

Impact of Soil Water Content on Bermudagrass Athletic Field Performance

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ABSTRACT

Soil water content (SWC) influences the consistency and performance of athletic fields. Two studies were conducted at the University of Tennessee Center for Athletic Field Safety (Knoxville, TN) to determine SWC impact on the performance of hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. x *C. transvaalensis*, Burt-Davy, ‘Tifway’] on silt loam (cohesive) and sand root zone conforming to United States Golf Association (USGA) specifications (non-cohesive) root zones. Soil water content treatments for the cohesive soil averaged $0.10 \text{ m}^3/\text{m}^3$ (± 0.035), $0.17 \text{ m}^3/\text{m}^3$ (± 0.035), $0.26 \text{ m}^3/\text{m}^3$ (± 0.035), and $0.35 \text{ m}^3/\text{m}^3$ (± 0.005); comparatively, SWC on the non-cohesive root zone averaged $0.08 \text{ m}^3/\text{m}^3$ (± 0.03), $0.16 \text{ m}^3/\text{m}^3$ (± 0.03), and $0.25 \text{ m}^3/\text{m}^3$ (± 0.05). To determine the effects of SWC on wear tolerance of hybrid bermudagrass, plots were subjected to 50 traffic events annually with the Baldree traffic simulator. For the cohesive soil, the highest SWC treatment ($0.35 \text{ m}^3/\text{m}^3$) lost green turfgrass cover (GTC) four times faster than plots averaging $0.10 \text{ m}^3/\text{m}^3$ or $0.17 \text{ m}^3/\text{m}^3$. However, non-cohesive root zones saw minimal differences in GTC loss among SWC treatments. Results indicated, for both root zones, that surface hardness was inversely related to SWC. Soil bulk density increased and air-filled porosity decreased as traffic events increased for both root zone constructions regardless of SWC. Our findings indicate that 0.10 to $0.17 \text{ m}^3/\text{m}^3$ SWC means was the optimal range for hybrid ‘Tifway’ bermudagrass subjected to simulated traffic on cohesive soil, while 0.08 to $0.16 \text{ m}^3/\text{m}^3$ SWC means was the optimal range for the non-cohesive root zone. Using data from the experiments on cohesive and sand soil constructions, predictive models were created to calculate the loss of turf cover based on SWC and traffic events ($P \leq 0.05$, $R^2 = 0.87$; $P \leq 0.05$, $R^2 = 0.91$). These models will help decision makers determine hybrid bermudagrass field performance expectations under varying soil moisture conditions and traffic on both cohesive and non-cohesive root zones.

TABLE OF CONTENTS

INTRODUCTION.....	1
BACKGROUND.....	2
WORK CITED.....	12
CHAPTER 1: Impact of Soil Water Content on Hybrid Bermudagrass Athletic Field Performance.....	19
ABSTRACT.....	20
INTRODUCTION.....	21
MATERIALS AND METHODS	23
RESULTS	27
Study I: Cohesive Root Zone	27
Study II: Non-Cohesive Root Zone	29
DISCUSSION	30
CONCLUSION.....	33
WORK CITED.....	34
APPENDIX A. TABLE	40
APPENDIX B. FIGURES.....	43
APPENDIX C. ADDITIONAL MATERIALS AND METHODS	48
APPENDIX D. ADDITIONAL RESULTS AND DISCUSSIONResults and Discussion	50
APPENDIX E. ADDITIONAL WORK CITED.....	56
APPENDIX F. ADDITIONAL FIGURES.....	60
CHAPTER 2: Predictive Models.....	67
ABSTRACT.....	68
INTRODUCTION.....	69
MATERIALS AND METHODS	71
RESULTS	75
DISCUSSION	76
CONCLUSION.....	78
WORK CITED.....	79
APPENDIX A. TABLES	85
APPENDIX B. FIGURES.....	89
CONCLUSIONS	93
VITA	95

LIST OF TABLES

TABLE 1- 1. REGRESSION ANALYSES OF GREEN TURFGRASS COVER IN RESPONSE TO TRAFFIC EVENTS FOR HYBRID BERMUDAGRASS [<i>CYNODON DACTYLON</i> (L.) PERS. X <i>C. TRANSVAALENSIS</i> , BURTT-DAVY, ‘TIFWAY’] ESTABLISHED ON A SILT LOAM SOIL (A) AND ON USGA SAND ROOT ZONE (B). FIFTY TRAFFIC EVENTS WERE APPLIED OVER 10 WEEKS (5 PER WEEK) ACROSS FOUR SOIL WATER CONTENTS DURING FALL 2014 AND 2015 IN KNOXVILLE, TN.....	41
TABLE 1- 2. REGRESSION ANALYSES OF TURFGRASS SHEAR STRENGTH IN RESPONSE TO TRAFFIC EVENTS FOR HYBRID BERMUDAGRASS [<i>CYNODON DACTYLON</i> (L.) PERS. X <i>C. TRANSVAALENSIS</i> , BURTT-DAVY, ‘TIFWAY’] ESTABLISHED ON A SILT LOAM SOIL. FIFTY TRAFFIC EVENTS WERE APPLIED OVER 10 WEEKS (5 PER WEEK) ACROSS FOUR SOIL WATER CONTENTS DURING FALL 2014 AND 2015 IN KNOXVILLE, TN.	42
TABLE 2- 1. VARIABLES EVALUATED FOR MODEL CONSTRUCTION TO PREDICT GREEN TURFGRASS COVER WHEN SUBJECTED TO TRAFFIC ON HYBRID BERMUDAGRASS [<i>CYNODON DACTYLON</i> (L.) PERS. X <i>C. TRANSVAALENSIS</i> BURTT DAVY, ‘TIFWAY’] ESTABLISHED ON SILT LOAM SOIL AND SAND CONFORMING TO UNITED STATES GOLF ASSOCIATION SPECIFICATIONS. FIFTY TRAFFIC EVENTS WERE APPLIED OVER 10 WEEKS (5 PER WEEK) ACROSS FOUR SOIL WATER CONTENTS (LOW = 0.10, MEDIUM = 0.17, MEDIUM-HIGH = 0.26, AND HIGH = 0.35 M ³ /M ³) FOR SILT LOAM ROOT ZONE AND THREE WATER CONTENTS (LOW = 0.08, MEDIUM = 0.16, AND HIGH = 0.25 M ³ /M ³) FOR SAND ROOT ZONE DURING FALL 2014 AND 2015 IN KNOXVILLE, TN.....	86
TABLE 2- 2. MODELS AND COEFFICIENTS OF DETERMINATION (R ²), AKAIKE’S AN INFORMATION CRITERION (AIC), AND LEAVE-ONE-OUT CROSS-VALIDATION COEFFICIENT OF DETERMINATION (CROSS R ²) EVALUATED FOR USE TO PREDICT GREEN TURFGRASS COVER	

LOSS IN RESPONSE TO SOIL WATER CONTENTS ACROSS TRAFFIC EVENTS APPLIED TO
HYBRID BERMUDAGRASS [*CYNODON DACTYLON* (L.) PERS. X *C. TRANSVAALENSIS* BURTT
DAVY, ‘TIFWAY’] ESTABLISHED ON SILT LOAM SOIL. FIFTY TRAFFIC EVENTS WERE APPLIED
OVER 10 WEEKS (5 PER WEEK) ACROSS FOUR SOIL WATER CONTENTS (LOW = 0.10, MEDIUM =
0.17, MEDIUM-HIGH = 0.26, AND HIGH = 0.35 M³/M³) DURING FALL 2014 AND 2015 IN
KNOXVILLE, TN. 86

TABLE 2- 3. MODELS AND COEFFICIENTS OF DETERMINATION (R²), AKAIKE’S AN INFORMATION
CRITERION (AIC), AND LEAVE-ONE-OUT CROSS-VALIDATION COEFFICIENT OF
DETERMINATION (CROSS R²) EVALUATED TO PREDICT GREEN TURFGRASS COVER IN
RESPONSE TO SOIL WATER CONTENTS ACROSS TRAFFIC EVENTS APPLIED TO HYBRID
BERMUDAGRASS [*CYNODON DACTYLON* (L.) PERS. X *C. TRANSVAALENSIS* BURTT DAVY,
‘TIFWAY’] ESTABLISHED SAND ROOT ZONE MEETING USGA SPECIFICATIONS. FIFTY TRAFFIC
EVENTS WERE APPLIED OVER 10 WEEKS (5 PER WEEK) ACROSS THREE WATER CONTENTS
(LOW = 0.08, MEDIUM = 0.16, AND HIGH = 0.25 M³/M³) DURING FALL 2014 AND 2015 IN
KNOXVILLE, TN. 87

LIST OF FIGURES

FIGURE 1- 1. GREEN TURFGRASS COVER CHANGES IN RESPONSE TO SOIL WATER CONTENTS

ACROSS TRAFFIC EVENTS APPLIED TO HYBRID BERMUDAGRASS [*CYNODON DACTYLON* (L.) PERS. X *C. TRANSVAALENSIS* BURTT DAVY, ‘TIFWAY’] ESTABLISHED ON (A) SILT LOAM SOIL AND (B) SAND MEETING USGA SPECIFICATION ROOT ZONE. FIFTY TRAFFIC EVENTS WERE APPLIED OVER 10 WEEKS (5 PER WEEK) ACROSS FOUR SOIL WATER CONTENTS (LOW = 0.10, MEDIUM = 0.17, MEDIUM-HIGH = 0.26, AND HIGH = 0.35 M³/M³) FOR A AND THREE WATER CONTENTS (LOW = 0.08, MEDIUM = 0.16, AND HIGH = 0.25 M³/M³) FOR B DURING FALL 2014 AND 2015 IN KNOXVILLE, TN.....44

FIGURE 1- 2. SURFACE HARDNESS (G_{MAX}) CHANGES IN RESPONSE TO SOIL WATER CONTENTS

ACROSS TRAFFIC EVENTS APPLIED TO HYBRID BERMUDAGRASS [*CYNODON DACTYLON* (L.) PERS. X *C. TRANSVAALENSIS* BURTT DAVY, ‘TIFWAY’] ESTABLISHED ON (A) SILT LOAM SOIL AND (B) SAND MEETING USGA SPECIFICATION ROOT ZONE. FIFTY TRAFFIC EVENTS WERE APPLIED OVER 10 WEEKS (5 PER WEEK) ACROSS FOUR SOIL WATER CONTENTS (LOW = 0.10, MEDIUM = 0.17, MEDIUM-HIGH = 0.26, AND HIGH = 0.35 M³/M³) FOR A AND THREE WATER CONTENTS (LOW = 0.08, MEDIUM = 0.16, AND HIGH = 0.25 M³/M³) FOR B DURING FALL 2014 AND 2015 IN KNOXVILLE, TN.....45

FIGURE 1- 3. SOIL BULK DENSITY (G CM⁻³) DIFFERENCES FOR SOIL WATER CONTENTS (LOW = 0.10,

MEDIUM = 0.17, MEDIUM-HIGH = 0.26, AND HIGH = 0.35 M³/M³) APPLIED TO TRAFFICKED HYBRID BERMUDAGRASS [*CYNODON DACTYLON* (L.) PERS. X *C. TRANSVAALENSIS* BURTT DAVY, ‘TIFWAY’] ESTABLISHED ON A SILT LOAM SOIL. FIFTY TRAFFIC EVENTS WERE APPLIED OVER 10 WEEKS (5 PER WEEK) ACROSS FOUR SOIL WATER CONTENTS DURING FALL 2014 AND 2015 IN KNOXVILLE, TN.. 46

FIGURE 1- 4. SHEAR STRENGTH DIFFERENCES IN HYBRID BERMUDAGRASS [*CYNODON DACTYLON*

(L.) PERS. X *C. TRANSVAALENSIS* BURTT DAVY, ‘TIFWAY’] ATHLETIC FIELD ESTABLISHED ON

A SILT LOAM SOIL SHEAR STRENGTH (N-M) ACROSS 50 TRAFFIC EVENTS (5 PER WEEK) WITH VARYING LEVELS OF SOIL WATER CONTENT (LOW = 0.10, MEDIUM = 0.17, MEDIUM-HIGH = 0.26, AND HIGH = 0.35 M ³ /M ³) DURING FALL 2014 AND 2015 IN KNOXVILLE, TN. ERROR BARS REPRESENT FISHER’S LSD VALUES AT A < 0.05 WITHIN EACH TRAFFIC EVENT.....	47
FIGURE 1- 5. INFILTRATION RATE (DOUBLE RING INFILTROMETER) DIFFERENCES ON HYBRID BERMUDAGRASS [<i>CYNODON DACTYLON</i> (L.) PERS. X <i>C. TRANSVAALENSIS</i> BURTT DAVY, ‘TIFWAY’] ATHLETIC FIELDS ESTABLISHED ON SILT LOAM SOIL WITH POOLED DATA FROM VARYING SOIL WATER CONTENTS PRIOR TO AND AFTER THE CONCLUSION OF 50 TRAFFIC EVENTS DURING FALL 2014 AND 2015 IN KNOXVILLE, TN.....	61
FIGURE 1- 6. LEAF TEXTURE DIFFERENCES ON HYBRID BERMUDAGRASS [<i>CYNODON DACTYLON</i> (L.) PERS. X <i>C. TRANSVAALENSIS</i> BURTT DAVY, ‘TIFWAY’] ATHLETIC FIELDS ESTABLISHED ON SILT LOAM SOIL WITH POOLED DATA FROM VARYING SOIL WATER CONTENTS PRIOR TO AND AFTER THE CONCLUSION OF 50 TRAFFIC EVENTS DURING FALL 2014 AND 2015 IN KNOXVILLE, TN.. ..	62
FIGURE 1- 7. CLIPPING COLLECTION DIFFERENCES ON A HYBRID BERMUDAGRASS [<i>CYNODON DACTYLON</i> (L.) PERS. X <i>C. TRANSVAALENSIS</i> BURTT DAVY, ‘TIFWAY’] ATHLETIC FIELD ESTABLISHED ON SILT LOAM SOIL WITH POOLED DATA FROM VARYING SOIL WATER CONTENTS AT 0, 25, AND 50 TRAFFIC EVENTS DURING FALL 2014 AND 2015 IN KNOXVILLE, TN.....	63
FIGURE 1- 8. INFILTRATION RATE (DOUBLE RING INFILTROMETER) DIFFERENCES ON HYBRID BERMUDAGRASS [<i>CYNODON DACTYLON</i> (L.) PERS. X <i>C. TRANSVAALENSIS</i> BURTT DAVY, ‘TIFWAY’] ATHLETIC FIELDS ESTABLISHED ON SAND ROOT ZONE CONFORMING TO USGA SPECIFICATIONS WITH POOLED DATA FROM VARYING SOIL WATER CONTENTS PRIOR TO	

AND AFTER THE CONCLUSION OF 50 TRAFFIC EVENTS DURING FALL 2014 AND 2015 IN KNOXVILLE, TN	64
FIGURE 1- 9. LEAF TEXTURE DIFFERENCES ON HYBRID BERMUDAGRASS [<i>CYNODON DACTYLON</i> (L.) PERS. X <i>C. TRANSVAALENSIS</i> BURTT DAVY, ‘TIFWAY’] ATHLETIC FIELDS ESTABLISHED ON SAND ROOT ZONE CONFORMING TO USGA SPECIFICATIONS WITH POOLED DATA FROM VARYING SOIL WATER CONTENTS PRIOR TO AND AFTER THE CONCLUSION OF 50 TRAFFIC EVENTS DURING FALL 2014 AND 2015 IN KNOXVILLE, TN.....	65
FIGURE 1- 10. CLIPPING COLLECTION DIFFERENCES ON HYBRID BERMUDAGRASS [<i>CYNODON DACTYLON</i> (L.) PERS. X <i>C. TRANSVAALENSIS</i> BURTT DAVY, ‘TIFWAY’] ATHLETIC FIELDS ESTABLISHED ON SAND ROOT ZONE CONFORMING TO USGA SPECIFICATIONS WITH POOLED DATA FROM VARYING SOIL WATER CONTENTS AT 0, 25, AND 50 TRAFFIC EVENTS DURING FALL 2014 AND 2015 IN KNOXVILLE, TN.	66
FIGURE 2-1. PLOTS TO DETERMINE BEST FIT FOR THE PREDICTIVE MODEL OF LOSS OF GREEN TURFGRASS COVER CHANGES IN RESPONSE TO SOIL WATER CONTENTS ACROSS TRAFFIC EVENTS APPLIED TO HYBRID BERMUDAGRASS [<i>CYNODON DACTYLON</i> (L.) PERS. X <i>C. TRANSVAALENSIS</i> BURTT DAVY, ‘TIFWAY’] ESTABLISHED ON A SILT LOAM SOIL. FIFTY TRAFFIC EVENTS WERE APPLIED OVER 10 WEEKS (5 PER WEEK) ACROSS FOUR SOIL WATER CONTENTS (LOW = 0.10, MEDIUM = 0.17, MEDIUM-HIGH = 0.26, AND HIGH = 0.35 M ³ /M ³) DURING FALL 2014 AND 2015 IN KNOXVILLE, TN.	90
FIGURE 2-2. PLOTS TO DETERMINE BEST FIT FOR THE PREDICTIVE MODEL OF LOSS OF GREEN TURFGRASS COVER CHANGES DUE IN RESPONSE TO SOIL WATER CONTENTS ACROSS TRAFFIC EVENTS APPLIED TO HYBRID BERMUDAGRASS [<i>CYNODON DACTYLON</i> (L.) PERS. X <i>C. TRANSVAALENSIS</i> BURTT DAVY, ‘TIFWAY’] ESTABLISHED ON A SAND ROOT ZONE MEETING	

USGA SPECIFICATIONS. FIFTY TRAFFIC EVENTS WERE APPLIED OVER 10 WEEKS (5 PER WEEK) ACROSS THREE WATER CONTENTS (LOW = 0.08, MEDIUM = 0.16, AND HIGH = 0.25 M³/M³) DURING FALL 2014 AND 2015 IN KNOXVILLE, TN.....91

FIGURE 2-3. PREDICTED VERSUS ACTUAL CHANGES IN GREEN TURFGRASS COVER IN RESPONSE TO SOIL WATER CONTENT (A = 0.17 M³/M³, B = 0.16 M³/M³) ACROSS TRAFFIC EVENTS APPLIED TO HYBRID BERMUDAGRASS [*CYNODON DACTYLON* (L.) PERS. X *C. TRANSVAALENSIS* BURTT DAVY, ‘TIFWAY’] ESTABLISHED ON (A) SILT LOAM SOIL AND (B) SAND MEETING USGA SPECIFICATION ROOT ZONE. FIFTY TRAFFIC EVENTS WERE APPLIED OVER 10 WEEKS (5 PER WEEK) DURING FALL 2014 AND 2015 IN KNOXVILLE, TN.....92

INTRODUCTION

BACKGROUND

Nearly 38 million children and adolescents participate in organized sports on lower input high school or municipal fields annually (NIH, 2009). From 1990 to 2003, 1,597,528 injuries occurred on natural grass athletic fields, 50% of which were strains of the wrist, ankle, and knee (Leininger et al., 2007). A survey of high school football injuries in Pennsylvania found that up to 21% of sports related injuries were likely linked to the surface condition of the athletic field (Harper et al., 1984). Due to the vast amount of injuries that take place on athletic fields, surface consistency is key in maintaining field safety. As the number of sporting events increase, the amount of traffic is magnified, creating worn areas (Carrow and Petrovic, 1992).

In the transition zone, bermudagrass (*Cynodon* spp.) is the most commonly used turfgrass on athletic fields due to its superior recuperative potential and summer heat tolerance compared to other species (Christians, 2004). One of the most popular bermudagrass varieties for athletic fields is 'Tifway' hybrid bermudagrass [*C. dactylon* (L.) Pers. x *C. transvaalensis* Burt-Davy, 'Tifway'] because of its fine leaf texture, dense cover, and superior wear tolerance compared to other cultivars of bermudagrass (Thoms et al., 2011; Brosnan and Deputy, 2009; Goddard et al., 2008; Trenholm et al., 2000; Younger, 1958).

COHESIVE ROOT ZONE ATHLETIC FIELDS

According to the Sports Turf Managers Association, there are greater than 40,000 athletic fields in the United States (U.S; Campbell, 2004). Many of these athletic fields are constructed on the existing soils, which can result in large variations of soil physical properties within the same field, making drainage rates and water holding capacity variable (Bigelow and Soldat, 2013). While there are a large variety of native soils found across the U.S., silt loam soils are

common in the east Tennessee with a wide breadth of uses from agriculture to athletic fields. The inherently slow infiltration rates of cohesive soils can be problematic when precipitation occurs prior to athletic events. Silt loam soils are higher in silt and clay (minimum 50%) content than constructed sand ($\leq 5\%$ silt and clay) root zones, resulting in higher soil water content (SWC) and lower infiltration rates (Pitt et al., 2008). Soils high in SWC have decreases in viscosity, shear modulus, and yield stress, limiting the stability of the soil thereby decreasing the playability of the surface (Ghezzehei and Or, 2001). The microrheological properties of a soil system determine the relationship of water within a soil. Soils containing high amounts of silt and clay are significantly affected by water content because of weak cohesive forces between water molecules and water acting as a lubricant decreasing solid-solid friction (Israelachvili and Adams, 1964; Schoen et al., 1987). The amount of SWC in the soil is critical in managing the surface playing conditions of a native soil athletic field to provide a safe and consistent playing surface.

Soil water content was demonstrated to have a significant effect on green turf cover (GTC) as a study looking at three varieties of bermudagrass [*Cynodon* spp.] under elevated SWC lost more GTC in response to traffic compared to than those with lower SWC (Carrow et al., 2001). Similar to work conducted by Carrow, Minner and Valverde (2004) found that high SWC induced greater GTC loss (compared to low SWC) for Kentucky bluegrass [*Poa pratensis* (L.)] on a loam soil. However, none of the aforementioned studies investigated soil physical properties known to affect water holding capacity as well as soil strength.

NON-COHESIVE ROOT ZONE ATHLETIC FIELDS

There has been a history of sand root zones (> 80% v/v) in the turf industry utilizing varying methods and designs (Bigelow and Soldat, 2013). Two of the primary sand root zones follow either the California or the United States Golf Association (USGA) method (Davis et al., 1990; USGA Green Section Staff, 2007). The USGA method was originally designed for golf greens (USGA Green Section Staff, 2007). Some of the differences between the two methods are the California method uses a slightly finer texture sand, but does not have a 100 mm gravel blanket, and the root zone is not amended with a peat moss like the USGA (Davis et al., 1990; USGA Green Section Staff, 2007; Bigelow and Soldat, 2013).

While the USGA and California method were originally developed for golf course greens, athletic fields also have specific system designs. In the 1970's, the Prescription Athletic Field (PAT) system was developed at Purdue University (Daniels, 1972). The distinctive characteristic of this method is the ability to fluctuate the SWC content above the soil barrier by pumping water in or out of a grid piping system (Daniels, 1972). The PAT method can draw water down through the sand or pump water in through drainage lines (Daniels, 1972). This method addresses the problem of SWC management in a sand root zone. The American Society for Testing Materials also developed a standard (F2396-04) guide for construction of high performance sand root zones for sports fields to provide a better sand athletic field (ASTM, 2004). The ASTM standard for athletic fields allow for more large sand particles (> 2.0 mm) than USGA root zones in an effort to provide greater stability for a root zone under athlete traffic (ASTM, 2004). Even with the development of sports specific guidelines and standards, the USGA method for sand root zone construction is still one of the most popular methods for athletic fields.

The United States Golf Association (USGA) specifications for constructing sand root zones are popular throughout the turfgrass industry (Bigelow and Soldat, 2013; USGA Green Section Staff, 2007). Originally, the USGA specifications were designed for golf course putting greens, but use has expanded to other areas in the turfgrass industry including athletic fields (Bigelow and Soldat, 2013; USGA Green Section Staff, 2007). In fact, many collegiate and professional football fields are constructed on root zones conforming to USGA specifications.

Due to the economic importance of avoiding event cancellations, many athletic fields are established on constructed sand root zones for rapid drainage compared to soils containing more than 20% silt and clay (Brockhoff et al., 2010). Sands have been used as the primary component of high performance root zones because of its high particle stability, availability, and ability to maintain a point of maximum bulk density when compacted (Bigelow and Soldat, 2013). The particle size distribution of constructed sand root zones provides optimal drainage and stability making it the main reason for the popularity of the USGA specification root zone (Bigelow and Soldat, 2013). Constructed sand root zones maintain air-filled porosity and drainage from compaction due to traffic (Bingaman and Kohnke, 1970). In a study evaluating the traffic tolerance of hybrid bermudagrass athletic fields established on varying root zones, Thoms et al. (2016) found that USGA sand root zones required eight additional traffic events to reach 50% GTC compared to native soil root zones (Thoms et al., 2016). Unfortunately, the significant costs of construction of USGA specification root zones have prevented the widespread adoption throughout the athletic field industry (STMA, 2008).

While there are many advantages of having a sand root zone for an athletic field, there are still issues that can arise. Improper graduation of sand root zones can result in lack of particle stability creating an insecure surface (Adams, 1982). Additionally, factors such as low buffering

capacities, soil moisture, CEC, and surplus accumulations of organic matter can create instability when turf cover declines (Brady and Weil, 2001; Bigelow and Soldat, 2013). Loss of turf cover can result in poor traction and footing due to physical properties of the sand being less stable than native soils as well (Bigelow and Soldat, 2013).

ATHLETIC FIELD PERFORMANCE EVALUATIONS

One of the most important field evaluation parameters is the hardness of the surface. Surface hardness was first evaluated for athletic field performance by Rogers (1988) who reported an inverse relationship between surface hardness and SWC. In the absence of traffic, SWC and surface hardness were negatively correlated on a non-trafficked sand root zone (Li et al., 2009). A field study of 15 locations following sand and native soil root zones pitches in Europe determined that sand fields were more consistent compared to native soils (clay, clay loam, and sandy clay loam) across performance parameters including surface hardness, penetration resistance, and shear resistance under wet and dry conditions (Caple et al., 2012). Wet conditions resulted in a negative correlation with surface hardness, shear resistance, penetration resistance, and energy absorption throughout the season on sand as well as the native soils (Caple et al., 2012). These wet and dry conditions reported were the state of the field the day of testing; no SWC ranges was established for testing of different parameters (Caple et al., 2012). Sand root zone mixes containing 10 and 12% silt + clay at five percent SWC have been shown to increase soil strength over 100% compared to those with lower amounts of silt + clay (2, 5, 7, and 8%) (Henderson et al., 2005).

The measuring of surface hardness on athletic fields has become a popular method used to help determine overall safety. Surface hardness is measured in G_{MAX} (units of gravity), which

is the peak deceleration of an impact missile released onto a surface (Clegg, 1976). A study performed by Twomey et al. (2012) determined surface hardness above 120 or below 50 G_{MAX} as measured by a Clegg Impact Tester (CIT) related to an increased number of soft tissue injuries for professional rugby athletes. Rogers and Waddington (1990) found that surface hardness was reduced most by SWC on Kentucky bluegrass and tall fescue established on a silt loam root zone. Other studies have found negative correlations between surface hardness and SWC for both sand and native soil athletic fields (Berlie et al., 2004; Caple et al., 2012). While SWC is one of the factors that affect surface hardness, soil bulk density can influence surface hardness as well. Traffic events and increased SWC increase soil bulk density, which coincides with increases in surface hardness (Canaway, 1978; Vanini et al., 2007; Kowalewski et al., 2013).

Increased in soil bulk density not only impact surface hardness but also have a detrimental effect on GTC. A study on Kentucky bluegrass [*Poa pratensis* L.], perennial ryegrass [*Lolium perenne* L.], and tall fescue [*Festuca arundinacea*, Schreber] found negative correlations between soil bulk density and percent turf cover when turf was subjected to compaction treatments (Carrow, 1980). As application of treatments increased, an increase in soil bulk density was observed (Carrow, 1980). On hybrid bermudagrass, Kowalewski et al. (2013) found that four traffic events per week caused a nine percent increase in soil bulk density and a 30% decrease in GTC compared to two traffic events per week. However, not all of the decrease in GTC from trafficking can be attributed to increases in soil bulk density. The mechanical pressure, abrasion, scuffing, tearing, and divoting caused by the trafficker adds to the reduction in GTC (Rogers and Waddington, 1990; Carrow and Petrovic, 1992; Dest et al., 2009).

Air-filled porosity of a soil has an inverse relationship with soil bulk density under traffic. The loss of soil air-filled porosity associated with compaction reduces gas exchange,

water movement, and rooting (Carrow et al., 2001). A study performed on Kentucky bluegrass subjected to traffic found that air-filled porosity decreased while soil bulk density increased as the turf was subjected to increasing amounts of traffic on a loam soil (Vanini et al., 2007). A study looking at three turfgrass species (Kentucky bluegrass, perennial ryegrass, and tall fescue) on silt loam soil subjected to roller compaction found decreased air-filled porosity of the soil in response to increased soil bulk density (Carrow, 1980). On seven different varieties of seashore paspalum and three varieties of hybrid bermudagrass, traffic decreased air-filled porosity of the sandy loam soil (Carrow et al., 2001).

The trend of decreased air-filled porosity is consistent for both cool and warm season grasses across native soils. However, water-filled porosity of a soil is much less prone to change in relation to compaction. There were no changes in water-filled porosity of a silt loam soil with bermudagrass when subjected to traffic due to the increased strength of the pores ability to withstand traffic (Goddard et al., 2008). A study looking at compaction of loamy sand soil with four grass species (tall fescue, fine fescue [*Festuca rubra*], Kentucky bluegrass, and perennial ryegrass) found no changes in water-filled porosity even though air-filled pores decreased (Głąb and Szewczyk, 2014). Also, on Kentucky bluegrass overseeded with perennial ryegrass subjected to traffic with six different fertility management regimes, no difference in water-filled porosity were observed (Miller and Henderson, 2013).

The presence of organic matter has numerous positive benefits including increasing cation exchange capacity and water holding capabilities of a soil and improving wear tolerance of turf (White and Dickens, 1984; Barton et al., 2009; McCarty et al., 2007). Few differences have been observed in organic matter content when subjected to traffic in both cool and warm season grasses. Kentucky bluegrass and perennial ryegrass subjected to traffic demonstrated no

difference in organic matter from initiation to completion of simulated traffic (Dest et al., 2009). A study on hybrid bermudagrass with a silt loam root zone in Tennessee and Arkansas found traffic to have no impact on soil organic matter content (Goddard et al., 2008). While previous studies looked at the impact of traffic on organic matter content, few turf studies have investigated the combined effect of SWC and traffic on reductions or gains in organic matter.

Outside of the soil texture differences between silt loam and constructed sand root zones, infiltration can also be reduced by compaction, with traffic negatively affecting both parameters (Morgan et al, 1966; Gregory et al., 2006; Unger and Kaspar, 1994). On both Kentucky bluegrass and perennial ryegrass on a silt loam soil, infiltration was 12.2 cm/hr less in compacted compared with non-compacted plots (Dest et al., 2009). Henderson et al. (2005) found that infiltration rates of seven different root zone mixes decreased in relation to applied traffic for Kentucky bluegrass. However, Goddard et al., (2008) found increases in compaction on hybrid bermudagrass on a silt loam root zone did not change infiltration rates.

The shear strength, of a turf athletic field, is affected by soil water content, infiltration rate, turfgrass species, soil type, and turfgrass density (Rogers et al., 1998; Anderson et al., 2015). Shear strength of a turfgrass system is crucial for playability as forces up to 13 kN can be experienced during play (Anderson et al., 2015), and reductions of shear strength have been demonstrated for multiple turfgrass species when subjected to traffic (Rogers and Waddington, 1990; Stier and Rogers, 2001; Vanini et al., 2007; Anderson et al., 2015). On Kentucky bluegrass and tall fescue, differences in shear strength between the two species and over time was related to SWC (Rogers and Waddington, 1990). However, Anderson et al. (2015) attributed differences in shear strength among rugby pitches to variability in both soil moisture and soil

type. Effects of SWC on athletic fields established on different root zones under traffic have not been evaluated.

PREDICTIVE MODELS

Predictive modeling is defined as an analytical process used to predict future behavior based on past behavior and other parameters (Geisser, 1993). There are a wide variety of models used in turfgrass management, ranging from growing degree days to predict smooth crabgrass [*Digitaria ischaemum* (Schreber) Schreber ex Muhlenb.] emergence, to using temperature and leaf wetness duration to predict grey leaf spot [*Pyricularia grisea*] incidence on perennial ryegrass (Uddin et al., 2003; Fidanza et al., 1996). Soil science also uses models of particle-size distribution, soil bulk density, and particle density to predict soil moisture characteristics or soil strength (measured using a force transducer and amplifier-indicator) to predict root growth (Arya and Paris, 1981; Gerard et al., 1982). Currently, there models to predict GTC loss on athletic fields due to changes in SWC and traffic events. However, several studies have indicated that SWC impacts GTC when subjected to traffic, leading to the conclusion that a predictive model could be constructed to explain the relationship (Carrow et al., 2001; Thoms et al., 2016). Developing a predictive model for GTC loss due to SWC and traffic events would enable game administrators to make a choice of postponement or play based on scientific data.

Previous research has indicated a relationship between SWC and wear tolerance of turf used for athletic surfaces. However, beyond that relationship, very little work has investigated the other parameters involved in the SWC and GTC relationship including soil physical properties as well as athletic surface performance characteristics. Therefore, it was the objective of this research to determine the impact of SWC on the performance of hybrid bermudagrass on

cohesive and USGA specified root zones when subjected to traffic. Additionally, considering the proven relationship between SWC and wear tolerance, this research intended to create predictive models to calculate GTC based on soil physical properties, traffic levels, and surface performance.

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**CHAPTER 1: Impact of Soil Water Content on Hybrid Bermudagrass Athletic Field
Performance**

Impact of Soil Water Content on Hybrid Bermudagrass Athletic Field Performance

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My primary contributions to this paper include (i) discovering the concept (ii) designing and conducting the experiments, (iii) processing, analyzing and interpreting data, (iv) reading literature, (v) writing the manuscript

ABSTRACT

Soil water content (SWC) influences the consistency and performance of athletic field surfaces. Two studies were conducted at the University of Tennessee Center for Athletic Field Safety (Knoxville, TN) to determine how SWC affects wear tolerance of hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. x *C. transvaalensis*, Burt-Davy, 'Tifway'] on root zones comprised of either silt loam (cohesive) or sand meeting USGA specifications (non-cohesive). Soil water content treatments for cohesive root zones averaged 0.10 m³/m³ (+/- 0.035), 0.17 m³/m³ (+/- 0.035), 0.26 m³/m³ (+/- 0.035), and 0.35 m³/m³ (+/- 0.005); comparatively, SWC on non-cohesive averaged 0.08 m³/m³ (+/- 0.03), 0.16 m³/m³ (+/- 0.03), and 0.25 m³/m³ (+/- 0.05). Plots were subjected to 50 traffic events annually with the Baldree traffic simulator. Green turfgrass cover (GTC) was reduced four times faster at 0.35 m³/m³ SWC than the 0.10 m³/m³ and 0.17 m³/m³ SWC treatments on cohesive soil. All SWC treatments on non-cohesive lost GTC at a similar rate. Surface hardness increased as SWC decreased for both root zones, while a minimum surface hardness of 50 G_{MAX} is suggested for optimal athletic field performance based on the combined impact GTC and shear strength values. Turfgrass shear strength decreased with traffic for all treatments on cohesive soils, particularly at 0.35 m³/m³ SWC. Soil water content of

non-cohesive did not compound the effect of traffic on turfgrass shear strength. The optimal mean SWC ranges to maximize hybrid bermudagrass wear tolerance on cohesive soils were 0.10 m³/m³ to 0.17 m³/m³, and 0.08 m³/m³ to 0.16 m³/m³ on non-cohesive soils.

INTRODUCTION

There are greater than 2.7 million ha⁻¹ of athletic fields in the United States (U.S.) ranging from local parks and recreational fields to professional stadiums (STMA, 2003). In the U.S., over 40 million athletes participate in organized sports annually (Micheli, 2000). Annual medical expenses for sports related injuries were estimated to be over \$1.3 billion (Hergenroeder, 1998). A survey of high school football injuries in Pennsylvania found that up to 21% of sports related injuries could have been linked to surface conditions of athletic fields (Harper et al., 1984). Surface consistency is key for reducing injuries. However, accumulation of traffic events creates inconsistent surfaces as a result of wear (Carrow and Petrovic, 1992).

Many athletic fields in the U.S. are built with native soils compared to constructed sand root zones such as those developed according to the United States Golf Association (USGA; USGA Green Section Staff, 2007). Native soils high in silt and clay tend to have greater soil water contents (SWC) and slower water infiltration rates compared to constructed sand root zones (Pitt et al., 2008). The inherently slow water infiltration rates of cohesive soils (i.e., non-sand soils) are potentially problematic when precipitation occurs prior to athletic events. Cohesive soils with SWC are subject to extreme decreases in viscosity, shear modulus, and yield stress, compromising soil stability and decreasing playability (Ghezzehei and Or, 2001). Soils containing high amounts of silt and clay are significantly affected by water content because water acts as a lubricant decreasing solid-solid friction (Israelachvili and Adams, 1978; Schoen et al., 1987). The Atterberg limits of a soil define changes in soil behavior and consistency

depending on SWC; as SWC increases the consistency of a soil changes from a semi-solid to plastic, and then to a liquid state (Dolinar et al., 2007). The amount of SWC in cohesive soils is critical to provide safe and consistent playing surfaces.

It has been reported that cohesive soil athletic fields with high SWC tend to lose green turfgrass cover (GTC) faster than those with low SWC. Carrow et al. (2001) found greater loss of GTC in seashore paspalum [*Paspalum vaginatum* (Swartz)] and hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. x *C. transvaalensis* (Burt-Davy)] when SWC neared saturation compared to field capacity. Similarly, Minner and Valverde (2004) reported 30% greater GTC loss on Kentucky bluegrass [*Poa pratensis* (L.)] when subjected to traffic and SWC neared saturation. Over a two-year period, Roche et al. (2009) observed that natural rain events occurring immediately before professional soccer games in England resulted in greater GTC loss, likely due to increases in SWC. While previous studies established a greater loss of GTC with increased SWC, neither soil physical properties nor shear resistance were measured. Dest et al. (2005) found constructed sand root zones provided improved wear tolerance and better surface playing conditions compared to cohesive soils, while noting a difference in SWC.

Constructed sand root zones are used on many U.S. collegiate and professional football fields. Sand root zones are preferred because of consistent air-filled porosity, rapid drainage, and compaction resistance which help avoid rain delays or cancellations (Bingaman and Kohnke, 1970; Bigelow and Soldat, 2013; Brockhoff et al., 2010). While multiple types of constructed sand root zones exist, the USGA specification is the most common for high end athletic fields because the well graded particle size distribution provides acceptable stability and optimal drainage (Bigelow and Soldat, 2013). However, sand root zones are not used on all athletic fields due to high construction costs (STMA, 2008).

Field performance is a function of GTC, shear strength, and surface hardness, with changes in these parameters affecting both safety and playability. Green turfgrass cover is simply a measure of how much of the playing surface is covered with turfgrass (Richardson et al., 2001). Shear strength measures the stability of the foot when making a horizontal change of direction on the playing surface (Rogers et al., 1998). Surface hardness can be used to evaluate the potential for player injury and is affected by both the root zone and the condition of turf (Twomey et al., 2012; Bradley, 2014). High SWC conditions have been negatively correlated with shear strength, surface hardness, penetration resistance, and energy absorption throughout the season on constructed sand root zones (Caple et al., 2012). Similarly, shear strength was reduced by additional SWC across different root zones (Rogers et al., 1998; Anderson et al., 2015).

Optimal ranges of SWC for hybrid bermudagrass athletic fields have yet to be determined. Soil water content interacts with other soil physical properties such as bulk density and water infiltration rate, which are known to influence wear tolerance and therefore GTC loss (Carrow et al., 2001; Goddard et al., 2008; Caple et al., 2012). The objective of this research was to determine the impact of SWC on the performance of hybrid bermudagrass on cohesive soil (silt loam) and non-cohesive (USGA specification) root zone when subjected to traffic. Our hypothesis was increases in SWC would result in increased soil compaction and greater loss of GTC from traffic events on cohesive root zones, while having minimal impact on non-cohesive soils.

MATERIALS AND METHODS

Two field studies were conducted from 2014-2015 at the University of Tennessee Center for Athletic Field Safety (Knoxville, TN) to determine SWC impact on compaction and loss of

GTC on ‘Tifway’ hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. x *C. transvaalensis*, Burt-Davy] established from sod in 2011. Study I was conducted using plots established on a Sequatchie silt loam soil (28% sand, 48% silt, and 24% clay) with a 6.2 soil pH, 9 mg kg⁻¹ initial phosphorous, 81 mg kg⁻¹ initial potassium, and 25 g kg⁻¹ organic matter content. Study II used plots established on a sand meeting USGA specifications (0.7% very coarse, 14.3% coarse, 61.4% medium, 18.1% fine, 5.1% very fine, and 0.4% silt and clay by weight) mixed with 20% (volume) reed sedge peat moss (United States Golf Association, 2007).

Granular urea (46 N - 0 P₂O₅ - 0 K₂O) was applied monthly at 49 kg N ha⁻¹, May through September, in both years of the study. During the growing season (May- October), plots were mown at 2.2 cm three times per week using a triplex reel mower (TriKing 1900D; Jacobsen, Charlotte, NC), with occasional mowing each November as needed. Clippings were returned to the surface while mowing. All plots were treated with oxadiazon (Ronstar 50WP, Bayer Environmental Sciences, Research Triangle Park, NC) at 3.4 kg ai ha⁻¹ on 24 February 2014 and 26 February 2015 to control summer annual weeds. Irrigation was applied May through July as needed to prevent drought stress. No irrigation was applied during August through November in 2014 and 2015, except for hand watering to keep SWC levels within desired treatment ranges. Water was applied to each experimental unit as needed based on the average of seven root zone moisture measurements (3.8 cm depth) collected daily using a handheld time domain reflectometer (TDR) probe (FieldScout 300 Probe, Spectrum Technologies, Inc. Plainfield, IL).

Study I had four soil moisture ranges selected from just above permanent wilting point (6%) to field capacity (40%) as determined using American Society for Testing Materials (ASTM) standard F1815-11 (ASTM, 2011). Soil water content treatments were: low (0.10 m³/m³ +/- 0.035), medium (0.17 m³/m³ +/- 0.035), medium-high (0.26 m³/m³ +/- 0.035), and high (0.35

$\text{m}^3/\text{m}^3 \pm 0.050$). Study II soil moisture ranges were selected similar to methods described for Study I, but ranges differed based on root zone construction. The non-cohesive root zone had three SWC treatment ranges: low ($0.08 \text{ m}^3/\text{m}^3 \pm 0.03$), medium ($0.16 \text{ m}^3/\text{m}^3 \pm 0.03$), and high ($0.25 \text{ m}^3/\text{m}^3 \pm 0.05$) throughout the study for both years. The experimental design for both studies was a randomized complete block with four replications and experimental unit (plot) dimensions were 2.0 m x 4.2 m with a boarder of 2.0 m between plots. Both studies were completed on unique plot areas each year within the same athletic field. For both studies, SWC was maintained 30 days prior to study initiation.

Traffic was applied to both studies using a self-propelled core aerifier (ProCore 648, Toro, Bloomington, MN) modified by replacing coring heads with six spring loaded metal plates topped with cap nuts (2.0 x 1.2 cm) similar to the Baldree Traffic Simulator (BTS) described by Kowalewski et al. (2013). One pass (traffic event) using our traffic simulator applied approximately 678 cleat marks per m^2 . This traffic is similar to the number of cleat marks that occur during one National Football League or intercollegiate football game on the highest wear area (Cockerham and Brinkman, 1989; Kowalewski et al., 2013). Traffic was applied 10 times per week (Monday thru Friday) from 15 September to 19 October 2014, and 14 September to 21 October 2015. Traffic rates and dates coincide with a typical high school football season in Knoxville, TN. Each plot received 50 traffic events each year.

In both studies, green turfgrass cover was quantified immediately after each traffic event in the fall using digital image analysis (DIA) methods of Dickson et al. (2017). Clipping were collected to quantify turfgrass growth and validate soil moisture treatments provided sufficient plant available water. Clippings were collected at 0, 25, and 50 traffic events each year following the methods of Easton and Petrovic (2004) using a Jacobsen 526A PG mower at 2.2 cm. Samples

were dried for 24 hours at 65 °C and weighed using a digital scale (Adventurer, Ohaus Corp, Pine Brook, NJ). A Clegg Impact Soil Tester (Lafayette Instrument Co., Lafayette, IN) with a 2.25 kg missile dropped from 46 cm was used to determine surface hardness after each traffic event based on the ASTM F1702-96 standard by collecting four test units from each experimental unit (ASTM, 2000). Turfgrass shear strength was collected after 0, 10, 20, 30, 40, and 50 traffic events from five locations within each plot using the shear vane apparatus (Turf-Tec Shear Strength Tester, Turf-Tec International, Tallahassee, FL) as described by Rogers et al. (1998).

Soil physical properties including soil bulk density, air-filled porosity, water-filled porosity, and organic matter content were measured on all plots. After every two traffic events, four soil cores (5 cm diameter, by 5 cm depth) were extracted from the interior of each experimental unit to determine soil bulk density following the methods of Grossman and Reinsch (2002). An additional four soil cores were extracted from each experimental unit after ten traffic events and analyzed for air-filled porosity (gravimetric), water-filled porosity (water-filled desorption), and soil organic matter content (loss on ignition) following methods described by Flint and Flint (2002).

Analyses of variance were conducted in SAS (v. 9.3; SAS Institute Inc., Cary, NC). Each study (i.e., cohesive and non-cohesive soil) was analyzed separately. No significant year-by-treatment interactions were detected; therefore, data from each year were pooled. Fisher's least significant difference (LSD) was used to separate means at $\alpha = 0.05$. The number of traffic events required to reduce GTC to 50% (Events₅₀) was calculated to determine the impact of soil moisture on traffic tolerance. Changes in GTC were analyzed using regression analyses in GraphPad Prism 6 (GraphPad Software; San Diego, CA) with non-linear models fitting data

from cohesive root zones and linear models best capturing responses on non-cohesive (i.e., sand) root zones.. Soil bulk density and air-filled porosity data were linear regressed over traffic events for both root zones as well. Correlations were calculated in GraphPad Prism 6.

RESULTS

Study I: Cohesive Root Zone

As traffic was applied, the low and medium SWC treatments retained GTC longer than the medium-high and high SWC treatments. Saturated soil conditions lost GTC approximately four times faster than the low or medium SWC and three times faster than medium-high SWC treatment (Table 1-1). These findings are supported by previous studies that reported accelerated GTC loss from traffic at greater SWC (Rogers and Waddington, 1989; Rogers and Waddington, 1992; Roche et al., 2009). Clipping yields were similar ($P \geq 0.05$) for all SWC treatments (data not shown) which indicated that low and medium SWC treatments provided sufficient plant available water for turfgrass growth.

Surface hardness varied across traffic events as a function of soil water content (Fig. 1-2). Traffic increased surface hardness at the low and medium SWC treatments, from 58 to 90 G_{MAX} and 51 to 68 G_{MAX} , respectively. This response was far more muted with the high SWC treatment as surface hardness values fell from 34 to 15 G_{MAX} , suggesting that elevated soil moisture had a more pronounced effect on surface hardness values than applied traffic. Surface hardness was minimally influenced by traffic at the medium-high SWC treatment as well.

Soil bulk density increased as a function of increasing soil water content or traffic. The medium-high and high SWC treatments had the greatest percentage (4% and 6%) increases in soil bulk density (Fig. 1-3). The low and medium SWC treatments had minimal (1%) increases

in soil bulk density. Regardless of SWC, soil bulk density increased as traffic events increased.

Linear regression of the rate of soil bulk density increase per traffic was as follows:

$$\text{soil bulk density} = (6.6 \times 10^{-3}) * \text{traffic events} + 1.5$$

the model was found to be significant ($\alpha \leq 0.001$). The increase in soil bulk density was due to compaction of the air-filled pore space of soil. A 9% increase in soil bulk density occurred between traffic event one and 50, regardless of SWC, with a commensurate decrease in air-filled porosity from 35% to 26%. The air-filled porosity model:

$$\text{air - filled porosity} = -0.4 * \text{traffic events} + 35.6$$

decreased ($\alpha \leq 0.001$) in a linear fashion as a function of traffic. Using a power roller to increase compaction, Carrow (1980) found a positive correlation between air-filled porosity and GTC with three cool season turfgrass species (Kentucky bluegrass, perennial ryegrass, and tall fescue) on a silt loam soil irrigated to saturation 24 hours prior to compaction. Our study further investigated different volumetric soil moisture ranges while applying traffic stress, which combines both wear and soil compaction (Carrow and Petrovic, 1992). Soil bulk density was negatively correlated with GTC ($r = -0.98$, $N = 1,200$) in the current study, supporting previous reports that losses in GTC were associated with changes in soil bulk density (Kowalewski et al., 2013). Increased soil bulk density can decrease rooting, water infiltration, clipping yields, and lower water holding capacities; all of which can lead to poor turfgrass growth (Carrow, 1980; Głab and Szewczyk, 2014). Our study is the first to state the rate of increase in soil bulk density, and air-filled porosity, on silt loam athletic fields due to traffic. Predictive models using this approach can be developed for other soil types.

A traffic event by SWC treatment interaction occurred for turfgrass shear strength. Shear strength declined most rapidly at the high SWC treatment, falling to below 10 Nm after the 10th traffic event (Fig. 1-4; Table 1-2). All other treatments maintained shear strength greater than 18 Nm throughout the study. A statistically significant ($P \leq 0.05$), but biologically trivial, interaction was detected once after the 40 traffic events (Fig. 1-4).

Study II: Non-Cohesive Root Zone

Soil water content treatments had little impact on the non-cohesive root zone when trafficked. The low, medium, and high SWC treatments maintained 50% GTC through 36 or 37 traffic events with the rate of GTC loss (measured as β_1 estimates) not significantly different from one another (Table 1-1).

Surface hardness values increased through 20 traffic events for the low SWC treatment (Fig. 1-2) on the non-cohesive root zone. The medium and high SWC treatments remained relatively unchanged not varying more than 8 G_{MAX} throughout the study compared to a variation of 15 G_{MAX} for the low SWC treatment. This contradicts previous research that reported a negative correlation between surface hardness and SWC for sand athletic fields (Caple et al., 2012).

Soil bulk density increased six percent after 50 traffic events, which was accompanied by a six percent decrease in air-filled porosity ($P < 0.001$). Linear models were fit to capture the rate of increase in soil bulk density was:

$$\text{soil bulk density} = (6.1 \times 10^{-3}) * \text{traffic events} + 1.5$$

and the rate of decrease of air filled porosity was:

$$\text{air-filled porosity} = -0.2 * \text{traffic events} + 32.3$$

in response to simulated traffic. A negative Pearson's correlation ($r = -0.98$, $N = 800$) occurred between GTC and soil bulk density values measured on the non-cohesive root zone, regardless of traffic level.

Turfgrass shear strength decreased in a linear fashion from 26.1 Nm to 17.1 Nm through 50 traffic events, regardless of SWC. Our model:

$$\text{shear strength} = -0.4 * \text{traffic events} + 26.23$$

predicted ($P \leq 0.001$) that hybrid bermudagrass on the non-cohesive root zone would decrease in shear strength 0.4 Nm per traffic event, regardless of SWC. Results suggest that shear strength values were not affected by SWC in the non-cohesive root zone. All treatments maintained acceptable bermudagrass shear strength (>18 Nm) when trafficked through 40 traffic events.

DISCUSSION

This study supported our hypothesis that increased SWC on cohesive soils resulted in greater loss of GTC when trafficked. Previous research found that increases in SWC on trafficked cool-season turfgrasses on cohesive root zones resulted in greater GTC loss (Minner and Valverde, 2004; Roche et al., 2009). Our data suggest that the optimum SWC range for hybrid bermudagrass traffic tolerance on cohesive root zones is 0.10 to 0.17 m^3/m^3 . It is plausible that the accelerated loss of GTC in the high SWC treatment was attributed to the Atterberg limit being reached (Dolinar et al., 2007). Green turfgrass cover was likely lost as a result of hybrid bermudagrass shearing injury. As SWC increased, the cohesive soil entered a liquid state, altering soil structure when a compressive force was applied, as indicated by shear strength and surface hardness data measured herein.

The low, medium, and medium-high SWC treatments behaved similarly to previous research on hybrid bermudagrass which found increases in surface hardness corresponded to higher soil bulk density from pre-trafficked values (Carrow et al., 2001; Goddard et al., 2008; Kowalewski et al., 2013). However at high SWC, changes in soil bulk density and surface hardness in response to traffic were less pronounced, likely due to soil reaching its Atterberg limit. Previous research identified differences in surface hardness between wet and dry soils (Rogers and Waddington, 1989; Rogers and Waddington, 1992; Carrow et al., 2001, Minner and Valverde, 2004); however, our research was the first to investigate SWC ranges in hybrid bermudagrass subjected to traffic. Additionally, our research is the first to investigate trafficking when plots were at field capacity. These findings indicate surface hardness of a field can be manipulated by adjusting SWC.

Cohesive soils, due to the higher quantities of silt and clay, are more responsive to increases in water content which decrease solid-solid friction (Israelachvili and Adams, 1978; Schoen et al., 1987). The regression analysis predicted the greatest slope of GTC at $0.34 \text{ m}^3/\text{m}^3$ SWC, which yielded surface hardness values $\leq 34 G_{\text{MAX}}$ and unacceptable shear strength throughout a majority of this study. Conversely, plots maintained at an optimal SWC (0.07 to $0.20 \text{ m}^3/\text{m}^3$) always yielded surface hardness values $\geq 50 G_{\text{MAX}}$ with acceptable shear strength ($\geq 18 \text{ Nm}$). This response is important considering that surface hardness values of 70 to $89 G_{\text{MAX}}$ have been identified as safest for reducing lower extremity injuries (Twomey et al., 2012). Based on the findings of this study, we suggest a minimum surface hardness value of $50 G_{\text{MAX}}$ to offer acceptable performance characteristics for hybrid bermudagrass fields established on cohesive soils. Future research is warranted to determine impact of SWC on fields established using different turfgrass species on root zones varying in silt and clay content.

The second part of our hypothesis was partially supported in that SWC had minimal impact on non-cohesive soils, affecting only surface hardness. The complete SWC range tested identified all SWC treatments as optimal for field performance parameters on non-cohesive soils. Thoms et al. (2016) suggested that addition moisture results in greater GTC retention on non-cohesive soils, but our findings indicated SWC had minimal effect under the conditions of this experiment, similar to previous reports (Rogers, 1988; McNitt and Landschoot, 2003; Henderson et al., 2005; Caple et al., 2012).

The high SWC treatment resulted in less than ideal surface hardness values, proving that over watering of non-cohesive root zones should be avoided. Previous studies have shown that rugby players prefer surfaces with hardness in the 50 to 100 G_{MAX} range, with the fewest injuries occurring on surfaces measuring 70 to 89 G_{MAX} in Australia rules football (McClements and Baker, 1994; Twomey et al., 2012). The high SWC treatment in cohesive soils produced G_{MAX} unacceptable values in both player preference and safety.

Previous research on cool-season grasses demonstrated that shear strength decreased as a result of traffic (Gibbs et al., 1989; Rogers and Waddington, 1989; Sorochan et al., 2001; Roche et al., 2007, Vanini et al., 2007). Our research indicated that bermudagrass performed similarly, but consistently maintained shear strength beyond the established minimum acceptable value (>10 Nm) excluding the high SWC in the cohesive root zone (Stier et al., 1999). The minimum limit established by Stier et al. (1999), defined when the turf that was easily torn from the soil and was determined to be unacceptable for sporting events. A study comparing the shear strength of bermudagrass and Kentucky bluegrass found that bermudagrass offered greater (8 Nm) shear strength (Goddard et al., 2008). We suggest that the threshold for hybrid bermudagrass be set at

18 Nm, because when turfgrass shear strength was below 18 Nm, similar poor conditions as described by Stier et al. (1999) occurred.

While Events₅₀ values were calculated to determine the loss of GTC in response to SWC and traffic, the authors are not implying that 50% GTC is acceptable. In this study 50% was selected as the worst case for low input athletic fields (i.e., parks, recreation, etc). The authors are aware that 80% or higher could be the minimum acceptable limit for some professional athletic fields. No GTC threshold could be found in the literature for athletic fields regardless of maintenance level. Future research should survey field managers across different levels of competition to establish minimum acceptable levels of GTC.

CONCLUSION

Results obtained from this research indicated that hybrid bermudagrass established on a cohesive soil performs best when SWC mean ranges are between 0.10 to 0.17 m³/m³. The high SWC treatment (0.35 m³/m³) lost cover at a rate four times faster than the low and medium SWC treatments. The high SWC treatment decreased turfgrass stability and negatively impacted field performance because of the saturated soil conditions. A minimum limit of 50 G_{MAX} is suggested for establishment as a guideline for athletic field safety on hybrid bermudagrass fields established upon cohesive root zones. Soil water content treatments minimal impact on hybrid bermudagrass traffic GTC loss on non-cohesive (i.e. sand) root zones with few differences detected among field performance characteristics or soil physical properties. Our results indicate that SWC values of 0.08 to 0.16 m³/m³ provide optimum field performance for hybrid bermudagrass on non-cohesive root zones.

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APPENDIX A. TABLE

Table 1- 1. Regression analyses of green turfgrass cover in response to traffic events for hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. x *C. transvaalensis*, Burt-Davy, ‘Tifway’] established on a silt loam soil (a) and on USGA sand root zone (b). Fifty traffic events were applied over 10 weeks (5 per week) across four soil water contents during fall 2014 and 2015 in Knoxville, TN. Confidence interval values for each parameter are listed in parentheses.

(a)

Soil Water Content†	r^2	β_0	β_1	β_2	Events _{50‡}
Low (0.10 m ³ /m ³)	0.97	100 (+/- 1.2)	-2.0 (+/- 0.08)	-0.04 (+/- 0.008)	40 (+/- 0.3)
Medium (0.17 m ³ /m ³)	0.97	94 (+/- 1.3)	-1.3 (+/- 0.06)	-0.05 (+/- 0.009)	40 (+/- 0.4)
Med-High (0.26 m ³ /m ³)	0.97	100 (+/- 1.3)	-2.9 (+/- 0.06)	-0.02 (+/- 0.008)	32 (+/- 0.3)
High (0.35 m ³ /m ³)	0.97	95 (+/- 2.8)	-10.7 (+/- 0.05)	-0.30 (+/- 0.002)	10 (+/- 0.4)

(b)

Soil Water Content	r^2	β_0	β_1	Events _{50†}
Low (0.08 m ³ /m ³)	0.97	99 (+/- 0.08)	-1.2 (+/- 0.03)	36 (+/- 0.3)
Medium (0.16 m ³ /m ³)	0.95	100 (+/- 0.90)	-1.0 (+/- 0.03)	37 (+/- 0.2)
High (0.35 m ³ /m ³)	0.97	100 (+/- 1.10)	-1.3 (+/- 0.04)	36 (+/- 0.2)

† A sum of squares reduction *F*-test determined that the sums of squares from a global model (all treatments shared the same parameter estimates) was significantly different ($P < 0.0001$) from a cumulative model where unique parameter estimates were calculated for each treatment.

‡ Events₅₀ equals the number of traffic events to 50% green turfgrass cover.

Table 1- 2. Regression analyses of turfgrass shear strength in response to traffic events for hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. x *C. transvaalensis*, Burt-Davy, ‘Tifway’] established on a silt loam soil. Fifty traffic events were applied over 10 weeks (5 per week) across four soil water contents during fall 2014 and 2015 in Knoxville, TN. Confidence interval values for each parameter are listed in parentheses.

Soil Water Content†	r^2	β_0	β_1	β_2
Low (0.10 m ³ /m ³)	0.94	28.5 (+/- 0.4)	-0.61 (+/- 0.06)	-0.007 (+/- 0.002)
Medium (0.17 m ³ /m ³)	0.84	25.5 (+/- 0.3)	-0.08 (+/- 0.04)	-0.007 (+/- 0.002)
Med-High (0.26 m ³ /m ³)	0.89	28.4 (+/- 0.5)	-0.64 (+/- 0.09)	-0.009 (+/- 0.003)
High (0.35 m ³ /m ³)	0.88	25.9 (+/- 0.9)	-2.08 (+/- 0.20)	-0.055 (+/- 0.010)

† A sum of squares reduction *F*-test determined that the sums of squares from a global model (all treatments shared the same parameter estimates) was significantly different ($P < 0.0001$) from a cumulative model where unique parameter estimates were calculated for each treatment.

APPENDIX B. FIGURES

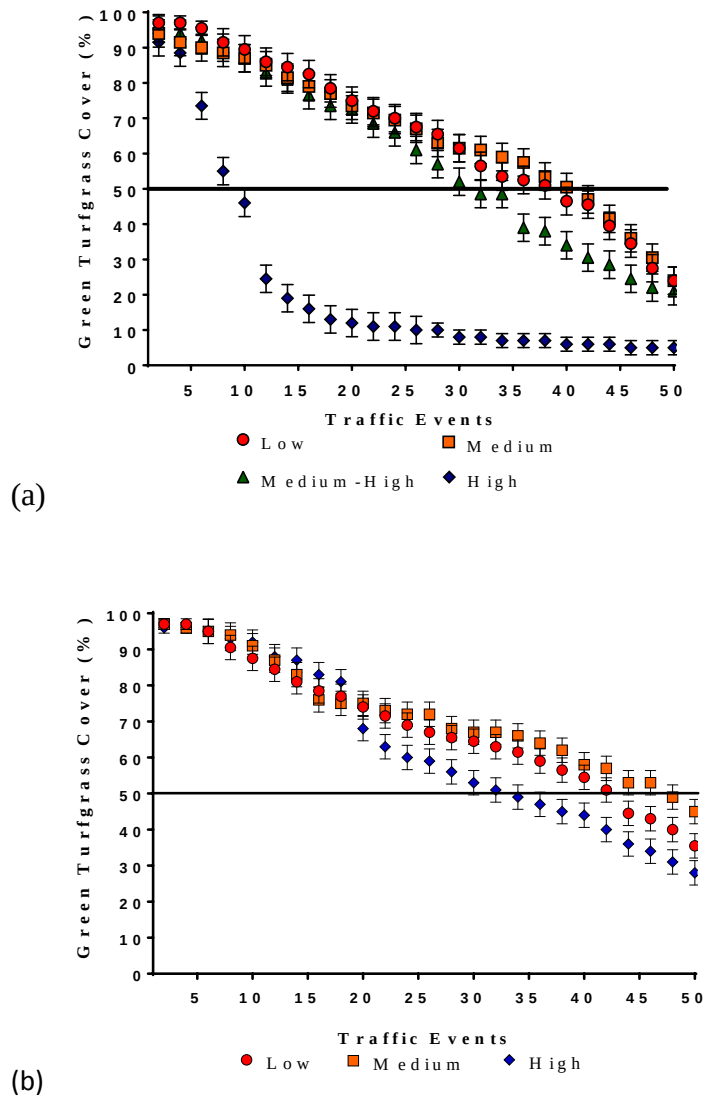
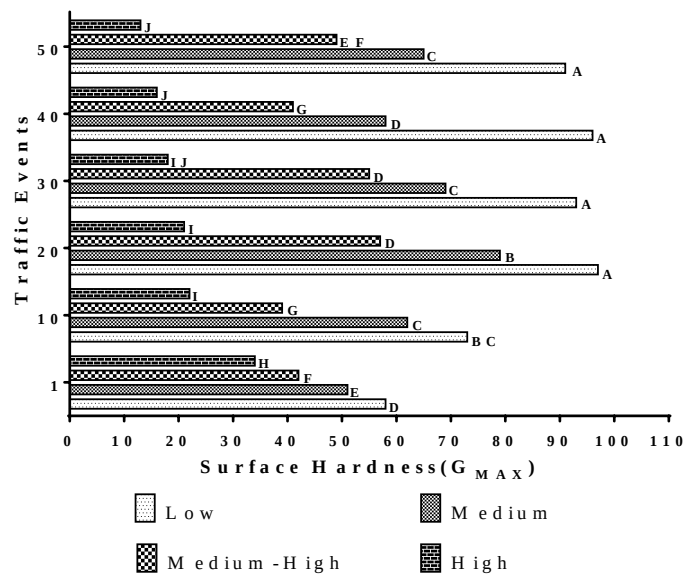
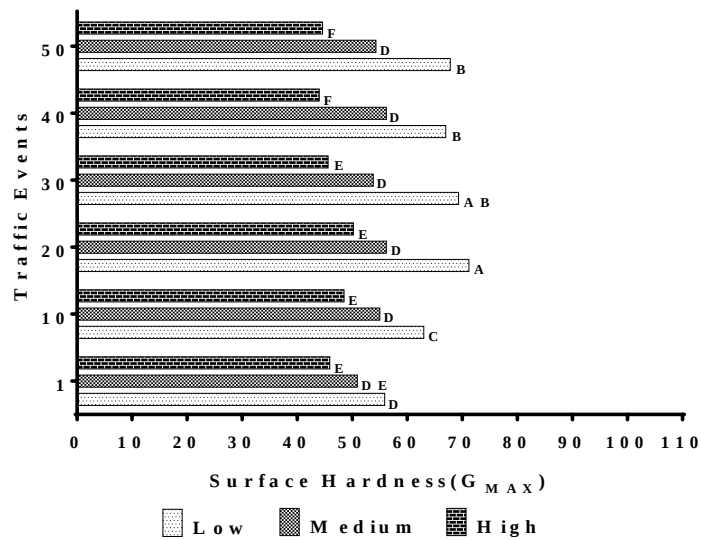


Figure 1- 1. Green turfgrass cover changes in response to soil water contents across traffic events applied to hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. X *C. transvaalensis* Burt Davy, ‘Tifway’] established on (a) silt loam soil and (b) sand meeting USGA specification root zone. Fifty traffic events were applied over 10 weeks (5 per week) across four soil water contents (Low = 0.10, Medium = 0.17, Medium-High = 0.26, and High = 0.35 m³/m³) for a and three water contents (Low = 0.08, Medium = 0.16, and High = 0.25 m³/m³) for b during fall 2014 and 2015 in Knoxville, TN. Error bars represent Fisher’s LSD values at $\alpha \leq 0.05$ within each traffic event as a means statistical comparison. Black line in graph represents when 50% green turfgrass cover is achieved. Best fit parameter regression estimates are found in Table 1-1.



(a)



(b)

Figure 1- 2. Surface hardness (G_{MAX}) changes in response to soil water contents across traffic events applied to hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. X *C. transvaalensis* Burt Davy, ‘Tifway’] established on (a) silt loam soil and (b) sand meeting USGA specification root zone. Fifty traffic events were applied over 10 weeks (5 per week) across four soil water contents (Low = 0.10, Medium = 0.17, Medium-High = 0.26, and High = 0.35 m^3/m^3) for a and three water contents (Low = 0.08, Medium = 0.16, and High = 0.25 m^3/m^3) for b during fall 2014 and 2015 in Knoxville, TN. Letters that are similar are not significantly different at $\alpha = 0.05$ according to Fisher’s LSD.

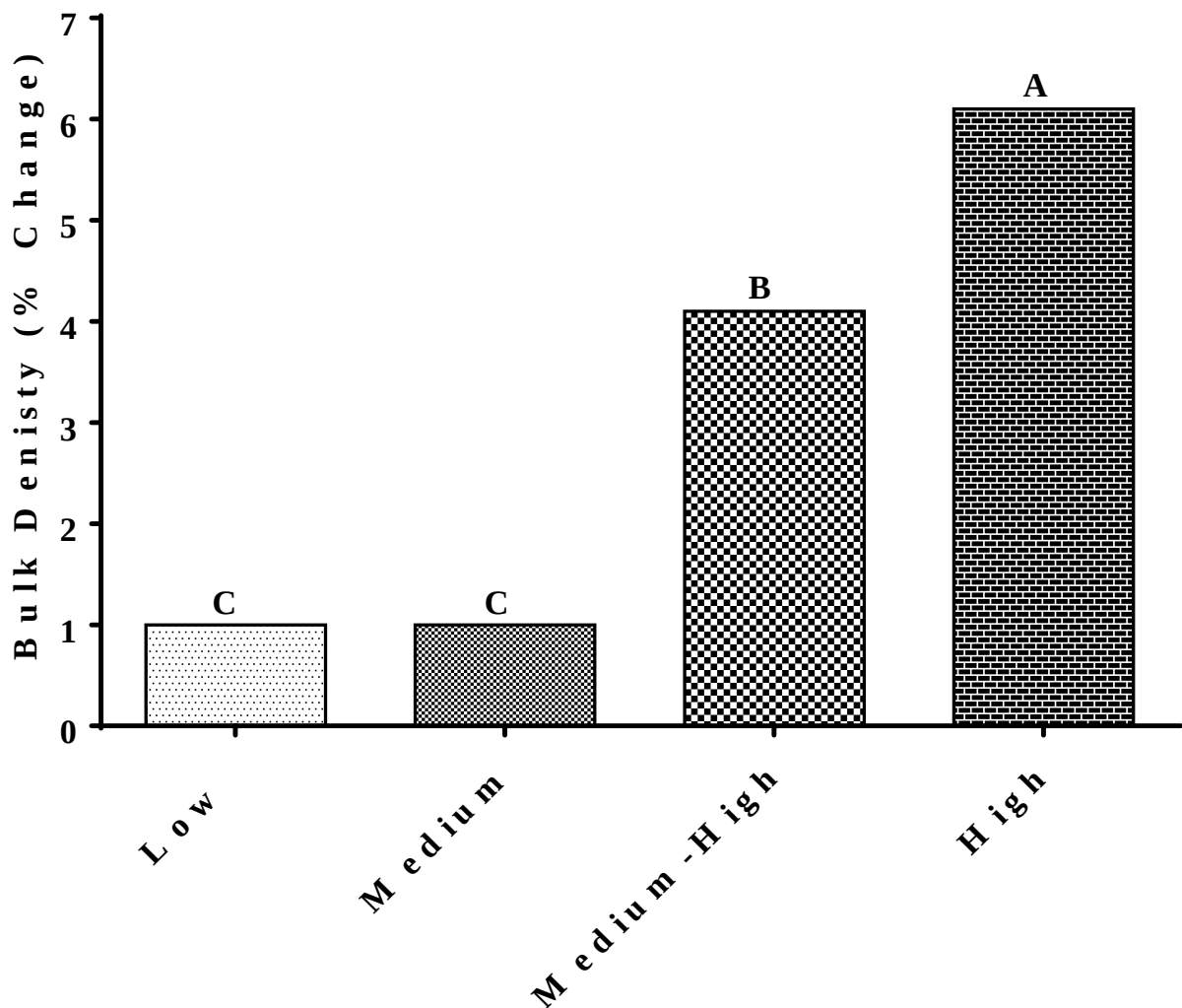


Figure 1- 3. Soil bulk density (g cm^{-3}) differences for soil water contents (Low = 0.10, Medium = 0.17, Medium-High = 0.26, and High = 0.35 m^3/m^3) applied to trafficked hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. X *C. transvaalensis* Burt Davy, 'Tifway'] established on a silt loam soil. Fifty traffic events were applied over 10 weeks (5 per week) across four soil water contents during fall 2014 and 2015 in Knoxville, TN. Letters that are similar are not significantly different at $\alpha = 0.05$ according to Fisher's LSD.

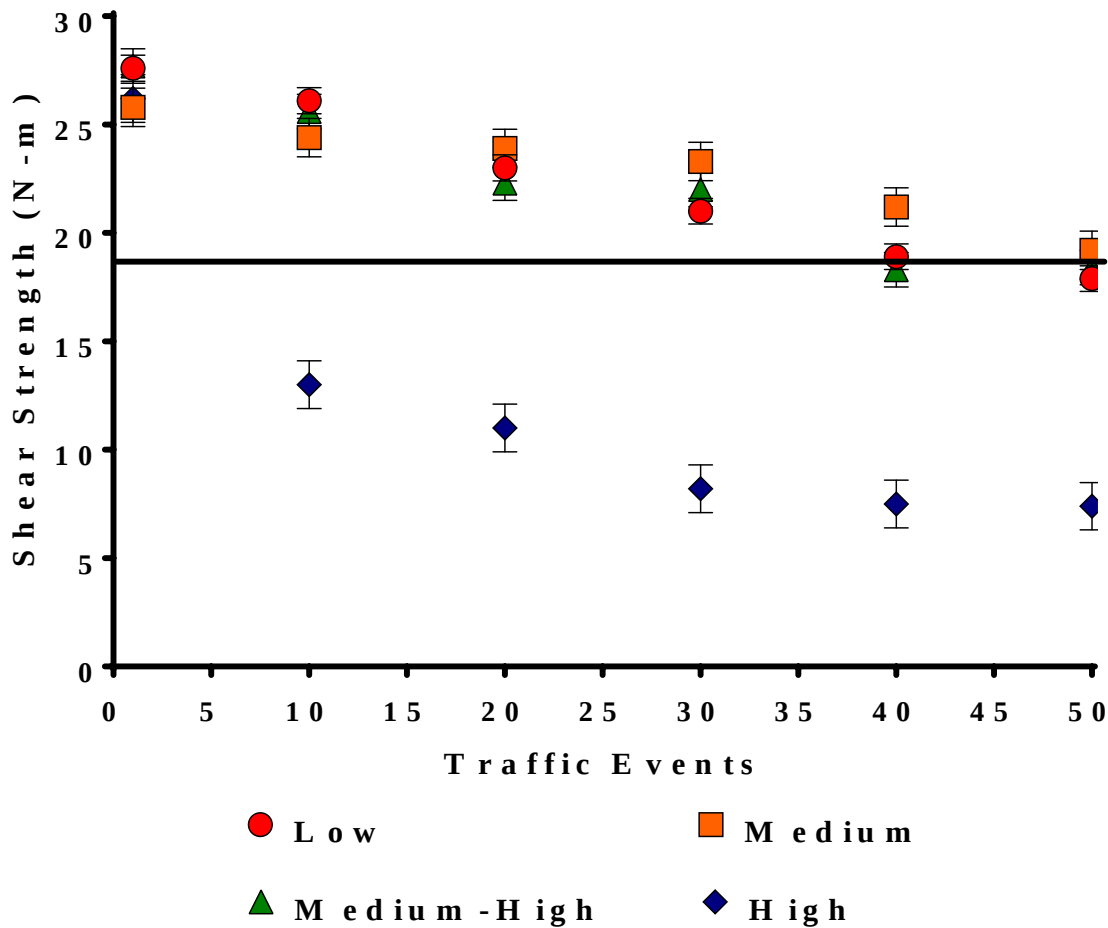


Figure 1- 4. Shear strength differences in hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. X *C. transvaalensis* Burtt Davy, ‘Tifway’] athletic field established on a silt loam soil shear strength (N-m) across 50 traffic events (5 per week) with varying levels of soil water content (Low = 0.10, Medium = 0.17, Medium-High = 0.26, and High = 0.35 m³/m³) during fall 2014 and 2015 in Knoxville, TN. Error bars represent Fisher’s LSD values at $\alpha < 0.05$ within each traffic event. Black line represents unacceptable level of shear strength for bermudagrass as suggested by the findings in this study. Best fit parameter regression estimates are found in Table 1-2.

APPENDIX C. ADDITIONAL MATERIALS AND METHODS

Materials and Methods

Water-filled porosity was analyzed every ten traffic events following the methods of Flint and Flint using the water-desorption method (2002). Collections of organic matter were collected at the start and conclusion of traffic applications each year. Eight soil samples were collected for each plot per collection event. Organic matter was determined using the loss-on-ignition method described by Ben-Dor and Banin (1989).

Soil water infiltration was collected for each plot. Four infiltration measurements were collected per plot at the beginning and end of each traffic season. Infiltration was collected using a double ring infiltrometer according to the methods of Reynolds et al. (2002).

Collection of clippings were done at 0, 25, and 50 traffic events each year. A basket was used to collect initial clippings and was then transferred into bags according to the methods of Easton and Petrovic (2004). Samples were dried for 24 hours and weighed.

Leaf texture was collected in at the beginning and end of the study. The methods of Roche and Loch (2005) were utilized to collect leaf texture. Twelve measurements were made per plot during the collection events each year. Measurements were collected using an electronic digital caliber (Electronic Digital Caliper, Titan, Renton, WA).

Green turfgrass cover (GTC) recovery was quantified immediately prior to each traffic event in the fall using digital image analysis (DIA) as described by Richardson et al. (2001) and Goddard et al. (2008). Recovery was monitored in the fall for regrowth after study completion. In spring of each year, GTC was collected for six weeks beginning 1 March.

APPENDIX D. ADDITIONAL RESULTS AND DISCUSSION

Results and Discussion

Study I:

In cohesive soils study the application of traffic increased soil bulk densities. Also, in cohesive soils the greater the SWC content the higher the increase in soil bulk density over time. The increase in soil bulk density was likely caused by the reduced load support capacity of the soil at higher water contents (Hamza and Anderson, 2005). Soil bulk density for the high SWC treatment had a five percent greater increase from study initiation than the low SWC treatment (Fig. 1-3) in cohesive soils. Carrow (1980) reported that a six percent increase in soil bulk density occurred in the top 10 cm of a compacted silt loam soil, established with Kentucky bluegrass, yielding a 32% reduction in root weight compared to the non-compacted control. Sills and Carrow (1983) found a 30% reduction in Kentucky bluegrass clippings when soil bulk densities increased by seven percent. Five percent changes in soil bulk densities found in our study, due to SWC, and previous findings demonstrate how small changes in soil bulk density can negatively impact turfgrass growth. The hypothesis was confirmed that in cohesive soils increased levels of SWC were found to accelerate the loss of GTC and resulted in increased soil compaction.

Water-filled soil porosity was not impacted by anything in this study. Similar results were found by Goddard et al. (2008) showing that on hybrid bermudagrass athletic fields over a cohesive soil subjected to traffic, no change was observed in water-filled porosity. Greater forces needed to be generated on the surface for compaction of water-filled pores than those applied. Due to the small size of the water-filled pores increased strength compared to air-filled pores (Jusoff, 1988). Greater force needs to be generated to cause differences in water-filled porosity than current traffic simulators can apply; however, current simulators are correlated with human

forces (Henderson et al., 2005; Kowalewski et al., 2013). Greater forces generated on the surface would apply unrealistic human foot traffic. This study suggests in cohesive soils the greatest difference in porosity from athletic field traffic is in air-filled porosity while water-filled porosity were not impacted by SWC.

Organic matter differences were subtle at best and were not shown to be significantly different after the completion of all traffic events. These findings correlate with a previous study that did not detect differences in organic matter content of hybrid bermudagrass with a silt loam root zone subjected to traffic events (Goddard et al., 2008). The lack of differences in organic matter could be due to the limited time (6 weeks) the study took place and the lack of growth of warm season grass in the fall. Summer applications of traffic may find changes in organic matter content subjected to different SWCs. Future studies warrant investigation into hybrid bermudagrass organic matter content during summer months on cohesive soils under varying SWC.

Significant infiltration differences were found to be due to traffic events only while SWC content did not impact the rate of infiltration. A significant decrease in infiltration rate was observed from traffic event 0 to 50 when pooled across all SWCs of over 7.5 mm per hour (Fig. 1-5). A strong negative correlation ($r^2 = -0.95$) was found between infiltration rate and soil bulk density. Some previous reports correlate with the findings that increased compaction due to traffic reduced infiltration rates (Gregory et al., 2006; Unger and Kaspar, 2007; Morgan et al, 66). These findings are in contrast to those of Goddard et al. (2008) who found that traffic events did not have a significant impact on infiltration rates on bermudagrass with a silt loam soil. The differences between the studies could potentially be accounted for in the study of Goddard et al. (2008) only half the number of traffic events were applied. A weakness of this study was the

interval at which infiltration rates were collected. A future study monitoring infiltration rates throughout the study would determine at what point and rate of decrease in infiltration.

Leaf texture decreased significantly from the start to the conclusion of traffic applications. Different SWC treatments did not have an impact on leaf texture, only differences due to traffic events. A decrease of an average of 0.49 mm was observed after the conclusion of 50 traffic events (Fig. 1-6). A strong negative ($r^2 = -0.91$) correlation was found with soil bulk density that as compaction increased a decrease in leaf texture was observed. This correlates with a previous study as compaction increases leaf texture decreases (den Haan et al., 2009). Even though a reduction of canopy was observed in the loss of GTC as traffic events increased leaf texture became finer. The normal response of an open canopy would be an increase in leaf texture; however, traffic applications caused the leaf texture to be reduced (Dedueck and Peacockk, 1992; den Haan et al., 2009). This response is potentially due to the reduction in growth to stress applied to the plants by traffic and increases in soil compaction. Plants were trying to conserve energy to stabilize tissue loss when traffic damaged the leaf.

Significant reductions in the amount of clippings were found as traffic events increased. The greatest reduction in clippings occurred in the first 25 traffic events with a reduction of 107 g on average across all SWC treatments (Fig. 1-7). For traffic events 25-50 only a reduction of 44 g was detected (Fig. 1-7). These result collaborate with previous studies finding as traffic increased a decrease in the amount of clippings collected were observed (Ervin and Koski, 2001; Rogers et al., 1998). The reduction could be attributed to less GTC shown in the plots thus less tissue to collect, as well as the plants stress due to traffic. Also, as the study continued into the fall temperatures decreased compared with the first collection date, this drop in temperature could decrease bermudagrass growth.

Study II:

No differences were detected in water-filled porosity when tested. A greater force would need to be applied to impact the water-filled pores. The micro-pore (water-filled) have a higher strength due to the small size giving greater strength to the pore (Jusoff, 1988). USGA sand specifications were created to give a root zone that drains well and sustains minimal compaction (Bingaman and Kohnke, 1970).

Organic matter had no differences due SWC, traffic events, or their combination. This correlates with a previous hybrid bermudagrass study showing no increase in organic matter subjected to traffic in the fall (Goddard et al., 2008). Some of the reasons for the lack of differences could be due to the study taking place in the fall and limited growth occurring during that time. A study taking place during the summer could provide different results to grass plants being actively growing.

Infiltration was reduced as traffic events increased. A trend of declining infiltration was observed from the first traffic event until the end of traffic (Fig. 1-8). Infiltration rate and soil bulk density had a strong negative correlation ($r^2 = -0.93$) across traffic events. These findings are supported by previous research demonstrating as soil bulk density increases infiltration rate decreases (Gregory et al., 2006; Unger and Kaspar, 2007; Morgan et al, 1966). A way to improve the strength of this study would have been to have a greater frequency of infiltration collections. With only the two collection events each year, differences could be gleaned from the increased interval of testing. Collections were limited in this study due to the potential delay of the study.

Leaf texture decreased by 0.39 mm after the completion of the study (Fig. 1-9). Soil bulk density and leaf texture were found to have a strong negative correlation of ($r^2 = -0.90$).

Previously it was reported that increases in compaction results in a decrease in leaf texture (den Haan et al., 2009). There are varietal differences found in leaf texture and it has been shown that finer leaf texture can be an indication of increased turfgrass traffic tolerance (Sherman and Beard, 1975; den Haan et al., 2009). One constraint of this study was that the SWC range was only monitored for eight weeks and maintaining these ranges consistently throughout an extended period of time would be worth investigating.

Clippings decreased greatly as traffic events increased. The amount of clippings collected decreased as traffic events increased (Fig. 1-10). Clippings decreased by 38 g at the end of the study. Previous studies reported similar findings as traffic events increased (Ervin and Koski, 2001; Rogers et al., 1998). The reduction in clippings has a strong positive relationship ($r^2 = 0.96$) with GTC. A 47% reduction of clippings was observed due to a 6% increase in bulk density; this corresponds with previous findings of Sills and Carrow (1983). The stress of the grass due to increased compaction and traffic impacts grass growth, with the plant trying to conserve its energy to survive. Carbohydrate analysis could give more detailed information to what was happening inside the plant and is warranted for further research.

APPENDIX E. ADDITIONAL WORK CITED

WORK CITED

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APPENDIX F. ADDITIONAL FIGURES

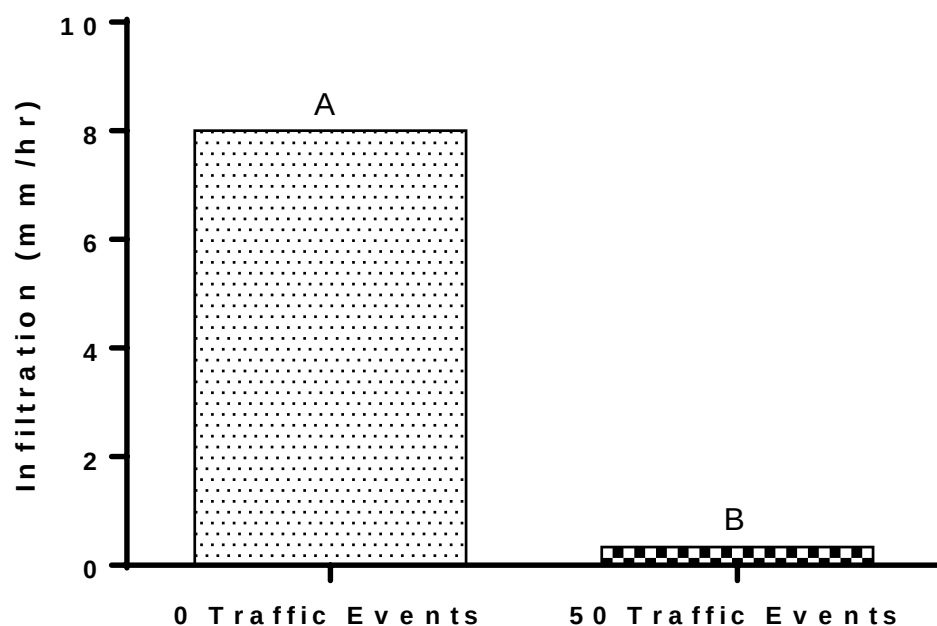


Figure 1- 5. Infiltration rate (double ring infiltrometer) differences on hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. X *C. transvaalensis* Burt Davy, 'Tifway'] athletic fields established on silt loam soil with pooled data from varying soil water contents prior to and after the conclusion of 50 traffic events during fall 2014 and 2015 in Knoxville, TN. Means within each chart that share letters are not significantly different according to Fisher's Protected LSD $\alpha \leq 0.05$.

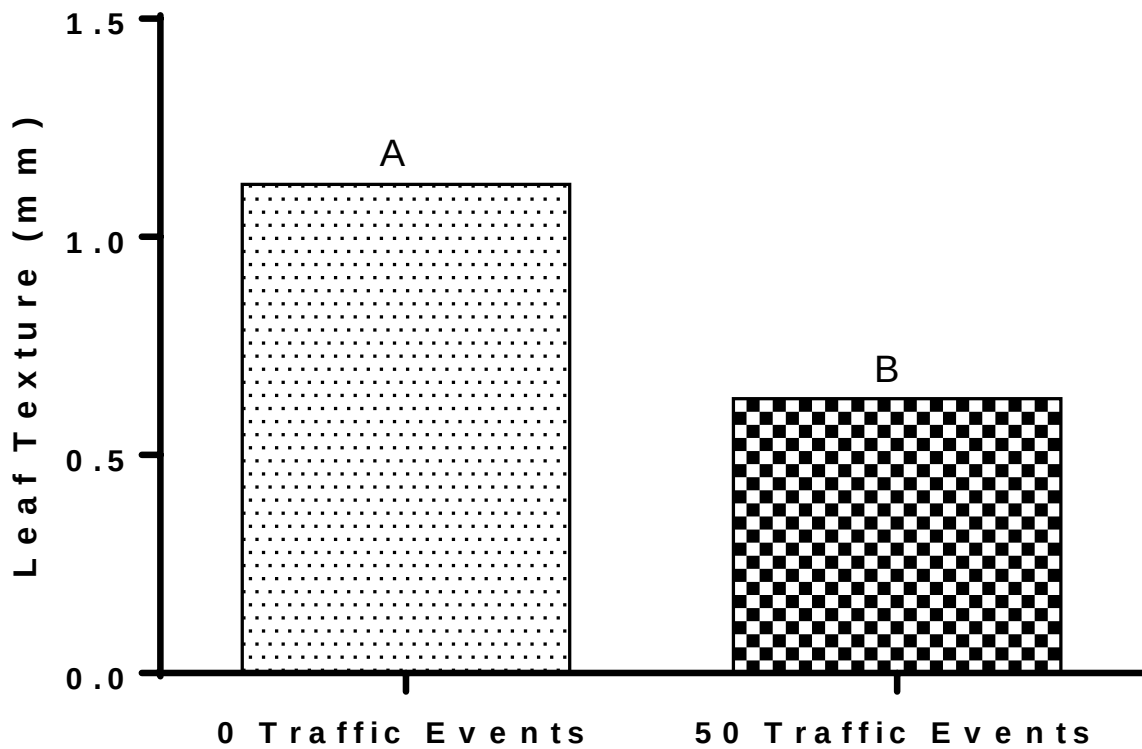


Figure 1- 6. Leaf texture differences on hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. X *C. transvaalensis* Burt Davy, 'Tifway'] athletic fields established on silt loam soil with pooled data from varying soil water contents prior to and after the conclusion of 50 traffic events during fall 2014 and 2015 in Knoxville, TN. Means within each chart that share letters are not significantly different according to Fisher's Protected LSD $\alpha \leq 0.05$.

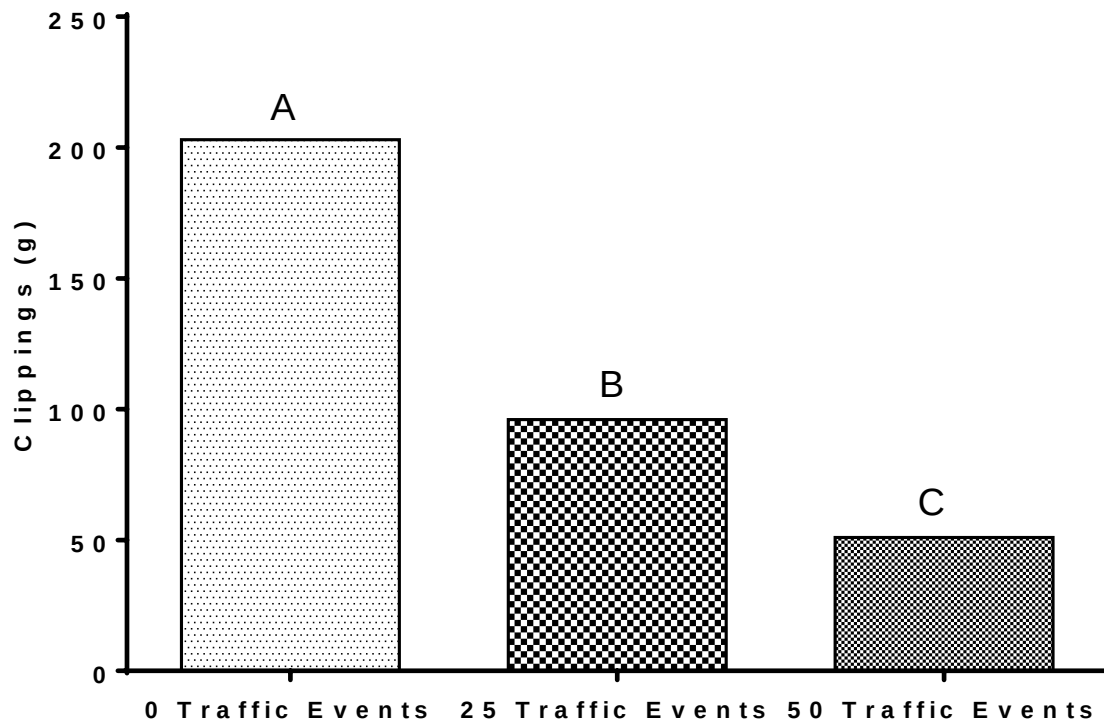


Figure 1- 7. Clipping collection differences on a hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. X *C. transvaalensis* Burt Davy, ‘Tifway’] athletic field established on silt loam soil with pooled data from varying soil water contents at 0, 25, and 50 traffic events during fall 2014 and 2015 in Knoxville, TN. Means within each chart that share letters are not significantly different according to Fisher’s Protected LSD $\alpha \leq 0.05$.

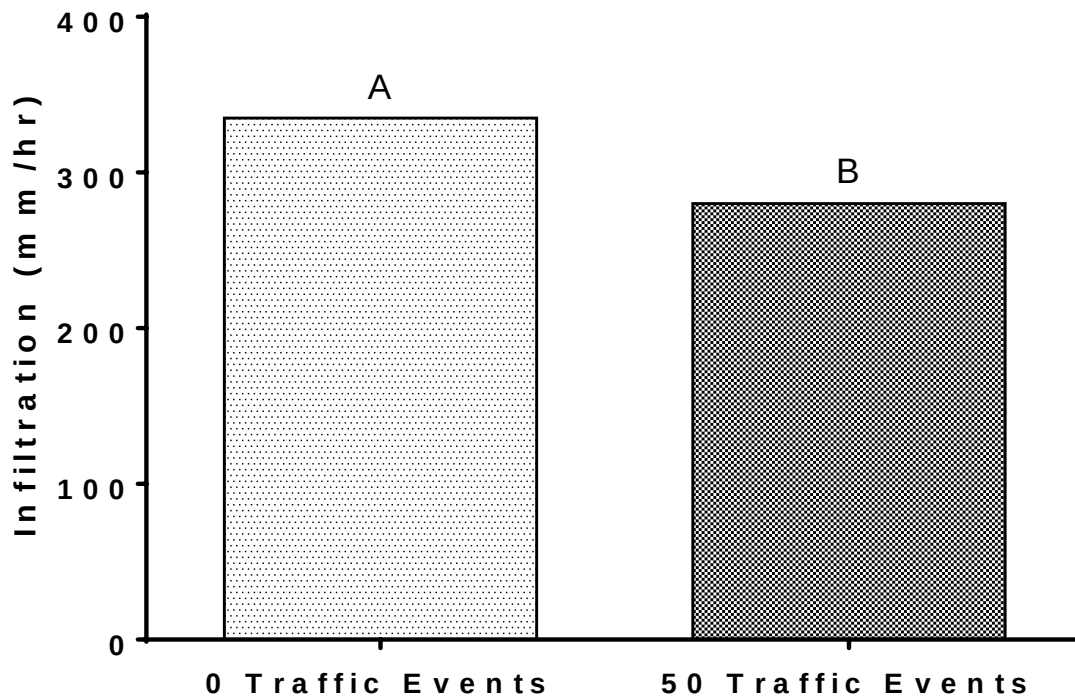


Figure 1- 8. Infiltration rate (double ring infiltrometer) differences on hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. X *C. transvaalensis* Burt Davy, 'Tifway'] athletic fields established on sand root zone conforming to USGA specifications with pooled data from varying soil water contents prior to and after the conclusion of 50 traffic events during fall 2014 and 2015 in Knoxville, TN. Means within each chart that share letters are not significantly different according to Fisher's Protected LSD $\alpha \leq 0.05$.

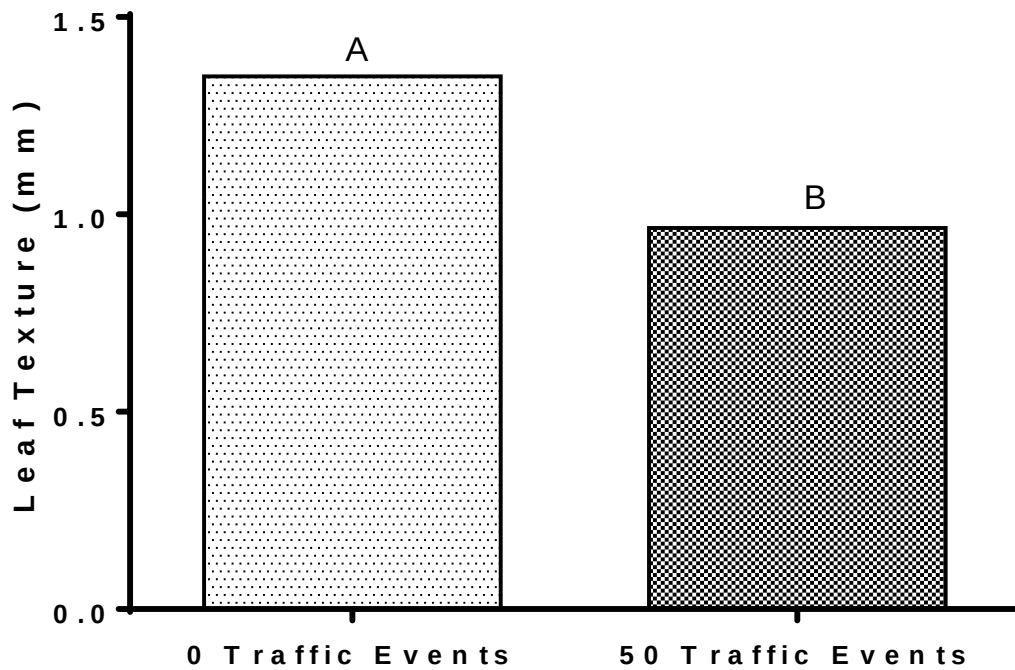


Figure 1- 9. Leaf texture differences on hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. X *C. transvaalensis* Burt Davy, ‘Tifway’] athletic fields established on sand root zone conforming to USGA specifications with pooled data from varying soil water contents prior to and after the conclusion of 50 traffic events during fall 2014 and 2015 in Knoxville, TN. Means within each chart that share letters are not significantly different according to Fisher’s Protected LSD $\alpha \leq 0.05$.

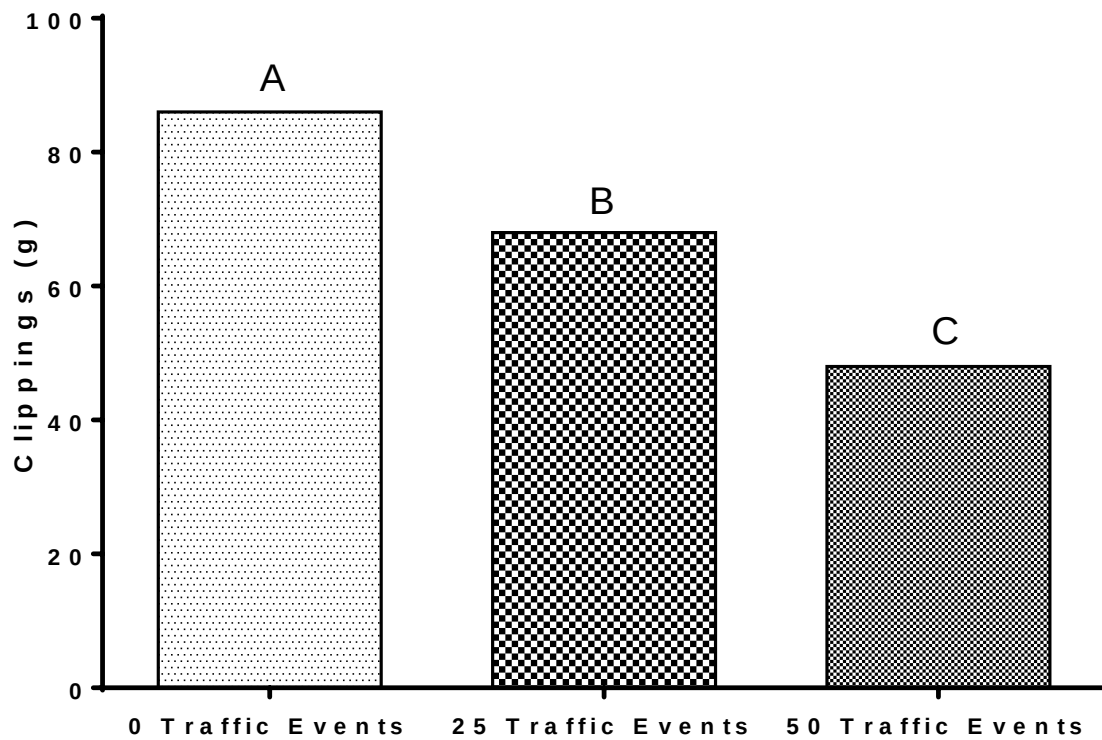


Figure 1- 10. Clipping collection differences on hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. X *C. transvaalensis* Burt Davy, ‘Tifway’] athletic fields established on sand root zone conforming to USGA specifications with pooled data from varying soil water contents at 0, 25, and 50 traffic events during fall 2014 and 2015 in Knoxville, TN. Means within each chart that share letters are not significantly different according to Fisher’s Protected LSD $\alpha \leq 0.05$.

CHAPTER 2: Predictive Models

Predictive Green Turfgrass Cover Loss Models for Hybrid Bermudagrass

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My primary contributions to this paper include (i) discovering the concept (ii) design and conducting the experiment, (iii) processing, analyzing and interpreting data, (iv) reading literature, (v) writing the manuscript

ABSTRACT

Predictive models are wide spread in the scientific community and could be used to improve athletic field safety. Two field research studies were conducted at the University of Tennessee Center for Athletic Field Safety (Knoxville, TN) to determine soil water content (SWC) impact on green turf cover (GTC) loss of hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. x *C. transvaalensis* Burt-Davy, ‘Tifway’] athletic fields subjected to traffic. Each study evaluated responses a different root zone: silt loam (cohesive) or sand conforming to United States Golf Association (USGA) specifications (non-cohesive). Four SWC ranges were tested on the cohesive root zone and three were tested on the non-cohesive. Each root zone was subjected to 50 traffic events using a Baldree Traffic Simulator during 2014-2015. Multiple evaluations of 11 variables found that two (soil water content and traffic events) accurately predicted GTC loss in both root zones. A predictive model was successfully created for the cohesive root zone having an R^2 of 0.87 (+/- 3.5%). The non-cohesive root zone predictive model was accurate in

predicting loss of GTC as well ($R^2 = 0.91$, +/- 2%). The information generated from these models could prevent athletic events that may cause increase field longevity.

INTRODUCTION

Athletic fields are widely used for a variety of events each year, which subjects them to wear. These events occur across a wide range of soil water content (SWC) from both dry soils to saturated conditions (Orchard, 2002). American football traffic applies 93% of the traffic on 7% of the playing surface (Cockerham and Brinkman, 1989). Concentrated traffic can create worn areas that are inconsistent and offer less stable surfaces for athletes to run, jump, and change direction during play (Carrow and Petrovic, 1992). Various factors (SWC, number of traffic events, soil type, etc.) impact wear on an athletic field and require monitoring to increase field longevity. With over 40,000 athletic fields in the United States, proper field management to mediate the effects of traffic events is essential (Campbell, 2004).

Traffic is defined as the application of force to the surface causing soil compaction, turfgrass wear, losses in green turf cover (GTC), soil displacement, and rutting (Beard, 1973; Whitecotton et al., 2000). Several different traffic simulators (e.g., Brinkman, Baldree, Cady, D.S.1, Georgia Soil Compaction Wear Traffic simulator, and Nebraska Soil Compaction Wear Traffic Simulator) have been developed to simulate effects of human foot traffic on turfgrass research plots (Canaway, 1976; Cockerham and Brinkman, 1989; Carrow et al., 2001; Shearman et al., 2001; Henderson et al., 2005; Kowaleski et al., 2013). While these simulators apply the same traffic as the highest wear areas of an athletic field, they can also provide insight into how different turfgrass species and soil types respond to traffic.

Athletic fields are constructed of the existing soil found at a location. These fields, often termed “native soil athletic fields,” can have surface conditions that vary widely within a field and across multiple locations (Bigelow and Soldat, 2013). Often native soil fields are established on root zones high in silt and clay content, resulting in a cohesive soil has the ability to hold water required for turfgrass growth; moreover, native soil fields are less expensive to construct than those using engineered, non-cohesive (i.e., sand) root zones (Pitt et al., 2008). However, excessive SWC on cohesive soils can result in unstable soil conditions that compromise player safety (Antunes et al., 2011; Anderson et al., 2015). To that end, non-cohesive root zones can be used to provide rapid infiltration, drainage, and resistance to compaction under trafficked conditions, which can limit the likelihood of events being cancelled due to inclement weather (Bingaman and Kohnke, 1970; Bigelow and Soldat, 2013). However, constructing an athletic field using a non-cohesive (sand) root zone requires a high initial investment (STMA, 2008).

Bermudagrass (*Cynodon* spp.) is the most commonly used turfgrass species 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). ‘Tifway’ hybrid bermudagrass [*C. dactylon* Pers. x *C. transvaalensis* Burt-Davy, 'Tifway'] has improved tolerance traffic compared to other bermudagrass cultivars and turfgrass species (Goddard et al., 2008; Brosnan and Deputy, 2009; Thoms et al., 2011). As a result, ‘Tifway’ hybrid bermudagrass has been the standard for use on athletic fields in the southern United States for decades. Loss of GTC is attributed to a combined impact of several factors (soil bulk density, surface hardness, SWC, etc.) outside of variety selection (Rogers et al., 1989).

Athletic events occur under a multitude of environmental conditions that can affect rates of GTC loss. Previous studies on cool-season grasses established upon a cohesive soil have

observed that as traffic and SWC increased, losses of GTC were accelerated (Rogers and Waddington, 1989; Rogers and Waddington, 1992). Warm season turfgrass athletic fields followed the same trend with high SWC being associated with accelerated rates of GTC loss. For example, Carrow et al. (2001) reported that three varieties of *Cynodon* Spp. (Burt-Davy) established on a cohesive lost GTC at a greater rate when SWC was elevated compared to imparting the same traffic on turfgrass established at a lower SWC. Roche et al. (2009) reported a similar response as well.

Despite the reports of a relationship between SWC and GTC loss in response to traffic, no predictive models for GTC loss have been developed for use in turfgrass. Predictive models for an array of turfgrass management operations are numerous and can be used to schedule applications for pest management to applying plant growth regulators (Van Genuchten, 1980; Morgan et al., 1984; Throssell et al., 1987; Niemczyk et al., 1992; Fidanza et al., 1996; Moldrup et al., 1998; Uddin et al., 2003; Milesi et al., 2005). Predicting losses of GTC in response to changes in SWC before an event may prevent excessive field damage, thereby helping field managers, coaches, and event coordinators make decisions regarding event scheduling. The objective of this study was to develop a model to predict traffic-related losses of hybrid bermudagrass GTC on cohesive and non-cohesive root zones varying in SWC that field managers could use to determine the impact of an event.

MATERIALS AND METHODS

Two studies were conducted to determine SWC impacts on loss of GTC in ‘Tifway’ hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. x *C. transvaalensis*, Burt-Davy] subjected to simulated traffic. Study I was conducted on a Sequatchie silt loam soil (28% sand, 48% silt, and 24% clay) with a 6.2 soil pH, 9 mg kg⁻¹ initial phosphorous, 81 mg kg⁻¹ initial potassium, and 25

g kg⁻¹ organic matter content. Study II used a non-cohesive (sand) root zone conforming to the USGA specifications (0.7% very coarse, 14.3% coarse, 61.4% medium, 18.1% fine, 5.1% very fine, and 0.4% silt and clay by weight) mixed with 20% (volume) reed sedge peat moss (United States Golf Association, 2007). All plot management information are reported in chapter one.

Study I had four soil moisture ranges selected from just above permanent wilting point (0.06 m³/m³) to field capacity (0.40 m³/m³) as determined using American Society for Testing Materials (ASTM) standard F1815-11 (ASTM, 2011). Soil water content treatments were low (0.10 m³/m³ +/- 0.035), medium (0.17 m³/m³ +/- 0.035), medium-high (0.26 m³/m³ +/- 0.035), and high (0.35 m³/m³ +/- 0.050). Study II soil moisture ranges were selected similar to methods described for study I, but ranges differed based on root zone construction. The cohesive root zone had three SWC treatment ranges: low (0.08 m³/m³ +/- 0.03), medium (0.16 m³/m³ +/- 0.03), and high (0.25 m³/m³ +/- 0.05) throughout the study for both years. The experimental design for both studies was a randomized complete block with four replications and experimental unit (plot) dimensions were 2.0 m x 4.2 m with a boarder of 2.0 m between plots. Both studies were repeated in the second year using a different experimental area. For both studies, SWC was maintained 30 days prior to study initiation.

Traffic was applied to plots using the Baldree traffic simulator. The Baldree traffic simulator is a self-propelled modified core aerifier (ProCore 648, Toro, Bloomington, MN) that has impact forces on turf similar to those generated on the highest wear areas by American football players (Kowalewski et al., 2013). Traffic was applied ten times per week (Monday thru Friday) from 15 September to 19 October 2014, and 14 September to 21 October 2015. Traffic rates and dates coincide with a typical high school football season in Knoxville, TN. Each plot received 50 traffic events each year.

Digital image analysis was used to quantify green turfgrass cover (GTC) following every two traffic events using the methods of Richardson et al. (2001). Sigma Scan Pro Software (v. 5.0, SPSS. Inc., Chicago, IL) was used to analyze the images following the methods of Richardson et al. (2001). Green pixels in each image were those having a saturation of 0 to 100 percent and hue between 35 and 145.

Surface hardness values were collected after each two traffic events using the Clegg Impact Soil Tester with a 2.25 kg missile dropped from a height of 46 cm according to the ASTM standard F1702-96 (ASTM, 2000), and were the composite of three test locations within a plot comprised of three measurements at each location. Following every two traffic events, four soil cores were extracted randomly from the interior of each plot (Goddard et al., 2008). Soil bulk density was determined using methods as described by Grossman and Reinsch (2002). Air-filled porosity was collected following the gravimetric method described by Flint and Flint (2002) by the collection of four additional cores per plot every ten traffic events. Collections of water-filled porosity were done every ten traffic events utilizing the water-desorption method (Flint and Flint, 2002). Soil organic matter was determined from eight cores from the initial and completion of traffic each year following the loss-on-ignition method described by Ben-Dor and Banin (1989).

Infiltration was collected at the beginning and end of each traffic season with four samples per plots using a double ring infiltrometer according to the methods of Reynolds et al. (2002). Leaf texture was collected at the beginning and end of the study with a digital caliber using the methods of Roche and Loch (2005). Clippings were collected (0, 25, and 50 traffic events) according to the methods of Easton and Petrovic (2004). Shear strength was collected

with the shear vane (Turf-Tec Shear Strength Tester, Turf-Tec International, Tallahassee, FL) as described by Rogers et al. (1998) with five collections per plot.

Predictive models for loss of GTC were constructed using data from fall 2014 and 2015 on study I (cohesive root zone) and study II (non-cohesive root zone). Separate predictive models were created for both root zones and were subjected to the following analysis techniques to determine model fit. All data collected were subjected to an ANOVA in SAS (SAS institute, Cary, NC) at $\alpha = 0.05$. Exploratory models examined various model fits using 10 different variables (i.e., SWC, traffic events, surface hardness, soil bulk density, soil air-filled porosity, organic matter content, infiltration, leaf texture, clipping yields, and shear strength) in R Studio (version 0.98.1091; R Studio Inc, Boston, MA). Variables were selected based on the ability of a field manager to obtain the data for the previously listed variables for model calculations. Once variable significance was determined, collinearity was calculated through validation analyses (variance inflation factor, correlation coefficients, and Akaike's An Information Criterion (AIC) values) in R Studio. After the removal of collinear terms, the remaining variables were subjected to multivariate regression in R Studio at $\alpha = 0.05$ to determine model parameters that could be used to predict GTC after each traffic event.

After selection of the model parameters, seven evaluations were used to determine the best predictive model. Initially, a series of diagnostic plots were evaluated to evaluate model fit (Fahmeir et al., 2013; Wilk and Gnanadesikan, 1968; Cook, 1977). After the evaluation of these diagnostic plots, a second AIC analysis was performed from the initial AIC analysis completed following methods of Posada and Buckley (2004). A stepwise comparison of the models was completed in R studio to determine the highest coefficient of determination (R^2) (Fahmeir et al., 2013). Models with optimal diagnostic plots, AIC, and highest R^2 were further evaluated for

accuracy in R studio using leave-one-out cross-validation. Leave-one-out cross-validation is a technique that incorporates one data point using all other data points to predict data to determine best fit (Cawley and Talbot, 2003).

RESULTS

Exploratory models were calculated across 10 variables for study I and II with similar trends observed. Two of the variables were explanatory variables (SWC and traffic events) while the rest were response variables (Table 2-1). Initial tests for significance yielded one variable (organic matter) that was not significant ($P \leq 0.05$) and dropped from model evaluations (Table 2-1). The remaining variables were found to be significant to the model; however, two groups were highly correlated to each other and therefore collinear. Surface hardness, soil bulk density, shear strength, and SWC were all collinear, but due to SWCs impact on soil physical properties, it was selected while the other collinear variables were dropped from model consideration. A second group of variables was also found to be collinear including: air-filled porosity, infiltration, leaf texture, clipping yield, and traffic events. In the second group of collinear variables, traffic events were selected with all other variables dropped from model consideration. The explanatory variables after initial evaluations were the variables selected for the model. The two variables (SWC and traffic events) used to create predictive models through the process described in the materials and methods for each soil type.

For the cohesive soil predictive model, GTC values ranged from 0 to 100% across 50 traffic events on Tifway hybrid bermudagrass. The selected model:

$$\text{Green Turfgrass Cover} = 124 + (-1.3 * \text{Traffic Events}) + ((\text{Traffic Events} * \text{SWC}) * -0.009) + (-1.28 * \text{SWC})$$

accounted for the highest percentage of the variability in GTC among all models tested with an $R^2 = 0.87$. Additionally, the selected model offered optimal diagnostic plots AIC values, and the greatest R^2 in leave-one-out cross validation testing (Fig. 2-1, Table. 2-2). Our model predicts GTC for Tifway hybrid bermudagrass established on a cohesive soil with an accuracy of +/- 3.5% GTC per traffic event and SWC combination.

For the non-cohesive soil predictive model, values ranged from 0 to 100% GTC across 50 traffic events on Tifway hybrid bermudagrass. More than 30 models were evaluated to determine the model of best fit (Table 2-3). The model:

$$\text{Green Turfgrass Cover} = 101.0 + (-1.4 * \text{Traffic Events}) + ((\text{SWC} * \text{Traffic Events}) * -0.01)$$

selected had an R^2 of 0.91, accounting for a significant percentage of the variability in GTC data. Furthermore, as with the cohesive model, the chosen model for the non-cohesive soil had optimal diagnostic plots, AIC values, and the highest R^2 in leave-one-out cross validation (Table 2.3, Fig. 2-3). The model was found to be accurate within +/- 2% GTC.

DISCUSSION

The SWC ranges of cohesive soils responded differently in GTC loss between high ($> 0.3 \text{ m}^3/\text{m}^3$) and low ($< 0.1 \text{ m}^3/\text{m}^3$) SWCs. The reason the higher SWC behaved differently was as SWC increased, the cohesive soil entered a semi-liquid state, altering soil structure when a compressive force was applied. When investigating SWC further, the fastest GTC loss was detected at the SWC where GTC has the steepest slope. These results suggest that maintaining hybrid bermudagrass athletic fields with a cohesive root zone $\geq 0.34 \text{ m}^3/\text{m}^3$ SWC will have the fastest GTC loss when subjected to traffic. While, a minimum SWC was not established in chapter one; however, $\geq 0.06 \text{ m}^3/\text{m}^3$ would be needed to sustain grass growth above permanent

wilting point. Further research is needed to determine the SWC of fastest loss of different soil textures when trafficked.

The high R^2 and low number of models needed to select the best fit on the non-cohesive root zone was due to the linear behavior of GTC values in response to SWC treatments. Among the SWC treatments tested, no SWC of greatest GTC loss could be established on non-cohesive soils. The lack of a breaking point was attributed to the design of the USGA root zone providing optimal particle stability and rapid drainage. These results suggest that SWC has a marginal impact on GTC loss on hybrid bermudagrass established on a non-cohesive root zone similar to that evaluated herein; however, traffic events have a significant impact on GTC loss. The objective was completed in that model was created to predict loss of GTC that can be used by field managers using as few variables as possible. These models can now be input into web-based platforms (web sites, phone apps, etc.) that can be used by field managers. This paper provides the science behind the use of the model on accessible platform for end users.

Both selected models provide GTC loss predictions there are limitations to each. Both models have only been verified for ‘Tifway’ hybrid bermudagrass in the fall using data from a single cohesive and non-cohesive root zone. One of the limitations of this study was that it was completed during autumn (range of 9 to 31 °C) when environmental conditions for hybrid bermudagrass growth are not optimal. The selection of autumn for traffic application was to coincide with the high school football season in Knoxville, TN; had this study taken place during the summer when hybrid bermudagrass was actively growing, different responses would be expected. Further work is still warranted to determine rates of GTC loss with varying SWC at other times of the year. Additionally, other cultivars of hybrid bermudagrass and different turfgrass species would likely differ from the predictive models as differences in traffic tolerance

among cultivars and species have been reported (Goddard et al., 2008; Brosnan and Deputy, 2009; Thoms et al., 2011).

Investigation of SWC influence on GTC loss in different soil textures could yield new discoveries as well. In a laboratory setting, additions of silt plus clay to a well graded sand in combination with different SWC without turfgrass have been evaluated for bearing capacity and permeability (Henderson et al., 2005). Henderson et al. (2005) found greater silt plus clay content lead to more compaction and reduced root zone permeability. Soil water content and water movement are considered to be key variables in determining playing quality of a sports surface (Canaway and Baker, 1993). Our results suggest increased silt and clay between cohesive and non-cohesive root zones impacted the behavior of the predictive models. The negative impacts of SWC on root zone permeability observed by Henderson et al. (2005) corresponded with trends of GTC loss in this study. Greater investigation into differences between silt plus clay amounts would provide further detail into GTC loss behavior in varying SWCs.

CONCLUSION

Separate models to predict GTC loss due SWC and traffic were established for hybrid bermudagrass established on cohesive and non-cohesive root zones. These models can accurately predict loss of GTC based on SWC and number of traffic events with $\leq 4\%$ accuracy. The simplicity of including only two variables (SWC and traffic events) in these models makes GTC loss prediction accurate and easy. Technological advances have made SWC measurements practical for most field managers prior to an athletic event. Additionally, these models may be useful to field managers, coaches, and event coordinators in making decisions on athletic events based on potential field damage. In the future web-based applications can be used to create an interface for end users to use the model for GTC loss predictions.

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APPENDIX A. TABLES

Table 2- 1. Variables evaluated for model construction to predict green turfgrass cover when subjected to traffic on hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. X *C. transvaalensis* Burt Davy, ‘Tifway’] established on silt loam soil and sand conforming to United States Golf Association specifications. Fifty traffic events were applied over 10 weeks (5 per week) across four soil water contents (Low = 0.10, Medium = 0.17, Medium-High = 0.26, and High = 0.35 m³/m³) for silt loam root zone and three water contents (Low = 0.08, Medium = 0.16, and High = 0.25 m³/m³) for sand root zone during fall 2014 and 2015 in Knoxville, TN.

Variable	Type	Significance
Traffic Events	Explanatory	***†
Soil Water Content	Explanatory	***
Surface Hardness	Response	***
Soil Bulk Density	Response	***
Shear Strength	Response	***
Air-Filled Porosity	Response	***
Infiltration	Response	**‡
Leaf Texture	Response	*§
Clipping Yield	Response	**
Organic Matter Content	Response	NS¶

†Significant at the $\alpha = 0.001$ probability level.

‡Significant at the $\alpha = 0.01$ probability level.

§Significant at the $\alpha = 0.05$ probability level.

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

Table 2- 2. Models and coefficients of determination (R^2), Akaike's An Information Criterion (AIC), and leave-one-out cross-validation coefficient of determination (Cross R^2) evaluated for use to predict green turfgrass cover loss in response to soil water contents across traffic events applied to hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. X *C. transvaalensis* Burt Davy, 'Tifway'] established on silt loam soil. Fifty traffic events were applied over 10 weeks (5 per week) across four soil water contents (Low = 0.10, Medium = 0.17, Medium-High = 0.26, and High = 0.35 m³/m³) during fall 2014 and 2015 in Knoxville, TN.

	Model	R ²	AIC	Cross R ²
1.	Percent Green Cover† = 124 + (-1.3*Traffic Events‡) + ((Traffic Events*SWC§) * -0.009) + (-1.28*SWC)	0.87	189	0.92
2.	Percent Green Cover = 124 + (-1.3*Traffic Events) + ((Traffic Events+SWC)*-0.009) - (-1.28*SWC)	0.80	255	0.88
3.	Percent Green Cover = 124+ ((-1.3*Traffic Events) * (SWC * -1.28)) - (-1.3*Traffic Events)	0.72	278	0.85
4.	Percent Green Cover = 91 + ((-0.4*Traffic Events) * (SWC * -1.28)) - (-0.5*SWC)	0.70	289	0.81
5.	Percent Green Cover = 91 + ((-1.3*Traffic Events) * (SWC * -1.28)) * (-1.3*Traffic Events)	0.65	394	0.73
6.	Percent Green Cover = 124 + (((-1.3*Traffic Events) * (SWC * -1.28)) * -0.009) / (-1.3*Traffic Events)	0.62	456	0.71
7.	Percent Green Cover = 96 + (((-1.3*Traffic Events) / (SWC * -1.28)) * -0.009) / (-1.3*Traffic Events)	0.61	487	0.68
8.	Percent Green Cover = 96 + (((-1.3*Traffic Events) / (SWC * -1.28)) * -0.009) / (-0.06*SWC)	0.60	521	0.65
9.	Percent Green Cover = 96 + (((-1.3*Traffic Events) * (SWC * -1.28)) * -0.009) / (-0.06*SWC)	0.55	549	0.61
10.	Percent Green Cover = 96 + (((-1.3*Traffic Events) * (SWC * -1.28)) * -0.009) * (-0.06*SWC)	0.55	578	0.59
11.	Percent Green Cover = 96 + (((-1.3*Traffic Events) * (SWC * -1.28)) / -0.009) * (-0.06*SWC)	0.54	599	0.57
12.	Percent Green Cover = 124 / ((-1.3*Traffic Events) * (SWC * -1.28)) / ((SWC*SWC) * -1.28)	0.53	676	0.56
13.	Percent Green Cover = 124 / ((-1.3*Traffic Events) - (SWC * -1.28)) / ((SWC*SWC) * -1.28)	0.52	732	0.56
14.	Percent Green Cover = 124 / ((-1.3*Traffic Events) + (SWC * -1.28)) / ((SWC*SWC) * -1.28)	0.51	756	0.55
15.	Percent Green Cover = 124 / ((-1.3*Traffic Events) * (SWC * -1.28)) * ((SWC*SWC) * -1.28)	0.51	783	0.54
16.	Percent Green Cover = 124 / ((-1.3*Traffic Events) * (SWC * -1.28)) / ((Traffic Events*Traffic Events) * -1.28)	0.50	799	0.51
17.	Percent Green Cover = 124 + ((-1.3*Traffic Events) * (SWC * -1.28)) * ((Traffic Events*Traffic Events) * -1.28)	0.49	825	0.50
18.	Percent Green Cover = 124 - ((-1.3*Traffic Events) * (SWC * -1.28)) / ((Traffic Events*Traffic Events) * -1.28)	0.49	857	0.48
19.	Percent Green Cover = 124 * ((-1.3*Traffic Events) * (SWC * -1.28)) / ((Traffic Events*Traffic Events) * -1.28)	0.48	894	0.47
20.	Percent Green Cover = 124 - ((-1.3*Traffic Events) * (SWC * -1.28)) * ((Traffic Events*Traffic Events) * -1.28)	0.48	943	0.45
21.	Percent Green Cover = 124 + ((-1.3*Traffic Events) * (SWC * -1.28)) - ((Traffic Events*Traffic Events) * -1.28)	0.47	978	0.43
22.	Percent Green Cover = 124 - ((-1.3*Traffic Events) * (SWC * -1.28)) + ((Traffic Events*Traffic Events) * -1.28)	0.46	1045	0.43
23.	Percent Green Cover = 124 - ((-1.3*Traffic Events) * (SWC * -1.28)) * ((Traffic Events*-1.28) + (SWC*-1.3))	0.45	1280	0.42
24.	Percent Green Cover = 124 * (-1.3*Traffic Events) + ((Traffic Events+SWC)*-0.009) - (-1.28*SWC)	0.44	1331	0.42
25.	Percent Green Cover = 124 / (-1.3*Traffic Events) + ((Traffic Events+SWC)*-0.009) - (-1.28*SWC)	0.43	1356	0.41
26.	Percent Green Cover = 124 + (-1.3*Traffic Events) * ((Traffic Events+SWC)*-0.009) * (-1.28*SWC)	0.42	1388	0.40
27.	Percent Green Cover = 124 + (-1.3*Traffic Events) + ((Traffic Events+SWC)*-0.009) + (-1.28*SWC)	0.42	1412	0.40
28.	Percent Green Cover = 124 - (-1.3*Traffic Events) - ((Traffic Events+SWC)*-0.009) - (-1.28*SWC)	0.41	1489	0.38
29.	Percent Green Cover = 124 * (-1.3*Traffic Events) * ((Traffic Events*SWC)*-0.009) * (-1.28*SWC)	0.42	1532	0.37
30.	Percent Green Cover = 124 / (-1.3*Traffic Events) / ((Traffic Events+SWC)/-0.009) / (-1.28*SWC)	0.41	1567	0.36
31.	Percent Green Cover = 124 + (-1.3*Traffic Events) + ((Traffic Events+SWC)*-0.009) / (-1.28*SWC)	0.40	2845	0.35
32.	Percent Green Cover = 90 * (-1.52*SWC) + (Traffic Events*Traffic Events)	0.40	3189	0.34
33.	Percent Green Cover = 90 / (-1.52*SWC) + (Traffic Events*Traffic Events)	0.39	3697	0.34
34.	Percent Green Cover = 90 - (-1.52*SWC) + (Traffic Events*Traffic Events)	0.38	3976	0.33
35.	Percent Green Cover = 90 + (-1.52*SWC) - (Traffic Events*Traffic Events)	0.37	4589	0.32
36.	Percent Green Cover = 90 + (-1.52*SWC) + (Traffic Events*Traffic Events)	0.36	5034	0.31
37.	Percent Green Cover = 90 + (-1.52*SWC) / (Traffic Events*Traffic Events)	0.35	5069	0.30
38.	Percent Green Cover = 90 + (-1.52*SWC) * (Traffic Events*Traffic Events)	0.34	5312	0.30
39.	Percent Green Cover = 95 + (-1.55*Traffic Events) - SWC*-1.28	0.33	5467	0.28
40.	Percent Green Cover = 95 - (-1.55*Traffic Events) - SWC/Traffic Events	0.32	5899	0.27
41.	Percent Green Cover = 95 * (-1.55*Traffic Events) - SWC*Traffic Events	0.31	6456	0.26
42.	Percent Green Cover = 95 / (-1.55*Traffic Events) - SWC*SWC	0.25	6948	0.25
43.	Percent Green Cover = 95 / (-1.55*Traffic Events) - SWC	0.20	7329	0.21
44.	Percent Green Cover = 129 + (-1.55*Traffic Events) + (SWC * -1.52)	0.20	7409	0.21
45.	Percent Green Cover = 90 + (-1.52*SWC)	0.15	7654	0.18
46.	Percent Green Cover = 95 + (-1.55*Traffic Events)/SWC	0.10	8345	0.08
47.	Percent Green Cover = 95 + (-1.55*Traffic Events)*SWC	0.05	9323	0.05
48.	Percent Green Cover = 95 + (-1.55*Traffic Events)-(SWC*SWC)	0.05	9345	0.03
49.	Percent Green Cover = 95 + (-1.55*Traffic Events)+SWC	0.01	10214	0.01
50.	Percent Green Cover = 95 + (-1.55*Traffic Events)	0.01	12456	0.01
		0.01	14567	0.01
		0.01	15788	0.01

†Percent green cover measured using digital image analysis every two traffic events

‡Number of traffic events simulated using Baldree traffic simulator

§Soil water content determined by time domain reflectometer

Table 2- 3. Models and coefficients of determination (R^2), Akaike's An Information Criterion (AIC), and leave-one-out cross-validation coefficient of determination (Cross R^2) evaluated to predict green turfgrass cover in response to soil water contents across traffic events applied to hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. X *C. transvaalensis* Burt Davy, 'Tifway'] established sand root zone meeting USGA specifications. Fifty traffic events were applied over 10 weeks (5 per week) across three water contents (Low = 0.08, Medium = 0.16, and High = $0.25 \text{ m}^3/\text{m}^3$) during fall 2014 and 2015 in Knoxville, TN.

	Model	R^2	AIC	Cross R^2
1.	Percent Green Cover [†] = $101 + (-1.36 * \text{Traffic Events}^\ddagger) + ((\text{Traffic Events} * \text{SWC}^\S) * -0.01)$	0.91	81	0.95
2.	Percent Green Cover = $101 - (-1.36 * \text{Traffic Events}) - ((\text{Traffic Events} * \text{SWC}) * -0.01) + 0.197$	0.80	155	0.93
3.	Percent Green Cover = $100 * (1.96 * \text{SWC}) + ((\text{Traffic events} * \text{SWC}) * -0.08)$	0.76	244	0.84
4.	Percent Green Cover = $106 + (-1.55 * \text{Traffic Events}) + (\text{SWC} + -0.022934)$	0.76	333	0.82
5.	Percent Green Cover = $66 + (1.96 / \text{Traffic Events}) - ((\text{SWC} / \text{Traffic Events}) * -0.08)$	0.75	367	0.80
6.	Percent Green Cover = $104 - (-1.45 * \text{Traffic Events}) / ((\text{SWC}) * -0.005)$	0.74	399	0.78
7.	Percent Green Cover = $104 / (-1.46 * \text{Traffic Events}) \wedge ((\text{Traffic Events} * \text{SWC}) * -0.05)$	0.69	457	0.75
8.	Percent Green Cover = $100 - ((-1.46 * \text{Traffic Events}) \wedge ((\text{Traffic Events} * \text{SWC}) * -0.06)) / -1.46$	0.68	488	0.65
9.	Percent Green Cover = $104 - ((-1.46 * \text{Traffic Events}) \wedge (\text{Traffic Events} * -1.46)) / -0.06$	0.68	492	0.63
10.	Percent Green Cover = $66 - (1.96 * \text{SWC}) / ((\text{Traffic Events} * \text{SWC}) * -0.08)$	0.66	543	0.60
11.	Percent Green Cover = $67 / (-2.723959 / \text{Traffic Events}) / ((\text{Traffic Events} * \text{SWC}) * -0.06)$	0.65	645	0.56
12.	Percent Green Cover = $100 + (\text{SWC} / \text{Traffic Events}) * ((\text{Traffic Events} * \text{SWC}) / -0.02)$	0.61	678	0.53
13.	Percent Green Cover = $100 - (\text{Traffic Events} * \text{SWC}) + ((\text{SWC} - \text{Traffic Events}) * -0.08)$	0.59	711	0.51
14.	Percent Green Cover = $101 - (-1.36 * \text{Traffic Events}) + ((\text{SWC} / \text{Traffic Events}) * -0.022934)$	0.54	769	0.49
15.	Percent Green Cover = $100 - (-2.72 / (\text{SWC} + \text{Traffic Events})) * ((\text{SWC} - \text{Traffic Events}) * -0.01)$	0.50	821	0.47
16.	Percent Green Cover = $67 / (-1.96 * \text{Traffic Events}) / \text{Traffic Events} + ((\text{SWC} / \text{Traffic Events}) / -0.08)$	0.49	855	0.45
17.	Percent Green Cover = $101 - ((-1.36 - \text{Traffic Events}) / \text{SWC}) - ((\text{Traffic Events} + \text{SWC}) - 0.08)$	0.48	889	0.43
18.	Percent Green Cover = $106 + (-1.55 + \text{Traffic Events}) + ((\text{Traffic Events} + \text{SWC}) * -0.08)$	0.47	932	0.42
19.	Percent Green Cover = $67 / ((1.96 / \text{SWC}) * ((\text{SWC} / \text{Traffic Events}) / -0.028))$	0.46	967	0.40
20.	Percent Green Cover = $101 - (-1.55 * \text{Traffic Events}) * ((\text{Traffic Events} * \text{SWC}) / -0.08)$	0.44	988	0.39
21.	Percent Green Cover = $100 - ((-1.45 * \text{Traffic Events}) + ((\text{Traffic Events} * \text{SWC}) * -0.08)) - 1.45$	0.42	1120	0.37
22.	Percent Green Cover = $100 + (-0.26 - \text{SWC}) + ((\text{SWC} - \text{Traffic Events}) / -0.01)$	0.41	1345	0.36
23.	Percent Green Cover = $67 + ((-1.45 * \text{Traffic Events}) / (\text{SWC} * 0.6)) - ((\text{SWC}) * -0.01)$	0.41	1590	0.34
24.	Percent Green Cover = $100 * (-1.45 * \text{Traffic Events}) * ((\text{Traffic Events} * \text{SWC}) * 0.08)$	0.40	1678	0.33
25.	Percent Green Cover = $101 / (-1.45 + \text{Traffic Events}) + ((\text{Traffic Events} + \text{SWC}) + -0.08)$	0.39	1754	0.31
26.	Percent Green Cover = $104 * (-1.45 * \text{Traffic Events}) + ((\text{SWC} / \text{Traffic Events}) / -0.01)$	0.38	1789	0.29
27.	Percent Green Cover = $104 + ((-1.45 + -1.45) * \text{Traffic Events}) / (\text{SWC} * -0.01)$	0.37	1832	0.27
28.	Percent Green Cover = $104 / (-1.45 * \text{Traffic Events}) + (\text{SWC} * -0.01)$	0.24	1845	0.23
29.	Percent Green Cover = $101 + ((-2.723959 * \text{Traffic Events}) * \text{Traffic Events}) + (\text{SWC} * -0.01)$	0.15	1932	0.17
30.	Percent Green Cover = $70 + (-0.26 * \text{SWC}) \wedge (-0.27 * \text{SWC})$	0.10	2156	0.12
31.	Percent Green Cover = $106.4 + (-1.55 * \text{Traffic Events}) * ((\text{SWC} * 0.06)$	0.09	2289	0.06
32.	Percent Green Cover = $106.4 - (-1.55 * \text{Traffic Events}) - (\text{SWC} * -0.09)$	0.08	3590	0.03
33.	Percent Green Cover = $69 * (-0.26 * \text{SWC}) + (\text{Traffic Events} \wedge -0.022934)$	0.01	6900	0.01
34.	Percent Green Cover = $69.9 - (-0.26 * \text{SWC})$	0.01	8450	0.01

[†]Percent green cover measured using digital image analysis every two traffic events

[‡]Number of traffic events simulated using Baldree traffic simulator

[§]Soil water content determined by time domain reflectometer

APPENDIX B. FIGURES

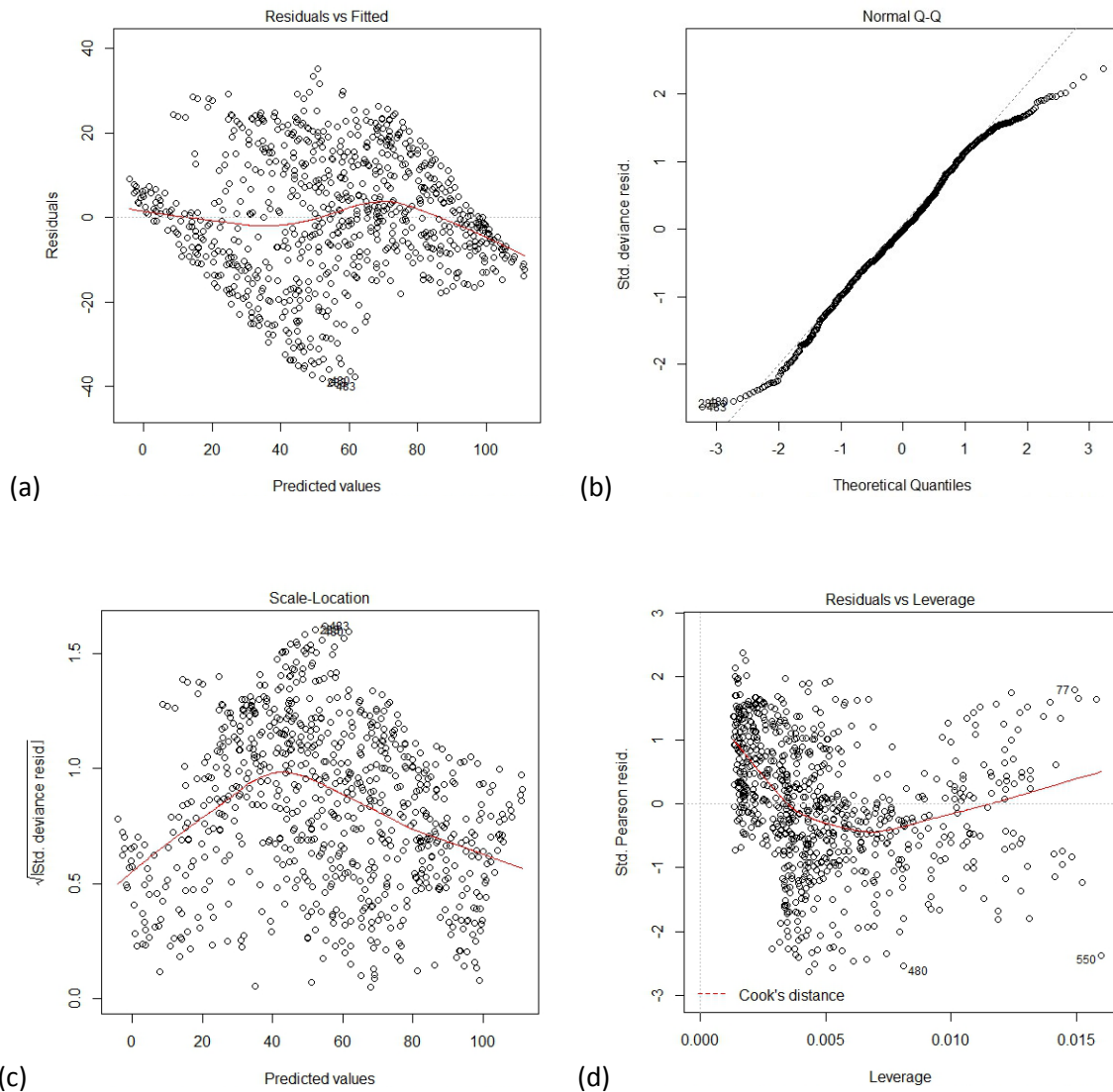


Figure 2-1. Plots to determine best fit for the predictive model of loss of green turfgrass cover changes in response to soil water contents across traffic events applied to hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. X *C. transvaalensis* Burt Davy, ‘Tifway’] established on a silt loam soil. Fifty traffic events were applied over 10 weeks (5 per week) across four soil water contents (Low = 0.10, Medium = 0.17, Medium-High = 0.26, and High = 0.35 m³/m³) during fall 2014 and 2015 in Knoxville, TN.

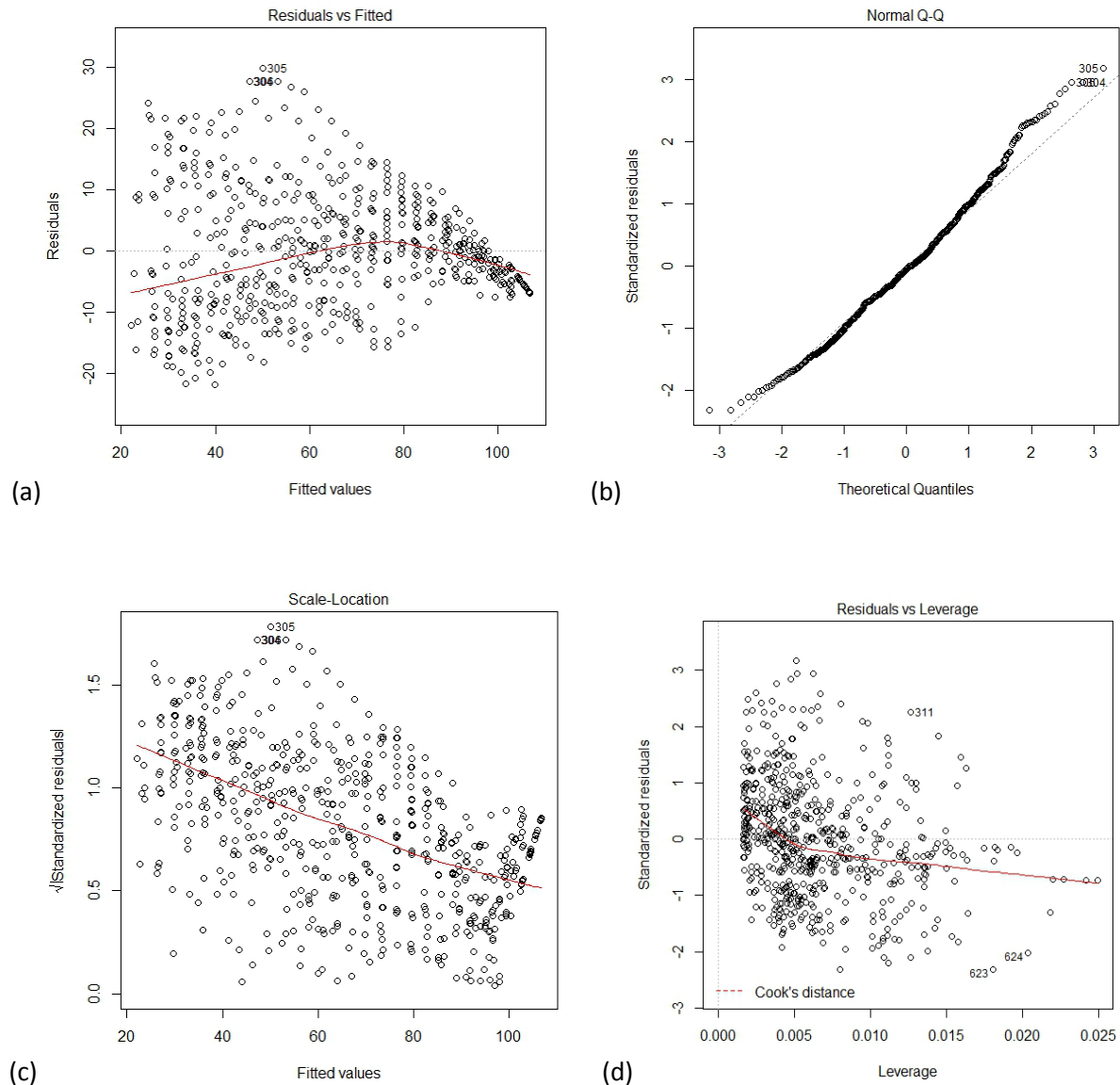


Figure 2-2. Plots to determine best fit for the predictive model of loss of green turfgrass cover changes due in response to soil water contents across traffic events applied to hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. X *C. transvaalensis* Burt Davy, ‘Tifway’] established on a sand root zone meeting USGA specifications. Fifty traffic events were applied over 10 weeks (5 per week) across three water contents (Low = 0.08, Medium = 0.16, and High = 0.25 m³/m³) during fall 2014 and 2015 in Knoxville, TN.

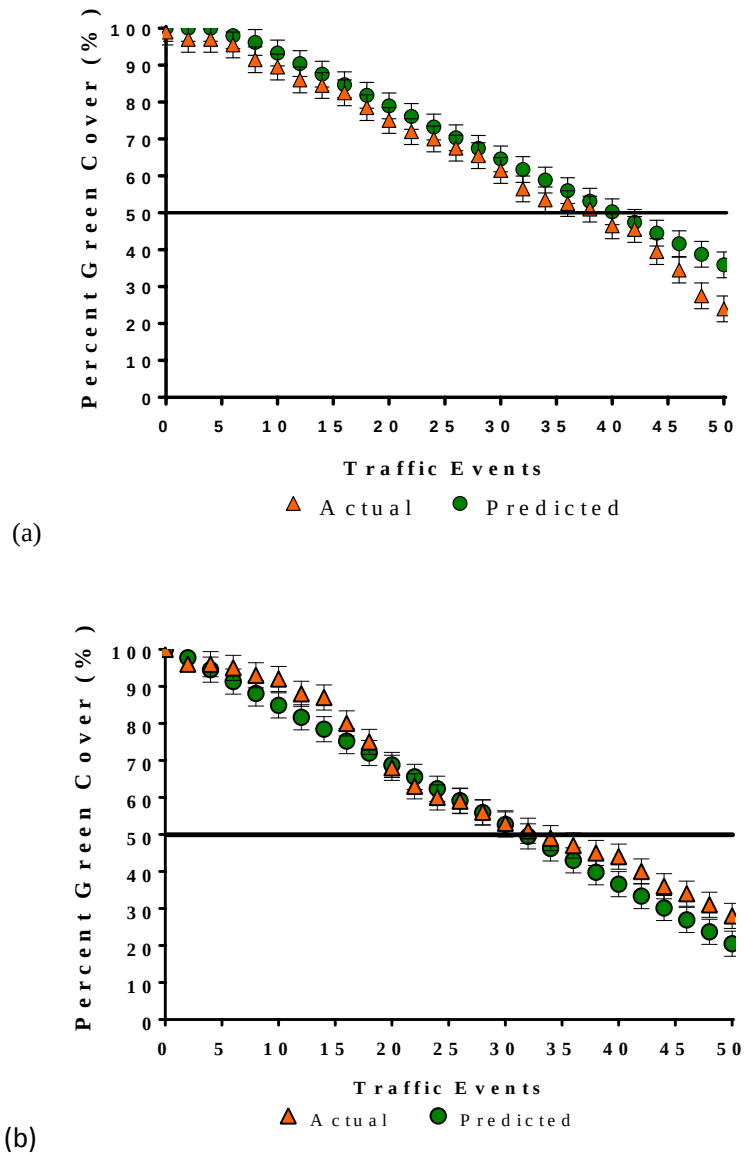


Figure 2-3. Predicted versus actual changes in green turfgrass cover in response to soil water content ($a = 0.17 \text{ m}^3/\text{m}^3$, $b = 0.16 \text{ m}^3/\text{m}^3$) across traffic events applied to hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. X *C. transvaalensis* Burtt Davy, 'Tifway'] established on (a) silt loam soil and (b) sand meeting USGA specification root zone. Fifty traffic events were applied over 10 weeks (5 per week) during fall 2014 and 2015 in Knoxville, TN. Error bars represent Fisher's LSD values at $\alpha \leq 0.05$ within each traffic event as a means statistical comparison. Black line in graph represents when 50% green turfgrass cover is achieved.

CONCLUSIONS

Hybrid bermudagrass established in a cohesive soil performed best at a SWC range of $0.07 \text{ m}^3/\text{m}^3$ to $0.20 \text{ m}^3/\text{m}^3$ in this experiment. Plots maintained using the high SWC treatment lost cover at a rate four times faster than those maintained via the low and medium SWC treatments, and 3.2 times faster than the medium-high SWC treatment. As SWC increased, the cohesive soil entered a liquid state, altering soil structure when a compressive force was applied, as indicated by shear strength and surface hardness data. A minimum limit of 50 G_{MAX} is suggested for establishment as a guideline for maximizing athletic field safety on Tifway hybrid bermudagrass surfaces established on cohesive root zones similar to that studied herein.

On a non-cohesive root zone, few differences in hybrid bermudagrass GTC loss were detected among SWC treatments; however traffic increased compaction and reduced GTC for all SWC treatments evaluated. All SWC ranges (0.06 to $0.30 \text{ m}^3/\text{m}^3$) tested provide consistent soil physical properties and GTC loss due to traffic application.

Models were developed to accurately predict loss of GTC due to SWC on cohesive and non-cohesive root zones. Separate models were created for each root zone; however, the same variables (SWC and traffic events) predicted GTC loss on each. The impact of SWC is strongly reflected in the model of the cohesive root zone. However, there are limitations (grass species, soil texture, time of year, etc.) to the models; further study is needed to determine the extent of these limitations.

VITA

Kyley Hampton Dickson was born in Cleveland, TN on June 14, 1989 to Dwight and Ginny Dickson. He grew up in Jamestown, TN and attended York Agricultural Institute, graduating in 2008. After graduation he pursued a B.S. degree from the University of Tennessee with an emphasis in turfgrass management. He graduated in the spring of 2012 and started work on a M.S. degree. In 2014, he completed his M.S. and began work on his Ph. D. under Dr. John Sorochan. Upon finishing his dissertation, Kyley plans to pursue a job as a professor at a university.