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Evaluation of Crumb Rubber Dynamics for Improving Athletic Field Quality

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I am submitting herewith a thesis written by Kyley Hampton Dickson entitled "Evaluation of Crumb Rubber Dynamics for Improving Athletic Field Quality." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Plant Sciences.

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(Original signatures are on file with official student records.)

Evaluation of Crumb Rubber Dynamics for Improving Athletic Field Quality

A Thesis Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Kyley Hampton Dickson

May 2014

DEDICATION

I would like to dedicate this thesis to my grandparents, Dwight and Gloria, and my family. They always encouraged me and never let me give up. Lastly, I would like to thank my wonderful wife, Courtney, for her support and encouragement.

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I would like to thank my advisor, Dr. John Sorochan, for his guidance and for providing me with the opportunity to complete my Master's degree at the University of Tennessee. Without Dr. Sorochan's guidance I would not be here today. Also, I would like to thank my graduate committee members, Dr. John Stier and Dr. Jim Brosnan, for their guidance and aid.

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ABSTRACT

Crumb rubber (CR) is an amendment used to reduce surface hardness and increase wear-tolerance on athletic fields. Turf managers can topdress CR particles into highly trafficked portions of athletic fields; however, optimum particle size and topdressing depth combinations for use on bermudagrass (*Cynodon* spp) athletic fields have not been determined. Optimum CR particle size and depth to maximize performance of hybrid bermudagrass (*C. dactylon* (L.) Pers. x *C. transvaalensis* Burtt-Davy, 'Tifway') athletic field turf established on a Sequatchie silt loam soil was investigated at the University of Tennessee Center for Athletic Field Safety (Knoxville, TN) in 2011 and 2012. The experimental design was a randomized complete block with four replications. Treatments included five CR particle sizes (30, 20, 10:14, 14:30, and 8:20 mesh size, respectively) and three topdressing depths (0.6, 1.3 and 1.9 cm, respectively). The coefficient of uniformity for each particle size tested was 1.83 (30 mesh), 2.28 (20 mesh), 1.82 (10:14 mesh), 1.38 (14:30 mesh), and 1.79 (8:2 mesh), respectively. All plots were subjected to 25 simulated traffic events with the Cady traffic simulator. In 2011, significantly greater green turfgrass cover was retained in 1.3 and 1.9 cm depths than the control. Surface hardness was significantly lower on 1.3 and 1.9 cm depth plots, whereas, particle size had no significant effect on surface hardness. However, no differences were observed in 2012. Our findings indicate that CR topdressing depth is more important than CR particle size in optimizing performance of hybrid bermudagrass athletic fields under simulated traffic.

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1. Introduction

Athletic fields. In almost every country around the world sporting events take place, with a majority of these events happening on grass athletic fields. It is estimated that 25 million student athletes and 20 million organized community-based youths participate in sports annually in the United States (Micheli, 2000). With such a large portion of the population playing sports, safe fields are a major factor in reducing sports related injuries. In 2004, the Sports Turf Managers Association estimated that there were over 40,000 athletic fields in the United States (Campbell, 2004). A survey of high school football injuries in Pennsylvania found that found that 5.7% were definitely related to playing surface conditions while another 15.7% may have been linked to playing surface conditions as well (Harper et al., 1984).

Nearly 38 million children and adolescents participate in organized sports, mostly on lower input high school or municipal fields (NIH, 2009). In 1999, it was estimated that in high school sports, 62,816 athletes suffer concussions annually, and 60 percent of these concussions are due to football related injuries (Powell and Barber-Foss, 1999). A study completed in 2009 found that the number of concussions have risen to over 250,000 reported cases across all high school sports in the U.S. (IOM, 2013). In college football, 5.5% of all players reported to have sustained a concussion during their playing career (Guskiewicz et al., 2000). National Football League players suffer concussions at a rate of 9.2 concussions per week of play during the 2012-2013 season (Fainaru and Fainaru-Wada, 2012). Approximately 10% of concussions are caused by an athlete's head impacting the playing surface (McNitt, 2010). There are approximately three million injuries that occur annually in organized sports, costing an estimated $1.3 billion per year in direct and indirect costs (Hergenroeder, 1998). Dougherty (1988) reported that 10% of sports injury lawsuits claim that the athletic field was inadequately maintained. In addition, 3.5 million children under the age of fourteen receive medical treatment for sports related injuries annually (Safe Kids, 2007), and 50% of these injuries are said to be preventable (Brenner, 2007; Safe Kids, 2007). Maintaining a safe playing surface is imperative in reducing the rate of sports related injury incidence.

Ground reaction forces, which are commonly 2.5 to 3.0 times greater on an individual's body weight during an athletic maneuver, have been cited as risk factors in the incidence of both chronic and acute athletic injuries (Boden et al., 2000; LaStayo et al., 2003). As a surface becomes harder, the ground reaction forces become harder on the athlete and the potential for injury increases. Ground reaction forces are defined as the forces exerted on an athlete by the surface upon impact (Elftman, 1938; Nigg et al., 1984; Brosnan et al., 2009).

Adequately maintaining an athletic field can reduce compaction and lessen the amount of turf cover loss due to traffic resulting in poor playing quality. Poor playing quality on athletic fields can negatively impact player performance and safety (Cockerham et al., 1993). The definition of playing quality of an athletic field is defined as the playability and safety of a field, which can be attributed to surface hardness and traction (Guise, 1996). With reduced turf cover on athletic fields, there is an increase in surface hardness and a reduction in traction (Holmes and Bell, 1986). Worn fields lose turf cover which in turn causes soil to become compacted leading to increases surface hardness and potentially injuries (Rogers III and Waddington, 1988).

Bermudagrass research. Bermudagrass (*Cynodon* spp) is the most commonly used turfgrass on athletic fields in the United States transition zone because it offers increased recuperative potential and summer heat tolerance compared to other species (Christians, 2004). In addition, bermudagrass has excellent heat and drought tolerance. Bermudagrass is a perennial grass that grows by both rhizomes and stolons (Juska and Hanson, 1964). Due to its growth habit, it has the ability to recover from wear compared to other commonly used turfgrasses. Hybrid bermudagrasses [*C. dactylon* (L.) Pers. x *C. transvaalensis* Burtt-Davy] are preferred for athletic fields over common bermudagrass [*Cynodon dactylon* (L.) Pers] because they provide a finer texture and more dense cover (Trenholm et al., 2000; Younger, 1958).

Traffic is the combined stresses of plant wear and soil compaction (Carrow and Weicko, 1989). Characteristics of wear-tolerant bermudagrass varieties are: less stem cellulose, higher stem moisture, and higher concentrations of manganese, magnesium and potassium (Trenholm et al., 2000). ‘Tifway’ hybrid bermudagrass has been shown to have improved tolerance to simulated athletic field traffic compared to other cultivars of bermudagrass (Goddard et al., 2008; Thoms et al., 2011; Haselbauer, 2010; Brosnan and Deputy, 2009). In addition, Trappe et al. (2009) reported that ‘Riviera’ common bermudagrass and ‘Tifway’ exhibited the best traffic tolerance in a study of 42 bermudagrass varieties, subjected to simulated traffic with the Cady Traffic Simulator (CTS). A grass desirable for athletic fields is ‘Tifway’ bermudagrass because of its excellent wear tolerance and recuperative potential (Puhalla et al., 1999). Goddard et al. (2008) found that ‘Riviera’ and ‘Tifway’ had the highest traffic tolerance and are best suited for high use athletic fields.

Simulated traffic. Two devices used to simulate athletic field traffic are the CTS and the Brinkman Traffic Simulator (BTS). The CTS is a walk-behind aerification unit with modified feet attached to each of the four coring heads. The feet for the CTS are built using rubber tires and four bolts that act as cleats that strike the surface. These feet strike the surface creating forces similar to those generated during foot-to-surface interactions on athletic fields (Henderson et al., 2005). The BTS is a two-drummed roller equipped with connected cleats that turns at uneven speeds to create a shearing of the turf while compacting the soil (Cockerham and Brinkman, 1989). When compared, plots trafficked using the CTS increased surface hardness, reduced traction, and had lower plant counts than plots trafficked using the BTS (Vanini et al., 2007). Another study comparing the Baldree traffic simulator to the CTS and BTS found that the Baldree produces more cleat marks per pass. Also, the Baldree was found to produces a substantially higher ground force than the BTS and CTS when ran across a force plate (Kowalewski et al., 2013).

Areas that receive traffic will lose turf cover leading to accelerated soil compaction. Heavy traffic creates negative soil conditions for plant growth (Carrow and Weicko, 1989); particularly, reduced oxygen to the root system and the creation of a physical barrier impeding root growth (Puhalla et al., 1999). Core aerification is a commonly used cultural practice to reduce soil compaction on athletic fields (Christians, 2004). In addition, soil amendments can also be used to mitigate the negative effects of athletic field traffic (Rogers III et al., 1998).

Crumb rubber research. Crumb rubber (CR) is a product that is generated from recycled automotive tires that can be used as a soil amendment on athletic fields. Cryogenic freezing and shredding of recycled car tires are the primary methods of producing CR (Khalid et al., 2004). Tires are ground into particles ranging from 0.05 mm to 9.5 mm in diameter based on the desired use; all other components (steal and nylon belts) of the tire are extracted and recycled (Khalid et al., 2004). Highways use CR primarily as a source of rubber for asphalt; however, other uses on roads include fills and embankments, erosion control, valve box coverings, drainage aggregates and culverts (Epps, 1994). Crumb rubber is also used as an amendment in coal generation in the United States, as much as 0.3% of the generation is made up of CR each year (Yiannis et al., 1996). CR is an alternative amendment that can be added to athletic field to help reduce the rate of soil compaction under traffic. Research has shown that topdressing CR to a 2 cm depth reduced surface hardness on cool-season athletic fields and reduces turfgrass wear (Groenevelt and Grunthal, 1998; Rogers III et al., 1998; Goddard et al., 2008).

Effects of CR topdressing have been researched on cool-season turfgrass athletic fields. Rogers III et al. (1998) found that topdressing fine sized CR (0.25 to 2.0 mm) at 44.1 and 88.2 Mg ha^{-1} increased Kentucky bluegrass (*Poa pratensis*) wear tolerance. The researchers observed that smaller sized CR (0.25 to 2 mm) incorporated faster than larger diameter particle sizes (2 to 6 mm) in the first year of the study but after two years of applications all CR sizes (0.025 to 6 mm) reduced surface hardness when compared to Kentucky bluegrass not topdressed with CR (Roger III et al., 1998). The 88.2 Mg ha^{-1} topdressing rate increased soil surface temperature an average of +2˚C, regardless of particle size, (Rogers III et al., 1998). Percent green cover increased with CR topdressing rate; plots receiving 0, 44.1, and 88.2 Mg ha^{-1} had 42%, 66%, and 88% green cover, respectively. Increases in temperature and green cover following CR topdressing may provide more favorable growing conditions for warm-season turfgrass species on athletic fields during peak use periods in spring and fall (Rogers III et al., 1998). Another study found using the soil core method that plots topdressed with 10 mm CR measured lower in soil bulk density and micro pores; while also measuring higher in saturated hydraulic conductivity and macro pores than plots with 3.5mm CR (Baker et al., 2001).

While CR has found to be effective at increasing the performance of cool-season grass, data describing the effects of CR on bermudagrass are limited. However, a study in both Tennessee and Arkansas on hybrid bluegrass *(Poa pratensis L. x P. arachnifera Torr.)* and improved common and hybrid bermudagrasses showed benefits of CR topdressing. Crumb rubber was topdressed at a 5.86 kg m^{-2}, with all plots receiving traffic at a rate of one or three games a week for seven weeks from 7 October 2005 to 9 December 2005. Percent green cover values were collected weekly during traffic, while surface hardness values were taken at the start and completion of each traffic event. Crumb rubber topdressed plots in Arkansas had a mean of 42% green cover, while plots without CR had a mean of 21% regardless of traffic level. Tennessee found plots containing CR to have a mean of 63% green cover, while plots without rubber had a mean of 40% regardless of traffic level. A significant reduction in surface hardness was found at both locations with Arkansas plots containing CR having a mean surface hardness of 63 G_{max} while plots without a cover mean was found to be 116 G_{max}. Tennessee plots also had a significant reduction in surface hardness with a mean of 71 G_{max} for plots with CR, while plots without a CR had a mean of 96 G_{max}(Goddard et al., 2008). This leads to two hypothesis for this study. One, the increase in CR depth will decrease surface hardness and maintain higher PGTC. Two, the finer the CR particle size the greater the increase in wear tolerance.

Turf covers. Turf covers are an agricultural blanket that is applied to a stand of grass to delay winter dormancy. The use of polyethylene turf covers is a tool to extend the fall growing season in warm season turfgrasses. The use of turf covers can be done daily or just when the temperature becomes of a concern for a field manager. Turf covers are normally applied when temperatures reach below 30 C°. A study on ‘Riviera’ bermudagrass in Ohio found that applying White polypropylene turf covers extended acceptable fall color retention by 4 to 6 weeks (Goatley et al., 2005). To keep bermudagrass actively growing during periods below 30 C° turf managers can use covers to augment canopy temperature. Research in Mississippi evaluating fall and winter dormancy found, that hybrid bermudagrass covered with a white polypropylene turf cover offered higher turf quality in fall than turf not subjected to a turf cover (Goatley et al., 2005). A study comparing aluminum composite, white and black polypropylene turf covers on 'Riviera' bermudagrass found that all cover types, significantly increased canopy temperatures compared to uncovered plots (Goatley et al., 2009). This leads to the final hypothesis: turf covers will be more effective at delaying winter dormancy than crumb rubber on improved common bermudagrass.

Justification

While researchers have reported that crumb rubber can improve both cool and warm season grass performance on athletic fields, data describing effects of finer particle sizes (< 2.0 mm) and topdressing depth are limited.

Objectives

The objectives for this research are:

1. Determine the optimal CR particle size and depth for use on hybrid bermudagrass athletic fields in fall
2. Determine effects of various CR particle size and topdressing depth combinations on soil temperature
3. Monitor effects of various CR particle size and topdressing depth combinations on hybrid bermudagrass recovery from fall traffic

2. Materials and Methods

Study I

Plot establishment. Field research was conducted 2011 to 2013 at the University of Tennessee Center for Athletic Field Safety (Knoxville, TN) to determine the optimal CR particle size and topdressing depth combinations for use on hybrid bermudagrass athletic fields. ‘Tifway’ hybrid bermudagrass sod (cut to a 5 cm depth) was established to plots on 23 June 2011 on a leveled Sequatchie silt loam soil (fine-loamy, siliceous, semiactive, thermic Humic Hapludult) measuring 6.2 in soil pH and 25 g kg^{-1} in organic matter content. Irrigation was applied daily until rooting occurred for 10 minutes, unless rain events occurred. Plots were mown weekly with a rotary mower, clippings were allowed to return to the surface (260Z; Gravely. Brillion, WI) at a height of 4.5 cm. After sod installation, each plot was treated with urea at 24 kg N ha^{-1} once every two weeks until rooting occurred.

Plot maintenance. After establishment plots were mown with a triplex reel mower (TriKing 1900D; Jacobsen. Charlotte, NC) three times per week at a height of 2.22 cm from May through October. Clippings were not collected and were allowed to return to the surface during mowing. Nitrogen was applied monthly to all plots in the form of urea at a rate of 49 kg N ha^{-1} from May through September. Plots were irrigated as needed to supplement rainfall from May through October. During the summer of 2012, plots were core aerified to relieve soil compaction from traffic applied in the fall of 2011. All plots were subjected to two passes with a hollow-tine aerifier (ProCore 648, Toro. Bloomington, MN) equipped with 9.5 mm diameter coring tines on 5 cm spacing. On each plot cores were reincorporated into the surface with an industrial broom;

this was done to manually minimize CR movement between plots. Additionally, all plots received an application of Oxadiazon (Ronstar 50WP; Bayer Environmental Sciences, Research Triangle Park, NC) at 3.4 kg ai ha^{-1} on 23 February 2012 and 25 February 2013 to control summer annual weeds preemergence.

Treatments. Five CR particle sizes were evaluated in this study with each having a different coefficient of uniformity (CU) of: 1.38 (8:20 mesh), 1.79 (14:30 mesh), 1.82 (10:14 mesh), 2.28 (20 mesh), and 1.83 (30 mesh), respectively (Table 1). The CR with 1.83 CU had the highest percentage of fine particles (< 0.15 mm diameter), while the 1.79 CU had the greatest percentage of particles measuring 2 mm in diameter. For all CR treatments, the highest percentage of particles ranged from 0.25 to 1.0 mm in diameter. Plots were arranged in a randomized complete block design with four replications repeated in time during 2011 and 2012.

The five CR products were topdressing by hand and brushed in at three depths: 0.6 cm, 1.3 cm, and 1.9 cm, respectively. An untreated control was included for comparison. On an area basis, these depths equated to 0, 29272, 58545 and 87817 kg CR ha^{-1}, respectively. Treatment applications were applied in 0.6 cm increments (2.45 kg per plot), seven days apart until desired depths (0.6 cm, 1.3 cm and 1.9 cm) were achieved. Individual plots measured 91 x 91 cm with four replications. New plots were used each year and CR was applied as topdressing using these methods. Simulated traffic began seven days after the last application of CR on 12 September 2011 and 10 September 2012.

Simulated traffic. Three simulated traffic events were applied weekly using a CADY traffic simulator (CTS) beginning on 12 September 2011 through 18 November 2011 and 10 September 2012 through 31 October 2012. The dates selected for this study coincide with the local high school football season. Traffic was applied until all plots received 25 simulated traffic events each year, similar to previous research and to mimic the use of a high use high school practice field (Henderson et al., 2005; Goddard et al., 2008; Thoms et al., 2011). One simulated traffic event consisted of making two passes over the surface of each plot with the CTS. The CTS is a modified core aerifier (Jacobsen VA 24; Textron Co., Charlotte, NC) that generates impact forces similar to football player's cleats striking turf (Henderson et al., 2005). Traffic applications were not applied on days that volumetric soil moisture content exceeded 45%. Weeks that could not have three traffic events completed due to moisture were moved to the following weeks delaying the end of the study until all games were achieved. Volumetric soil moisture content was measured using a time domain reflectrometry (TDR) probe (FieldScout 300 Spectrum Technologies, Inc., Plainfield, IL) at three locations in the center of each plot at a depth of 3 cm. The probe was equipped with two 7.5 cm rods; rods were checked for damage before each collection event.

Data collection. Hybrid bermudagrass percent green turfgrass cover (PGTC) was measured immediately after each traffic event using digital image analysis (DIA) (Karcher et al., 2001). This method gives quantifiable measurements of PGTC and removes observational partiality associated with visual ratings. A 0.28 m^2 light box with four Technical Consumer Product 40w Spring Lamps® (Lighthouse Supply Co., Bristol, VA) powered by a Xantrex 600 Heavy Duty Power Pack ® (Xantrex Technology, Vancouver, British Columbia) was used to provide the consistent lighting for DIA. A Canon G12 (Canon inc., Japan) camera with 12 million mega pixels was used to capture each picture for DIA. Each picture was 307,200 pixels. Sigma Scan Pro Software (v. 5.0, SPSS. Inc., Chicago, IL) was used to determine the number of green pixels in each image. Green pixels were defined as those having a hue between 45 and 135 and saturation 0 to 100 percent. The total number of green pixels in each image was divided by the total number of pixels (regardless of color) in each image in order to calculate PGTC. Each spring DIA was also collected to track spring recovery, and DIA was collected weekly beginning 15 March 2012 and 15 March 2013 and continuing until 90 PGTC was achieved.

Surface hardness was measured for each plot immediately following every traffic event using a Clegg Impact Soil Tester equipped with a 2.25 kg missile. The missile was dropped in three locations at the center of the plot to determine a mean surface hardness value for each treatment. Volumetric soil moisture content (%) was monitored on each plot after each simulated traffic event using a time domain reflectometry (TDR) probe equipped with 7.5 cm tines (FieldScout 300 Probe. Spectrum Technologies, Inc. Plainfield, IL). Time domain reflectometry means were calculated using three sub-samples per plot.

Statistical analysis. Surface hardness, soil moisture and PGTC data were subjected to analysis of variance in SAS (v. 9.3., SAS Institute Inc., Cary, NC). Significant year-by-treatment interactions were detected in surface hardness, soil moisture and PGTC; therefore, data from each year were analyzed separately. Fisher's least significant difference (LSD) was used to separate surface hardness and soil moisture means at the $P = 0.05$ level of significance. Percent green turfgrass cover data were analyzed using non-linear regression techniques in GraphPad Prism 6 (GraphPad Software, San Diego, CA). A sum of squares reduction F-test was used to compare sums of squares from a global model (i.e. all treatments shared the same parameter estimates) to a collective model where distinctive parameters estimates were calculated for each treatment. Time required to reach 50% cover (events$_{50}$ values) were calculated each fall to compare traffic tolerance among treatments. In spring, weeks required to reach 90% cover (Weeks$_{90}$ values) were used evaluate differences in traffic recovery due to treatment. Pearson's correlation coefficients were also calculated in SAS to determine relationships between volumetric soil moisture content and surface hardness.

Study 2

Plot establishment, plot maintenance and treatments. Plots were developed and managed as previously described in study one; however, this study was adjacent to the first study. Also this study received no simulated traffic events, this study collected soil temperature only.

Data collection. Soil temperature was monitored hourly throughout the study using data loggers (WatchDog B series button loggers. Spectrum Technologies. E. Plainfield, IL) buried 1.3 cm below the soil surface of each plot. These data loggers measured soil temperatures hourly from -10 to 85°C at an accuracy of +/- 1.1°C. Soil temperatures were monitored from 12 September to 17 November 2011 and 9 September to 1 November 2012. Data loggers remained in the ground for the same duration that traffic was applied in study 1. Soil temperature was again quantified in spring from 15 March to 24 May 2012 and 15 March to 7 May 2013 until spring green-up reached 90 PGTC on all plots.

Statistical analysis. Plots were arranged in a randomized complete block design with three replications. This study was repeated in time during 2011 and 2012. Soil temperature data were subjected to analysis of variance in SAS (v. 9.3., SAS Institute Inc., Cary, NC). No significant year-by-treatment interactions were found; therefore, data from each year were combined. Means were separated using Fisher's protected LSD at the $P = 0.05$ level of significance.

Study 3

Plot establishment. In 2011 and 2012 a study was conducted at the University of Tennessee Center for Athletic Field Safety (Knoxville, TN) to determine the effects of using turf cover (Evergreen Origninal Turf Cover, Covermaster Inc. Rexdale, ON) and late season CR topdressing on green color of 'Riviera' bermudagrass in fall and spring. 'Riviera' bermudagrass was seeded at 73 kg ha^{-1} on 11 July 2011 on a leveled Sequatchie silt loam soil (fine-loamy, siliceous, semiactive, thermic Humic Hapludult) measuring 6.2 in soil pH and 25 g kg^{-1} in organic matter content. Plots were covered with germination blankets (0.5 ounce germination blanket., A. M. Leonard., Piqua, OH) for three weeks and then removed. Each plot treated with urea at 24 kg N ha^{-1} bi-weekly until 90 percent turfgrass cover was achieved, before covers were applied and after covers were removed. Irrigation was applied daily for a period of ten minutes until 90 percent cover was reached after germination blankets were applied. Once canopy height reached 7.6 cm, plots were mown weekly with a rotary mower (260Z; Gravely. Brillion, WI) at a height of 4.5 cm. Clippings were allowed to return to the surface.

Plot maintenance. Plots were maintained as described in study one; this study took place on a block of grass separate from study one and two.

Treatments. Treatments in this study included use of a polyethylene turf cover with 30% green lace and 70% white lace (Evergreen Original Turf Cover. Covermaster Inc, Rexdale, ON), application of CR topdressing at 58545 kg ha^{-1} (i.e. 0.6 cm depth), or the combination of CR topdressing and use of a turf cover. Turf cover treatments were applied 28 October to 9 December 2011 and 1 November to 4 December 2012. Turf cover treatments were applied to plots in the late afternoon/evening before dew formation and removed at 10 am. Crumb rubber particles applied as a topdressing ranged in diameter from 1 to 2 mm and were applied incrementally over a 7 day period. CR treatments were applied on 21 October 2011 and 18 October 2012. Plots size was 122 by 122 cm.

Data collection. Percent green turfgrass cover was monitored weekly using DIA to determine PGTC using methods similar to Karcher et al., 2001. Digital image analysis method used as previously described in study one. Data was collected in the fall 24 October through 14 December 2011 and 29 October through 12 December 2012 and in the spring until each plot reached over 90 PGTC 15 March through 27 April 2012 and 15 March through 18 April 2013

Soil temperature was monitored hourly throughout the study using data loggers (WatchDog B series button loggers. Spectrum Technologies. E. Plainfield, IL) buried 1.3 cm below the soil surface of each plot. These data loggers measured soil temperatures from -10 to 85°C at an accuracy of +/- 1.1°C. Fall soil temperatures were monitored from 21 October through 14 December 2011 and 28 October through 8 December 2012. Spring soil temperature data loggers were collected 14 March – 24 May 2012 and 15 March – 10 May 2013 until PGTC was greater than or equal to 90.

Statistical analysis. The experiment was a randomized complete block with four replications that was repeated in time during 2011 and 2012. PGTC data were subjected to analysis of variance in SAS (v. 9.3., SAS Institute Inc., Cary, NC). Significant year-by-treatment interactions were detected; therefore, PGTC data from each year were analyzed separately. PGTC data were subjected to non-linear regression in in GraphPad Prism 6 (GraphPad Software, San Diego, CA). A sum of squares reduction F-test was conducted to compare sums of squares from a global model (all treatments shared the same parameter estimates) to a cumulative model where unique parameters estimates were calculated for each treatment. Soil temperature data were inserted subjected to analysis of variance in SAS. No significant year-by-treatment interactions were found; therefore, data from each year were combined and analyzed. Means were compared using Fisher’s protected LSD to separate treatments at the $P = 0.05$ level of significance.

3. Results and Discussion

Study 1

Percent green turfgrass cover. In 2011, all plots receiving CR topdressing maintained significantly higher PGTC longer than plots without CR. Plots not receiving CR were reduced to 50 PGTC after ~12 simulated traffic events compared to 16 to 17 events for those receiving CR at 1.3 and 1.9 cm (Table 2). Goddard et al. (2008) also found that CR topdressing increased the turf cover of bermudagrass under simulated traffic compared to plots without CR. Rogers III et al. (1998) reported that Kentucky bluegrass topdressed with at least 7.6 mm CR under simulated traffic found an increase in turfgrass cover compared to plots without CR.

Crumb rubber particle sizes affected PGTC values in 2011 following simulated traffic. Plots receiving no CR were reduced to 50% cover after ~12 events. Comparatively, plots with the lowest CU took the fewest traffic events to reach 50% green cover ~16, 15, 15, 17, and 16 (1.38 (8:20), 1.82 (14:30), 1.79 (10:14), 2.28 (20), and 1.83 (30) CU, respectively).The CR with 2.28 CU took five more simulated traffic events to reach 50% green cover compared to the untreated control (Table 3). A potential reason for the improved wear tolerance using CR may be a result of the CR particles protecting the crown of the plant. Thus, the greater the CR depth, the greater the turfgrass crown is protected. Rogers III et al. (1998) reported that Kentucky bluegrass (*Poa pratensis* L.) topdressed with 0.05-2 mm CR had greater tolerance to simulated traffic compared to turf topdressed with 2-6 mm CR.

In 2012, among all CR depths there was no significant difference found among treatments (*P* = 0.71). Differences in rainfall late in the traffic season could have attributed to differences between years due to 2011 having more total rainfall than 2012. The research site received 125 mm more rainfall in 2011 than 2012 during the period in which simulated traffic was applied. One study reported that wet soils conditions can accelerate turf injury and turfgrass cover loss under simulated traffic when compared to dry conditions (Minner and Valverde, 2004). With wet soil moisture conditions, soil structure can be damaged easier while providing less protection for the plant, since the soil is not as firm as when under dry conditions. Therefore, the higher amount of rain in 2011 may have contributed to the increased loss in turf cover compared to 2012. Overall, PGTC levels were higher in 2012; higher rates of PGTC may have been due to warmer temperatures and less rainfall during the study. The growing conditions in 2012,were more favorable for bermudagrass than in 2011. This may have resulted in the less overall cover loss; therefore, making the CR treatments less effective.

Surface hardness and soil moisture. In fall 2011, a particle size-by-topdressing depth interaction was detected in surface hardness data on all dates (Table 4). Plots topdressed with CR at 1.9 cm measured lower surface hardness than those receiving 0.6 cm CR topdressing on all dates, regardless of particle size (Figure 3). In addition, plots receiving CR topdressing at 1.3 cm yielded lower surface hardness values than those receiving 0.6 cm CR on 73% of evaluation dates in 2011 (Table 4). Changes in surface hardness due to CR particle size at each depth were variable over the sampling period. Our findings support previous research quantifying effects of crumb rubber topdressing on cool-season turfgrasses subjected to traffic (Rogers III et al., 1998; Goddard et al., 2008). During the sampling period in 2011, soil moisture content was never less than 24.5%, and was significantly correlated with surface hardness (Table 6).

During the second year of the study, a particle size-by-topdressing depth interaction was detected in surface hardness data on all dates (Table 7). Unlike 2011, differences in surface hardness between particle size and depth combinations were not consistent over time (Table 4). In 2011, soil moisture values never dropped below 22%. In 2012, soil moisture values measured less than 20% for all but two simulated traffic events (Table 5). These differences between years can explain the variability in surface hardness. In 2011, there was 125 mm more rainfall than in 2012. Previous research found that soil volumetric water content and surface hardness have an inverse relationship, as the water content increases, surface hardness drops (Zebarth and Sheard, 1985).

Spring recovery. In spring 2012, recovery was not affected by CR treatment. Plots without CR had a wide range of variability contributing to experimental error. $Weeks_{90}$ values ranged from ~7 to ~5 weeks (data not presented). In spring 2013, differences were found among all CR depths and particle sizes (Table 7, Table 8; Figure 4, Figure 5). Plots not receiving CR required 8.2 weeks to reach 90% green cover, which was significantly slower compared to 7.4 to 7.7 weeks for plots receiving 0.6 cm, 1.3 cm, 1.9 cm depth CR topdressing. Similarly, plots topdressed with a CU of 1.38, 1.79, 1.82, 2.28, 1.83 CR took 7.5, 7.7, 7.8, 7.5, and 7.7 weeks to reach 90% PGTC, respectively. Plots not receiving CR reached 90% PGTC in 8.2 weeks (Table 5). Our findings suggest that differences in hybrid bermudagrass spring green-up due to CR topdressing may be subtle. Differences in rainfall data from March through May were found between years, with 2013 having 77 mm more rainfall than 2012. This increase in rainfall could account for the differences between years, making 2013 more conducive to bermudagrass growth and effects of CR treatments less pronounced.

Study 2

Fall soil temperature. No year-by-treatment interactions were detected in soil temperature data collected in fall 2011 and 2012 at a 1.3 cm depth; therefore, data were pooled over years (Table 9). No soil temperature differences due to CR treatment were detected. This response supports previous findings by Vanini et al (1999) who observed minimal differences in soil temperature with CR topdressing on Kentucky bluegrass.

Spring soil temperature. Similar to observations from the fall, no differences in soil temperature were detected between CR treatments (Table 9). No year-by-treatment interactions were detected in spring temperature data; therefore, data were pooled over both years of the study (Table 10).

Study 3

Percent green turfgrass cover. Plots treated with turf covers maintained PGTC longer than uncovered plots (Figure 6). Slope (β_1) values for equations fitting the untreated plots, those receiving CR only, those receiving CR and a turf cover, and those receiving only a turf cover were 11.7, 14.3, 15.3 and 3.1, respectively (Table 11). This response indicates that extending the fall growing season was most impacted by applying both CR topdressing and a turf cover (Table 11). In 2011, PGTC never fell below 80% in plots with a turf cover for the duration of the sampling period; while, PGTC of uncovered plots was < 50% (Figure 6). Previous research correlates with the findings of this study, in that turf covers were found to extend the fall growing season of bermudagrass by 5 to 8 weeks (Goatley et al., 2005).

In 2012, plots with cover treatments maintained PGTC longer than plots with no cover (Figure 7). Slope (β_1) values for equations fitting the untreated plots, those receiving CR only, those receiving CR and a turf cover, and those receiving only a turf cover were -41.11, -13.36, 2.01 and -6.40, respectively (Table 12). These slopes indicate that plots without a cover lost PGTC at least twice as fast as those not treated with a cover. Percent green turfgrass cover values never fell below 80% for the duration of the sampling period in 2012, compared to < 20% for plots not treated with a cover (Figure 7). Roberts (1986) also found that turf covers increased PGTC among a variety of different turf covers used on cool-season grasses during winter.

Spring recovery. No significant differences in PGTC were detected among treatments during spring 2012, potentially due to abnormally warm temperatures. Air temperatures in March rose to more than 26 °C on four dates, with air temperature on 16 days measuring greater than 21 °C. Differences in rainfall data from March through May were found between years, with 2013 having 77 mm more rainfall than 2012. These conditions may have encouraged bermudagrass growth earlier than normal, making effects due to CR or turf cover application less noticeable.

In spring 2013, PGTC was greatest in plots with turf covers (Table 13). Slope (β_1) values for equations fitting the untreated plots, those receiving CR only, those receiving CR and a turf cover, and those receiving only a turf cover were -34.88, -35.78, -15.48 and -13.85, respectively (Table 13). The variation among slopes indicates that plots receiving a turf cover reached 90 PGTC twice as fast as those not treated with a cover (Figure 8). This study correlates with previous research demonstrating that covering bermudagrass during the winter months accelerates spring green-up compared to uncovered bermudagrass (Goatley et al., 2005).

Soil temperature. No year-by-treatment interactions were detected in soil temperature data; therefore, data from 2011 and 2012 were pooled. No significant differences in fall or spring soil temperature due to treatment were detected in this study. These findings are similar to those reported by Vanini et al. (1999) on Kentucky bluegrass. In the current study, temperature was measured at a 1.3 cm soil depth. Covers may increase temperature in the turf canopy and not in the soil. Goatley et al (2007) evaluated ten different turf covers on a ‘MS Express’ bermudagrass green and found that all the turf covers increased canopy temperature by at least 0.7 C° compared to a plots without a cover. However, canopy temperature was not monitored in this study.

4. Conclusion

Application of CR topdressing increased traffic tolerance and decreased surface hardness of hybrid bermudagrass subjected to simulated traffic. These findings are similar to those reported by Goddard et al. (2008), that common bermudagrass retained greater PGTC when topdressed with CR. In year 1 of this study, CR particle size and depth increased traffic tolerance, similar to results reported by Rogers III et al. (1998) on Kentucky bluegrass. However, these responses were not observed in the second year of this study. This could be related to differential soil moisture content between years. Applications of CR had limited effect on spring green-up in year 2. However, this response was not associated with increased soil temperature at a 1.3 cm depth. This supports previous research by Vanini et al (1999) on Kentucky bluegrass.

Turf covers were more effective at extending bermudagrass PGTC in fall than CR alone or no cover. Plots treated with a turf cover yielded PGTC values greater than 80% in December, compared to less than 20% for those not treated with a turf cover. Plots not protected with a turf cover lost PGTC twice as fast as plots topdressed with CR and protected with a turf cover. This response is consistent with findings of Goatley et al. (2005) who reported that white polypropylene covers extended the growing season of improved common bermudagrass from 5 to 8 weeks. In our research, plots with a turf cover reached 90 PGTC one week faster than those with no turf cover.

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Appendices

Appendix A
Tables

Table 1. Particle size analysis[†] and coefficient of uniformity[‡] (CU) for five crumb rubber treatments topdressed into hybrid bermudagrass (*Cynodon dactylon* x *C. transvaalensis* Burtt-Davy, cv. 'Tifway') in Knoxville, TN, 2011 and 2012.

	1.79[†]	**1.38**	**1.82**	**2.28**	**1.83**
> 2mm[§]	**35%**	**3%**	**0%**	**0%**	**0%**
2-1 mm	**58%**	**97%**	**50%**	**0%**	**0%**
1-0.5 mm	**7%**	**0%**	**50%**	**51%**	**34%**
0.5 – 0.25 mm	**0%**	**0%**	**0%**	**39%**	**57%**
0.25 – 0.15 mm	**0%**	**0 %**	**0 %**	**8%**	**7%**
0.15 – 0.05 mm	**0%**	**0%**	**0%**	**3%**	**2%**

[†] United States Golf Association specifications for sieve size analysis to breakdown particle size.

[‡] The coefficient of uniformity was calculated using the D_{90}/D_{10}.

Table 2. Parameters for predicting hybrid bermudagrass (*C. dactylon* x *C. transvaalensis* Burtt-Davy, cv. Tifway) percent green turfgrass cover (PGTC) after 25 simulated traffic events with various depths of crumb rubber treatments applied during the fall in Knoxville, TN in 2011. The larger the slope values the faster the rate at which PGTC was lost over time. $Events_{50}$ is the predicted number of simulated traffic events to reach 50% hybrid bermudagrass cover. Standard error values for each parameter are listed in parentheses.

Depth	$Events_{50}$	R^2
0 cm	11.60 (0.08)	0.84
0.6 cm	13.90 (0.04)	0.89
1.3 cm	15.80 (0.04)	0.89
1.9 cm	16.80 (0.05)	0.87

Table 3. Parameters for predicting hybrid bermudagrass (*Cynodon dactylon* x *C. transvaalensis* Burtt-Davy, cv. Tifway) percent green turfgrass cover (PGTC) under 25 simulated traffic events with various particle sizes of crumb rubber applied during the fall in Knoxville, TN in 2011. The larger the slope value the faster the rate at which PGTC was lost over time. Events_{50} is the predicted number of simulated traffic events to reach 50% hybrid bermudagrass cover. Standard error values for each parameter are listed in parentheses.

Treatment[†]	Events_{50}	R^2
No Crumb Rubber	11.60 (0.08)	0.84
1.38	15.60 (0.06)	0.88
1.78	14.80 (0.05)	0.88
1.82	15.10 (0.06)	0.88
2.28	16.60 (0.06)	0.87
1.83	15.60 (0.06)	0.87

[†] The coefficient of uniformity for each crumb rubber particle size was calculated using the D_{90}/D_{10}.

Table 4. Surface hardness values following 5, 10, 15, 20 and 25 simulated traffic events to hybrid bermudagrass (*Cynodon dactylon* (L.) Pers. X *C. transvaalensis* Burtt Davy) treated with three depths of crumb rubber topdressing and five crumb rubber topdressing particles sizes during 2011 and 2012 in Knoxville, TN. The coefficient of uniformity of each different particle size used was calculated using United States Golf Association sieve size analysis. The coefficient of uniformity was used to separate particle sizes for comparison. Fisher's protected least significant difference (LSD) test was used to separate treatment means at *P* = 0.05.

		Surface Hardness†											
		2011						2012					
Crumb Rubber‡	Topdressing Depth	0 events§	5 events	10 events	15 events	20 events	25 events	0 events	5 events	10 events	15 events	20 events	25 events
	cm	Gmax											
1.38	0.6	45	54	56	45	44	47	57	61	58	56	53	55
	1.3	41	43	54	39	44	43	52	67	62	59	60	59
	1.9	38	39	47	35	38	39	62	69	61	61	56	64
1.79	0.6	44	52	61	45	48	50	65	59	67	63	57	56
	1.3	41	51	55	41	43	43	60	63	69	58	60	62
	1.9	39	46	50	40	43	40	68	77	60	64	52	55
1.82	0.6	47	56	63	46	49	53	56	61	64	59	54	55
	1.3	46	51	55	41	43	44	59	57	60	53	58	49
	1.9	38	45	49	39	40	39	73	67	51	50	52	54
2.28	0.6	46	53	62	45	49	48	65	63	63	65	69	56
	1.3	44	49	54	42	46	45	55	64	65	61	69	60
	1.9	39	45	47	37	39	40	59	59	66	61	70	52
1.83	0.6	44	53	61	45	47	49	58	67	61	54	61	54
	1.3	42	46	52	40	43	41	54	51	59	67	62	59
	1.9	37	45	48	37	36	40	62	70	64	60	50	58
$LSD_{0.05}$		2.8	3.1	4.2	3.1	3.2	3.1	8.8	8.0	6.3	8.2	7.4	8.2

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† Surface hardness was measured with a Clegg Soil Impact Tester equipped with a 2.25 kg missile and accelerometer in units of G_{max}. Means represented the average of three sub-samples from each plot.

‡ Coefficient of uniformity for each crumb rubber particle size was calculated using the D_{90}/D_{10}.

§ Plots were subjected to 25 simulated traffic events from 12 Sep to 18 Nov 2011 and 10 Sep to 31 Oct 2012 at a rate of three simulated games per week.

Table 5. Volumetric soil moisture content values following 5, 10, 15, 20 and 25 simulated traffic events to hybrid bermudagrass (*Cynodon dactylon* (L.) Pers. X *C. transvaalensis* Burtt Davy) treated with three depths of crumb rubber topdressing and five crumb rubber topdressing particles sizes during 2011 and 2012 in Knoxville, TN. The coefficient of uniformity of each different particle size used was calculated using United States Golf Association sieve size analysis. The coefficient of uniformity was used to separate particle sizes for comparison. Fisher's protected least significant difference (LSD) test was used to separate treatment means at *P* = 0.05.

		Volumetric Soil Moisture Content[†]									
		2011					2012				
Crumb Rubber[‡]	Topdressing Depth	5 events[¶]	10 events	15 events	20 events	25 events	5 events	10 events	15 events	20 events	25 events
	cm	%									
1.38	0.6	28	26	31	30	33	32	23	18	17	17
	1.3	27	24	30	28	34	32	23	19	17	18
	1.9	27	25	29	28	34	30	23	18	16	18
1.78	0.6	30	27	34	31	35	31	26	16	21	18
	1.3	25	23	30	28	35	32	24	25	1	18
	1.9	25	23	29	28	35	29	22	17	16	16
1.82	0.6	28	25	32	31	35	33	25	18	17	18
	1.3	27	26	32	29	35	42	22	18	17	17
	1.9	25	23	29	26	34	31	25	18	18	18
2.28	0.6	27	24	31	29	33	32	23	19	20	18
	1.3	27	24	31	27	36	30	23	18	18	17
	1.9	25	25	30	28	35	32	25	19	19	20
1.83	0.6	27	26	32	29	33	32	23	19	17	17
	1.3	26	25	30	28	38	30	21	19	18	17
	1.9	26	25	31	27	32	30	24	16	16	18
$LSD_{0.05}$		1.5	1.8	1.8	1.7	1.7	2.0	2.8	1.4	1.2	1.3

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† Volumetric soil moisture content was measured on each date that surface hardness data were collected using a time domain reflectometry (TDR) probe equipped with 5 cm tines in three locations per plot. Volumetric soil moisture content averaged 29% during 2011 data collection and 22% in 2012.

‡ Coefficient of uniformity for each crumb rubber particle size was calculated using the D_{90}/D_{10}.

§ Plots were subjected to 25 simulated traffic events from 12 Sep to 18 Nov 2011 and 10 Sep to 31 Oct 2012 at a rate of three simulated games per week.

Table 6. Pearson's correlation coefficients associating changes in hybrid bermudagrass (*C. dactylon* x *C. transvaalensis* Burtt-Davy, cv. Tifway) volumetric soil moisture† content to changes in surface hardness‡ following 5, 10, 15, 20, and 25 simulated traffic events in Knoxville, TN during 2011 and 2012.

Traffic event§	r
5 games	0.46***
10 games	-0.05***
15 games	-0.61***
20 games	-0.49***
25 games	-0.51***

† Volumetric soil moisture content (%) was monitored using a time domain reflectometry (TDR) probe equipped with 5 cm tines.

‡ A Clegg Impact Soil Tester equipped with a 2.25 kg missile was used to collect surface hardness. Three drops per location in the middle of each plot.

§ Plots were subjected to 25 simulated traffic events from 12 September to 18 November 2011 and 10 September to 31 October 2012 at a rate of three simulated games per week.

*** P values found to be highly significant at the ≤ 0.0001 level.

Table 7. Parameters for predicting hybrid bermudagrass (*Cynodon dactylon* x *C. transvaalensis* Burtt-Davy, cv. Tifway) percent green turfgrass cover (PGTC) spring recovery after fall simulated traffic with various depths of crumb rubber in Knoxville, TN in 2013. The larger the slope value the faster the rate at which PGTC was gained over time. Weeks_{90} is the predicted number of weeks to reach 90% hybrid bermudagrass cover. Standard error values for each parameter are listed in parentheses.

Treatment	Weeks_{90}	R^2
0 cm	8.20 (0.18)	0.96
0.6 cm	7.70 (0.09)	0.95
1.3 cm	7.70 (0.11)	0.93
1.9 cm	7.40 (0.07)	0.96

Table 8. Parameters for predicting hybrid bermudagrass (*Cynodon dactylon* x *C. transvaalensis* Burtt-Davy, cv. Tifway) percent green turfgrass cover (PGTC) spring recovery after fall simulated traffic with various particle sizes of crumb rubber in Knoxville, TN in 2013. The larger the slope values the faster the rate at which PGTC was gained over time. $Weeks_{90}$ is the predicted number of weeks to reach 90% hybrid bermudagrass cover. Standard error values for each parameter are listed in parentheses.

Treatment†	$Weeks_{90}$	R^2
No Crumb Rubber	8.20 (0.19)	0.96
1.38	7.50 (0.09)	0.96
1.78	7.70 (0.10)	0.96
1.82	7.80 (0.16)	0.91
2.28	7.50 (0.08)	0.97
1.83	7.70 (0.16)	0.91

† The coefficient of uniformity for each crumb rubber particle size was calculated using the D_{90}/D_{10}.

Table 9. Partial analysis of variance for crumb rubber particle size[†], depth[‡] and time segment[§] on hybrid bermudagrass (*Cynodon dactylon* X *C. transvaalensis* Burtt Davy) for soil temperature in Knoxville, TN during fall 2011, 2012 and Spring 2012, 2013. Fall temperatures were recorded

Treatment	DF	Fall Significance	Spring Significance
Year	1	NS[¶]	NS
Particle Size(PS)	4	NS	NS
Depth	2	NS	NS
PS*Depth	8	NS	NS
Time Segment	23	***	***
PS*Time Segment	92	NS	NS
Depth*Time Segment	46	NS	NS
PS*Depth*Time Segment	184	NS	NS
Error	360		

*,**,***, significant at the 0.001 probability levels.

[†] The coefficient of uniformity was calculated using the D_{90}/D_{10}.

‡ Depth had each rubber at three different depths 0.6 cm, 1.3 cm and 1.9 cm.

§ Each day was divided up into six different three hour long time segments and they are: 1-3, 3-6, 6-9, 9-12, 12-15, 15-18, 18-21, 21-24.

¶ Designates that data for this interaction was non-significant.

Table 10. Best-fit parameter estimates for regression equations characterizing changes in improved common bermudagrass (*Cynodon dactylon* (L.) Pers.) percent green turfgrass cover when subjected to crumb rubber and turf cover treatments in Knoxville, TN. Study took place from 28 October 2011 to 9 December 2011 and 1 November 2012 and ended 4 December 2012. Standard deviations for each parameter estimate are listed in parentheses.

	2011			2012		
Treatment	β_0	β_1	R^2	β_0	β_1	R^2
Control	86.63 (+/- 4.98)	11.65 (+/- 3.26)	0.95	134.60 (+/- 7.79)	-41.11 (+/- 5.10)	0.94
Crumb Rubber[†]	65.49 (+/- 4.60)	14.28 (+/- 3.00)	0.90	115.50 (+/-10.00)	-13.36 (+/- 6.54)	0.91
Crumb Rubber + Cover[‡]	66.43 (+/- 2.80)	15.34 (+/- 1.84)	0.71	96.00 (+/- 2.81)	2.01 (+/- 1.84)	0.38
Cover	91.95 (+/- 2.93)	3.06 (+/- 1.92)	0.60	96.00 (+/- 7.52)	-6.40 (+/- 4.92)	0.12

[†] Crumb rubber was applied at a 1.3 cm depth using a particle size range of 1 - 2 mm.

[‡] Covermaster® Evergreen turf covers were used, they were made of white polyethylene cover composed of tapes and coating (Covermaster Inc, Rexdale, ON).

Table 11. Best-fit parameter estimates for regression equations characterizing changes in improved common bermudagrass (*Cynodon dactylon* (L.) Pers.) percent green turfgrass cover when subjected to crumb rubber and turf cover treatments from 15 March 2013 and ended 27 April 2013 in Knoxville, TN. Standard deviations for each parameter estimate are listed in parentheses.

Treatment	β_0	β_1	β_2	R^2
Control	35.10 (+/- 6.50)	-34.88 (+/- 4.25)	7.45 (+/- 0.59)	0.96
Crumb Rubber[†]	36.30 (+/- 7.30)	-35.78 (+/- 4.78)	7.70 (+/- 0.67)	0.96
Crumb Rubber + Cover[‡]	10.30 (+/- 11.61)	-15.48 (+/- 7.60)	5.32 (+/- 1.06)	0.91
Cover	10.10 (+/- 10.43)	-13.85 (+/- 6.83)	5.01 (+/- 0.96)	0.93

[†] Crumb rubber was applied at a 1.3 cm depth using a particle size range of 1 - 2 mm.

[‡] Covermaster® Evergreen turf covers were used, they were made of white polyethylene cover composed of tapes and coating (Covermaster Inc, Rexdale, ON).

Appendix B
Figures

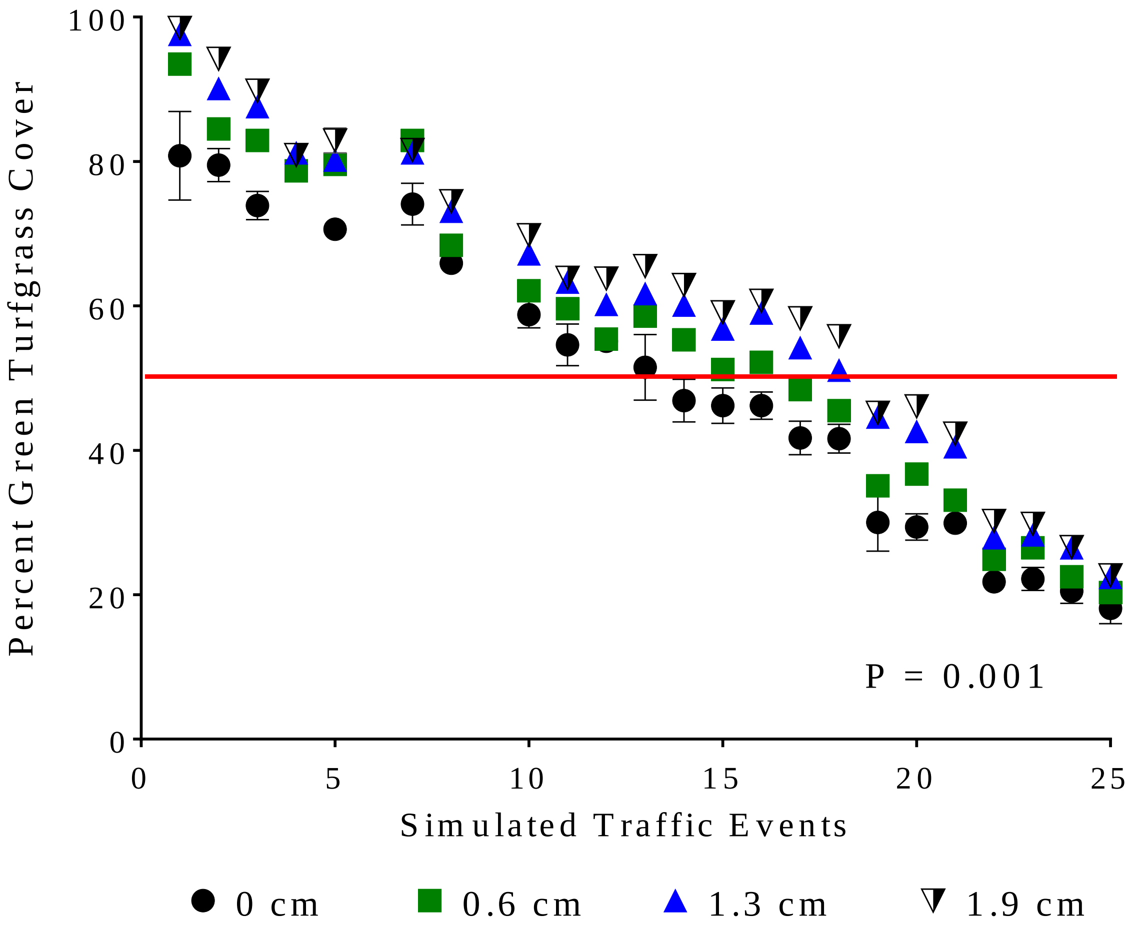

Figure 1. Changes in hybrid bermudagrass (*C. dactylon* (L.) Pers. X *C. transvaalensis* Burtt Davy) percent green turfgrass cover with different crumb rubber topdressing depths following 25 simulated traffic events during fall 2011 in Knoxville, TN. Standard error values are presented as a means of statistical comparison. Best-fit parameter estimates for non-linear regression equations modeling responses are presented below.

Depth	Events$_{50}$	R^2
0 cm	11.60 (0.08)	0.84
0.6 cm	13.90 (0.04)	0.89
1.3 cm	15.80 (0.04)	0.89
1.9 cm	16.80 (0.05)	0.87

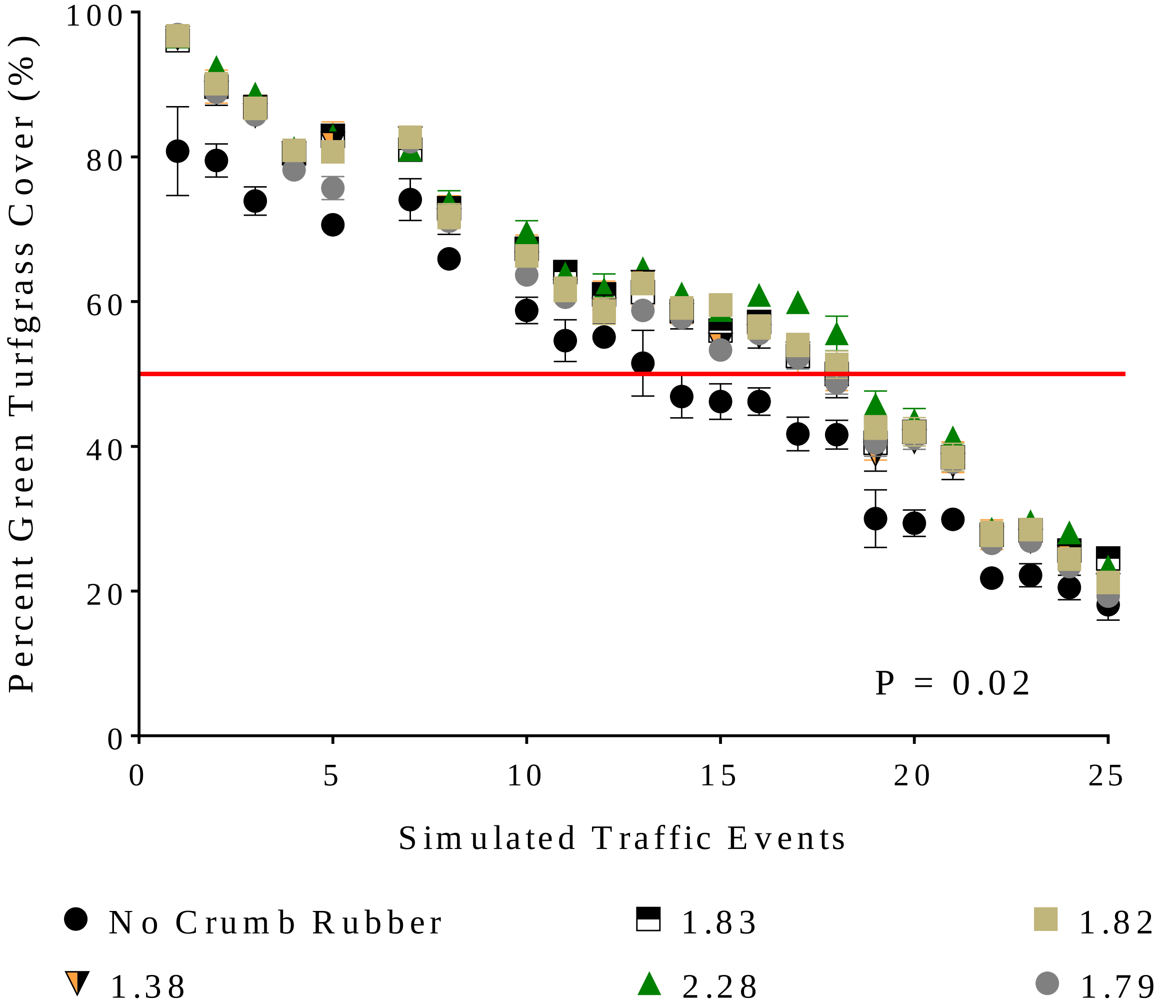

Figure 2. Changes in hybrid bermudagrass (*C. dactylon* (L.) Pers. X *C. transvaalensis* Burtt Davy) percent green turfgrass cover due to crumb rubber particle size following 25 simulated traffic events during fall 2011 in Knoxville, TN. The coefficient of uniformity of each different particle size used was calculated using United States Golf Association sieve size analysis. The coefficient of uniformity was used to separate particle sizes for comparison. Standard error values are presented as a means of statistical comparison. Best-fit parameter estimates for non-linear regression equations modeling responses are presented below.

Treatment†	Events_{50}	R^2
No Crumb Rubber	11.60 (0.08)	0.84
1.38	15.60 (0.06)	0.88
1.78	14.80 (0.05)	0.88
1.82	15.10 (0.06)	0.88
2.28	16.60 (0.06)	0.87
1.83	15.60 (0.06)	0.87

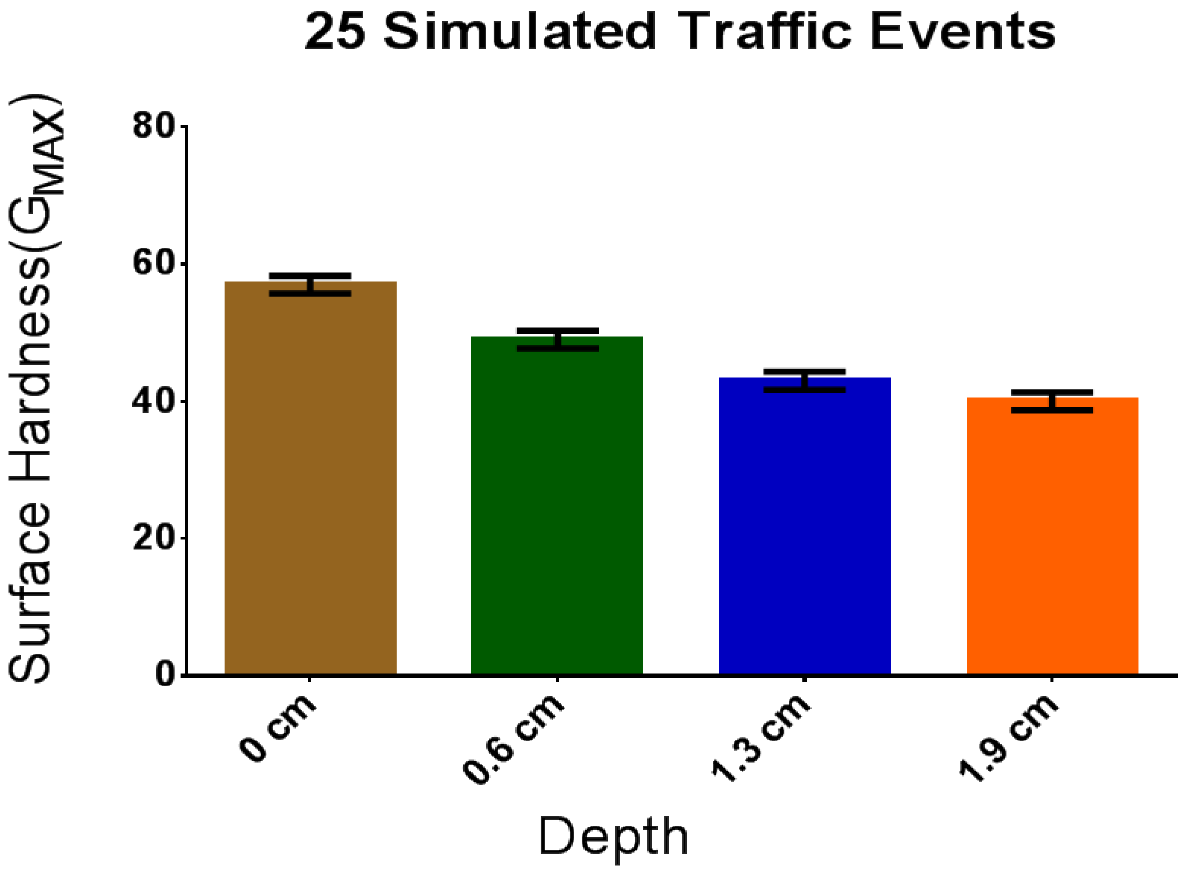

Figure 3. Changes in hybrid bermudagrass (*C. dactylon* (L.) Pers. X *C. transvaalensis* Burtt Davy) surface hardness due to crumb rubber topdressing depth following 25 simulated traffic events during fall 2011 in Knoxville, TN. A Clegg Impact Soil Tester equipped with a 2.25 kg missile was used to collect surface hardness data. Standard error values are presented as a means of statistical comparison.

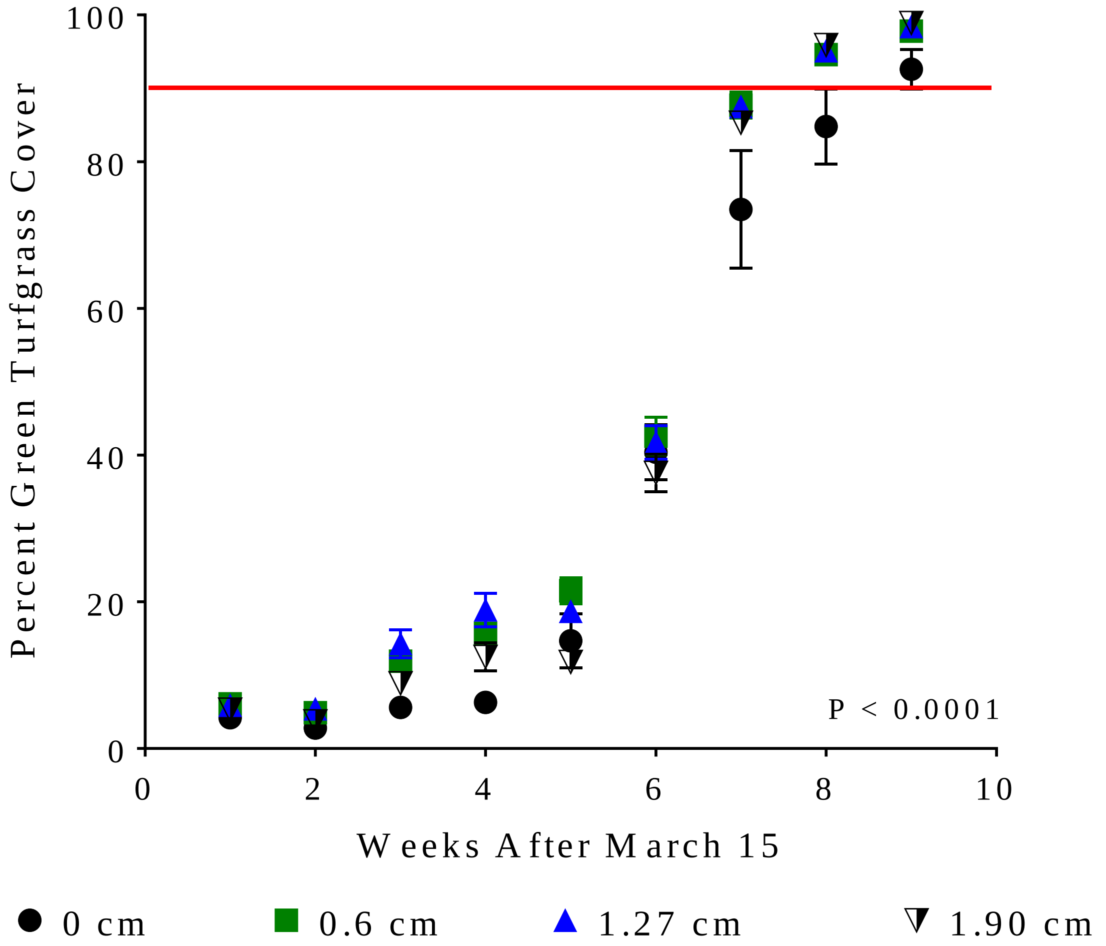

Figure 4. Changes in hybrid bermudagrass (*C. dactylon* (L.) Pers. X *C. transvaalensis* Burtt Davy) percent green turfgrass cover due to crumb rubber topdressing depth following a fall where each depth was subjected to 25 simulated traffic events. Data collection began on March 15, 2013 in Knoxville, TN. Standard error values are presented as a means of statistical comparison. Best-fit parameter estimates for non-linear regression equations modeling responses are presented below.

Treatment	Weeks_{90}	R^2
0 cm	8.20 (0.18)	0.96
0.6 cm	7.70 (0.09)	0.95
1.3 cm	7.70 (0.11)	0.93
1.9 cm	7.40 (0.07)	0.96

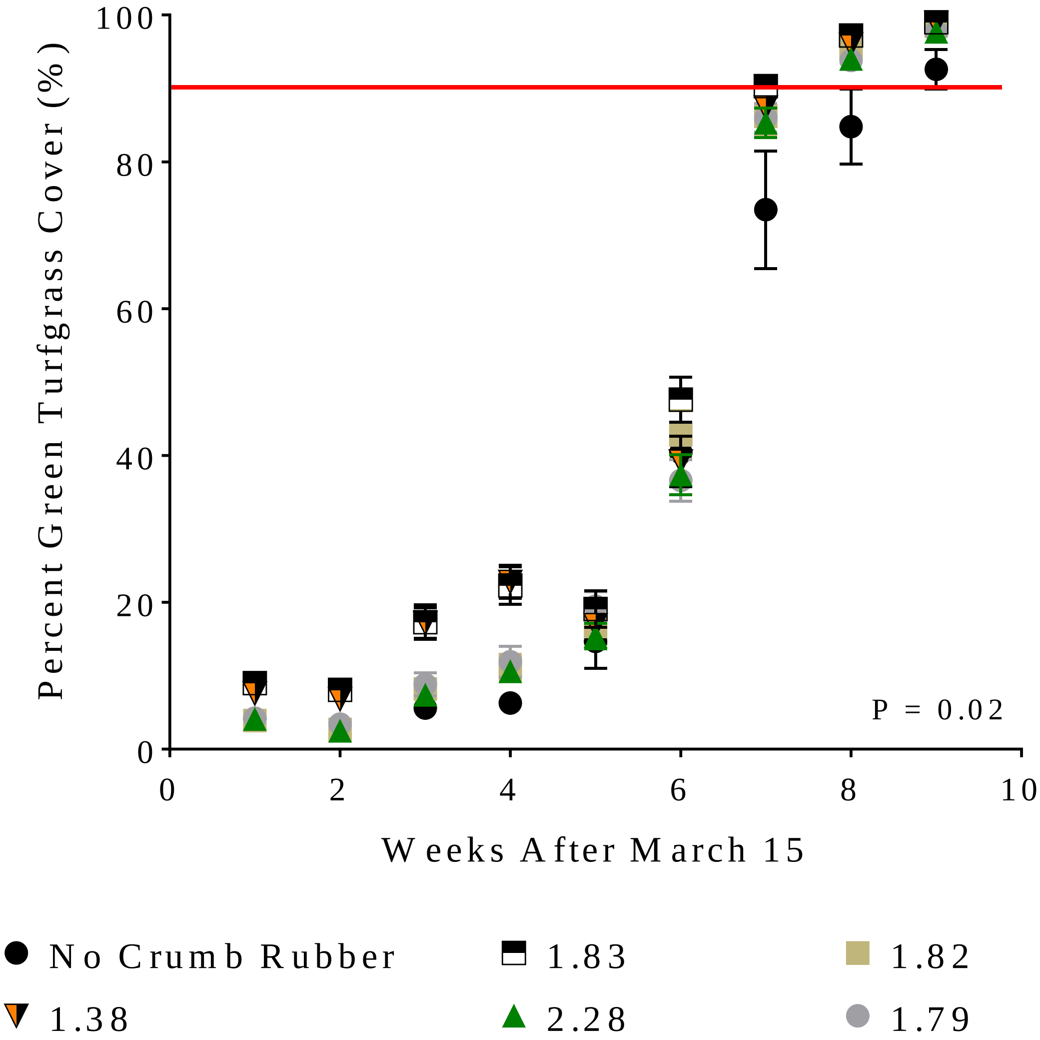

Figure 5. Changes in hybrid bermudagrass (*C. dactylon* (L.) Pers. X *C. transvaalensis* Burtt Davy) percent green turfgrass cover due to crumb rubber particle size where each treatment was subjected to 25 simulated traffic events. Data collection began on March 15, 2013 in Knoxville, TN. The coefficient of uniformity of each different particle size used was calculated using United States Golf Association sieve size analysis. The coefficient of uniformity was used to separate particle sizes for comparison. Standard error values are presented as a means of statistical comparison. Best-fit parameter estimates for non-linear regression equations modeling responses are presented below.

Treatment†	Weeks$_{90}$	R^2
No Crumb Rubber	8.20 (0.19)	0.96
1.38	7.50 (0.09)	0.96
1.78	7.70 (0.10)	0.96
1.82	7.80 (0.16)	0.91
2.28	7.50 (0.08)	0.97
1.83	7.70 (0.16)	0.91

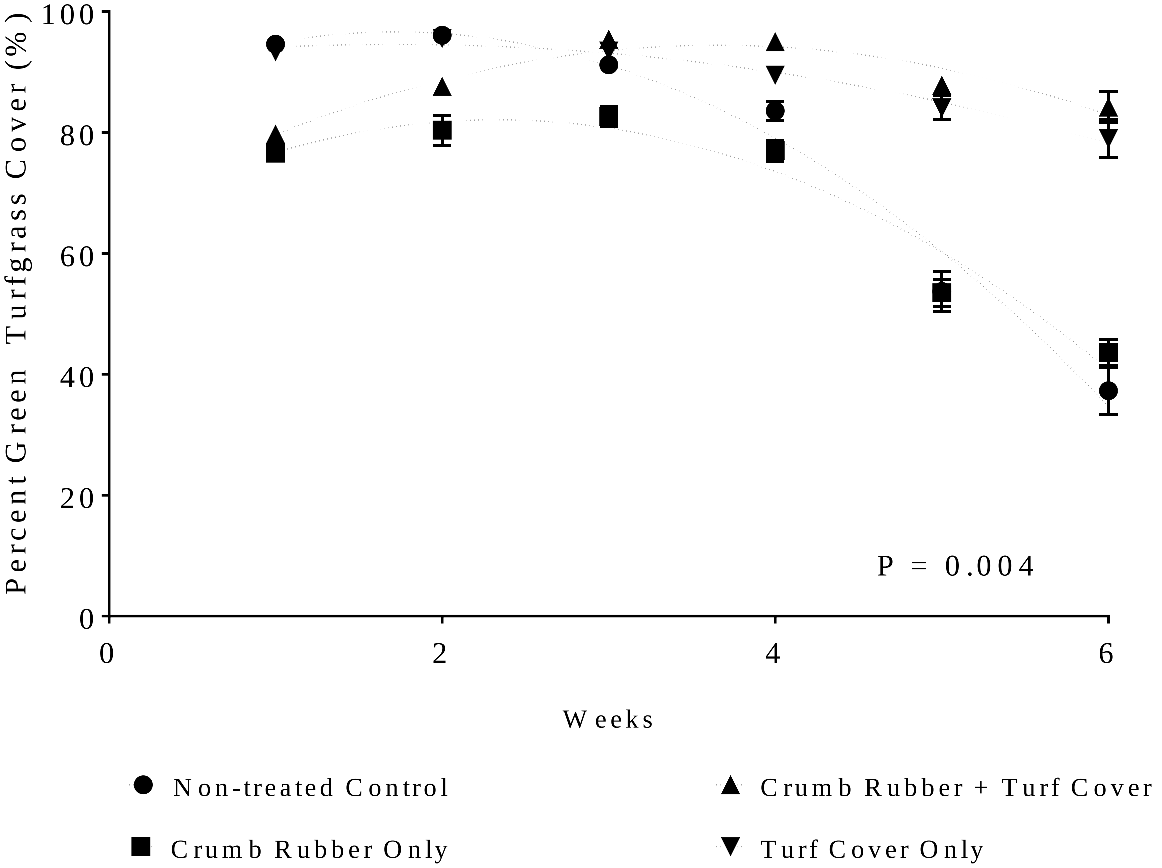

Figure 6. Changes in common bermudagrass (*Cynodon dactylon* (L.) Pers.) percent green turfgrass cover retention with treatments of a non-treated control, turf cover only, crumb rubber only and crumb rubber with a turf cover during fall 2011 in Knoxville, TN. Study started 28 October 2011 and ended 9 December 2011. Crumb rubber was applied at a 1.3 cm depth using particles 1 to 2 mm in diameter. Covermaster™ Evergreen original turf covers were used, they were made of white polyethylene cover composed of tapes and coating (Covermaster Inc, Rexdale, ON). Standard error values are presented as a means of statistical comparison.

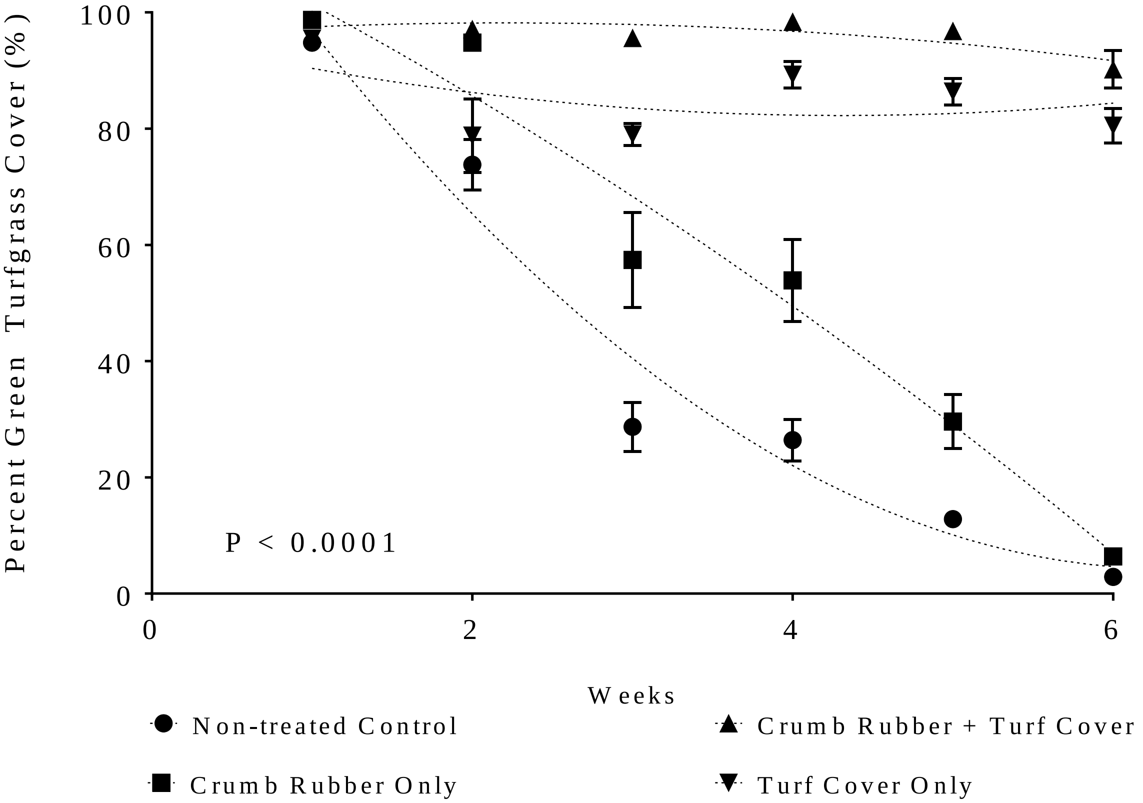

Figure 7. Changes in common bermudagrass (*Cynodon dactylon* (L.) Pers.) percent green turfgrass cover retention with treatments of a non-treated control, turf cover only, crumb rubber only and crumb rubber with a turf cover during fall 2012 in Knoxville, TN. Study started 1 November 2011 and ended 4 December 2011. Crumb rubber was applied at a 1.3 cm depth using particles 1 to 2 mm in diameter. Covermaster™ Evergreen original turf covers were used, they were made of white polyethylene cover composed of tapes and coating (Covermaster Inc, Rexdale, ON). Standard error values are presented as a means of statistical comparison.

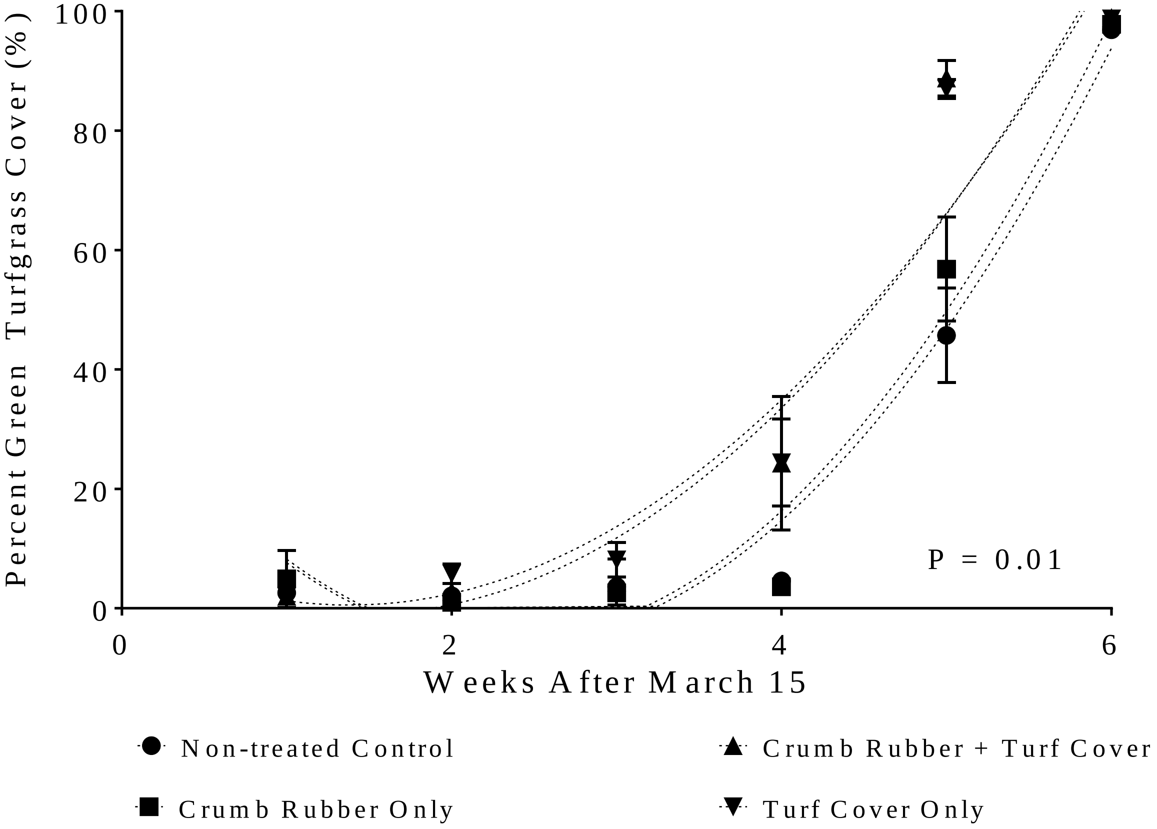

Figure 8. Changes in common bermudagrass (*Cynodon dactylon* (L.) Pers.) percent green turfgrass cover with treatments of a non-treated control, turf cover only, crumb rubber only and crumb rubber with a turf cover during spring 2013 in Knoxville, TN. Crumb rubber was applied at a 1.3 cm depth the previous fall using particles 1 to 2 mm in diameter. Covermaster™ Evergreen original turf covers were used, they were made of white polyethylene cover composed of tapes and coating (Covermaster Inc, Rexdale, ON). Standard error values are presented as a means of statistical comparison.

VITA

Kyley Hampton Dickson was born in Cleveland, TN on June 14, 1989. He grew up in Jamestown, TN and attended York Agricultural Institute, graduating in 2008. After graduation he pursued a Bachelor of Science degree from the University of Tennessee with an emphasis on turfgrass management. He graduated in the spring of 2012 and accepted a graduate research assistant position at the University of Tennessee in Plant Sciences under Dr. John Sorochan. Upon finishing his thesis, Kyley plans to pursue a Ph. D at the University of Tennessee, Knoxville.