0 e	9.5 a
		LSD (0.05)	2.1		1.5		0.5		1.1	
		P value	0.0019		0.01		0.0031		0.0004	
		R^2	0.42		0.34		0.40		0.47	
			Chlorophyl A		Chlorophyl B		Chlorophyl A/B ratio		Total carotenoids	
2013	6 WAI	Shade regime	Tifway	TifGrand	Tifway	TifGrand	Tifway	TifGrand	Tifway	TifGrand
		Full sun	20.8 c	28.7 a-c	3.1 a	3.5 a	6.7 a	8.5 a	4.1 a	4.8 a
		Continuous shade	21.1 c	34.0 a	1.7 a	5.6 a	12.6 a	7.4 a	2.4 a	6.4 a
		AM only shade	28.5 a-c	27.3 a-c	3.5 a	5.6 a	10.7 a	8.2 a	3.7 a	6.4 a

Shade regime	Tifway		TifGrand		Tifway		TifGrand		Tifway		TifGrand		Tifway		TifGrand	
PM only shade	25.2	bc	30.0	ab	3.7	a	6.6	a	6.8	a	5.3	a	4.4	a	7.5	a
LSD (0.05)	7.9				4.0				7.8				3.5			
P value	0.0382				NS[d]				NS				NS			
R^2	0.56				0.39				0.27				0.47			

12 WAI

	Chlorophyl A				Chlorophyl B				Chlorophyl A/B ratio				Total carotenoids			
Shade regime	Tifway		TifGrand		Tifway		TifGrand		Tifway		TifGrand		Tifway		TifGrand	
Full sun	17.4	bc	15.6	c	3.7	a	6.4	a	4.6	a	2.5	a	6.1	a	9.6	a
Continuous shade	18.6	a-c	19.0	ab	3.9	a	5.9	a	5.5	a	3.3	a	6.5	a	8.1	a
AM only shade	16.8	bc	17.9	bc	4.5	a	5.4	a	4.5	a	3.5	a	5.6	a	7.6	a
PM only shade	17.5	bc	21.5	a	4.7	a	5.9	a	3.8	a	3.7	a	7.5	a	8.9	a
LSD (0.05)	3.03				2.33				2.60				3.06			
P value	0.0328				NS				NS				NS			
R^2	0.57				0.42				0.34				0.45			

[a]Spectral determination of chlorophylls *a* and *b*, and total carotenoids using 100% acetone extraction according to Lictenthaler (1987). Spectophotometer absorbances set to 470, 644.8, and 661.6.

[b]Shade regimes consistent of a non-treated, full sun treatment, and 70 % conyinuous artificial shade, 70 % in the morning only, and 70 % shade in the afternoon only. Duration of treatments was from May 24 to August 17 in 2012, and June 5 to August 28 in 2013.

[c]For each rating timing, means sharing the same letter are not statistically different according to Fisher's protected test ($\alpha = 0.05$).

[d]NS, not significant at the $\alpha = 0.05$ level.

Table 17. Turfgrass quality (TQ) scores[a] for bermudagrass cultivars maintained under different shade levels[b] in 2012 and 2013, in Auburn, AL.

	------------------------- Shade level (%) -------------------------							
Cultivar	0		30		60		90	
Celebration	6.7	c[c]	7.4	ab	4.4	c	3.6	a
Patriot	8.1	ab	6.8	b	5.6	b	2.4	a
TifGrand	7.4	bc	8.1	a	6.7	a	3.9	a
TifSport	8.5	a	7.9	a	5.8	ab	3.1	a
Tifway	8.1	ab	7.1	b	5.3	bc	3.4	a
P value	< 0.0001		< 0.0031		< 0.0009		NS[d]	
LDS (0.05)	0.8		0.7		1.0		1.8	

[a]Assessed visually, on a 1-9 scale, according to the NTEP turfgrass evaluation guidelines.

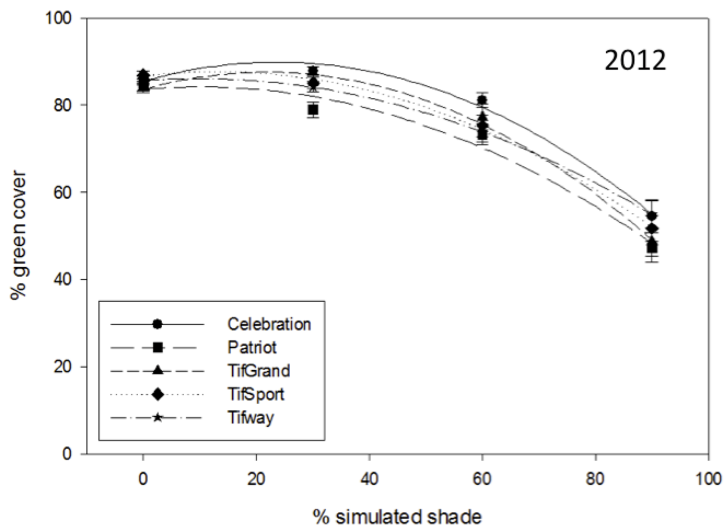
[b]Simulated shade levels consisted of individual, replicated shade tents simulating 30, 60, and 90% shade. Treatment duration was from May 23 to August 17, 2012, and June 5 to August 28, 2013.

[c]Within each column, means sharing a common letter are not significantly different according to Fisher's proteted test at $\alpha = 0.05$ level.

[d]NS, not significant at the $\alpha = 0.05$ level.

Figure 9. Effect of increasing levels of simulated shade on bermudagrass cultivars percent green cover in 2012(a), and 2013(b), in Auburn, AL.

a)



b)

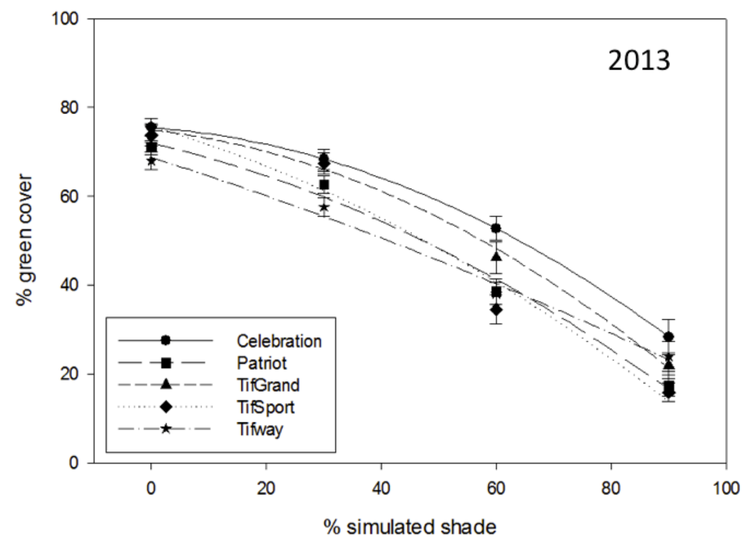
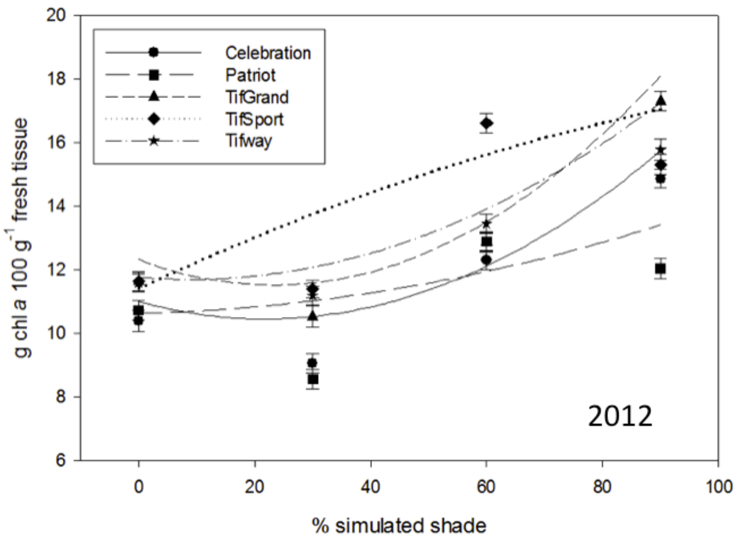


Figure 10. Effect of increasing levels of simulated shade on bermudagrass chlorophyll concentration in 2012(a) and 2013(b), in Auburn, AL.

a)



b)

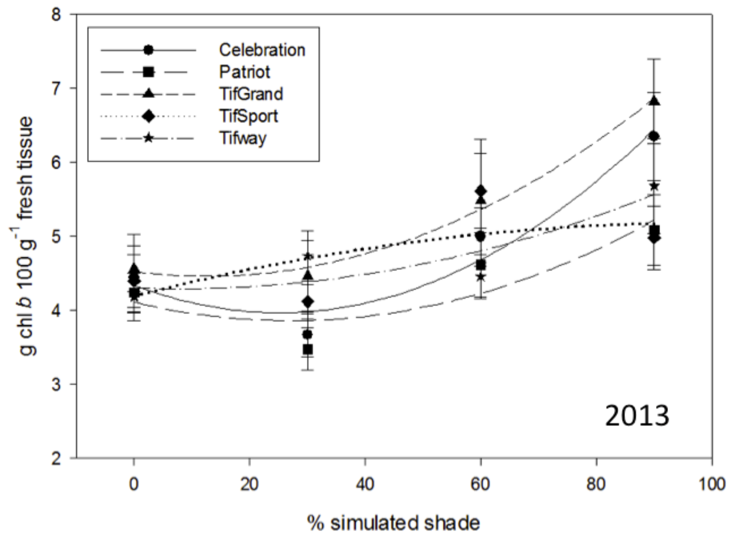


Figure 11. Effect of increasing levels of simulated shade on bermudagrass chlorophyll *a* to *b* ratio, in 2012 and 2013, in Auburn, AL.

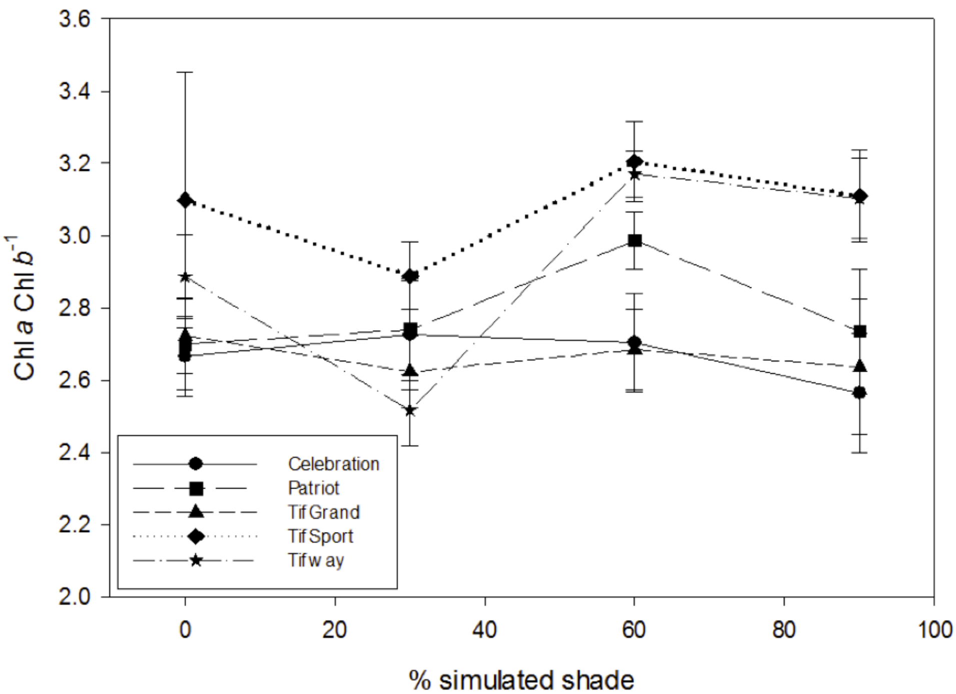


Figure 12. Effect of increasing levels of simulated shade on bermudagrass total carotenoid concentration, in 2012 and 2013, in Auburn, AL.

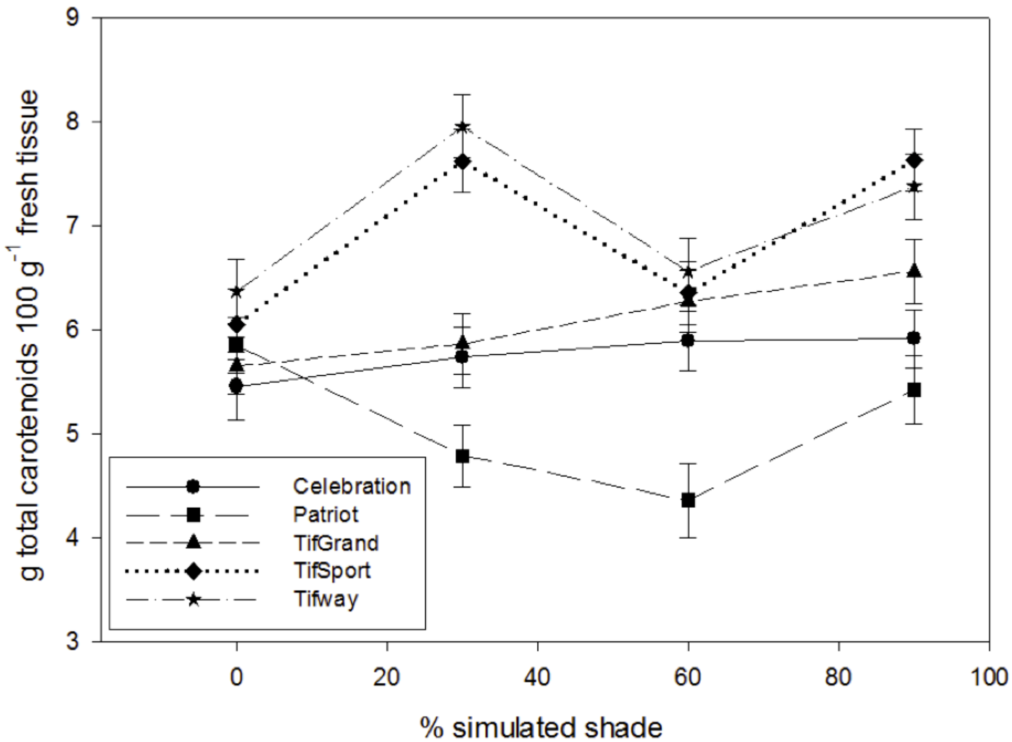


Figure 13. Effect of increasing levels of simulated shade on bermudagrass total shoot dry biomass assessed as total clipping yield in 2012 and 2013, in Auburn, AL.

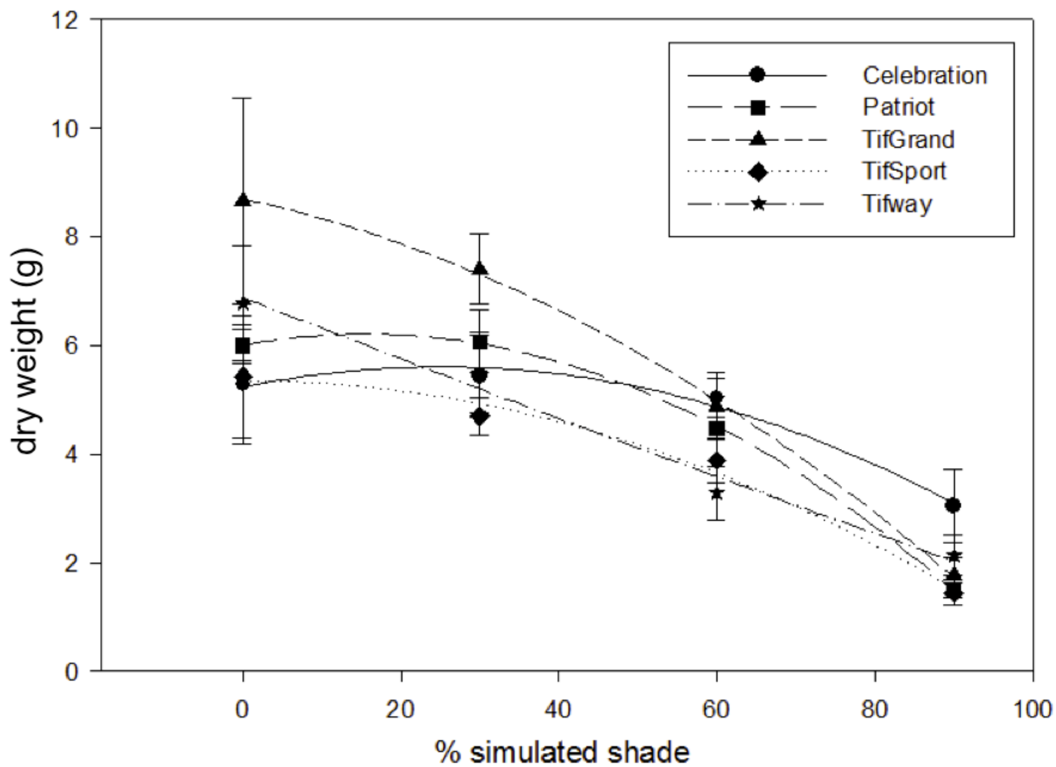


Figure 14. Effect of increasing levels of simulated shade on bermudagrass total root fresh biomass in 2012 and 2013, in Auburn, AL.

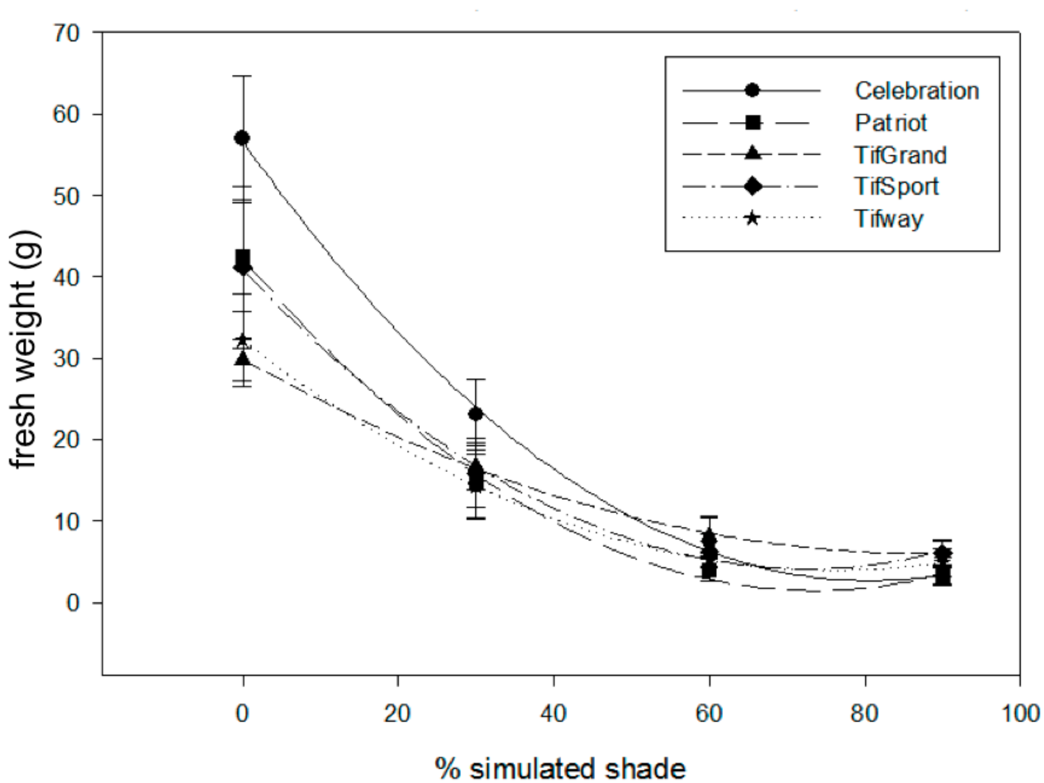
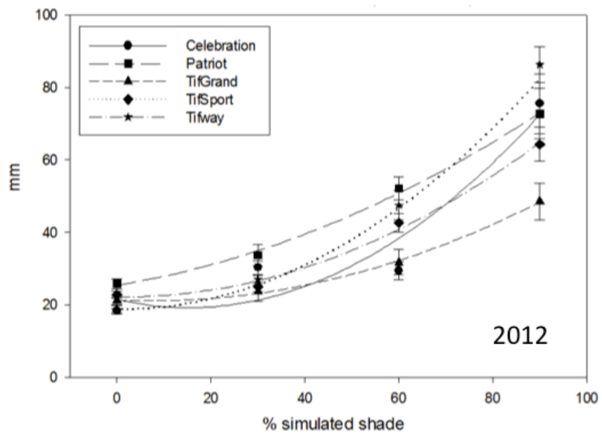
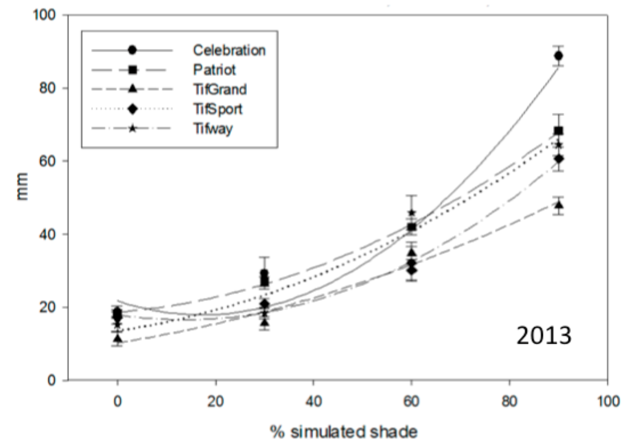


Figure 15. Effect of increasing levels of simulated shade on bermudagrass etiolation in Auburn, AL.

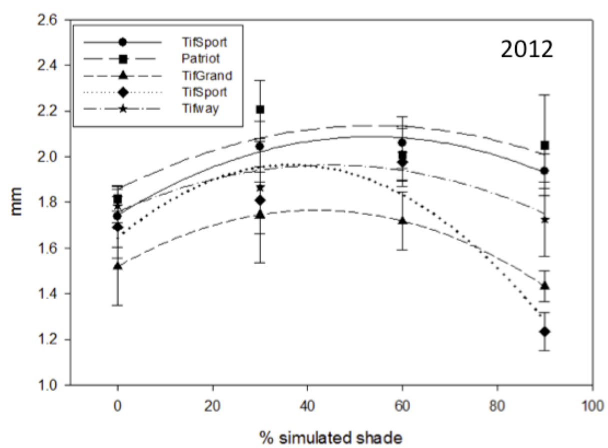
a)



b)



c)



d)

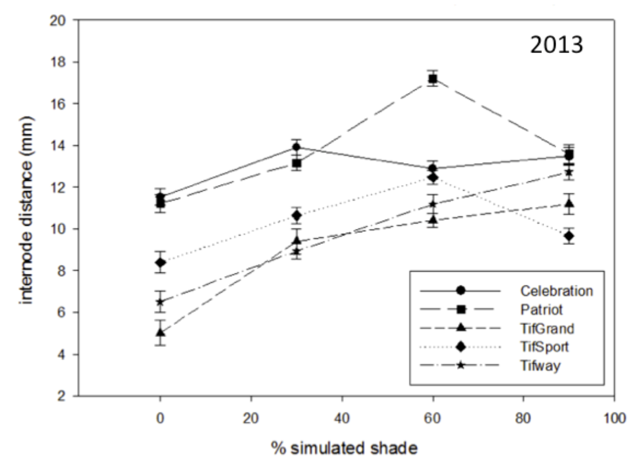
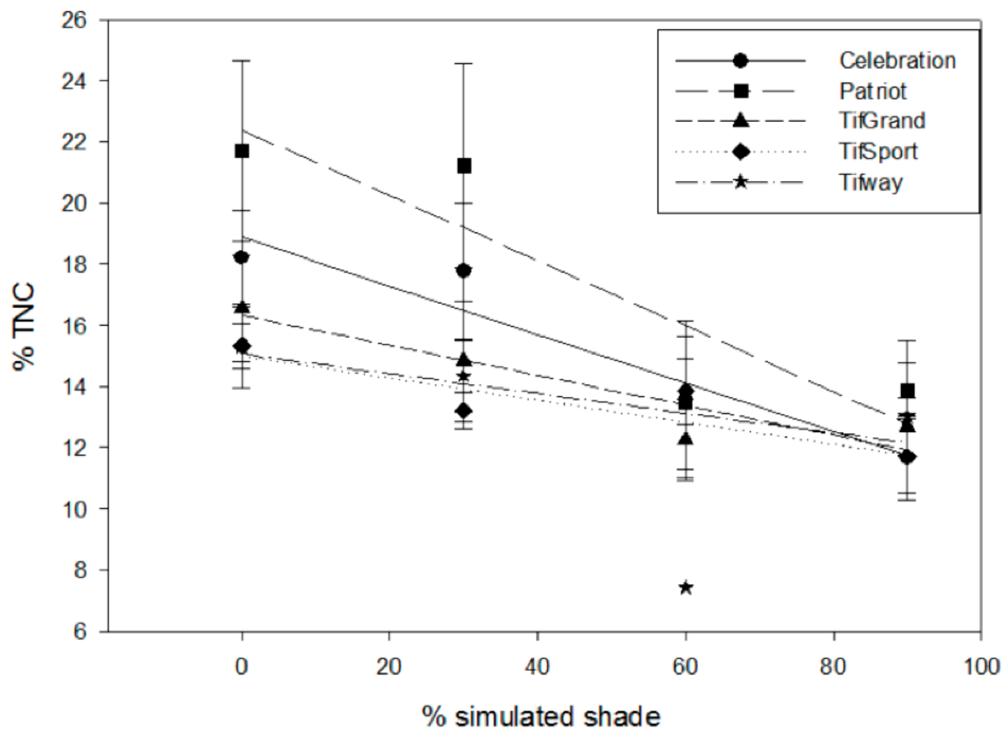


Figure 16. Effect of increasing levels of simulated shade on bermudagrass shoot total shoot carbohydrates (TNC) in Auburn, AL.



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USE OF PLANT GROWTH REGULATORS AND HERBICIDES FOR TIFGRAND SEEDHEAD SUPPRESSION AND QUALITY IMPROVEMENT

Introduction

Bermudagrass (*Cynodon dactylon* L. Pers) is one of the most widespread turfgrasses around the world, found in over one hundred countries, and throughout the Southern U.S., the U.S turfgrass transition zone, and possibly north of the transition zone (Juska and Hanson, 1964; McBee and Holt, 1966; Taliaferro et al., 2006; Wu et al., 2011; Thoms et al., 2011). Bermudagrass widespread distribution and use is associated with desirable turfgrass characteristics such as wear tolerance, aggressive growth, and summer heat tolerance (Gibeault et al., 1992; Christians, 2004; Roche et al, 2009). Poor shade adaptation, however, has been reported for bermudagrass in comparison to other warm-season grass species. St. Augustinegrass (*Stenotaphrum secundatum* (Walt.) Kuntze), *Zoysia* spp., centipedegrass (*Eremochloa ophiuroides* (Munro) Hack.), and seashore paspalum (*Paspalum vaginatum* Sw.) are reportedly more shade tolerant than bermudagrass (Beard, 1973; Jiang et al., 2004). Shade reduces turfgrass quality as a result of increased leaf and internode etiolation, and depletion of pigment and carbohydrate concentrations (McBee and Holt, 1966; Gaussoin et al., 1988; Ervin et al., 2002; Baldwin et al., 2008). Despite low performance under shade, relative intraspecific shade tolerance is found amongst bermudagrasses: 'Celebration' is reportedly more shade tolerant than 'Tifway, 'Patriot', and 'TifSport' (Bunnell et al., 2005a; Baldwin et al., 2008). Recently, 'TifGrand' bermudagrass (*Cynodon dactylon* L. Pers. X *C. transvaalensis* Burtt Davy) was released as a shade tolerant bermudagrass cultivar (Hanna et al., 2010), and further reported wear and drought tolerant as well (Thapa, 2011; Haselbauer et al., 2012). Previous reports would justify TifGrand's use as a sports turf bermudagrass cultivar for shaded environments. TifGrand, however, has a proliferous seedhead production habit (Hanna et al., 2010), which reduces turfgrass aesthetic and functional quality (Kane and Miller, 2003). Johnson (1994a) and McCullough et al. (2007) reported greater bermudagrass seedhead production during spring and early summer. Excessive seedhead production has been associated with plant stress, including photo-oxidative damages and formation of ROS (Asada, 2006; Xu et al., 2010). Often times, even "shaded turf" receives sunlight in the form of sun flecks (Evans, 1956; Beard, 1997), or due to diurnal variations in the shaded environment (Bunnell et al., 2005b), which could influence TifGrand's excessive seedhead production.

Turfgrass seedhead suppression, stress tolerance, and ultimately, turfgrass quality (TQ) improvement can be achieved via herbicide and plant growth regulator (PGR) applications (Jiang and Fry, 1998; Quian and Engelke, 1999; Fargerness and Yelverton, 2000; McCarty et al., 2004; Barker et al., 2005), however, most herbicides and PGRs result in either excessive injury or inconsistent performance (Christians, 1985). Trinexapac-ethyl is widely used for turfgrass quality enhancement, despite inconsistent seedhead suppression (Johnson, 1993; Fargerness and Yelverton, 2000; Heckman et al., 2001; McCarty et al., 2004). Sethoxydim, fluazifop, glyphosate, and mefluidide have been reported to suppress seedheads in tall fescue (*Festuca arundinaceae* Schreb.) (Reynolds et al., 1993). Long-term seedhead suppression in centipedegrass was obtained with mefluidide at 0.06 kg ai ha^{-1}, whereas flurprimidol, trinexapac-ethyl, and pacolbutrazol applied to bermudagrass did not consistently suppress seedheads, and further reduced TQ (Johnson, 1994a; 1994; McCullough et al., 2007). Imazethapyr at 0.3 kg ai ha^{-1} efficiently suppressed common bermudagrass seedheads, despite turfgrass injury (Johnson, 1994b). Imazapic at various rates successfully suppressed seedheads in cool- and warm-season turfgrasses, however, short-lived turfgrass injured followed applications (Goatley et al., 1993; Goatley et al., 1998; Yelverton et al. 1997; Hixson et al., 2007; Baker, 1999). Fenoxaprop at lower than label-recommended rates safely suppressed seedheads on common bermudagrass (Brosnan et al., 2011). Considering the possible use of TifGrand for shaded environments, the detrimental effects of shade on turfgrasses (especially in regard to etiolation), and TifGrand's excessive seedhead production, there is potential in using herbicides and PGRs for TifGrand seedhead suppression and quality improvement.

The objective of this study was to evaluate several herbicides and PGRs, applied to TifGrand bermudagrass throughout late-spring and summer, on TifGrand seedhead suppression and quality improvement.

Materials and Methods

Two research projects were conducted in 2013 and 2014 to evaluate the use of herbicides and PGRs on TifGrand bermudagrass seedhead suppression and quality improvement. Research was located at the Auburn University Turfgrass Research and Education Center in Auburn, AL (32.58° N, 85.50° W), on three distinct locations within a field plot established with TifGrand bermudagrass. Soil type was a Marvyn sandy loam (fine-loamy, kaolinitic, thermic, Typic Kanhapludult) with pH 6.2 and 2.1% organic matter. TifGrand was established via sprigs on June 15, 2012. Sprigging rate was 13.5 m^3 fresh sprigs ha^{-1}. During turfgrass establishment, water, fertilization, and weed control were provided adequately. TifGrand was fully established after 10 weeks after sprigging. Following turfgrass establishment, polyon® (43-0-0, Harrel's Fertilizer Inc., Sylacauga AL) slow release fertilizer was applied monthly providing 49 kg N ha^{-1}

during active bermudagrass growth (May-August). No testing of any kind was done on the TifGrand area until June 2013, when our chemical applications initiated.

Study one. Study one was initially applied on June 17 and June 6, for 2013 and 2014, respectively. Study one treatments included trinexapac-ethyl (Primo Maxx, Syngenta Crop Protection, Greensboro NC) at 0.096 kg ai ha^{-1}, imazapic (Plateau, BASF Corp., Research Triangle Park NC) at 0.009 and 0.018 kg ai ha^{-1}, fenoxaprop (Fusilade II, Syngenta Crop Protection) at 0.018 and 0.035 kg ai ha^{-1}, imazamox (Clearcast, SePRO Corp., Carmel IN) at 0.035 kg ai ha^{-1}, glyphosate (Roundup Pro, Monsanto Company., St. Louis MO) at 0.105 kg ai ha^{-1}, flucarbazone (Everest, Arysta Lifescience, Cary NC) at 0.029 kg ai ha^{-1}, flucarbazone plus trinexapac-ethyl at 0.029 plus 0.096 kg ai ha^{-1}, and a nontreated control. Applications were made 4 times sequentially, with a 21-day interval, on 1 year-old TifGrand stands, to 1 by 1 m plots arranged in a randomized complete block design with 3 replications.

Study two. Due to the lack of seedhead suppression for many treatments in study one, study two aimed to investigate other, uncommonly used herbicides and PGRs for seedhead suppression and quality improvement, including other ALS inhibitors than flucarbazone (applied on study one). Study two was initially applied on June 12, 2014, and also consisted of 4 sequential applications every 21 days. Differently from study one, treatments were applied to a 2 year-old TifGrand stand. Treatments included trinexapac-ethyl (Primo Maxx, Syngenta Crop Protection) at 0.193 kg ai ha^{-1}, trinexapac ethyl at 0.096 kg ai ha^{-1} followed by (fb) flurprimidol (Cutless, SePro Corporation) three times at 0.42 kg ai ha^{-1}, flurprimidol at 0.21, 0.42, and 0.84 kg ai ha^{-1}, metsulfuron (Manor, Nufarm Americas Inc., Burr Ridge IL) at 0.032 kg ai ha^{-1}, chlorsulfuron (Telar, DuPont Crop Protection, Wilmington DE) at 0.013 kg ai ha^{-1}, chlorsulfuron (Telar, DuPont Crop Protection) fb mefluidide (Embark, PBI/Gordon Corporation, Kansas City

MO) three times at 0.14 kg ai ha^{-1}, mefluidide (Embark, PBI/Gordon Corporation) at 0.14 kg ai ha^{-1}, sulfometuron (Spyder, Nufarm Americas Inc., Burr Ridge IL) at 0.026 kg ai ha^{-1}, and imazethapyr (Pursuit, BASF Corporation, Research Triangle Park NC) at 0.022 kg ai ha^{-1}. A nontreated control was also included. Treatments were applied to 1 by 1 m plots arranged in a randomized complete block, and replicated 4 times.

Applications used a hand-held sprayer equipped with four TeeJet 8002VS nozzles (Spraying System Co., Wheaton IL) spaced at 25 cm, and calibrated to deliver 280 L ha^{-1}. Data were collected for 63 days after application (DAIA) and included visual ratings for TQ, seedhead suppression relative to the nontreated, turfgrass injury, and seedhead counts. Assessment of TQ was done on a 1-9 scale, where 1 represented brown, low-density, seedhead-infested turf, and 9 represented dark green, dense, seedhead-free turf. A TQ of 6 or above was considered acceptable. Turfgrass injury was rated on a 0-100% basis, where 0 represented no injury, and 100 represented complete plant necrosis/death. Turfgrass injury over 20% was considered unacceptable. Seedhead suppression was also assessed on a percent basis, compared to the nontreated. Counts were performed within a 0.15 by 0.15 m frame, with 3 subsamples per plot. Count data were further converted to number of seedheads per square meter. Data analysis was performed in SAS 9.2 (SAS Institute, Cary NC), using PROC GLIMMIX and PROC GLM. All data were subjected to ANOVA and separated by Fisher's protected LSD at $\alpha = 0.05$ level.

Results and Discussion

Study one. TifGrand excessive seedhead production was observed in 2013 and 2014 on nontreated plots (Figure 17). Seedhead production in 2013 peaked 35 DAIA, with approximately 1,000 seedheads per square meter. Greatest seedhead production in 2014 occurred 0 and 14

DAIA, with approximately 1,300 seedheads per square meter, and decreased overtime to approximately zero, 63 DAIA. These results agree with Johnson (1994a) and McCullough et al., who reported TifGrand excessive seedhead production during late spring and early summer. According to ANOVA for TifGrand injury, only main effects for year (P = 0.0004) and DAIA (P < 0.0001) were significant, therefore, data is presented separately (Figure 18). Unacceptable injury (≥ 20%) was only noticed in 2013 at 7 and 14 DAIA. All other rating dates resulted in injury ≤ 20%. Seedhead suppression was observed in both years (Table 18). In 2013, imazapic at 0.018 kg ai ha^{-1} suppressed seedheads in 71% relative to the nontreated. Fenoxaprop at 0.018 and 0.035 kg ai ha^{-1} provided 62 to 71% seedhead suppression. Conversely, trinexapac-ethyl increased seedhead production in 2013 by 1,563% relative to the nontreated. In 2014, fenoxaprop at 0.018 kg ai ha^{-1}, imazamox at 0.035 kg ai ha^{-1}, and flucarbazone (0.029 kg ai ha^{-1}) plus trinexapac-ethyl (0.096 kg ai ha^{-1}) resulted in similar seedhead suppression: 98, 99, and 100% respectively, relative to the nontreated. Interactions for DAIA by year were found for TQ, and therefore, data are presented separately (Table 19). A decrease to below-minimum standards for TQ was noticed in 2013 for imazapic and fenoxaprop, both applied sequentially at 0.018 kg ai ha^{-1}. Such decrease in TQ is associated with turfgrass injury immediately after initial application in 2013. Despite short-lived injury, turfgrass recovered from both treatments applications in 2013, when all treatments resulted in similar TQ relative to the nontreated at 35 and 63 DAIA. In 2014, imazapic and fenoxaprop applied sequentially at 0.018 kg ai ha^{-1}, and flucarbazone (0.029 kg ai ha^{-1}) plus trinexapac-ethyl (0.096 kg ai ha^{-1}) resulted in greater TQ compared to the nontreated 35 DAIA. Based on these results, injury-free, relative TifGrand seedhead suppression and quality improvement can be achieved via sequential applications of flucarbazone plus trinexapac-ethyl. While fenoxaprop at 0.035 kg ai ha^{-1} did not consistently suppress seedheads and resulted in excessive injury, fenoxaprop at 0.018 can efficiently suppress TifGrand seedheads and resulted in long-term (63 DAIA) quality improvement, however, initial injury can occur. Other treatments either did not suppress TifGrand seedheads, or resulted in decreased TQ from excessive injury.

Study two. Significant interactions for treatment by DAIA by year were found for seedhead suppression and TQ, and therefore, data are presented separately (Table 20). No turfgrass injury was noticed from chemical treatments ($P \geq 0.0951$). Seedhead production 35 DAIA on nontreated plots was significantly lower than in *study one*, averaging 135 seedheads per square meter, which could be associated with increased TifGrand maturity. Increased bermudagrass maturity has been associated with less injury following chemical treatments (Rogers et al., 1987). To the same end, bermudagrass maturity could be associated with reduced plant stress, and reduced seedhead formation. Significant differences for TQ were found 14, 28, and 63 DAIA, whereas TifGrand relative seedhead suppression was observed for 49 DAIA. None of the treatments completely suppressed TifGrand seedheads. Imazethapyr at 0.022 kg ai ha^{-1} resulted in season-long, relative seedhead suppression (80%), while maintaining greater TQ scores compared to the nontreated. Flurprimidol at 0.42 kg ai ha^{-1} resulted in inconsistent, relative seedhead suppression, and TQ similar to the nontreated. Flurprimidol rates above 0.42 kg ai ha^{-1} resulted in reduced TQ, whereas rates below 0.42 kg ai ha^{-1} did not consistently suppress seedheads. While maintaining TQ similar to the nontreated, metsulfuron (0.0315 kg ai ha^{-1}), chlorsulfuron (0.0131 kg ai ha^{-1}), and sulfometuron (0.0263 kg ai $ha^{-1)}$ resulted in late season (49 DAIA) relative seedhead suppression: 28, 49, 63, and 69%, respectively. Chlorsulfuron (0.0131 kg ai ha^{-1}) followed by mefluidide (0.14 kg ai ha^{-1}) also resulted in inconsistent, relative seedhead suppression (55%) with no reduction in TQ compared to the nontreated. Trinexapac-ethyl (0.193 kg ai ha^{-1}) resulted in late season (after 35 DAIA) relative suppression (50%) and TQ similar to the nontreated, whereas trinexapac-ethyl followed (0.096 kg ai ha^{-1}) by flurprimidol (0.42 kg ai ha^{-1}) resulted in early season (up to 35 DAIA) relative seedhead suppression (30-31%). Treatments inconsistency suppressing TifGrand seedheads are in agreement with Johnson (1994b), and may be associated with application interval.

Conclusions

Our results indicate that injury-free, greater relative TifGrand seedhead suppression and TQ can be achieved by sequential applications of flucarbazone (0.029 kg ai ha^{-1}) plus trinexapac-ethyl (0.096 kg ai ha^{-1}), and imazethapyr at 0.022 kg ai ha^{-1}. Despite potential for initial injury, other treatments resulted in relative, periodic seedhead suppression.

Table 18. Effect of herbicides and PGR's[a] on seedhead production[b] for TifGrand bermudagrass 35 days after initial application (DAIA), in 2013 and 2014, in Auburn, AL.

Treatment	Rate (kg ai ha^{-1})	2013 Seedheads m^{-2}		2013 %[c]	2014 Seedheads m^{-2}		2014 %
nontreated		58	bc		745	a	
trinexapac-ethyl	0.096	956	a	+1563	364	a	-51
imazapic	0.009	156	a-c	+171	474	a	-36
imazapic	0.018	17	c	-71	293	a	-61
fenoxaprop	0.018	22	c	-62	14	bc	-98
fenoxaprop	0.035	230	a-c	+301	782	a	+5
imazamox	0.035	150	a-c	+161	9	c	-99
glyphosate	0.105	667	ab	+1060	106	ab	-86
flucarbazone	0.029	701	ab	+1120	101	ab	-86
flucarbazone + trinexapac-ethyl	0.029 + 0.096	118	a-c	+105	0	d	-100
P value		0.0412			< 0.0001		
LSD (0.05)		16			8		

[a]Initially applied on 17 Jun, and 6 Jun, for 2013 and 2014, respectively. Four applications were made sequentially, within a 21-day interval.

[b]Seedhead production measured by counting number of seedheads within a 6.25 cm^2 frame, and converted to number of seedheads per square meter.

[c]Percent seedhead production relative to nontreated. Positive values indicate increased seedhead production and negative values indicate relative seedhead suppression.

[d]For each rating timing, means sharing the same letter are not statistically different according to Fisher's protected test (α = 0.05).

[e]NS, not significant at α = 0.05.

Table 19. TifGrand quality[a] at 14, 35, and 63 days after initial application[b] (DAIA) in 2013 and 2014, in Auburn, AL.

Treatment	Rate (kg ai ha^{-1})	TQ (1-9) 14 DAIA 2013	35 DAIA 2013	63 DAIA 2013	14 DAIA 2014	35 DAIA 2014	63 DAIA 2014
nontreated		7a[c]	7a	7a	7bc	6cd	7a
trinexapac-ethyl	0.096	7a	7a	6a	7bc	6b-d	7a
imazapic	0.009	7a	7a	7a	6c	6d	7a
imazapic	0.018	5b	7a	6a	8a	7ab	7a
fenoxaprop	0.018	4b	7a	7a	7ab	8a	7a
fenoxaprop	0.035	6ab	8a	8a	6c	6cd	7a
imazamox	0.035	8a	7a	8a	6bc	5d	8a
glyphosate	0.105	7a	8a	7a	7bc	7b-d	8a
flucarbazone	0.029	7a	8a	8a	7ab	7a-c	7a
flucarbazone + trinexapac-ethyl	0.029 + 0.096	7a	7a	7a	7a-c	7ab	8a
P value		0.02	NS[d]	NS	0.0265	0.0011	NS
LSD (0.05)		2	1	2	1	1	1

[a]Assessed visually on a 1-9 scale. Ratings considered turfgrass color, density, injury and seedhead production. A rating of 6 or above was considered acceptable.

[b]Treatments initially applied on 17 Jun, and 6 Jun, for 2013 and 2014, respectively. For applications were made sequentially, within a 21-day interval.

[c]Within each column, means sharing the same letter are not significantly different according to Fisher's protected test ($\alpha = 0.05$).

[d]NS, not significant at $\alpha = 0.05$.

Table 20. Effect of other chemicals on TifGrand relative seedhead suppression[a] and TQ[b] in 2014, in Auburn, AL.

Treatment	Rate (kg ai ha^{-1})	Seedhead suppression (%) 14 DAIA	28 DAIA	35 DAIA	49 DAIA	TQ (1-9) 14 DAIA	28 DAIA	63 DAIA
nontreated		0b[d]	0d	0d	0e	6c	5b	8ab
trinexapac-ethyl	0.193	25ab	28b-d	69a	50a-c	7a-c	5b	7cd
trinexapac-ethyl fb[c] flurprimidol	0.096 fb 0.42	31ab	30bc	25b-d	25c-e	6bc	6b	7b-d
flurprimidol	0.21	0b	5cd	8cd	46a-d	7a-c	5b	8ab
flurprimidol	0.42	43a	43b	21cd	49a-d	7a-c	6b	8ab
flurprimidol	0.84	50a	46ab	0d	13de	7ab	6b	6d
metsulfuron	0.0315	5b	24b-d	5cd	49a-d	7a-c	5b	8a-c
chlorsulfuron	0.0131	8b	25b-d	0d	63ab	7a-c	5b	8a-c
chlorsulfuron fb mefuidide	0.0131 fb 0.14	50a	34bc	13cd	55a-c	7a	6b	8ab
mefluidide	0.14	0b	11cd	25b-d	69ab	6c	5b	8a
sulfometuron	0.0263	0b	20b-d	55ab	69ab	6bc	5b	8ab
imazethapyr	0.022	59a	74a	34bc	80a	7a-c	7a	8ab
P value		0.0012	0.0009	0.0009	0.0038	0.0265	0.0038	0.0159
LSD (0.05)		34	29	32	37	1	1	1

[a]Assessed visually on a percent basis, relative to the nontreated.

[b]Assessed visually on a 1-9 scale. Ratings considered turfgrass color, density, injury and seedhead production. A rating of 6 or above was considered acceptable.

[c]fb, followed by.

[d]Within each column, means sharing the same letter are not significantly different according to Fisher's protected test ($\alpha = 0.05$).

Figure 17. TifGrand seedhead production on nontreated plots for 2013 and 2014, in Auburn, AL.

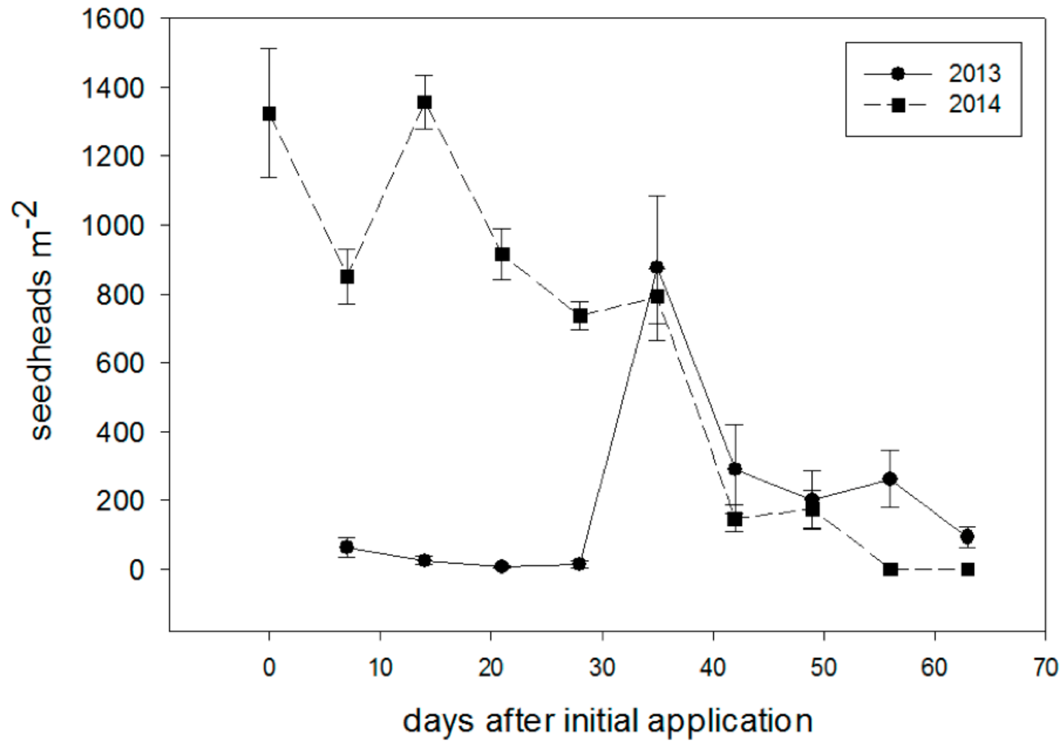
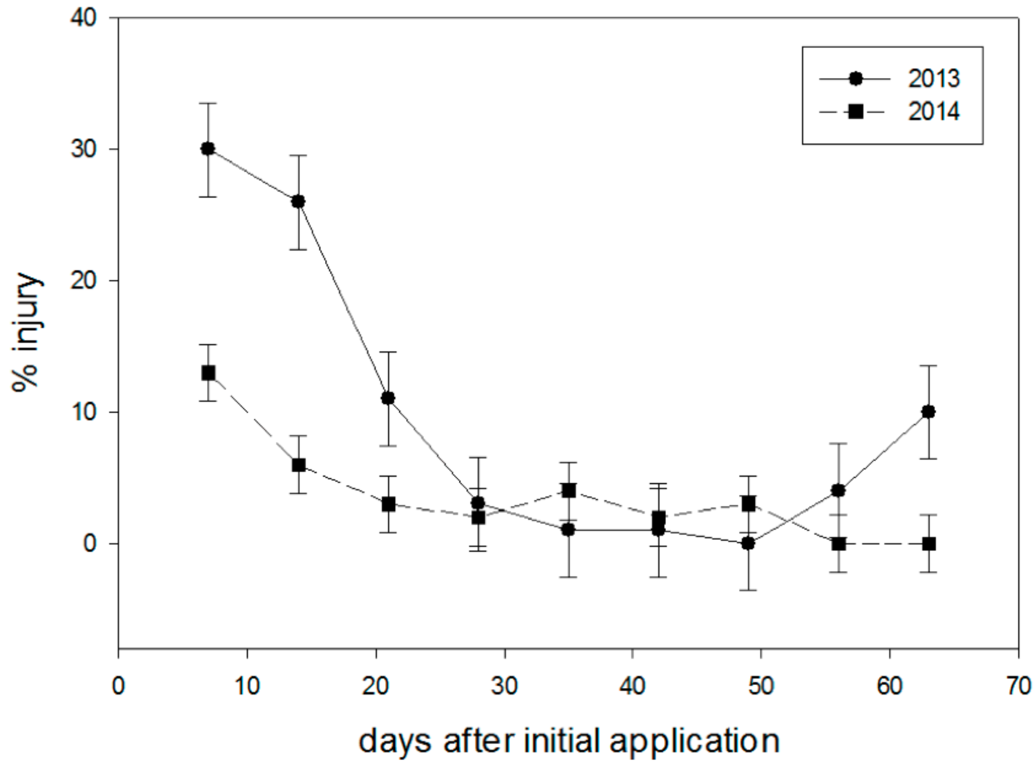


Figure 18. TifGrand injury following chemical treatments for seedhead suppression and quality improvement in 2013 and 2014, in Auburn, AL.



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