8-2006

Determining Wear Tolerance of Turfgrass Species for Athletic Fields in the Transition Zone

Jordan Rhea Goddard

University of Tennessee - Knoxville

To the Graduate Council:

I am submitting herewith a thesis written by Jordan Rhea Goddard entitled "Determining Wear Tolerance of Turfgrass Species for Athletic Fields in the Transition Zone." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Plant Sciences.

John C. Sorochan, Major Professor

We have read this thesis and recommend its acceptance:

J. Scott McElroy, Robert S. Freeland, Thomas J. Samples, Douglas E. Karcher

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

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

To the Graduate Council:

I am submitting herewith a thesis written by Matthew Jordan Rhea Goddard entitled "Determining Wear Tolerance of Turfgrass Species for Athletic Fields in the Transition Zone." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Plant Sciences.

John C. Sorochan
Major Professor

We have read this thesis and recommend its acceptance:

J. Scott McElroy

Robert S. Freeland

Thomas J. Samples

Douglas E. Karcher

Accepted for the Council:

Anne Mayhew
Vice Chancellor and Dean of Graduate Studies

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

DETERMINING WEAR TOLERANCE OF TURFGRASS SPECIES FOR ATHLETIC FIELDS IN THE TRANSITION ZONE

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee,
Knoxville

Matthew Jordan Rhea Goddard
August 2006

DEDICATION

I dedicate this Thesis to my parents, Ken and Linda, my sister Kara, and my loving family and friends. They are the joy of my life and have provided me with the love and support that keeps me going everyday.

“Dream as if you’ll live forever:
Live as if you’ll die today.”
-James Dean (1931-55)

“I shall be telling this with a sigh
Somewhere ages and ages hence:
Two roads diverged in a wood, and I-
I took the one less traveled by,
And that has made all of the difference.”
-Robert Frost (1915)

ACKNOWLEDGMENTS

For their support and guidance at the University of Tennessee I wish to express sincere appreciation to my graduate committee members: Dr. J. Scott McElroy, Dr. Robert S. Freeland, Dr. Thomas J. Samples, and Dr. Douglas E. Karcher (University of Arkansas). Thank you for your continued guidance, support, and friendship during my time at UT. Also, I give special thanks to committee chair Dr. John Sorochan, not only for guidance, but for his fellowship, his commitment to excellence, and allowing me the opportunity to excel in my chosen discipline.

I also give special thanks to Travis Tueton, Josh Landreth, Dan Strunk, Rodney Tocco, and Johnny Parham for their guidance, much needed assistance, and the friendships I have gained. They helped to make this research possible and their fellowship helped to make my time at the University of Tennessee enjoyable.

I would also like to express my sincere appreciation for Lee Ellis, Bobby McKee, and their staff at the East Tennessee Research and Education Center. Their dedication and enthusiasm towards helping students and faculty in continued research projects is very much appreciated.

ABSTRACT

A study to evaluate the performance of four different turfgrass varieties under simulated athletic field traffic in the transition zone was conducted in Tennessee and Arkansas. 'Thermal Blue' hybrid bluegrass (*Poa arachnifera* Torr. x *P. pratensis* L.) has been introduced as a bluegrass variety bred for increased heat and drought tolerance. This variety provides a possible alternative to bermudagrass varieties in transition zone athletic fields. 'Thermal Blue' was compared to common bermudagrass (*Cynodon dactylon* L. Pers.) varieties 'Riviera' and 'Quickstand' and the hybrid bermudagrass (*C. dactylon* L. Pers. *x C. transvaalensis* Burt-Davy) variety 'Tifway'. Each turfgrass species was tested with and without a 2 cm crumb rubber topdressing application in their first year of establishment. The Cady Traffic Simulator was used to simulate athletic field traffic on each plot. Low and high traffic conditions were obtained by applying 1 and 3 traffic applications, respectively week^{-1}. 'HTBG' proved to be acceptable for use in transition zone athletic fields. 'Riviera' showed comparable wear tolerance to 'Tifway'. 'Quickstand' showed the lowest wear tolerance of the varieties tested. Crumb rubber topdressing resulted in a significant increase in turfgrass wear tolerance, and a decrease in surface hardness, soil bulk density, and shear resistance.

Ground-Penetrating Radar (GPR) was tested to see if it could be used to detect soil compaction incidences in athletic field environments. GPR readings were compared to Clegg Impact Soil Tester (Clegg hammer) readings taken from Shields-Watkins Field in Neyland Stadium, Knoxville, Tenn. Visual comparisons between the two methods showed that maps produced using GPR were comparable to those produced with the

Clegg hammer. GPR can possibly be a method for predicting compaction in athletic field soils.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

PART 1

INTRODUCTION

INTRODUCTION

Throughout the world, athletic fields are used for many different kinds of sports and recreational activities. The majority of athletic fields are faced with budget limitations which can result in improper construction and maintenance. For example, due to budget constraints, the field managers of many municipal and high school athletic fields are unable to implement proven turfgrass maintenance techniques, which would allow turfgrasses to recover from intense traffic. As a result, the quality and safety of these fields suffer. To address this problem, a study to investigate alternative species and crumb rubber application was initiated for municipal and grade school athletic field managers with limited budgets in the transition zone.

The transition zone is a region known in the turf industry located in the central U.S. which includes parts of four distinct climate regions (Christians, 2004). The boundary between the temperate and subtropical climates in the eastern United States marks the approximate location of the transition zone (Turgeon, 1996). Most cool-season and warm-season grasses are not well-adapted to the transition zone (Christians, 2004). In this area, warm-season turfgrasses have difficulty surviving the low temperature extremes. Conversely, cool-season turfgrasses struggle to survive the warm humid summer conditions. Although most turfgrass species will grow in this area, very few will thrive if even survive.

Most Kentucky bluegrass (*Poa pratensis*) (KBG) varieties do not perform well in the transition zone due to their lack of tolerance to heat, drought, and disease (NTEP, 2004). Texas bluegrass (*Poa arachnifera*) (TBG), mainly a forage grass, demonstrates

better heat and drought tolerance relative to KBG, but has poor turfgrass quality (Abraham et al., 2004). Recent crossings of KBG and TBG have introduced improved bluegrass hybrids for use in the transition zone. A resulting hybrid, 'Thermal Blue' KBG (HTBG), which has some desirable characteristics of each species (Carson 2004), will be used in this study. This turf variety was compared to three different bermudagrass (*Cynodon dactylon* L. Pers.) and hybrid bermudagrass (*Cynodon dactylon* L. Pers. *x C. transvaalensis* Burt-Davy) varieties to determine which of the grasses performs best under simulated athletic field traffic.

Bermudagrass is a common warm-season athletic turf in the southern United States. This species is widely adapted warm-season turfgrass and is used in numerous applications from the transition zone to tropical regions of the world (Beard, 1973). In warm-season areas, sports turf is generally dominated by bermudagrass cultivars (Puhalla et al., 1999). The transition zone is an area where bermudagrass reaches its northern limit of adaptation (Bruneau et al., 2004). Warm-season grasses are known to go into complete dormancy and lose color as temperatures decline and when frost occurs (Minner & Valverde, 2004). A dormant turf lacks the ability to fill worn areas.

As athletic fields are used, wear patterns form in the high traffic areas and soils become compacted. It is difficult for any turfgrass to recover and actively grow in compacted soils. Compaction ultimately becomes detrimental to turfgrass growth for two primary reasons: turf root systems cannot get the oxygen they need, and the compacted soil becomes a physical barrier to root penetration (Puhalla et al., 1999). As a result, surface hardness increases and turf cover decreases. Core aerification is a common and

effective cultural practice used to alleviate soil compaction on athletic fields (Christians, 2004). However, many sports turf mangers of low budget athletic fields consider core aerification too expensive (Smith, 2000).

Another preventative method of reducing wear and compaction on athletic fields is through the use of crumb rubber topdressing. In the United States alone, there are 281 million scrap tires generated each year. This is a 20% increase from the 234 million tires generated in 1991 (Priselac, 2006). Many state governments prohibit these tires from landfills and most have legislated government funding to recycle these tires (Riggle, 1994). Crumb rubber is a product of recycled tires. The rubber from these tires is ground into small particles (7mm or less) for use in other markets.

One such market is the use of crumb rubber as a soil amendment for the sports turf industry. A United States Patent by R.C. Malmgren et al. (1991) explains the use of crumb rubber as a soil amendment and the reduction of negative impacts associated with soil compaction from heavy athletic wear. Studies show that crumb rubber is an efficient, economical and environmentally sound soil amendment, and that topdressing crumb rubber (2 cm) provided a softer, more resilient surface, and as a soil amendment significantly reduces the amount of compaction or surface hardness on athletic fields (Groenevelt and Grunthal, 1998; Rogers, et al., 1998). In addition, crumb rubber topdressing increases turfgrasses wear tolerance under trafficked conditions (Rogers, et al., 1998). For this study, crumb rubber topdressing was applied at a depth of 2 cm.

Soil compaction data was collected using a Clegg Impact Soil Tester (Clegg, 1976) or Clegg hammer. Clegg hammers have been used for years to measure the hardness or

compaction of road bases and construction sites. These techniques, adapted through highway and building construction, are now being used to determine the playability of athletic fields by measuring the soil compaction. A Clegg hammer can be used to test natural and artificial athletic fields where hardness is a concern (GENEQ Inc.). If an athletic field is too hard, a greater risk of injury to the player is present.

A Clegg hammer uses a compaction hammer to measure surface soil compaction. The hammer, contained within a tube, is dropped from a certain height to the point of impact on the soil surface. An accelerometer located within the system calculates the surface hardness by measuring the duration of impact. The shorter the time period it takes for the hammer to stop, the greater the deceleration and the harder the tested surface (Clegg, 1978). Upon impact with the soil, a signal is displayed as deceleration time curves which store data reliable to 1 g (g = acceleration due to gravity) (Rogers and Waddington, 1992). Higher values reflect increased soil compaction and a harder surface.

Another way of measuring soil compaction is by using Ground-Penetrating Radar (GPR). GPR is a means of measuring variations in soil profiles. GPR uses broad band radar waves to provide a subsurface soil profile without disrupting the soil. As the GPR system moves across the ground, radar waves are sent down into the soil profile. The length of time it takes for the reflections to reach the antenna determines depth, shape, and even type of material present. Radar waves are reflected back to the reciever and a vertical or lateral map is produced. These maps are color coded and given values to show the areas containing significant variations in the soil profile. Traditionally GPR is used to

locate foreign objects buried deep in soil profiles. For this study we investigated the potential of using GPR as a method to measure slight variations in soil surface and subsurface characteristics (compaction). This technology may prove to be a valuable tool for timing preventative soil compaction practices.

A GPR system consists of an antenna which slides across the ground surface sending and receiving electromagnetic pulses. GPR offers a fast and nondestructive way for estimating the soils dielectric constant (Chanzy et al., 1996). Reflected waveforms are formed by subsurface layers of differing dielectric contrasts (Freeland et al., 2002). Increased reflectivity, characteristic of more highly compacted soils, produces brighter reflections that are received by the GPR unit. A GPS receiver mounted on top of the GPR system provides ground truthing of these waveforms using DGPS, allowing the operator to precisely mark the location of the GPR data. The operator of a GPR system uses a hand switch to insert points of reference into the radar image as the system passes over a predetermined grid or marker. These marks allow for linear positioning of the images later during post-processing of the data.

Justification

Many municipal facilities and high schools have bermudagrass based athletic fields. Unfortunately, these fields provide the best playing surface during the summer months when the fields are not being used, and a dormant surface in the early parts of fall when the fields are often exposed to high traffic and use. Dormant turf lacks the ability to fill in areas of the playing surface which become worn or damaged during competition. The risk of player injury increases to potential inconsistencies in uniform turf cover. The

ability of a turf to provide foot traction, surface friction, and cushion from shock reduces the potential for player injury (Sherratt, 2004).

Objectives

The objectives of this study are 1) to determine the optimum turfgrass species for transition zone athletic fields, 2) to determine the effects of crumb rubber topdressing on warm and cool-season turfgrass athletic fields in the transition zone, 3) to investigate the effectiveness of Ground Penetrating Radar as a method to measure surface hardness variations in athletic fields.

LITERATURE CITED

Abraham, E.M., B. Huang, S.A. Bonos, and W. A. Meyer. 2004. Evaluation of drought resistance for Texas bluegrass, Kentucky bluegrass, and their hybrids. Crop Science 44.5 (Sept-Oct): 1746-1753.

Beard, J.B. 1973. Turfgrass: Science and culture. Prentice Hall Publishing, Englewood Cliffs, NJ.

Bruneau, A.H., Peacock, C.H., Cooper, R.J. and Erickson, E.J. 2004. Cynodon Spp. Management Programs for the Upper Transition Zone in the Southeastern United States. Acta Hort. (ISHS) 661:551-557

Carson, T. 2004. Beating the Heat but not the Blues. Golf Course Management. Vol. 72, No. 9, September, p. 28.

Chanzy, A, A. Tarrussov, A. Judge, F. Bonn. 1996. Soil water Determination using a digital Ground-Penetrating Radar. Soil Sci. Soc. Of America Journal 60(5): 1318-1326

Christians, N. E. 2004. Fundamentals of Turfgrass Management. 2nd. John Wiley & Sons, Inc., Hoboken, New Jersey.

Clegg, B. 1976. An impact testing device for in situ base course evaluation. Australian Road Res. Bur. Proc., 8, 1-6

Clegg, B., 1978. An impact soil test for low cost roads. In: Proceedings of the 2nd conference of the road engineers association of Asia and Australia, Australia, pp. 62–66

Freeland, R. S., R. E. Yoder, J. T. Ammons, L. L. Leonard. 2002. Integration of Real-Time Global Positioning With Ground-Penetrating Radar Surveys. Applied Engineering in Agriculture. Vol. 18(5):647–650

Groenevelt P.H., and P.E. Grunthal. 1998. Utilization of crumb rubber as a soil amendment for sports turf. Soil & Tillage Research 47:169-172

Malmgren, R.C., Parviz, N., Soltanpour, P.N., Cipra, J.E., 1991. Soil amendments with rubber particles, U.S. Patent 5, 014, 562

Minner, D. D., and F. J. Valverde. 2004. Effect of plastic mulching on color retention on seeded bermudagrass varieties during fall season. Iowa Turfgrass Res. Rep. p. 58-59.

National Turfgrass Evaluation Program. 2004. http://www.ntep.org/data/kb00/kb00_05-9/kb0005t06.txt

Priselac, A. Mar 2006. Scrap Tires in Region 9. U.S. Environmental Protection Agency, Region 9 Solid Waste Program. http://www.epa.gov/region09/waste/solid/tires/.

Puhalla J., J. Krans, and M. Goatley. 1999. Sports Fields: A Manual for Design, Construction and Maintenance. Ann Arbor Press, Chelsea, New Jersey.

Riggle, D., 1994. Finding markets for scrap tires: utilization options. Biocycle 35 (3), pp. 41–55

Rogers, J. N., III, and D.V. Waddington. 1992. Impact Absorption and traction Characteristics of Turf and Soil Surfaces. Agronomy Journal 84 (2):203-209

Rogers, J. N., III, J. T. Vanini, and J. R. Crum. 1998. Simulated traffic on Turfgrass Topdressed with Crumb Rubber. Agronomy Journal 90 (2):215-221 Mar-Apr.

Smith, T. 2000. Managing Athletic Fields on a Tight Budget. Grounds Maint. 35(9):p. C1, C4, C16.

Sherratt, P. J., J. R. Street, and R. Margraf. 2004. Athletic field grass establishment and wear tolerance endorsed by the Safe Foundation. p. [1-5]. In 74th Annual Michigan Turfgrass Conference Proceedings. January 19-21, 2004, Lansing, MI. East Lansing, MI: Michigan State University.

Turgeon, A. J. 1996. Turfgrass Management. 4th. Prentice Hall, Upper Saddle River, New Jersey.

PART 2

THE EFFECTS OF CRUMB RUBBER TOPDRESSING ON KENTUCKY BLUEGRASS AND BERMUDAGRASS ATHLETIC FIELDS IN THE TRANSITION ZONE

ABSTRACT

Crumb rubber is a material produced from recycled car tires. The rubber from these tires is ground into particles, 6 mm or less and used for other markets. One such market is for athletic fields. Topdressing crumb rubber has shown to reduce surface hardness and increase turfgrass wear tolerance under simulated athletic traffic. Plots containing ‘Thermal Blue’ Kentucky bluegrass (HTBG), and ‘Riviera,’ ‘Quickstand,’ and ‘Tifway’ bermudagrasses, were topdressed twice at 2.93 kg m^{-2} each to achieve a 2 cm depth. Traffic was applied to each plot using a Cady Traffic Simulator at low (2 passes $week^{-1}$) and high (6 passes $week^{-1}$) traffic levels to simulate athletic field wear. Timing of traffic applications coincided with actual fall athletic seasons ranging from October to December 2005 in Knoxville, TN and Fayetteville, AR. ‘HTBG’ proved to be acceptable for use in transition zone athletic fields. ‘Riviera’ showed comparable wear tolerance to ‘Tifway’. ‘Quickstand’ showed the lowest wear tolerance of the varieties tested. Crumb rubber topdressing resulted in a significant increase in turfgrass wear tolerance, and a decrease in surface hardness, soil bulk density, and shear resistance.

INTRODUCTION

The turfgrass transition zone is a region found in the central part of the U.S. which includes parts of four distinct climactic regions (Christians, 2004). The boundary between the temperate and subtropical climates in the eastern United States marks the approximate location of the transition zone (Turgeon, 1996), and most cool-season and warm-season grasses are not well adapted to this region (Christians, 2004). In this area, warm-season turfgrasses often have difficulty surviving low temperature extremes. Conversely, cool season turfgrasses struggle to survive the warm, humid summer conditions. Although most turfgrass species will grow in this area, few will thrive if they are capable of surviving.

Athletic fields require a turfgrass species that can withstand traffic and recuperate from wear. Kentucky bluegrass (*Poa pratensis* L.) (KBG) and perennial ryegrass (*Lolium perenne* L.) are used extensively on cool season athletic fields; where as, bermudagrass (*Cynodon dactylon* L. Pers.) is used extensively on warm season athletic fields. In the transition zone, bermudagrass is the most common turfgrass used for athletic fields, because of its excellent wear and recuperative potential. 'Tifway' bermudagrass (*C. dactylon* L. Pers. *x C. transvaalensis* Burt-Davy) has excellent wear and recuperative potential and is a desirable choice for athletic fields (Puhalla et al., 1999). However, cost and cold tolerance often limit its use for athletic fields in the transition zone. Instead, less expensive and wear tolerant seeded varieties are often used. Overseeding athletic fields in the transition zone, with perennial ryegrass, provides an actively growing turf surface when the bermudagrass enters winter dormancy from first

frost in late fall until early spring (Puhalla et al., 1999). Perennial ryegrass helps maintain a safer and more playable athletic field surface when recuperative growth of bermudagrass has ceased and use continues. Unfortunately, overseeding is limited to athletic fields with substantial budgets, and in Tennessee most municipal and grade school athletic field managers do not have budgets to permit fall overseeding. As a result, these athletic fields are subjected to significant wear during periods when active growth does not occur.

Turfgrass breeding efforts have developed improved turfgrass varieties that are better adapted to the transition zone. Most Kentucky bluegrass varieties do not perform well in the transition zone due to a lack of tolerance to heat, drought, and disease. Texas bluegrass (*Poa arachnifera* Torr.) (TBG), mainly a forage grass, demonstrates higher levels of heat and drought resistance relative to KBG, but has poor turfgrass quality (Abraham et al., 2004). Recent crossings of KBG and TBG have introduced improved bluegrass varieties. Interspecific hydridization of KBG and TBG have been recently released with improved heat and drought. A resulting hybrid, 'Thermal blue' (*P. pratensis x P. arachnifera*; HTBG), is a turfgrass possessing genetic traits from each species (Carson, 2004). As an athletic turf, 'HTBG' can survive the hot humid summer conditions of the transition zone, and actively grow during the fall when fields are in use. The ability to manager 'HTBG' in the transition zone introduces the possibility of using a cool-season turfgrass on athletic fields and thereby eliminating the need for fall overseeding.

‘Riviera’ bermudagrass is an improved common bermudagrass cultivar that is similar to ‘Tifway’ bermudagrass in density and overall quality (Morris, 2002). In addition, it has greater cold tolerance and can be established from seed. However, the wear tolerance and recuperative potential of ‘Riviera’ is not well defined.

Previous research determined crumb rubber topdressing significantly improved Kentucky bluegrass wear tolerance when subjected to simulated athletic field traffic (Rogers et al., 1998). Crumb rubber is finely ground rubber from used car tires. Studies show that crumb rubber is an efficient, economical, and environmentally sound soil amendment. By topdressing crumb rubber (2 cm), a softer, more resilient surface, is provided (Groenevelt and Grunthal, 1998; Rogers et al., 1998). As a soil amendment, crumb rubber significantly reduces the amount of compaction or surface hardness on athletic fields (Rogers et al., 1998). In addition, crumb rubber topdressing increases turfgrasses wear tolerance under trafficked conditions. However, the use of crumb rubber topdressing for bermudagrass athletic fields is not well documented, and comparisons with Kentucky bluegrass warrant investigation.

There are thousands of high school and municipal athletic fields in the transition zone. In warm-season areas, sports turf is generally dominated by bermudagrass cultivars (Puhalla et al., 1999). ‘Tifway’ bermudagrass is the benchmark variety for this region. The transition zone is an area where bermudagrass reaches its northern limit of adaptation (Bruneau et al., 2004). Warm-season turfgrasses are known to lose color as temperature declines and when frost occurs. Overseeding athletic fields in this area is a common practice among athletic field managers to provide a lush, green, actively growing turf

surface as bermudagrasses enter winter dormancy. Because of budget limitations, most of the athletic field managers do not overseed. This would provide an actively growing turf surface during the fall athletic season. A dormant turf lacks the ability to fill worn areas.

Research Objectives

The objectives of this study are to 1) to determine the wear tolerance of four turfgrasses in the transition zone under simulated athletic field conditions, 2) to compare the effects of crumb rubber topdressing on four turfgrass species in the transition zone under simulated athletic field conditions, 3) to determine if improved cool and warm-season turfgrass species can be used for athletic fields in the transition zone.

MATERIALS AND METHODS

A study to evaluate turfgrass species and crumb rubber under simulated athletic field traffic was conducted in Tennessee and Arkansas. Research locations included the East Tennessee Research and Education Center in Knoxville, TN, and the University of Arkansas Agricultural Research and Extension Center, in Fayetteville, AR. Experiments were initiated on 25 Sept 2005 at both locations. The study was conducted on Sequatchie silt loam soil (fine-loamy, siliceous, semiactive, thermic Humic Hapludult) in Tennessee, and on Captina silt loam soil (fine-silty, siliceous, active, mesic Typic Fragiudult) in Arkansas.

Experimental design was a randomized complete block with a split-strip plot treatment arrangement. Turfgrass species served as main plot factors. Main plots were split into crumb rubber or no crumb rubber treatments. Two traffic levels (low and high)

were stripped over each plot as a strip factor. Turf species included ‘Thermal Blue’ Kentucky bluegrass (HTBG), and ‘Riviera,’ ‘Quickstand,’ and ‘Tifway’ bermudagrasses. Each turf species was established using methods that would most likely be used by high school or municipal athletic field managers. ‘HTBG’ plots were established as sod and ‘Riviera’ plots were seeded at 150 kg ha^{-1}on 6 May 2005 and 10 May 2005 in Fayetteville, AR and Knoxville, TN, respectively. ‘Quickstand’ and ‘Tifway’ plots were sprigged at 3.1 m^3 ha^{-1} on 7 June 2005 and 9 June 2005 in Fayetteville, AR and Knoxville, TN, respectively. The ‘HTBG’ and bermudagrass treatments received 12 kg ha^{-1} and 49 kg ha^{-1} ammonium nitrate (34-0-0, Tennessee Farmers Cooperative, LaVergne, Tenn. 37086) $week^{-1}$, respectively during establishment (Table 1, all tables and figures are in the appendix). Once established, 24 kg N ha^{-1} and 49 kg N ha^{-1} complete fertilizer (15-15-15, Tennessee Farmers Cooperative, LaVergne, Tenn. 37086) $month^{-1}$ was applied to the ‘HTBG’ and bermudagrasses, respectively (Table 1). Plots were mown three times $week^{-1}$ with a rotary mower, at a height of 3.2 cm for the ‘HTBG’ and 2 cm for the bermudagrasses during active growth. Irrigation was applied throughout the study as needed to prevent drought stress. Weeds were removed by hand to hasten grow-in.

Crumb rubber plots were topdressed twice at 2.93 kg m^{-2} each to achieve a two centimeter depth. Topdressing was applied by hand brushed in with an industrial broom. The crumb rubber was a 10/20 mesh particle size.

Traffic was applied using the Cady Traffic Simulator (CTS) (Henderson et al., 2005). The CTS is a walk-behind Jacobsen™ core cultivation unit with artificial feet to

simulate athletic wear. The CTS unit produces approximately 667 cleat marks m^{-2} and has a traffic width of 2.19 m. Traffic applications consisted of low and high wear levels using one and three traffic applications $week^{-1}$, respectively, in Tennessee and Arkansas, starting 7 Oct 2005 and ending 9 Dec 2005; where one traffic application consisted of two passes with the CTS (Henderson et al., 2005). Timing of traffic applications was established to mimic fall high school football schedules.

Percent green cover was evaluated weekly during the traffic applications using digital image analysis (DIA) (Karcher and Richardson, 2005). Turfgrass cover was visually estimated using a percent scale (0-100) at the conclusion of the traffic treatments to determine total vegetative cover. Visual vegetative cover ratings were also measured to account for both green and dormant turf vegetation. A 2.5 kg Clegg Impact Hammer (Lafayette Instruments, Lafayette, IN) was used to measure (three random drops per plot) surface hardness (G_{max}) prior to and at the conclusion of traffic treatments. A Turfgrass Shear Tester (TST) (Dr Baden Clegg Pty Ltd, Jolimont, Western Australia) was used to determine turfgrass shear strength (Nm) (three per plot) prior to and at the conclusion of the traffic treatments (Gaussoin et al., 2002).

Soil samples were collected from each treatment and a control plot where no traffic was applied using a 5 cm x 5 cm sampling tube similar to the one described by Uhland (1950) to determine soil physical properties. Soil physical analysis included soil bulk density (BD), macro (air filled porosity-AP) and micro-porosity (capillary porosity-CP), saturated hydraulic conductivity (k_{sat}), and percent organic matter (OM) accumulation. Immediately after removing the cores, excess soil was removed from the bottom of each

sample and cheese cloth was attached to the bottom end using a rubber band. Verdure, thatch, and rubber were also removed from the top of the cores to leave only soil. Each sample tube was measured for height (mm) and recess (mm) to obtain a volume calculation for each sample. Once volume was obtained, a 2.5 cm deep extension ring was secured to the top of each sample using a section of a rubber bicycle inner-tube (Callahan et al., 2001). Samples were placed in a room temperature water bath, with approximately 4mm head of water. Soil analyses were conducted in accordance with USGA analytical methods (Ferguson et al., 1960; USGA, 1973).

Data were analyzed using PROC MIXED from the SAS system for Microsoft Windows, version 9.1 (Statistical Analysis Software, Cary, N.C.) ($p = 0.05$).

RESULTS AND DISCUSSION

After six weeks of traffic (low = 14 and high = 42 passes, respectively) percent green cover measurements in Arkansas showed significant interaction between turfgrass variety, crumb rubber topdressing, and traffic levels (Table 2). Low traffic did not significantly affect percent turfgrass green cover for ‘Riviera’ and ‘Quickstand’ bermudagrasses regardless of crumb rubber levels (Table 3). However, green turfgrass cover was higher in plots with crumb rubber for all turfgrass species under high traffic levels (Table 4). ‘Tifway’ and ‘Riviera’ bermudagrass maintained greater green turfgrass cover than ‘Quickstand’ (47.5, 44.8, and 37.1 %, respectively) bermudagrass but not ‘HTBG’ (42.3 %)(Figure 1).

After seven weeks of traffic (low = 16 and high = 48 passes, respectively), regardless of traffic levels or crumb rubber topdressing, ‘Riviera’ bermudagrass

maintained more turfgrass cover than ‘Tifway’ or ‘HTBG’, which were significantly greater than ‘Quickstand’ bermudagrass (66, 55, 51, and 41 %, respectively) (Table 5). As expected, high traffic plots maintained lower vegetative turfgrass cover than low traffic plots regardless of species and crumb rubber levels (Table 4). In addition, when subjected to high traffic, plots receiving crumb rubber topdressing had significantly higher vegetative turfgrass cover (42%) than plots without crumb rubber (21%) at the same level of traffic, regardless of species.

In Tennessee, after six weeks of traffic (low = 14 and high = 42 passes, respectively), under low traffic, HTBG maintained greater green turfgrass cover (77%) than ‘Quickstand’ and ‘Tifway’ bermudagrasses (68 and 57%, respectively), but not ‘Riviera’ (70 %). ‘Riviera’ maintained greater green turf cover than ‘Tifway’ but not greater than ‘Quickstand’ under low traffic (Table 3). No significant differences occurred among species in high traffic plots for any of the varieties tested. ‘HTBG’ maintained greater green turfgrass cover in low traffic plots versus high traffic plots (77 and 69%, respectively).

Vegetative cover, after seven weeks of traffic (low = 16 and high = 48 passes, respectively), was significantly higher in ‘Riviera’, ‘HTBG’, and ‘Tifway’ plots than the ‘Quickstand’ plots in the low traffic treatments (88, 84, 83, and 72%, respectively) (Table 3). Similar results occurred in the high traffic plots with ‘HTBG’, ‘Tifway’, and ‘Riviera’ having significantly greater vegetative turf cover than the ‘Quickstand’ plots (62, 59, 56, and 29%, respectively). In addition, all species had greater vegetative turfgrass cover in low traffic treatments. Percent green cover measurements were lower

than vegetative cover measurements because of the turfgrass species entering winter dormancy. These observations show that even though the bermudagrass species included in this study were entering winter dormancy during the fall athletic season, ‘Riviera’ and ‘Tifway’ still provided acceptable turfgrass cover. ‘Quickstand’ provided significantly less vegetative cover than the other turfgrass varieties at each traffic level even though it retained its green cover longer than ‘Tifway’. Crumb rubber significantly improved vegetative turf cover for both levels of traffic (Table 4). As expected, high traffic treatments had significantly less vegetative turf cover than low traffic treatments regardless of species and crumb rubber topdressing. In addition, crumb rubber topdressing significantly increased vegetative turfgrass cover regardless of species and traffic level.

Regardless of location, significant differences for surface hardness and shear resistance were noticed among plots receiving crumb rubber topdressing (Table 6). Crumb rubber topdressing significantly decreased surface hardness regardless of turfgrass species or traffic intensity (Table 7). These results support previous research showing the beneficial effects crumb rubber has on reducing turfgrass surface hardness for athletic fields (Rogers, et al., 1998). Initially, crumb rubber reduced surface hardness by 34% in low traffic plots, and by 40% in high traffic plots in Arkansas. At the end of the study, crumb rubber topdressing reduced surface hardness by 35% in low traffic plots and by 46% in high traffic plots. In Tennessee, plots topdressed with crumb rubber showed a 20% reduction in surface hardness in low traffic plots, and an 18% reduction in high traffic plots at the beginning of the study. At the end of the study, a 20 and 26%

reduction was observed in low and high traffic plots, respectively. A non-peer reviewed publication regarding specifications for acceptable Clegg impact ratings on athletic fields state an acceptable impact range between 30 – 130 G_{max}, with an optimum range of 75-95 G_{max} (Stewart, 2003). In both Arkansas and Tennessee, plots receiving crumb rubber topdressing consistently maintained G_{max} values below 75 (Table 7). Plots without crumb rubber were as high as 116 G_{max} and were always greater than 80, except for the low traffic treatment in Arkansas in December. This may have been caused by higher soil moisture levels late in the year.

Shear strength measurements were taken at each location at the end of the study. Crumb rubber applications also affected turfgrass shear strength, or its resistance to tearing. Plots receiving a 2 cm crumb rubber topdressing had significantly lower shear strengths than plots with out crumb rubber (Figure 2, Table 8). Crumb rubber decreases shear strength measurements because of the reduced contact the turfgrass shear tester has with the thatch and soil surface.

Significant differences ($P<0.05$) among soil data were calculated within turfgrass species at both Tennessee and Arkansas locations, and among traffic levels in Arkansas (Table 11). In Arkansas, regardless of traffic level, 'Riviera' plots had significantly higher bulk density than 'HTBG' and 'Tifway' (1.79, 1.73, and 1.68, respectively) (Table 12). Air filled and total porosity measurements were significantly lower in the 'Riviera' soils, showing that as bulk density increases, air filled porosity decreases. The increased bulk density was a result of the significant decrease in air-filled porosity, or compaction caused by the traffic treatments (12.0, 13.7, and 14.6 %, respectively). 'Quickstand' had

significantly higher bulk density and lower air-filled porosity than ‘Tifway’, but not from ‘HTBG’. ‘Riviera’ has no rhizomes during its first year of growth (Munshaw et al., 2001, Richardson et al., 2003). Because of this, less thatch is accumulated, thus soils are more easily compacted. ‘Quickstand’ is less dense and forms less thatch than ‘Tifway’. ‘HTBG’ sod had an accumulated thatch layer that may have provided a more resilient surface than ‘Riviera’ but not ‘Quickstand’. Organic matter accumulation in ‘HTBG’ was also significantly higher than ‘Riviera’. Both of these growth habits could have contributed to the differing amounts of OM accumulation noticed in these soils. Seeded establishment of ‘Riviera’ promotes vertical growth of young plants before lateral growth ensues. Traffic effects on soils in Arkansas showed that as traffic increases, bulk density increases, reducing soil porosity levels (Table 13) and concluding that increased athletic field wear can significantly increase soil compaction and the potential need for an athletic field manager to aerify.

In Tennessee, ‘Quickstand,’ ‘Riviera’, and ‘Tifway’ showed higher bulk density levels than ‘HTBG’. However, organic matter accumulation was higher in ‘HTBG’ (Table 12). This could also be caused by the aforementioned establishment of ‘HTBG’ by sod. Increased thatch accumulation in the ‘HTBG’ sod may have provided an increase in organic matter and a more resilient turf surface to combat surface soil compaction.

Conclusions

‘HTBG’ showed to be a suitable turfgrass species for use on high school and municipal athletic fields. ‘HTBG’ manufactured green color throughout the study and remained actively growing when bermudagrass species entered winter dormancy. Of the

bermudagrass varieties used, ‘Riviera’ and ‘Tifway’ showed the best tolerance to wear. ‘Quickstand’ consistently ranked lowest in percent vegetative cover at each location, showing that ‘HTBG’, ‘Riviera’, and ‘Tifway’ have heightened wear tolerance and are better suited for high use athletic fields.

A general increase in soil compaction over the course of the study as a result of traffic was observed. Plots receiving crumb rubber topdressing showed increased wear tolerance, and reduced surface hardness, shear strength, and bulk densities than plots without crumb rubber. Crumb rubber provided a more resilient surface reducing turfgrass wear as a result of athletic traffic, and a safer playing surface by prolonging turfgrass cover, and reducing surface hardness.

Further research to determine the effects of crumb rubber at different topdressing depths as well as traffic effects on each turfgrass variety once fully established, will be conducted in Knoxville, TN. This study will be continued to determine the effects of crumb rubber on turfgrass cover and soil characteristics over time.

LITERATURE CITED

Abraham, E.M., B. Huang, S.A. Bonos, and W. A. Meyer. 2004. Evaluation of drought resistance for Texas bluegrass, Kentucky bluegrass, and their hybrids. Crop Science 44.5 (Sept-Oct): 1746-1753.

Bruneau, A.H., Peacock, C.H., Cooper, R.J. and Erickson, E.J. 2004. Cynodon Spp. Management Programs for the Upper Transition Zone in the Southeastern United States. Acta Hort. (ISHS) 661:551-557

Callahan, L. M., R. S. Freeland, J. M. Parham, A. M. Saxton, R. D. von Bernuth, D. P. Shepard and J. M. Garrison. 2001. Geotextiles as an intermediate layer in USGA and USGA-Type Greens. Univ. of Tennessee Institute of Agriculture. Bulletin 699.

Carson, T. 2004. Beating the Heat but not the Blues. Golf Course Management. Vol. 72, No. 9, September, p. 28.

Cockerham, S.T. 1989., and D.J. Brinkman. 1989. A simulator for cleated-shoe sports traffic on turfgrass research plots. Calif. Turfgrass Cult. 39(3-4):9-10.

Christians, N. E. 2004. Fundamentals of Turfgrass Management. 2nd. John Wiley & Sons, Inc., Hoboken, New Jersey.

Ferguson, M. H., L. Howard, and M. E. Bloodworth. 1960. Laboratory methods for evaluation of putting green soil mixtures. U. S> Golf Assn. J. of Turf Mgt. 13:5-8.

Gaussoin, R., D. Minner, J. Sorochan, J. Stier, J. III Rogers, R. Shearman, et al. 2002. A method for determining lateral shear strength in turf. Annu. Meet. Abstr.

Groenevelt P.H., and P.E. Grunthal. 1998. Utilization of crumb rubber as a soil amendment for sports turf. Soil & Tillage Research 47:169-172

Henderson, J. J., J. L. Lanovaz, J. N. Rogers, III, J. C. Sorochan, and J. T. Vanini. 2005. A new apparatus to simulate Athletic field Traffic: The Cady Traffic Simulator. Agron. J 97: 1153-1157.

Karcher, D. E., M. D. Richardson. 2005. Batch Analysis of Digital Images to Evaluate Turfgrass Characteristics. Crop Sci. 45:1536-1539

Morris, K.N. 2002. National Turfgrass Evaluation Program. 1997 National Bermudagrass Test. NTEP No. 02–7. USDA, Beltsville, MD.

Munshaw, G.C, D.W. Williams and P.L. Cornelius. 2001. Management strategies during the establishment year enhance production and fitness of seeded bermudagrass stolons. Crop Science 41:1558-1564.

Richardson, M.D., D. E. Karcher, and L. C. Purcell. 2001. Quantifying turfgrass cover using digital image analysis. Crop Science 41 (6):1884-1888 Nov-Dec.

Richardson, M., D. Karcher, J. Boyd, and J. McCalla. 2003. Managing the new seeded bermudagrasses. Golf Course Manage. 71(12):p. 81-84.

Rogers, J. N., III, J. T. Vanini, and J. R. Crum. 1998. Simulated traffic on Turfgrass Topdressed with Crumb Rubber. Agronomy Journal 90 (2):215-221 Mar-Apr.

Puhalla J., J. Krans, and M. Goatley. 1999. Sports Fields: A Manual for Design, Construction and Maintenance. Ann Arbor Press, Chelsea, New Jersey.

Stewart, B. 2003. What to do with a hard field. SportsTURF. 19(1):p. 24, 26.

Turgeon, A. J. 1996. Turfgrass Management. 4th. Prentice Hall, Upper Saddle River, New Jersey.

Uhland, R. E. 1950. Physical Properties of soils as modified by crops and management. Soil Sci. Soc. Am. Proc. 194:361-366

USGA Green Section Staff. 1973. Refining the green section specifications for putting green construction. U.S. Golf Assn. Green Sec. Rec. 11:1-8.

APPENDICES

APPENDIX A

METHODOLOGY FOR USING GROUND-PENETRATING RADAR TO DETERMINE SOIL COMPACTION AND SOIL LAYERING IN ATHLETIC FIELDS

ABSTRACT

A unique survey protocol has been developed that maps subsurface soil inconsistencies using ground-penetrating radar (GPR) and differentially corrected geographical positioning systems (DGPS) in athletic fields. This article describes the methods used to combine DGPS with GPR subsurface imagery technologies to provide real-time position location and differences in soil profiles on athletic field surfaces. GPR is effective in providing nondestructive, near-surface underground images. Features surveyed for athletic field root zone profiles include soil compaction variances, and soil horizon depth and layering. Soil compaction is a major issue in modern day athletic fields. Information provided by the GPR system is compared to surface hardness measurements taken with a Clegg Impact Soil Tester (Clegg hammer) to determine if GPR can identify variances in soil reflections and predict soil compaction. Images produced by the GPR system were similar to those produced by the Clegg hammer.

INTRODUCTION

Throughout the world, athletic fields are used for many different kinds of sports and recreational activities. Thus, fields require regular maintenance and care. Soil compaction is a problem on many native soil athletic fields. However, the majority of athletic fields are faced with budget limitations which can result in improper construction and maintenance. For example, field managers of many municipal and high school athletic fields are unable to utilize proven turfgrass maintenance techniques, such as aerification, which would allow turfgrasses to recover from intense traffic. As a result, the quality and safety of these fields suffer.

Athletic fields are areas subject to high use and wear, which ultimately results in loss of turfgrass cover and a potential increase in soil compaction. Compaction problems occur in athletic fields when the soils macro porosity (air-filled pores) is reduced which increases the bulk density ($^{mass}/_{volume}$ of dry soil). It is difficult for any turfgrass to actively grow and recover from wear in compacted soils. Compaction ultimately becomes detrimental to turfgrass growth for two primary reasons: turf root systems cannot get the oxygen they need, and the compacted soil becomes a physical barrier to root penetration (Puhalla et al., 1999). When soils become compacted, athletic field managers aerify, which is a common and effective cultural practice used to alleviate soil compaction on athletic fields (Christians, 2004). This can be a costly practice, especially to low budgeted high school and municipal athletic fields. For many sports turf mangers aerification is often too expensive (Smith, 2000). Until now, depicting areas of concern where increased soil compaction is present has been a guessing game. Managers often

treat the entire field surface, not knowing where major problem areas are located. However, Ground-Penetrating Radar (GPR) can potentially reduce the cost of properly maintaining athletic fields by pinpointing compacted areas before they become to problematic.

Measuring Soil Compaction

Several tools have been developed to measure amounts of soil compaction. For instance, the Clegg Impact Soil Tester (Clegg, 1976) has been used for years to measure the hardness or compaction of road bases and construction sites. These techniques, adapted through highway and building construction, are now being used to determine the acceptability of athletic fields for play by measuring the surface hardness or soil compaction. A Clegg hammer can be used to test natural and artificial athletic fields where surface hardness is a concern (Lafayette Instuments, Lafayette, IN). If an athletic field is too hard, there is a greater risk of injury to a player.

A Clegg hammer uses a compaction hammer to measure surface soil compaction. The hammer, contained within a tube, is dropped from a certain height to the point of impact on the soil surface. An accelerometer located within the system calculates the amount of compaction by determining the amount of resistance on the hammer when it reaches the soil surface (World Enzymes Australia). Upon impact with the soil, a signal is displayed as deceleration time curves which store data reliable to 1 g (g = acceleration due to gravity) (Rogers 1992). Higher values reflect increased soil compaction incidences.

Ground Penetrating Radar (GPR) (Geophysical Survey Systems, Inc.) is a means of measuring variations in soil profiles. GPR is a system that uses broad band radar waves to provide a subsurface soil profile without disrupting the soil. As the GPR system moves across the ground, radar waves are sent down into the soil profile. The length of time it takes for the reflections to reach the antenna determines depth, shape, and type of material present. The waves are reflected back to the reciever and a vertical or lateral map is produced. These maps are color coded and given values to show the areas containing significant variations in the soil profile. Traditionally GPR is used to locate foreign objects buried deep in soil profiles. For this study, the potential of using GPR as a method to measure slight variations in soil surface characteristics (compaction) will be investigated. This technology may prove to be a valuable tool for preventative soil compaction measurements.

A GPR system consists of an antenna which slides across the grounds surface sending and receiving electromagnetic pulses. GPR offers a fast and nondestructive way of estimating the soils dielectric constant (Chanzy et al., 1996). Reflected waveforms are formed by subsurface layers of differing dielectric contrasts (Freeland et al., 2002). Increased reflectivity, characteristic of more highly compacted soils, produces brighter reflections that are received by the GPR unit. A GPS receiver mounted on top of the GPR system provides ground truthing of these waveforms using DGPS (Trimble Navigation Limited), allowing the operator to precisely mark the location of the GPR data. The operator of a GPR system uses a hand switch to insert points of reference into

the radar image as the system passes over a predetermined grid or marker. These marks allow for linear positioning of the images later during post processing of the data.

GPR is a surface-geophysical method that depends on the emission, transmission, reflection, and reception of an electromagnetic pulse and can produce continuous high-resolution profiles of the subsurface rapidly and efficiently (Beres and Haeni, 1991). GPR has several uses including water-related subsurface issues such as locating the groundwater table, estimating the soil water content, mapping wetting front movement, and identifying preferential flow pathways through which contaminant-loaded water may flow (Freeland et al., 2006). In other studies, GPR has been used for environmental sensing to detect buried tanks, landfill debris, water levels, and contaminated fluids (Peters et al., 1994). It was concluded that GPR provides clear, continuous delineation of subsurface features on sandy upland soils of Georgia's Coastal Plain (Hubbard et al., 1990). GPR can also detect the depth and spatial viability of argillic soil horizons and water tables (Truman et al., 1988). Finally, GPR has been used to study fragipan depth in a fragiudalf map unit in Northern Idaho (Doolittle et al., 2000). However, GPR has never been used in an athletic field environment; particularly, to measure soil compaction and layering.

Objective

The objectives of this project were to: 1) Determine if GPR combined with GPS can precisely determine where and when compaction problems may occur in an athletic field, Determine if GPR when combined with Clegg and GPS, data can produce a map

illustrating soil compaction, and 3) determine if GPR can determine root zone depths and location of soil layers within an athletic field.

MATERIALS AND METHODS

Equipment used in this project included: 1) a Clegg Impact Soil Tester (Clegg hammer), 2) a GPR unit, 3) a DGPS system for real–time positional data, 4) a GIS package (manufacturer), 5) a laptop computer, and 6) an electric powered golf cart (Figure 3). The DGPS antenna was mounted on top of the GPR antenna which was secured to a plastic sled. The sled was attached to the golf cart which was used to pull the sled across the turf surface. A computer connected to the GPR antenna continually recorded soil profiles, or slices, produced by the GPR system. The antenna was pulled at approximately 4.8 km hr^{-1} from one end zone to the other beginning on the east end of the field. Individual passes were approximately 1 meter apart. The GPR system was drawn over the field to make 26 total slices (Figure 4). A hand switch was used by the operator to insert points of reference into the radar image every 10 yards (9.14 m) to aid in post processing of the data.

Clegg data were obtained after the football season using a Clegg Impact Soil Tester in 2004 and 2005. In 2004, data points were taken every 20 yards (18.29 m) at 4 locations across the field, totaling 28 sampling locations. In 2005, data points were taken every 10 yards (9.14 m) at 7 locations across the field, totaling 77 sampling locations (Figure 5, 6). The average of 3 Clegg hammer readings was used to obtain values for each location.

Clegg hammer and GPR data were analyzed using ESRI's ArcView 9.1 software. GPR and Clegg data were interpolated using the Kriging method to estimate compaction incidences between data points. Maps produced by the GPR system were visually compared to maps produced using a Clegg hammer.

RESULTS AND DISCUSSION

GPR data collected from Neyland Stadium in Knoxville, Tenn. showed that compaction patterns produced by the GPR system reflected similar patterns as did the Clegg hammer data (Figure 7). Differing dielectric constants of the compacted soil layers allow the GPR system to detect areas where compaction is a concern. Reflections of areas of increased soil compaction showed up brighter than areas with lower compaction levels. Figure 8 shows a GPR slice taken from Neyland stadium. Figure 9 shows a section of the same GPR slice compared to a soil profile of Shields-Watkins field in Neyland Stadium, Knoxville, Tenn. Brighter reflections depict the soil layers associated with a sand-based athletic field profile.

Conclusions

Quantitative values for soil compaction cannot be determined using GPR alone. However, differences in surface hardness measurements using a Clegg hammer are visible via color difference using GPR. Soil layering issues, particularly organic matter build up, are easily detected using the GPR system. Further research is warranted for using GPR analysis for turfgrass root zones. Benefits associated with GPR could also include identifying irrigation breaks, or over-watering in athletic fields and golf courses,

pinpointing drainage problems, and identifying root zone depths in golf course putting greens.

LITERATURE CITED

Beres, Milan Jr, Haeni, F. P. 1991. Application of ground-penetrating-radar methods in hydrogeologic studies. Ground Water. Vol. 29, no. 3, pp. 375-386.

Chanzy, A, A. Tarrussov, A. Judge, F. Bonn. 1996. Soil water Determination using a digital Ground-Penetrating Radar. Soil Sci. Soc. Of America Journal 60(5): 1318-1326

Christians, N. E. 2004. Fundamentals of Turfgrass Management. 2nd. John Wiley & Sons, Inc., Hoboken, New Jersey.

Clegg, B. 1976. An impact testing device for in situ base course evaluation. Australian Road Res. Bur. Proc., 8, 1-6

Doolittle, J. A., G. Hoffmann, P. McDaniel, N. Peterson, B. Gardner, and E. Rowan. 2000. Ground–penetrating radar interpretations of a fragipan in Northern Idaho. Soil Surv. Hor. 41(3): 73–82.

Freeland, R. S., R. E. Yoder, J. T. Ammons, L. L. Leonard. 2002. Integration of Real-Time Global Positioning With Ground-Penetrating Radar Surveys. Applied Engineering in Agriculture. Vol. 18(5):647–650

Freeland, R. S., L.O. Odhiambo, J.S. Tyner, J.T. Ammons, W.C. Wright. 2006. Nonintrusive Mapping of Near-Surface Preferential Flow. Applied Engineering in Agriculture. Vol. 22(2): 315-319.

Hubbard, R. K., L. E. Asmussen, and H. F. Perkins. 1990. Use of ground–penetrating radar on upland Coastal Plain soils. J. of Soil and Water Conservation 45(May–June): 399–404.

Peters, L.P., Jr. Daniels, J.J. Young, J.D. 1994. Ground penetrating radar as a subsurface environmental sensing tool. Proceedings of the IEEE 82(12): 1802-1822.

Puhalla J., J. Krans, M Goatley. 1999. Sports Fields: A Manual for Design, Construction and Maintenance.

Rogers, J. N., III. 1992. Impact Absorption and traction Characteristics of Turf and Soil Surfaces. Agronomy Journal 84 (2):203-209 Mar-Apr

Smith, T. 2000. Managing Athletic Fields on a Tight Budget. Grounds Maint. 35(9):p. C1, C4, C16.

Truman, C. C., H. F. Perkins, L. E. Asmussen, and H. D. Allison. 1988. Using ground penetrating radar to investigate selected soil properties. J. of Soil and Water Conservation 43(4): 341–345.

APPENDIX B

TABLES

Table 1. Total nitrogen fertilization applied to turf species in Arkansas and Tennessee (kg ha^{-1}).

Turf Species	**May**†	**June**	**July**	**Aug**	**Sept**	**Oct**	**Nov**	**Total N**
HTBG	24‡	24	24	24	24	24	24	168
Riviera	195§	195	195	195	49	49	-	878
Quickstand	-	195	195	195	49	49	-	683
Tifway	-	195	195	195	49	49	-	683

† = May-Aug 34-0-0 was used, Sept-Nov 15-15-15 was used

‡ = 1/2 N rate was applied to the Bluegrasses 2x $month^{-1}$ May-Aug, 1/2 N rate was applied 1x $month^{-1}$ Sept-Nov

§ = 1x N rate was applied to the bermudagrasses weekly May-Aug, 1x N rate was applied 1x $month^{-1}$ Sept-Nov

Table 2. Analysis of variance of turfgrass cover showing significance among species, crumb rubber, and traffic treatments, Fayetteville, Ark and Knoxville, Tenn. November – December 2005.

Location	Effect	df	% Green Cover†	% Vegetative Cover‡
Arkansas	Rep	3	ns	ns
	Species (SP)	3	ns	<.0001
	Crumb Rubber (CR)	1	<.0001	0.0007
	SP*CR	3	ns	ns
	Traffic (TRF)	1	0.0009	0.0003
	SP*TRF	3	ns	ns
	CR*TRF	1	<.0001	<.0001
	SP*CR*TRF	3	0.0019	ns
Tennessee	Rep	3	ns	ns
	SP	3	0.016	<.0001
	CR	1	ns	<.0001
	SP*CR	3	ns	ns
	TRF	1	ns	0.0045
	SP*TRF	3	0.004	0.0012
	CR*TRF	1	ns	0.0017
	SP*CR*TRF	3	ns	ns

† = % green cover measured using digital image analysis to determine actively growing turf.

‡ = % vegetative cover measured visually to determine total turfgrass cover including dormant and actively growing turf.

Table 3. Interaction of turfgrass species and traffic showing significance for percent green (14 Nov 2005) and vegetative turfgrass cover (Dec 2005). Knoxville, Tenn.

		Traffic‡	
Cover	**Species**	**Low**	**High**
Green	HTBG	77 A	69 B
	Riviera	70 AB	67 B
	Quickstand	68 B	67 B
	Tifway	57 C	63 BC
Vegetative	HTBG	84 A	62 BC
	Riviera	88 A	56 C
	Quickstand	72 B	29 D
	Tifway	83 A	59 C

† = LSD $_{(0.05)}$

‡ = Traffic was applied using the Cady Traffic Simulator.

Table 4. Percent vegetative cover† as affected by crumb rubber and traffic at the end of the study at both locations.

		Crumb Rubber	
Location	**Traffic‡**	**0**	**2**
Arkansas	Low (14)	76 A	74 A
	High (42)	21 C	42 B
Tennessee	Low (14)	76 B	87 A
	High (42)	40 D	63 C

† = Visually estimated using a 1-100 percent scale

‡ = Traffic applied using CTS with low being 1x week^{-1}(2 passes) and high being 3x week^{-1} (6 passes)

Table 5. Percent vegetative cover as affected by turfgrass species in Fayetteville, Ark, December 2005.

Location	**Species**	**Percent Cover**
Arkansas	HTBG	51 B
	Riviera	66 A
	Quickstand	41 C
	Tifway	55 B

Table 6. Analysis of variance of surface hardness and shear resistance showing significance among treatments.

	Effect	df	Surface Hardness Dec	Shear Strength Dec
Arkansas	Rep	3	ns	ns
	Species (SP)	3	0.0005	0.0431
	Crumb Rubber (CR)	1	<.0001	<.0001
	SP*CR	3	ns	ns
	Traffic (TRF)	1	0.0007	0.0318
	SP*TRF	3	0.0153	0.0195
	CR*TRF	1	<.0001	ns
	SP*CR*TRF	3	ns	0.021
Tennessee	Rep	3	ns	ns
	SP	3	0.0144	ns
	CR	1	<.0001	<.0001
	SP*CR	3	0.0014	ns
	TRF	1	ns	ns
	SP*TRF	3	ns	ns
	CR*TRF	1	0.0005	ns
	SP*CR*TRF	3	ns	ns

Table 7. Surface hardness[†] as affected by crumb rubber and traffic in 2005.

		Traffic			
		October		December	
Location	**Crumb Rubber (cm)**	**Low**	**High**	**Low**	**High**
Arkansas	0	88 B	110 A	78 B	116 A
	2	58 D	65 C	51 D	63 C
Tennessee	0	90 A	89 A	88 B	96 A
	2	72 B	73 B	70 C	71 C

† = Surface hardness measured using a 2.5 kg Clegg Impact Hammer (G_{max})

Table 8. Surface hardness† and shear strength‡ as affected by crumb rubber in Knoxville, Tenn.

Location	**Crumb Rubber (cm)**	**Surface Hardness**	**Shear Strength**
		Oct	**Dec**
Tennessee	0	90 A	105 A
	2	73 B	80 B

† = Surface hardness measured using a 2.5 kg Clegg Impact Hammer (G_{max}).

‡ = Shear strength was measured using a Clegg Shear Tester (Nm).

Table 9. Surface hardness as affected by turfgrass species and crumb rubber in 2005.

		Crumb Rubber (cm)	
		December	
Location	**Species**	**0**	**2**
Arkansas	HTBG	108 A	60 D
	Riviera	87 C	50 E
	Quickstand	98 B	59 D
	Tifway	96 BC	59 D
Tennessee	HTBG	93 B	67 E
	Riviera	100 A	68 E
	Quickstand	90 BC	78 D
	Tifway	85 C	68 E

Table 10. Surface hardness as affected by species and traffic in Fayetteville, Ark, December 2005.

		Traffic	
Location	**Species**	**Low**	**High**
Arkansas	HTBG	66 D	101 A
	Riviera	58 E	79 C
	Quickstand	66 D	91 B
	Tifway	67 D	88 B

Table 11. Analysis of variance of different traffic levels on soil bulk density, porosity, organic matter, and infiltration rates in December 2005.

Location	**Effect**	**DF**	**BD**	**% AP**	**% CP**	**% TP**	**% OM**	**IR (cm/hr)**
Arkansas	Rep	3	ns	ns	ns	ns	0.05	ns
	Species (SP)	3	0.0017	0.018	ns	0.049	0.021	ns
	Crumb Rubber (CR)	1	ns	ns	ns	ns	ns	ns
	SP*CR	3	ns	ns	ns	ns	ns	ns
	Traffic (TRF)	1	0.0131	ns	0.033	0.046	ns	ns
	SP*TRF	3	ns	ns	ns	ns	ns	ns
	CR*TRF	1	ns	ns	ns	ns	ns	ns
	SP*CR*TRF	3	ns	ns	ns	ns	ns	ns
Tennessee	Rep	3	ns	ns	ns	ns	ns	ns
	SP	3	0.0047	ns	ns	ns	0.007	ns
	CR	1	ns	ns	ns	ns	ns	ns
	SP*CR	3	ns	ns	ns	ns	ns	ns
	TRF	1	ns	ns	ns	ns	ns	ns
	SP*TRF	3	ns	ns	ns	ns	ns	ns
	CR*TRF	1	ns	ns	ns	ns	ns	ns
	SP*CR*TRF	3	ns	ns	ns	ns	ns	ns

Table 12. Soil characteristics as affected by turfgrass species December 2005.

Soil Characteristics	Species	Arkansas Estimate	Tennessee Estimate
Bulk Density	HTBG	1.73 BC	1.78 B
	Riviera	1.79 A	1.91 A
	Quickstand	1.74 AB	1.94 A
	Tifway	1.68 C	1.91 A
Airfilled Porosity	HTBG	13.71 A	14.71 A
	Riviera	11.98 B	13.34 AB
	Quickstand	13.21 AB	12.64 B
	Tifway	14.63 A	13.76 AB
Total Porosity	HTBG	49.04 A	53.91 A
	Riviera	46.58 B	52.67 A
	Quickstand	48.08 AB	51.02 A
	Tifway	49.29 A	53.54 A
Organic Matter	HTBG	1.10 AB	1.11 A
	Riviera	1.08 B	1.07 B
	Quickstand	1.09 AB	1.07 B
	Tifway	1.11 A	1.08 B

Table 13. Soil characteristics as affected by traffic in Arkansas.

Soil Characteristics	**Traffic**	**Estimate**
Bulk Density	Low	1.69 B
	High	1.78 A
Capillary Porosity	Low	36.12 A
	High	33.61 B
Total Porosity	Low	49.40 A
	High	47.10 B

APPENDIX C

FIGURES

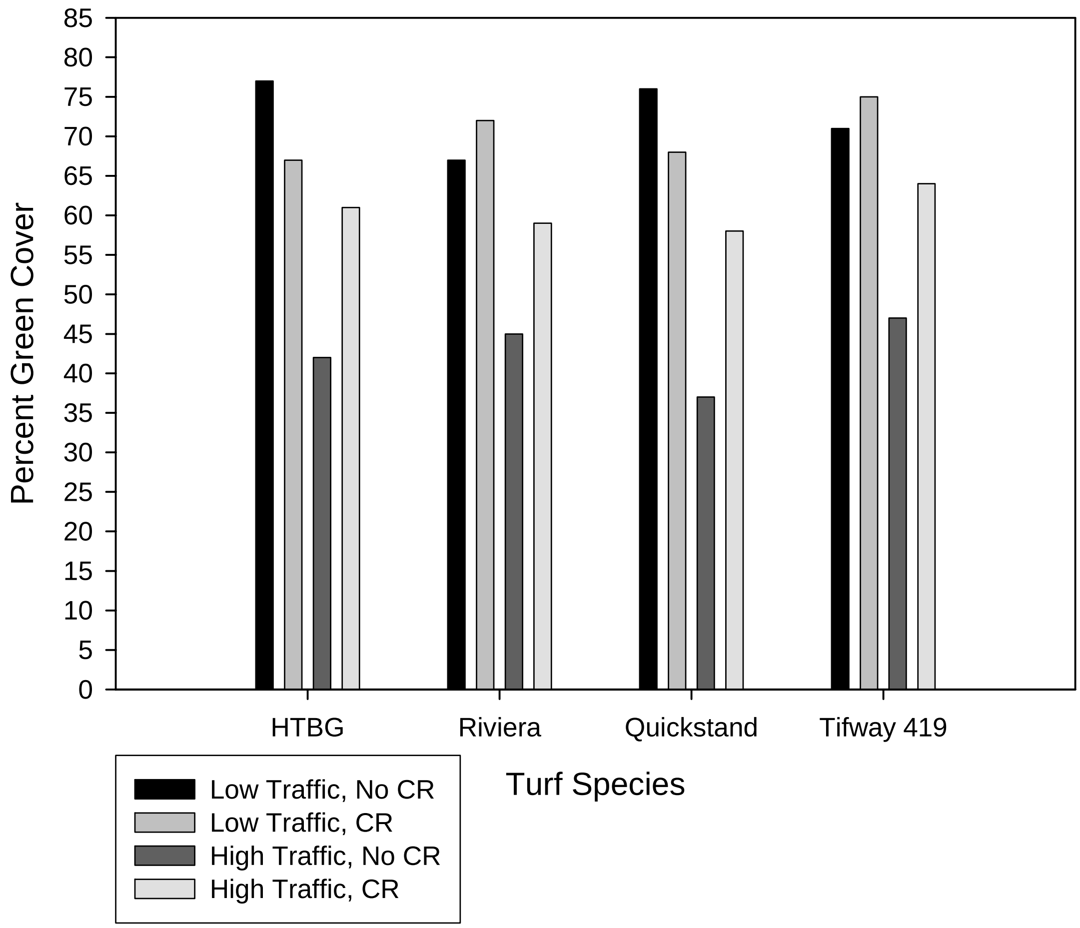

Figure 1. Green turfgrass cover as affected by turfgrass species, crumb rubber topdressing, and traffic levels in, Fayetteville, Ark. 11 Nov, 2005.

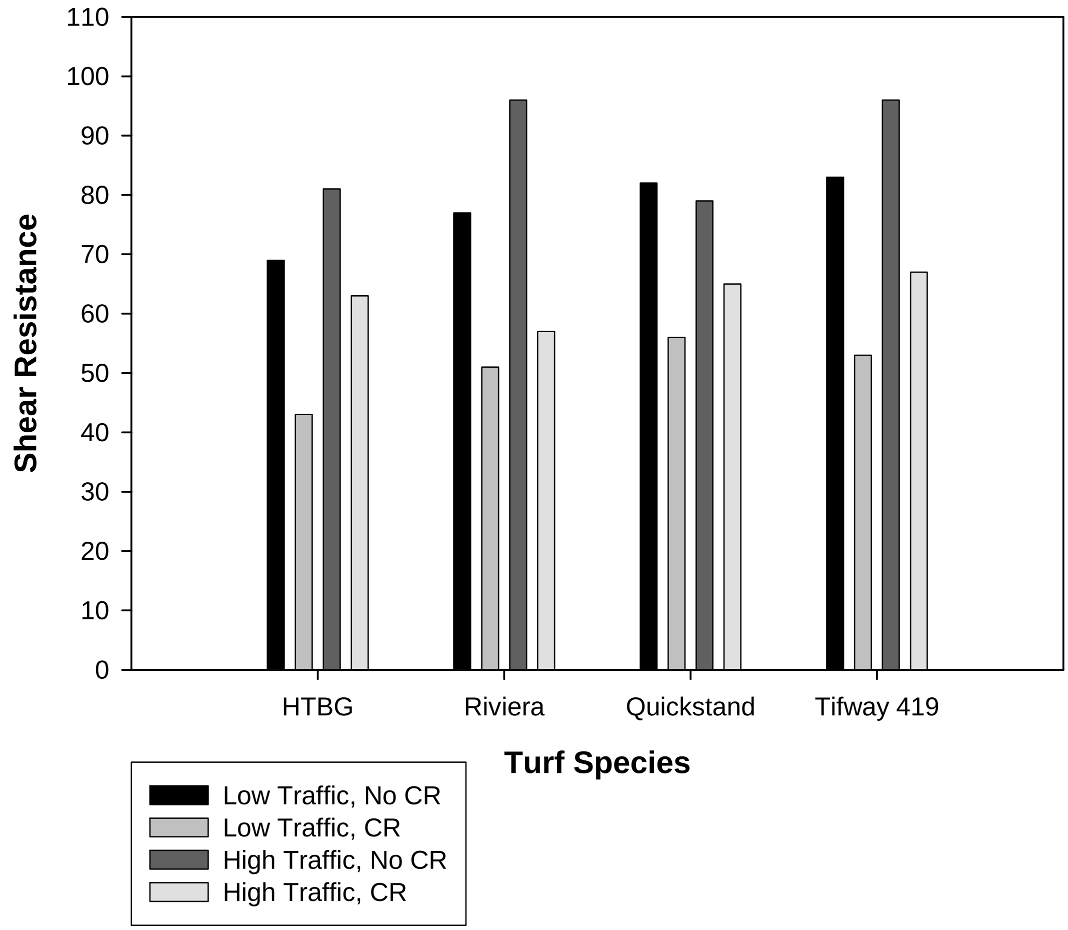

Figure 2. Turfgrass shear strength as affected by turfgrass species, crumb rubber topdressing, and traffic in Fayetteville, Ark. 11 Nov, 2005.

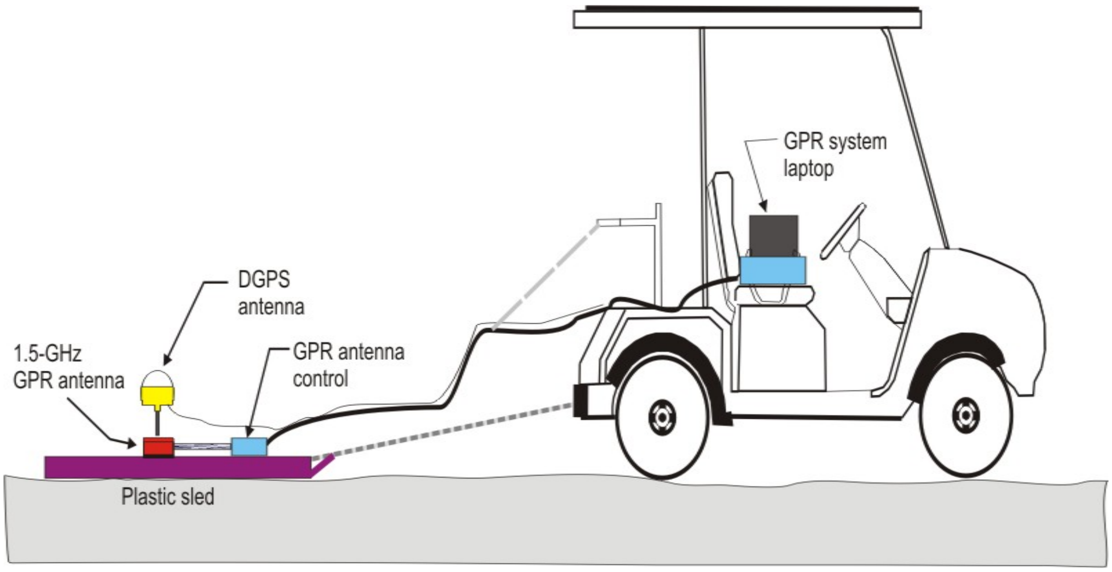

Figure 3. Drawing of GPR system used in study.

Figure 4. 2005 GPR transects of Shields-Watkins field in Neyland Stadium, Knoxville, Tenn.

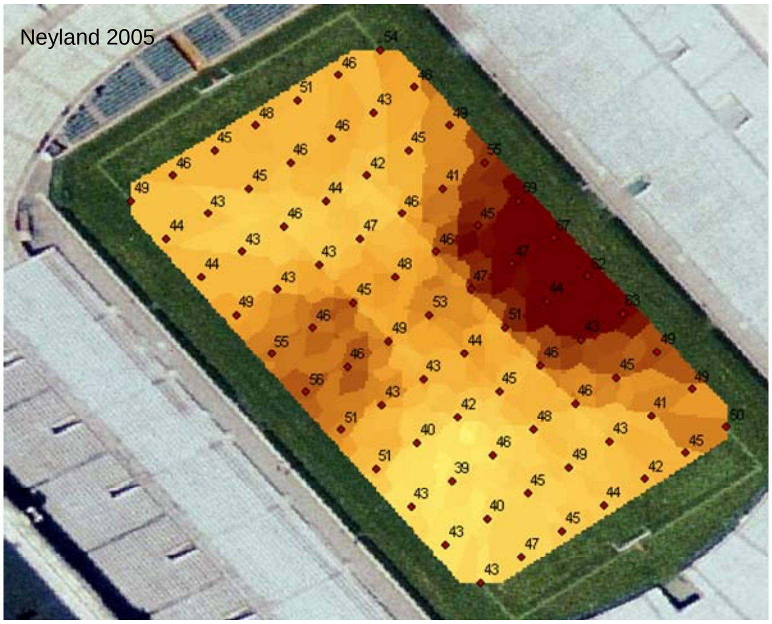

Figure 5. 2004 and 2005 post season interpolation of Clegg hammer data using the kriging method taken of Shields-Watkins field in Neyland Stadium, Knoxville, Tenn.

Figure 6. Grid showing locations of Clegg hammer data taken of Shields-Watkins field in Neyland Stadium, Knoxville, Tenn.

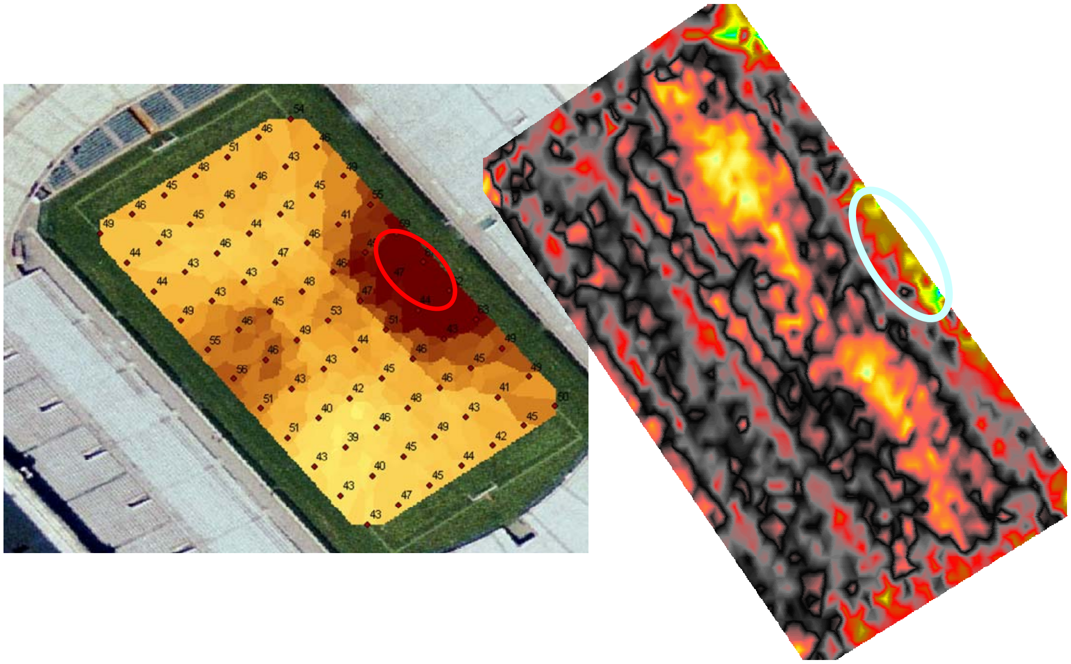

Figure 7. GPR slice of Shields-Watkins Field in Neyland Stadium in Knoxville, Tenn, December 2005.

GPR Slice (Neyland Stadium)

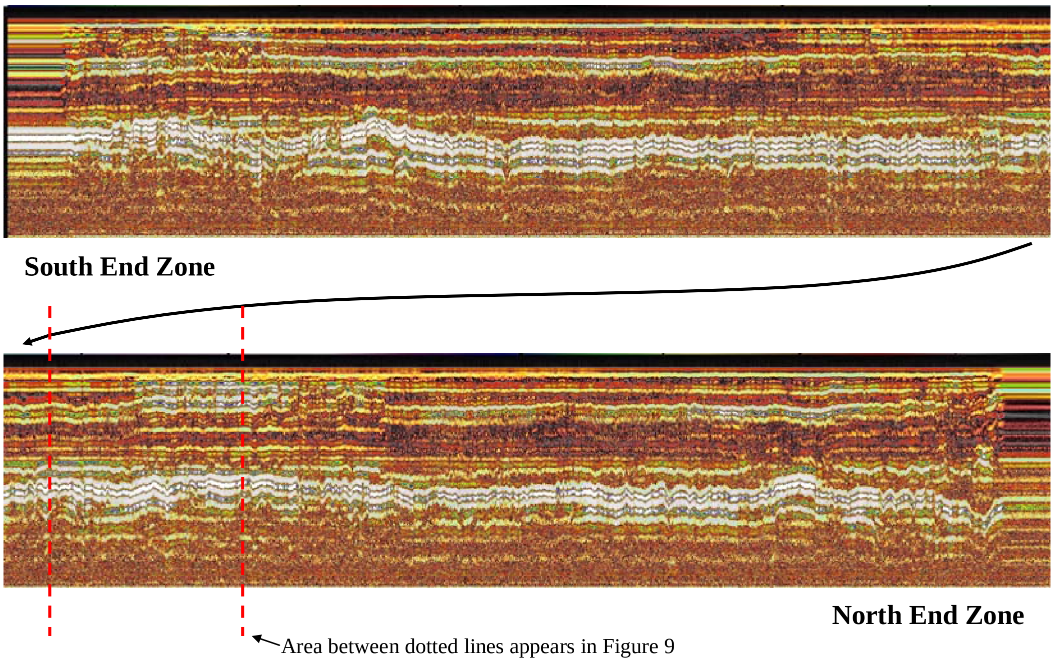

Figure 8. GPR slice of Shields-Watkins Field in Neyland Stadium in Knoxville, Tenn, December 2005.

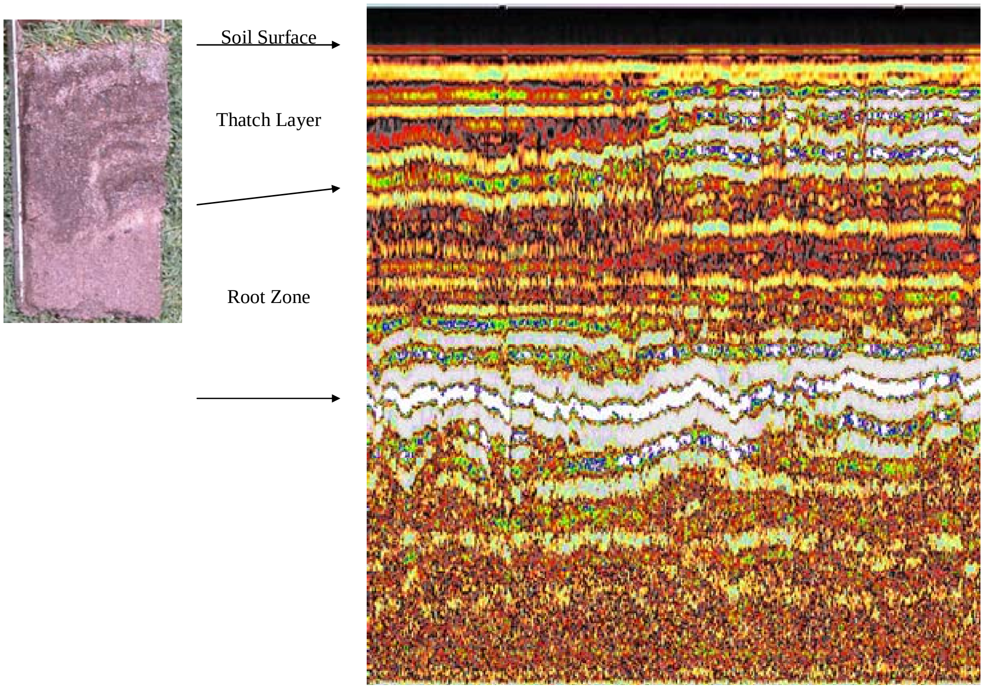

Figure 9. Soil profile compared to GPR slice of Shields-Watkins Field in Neyland Stadium in Knoxville, Tenn, December 2005.

VITA

Matthew Jordan Rhea Goddard was born in Paris, Tennessee, on August 25, 1982. He was raised on a small family farm in Elkhorn, Tennessee. He attended Henry County High School where he received his diploma in 2000. He then attended the University of Tennessee at Martin where he received his Bachelor of Science degree in Agriculture in 2004. He is currently attending the University of Tennessee at Knoxville where he is pursuing his Master of Science degree in Agriculture specializing in turfgrass science. Upon finishing his thesis, Matt plans to attend graduate school at Virginia Polytechnic and State University in pursuit of a PhD.