This is to certify that the
dissertation entitled

THE BUILT-UP SAND-CAPPED ATHLETIC FIELD
SYSTEM

presented by

Alexander R. Kowalewski

has been accepted towards fulfillment
of the requirements for the

Doctoral degree in Crop and Soil Sciences

Major Professor's Signature

Jan 27, 2010

Date

THE BUILT-UP SAND-CAPPED ATHLETIC FIELD SYSTEM

By

Alexander R. Kowalewski

A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Crop and Soil Sciences

2010

ABSTRACT

THE BUILT-UP SAND-CAPPED ATHLETIC FIELD SYSTEM

By

Alexander Robert Kowalewski

Native soil athletic fields high in silt and clay provide inadequate drainage during periods of heavy rainfall, resulting in reduced wear tolerance and surface stability when combined with heavy use. Renovation procedures range from $1,000,000, for a synthetic field, to $200,000, for a sand-capped system, and render the field temporarily useless, which is unacceptable for a municipality with a limited budget and high use requirement. However, drain tile installation and subsequent sand topdressing, providing a built-up sand-capped system is a cost effective renovation procedure that does not take the field out of play. Three research projects were designed to address the feasibility of this renovation process. The objective of the first project was to evaluate the effects of varying amounts of sand used for single topdressing applications on newly established turfgrass. Results determined that as much as 0.85 cm of sand depth can be applied in a single application. The second project evaluated the effects of varying cumulative amounts of sand topdressing on turfgrass wear tolerance and surface stability. Observations showed that 1.2 cm of sand topdressing, applied over a 5 week period, will provide the greatest fall wear tolerance and surface stability. The final project was designed to establish intercept drain tile spacing, in combination with sand topdressing, necessary to improve drainage, wear tolerance and stability. Findings determined that as topdressing accumulated from 0.0 to 2.4 cm, a 4.0 m drain spacing can provide adequate drainage and surface stability characteristics and, as topdressing depths exceed 2.4 cm, drain tile spacing can be increased to distances greater than 4.0 m apart.

ACKNOWLEDGEMENTS

First, I would like to thank my wonderful wife Heidi Jayne Kowalewski for tolerating my late night and weekend study habits, flying around the world with me to take care of grass and standing by me during the stressful times. Secondly, I would like to show appreciation to my family: Dad, Mom, Megan and Grandma. You have been my foundation and are the reason I had this opportunity, and I could not have done it without you.

Next I would like to acknowledge my major professor and mentor Dr. John N. Rogers, III. The adventures and experiences you exposed me to during my education were truly one of a kind and, beyond academic lessons, have taught me priceless lessons about virtue and strength of character. I would also like to thank my committee members, Dr. James R. Crum, Dr. James A. Flore and Dr. Joseph M. Vargas, Jr., for continually directing me along the way and challenging me to explore new ideas.

Special thanks must also go to Mark Collins and Frank Roggenbuck for giving me a start at the Hancock Turfgrass Research Center. Frank and Ryan O'Connor, your irrigation work was essential to the success of my research and I thank you for your efforts. Personal recognition must also be extended to Jeff Dunne for keeping everything going while I was abroad. Last but not least, I must also acknowledge my friend and office mate Aaron Hathaway. Over the years you have helped me countless times with work and much more, by providing a listening ear, wise advice, and a friendship I will never forget, thank you.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF IMAGES

INTRODUCTION

The typical Michigan high school athletic field serves as a focal point for social gatherings and community pride. It is often one of the few fields in town with lights, making it host to a variety of after school and work events including football, lacrosse, soccer, cheerleading, and band. Therefore, having an aesthetically pleasing and functional high school athletic field is often important to a variety of members in the average community (Hall, 2001).

Michigan high school athletic fields constructed on native soil high in silt and clay will drain slowly during periods of heavy rainfall, leading to soil saturation (Henderson et al., 2001). Saturated field conditions substantially reduce soil cohesion, adversely affecting traction and stability (Hillel, 2004). Reduced stability in combination with heavy use, typical of a fall athletic season, will result in turfgrass failure, decreased overall playability and visual aesthetics (Henderson, 2000). Current solutions to this problem include complete field renovation to a synthetic or sand-based turfgrass system.

Complete field renovation is costly and renders the athletic surface temporarily unusable during the process (Adamson, 2006). Renovation costs range from $600,000 – 1,000,000 for a synthetic athletic field; $400,000 – 600,000 for a conventional sand-based athletic field with a 30.5 cm sand-based root zone; $200,000 – 300,000 for a sand-capped system with a 15.2 cm sand root zone (Fresenburg, 2006a; Harler, 2009). These staggering upfront prices are often not an option for high schools and municipal areas with minimal budget allocations to grounds maintenance and high annual use requirements (Calhoun et al., 2002; Hall, 2001; Lundberg et al., 2001).

A possible alternative is the installation of an intercept drainage system (Puhalla et al., 2004) and subsequent sand topdressing applications (McAuliffe, 1994). Multiple sand topdressing applications will result in a "built-up sand-capped" soil system, while never rendering the field unusable for an extended period of time. Estimated initial cost for a built-up sand-capped system is $144,800 – 156,000 [price includes irrigation system installation ($15,000), 2.0 m drain tile spacing ($44,800 – 56,000) and a 15.0 cm deep sand layer ($85,000)] providing an alternative cost effective solution that does not interrupt field use for an extended period of time. The intent of this research is to determine the optimum cumulative sand topdressing depth and drain tile spacing necessary to produce an adequately drained sand-based athletic field.

Scientific Application

A possible alternative to complete field renovation is the installation of an intercept drainage system and subsequent sand topdressing applications, providing rapid surface drainage through the built-up sand topdressing layers and rapid removal of excess water through the intercept drain tile. The goal of this research is to provide Michigan schools and municipalities with a safe yet cost effective solution to native sports fields that fail regularly due to prolonged periods of saturation during athletic competition.

SPECIFIC OBJECTIVES

The following objectives will be implemented in the greenhouse or the field using cool-season turfgrass.

1) Evaluate the effects of varying amounts of sand used for single topdressing applications on recently established cool-season turfgrass health and vigor.
2) Evaluate the effects of varying cumulative amounts of sand topdressing on turfgrass wear tolerance and surface stability.
3) In combination with sand topdressing, establish intercept drain tile spacing necessary to prevent prolonged saturated surface soil conditions, thereby improving wear tolerance and surface stability.

LITERATURE REVIEW

The majority of Michigan's high school athletic fields are constructed on native soils. Fields constructed form native soils high in fine particles, silts and clays, provide excellent stability when dry, but are adversely affected by water (Henderson, 2000; Henderson, 2007). Native soils high in silt and clay have less macro-porosity than sand-based soils, which will reduce soil infiltration rates. As water is added to soils high in clay the water adheres to the clay reducing soil cohesion (Hillel, 2004). Reduced soil cohesion in combination with the lubricating effects of water on clay allows the particles to slip over each other. This not only has a deleterious effect on soil strength and stability, but also results in a densely packed or compacted soil (Das, 2006; Harler, 2009; Hillel, 2004). Compaction, or the reduction in existing macro-porosity, will even further reduce soil infiltration rates (Daniel, 1969).

Synthetic Turfgrass Systems

In response to this, artificial playing surfaces or synthetic turfgrass systems are used. Synthetic turfgrass has several advantages in comparison to natural grass, including immunity to pest problems, high traffic tolerances, and adaptability to extreme weather conditions (Henderson, 2000; McNitt and Petruniak, 2004; Lockyer, 2006). However, a field must not only be aesthetically pleasing and tolerant to regular traffic, but it must also provide a safe playing surface. Currently health concerns and cost are the major disadvantages associated with synthetic turfgrass systems.

Major health concerns associated with synthetic turfgrass include extreme increases in temperature and the potential for increased injury due to hard surfaces (Fresenburg 2006 b). Frensenburg (2006 b) observed a substantial increase in synthetic surface temperature, 173.0° F in comparison to natural grass which reached a maximum temperature of 105.0° F. More recently high levels of lead have been detected in several older, nylon fields, in New Jersey and New York (Anonymous. 2008; McCarty and Berkowitz, 2008). Field renovation to a synthetic turfgrass system can also cost as much as $1,000,000 to install, and $5,000 – 20,000 for annual maintenance (Fresenburg, 2006 a; Adamson, 2006), often not an option for high schools or municipal areas with minimal athletic field budget allocations. Field renovation to a sand-based system will provide a well draining playing surface that is resistant to compaction at a fraction of the cost of a synthetic turfgrass system.

Sand-Based Systems

Soil high in sand content will provide relatively high soil infiltration in comparison to soil with more fine soil particles, silt and clay (Hillel, 2004). Hillel (2004) defines infiltration as the downward flow of water through soil. Hydraulic conductivity, the ratio of water flux to hydraulic gradient, is often used to measure soil infiltration rates. The hydraulic conductivity of a sandy soil has an order of magnitude of 10.0^{-4} – 10.0^{-5} m sec^{-1}, while a clayey soil has 10.0^{-6} – 10.0^{-9} m sec^{-1}. Sand-based soils maintain structure, macro-porosity, and rapid infiltration rates when exposed to regular foot traffic and heavy rainfall (Bingaman and Kohnke, 1970). Realizing this relationship between increasing particle sizes and infiltration rates has resulted in the development of high sand content turfgrass systems, putting greens and athletic fields.

Sand-based athletic fields have been repeatedly constructed and successfully used over the last 40 years (Goss, 1965; Daniel, 1973). Magni et al. (2004) observed increased *Festuca arundinacea* Schreb. (tall fescue) and *Lolium perenne* L. (perennial ryegrass) turfgrass coverage, surface traction, and soil water infiltration rates as sand to soil ratios increased from native soil to a sand-based root zone. Currently a variety of specifications exist for sand-based putting greens and athletic fields including particle size distribution, total porosity, and saturated hydraulic conductivity (Puhalla et al., 1999; USGA Green Section Staff, 2004).

Many organizations and institutions have also developed a range of particle size distribution requirements, with sand contents ranging from 85.0 – 92.0%, and fines (<0.002 mm), silt and clay, ranging from 2.0 – 15.0%. Putting green specifications provided by Lunt (1956) suggest a 85.0 – 90.0% sand mixture with the remaining 10.0 – 15.0% composed of fiberous peat and a well aggregated clay (clay ≤ 7.5%). Lunt (1956) also suggests that 75.0% of the sand material be within a 0.2 – 0.4 mm range and 6.0 - 10.0% smaller than a 0.1 mm diameter. Root zone specification developed by Jakobsen and McIntyre (1999) for various sports facilities require a minimum of 85.0% sand, 2.0 – 15.0% fines, and a hydraulic conductivity greater than 5.0 mm hr^{-1}. In terms of sand particle size distributions requirement for sports fields the majority of recommendations require that a minimum of 60.0% of the sand particles fall within the coarse (0.5 – 1.0 mm) to medium sand (0.25 – 0.5 mm) range (Puhalla et al., 1999; USGA Green Section Staff, 2004). The American Society for Testing and Materials (ASTM) International standards also suggests that at least 60.0% of the sand be within the coarse and medium range, and no more than 15.0% less than 0.25 mm, which includes fine sand, very fine sand, silt and clay (ASTM, 2004).

The United States Golf Association (USGA) is an example of another organization that has developed a variety of sand-based root zone specifications. The

USGA sand specifications were originally developed for golf course putting greens, but due to their success have been adopted by sports field managers. United States Golf Association specifications for sand-root zones includes a minimum of 92.0% sand, maximum of 8.0% fines, and a minimum saturated hydraulic conductivity of 150.0 mm hr^{-1}. However, sands complying with USGA specifications may not provide the greatest stability for heavy athletic field traffic. These recommendations lean toward uniform or poorly graded sands, in which the majority of the soil grains are the same size (Hummel, 1994; Crum, 1996).

Uniform sand, while providing superior infiltration, lacks surface stability because they do not create an interlocking soil system (Das, 2006; Henderson, 2000). Conversely, sands with ranging particle size distributions result in an interlocking system; finer particles fill the voids spaces generated by the larger particles, generating a relatively strong soil system in comparison to uniform sand. Bingaman and Kohnke (1970) and Crum (1996) suggest well-graded sand particles distributed across a range of particle sizes, to maximize stability. Henderson (2000) suggests a well-graded soil with 90.0% sand – 10.0% silt/clay ratio to maximize soil stability while maintaining adequate soil infiltration. Research conducted by Henderson et al. (2005) determined that sand mixtures containing 10.0 and 12.0% silt/clay increased sand strength (log peak pressure) by more than 100.0%, while maintaining hydraulic conductivity rates of 19.0 and 8.5 cm hr^{-1}. The crucial component of this situation is finding a range of soil particle sizes that provides a stable surface when trafficked, but do not inhibit infiltration with a large number of fine particles (Sorochan, 2006).

Sand-based athletic field root zones have a variety of depth requirements ranging form 100.0 – 400.0 mm (ASTM, 2004; Gingell, 2003; Puhalla et al., 1999). Gingell (2003) defines a sand playing field or pitch as a constructed field with a top 100.0 mm soil with more than 70.0% sand. Puhalla et al. (1999) recommends a sand root zone depth of 127.0 mm to 229.0 mm for coarse and medium particle size sand, respectively. American Society for Testing and Materials International suggest a 150.0 mm to 300.0 mm sand-based root zone for athletic fields without a gravel layer and 230.0 mm to 400.0 mm for a sand-based with a gravel drainage layer (ASTM, 2004). Conventional sand-based athletic fields conforming to the USGA golf course green specifications have a root zone depth of 300.0 mm overlying a 100.0 mm layer of gravel (>2.0 mm) (Puhalla et al., 1999; USGA Green Section Staff, 2004). The infiltration rate of this system is limited by the saturated hydraulic conductivity of sand.

Conventional Sand-based System

A sand over gravel, or a conventional sand-based, system generates a zone of increased water content, often referred to as a perched water table (PWT), meaning the overlying sand layer has a lower matric potential (greater matric suction), interacting capillary and adsorptive forces, than the underlying gravel (McIntyre and Jakobsen, 2000). Research conducted by Taylor et al. (1993), in which a variety of soil mixtures were placed over a loam soil, 150.0 mm sand, 50.0 mm of sand and then 100.0 mm of gravel, and 150.0 mm of gravel, illustrates this concept well. Findings from this work showed that water retention values were greatest in the upper soil layer when placed over gravel, followed by sand over gravel, while the sand and loam soil sub layer resulted in the lowest water retention values. A similar circumstance occurs when sod grown on fine textured soil is placed over a sand-based soil (Davis, 1974; Spomer and Turgeon, 1977). A PWT prevents the water from draining into the underlying gravel until the overlying soil is saturated to a point at which the hydraulic head (hydrostatic pressure) exceeds matric suction of the soil (Hillel, 2004; Herbert, 2001). Therefore, when designing a sand over gravel system an adequate root zone depth is required to prevent the capillary fringe of saturated soil from generating anaerobic conditions within the rhizosphere, root-soil interface. Construction specifications often suggest a deeper sand root zone over a gravel layer to reduce the depth of the zone of increased water content (ASTM, 2004; McIntyre and Jackobsen, 2000).

A variety of research has been conducted evaluating the effects of various sand root zone depth on soil water content when placed over a gravel layer. Research evaluating various root zone depths (100.0 – 800.0 mm), and sand mixtures (five sand/peat mixtures) determined that 200.0 mm of a sand-based root zone was required to noticeable reduce the water content at the soil surface (Li et al., 2005). This work suggest that while a shallower root zone may be able to supply a greater amount of plant available water, a minimal root zone depth of 200.0 mm is required to prevent saturated soil conditions at the soil surface. McCoy and Kunkel (2001) observed that a wider range of soil moisture levels at a 230.0 mm depths during wetting and drying cycles in comparison to data collected at a 300.0 mm root zone depth.

Various sand root zone depths have also been shown to affect turfgrass physiology. For example, research evaluating various USGA specified root zone depths ranging from 100.0 – 300.0 mm observed no differences in *Agrostis palustris* Huds. (creeping bentgrass) root densities when grown in the 200.0 and 300.0 mm root zone

(Frazer et al., 2004). This research also determined that during an induced drought period the shorter root zone depth (100.0 mm) reached a permanent wilting point noticeably faster than the other root zones because of the reduced total water storage. These results suggest that a PWT requires a minimum sand-based root zone depth of 200.0 mm to maintain proper soil water content to satisfy turfgrass needs during potential water shortages.

Sand-Capped Systems

In an effort to further reduce the installation costs of sand-based systems, researchers have been exploring the use of sand-capped field. Daniel and Freeborg (1983) described a sand bed renovation method beginning with the establishment of a 1.0% subgrade soil slope, installation of narrow drain tiles (5.1 cm) spaced 3.0 to 6.0 m apart, backfill the drain lines with sand, and finally spread a 100.0 to 250.0 mm sand blanket over the subgrade, which is essentially a sand-capped field. Magni et al. (2004) observed increased drainage, ground cover, and traction in research plots with pipe drainage, spaced 5.0 m apart, and a 20.0 mm sand carpet over the native soil, in comparison to undrained native soil and native soil amended with sand (80.0% by volume) to a 80.0 mm depth.

Sand-capped fields are similar to the California putting green construction technique, in which sand is placed directly over a compacted native soil sub-grade, without a 100.0 mm gravel layer, which significantly reduces the price of installation (Davis et al., 1990). The California putting green construction technique calls for a 300.0 mm sand-based root zone over the native sub-soil. The sand root-zone depth of a sand capped athletic field ranges from 100.0 to 152.0 mm (Adamson, 2006; Gallagher, 1994), which will even further reduce soil preparation and installation costs. For example, Gallagher (1994) used a 100.0 mm deep sand carpet over a heavily compacted topsoil and clay layer. It is important to note that Lunt (1956) determined that a 100.0 mm layer of sand over a soil susceptible to compaction was necessary to prevent the underlying soil from compacting, which could adversely affect infiltration rates and root growth down into the underlying soil. Fresenburg (2006 a) estimates that the installation of a 150.0 mm sand-capped field would cost approximately $300,000, with an annual maintenance cost of $25,000. Sand-capped soil systems such as these function opposite to a PWT, the under lying soil draws water down into it because of an inverted matric potential relationship.

When a coarse material, like sand, is placed over a finer material, such as a native soil high in silt and clay, the underlying finer material functions as a vacuum sucking water down into it (Herbert, 2001). Fine textured soils, particularly clayey soils, have greater matirc suction than the coarser sand-based material (McIntyre and Jakobsen, 2000; Hillel, 2004). In unsaturated soils, water moves toward soils possessing greater matric suction, therefore the water is pulled down toward the underlying native soil. In this circumstance the sand root-zone layer can be substantially less than a conventional sand-based, or PWT system because the water in not retained by the sand in unsaturated conditions. However, in this system infiltration during periods of saturation will be inhibited by the soil layer below.

Saturated infiltration rates of sand-based root zones systems placed directly over a native soil high in fine particles (silt and clay), such as a sand-capped system, is limited by the underlying soil (Davis, 1974). In saturated soil conditions the flow of water is greatest through soils possessing greater macro-pore space, or low soil tension. Soils high in silt and clay have a hydraulic conductivity that is considerable less than sand-based soils (Hillel, 2004). For example, Henderson (2000) determined that a 90.0% sand – 10.0% silt/clay mixture posses a porosity ranging from 17.0 – 36.0%, air filled to dry, respectively, depending on variables such as compaction effort and soil moisture at the time of compaction. If an athletic field had a 100.0 mm layer of 90.0/10.0 sand and an impermeable subsoil without a surface slope or drain tiles the field could receive 17.0 – 36.0 mm of rainfall without developing standing water. Rainfall amounts greater than this would result in saturated playing surface conditions. Therefore, a method of excess water removal is required, which can be accomplished using a combination of soil slope and drain tiles (McAuliffe, 1992).

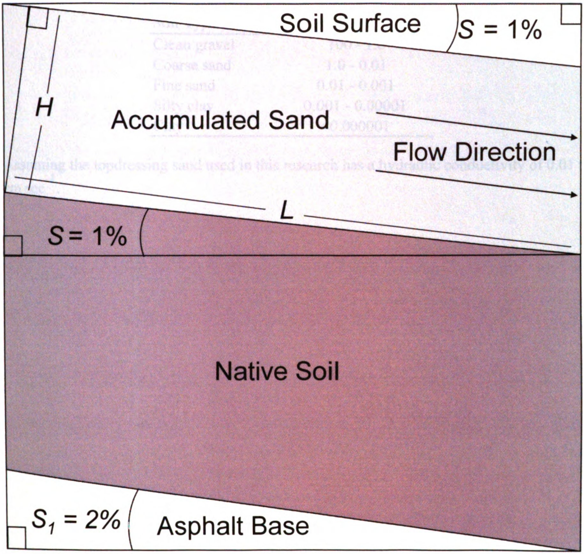
Drainage of excess water in sand-capped systems depends heavily on soil sub-grade slope and drain tile spacing. The sand-capped layer provides rapid surface drainage, while the drain tiles provide rapid subsurface drainage (Schwartzkopf, 1975). This is done by contouring the sub-soil during construction so the water will flow off the playing surface. After water infiltrates through the sand, the sloped sub-grade allows excess water to flow across the subsoil surface to the drain tiles for rapid removal. Without the proper slope and drain tile spacing, soil water levels will increase during rain events because of the reduced subsoil infiltration rates, producing saturated soil surface conditions. For example, putting green research conducted by Prettyman and McCoy (2003) observed, after 27 hrs of drainage at a 0.0% slope, the California style research plots (sand over native soil) had notably more soil water than the USGA style plots (sand over gravel). Suggesting, when a gravel layer is not included, slope plays an important role in soil system drainage. This research also determined that increased putting green surface slope, up to 4.0%, contributed to upslope drying of the root zones, producing considerable lateral variation in soil water content, particularly on the sand over native soil system.

Calculations derived from drainable pavement design can be used to make a conservative estimation of the drainage discharge capacity [steady-state flow (q)] and the time required to achieve 50.0% drainage [unsteady-state flow (T_{50})] of a sand-capped field (Barber and Sawyer, 1952; Casagrande and Shannon, 1952). These calculations suggest that a 152.0 mm sand-capped field with 4.6 m drain tile spacing and a 1.0% slope has a discharge capacity of 14.6 cm^3 hr^{-1} cm, and the time required to achieve 50.0% drainage after saturation is 1.9 days (Image 1; Table 1, 2 and 3).

To prevent dramatic lateral drying differences across the sand-based layer and provide adequate drainage a conservative soil slope is typically selected. Sand-capped athletic fields are typically designed with a slope of 0.5 – 1.0%. The ASTM International standards suggest a minimum surface slope of 0.5% (ASTM, 2004). Minimal slopes such as this put greater necessity on reduced drain tile spacing to provide adequate drainage.

Drain tile spacing varies depending on a number of factors including cost, tile depth, and root zone depth (Davis, 1974; Hillel, 2004). Beard (2002) lists the invention of the clay drain tile (1840s.) as one of the key advances in turfgrass management. Clay tiles were typically installed by hand and did not come into wide spread use until the invention of mechanical trencher in the 1990s. Drain tile spacing recommendations have a variety of ranges, from less than 3.1 m – 9.1 m (Davis, 1974). For example, the USGA green specifications suggest a drain tile spacing no greater than 4.5 m apart for sand

Image 1: Accumulated sand topdressing and native soil profile.



Assuming the compacted native loam soil is an impermeable layer.
H = Height of the drainage layer, accumulated sand topdressing (variable)
L = Length of drainage layer from drain tile to drain tile (variable)
S= Slope of the drainage layer (1% = 0.01)
S_1 = Natural slope of the HTRC asphalt parking lot (2% = 0.02)

Table 1: Typical values of hydraulic conductivity of saturated soils (Das, 2006).

Soil Type	cm sec^{-1}
Clean gravel	100 - 1.0
Coarse sand	1.0 - 0.01
Fine sand	0.01 - 0.001
Silty clay	0.001 - 0.00001
Clay	<0.000001

Assuming the topdressing sand used in this research has a hydraulic conductivity of 0.01 cm sec^{-1}.

Table 2: Void ratio (e) for typical soils in a natural state (Das, 2006); and porosity (n) calculated from the given e.

Type of soil	Void ratio (e)	Porosity (n)
Loose uniform sand	0.80	0.44
Dense uniform sand	0.45	0.31
Loose angular-grained silty sand	0.65	0.39
Dense angular-grained silty sand	0.40	0.29

Assuming the sand used in this research has a porosity (n) of 31% (0.31).

Table 3: Discharge capacity of a sand-capped field and time required to achieve 50% drainage (Barber and Sawyer, 1952; Casagrande and Shannon, 1952).

Steady-state flow

$q = kH(S+H/2L)$

Sand-capped Field			
Sand layer (H = cm)	Tile spacing (L = cm)	q = cm^3 sec^{-1} cm	cm^3 hr^{-1} cm
15.24	457.00	0.00407	14.63

Unsteady-state flow

$T_{50} = n_e L^2/(2k(H+SL)$

Sand-capped Field			
Sand layer (H) = cm	Tile Spacing (L) = cm	T_{50} = sec.	T_{50} = days
15.24	457.00	163410.37	1.89

q = Discharge capacity of the drainage layer (cm^3 hr^{-1} cm)

T_{50} = Time required to achieve 50% drainage

k = Hydraulic conductivity fine sand (0.01 cm sec^{-1})

H = Thickness of the drainage layer (15.24 cm)

S = Slope of the drainage layer (1% =0.01)

L = Length of drainage layer from drain tile to drain tile (457 cm)

n_e = effective porosity = assumed to be equal to the total porosity (0.31) (Das, 2006).

putting greens (USGA Green Section Staff, 2004). The ASTM International standards suggest drain tile spacing ranging from 4.5 m to 6.0 m apart (ASTM, 2004). Isaac (1999) on the other hand, suggests a tile spacing of 7.5 – 12.0 m for high sand content soils.

Sand-capped athletic field drain tiles are typically placed 30.5 – 45.7 cm below the soil surface (Puhalla et al., 1999). Davis (1974) states sand-capped football fields with drain tiles spaced 9.1 m apart at a 30.5 – 45.7 cm depth will produce saturated surface soil conditions between the drain tiles for an extended period of time and substantially compromising surface stability. Research conducted by Pettyman and McCoy (2003) on USGA and California style putting greens supports this statement. This research determined that drain tile spacing affected sand drying uniformity in the California construction method. This work observed an expected increase in water content midway between the drainage tiles during the early drainage period (1 – 9 hrs.) for the California style green.

Variable drying between drain tiles on an athletic field is more of a concern in regards to surface stability, rather than turfgrass health. The variable drying produced by the California style green may be a concern to turfgrass health when dealing with creeping bentgrass, which is typically maintained at a low mowing height (3.2 mm) (Turgeon, 2008). Michigan athletic fields typically consist of cool season turfgrass species such as, *Poa pratensis* L. (Kentucky bluegrass) and *Lolium perenne* L. (perennial ryegrass). These turfgrass species are maintained at a higher relative mowing weight (38.1 – 57.2 mm) (Christians, 1998), which will increase root development. Increased root development will reduce the effects of soil drought stress, possible negating the effects of variable drying on turfgrass health. While substantially less than a synthetic turfgrass surface, the manufacturing and installing of a sand-based systems with drain tiles is still expensive, and therefore not an option for institutions with minimal budget allocations to athletics. When native soil athletic field renovation is not an option field managers, coaches, and athletes are forced to make do.

Native Soil Systems

For a native soil athletic field high in silt and clay to function at a high level the field must be constructed properly, and receive aggressive annual maintenance (Henderson, 2007). A critical step in the construction of an acceptable native soil athletic field is developing a surface slope. During field constriction the establishment of a slope is a more cost effective solution to drainage issues than installing an elaborate subsurface drain system (Schwartskopf, 1975). Construction of a crowned native soil athletic field is estimated at $50,000, a substantial reduction in renovation costs in comparison to a synthetic, up to $1,000,000, and sand-cap, $300,000, field (Fresenberg, 2006 a; Harler, 2009). The typical surface slope of a native soil sports field ranges from 1.0 to 2.0% (Daniel, 1969; Puhalla et al., 1999). Puhalla et al. (1999) suggests that when subsurface drain systems are not installed use a slope at the high end of this scale. Henderson (2007) suggests that fields with low root zone permeability, consistent with native soil fields high in silt and clay, have a slope equal to or greater than 1.5%. Undulations in the surface slope will result in low spots substantially hindering the uniformity of surface water removal (McAuliffe, 1994). Low spots, wet spots, will collect excess water resulting in reduced turfgrass health, vigor, and surface coverage (Schwartskopf, 1975). This is the combined effect of reduced soil stability and anaerobic soil conditions.

During periods of heavy rainfall a sloped surface will not provide adequate removal and will result in standing water and saturated soil conditions. For example, Daniel (1969) states that for a sloped athletic fields area it would take approximately one hour for excess water to move up to 61.0 m across the surface. Therefore, an alternative removal method of excess water is required. In this circumstance, the overlying native soil substantially reduces the downward flow of water through the soil making a subsurface drain tile system insignificant (Henderson, 2007; Isaac, 1999). In such an instance an intercept, or by-pass, drainage system could be used to amend a native soil athletic field.

In by-pass drainage systems excess water flowing across the playing surface is intercepted by vertical pathways of coarse material installed into the existing finer soil (Daniel, 1969). McAuliffe (1992) suggests simple installing a trench backfilled with a coarse material that provides high hydraulic conductivity as a method to improve golf coarse putting green drainage. Daniel (1969) states that a variety of spacing for by-pass drainage systems are commonly used on golf courses ranging from 1.0 to 5.0 m. Daniel (1983) later goes on to suggest vertical trenches 4.5 m apart with slit drain tiles backfilled with washed sand. Daniel (1983), and McIntyre and Jackobsen (2000) also note the importance of backfilling sand within the drain to a level that exceeds the subgrade to prevent the flocculation of fine particles over the sand trench.

By-pass systems in athletic fields typically have perforated drain tiles installed at the bottom of the trench. Examples of such systems include interceptor, or strip, and sand-slit, or slit drained, drainage systems (Herbert, 2001; Puhalla et al., 1999). Interceptor and strip drains consist of a trench ranging from 305.0 to 457.0 mm deep and

50.0 to 305.0 mm wide with a perforated polyurethane pipe at the bottom covered with natural gravel, pea gravel, or coarse sand (Issac, 1999; Puhalla et al., 1999). Puhalla et al. (1999) suggests 6.1 m spacing for interceptor and strip drain systems on athletic fields. A sand-slit drainage system, also known as a Qwikdrain™ System (GreenONE Industries, Sedalia, CO), is a narrow sand-filled trench 44.0 to 120.0 mm wide spaced on 50.0 cm to 200.0 cm centers running perpendicular to the original intercept drain lines to channel water to the installed perforated pipes (McAuliffe, 1992). Magni et al. (2004) observed that a sand-slit drainage system improved water infiltration, but failed to improve turfgrass cover, when compared to an intercept drain tile system. While by-pass drainage systems, such as these, may prevent standing surface water from accumulating they do not prevent the native soil playing field from becoming saturated. Therefore surface stability and compaction is still an issue during extreme weather events.

Sand Topdressing

In an effort to improve native soil athletic field drainage sand topdressing has shown to provide some promising results. Sand topdressing provides a number of advantages to a playing surface including decreased organic matter build up, increased infiltration, and increasing playing surface uniformity (Stier et al., 2000; Vermeulen and Hartwiger, 2005).

Topdressing is often used on sand-based systems in combination with cultivation practices to mitigate the development of organic matter (McCarty et al., 2005; Barton et al., 2009), which when decomposed is very detrimental to water infiltration rates. McCartey et al. (2005) determined that topdressing alone decreased the thatch-mat accumulation depth by 25.0% and organic matter by 23.0 – 31.0% when used in combination with a variety of cultivation practices, such as core cultivation, vertical mowing, and grooming, on 'L-93' creeping bentgrass. This work also observed water infiltration rates 73.0% greater from topdressing alone in comparison to treatments that did not receive topdressing or cultivation. Barton et al. (2009) determined that topdressing, twice annually at a 5.0 mm depth, was up to three times more effective in reducing organic matter accumulation than core cultivation in established *Pennisetum clandestinum* Hochst. ex Chiov. (kikuyugrass), while coring plus topdressing did not further reduce organic matter levels. Barton et al. (2009) also observed increased kikuyugrass color levels throughout the study as a result of sand topdressing.

Using sand topdressing to improve native soil surface characteristics is a natural extension of currently proven applications. Sand topdressing has been used to develop a sand profile on golf course putting greens for over thirty years (Beard, 1978), and sand-based athletic fields have been shown to provide a high quality athletic field on a worldwide level (Anderson and VanLoo, 2005; Daniel, 1973; McAuliffe, 2001). Miller (2008) observed increased *Cynodon dactylon* (bermudagrass) turf shear strength, turfgrass cover, and rooting from sand topdressing applications in comparison to control treatments and treatments topdressed with crumb rubber and calcined clay. Beard (1973) suggests that sand topdressing can be used to modify the surface soil in the upper 5.1 – 7.6 cm, but suggest complete field renovation when a sand profile depth greater than this is required.

Currently there are a variety of recommended sand topdressing rates ranging from 1.6 – 9.5 mm deep per application, depending on the intended purpose of the topdressing and the mowing of the existing turfgrass stand (Beard, 1973; Puhalla et al., 1999; Stier et al., 2000). Stier et al. (2000) suggest a topdressing depth of 1.6 – 6.0 mm and Puhalla et al. (1999) suggest 1.6 – 9.5 mm for established sports fields, while Beard (1973) suggests a topdressing depth of 3.3 – 19.0 mm. Miller (2008) observed increased turf shear strength, cover, and rooting when three sand topdressing were applied at a rate of 2.0 mm (totaling 6.0 mm) over a five month period to bermudagrass maintained at a 2.5 cm mowing height.

However, excessive sand topdressing can be detrimental to a turfgrass stand. Turgeon (2008) suggests that high sand topdressing application rates can smother the turfgrass particularly during summer periods of high relative humidity, or prevent light from reaching the plants. Studzinska et al. (2006) observed that when sand topdressing applications were applied and not incorporated into 'Penncross' creeping bentgrass surface temperatures were approximately 25.0° C greater than treatments that did not receive topdressing. This research also observed that when topdressing applications were incorporated into the turfgrass canopy using a hand broom surface temperatures decrease by approximately 16.0° C, but were still around 7.0° greater than the control treatment. It has also been suggested that excessive sand topdressing applications can also decrease the satiability of the system because sand-based root zone systems rely on turfgrass interwoven roots for stability (Henderson, 2000).

SUMMARY

Research has shown that a sand-based athletic field system, in comparison to a native soil field, can be used to improve the drainage, surface stability, and wear tolerance during periods of heavy rainfall and simultaneous use (Henderson et al., 2005; Bingaman and Kohnke, 1970; Magni et al., 2004). However, using drain tile installation and sand topdressing to develop a built-up sand-capped system over time is a novel renovation procedure, lacking in research. Currently, there are a number of topdressing rate, drain tile spacing and sand layer depths recommendations to consider when instituting this renovation process (Stier et al., 2000; ASTM, 2004; Adamson, 2006), with little research to reinforce these recommendations.

REFERENCES

Adamson, C. 2006. Synthetic turfgrass costs far exceed natural grass playing fields. University of Missouri - Columbia. College of Agriculture, Food, and Natural Resources. Retrieved November 27, 2006.(http://cafnr.missouri.edu/research/turfgrass-costs.php).

Anderson, M., and T. VanLoo. 2005. Preparing for the Athens Olympics. 75th Annual Michigan Turfgrass Conference Proceedings. 75:1-3.

Anonymous. 2008. Artificial concerns: New York state assembly take a stand on synthetic and artificial surfaces. Pitchcare. 16:6.

ASTM. 2006. Standard practice for classification of soils for engineering purposes (United Soil Classification System). American Soc. for Testing and Materials International. D 2487-06:1-11.

ASTM. 2004. Standard guide for construction of high performance sand-based root zones for sports fields. American Soc. for Testing and Materials International. F 2396-04:1-12.

Barber, E.S. and C.L. Sawyer. 1952. Highway subdrainage. Public Roads 26(12):251–268.

Barton, L. G.G.Y. Wan, R.P. Buck and T.D. Colmer. 2009. Effectiveness of Cultural Thatch-Mat Controls for Young and Mature Kikuyu Turfgrass. Agron. J. 101:67–74.

Beard, J. 2002. The art and invention era: in the early evolution of turfs 1830-1952 (part 1). International Turfgrass Bulletin. 217:32-34.

Beard, J. B. 1978. Topdressing overview. 48th Annual Michigan Turfgrass Conference. January 10-11. pp. 36-39.

Beard, J.B. 1973. Turfgrass: science and culture. Prentice-Hall, Englewood Cliffs, N.J. pp.494.

Bingaman, D.E. and H. Kohnke. 1970. Evaluating sands for athletic turf. Agron. J. 62(4):464-467.

Calhoun, R., L. Sorochan, J. Rogers, III and J. Crum. 2002. Optimizing cultural practices to improve athletic field performance. Department of Crop and Soil Sciences, Michigan State University. Bulletin E18TURF. pp. 1-6.

Casagrande, A. and W.L. Shannon. 1952. Base course drainage for airport pavements. Proceedings of the American Society of Civil Engineers. 77: 792-814.

Christians, N. 1998. Fundamentals of Turfgrass Management. Ann Arbor Press, Chelsea, Mich.

Crum, J.R. 1996. Characterizing soil stability in high sand content soils and mixtures. Proceedings of the 66th Annual Michigan Turfgrass Conference. 25: 33-36.

Daniel, W.H. and R.P. Freeborg. 1983. Rootzone systems for natural turf. Conference Proceedings of the 54th International Golf Course Conference and Show. pp. 23-26.

Daniel, W.H. 1973. New natural turf system aids players: the PAT system – (Prescription Athletic Turf). Proceedings of the 43rd Annual Michigan Turfgrass Conference. 2: 67-69.

Daniel, W. H. 1969. Vertical drainage for compacted turf areas. J. of the Sports Turf Res. Inst. 45: pp. 41-47.

Das, B.M. 2006. Principles of Geotechnical engineering; sixth edition. Thomson Canada Limited. Toronto, Ontario.

Davis, W. 1974. Sand football fields. Proceedings of 1974 Midwest Regional Turf Foundation Conference. pp. 97-99.

Davis, W.B., J.L. Paul and D. Bowman. 1990. The sand putting green: construction and management. Publication Number 21488. University of California Division of Agriculture and Natural Resources, Davis, Calif.

Frazer, B.A., A.S. McNitt, M.J. Schlossberg, W. Uddin, D.M. Petrunak, and E.M. Lyons. 2004. Evaluation of creeping bentgrass root structure and development on golf greens of varying soil depth. 2004 ASA/CSSA/SSSA/CSSS Annual Meeting Abstracts. Madison, Wis.

Fresenburg, B. 2006 a. Synthetic turfgrass concerns: Part I. synthetic turf costs far exceed natural grass fields. TurfNews. 30(2):40.

Fresenburg, B. 2006 b. Synthetic turfgrass concerns: Part II. synthetic turf playing fields present unique dangers. TurfNews. 30(2):40-41.

Fresenburg, B. and C. Adamson. 2005. Synthetic turf playing fields present unique dangers. Appl. Turfgrass Sci. Online. pp. 1-2. Retrieved June 26, 2009. (http://www.plantmanagementnetwork.org/ats/search/search_action.asp).

Gallagher, M. 1994. From a soil to a sand carpet field: a case study. Proceedings of the 5th New Zealand Sports Turf. Convention. pp. 138-140.

Gingell, S. 2003. Maintenance of sand dominated football pitches. International Turfgrass Bulletin. 219: 14-16.

Goss, R.L. 1965. Specifications for turfgrass installations. Proceedings of the 21st Annual Northwest Turfgrass Conference. pp. 102-107.

Harler, C. 2009. Wetness and wealth key foes of native soil fields. SportsTurf. 25(3):15-16,18-19.

Hall, R. 2001. Where the action is hottest: As we marvel at the Major League fields, our schools and communities struggle to meet the demands on their fields. Athletic Turf: Maintenance & Technology. 4(5): 8-10.

Henderson, J.J. 2007. Right Root Zone Recipe Maximizes Performance. SportsTurf. 23(1):14, 16-18.

Henderson, J.J. 2000. Sand textured root zones in athletic fields: turfgrass establishment and constituent selected based on agronomic and engineering properties. M.S. Thesis. Michigan State University.

Henderson, J.J., J.R. Crum, T.F. Wolf and J.N. Rogers. 2005. Effects of particle size distribution and water content at compaction on saturated hydraulic conductivity and strength of high sand content root zone materials. Soil Sci. 170:315-324.

Henderson, J.J., J.R. Crum, T.F. Wolf and J.N. Rogers. 2001. Athletic field root zone mixes: What is the best mix for your field? 71st Annual Michigan Turfgrass Conference Proceedings. 30: 96-99.

Herbert, F. 2001. How to keep water moving off your field: why your fields drain the way they do, and what to look out for in building a new field or renovating an existing one. Athletic Turf: Maintenance and Technology. 4(1):22-24.

Hillel, D. 2004. Introduction to environmental soil physics. Academic Press, Burlington, Mass.

Hummel, N. 1994. Revisiting the USGA green specifications. Golf Course Management. 62(7): 57-59.

Issac, S. 1999. Sports turf drainage has wide range of solutions available. The Groundsman. 52(4): 7-8.

Li, D., D.D. Minner, N.E. Christians and S. Logsdon. 2005. Evaluating the impact of variable root zone depth on the hydraulic properties of sand-based turf systems. International Turfgrass Soc. 10(2): 1100-1107.

Lockyer, J. 2006. Third generation artificial football surfaces: maintenance issues. International Turfgrass Bulletin. 231: 5-8.

Lundberg, L. M., J.R. Crum and J. N. Rogers, III. 2001. Amendments for a low budget athletic field. 71st Annual Michigan Turfgrass Conference Proceedings. 30: 95.

Lunt, O.R. 1956. A method for minimizing compaction in putting greens. Southern Calif. Turfgrass Cult. 6(3):17-20.

Magni, S., M. Volterrani and S. Miele. 2004. Soccer pitches performances as affected by construction method, sand type and turfgrass mixture. Acta Hort. (ISHS). 661:281-285.

McAuliffe, K. 2001 Sports turf drainage systems require maintenance. New Zealand Turf Management J. August. 16(3): 6-9.

McAuliffe, K. 1994. Drainage: no two sites the same. Proceedings of the 5th New Zealand Sports Turf Conference. pp. 138-140.

McAuliffe, K.W. 1992. Drainage improvement: remedy without reconstruction in New Zealand. USGA Green Sec. Rec. 30(2):6-10.

McCarty, M. and S. Berkowitz. 2008. Artifical turf: health hazard? USA Today. Gannett Co., Inc., McLean, Va. May 7, 2008.

McCarty, L.B., M.F. Gregg, J.E. Toler, J.J. Camberato and H.S. Hill. 2005. Minimizing Thatch and Mat Development in a Newly Seeded Creeping Bentgrass Golf Green. Crop Sci. 45:1529-1535.

McCoy, E.L. and P.L. Kunkel. 2001. Root zone composition and depth effects on putting green turfgrass water use. ASA-CSSA-SSSA Annual Meetings, October 21-25, 2001, Charlotte, NC.

McIntyre, K. and B. Jakobsen. 2000. Practical drainage for golf, sportsturf and horticulture. Ann Arbor Press, Chelsea, Mich.

Jakobsen, B.F. and D.K. McIntyre . 1999. Turfgrass soils and drainage. In D.E. Aldous (ed.), International turf management: handbook (pp. 65-79). Inkata Press. Woburn, Mass.

McNitt, A. and D. Petruniak. 2004. Evaluation of playing surface characteristics of various in-filled systems. Penn State Department of Crop and Soil Sciences. pp. 1-34.

Miller, G.L. 2008. An evaluation of crumb rubber and calcined clay for topdressing sports fields. Acta Hort. (ISHS) 783:381-390.

Prettyman, G.W. and E.L. McCoy. 2003. Profile layering, root zone permeability, and slope affect on soil water content during putting green drainage. Crop Sci. 43: 958-994.

Puhalla, J., J. Krans and M. Goatley. 1999. Sports fields: a manual for design: construction and maintenance. Chelsea, MI: Ann Arbor Press.

Schwartskopf, 1975. Drainage: why and how. USGA Green Sec. Rec. 13(3): 1-3.

Sorochan, J. 2006. Managing sand-based athletic fields. SportsTurf. 22(12):8,10-12.

Spomer, L.A. and A.J. Turgeon. 1977. Vertical soil water retention in newly-sodded, drained turfgrass sites. Commun. in Soil Sci. and Plant Analysis. 8(5):417-423.

Stier, J. C., K. Delahaut, P. Pellitteri and B. Becker. 2000. Level A athletic fields. Wisconsin's School Integrated Pest Management Manual. pp. 1-14.

Sudzinska, A., J. Taylor and K. Danneberger. 2006. Heavy topdressing needs to be removed. Ohio State University TurfNotes. Retrieved March 10, 2009. (http://buckeyeturf.osu.edu/index.php?option=com_turfnotes&Itemid=84&noteid=1095.

Taylor, D.H., S.D. Nelson and C.F. Williams. 1993. Sub-root zone layering: effects on water retention in sports turf soil profiles. Agron. J. 85:626-630.

Turgeon, A.J. 2008. Turfgrass management: 8th edition. Pearson Education, Upper Saddle River, NJ.

USGA Green Section Staff. 2004. USGA recommendations for a method of putting green construction. United States Green Association World Wide Web Site. p. 1-11. Retrieved January 17, 2007. (http://www.usga.org/turf/course_construction/green_articles/putting_green_guidelines.html).

Vermeulen, P. and C. Hartwiger. 2005. Strategies for organic matter control: Using scientific and empirical approaches for managing organic matter accumulation can be frustrating. USGA Green Sec. Rec. 43(3):18-19.

CHAPTER 1

EFFECTS OF VARYING SAND TOPDRESSING RATES ON THE GROWTH AND DEVELOPMENT OF RECENTLY ESTABLISHED COOL-SEASON TURFGRASS.

ABSTRACT

Sand topdressing provides a number of advantages when applied to turfgrass established on a native soil high in silt and clay. However, aggressive topdressing application rates can be detrimental to an existing turfgrass stand. The objective of this research was to evaluate the effects of varying amounts of sand used for single topdressing applications on turfgrass health and vigor. Three RCBD greenhouse experiments, all utilizing a sandy loam soil, were seeded with *Lolium perenne* L., *Poa pratensis* L. and a mixture of the two on March 7, 2007, in East Lansing, Mich. Factors were topdressing application rate and simulated traffic applied approximately three weeks after establishment. Topdressing application rates consisted of a high sand (97.6% sand) content topdressing material applied at 0.00, 0.25, 0.34, 0.51, 0.68, 1.01, and 1.35 g cm^{-2} (equivalent to 0.0, 0.16, 0.21, 0.32, 0.42, 0.64, and 0.85 cm depths, respectively). Simulated traffic was applied to half of each 104.0 cm^{-2} pot, using a 52.0 cm^{-2} block. On May 30, 2007, the three experiments were repeated following the same establishment procedure defined above. Results from this research indicate that if rapid accumulation of a sand-based layer through sand topdressing is a priority application at rates as great as a 0.85 cm depth can be applied producing only a short term, less than 7 days, reduction in turfgrass cover, while producing no turfgrass injury or effect on turfgrass growth.

INTRODUCTION

Sand topdressing provides a number of advantages to a playing surfaces including decreased organic matter build up (Barton et al., 2009), increased surface infiltration (McCarty et al., 2005), resistance to compaction (Bingaman and Kohnke, 1970) and increased surface stability (Miller, 2008). Barton et al. (2009) determined that topdressing, twice annually at a 5.0 mm depth, was up to three times more effective in reducing kikuyugrass (*Pennisetum clandestinum* Hochst. ex Chiov.) organic matter accumulation than core cultivation when maintained at a 1.5 cm mowing height. Sand topdressing also increased color ratings throughout this study. McCartey et al. (2005) determined that topdressing alone at depths of 1.2 mm, annually, decreased the thatch-mat accumulation depth by 25.0% on 'L-93' creeping bentgrass (*Agrostis stolonifera* L.) maintained at 3.0 – 4.0 mm. This study also observed increased water infiltration rates, 73.0% greater from topdressing alone, in comparison to treatments that did not receive topdressing or cultivation. Miller (2008) observed increased turf shear strength, cover, and rooting from three sand topdressing applications totaling 6.0 mm applied over a five month period to bermudagrass (*Cynodon dactylon* L.) maintained at a 2.5 cm mowing height.

Increasing sand topdressing application rates will decrease the duration of time, and number of annual applications, required to accumulate an adequate sand root zone over the existing native soil (Li et al., 2005; Lunt, 1956; Magni et al., 2004). However, excessive sand topdressing can be detrimental to a turfgrass stand. Turgeon (2008) suggests that high sand topdressing application rates can smother the turfgrass, particularly during summer periods of high relative humidity, or prevent light from reaching the plants. Unpublished research by Studzinska et al. (2006) noted that when sand topdressing applications were applied and not incorporated into 'Penncross' creeping bentgrass surface temperatures were approximately 25.0° C greater than treatments that did not receive topdressing. Due to the current lack in published research developing an optimum topdressing regime capable of accumulating an adequate sand layer without being detrimental to turfgrass health and vigor is critical.

Objective:

Evaluate the effects of varying amounts of sand used for single topdressing applications on recently established cool-season turfgrass health and vigor.

Hypothesis:

High amounts of sand in single topdressing applications will be detrimental to turfgrass health and vigor.

MATERIALS AND METHODS

Research on the effects of varying sand topdressing application rates on recently established turfgrass was initiated March 7, 2007 at the Michigan State University (MSU), Plant Science Greenhouses, East Lansing, Mich. Factors included topdressing application rate [control (0.00 g cm^{-2}), 0.16 cm (0.25 g cm^{-2}), 0.21 cm (0.34 g cm^{-2}), 0.32 cm (0.51 g cm^{-2}), 0.42 cm (0.68 g cm^{-2}), 0.64 cm (1.01 g cm^{-2}) and 0.85 cm deep (1.35 g cm^{-2})] and simulated traffic (control and traffic).

Greenhouse pots (10.16 x 10.16 x 12.70 cm deep) were filled with the sandy loam field soil available at the MSU Greenhouses, with a pH of 7.6, 100.0 ppm phosphorus, and 110.0 ppm potassium (Soil and Plant Nutrient Laboratory, East Lansing, Mich.) (Table 4). Filled pots received an application of fertilizer 0-45-0 (48.80 kg ha^{-1} P), ground using a mortar and pistol, and 18-3-12 (24.40 kg ha^{-1} N), greens grade, prior to seeding. Pots were then seeded with *Lolium perenne* L. (perennial ryegrass), *Poa pratensis* L. (Kentucky bluegrass), and a bluegrass (90%) – ryegrass (10%) mixture. A perennial ryegrass blend (48.75% 'Ascend', 24.43% 'Enchanted', and 24.36% 'Majesty') was seeded at 439.40 kg ha^{-1}. 'Limousine' Kentucky bluegrass was seeded at 73.20 kg ha^{-1}. Finally, a mixture of 90% Kentucky bluegrass – 10% perennial ryegrass was seeded at a rate of 65.90 kg ha^{-1} and 43.90 kg ha^{-1} by weight, respectively, a common practice on cool-season sports fields (Brede and Duich, 1984). Pots were irrigated daily, using a misting hose, from the time of seeding throughout the data collection period.

Table 4: MSU Plant Science Greenhouse field soil test results; analysis performed at the MSU Soil and Plant Nutrient Laboratory, East Lansing, Mich., 2007.

pH	7.6
Soil Nutrient Levels	**ppm (mg kg^{-1})**
Phosphorus (P)	100.0
Potassium (K)	110.0
Calcium (Ca)	1032.0
Magnesium (Mg)	122.0
	meq $100g^{-1}$
CEC	6.5
Soil Particle Size Analysis	**%**
Sand	67.5
Silt	24.3
Clay	8.2
Soil Type	Sandy loam

Sand 0.05 – 2.00 mm; Silt 0.002 – 0.05 mm; Clay <0.002 mm.

Topdressing and Simulated Wheel Traffic

Seedlings received sand topdressing after they reached a maximum height of 5.10 cm and were mowed three times at 3.80 cm (Table 5). Prior to topdressing application, a 5.10 cm x 10.20 cm block was used to flatten half of the turfgrass within the surface area of the pot. This portion was flattened to simulate turfgrass areas in the field, which are flattened by work-cart or topdresser wheel traffic just prior to topdressing application. A WatchDog 2425 Temperature Station (Spectrum Technologies Inc., Plainfield, Ill) was used to monitor the daily high and low tmperature. Perennial ryegrass received sand topdressing applications on March 23 (28.9 – 17.8° C), while the Kentucky bluegrass and the Kentucky bluegrass – perennial ryegrass mixture received topdressing applications on March 30, 2007 (31.7 – 18.9 F). A variety of single topdressing application rates ranging from 0.00 – 0.85 cm deep, 0.00 – 1.35 g cm^{-2}, respectively, were applied to the recently established turfgrass.

Research was repeated at the MSU, Plant Science Greenhouses May 30, 2007 following the same procedure defined above. Perennial ryegrass received sand topdressing applications on June 19 (28.3 – 21.7° C) while the Kentucky bluegrass and the Kentucky bluegrass – perennial ryegrass mixture received topdressing applications on June 28, 2007 (27.2 – 20.6° C).

Response Variables

Change in living ground cover, turfgrass injury and growth (cm) were evaluated every three days. Living ground cover was estimated visually on a scale from 0.0 to 100.0%, based on the National Turfgrass Evaluation Program (NTEP) system of rating then compared to initial cover rating taken prior to topdressing and traffic applications to

Table 5: Particle size distribution of topdressing sand used in this experiment; analysis performed at the MSU Soil and Plant Nutrient Laboratory, East Lansing, Mich. 2007.

Particle Size (mm)	%
>2mm	0.1
Very Coarse Sand (1.0 - 2.0)	3.7
Coarse Sand (0.5 - 1.0)	24.0
Medium Sand (0.25 - 0.5)	45.8
Fine Sand (0.1 - 0.25)	23.1
Very Fine Sand (0.05 - 0.1)	0.9
Silt (0.002 - 0.05)	0.4
Clay (<0.002)	2.0
Soil Type	Sand

determine the changes in living ground cover over time (NTEP, 2009). Injury ratings were recorded using a 1 to 9 scale, with 1 equaling no injury and 9 equaling complete injury, or desiccation. Turfgrass growth was measured three day after being mowed to 3.8 cm height. Data was collected from the day of sand topdressing application until April 28, 2007 (Run 1) and July 20, 2007 (Run 2).

Statistical Analysis

Data were analyzed as a 7x2 randomized factorial, complete split-block design, with six replications using PROC MIXED procedure in SAS (version 9.1.3; SAS Institute Inc., Cary, N.C., 2007). Main effects were topdressing rate (whole-plot), and simulated traffic (sub-plot). Data were analyzed at a 0.05 level of probability. Normality of the residuals and homogeneity of variances were evaluated using PROC UNIVARIATE procedure. REPEATED/GROUP = treatment statement was used to grouped treatments with similar variances when variances were unequal. The Akaike information criterion (AIC) was used to determine whether to pursue an analysis with unequal variances or a regular analysis with a common variance (Littell et al., 2007). The analysis, either unequal variance or common variance, that produced the lowest AIC value, or the most accurate model, was selected to make conclusions regarding significance of main effects and their interactions. Mean separations were obtained based on the selected analysis using Fisher's least significant difference (LSD) at a 0.05 level of probability (Ott and Longnecker, 2001).

RESULTS AND DISCUSSIONS

Effects on Perennial Ryegrass

Significant main effects of topdressing depth and simulated traffic on change in living ground cover of recently established, 16-day old, perennial ryegrass were observed (Table 6). The highest topdressing depths, 0.64 and 0.85 cm, produced the greatest reduction in mean living ground cover observed the day after application only, while all other application depths produced results comparable to the control, 0.0 cm topdressing depth (Table 7). It is also important to note that the perennial ryegrass fully recovered from all reductions in ground cover caused by the topdressing applications within 14 days. Simulated traffic resulted in significantly less turfgrass cover in comparison to the control 14 days after application only. Reductions in perennial ryegrass cover produced by simulated traffic were corrected within 7 days of application.

No differences, main effect or interactions, in perennial ryegrass injury or growth rates were observed throughout the entirety of the data collection period (Table 8, 9, 10 and 11).

Effects on Kentucky bluegrass

Main effects of topdressing depth and simulated traffic on change in living ground cover were observed after application to 23-day old Kentucky bluegrass (Table 12). A significant topdressing depth x simulated traffic interactions was also observed.

Topdressing depths at the 0.64 and 0.85 cm depth produced a notable reduction in mean ground cover the day after application only, similar to the effects produced on perennial ryegrass (Table 13). All topdressing depths, while not all significant, produced some reduction in ground cover in comparison to the control. Simulated traffic resulted in lower mean ground cover in comparison to control 1 and 14 day after application. All

Table 6: Analysis of variance results for change in perennial ryegrass ground cover[z] collected after the application of sand topdressing and simulated traffic, East Lansing, Mich.

			Days After Topdressing and Traffic[y]				
	Num.	Den.	1	7	14	21	28
Source of Variation	df	df	*P*>F				
Topdressing Depth (TD)	6.0	33.0	0.0048	NS[x]	NS	NS	NS
Simulated Traffic (ST)	1.0	35.0	NS	NS	0.0395	NS	NS
TD X ST	6.0	35.0	NS	NS	NS	NS	NS

[z] Change in percent living ground cover in relation to initial cover ratings collected prior to topdressing and simulated traffic applications.

[y] Data collected 1, 7, 14, 21, and 28 days after topdressing and traffic applications were applied on March 23 (Run 1) and June 19 (Run 2), 2007.

[x] NS = not significant at $P > 0.05$.

Table 7: Effects of sand topdressing depth and simulated traffic on change in perennial ryegrass ground cover, East Lansing, Mich.

	Days After Topdressing and Traffic[z]						
	1		7	14		21	28
Topdressing Depth (cm)[y]	Mean Change in Cover (%)[x]						
0.00[w]	0.6	a[v]	15.2	26.6		60.2	68.5
0.16	-3.7	ab	6.5	29.5		63.0	68.3
0.21	2.7	a	13.8	21.9		53.8	71.9
0.32	-1.5	a	16.1	29.3		54.3	56.7
0.42	0.0	a	10.5	22.6		54.7	67.0
0.64	-15.5	bc	-5.3	18.2		53.1	63.7
0.85	-19.1	c	-2.1	13.8		46.8	52.8
			ns[u]	ns		ns	ns
Simulated Traffic[t]	Mean Change in Cover (%)						
control	-2.2		11.6	28.2	a	57.0	65.8
traffic	-8.2		4.0	18.1	b	53.3	62.5
	ns		ns			ns	ns

[z] Data collected 1, 7, 14, 21, and 28 days after topdressing and traffic applications were applied.

[y] cm of sand topdressing applied on March 23 (Run 1) and June 19 (Run 2), 2007.

[x] Change in percent living ground cover in relation to initial cover ratings collected prior to topdressing and simulated traffic applications.

[w] Number of replications for all treatments = 6.

[v] Means in a given column with the same letter do not differ using Fisher's least significant difference at $P = 0.05$.

[u] ns = not significant at $P = 0.05$.

[t] Prior to topdressing applications turfgrass was flattened using a 5.1 cm x 10.2 cm wooden block to simulate the effects of vehicle traffic prior to topdressing application.

Table 8: Analysis of variance results for perennial ryegrass injury[z] collected after the application of sand topdressing and simulated traffic, East Lansing, Mich.

			Days After Topdressing and Traffic[y]				
	Num.	Den.	1	7	14	21	28
Source of Variation	df	df			*P*>F		
Topdressing Depth (TD)	6.0	33.0	NS[x]	NS	NS	NS	NS
Simulated Traffic (ST)	1.0	35.0	NS	NS	NS	NS	NS
TD X ST	6.0	35.0	NS	NS	NS	NS	NS

[z] Injury based on a 1 – 9 scale, with 1 equaling no injury and 9 equaling complete injury or desiccation.

[y] Data collected 1, 7, 14, 21, and 28 days after topdressing and traffic applications were applied on March 23 (Run 1) and June 19 (Run 2), 2007.

[x] NS = not significant at $P > 0.05$.

Table 9: Effects of sand topdressing depth and simulated traffic on perennial ryegrass injury, East Lansing, Mich.

	Days After Topdressing and Traffic[z]				
	1	7	14	21	28
Topdressing Depth (cm)[y]	Mean Injury (1-9)[x]				
0.00[w]	1.0	1.0	1.0	1.0	1.0
0.16	1.1	1.0	1.0	1.0	1.0
0.21	1.0	1.0	1.0	1.0	1.0
0.32	1.0	1.0	1.0	1.0	1.0
0.42	1.1	1.0	1.0	1.0	1.0
0.64	1.3	1.0	1.0	1.0	1.0
0.85	1.3	1.0	1.0	1.0	1.0
	ns[v]	ns	ns	ns	ns
Simulated Traffic[u]	Mean Injury (1-9)				
control	1.0	1.0	1.0	1.0	1.0
traffic	1.1	1.0	1.0	1.0	1.0
	ns	ns	ns	ns	ns

[z] Data collected 1, 7, 14, 21, and 28 days after topdressing and traffic applications were applied.

[y] cm of sand topdressing applied on March 23 (Run 1) and June 19 (Run 2), 2007.

[x] Injury based on a 1 – 9 scale, with 1 equaling no injury and 9 equaling complete injury or desiccation.

[w] Number of replications for all treatments = 6.

[v] ns = not significant at $P = 0.05$.

[u] Prior to topdressing applications turfgrass was flattened using a 5.1 cm x 10.2 cm wooden block to simulate the effects of vehicle traffic prior to topdressing application.

Table 10: Analysis of variance results for perennial ryegrass growth[z] collected after the application of sand topdressing and simulated traffic, East Lansing, Mich.

			Days After Topdressing and Traffic[y]			
	Num.	Den.	7	14	21	28
Source of Variation	df	df	P>F			
Topdressing Depth (TD)	6.0	33.0	NS[x]	NS	NS	NS
Simulated Traffic (ST)	1.0	35.0	NS	NS	NS	NS
TD X ST	6.0	35.0	NS	NS	NS	NS

[z] cm of growth measured three day after being mowed to a 3.8 cm height.

[y] Data collected 7, 14, 21, and 28 days after topdressing and traffic applications were applied on March 23 (Run 1) and June 19 (Run 2), 2007.

[x] NS = not significant at $P > 0.05$.

Table 11: Effects of sand topdressing depth and simulated traffic on perennial ryegrass growth, East Lansing, Mich.

	Days After Topdressing and Traffic[z]			
	7	14	21	28
Topdressing Depth (cm)[y]	Mean Growth (cm)[x]			
0.00[w]	1.5	1.2	1.5	1.3
0.16	1.6	1.0	1.6	1.0
0.21	2.1	1.2	1.5	1.0
0.32	1.9	1.5	1.7	1.2
0.42	1.4	0.8	1.2	0.8
0.64	1.2	0.9	1.1	1.0
0.85	1.4	1.0	1.0	0.7
	ns[v]	ns	ns	ns
Simulated Traffic[u]	Mean Growth (cm)			
control	1.5	1.0	1.3	1.0
traffic	1.6	1.1	1.4	1.0
	ns	ns	ns	ns

[z] Data collected 7, 14, 21, and 28 days after topdressing and traffic applications were applied.

[y] cm of sand topdressing applied on March 23 (Run 1) and June 19 (Run 2), 2007.

[x] cm of growth measured three day after being mowed to a 3.8 cm height.

[w] Number of replications for all treatments = 6.

[v] ns = not significant at $P = 0.05$.

[u] Prior to topdressing applications turfgrass was flattened using a 5.1 cm x 10.2 cm wooden block to simulate the effects of vehicle traffic prior to topdressing application.

Table 12: Analysis of variance results for change in Kentucky bluegrass ground cover[z] collected after the application of sand topdressing and simulated traffic, East Lansing, Mich.

	Num.	Den.	Days After Topdressing and Traffic[y]				
			1	7	14	21	28
Source of Variation	df	df	*P*>F				
Topdressing Depth (TD)	6.0	33.0	<0.0001	NS[x]	NS	NS	NS
Simulated Traffic (ST)	1.0	35.0	0.0047	NS	0.0033	NS	NS
TD X ST	6.0	35.0	0.0432	NS	NS	NS	NS

[z] Change in percent living ground cover in relation to initial cover ratings collected prior to topdressing and simulated traffic applications.

[y] Data collected 1, 7, 14, 21, and 28 days after topdressing and traffic applications were applied on March 30 (Run 1) and June 28 (Run 2), 2007.

[x] NS = not significant at $P > 0.05$.

Table 13: Effects of sand topdressing depth and simulated traffic on change in Kentucky bluegrass ground cover, East Lansing, Mich.

	Weeks After Topdressing and Traffic[z]							
	1		7	14		21	28
Topdressing Depth (cm)[y]	Mean Change in Cover (%)[x]						
0.00[w]	0.0	a[v]	107.3	156.9		212.2	217.4
0.16	-0.9	a	65.2	89.1		149.8	219.2
0.21	-11.7	a	66.5	123.9		180.8	210.0
0.32	-4.0	a	68.0	143.8		231.0	244.2
0.42	-6.9	a	32.7	61.5		115.9	136.6
0.64	-37.9	b	69.9	109.2		125.0	204.0
0.85	-30.8	b	21.2	85.6		101.0	116.9
			ns[u]	ns		ns	ns
Simulated Traffic[t]	Mean Change in Cover (%)						
control	-7.9	a	69.4	134.6	a	172.5	214.5
traffic	-18.5	b	53.6	85.4	b	146.3	170.7
			ns			ns	ns

[z] Data collected 1, 7, 14, 21, and 28 days after topdressing and traffic applications were applied.

[y] cm of sand topdressing applied on March 30 (Run 1) and June 28 (Run 2), 2007.

[x] Change in percent living ground cover in relation to initial cover ratings collected prior to topdressing and simulated traffic applications.

[w] Number of replications for all treatments = 6.

[v] Means in a given column with the same letter do not differ using Fisher's least significant difference at $P = 0.05$.

[u] ns = not significant at $P = 0.05$.

[t] Prior to topdressing applications turfgrass was flattened using a 5.1 cm x 10.2 cm wooden block to simulate the effects of vehicle traffic prior to topdressing application.

reductions in living ground produced by topdressing and simulated traffic applications were corrected by turfgrass recovery within 7 days of application. A topdressing depth x simulated traffic interaction was observed the day after application only, with simulated traffic resulting in a greater reduction in mean ground cover for the 0.21 and 0.85 topdressing depths (Figure 1). This interaction supports earlier statements that simulated traffic significantly reduces ground cover the day after application only.

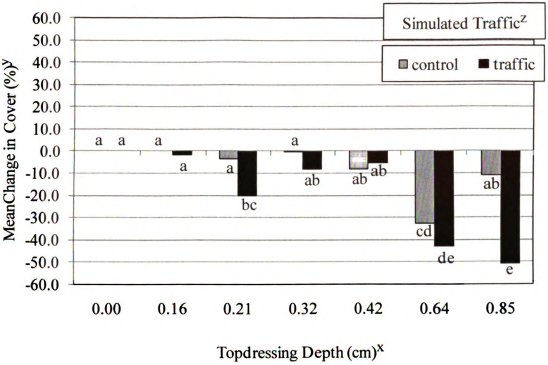
Similar to perennial ryegrass results, no differences in Kentucky bluegrass injury were observed throughout the entirety of the data collection period (Table 14 and 15). However, unlike perennial ryegrass results, significant effects of simulated traffic on turfgrass growth were observed (Table 16). Simulated traffic resulted in greater mean turfgrass growth, between mowing, 7 and 14 days after application (Table 17).

Effects on Turfgrass Mixture

Significant main effects of topdressing depth and simulated traffic on change in ground cover of recently established Kentucky bluegrass – perennial ryegrass mixture were observed (Table 18). A significant topdressing depth x simulated traffic interaction was also observed the day after treatment application.

Effects of topdressing depths on mixture ground cover produced results analogous to perennial ryegrass and Kentucky bluegrass findings, with the 0.64 and 0.85 cm depths producing the greatest reduction in mean ground cover observed the day after application only (Table 19). The cool-season turfgrass mixture fully recovered from reductions in ground cover produced by all topdressing depths within 7 days with the exception of the 0.85 cm application depth, which fully recovered within 14 days. Simulated traffic reduced mean turfgrass cover in comparison to the control the day after application, but

Figure 1: Effects of topdressing depth x simulated traffic on change in Kentucky bluegrass ground cover observed one day after topdressing and simulated traffic applications, East Lansing, Mich.



[z] Prior to topdressing applications turfgrass was flattened using a 5.1 cm x 10.2 cm wooden block to simulate the effects of vehicle traffic prior to topdressing application.
[y] Change in percent living ground cover in relation to initial cover ratings collected prior to topdressing and simulated traffic applications.
[x] cm of sand topdressing applied on March 30 (Run 1) and June 28 (Run 2), 2007. Columns with the same letter do not differ using Fisher's least significant difference at $P = 0.05$.

Table 14: Analysis of variance results for Kentucky bluegrass injury[z] collected after the application of sand topdressing and simulated traffic, East Lansing, Mich.

			Days After Topdressing and Traffic[y]				
	Num.	Den.	1	7	14	21	28
Source of Variation	df	df			*P*>F		
Topdressing Depth (TD)	6.0	33.0	NS[x]	NS	NS	NS	NS
Simulated Traffic (ST)	1.0	35.0	NS	NS	NS	NS	NS
TD X ST	6.0	35.0	NS	NS	NS	NS	NS

[z] Injury based on a 1 – 9 scale, with 1 equaling no injury and 9 equaling complete injury or desiccation.

[y] Data collected 1, 7, 14, 21, and 28 days after topdressing and traffic applications were applied on March 30 (Run 1) and June 28 (Run 2), 2007.

[x] NS = not significant at $P > 0.05$.

Table 15: Effects of sand topdressing depth and simulated traffic on Kentucky bluegrass injury, East Lansing, Mich.

	Days After Topdressing and Traffic[z]				
	1	7	14	21	28
Topdressing Depth (cm)[y]	Mean Injury (1-9)[x]				
0.00[w]	1.0	1.0	1.0	1.0	1.0
0.16	1.0	1.0	1.0	1.0	1.0
0.21	1.0	1.0	1.0	1.0	1.0
0.32	1.0	1.0	1.0	1.0	1.0
0.42	1.0	1.0	1.0	1.0	1.0
0.64	1.0	1.0	1.0	1.0	1.0
0.85	1.0	1.0	1.0	1.0	1.0
	ns[v]	ns	ns	ns	ns
Simulated Traffic[u]	Mean Injury (1-9)				
control	1.0	1.0	1.0	1.0	1.0
traffic	1.0	1.0	1.0	1.0	1.0
	ns	ns	ns	ns	ns

[z] Data collected 1, 7, 14, 21, and 28 days after topdressing and traffic applications were applied.

[y] cm of sand topdressing applied on March 30 (Run 1) and June 28 (Run 2), 2007.

[x] Injury based on a 1 – 9 scale, with 1 equaling no injury and 9 equaling complete injury or desiccation.

[w] Number of replications for all treatments = 6.

[v] ns = not significant at $P = 0.05$.

[u] Prior to topdressing applications turfgrass was flattened using a 5.1 cm x 10.2 cm wooden block to simulate the effects of vehicle traffic prior to topdressing application.

Table 16: Analysis of variance results for Kentucky bluegrass growth[z] collected after the application of sand topdressing and simulated traffic, East Lansing, Mich.

			Days After Topdressing and Traffic[y]			
	Num.	Den.	7	14	21	28
Source of Variation	df	df	*P*>F			
Topdressing Depth (TD)	6.0	33.0	NS[x]	NS	NS	NS
Simulated Traffic (ST)	1.0	35.0	0.0529	0.0421	NS	NS
TD X ST	6.0	35.0	NS	NS	NS	NS

[z] cm of growth measured three day after being mowed to a 3.8 cm height.

[y] Data collected 7, 14, 21, and 28 days after topdressing and traffic applications were applied on March 30 (Run 1) and June 28 (Run 2), 2007.

[x] NS = not significant at $P > 0.05$.

Table 17: Effects of sand topdressing depth and simulated traffic on Kentucky bluegrass growth, East Lansing, Mich.

	Days After Topdressing and Traffic[z]						
	7		14		21		28
Topdressing Depth (cm)[y]	Mean Growth (cm)[x]						
0.00[w]	1.2		1.8		1.8		1.5
0.16	1.5		2.0		1.6		1.5
0.21	1.5		2.3		1.6		1.2
0.32	1.5		2.2		1.9		1.4
0.42	1.5		2.3		1.9		1.4
0.64	1.4		2.3		2.0		1.3
0.85	1.6		2.3		1.7		1.2
	ns[v]		ns		ns		ns
Simulated Traffic[u]	Mean Growth (cm)						
control	1.3	b[t]	2.1	b	1.8		1.3
traffic	1.6	a	2.3	a	1.8		1.4
					ns		ns

[z] Data collected 7, 14, 21, and 28 days after topdressing and traffic applications were applied.

[y] cm of sand topdressing applied on March 30 (Run 1) and June 28 (Run 2), 2007.

[x] cm of growth measured three day after being mowed to a 3.8 cm height.

[w] Number of replications for all treatments = 6.

[v] ns = not significant at $P = 0.05$.

[u] Prior to topdressing applications turfgrass was flattened using a 5.1 cm x 10.2 cm wooden block to simulate the effects of vehicle traffic prior to topdressing application.

[t] Means in a given column with the same letter do not differ using Fisher's least significant difference at $P = 0.05$.

Table 18: Analysis of variance results for change in Kentucky bluegrass – perennial ryegrass mixture ground cover[z] collected after the application of sand topdressing and simulated traffic, East Lansing, Mich.

			Days After Topdressing and Traffic[y]				
	Num.	Den.	1	7	14	21	28
Source of Variation	df	df			*P*>F		
Topdressing Depth (TD)	6.0	33.0	0.0005	NS[x]	NS	NS	NS
Simulated Traffic (ST)	1.0	35.0	0.0001	NS	NS	NS	0.0403
TD X ST	6.0	35.0	0.0093	NS	NS	NS	NS

[z] Change in percent living ground cover in relation to initial cover ratings collected prior to topdressing and simulated traffic applications.

[y] Data collected 1, 7, 14, 21, and 28 days after topdressing and traffic applications were applied on March 30 (Run 1) and June 28 (Run 2), 2007.

[x] NS = not significant at $P > 0.05$.

Table 19: Effects of sand topdressing depth and simulated traffic on change in Kentucky bluegrass – perennial ryegrass mixture ground cover, East Lansing, Mich.

	Days After Topdressing and Traffic[z]						
	1		7	14	21	28	
Topdressing Depth (cm)[y]	Mean Change in Cover (%)[x]						
0.00[w]	0.0	a[v]	154.0	189.7	237.3	243.4	
0.16	0.6	a	71.1	121.2	147.9	191.6	
0.21	-1.7	ab	36.4	68.3	83.9	98.8	
0.32	0.0	a	51.9	93.1	112.5	121.3	
0.42	-2.8	ab	47.6	92.6	113.6	132.6	
0.64	-10.7	bc	17.0	59.1	70.4	136.2	
0.85	-20.0	c	-4.6	32.6	44.2	57.9	
			ns[u]	ns	ns	ns	
Simulated Traffic[t]	Mean Change in Cover (%)						
control	-0.6	a	50.6	89.1	108.7	127.9	b
traffic	-9.3	b	56.1	98.4	122.7	152.6	a
			ns	ns	ns		

[z] Data collected 1, 7, 14, 21, and 28 days after topdressing and traffic applications were applied.

[y] cm of sand topdressing applied on March 30 (Run 1) and June 28 (Run 2), 2007.

[x] Change in percent living ground cover in relation to initial cover ratings collected prior to topdressing and simulated traffic applications.

[w] Number of replications for all treatments = 6.

[v] Means in a given column with the same letter do not differ using Fisher's least significant difference at $P = 0.05$.

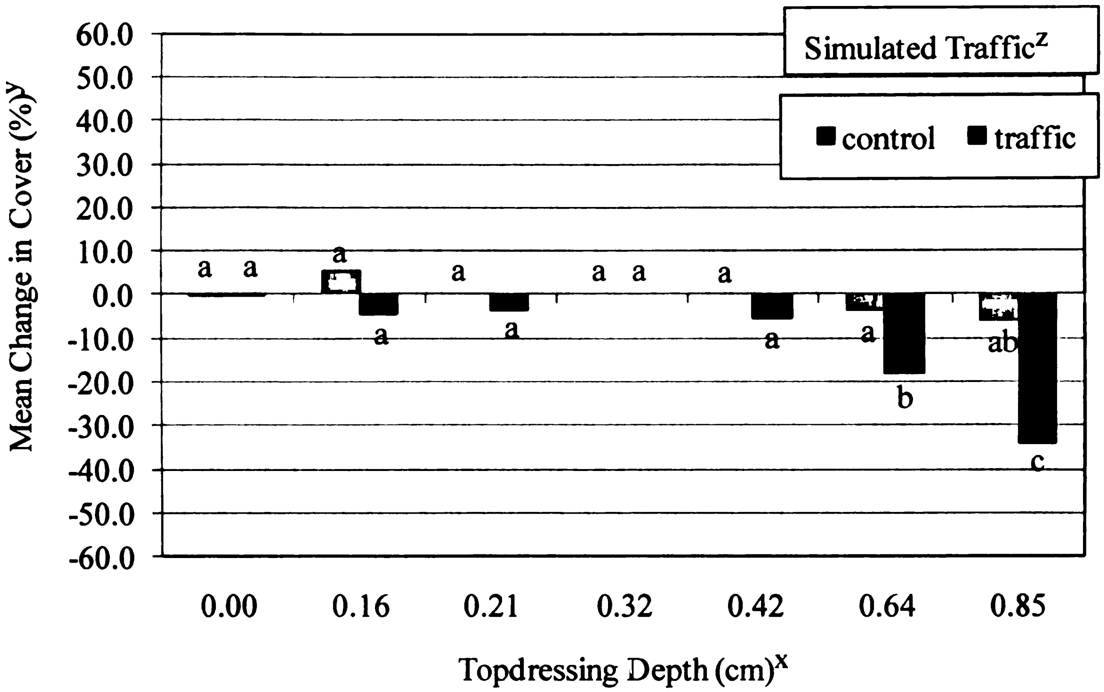
[u] ns = not significant at $P = 0.05$.

[t] Prior to topdressing applications turfgrass was flattened using a 5.1 cm x 10.2 cm wooden block to simulate the effects of vehicle traffic prior to topdressing application.

contrary to the overall trends resulted in increased ground cover in comparison to the control 28 days after application. The topdressing depth x simulated traffic interaction, observed the day after treatment application, determined that simulated traffic producing an increased reduction in mean turfgrass cover at the 0.21, 0.64 and 0.85 cm application depth (Figure 2). This interaction supports previous statements that simulated traffic significantly reduce ground cover the day after application only.

Similar to perennial ryegrass findings, no differences, main effect or interactions, in cool-season turfgrass mixture injury or growth rates were observed throughout the entirety of the data collection period (Table 20, 21, 22 and 23).

Figure 2: Effects of topdressing depth x simulated traffic on change in Kentucky bluegrass – perennial ryegrass mixture ground cover observed one day after topdressing and simulated traffic applications, East Lansing, Mich.



[z] Prior to topdressing applications turfgrass was flattened using a 5.1 cm x 10.2 cm wooden block to simulate the effects of vehicle traffic prior to topdressing application.
[y] Change in percent living ground cover in relation to initial cover ratings collected prior to topdressing and simulated traffic applications.
[x] cm of sand topdressing applied on March 30 (Run 1) and June 28 (Run 2), 2007.
Columns with the same letter do not differ using Fisher's least significant difference at $P = 0.05$.

Table 20: Analysis of variance results for Kentucky bluegrass – perennial ryegrass mixture injury[z] collected after the application of sand topdressing and simulated traffic, East Lansing, Mich.

			Days After Topdressing and Traffic[y]				
	Num.	Den.	1	7	14	21	28
Source of Variation	df	df			*P*>F		
Topdressing Depth (TD)	6.0	33.0	NS[x]	NS	NS	NS	NS
Simulated Traffic (ST)	1.0	35.0	NS	NS	NS	NS	NS
TD X ST	6.0	35.0	NS	NS	NS	NS	NS

[z] Injury based on a 1 – 9 scale, with 1 equaling no injury and 9 equaling complete injury or desiccation.

[y] Data collected 1, 7, 14, 21, and 28 days after topdressing and traffic applications were applied on March 30 (Run 1) and June 28 (Run 2), 2007.

[x] NS = not significant at $P > 0.05$.

Table 21: Effects of sand topdressing depth and simulated traffic on Kentucky bluegrass – perennial ryegrass mixture injury, East Lansing, Mich.

	Days After Topdressing and Traffic[z]				
	1	7	14	21	28
Topdressing Depth (cm)[y]	Mean Injury (1-9)[x]				
0.00[w]	1.0	1.0	1.0	1.0	1.0
0.16	1.0	1.0	1.0	1.0	1.0
0.21	1.0	1.0	1.0	1.0	1.0
0.32	1.0	1.0	1.0	1.0	1.0
0.42	1.0	1.0	1.0	1.0	1.0
0.64	1.0	1.0	1.0	1.0	1.0
0.85	1.0	1.0	1.0	1.0	1.0
	ns[v]	ns	ns	ns	ns
Simulated Traffic[u]	Mean Injury (1-9)				
control	1.0	1.0	1.0	1.0	1.0
traffic	1.0	1.0	1.0	1.0	1.0
	ns	ns	ns	ns	ns

[z] Data collected 1, 7, 14, 21, and 28 days after topdressing and traffic applications were applied.

[y] cm of sand topdressing applied on March 30 (Run 1) and June 28 (Run 2), 2007.

[x] Injury based on a 1 – 9 scale, with 1 equaling no injury and 9 equaling complete injury or desiccation.

[w] Number of replications for all treatments = 6.

[v] ns = not significant at $P = 0.05$.

[u] Prior to topdressing applications turfgrass was flattened using a 5.1 cm x 10.2 cm wooden block to simulate the effects of vehicle traffic prior to topdressing application.

Table 22: Analysis of variance results for Kentucky bluegrass – perennial ryegrass mixture growth[z] collected after the application of sand topdressing and simulated traffic, East Lansing, Mich.

			Days After Topdressing and Traffic[y]			
	Num.	Den.	7	14	21	28
Source of Variation	df	df	P>F			
Topdressing Depth (TD)	6.0	33.0	NS[x]	NS	NS	NS
Simulated Traffic (ST)	1.0	35.0	NS	NS	NS	NS
TD X ST	6.0	35.0	NS	NS	NS	NS

[z] cm of growth measured three day after being mowed to a 3.8 cm height.

[y] Data collected 7, 14, 21, and 28 days after topdressing and traffic applications were applied on March 30 (Run 1) and June 28 (Run 2), 2007.

[x] NS = not significant at $P > 0.05$.

Table 23: Effects of sand topdressing depth and simulated traffic on Kentucky bluegrass – perennial ryegrass mixture growth, East Lansing, Mich.

	Days After Topdressing and Traffic[z]			
	7	14	21	28
Topdressing Depth (cm)[y]	Mean Growth (cm)[x]			
0.00[w]	1.0	1.5	1.5	1.5
0.16	1.2	1.3	1.4	1.4
0.21	1.0	1.3	1.6	1.2
0.32	1.2	1.3	1.5	1.2
0.42	1.2	1.3	1.7	1.2
0.64	1.4	1.5	1.8	1.4
0.85	1.2	1.4	1.5	1.2
	ns[v]	ns	ns	ns
Simulated Traffic[u]	Mean Growth (cm)			
control	1.2	1.3	1.6	1.3
traffic	1.2	1.4	1.6	1.3
	ns	ns	ns	ns

[z] Data collected 7, 14, 21, and 28 days after topdressing and traffic applications were applied.

[y] cm of sand topdressing applied on March 30 (Run 1) and June 28 (Run 2), 2007.

[x] cm of growth measured three day after being mowed to a 3.8 cm height.

[w] Number of replications for all treatments = 6.

[v] ns = not significant at $P = 0.05$.

[u] Prior to topdressing applications turfgrass was flattened using a 5.1 cm x 10.2 cm wooden block to simulate the effects of vehicle traffic prior to topdressing application.

CONCLUSIONS

In all instances, the highest topdressing applications rates, 0.64 and 0.85 cm depth, produced a short term reductions in turfgrass cover, which the turfgrass quickly recovered from. These data suggest that if maximum continual turfgrass ground cover is a priority keep topdressing application rate to recently established perennial ryegrass, Kentucky bluegrass and mixtures of the two to rates equal to or less than a 0.42 cm depth. However, if rapid accumulation of a sand-based layer through sand topdressing is a priority application at rates as great as a 0.85 cm depth can be applied producing only a short term, less than 7 days, reduction in turfgrass cover, while producing no turfgrass injury or effect on turfgrass growth.

The highest temperatures observed on the day of topdressing application were 28.9° C for perennial ryegrass and 31.7° C for Kentucky bluegrass and the mixture of the two. These findings suggest that if the projected environmental temperature is similar to these values, application rates as heavy as 0.85 cm depth can be made to these turfgrass species without producing long term detrimental effects, as observed by others when applying sand topdressing prior to periods of high atmospheric temperature (Studzinska et al., 2006).

Effects of simulated traffic on change in turfgrass cover suggest that vehicle traffic prior to topdressing application will increase the short term reductions in turfgrass cover. Suggesting that if continual turfgrass cover is a priority when using heavy topdressing equipment application rates may have to be reduced or extra incorporation effort may be necessary. However, similar to topdressing depth findings, long term effects on turfgrass cover are minimal and effects on turfgrass injury are none existent.

Simulated traffic was shown to increase Kentucky bluegrass growth 7 and 14 days after application, which was likely the effect of turfgrass shoots returning to their original vertical orientation over time.

REFERENCES

Barton, L. G.G.Y. Wan, R.P. Buck and T.D. Colmer. 2009. Effectiveness of cultural thatch-mat controls for young and mature kikuyu turfgrass. Agron. J. 101:67-74.

Bingaman, D.E. and H. Kohnke. 1970. Evaluating sand for athletic turf. Agron. J. 62:464-467.

Brede, A.D. and J.M. Duich. 1984. Establishment characteristics of Kentucky bluegrass-perennial ryegrass turf mixtures as affected by seeding rate and ratio. Agron J. 76:875-879.

Li, D., D.D. Minner, N.E. Christians and S. Logsdon. 2005. Evaluating the impact of variable root zone depth on the hydraulic properties of sand-based turf systems. International Turfgrass Soc. 10(2): 1100-1107.

Littell, R.C., G.A. Milliken, W.W. Stroup, R.D. Wolfinger and O. Schabenberger. 2007. SAS for mixed models. 2nd ed. SAS Institute, Cary, N.C.

Lunt, O.R. 1956. A method for minimizing compaction in putting greens. Southern Calif. Turfgrass Cult. 6(3):17-20.

Magni, S., M. Volterrani and S. Miele. 2004. Soccer pitches performances as affected by construction method, sand type and turfgrass mixture. Acta Hort. (ISHS). 661:281-285.

McCarty, L.B., M.F. Gregg, J.E. Toler, J.J. Camberato and H.S. Hill. 2005. Minimizing thatch and mat development in a newly seeded creeping bentgrass golf green. Crop Sci 45:1529-1535.

Miller, G.L. 2008. An evaluation of crumb rubber and calcined clay for topdressing sports fields. Acta Hort. (ISHS) 783:381-390.

NTEP. 2009. A guide to NTEP Turfgrass Ratings: How is living ground cover evaluated? National Turfgrass Evaluation Program. Beltsville, Md. Retrieved April 6, 2009. (http://www.ntep.org/reports/ratings.htm #grcover).

Ott, R.M. and M. Longnecker. 2001. An introduction to statistical methods and data analysis: 5th edition. Duxbury, Pacific Grove, Calif.

Sudzinska, A., J. Taylor and K. Danneberger. 2006. Heavy topdressing needs to be removed. Ohio State University TurfNotes. Retrieved March 10, 2009. (http://buckeyeturf.osu.edu/index.php?option=com_turfnotes&Itemid=84&noteid=1095).

Turgeon, A.J. 2008. Turfgrass management: 8th edition. Pearson Education, Upper Saddle River, NJ.

CHAPTER 2

EFFECTS OF CUMULATIVE SAND TOPDRESSING APPLICATIONS AND SUMMER TRAFFIC ON FALL WEAR TOLERANCE AND SURFACE STABILITY OF A COOL-SEASON TURFGRASS STAND.

ABSTRACT

Drain tile installation into a native soil athletic field and subsequent sand topdressing applications is a cost effective alternate to complete field renovation. However, if cumulative topdressing rates far exceed root system development, surface stability will be compromised. The objectives of this research were to evaluate the effects of cumulative sand topdressing and summer traffic on the fall wear tolerance and stability of a 90% *Poa pratensis* L. – 10% *Lolium perenne* L. mixture established on a sandy loam soil. A RCBD was seeded on May 29, 2007, in East Lansing, Mich. Main effects included cumulative topdressing applications and summer traffic. Topdressing applications consisted of a well-graded sand (90.0% sand – 10.0% silt/clay) topdressing material applied 0, 2, 4, 6 and 8 times from July 11 – August 15, 2007, at a rate of 9.8 kg m^{-2} (0.6 cm depth). Summer traffic was applied once weekly throughout the topdressing periods using the Cady Traffic Simulator, and compared to a control. Fall traffic was applied to all treatments from October 10 to November 3, 2007. In 2008, topdressing applications and traffic, as described above, were repeated on the same experimental treatments. Results obtained from this research suggest that 2 applications applied within a 5 week period, during the summer, and restricting summer use when a re-establishment period is required will provide the greatest results in the subsequent fall.

INTRODUCTION

Athletic fields relatively high in silt and clay are prone to compaction during periods of substantial rainfall combined with heavy use (Benson and Daniel, 1990). Effects of compaction on turfgrass include: reduce turfgrass quality, percent cover, total nonstructural carbon, shoot density, verdure, and root growth (Carrow, 1980).

Sand has a high percentage of macropore space and is inherently low in silt and clay making it resistant to compaction (Bingaman and Kohnke, 1970). This resistance to compaction, in combination with high infiltration rates, makes sand a desirable and advantageous media for athletic field construction (Henderson et al., 2005). However, complete field renovation to a sand-based system is expensive; $400,000 – 600,000 for a conventional sand-based athletic field with a 30.5 cm sand-based root zone; $200,000 – 300,000 for a sand-capped system with a 15.3 cm sand root zone (Fresenburg, 2006 a; Harler, 2009), and renders the field temporarily useless. Because of these drawbacks complete field renovation is not an option for municipalities with high annual use requirements and limited budget allocations.

Alternatively to complete field renovation, developing a sand-cap athletic field system, sand over native soil similar to a California style putting green (Prettyman and McCoy, 2003), over time using sand topdressing is a possible alternative to complete field renovation, which does not take the field completely out of play. A variety of research has shown that sand topdressing can be used to improve the characteristics of a turfgrass system. For instance, Miller (2008) determined that three sand topdressing applications applied over a five month period, totaling 6.0 mm, increased surface hardness, stand density, and rooting of a bermudagrass (*Cynodon dactylon* L.) turfgrass stand subjected to intense traffic. McCartey et al. (2005) concluded that topdressing applied at an annual depth of 1.2 mm improved infiltration rates of 'L-93' creeping bentgrass (*Agrostis stolonifera* L.) in comparison to treatments that did not receive topdressing. Most recently, Barton et al. (2009) demonstrated that topdressing, twice annually at a 5.0 mm depth, increased kikuyugrass (*Pennisetum clandestinum* Hochst. ex Chiov.) color in comparison to treatments that did not receive topdressing or cultivation. Increasing the number of annual applications will decrease the duration of time required to accumulate an adequate sand root zone over the existing native soil (Li et al., 2005; Lunt, 1956). However, sand-based root zone systems rely on turfgrass interwoven roots for stability (Adams et al., 1985). Therefore, if topdressing application rates far exceed root system development, stability will be compromised. Therefore, developing an optimum topdressing regime capable of accumulating an adequate sand layer, without being detrimental to turfgrass wear tolerance is critical.

Objective:

Evaluate the effects of cumulative sand topdressing rates and summer traffic applications on the fall wear tolerance and surface stability of a cool-season turfgrass mixture established on a sandy loam soil.

Hypothesis:

Sand topdressing will increase turfgrass wear tolerance and surface stability, however high amounts of cumulative topdressing applications will be detrimental to these characteristics.

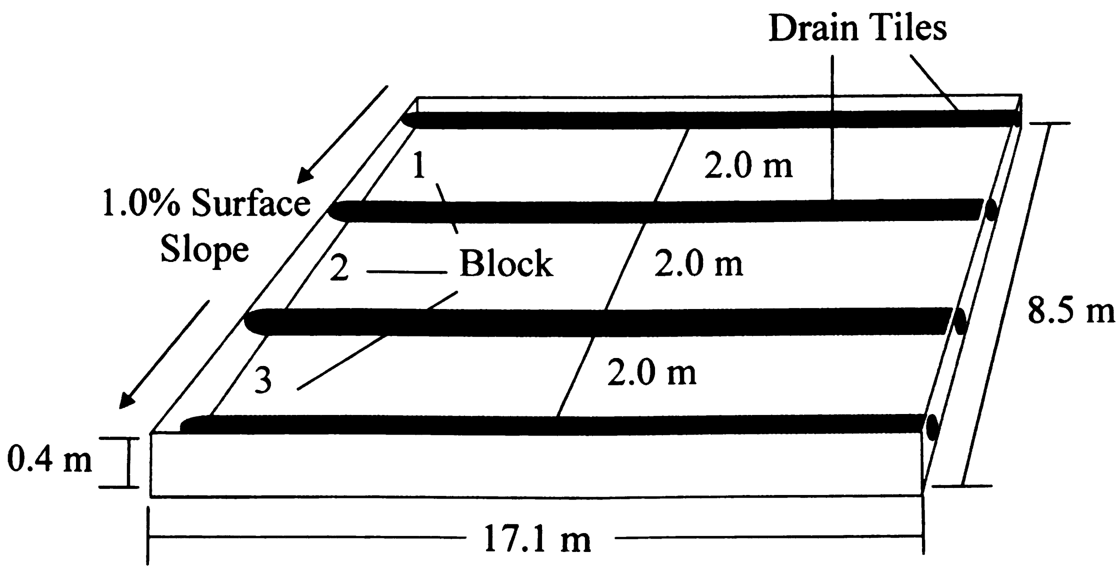
MATERIALS AND METHODS

Field research on the effects of cumulative sand topdressing applications and simulated summer traffic on a cool-season turfgrass mixture, established on compacted topsoil, was initiated at the Hancock Turfgrass Research Center (HTRC), East Lansing, Mich., April 10, 2007. The total experimental area was 145.7 m^2, and contained 30 treatments (3.0 m^2) divided into three blocks. Factors included cumulative topdressing applications [0 (control), 2, 4, 6 and 8, equal to 0.0, 19.6, 39.2, 58.8 and 78.4 kg m^{-2} annually accumulated sand, respectively] and simulated traffic (summer and fall and fall only).

Site Construction

A sandy loam soil, the A horizon of a Colwood-Brookston series (fine-loamy, mixed, active, mesic Typic Endoaquoll and Typic Argiaquoll), was excavated at the HTRC, transported to the northern HTRC parking lot, then thoroughly mixed from April 11 to 16, 2007, to ensure even particle distribution and degrade soil structure development (National Resources Conservation Services, 2007). The mixed soil was then placed into a 17.1 m wide x 8.5 m long x 0.4 m deep research plot, constructed of treated plywood, on the HTRC parking lot, April 16 – 21, 2007 (Image 2). The soil was irrigated repeatedly and compacted in layers using a Case Construction King (Case LLC, Racine, Wis.) pay loader and a Bartell vibratory compactor (Bartell Industries Inc., Brampton, Canada) to develop a worst case scenario in terms of subsoil drainage. On April 21, 2007 the research plot was graded at a 1.0% surface slope using a Kubota L2250 [Kubota Manufacturing of America Corporation (KMA), Gainesville, Ga.] with a box blade and a three point drag level to simulate a typical native soil athletic field.

Image 2: Constructed research plots 17.1 m x 8.5 m x 0.4 m, with drain tiles laterally spaced 2.0 m apart, Hancock Turfgrass Research Center, East Lansing, Mich., 2007.



Composite and core soil samples were then collected on May 11, 2007, from locations corresponding to future drain pathways to minimize surface disruption. The samples were analyzed to determine existing pH, soil nutrient levels, bulk density, and saturated hydraulic conductivity (pH 7.6, 149.0 ppm phosphorus, 127.0 ppm potassium, bulk density 1.6 g cm^{-3} and saturated hydraulic conductivity 0.3 cm hr^{-1}) (Table 24).

Drain Tile installation

Once the proper slope was established and soil samples were collected, four lateral (in relation to the slope) intercept drain tiles were installed in the experimental plot on May 11, 2007. Perforated, corrugated polyethylene (PE) drain tiles (10.2 cm diameter) were installed at a 30.5 cm depth and laterally spaced 2.0 m apart, with a 2.0% slope running to the edges of the research plot (Image 3). American Society for Testing and Materials (ASTM) International standards specify a minimum drain tile slope of 0.5% toward drain outlets (ASTM, 2004). Drain lines (15.2 cm) were cut using a walk-along trencher, Ditch Witch 1330 (Ditch Witch, Howell, Mich.) and the excavated soil was then removed from the surface of the research plot by hand. Individual treatments (1.5 x 2.0 m) were positioned between the laterally spaced drain tiles. Tile lines were then backfilled with 15.3 cm of bird's eye gravel and 15.3 cm of sand (Image 3; Table 25 and 26; Figure 3). Following drain tile installation the research plot was prepared for seeding.

Turfgrass Establishment and Preparation (2007)

Seeding preparation occurred on May 23, 2007, and included core cultivation, sand topdressing, and starter fertilizer application. Core cultivation was performed using a Toro Procore 648 (Toro Company, Bloomington, Minn.) with 1.3 cm diameter hollow

Table 24: Soil[z] pH, nutrient levels, cation exchange capacity (CEC), particle size analysis, bulk density, and saturated hydraulic conductivity of base soil, Hancock Turfgrass Research Center, East Lansing, Mich.; analysis performed at the MSU Soil and Plant Nutrient Laboratory, and Turfgrass Soil Science Laboratory, East Lansing, Mich., June 20, 2007.

pH	7.6
Soil Nutrients Levels	**ppm (mg kg^{-1})**
Phosphorus(P)	149.0
Potassium (K)	127.0
Calcium (Ca)	2086.0
Magnesium (Mg)	273.0
	meq $100g^{-1}$
CEC	13.0
Particle Size Analysis	%
Sand (0.05 – 2.0 mm)	71.4
Silt (0.002 – 0.05 mm)	24.2
Clay (<0.002 mm)	4.4
Soil Type	Sandy loam
Bulk Density (P_b)	g cm^{-3}
P_b= Ms/Vt	1.6
Sat. Hydraulic Conductivity (K_{sat})	cm hr^{-1}
K_{sat}= (V*L)/[A*t*(Hi+L)]	0.3

[z] Prior to excavation the soil was the A horizon of a Colwood series (fine-loamy, mixed, active, mesic Typic Endoaquoll) (NRCS, 2007).

Ms = mass of soil solids (g); Vt = core volume (344.8 cm^3).

V = volume of out flow (cm^3 water); L= core length (7.6 cm); A = core surface area (45.4 cm^2); t = time (hrs); Hi = hydraulic head (1.5 cm).

Image 3: Drain tiles (10.2 cm diameter) installed in base soil at 30.5 cm depth backfilled with bird's eye gravel and sand then treated with cumulative 90% sand-10% silt/clay topdressing applications, East Lansing, Mich., 2007.

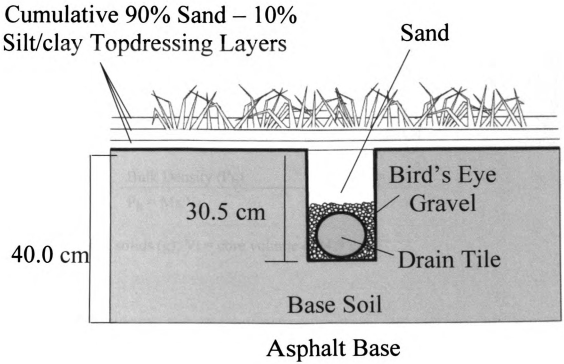


Table 25: Particle size distribution of bird's eye gravel[z] (15.25 - 30.5 cm depth over drain lines): analysis performed at the Turfgrass Soil Science Laboratory, East Lansing, Mich, June 20, 2007.

Particle Size (mm)	%
Medium Gravel (>4.76)	1.5
Fine Gravel (4.76 – 2.0)	67.3
Very Coarse Sand (1.0 - 2.0)	29.9
Coarse Sand (0.5 - 1.0)	1.1
Medium Sand (0.25 - 0.5)	0.1
Soil Type	Gravel

Bulk Density (P_b)	g cm^{-3}
$P_b = Ms/Vt$	1.7

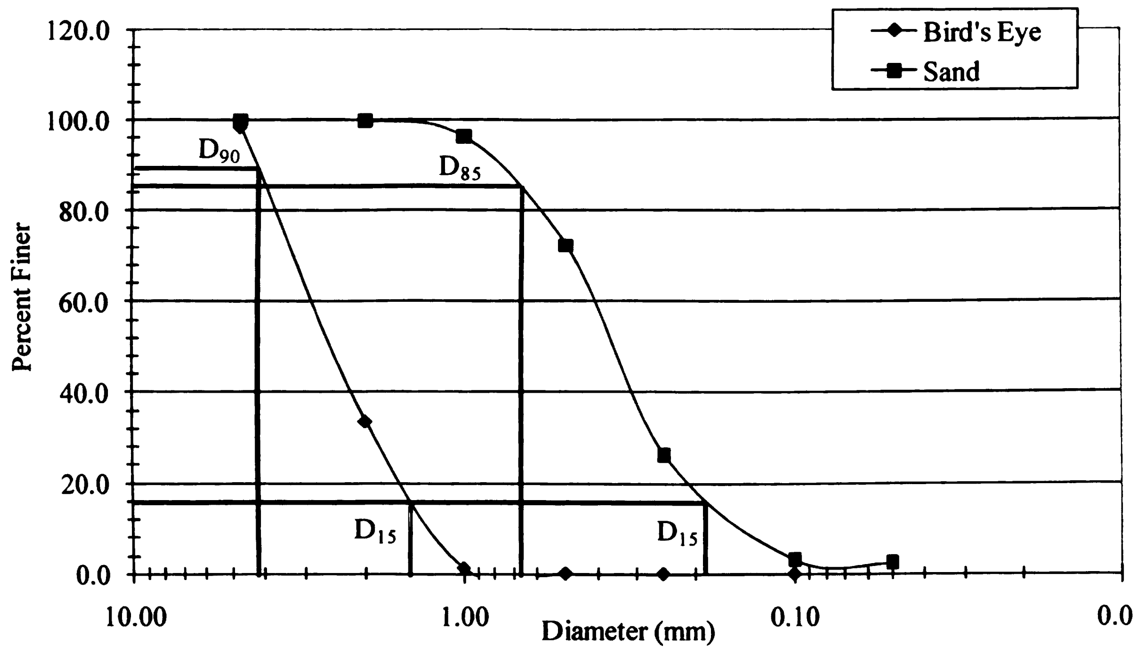
Ms = mass of soil solids (g); Vt = core volume (344.8 cm^3).

Table 26: Particle size distribution of sand material (0.0 - 15.25 cm depth over bird's eye gravel), bulk density and saturated hydraulic conductivity: analysis performed at the MSU Soil and Plant Nutrient Laboratory and Turfgrass Soil Science Laboratory, East Lansing, Mich, June 20, 2007.

Particle Size (mm)	%
>2mm	0.1
Very Coarse Sand (1.0 - 2.0)	3.7
Coarse Sand (0.5 - 1.0)	24.0
Medium Sand (0.25 - 0.5)	45.8
Fine Sand (0.1 - 0.25)	23.1
Very Fine Sand (0.05 - 0.1)	0.9
Silt (0.002 - 0.05)	0.4
Clay (<0.002)	2.0
Soil Type	Sand
Bulk Density (P_b)	g cm^{-3}
P_b = Ms/Vt	1.8
Sat. Hydraulic Conductivity (K_{sat})	cm hr^{-1}
K_{sat}= (V*L)/[A*t*(Hi+L)]	117.5

Ms = mass of soil solids (g); Vt = core volume (344.8 cm^3).
V = volume of out flow (cm^3 water); L= core length (7.6 cm); A = core surface area (45.4 cm^2); t = time (hrs); Hi = hydraulic head (1.5 cm).

Figure 3: Particle-size distribution curve of a sand material (0.0 - 15.25 cm depth) and bird's eye gravel (15.25 - 30.5 cm depth) used for drain tile backfill; analysis performed at the MSU Soil and Plant Nutrient Laboratory and Turfgrass Soil Science Laboratory, East Lansing, Mich., June 20, 2007.



Bridging Factor [$D_{15(gravel} \leq 8xD_{85(sand)}$] = 1.5≤4.8; Uniformity Factor [$D_{90(gravel)}/D_{15(gravel)} \leq 3$] = 2.7≤3; Permeability Factor [$D_{15(gravel)} \geq 5xD_{15(sand)}$] = 1.5≥1.0 (USGA Green Section Staff, 2004).

tines at a 5.0% affected surface area (25.8 cm^2 spacing) and 5.1 cm tine depth. The cores were incorporated back into the soil with hand rakes. Topdressing with a well-graded sand-based root zone material [90.0% sand – 10.0% silt/clay (90/10 sand)] was applied at a 5.0 mm depth using a Toro Topdrersser 2500 (Toro Company, Bloomington, Minn.) (Table 27; Figure 4). Starter fertilizer (16-25-13) (Lebanon Turf Products, Lebanon, Pa.) was applied last at 48.8 kg ha^{-1} P prior to seeding.

On May 29, 2007, the research plot was seeded with a 90% Kentucky bluegrass (*Poa pratensis* L.) (19.7% 'Arcadia', 19.7% 'Odyssey', 19.6% 'America', 19.6% 'SR100' and 19.6% 'Mercury') – 10% perennial ryegrass (*Lolium perenne* L.) (34.4% 'Harrier', 34.1% 'Peregrine' and 29.8% 'SR 4600') (Research Seeds, Inc., Fort Dodge, Iowa) mixture at 65.9 kg ha^{-1} and 43.9 kg ha^{-1} by weight, respectively, a common practice on cool-season sports fields (Brede and Duich, 1984). The preemergence herbicide Tupersan®, siduron [1-(2-methylcyclohexyl)-3-phenylurea] (Lebanon Seaboard Corp., Lebanon, Pa.), was applied at 4.6 kg ha^{-1} a.i. directly after seeding. Following seeding and preemergence herbicide applications, the research area was lightly raked by hand and topdressed again using the 90/10 sand at a 1.0 mm depth to ensure adequate seed to soil contact. At this time, a cumulative 6.0 mm of nonrestrictive rooting media (90/10 sand) had been accrued over the compacted base soil.

Due to the heavily compacted base soil conditions within this research area, turfgrass establishment was poor. The research area was core cultivated in response to unfavorable establishment at 15.0% affected surface area, three passes with the Procore 648, on June 11, 2007. Following core cultivation the Kentucky bluegrass – perennial

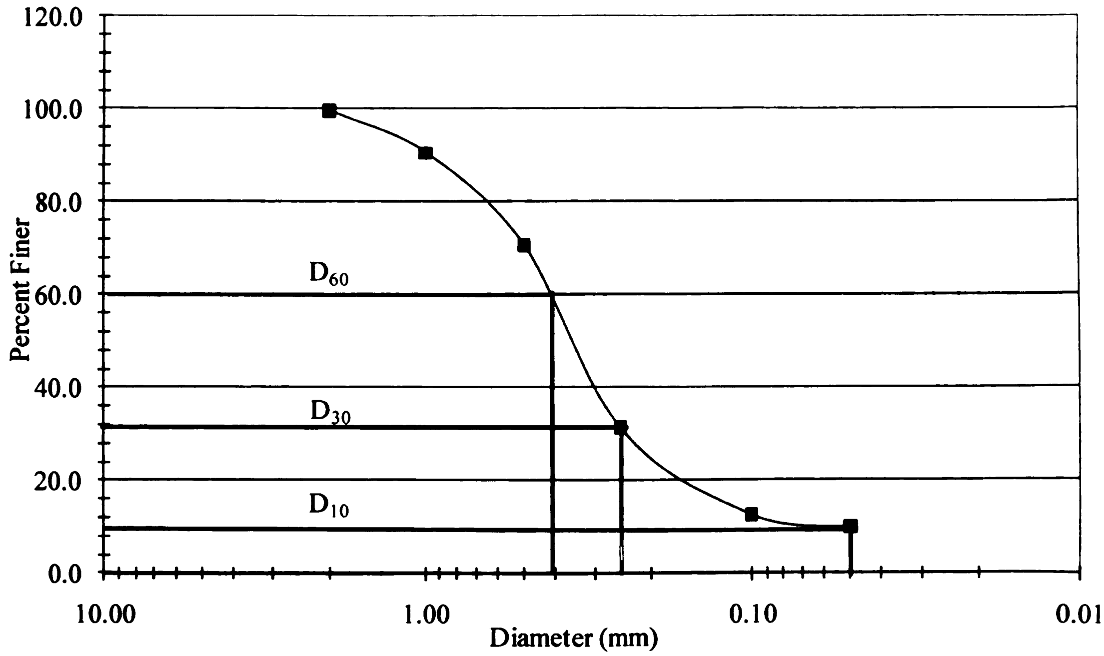
Table 27: Particle size distribution, bulk density, and saturated hydraulic conductivity of sand-based topdressing material; analysis performed at the MSU Soil and Plant Nutrient Laboratory and Turfgrass Soil Science Laboratory, East Lansing, Mich., June 20, 2007.

Particle Size (mm)	%
>2mm	0.3
Very Coarse Sand (1.0 - 2.0)	9.1
Coarse Sand (0.5 - 1.0)	19.9
Medium Sand (0.25 - 0.5)	39.3
Fine Sand (0.1 - 0.25)	18.7
Very Fine Sand (0.05 - 0.1)	2.7
Silt (0.002 - 0.05)	9.7
Clay (<0.002)	0.3
Soil Type	Sand
Bulk Density (Pb)	$g\ cm^{-3}$
Pb = Ms/Vt	1.8
Sat. Hydraulic Conductivity (K_{sat})	$cm\ hr^{-1}$
K_{sat}= (V*L)/[A*t*(Hi+L)]	15.4

Ms = mass of soil solids (g); Vt = core volume (344.8 cm^3).

V = volume of out flow (cm^3 water); L= core length (7.6 cm); A = core surface area (45.4 cm^2); t = time (hrs); Hi = hydraulic head (1.5 cm).

Figure 4: Particle-size distribution curve of 90% sand – 10% silt/clay topdressing material[z]; analysis performed at the MSU Soil and Plant Nutrient Laboratory, East Lansing, Mich., June 20, 2007.



[z] SW: Well-graded Sand ($C_u > 6$ and $1 < C_c < 3$); Effective size (D_{10}) = 0.05; D_{30} = 0.22; D_{60} = 0.4; Uniformity coefficient (C_u) = D_{60} / D_{10} = 8.0; Coefficient of gradation (C_c) = $D_{30}^2 / (D_{60} \times D_{10})$ = 2.4 (ASTM, 2006).

ryegrass mixture described above was applied again at the same rate, topdressed with 90/10 sand at 1.0 mm, lightly raked and covered with straw, 2 bails 145.4 m^{-2} (Sorochan and Rogers, 2001).

Cumulative Topdressing Applications

The newly established turfgrass stand received its first 90/10 sand topdressing treatments on July 11, 2007. All 90/10 sand topdressing applications were applied at the same rate, 9.8 kg m^{-2} (0.6 cm depth). Topdressing applications were made using a Mete-R-Matic self propelled topdresser (Turfco, Minneapolis, Minn.) with a 0.75 m spreading width. Individual topdressing treatments were 1.5 m wide, requiring two passes with the topdresser. Cumulative sand topdressing depths varied depending on the total number of applications made annually, ranging from 0 – 8, 0.0 – 4.8 cm, respectively (Table 28).

Turfgrass Maintenance

During establishment, July 3 – 7, 2007, the turfgrass was mown using a Honda Harmony (American Honda Motor Co, Inc., Alpharetta, Ga.) rotary mulching mower at 3.8 cm. The mowing height was raised to 6.4 cm on July 8, 2007. The newly established turfgrass was then maintained at a regular mowing height of 7.6 cm from July 11 to August 27, 2007, to promote rooting and increase heat stress tolerance, and then reduced to 5.0 cm prior to fall traffic applications (Vanini and Rogers, 2008). Throughout 2007, the turfgrass received regular applications of a poly coated fertilizer (26-7-14) (Agrium, Sylacauga, Ala.), and urea (46-0-0), providing a total of 23.7 g m^{-2} N (237.0 kg ha^{-1} N) annually (Puhalla et al., 1999) (Table 29). To provide postemergence weed control Drive® 75 DF, quinclorac (3, 7-dichloro-8-quinolinecarboxylic acid) (BASF Corp.,

Table 28: Cumulative 90% sand – 10% silt/clay topdressing applications, Hancock Turfgrass Research Center, East Lansing, Mich., 2007.

	Total Annual Topdressing Applications[z]				
2007	0	2	4	6	8
11-Jul		■	■	■	■
16-Jul					■
18-Jul				■	
20-Jul					■
23-Jul			■		
25-Jul				■	■
31-Jul					■
1-Aug		■	■	■	
6-Aug					■
8-Aug				■	
10-Aug					■
15-Aug			■	■	■

	Total Annual Topdressing Applications[z]				
2008	0	2	4	6	8
14-Jul		■	■	■	■
16-Jul					■
18-Jul				■	
20-Jul					■
23-Jul			■		
25-Jul				■	■
31-Jul					■
1-Aug		■	■	■	
6-Aug					■
10-Aug				■	■
22-Aug			■	■	■

[z] Topdressing 9.8 kg m^{-2} (0.6 cm) per application, producing a cumulative sand depth of 0.0 – 5.1 cm.

Table 29: Cumulative 90% sand - 10% silt/clay topdressing research plot fertilization schedule, Hancock Turfgrass Research Center, East Lansing, Mich., 2007 and 2008.

2007	Product	g m^{-2} N
21-Jun	Polyon (26-7-14)	4.7
11-Jul	Urea (46-0-0)	2.4
18-Jul	Polyon	4.7
24-Jul	Urea	2.4
15-Aug	Polyon	4.7
10-Oct	Urea	2.4
26-Oct	Urea	2.4
	Total Nitrogen (N)	23.7

2008	Product	g m^{-2} N
15-May	Polyon (26-7-14)	4.7
20-Jun	Polyon	4.7
15-Jul	Urea (46-0-0)	2.4
22-Jul	Polyon	4.7
5-Aug	Urea	2.4
25-Aug	Polyon	4.7
22-Sep	Urea	2.4
17-Oct	Urea	2.4
	Total Nitrogen (N)	28.4

Triangle Park, N.C.), was applied at 0.8 kg ha^{-1} a.i. with methylated seed oil (0.3% v/v) on July 24, 2007, and Trimec® Classic Broadleaf Herbicide, 2,4-D (2,4-dichlorophenoxyacetic acid), propionic acid [2-(2-methyl-4-chlorophenoxy)] and dicamba (3,6-dichloro-o-anisic acid) (PBI/Gordon Corporation, Kansas City, Mo.), was applied at a rate of 5.6 pt ha^{-1} a.i. on July 26, 2007.

Traffic Simulation

All research treatments were trafficked using the Cady traffic simulator to determine the effects of topdressing accumulation and summer traffic on the fall wear tolerance and surface stability of the turfgrass system (Henderson et al., 2005). Simulated traffic throughout the sand application period, July 11 – August 15, 2007, was applied using a split-block design, allowing for a comparison of trafficked and non-trafficked treatments during the topdressing regime. Traffic applied at this time simulated summer use on a low wear levels, one traffic application (two passes, one forward and one backward) per week (Goddard et al., 2008.), which would be typical of a multiuse municipal sports field.

At the conclusion of the cumulative 90/10 sand applications and summer traffic, August 15, 2007, perennial ryegrass (34.4% 'Harrier', 34.1% 'Peregrine' and 29.8% 'SR 4600') was inter-seeded at 439.0 kg ha^{-1} to provide some turfgrass recovery in the trafficked areas prior to the fall traffic applications. Traffic was then applied to all treatments at an intensified rate to simulate fall high school athletic field use from October 10 – November 3, 2007. High wear level traffic included two traffic applications (four passes, two forward and two backward) per week.

To ensure a worst case scenario in terms of rain events, rainfall was regularly monitored using the HTRC MAWN Weather Station (Enviro-weather, 2008) (Table 30). Rainfall data was compared to data collected from the HTRC Rain Bird Maxi Weather Station, Model WS-200 (Rain Bird, Glendora, Cal.) in 2006, a particularly wet fall season. Supplemental irrigation was applied to the research plot once weekly using Toro® LPS 10.2 cm pop-up spray heads with TVAN 3.7 m, 180° arc pattern, adjustable nozzles (Spartan Distributors Inc., Sparta, Mich.) to provide rainfall levels equivalent to fall 2006 levels.

Turfgrass Reestablishment and Maintenance (2008)

On April 22, 2008 treatments were core cultivated at 5.0% affected surface area and inter-seeded with the same Kentucky bluegrass – perennial ryegrass mixture at the initially stated rate. Following the inter-seeding the experimental area received a Starter fertilizer (16-25-13) application, at a rate of 48.82 kg ha^{-1} P, and Tupersan, applied at 4.6 kg ha^{-1} a.i.

On June 12, 2008, the research area was core cultivated at 15.0% affected surface area and inter-seeded with the Kentucky bluegrass – perennial ryegrass mixture at the same rate to ensure adequate turfgrass reestablishment. Turfgrass was maintained at a 7.6 cm mowing height from April 17 to August 27, 2008, and then reduced to 5.0 cm prior to the fall simulated traffic applications. Throughout 2008, the turfgrass received regular applications of poly coated fertilizer (26-7-14) and urea (46-0-0) providing a total of 28.4 g m^{-2} N (284.0 kg ha^{-1} N) annually (Table 29).

Table 30: Rainfall (2006, 2007 and 2008) and supplemental irrigation (2007 and 2008) data, East Lansing, Mich.

	2006[z]		2007[y]		2008[y]	
		cm		cm		cm
Oct. 11-14	Rainfall	1.4	Rainfall	0.8	Rainfall	0.0
			Irrigation	0.6	Irrigation	1.4
			Total	1.4	Total	1.4
Oct. 15-21	Rainfall	2.3	Rainfall	4.1	Rainfall	1.2
			Irrigation	0.0	Irrigation	1.1
			Total	4.1	Total	2.3
Oct. 22-28	Rainfall	2.5	Rainfall	2.0	Rainfall	1.3
			Irrigation	0.5	Irrigation	1.2
			Total	2.5	Total	2.5
Oct. 29-Nov. 04	Rainfall	0.0	Rainfall	0.3	Rainfall	0.8
			Irrigation	0.0	Irrigation	0.0
			Total	0.3	Total	0.8
Nov. 5-11	Rainfall	2.0	Rainfall	0.0	Rainfall	0.3
			Irrigation	2.0	Irrigation	1.7
			Total	2.0	Total	2.0

[z] Rainfall data collected using the Rain Bird Maxi Weather Station, Model WS-200.

[y] Rainfall data collected using the Hancock Turfgrass Research Center MAWN Weather Station.

Cumulative Topdressing Applications and Simulated Traffic

The same experimental treatments received cumulative sand topdressing applications ranging from 0 – 8 applied at 9.8 kg m^{-2} initiated July 14, 2008, providing two year cumulative rates ranging from 0 – 16 applications (0, 2, 4, 6, and 8 applications applied in 2007 and again in 2008) (Table 28). Simulated summer traffic was applied throughout this period until the conclusion of the topdressing applications on August 22, 2008, again applied using the same split-block design, allowing for an evaluation of the cumulative effects of summer trafficked and non-trafficked treatments during the topdressing regime over a two year period. After the conclusion of the cumulative 90/10 sand applications and summer traffic, August 23, 2008, perennial ryegrass was inter-seeded at 439.0 kg ha^{-1} to provide some turfgrass recovery in the trafficked areas prior to the fall traffic applications.

Traffic was then applied to all treatments at an increased intensity, two traffic applications per week, simulating fall athletic field use from October 14 – November 12, 2008. Again to insure a worst case scenario in terms of rain events, rainfall was regularly monitored using the HTRC MAWN weather station and supplemental irrigation was applied to the research plot to provide rainfall levels equivalent to fall 2006 levels (Table 30).

Response Variables

The following data were collected to evaluate the effects of cumulative 90/10 sand topdressing and simultaneous simulated summer traffic on fall turfgrass wear tolerance and surface stability. Data collected included percent living ground cover (0.0 to 100.0%) based on the National Turfgrass Evaluation Program (NTEP) system of rating

(National Turfgrass Evaluation Program, 2009). Shoot density and surface stability was also collected throughout the fall traffic period. One core sample per treatment was extracted using a 32.0 mm diameter soil sampling probe (Miltona Turf Products, Maple Gove, Minn.) to determine turfgrass shot density (shoots 8.0 cm^{-2}). After shoot density was determined these samples were returned to the research plots. Surface stability data included shear strength, evaluated using the Eijkelkamp shear vane (Eijkelkamp, Giesbeek, the Netherlands) and Clegg turf shear tester (TST) with a 50 (wide) x 40 mm (insertion depth) paddle (Baden Clegg PTY Ltd., Wembley DC, WA, Australia) (Stier and Rogers, 2001; Sherratt et al., 2005). Clegg Impact Tester, with a 2.25 kg missile, (Lafayette Instrument Co., Lafayette, Ind.) data were collected to evaluate differences in surface hardness, reported as G_{max} (McNitt and Landschoot, 2003).

After the conclusion of the high wear level simulated traffic on November 8, 2007 and November 12, 2008, two density samples (shoots 86.6 cm^{-2}) per treatment were collected using a 10.5 cm diameter cup cutter (Miltona Turf Products, Maple Gove, Minn.) in an attempt to reduce density data variability. Samples were returned to their respective treatments after turfgrass shoot density was counted.

Three soil core samples, 7.6 cm deep, per plot were collected using the 32.0 mm diameter soil sampling probe to determine the effects of cumulative topdressing and traffic on root development. Samples were separated into groups by sampling depth, 0.0 – 3.8 cm and 3.8 – 7.6 cm, bagged and stored at 0.0° C. Root washing was then initiated on January 13 and concluded January 24, 2008, and initiated the following season on January 15 and concluded January 27, 2009. Samples were placed in a 250.0 ml plastic beaker with a screw on cap. Beakers were then filled with a dispersal solution (35.7 g Sodium Metaphosphate, 7. 9 g Sodium Carbonate, and 1.0 L water) (Frank et al., 2005). Samples were agitated for 24 hrs then washed through a 0.05 mm sieve. Root samples retained on the sieve were then dried for 72 hrs at 100.0° C and weighed using a Mettler PE 3600 Delta Range Balance (Mettler-Toledo Inc., Columbus, Ohio) with a 0.01 g readability to determine the dry root density (g•91.9 cm^{-3}).

Statistical Analysis

Turfgrass cover, shoot density, shear vane, turf shear tester, and surface hardness data were analyzed as a 5x2 randomized factorial, complete split-block design, with three replications, using SAS (version 9.1.3; SAS Institute Inc., Cary, N.C., 2007). Main effects included cumulative sand topdressing application rates (whole-plot) and summer traffic (sub-plot). Normality of the residuals and homogeneity of variances were examined using PROC UNIVARIATE procedure. When variances were unequal the REPEATED/GROUP = treatment statement was used and treatments with similar variances were grouped accordingly. The Akaike information criterion (AIC) value was used to determine whether a regular analysis with a common variance or an analysis with unequal variance was required (Littell et al., 2007). The analysis that produced the lowest AIC value was selected to make conclusions on significance of factor effects and their interactions. Mean separations were obtained based on the selected analysis using Fisher's least significant difference (LSD) at a 0.05 level of probability (Ott and Longnecker, 2001)

Rooting density data were analyzed as a 5x2x2 with the same experimental design as discussed above with the addition of rooting depth. Because rooting depth could not be assigned at random repeated measures (REPEATED treatment/TYPE= variance-covariance structure) were explored. The variance-covariance structure that produced the lowest AIC value was selected to make conclusions on significance of factor effects and their interactions.

RESULTS

Fall Wear Tolerance Characteristics of a Spring Established Cool-Season Turfgrass Mixture (2007).

Main effects of simulated traffic on the living ground cover of spring established Kentucky bluegrass – perennial ryegrass mixture were significant throughout the fall data collection period, while the main effects of topdressing depths were not (Table 31). When differences were observed, the treatments that received summer and fall traffic showed reduced mean ground cover in comparison to treatments that received fall traffic only (Table 32).

Significant main effects of topdressing depth and traffic on turfgrass shoot density were observed during the fall data collection period (Table 33). Contrary to the overall trend, the control (0.0 cm topdressing depth) yielded the greatest mean shoot density on one occasion only, after 4 fall traffic applications (Table 34). When differences between traffic levels were observed, the treatments that received fall traffic only produced greater mean shoot densities in comparison to treatments that received summer and fall traffic.

Main effects of soil sampling depth on rooting density were significant, while no differences were observed between topdressing depth and traffic (Table 35). A significant traffic x soil sampling depth interaction was also observed at this time.

Soil samples collected from the 0.0 – 3.8 cm depth yielded greater mean root density than samples collected from the 3.8 – 7.6 cm depth (Table 36). The simulated traffic x soil sampling depth interaction demonstrated that the combination of summer and fall traffic will decrease the rooting density of samples collected from the 0.0 – 3.8 cm depth in comparison to samples collected from this depth that received fall traffic only (Figure 5).

Table 31: Analysis of variance results for cover[z] ratings collected after fall traffic simulator applications[y], East Lansing, Mich. (data collected in 2007).

			Fall Traffic Applications (2007)[x]					
	Num.	Den.	0	2	4	6	8	10
Source of Variation	df	df			P>F			
Topdressing Depth (TD)	4.0	8.0	NS[w]	NS	NS	NS	NS	NS
Traffic (T)	1.0	10.0	<0.0001	0.0007	0.0009	0.0157	NS	NS
TD X T	4.0	10.0	NS	NS	NS	NS	NS	NS

[z] Living ground cover, 0.0 – 100.0% percent.

[y] Traffic applications were applied using the Cady Traffic Simulator.

[x] Data collected after 0, 2, 4, 6 , 8, and 10 fall traffic simulator applications, observed on Oct. 10, 12, 19, 26, Nov. 2, and 10, 2007, respectively.

[w] NS = not significant at $P > 0.05$.

Table 32: Effects of topdressing depth and traffic on turfgrass cover following fall traffic simulator applications, East Lansing, Mich. (data collected in 2007).

	Fall Traffic Applications[z]									
	0		2		4		6		8	10
Topdressing Depth (cm)[y]	2007 Mean Cover (0-100%)[x]									
0.0[w]	92.5		86.7		68.3		64.2		39.2	16.7
1.2	92.5		88.3		70.8		66.7		45.8	20.8
2.4	95.0		91.7		71.7		73.3		54.2	21.3
3.6	93.3		87.5		65.0		65.0		45.0	13.3
4.8	90.0		81.7		65.0		60.8		40.8	18.3
	ns[v]									
Traffic[u]	2007 Mean Cover (0-100%)									
fall traffic only	100.0	a[t]	96.3	a	78.7	a	72.3	a	49.3	18.9
summer[s] & fall traffic	85.3	b	78.0	b	57.7	b	59.7	b	40.7	17.3
									ns	ns

[z] Data collected after 0, 2, 4, 6, 8, and 10 fall traffic simulator applications, observed on Oct. 10, 12, 19, 26, Nov. 2, and 10, 2007, respectively.

[y] cm of topdressing sand accumulated over a one month period, July 11- Aug. 15, 2007.

[x] Living ground cover, 0.0 – 100.0%.

[w] Number of replications for all treatments = 3.

[v] ns = not significant at $P = 0.05$.

[u] Traffic applications were applied using the Cady Traffic Simulator.

[t] Means in a given column with the same letter do not differ using Fisher's least significant difference at $P = 0.05$.

[s] Summer traffic treatments received one traffic applications per week from July 11 – Aug. 15, 2007.

Table 33: Analysis of variance results for shoot density[z] collected after fall traffic simulator applications[y], East Lansing, Mich. (data collected in 2007).

			Fall Traffic Applications[x]					
	Num.	Den.	0	2	4	6	8	10
Source of Variation	df	df			*P*>F			
Topdressing Depth (TD)	4.0	8.0	NS[w]	NS	0.0119	NS	NS	NS
Traffic (T)	1.0	10.0	<0.0001	NS	0.0306	NS	NS	NS
TD X T	4.0	10.0	NS	NS	NS	NS	NS	NS

[z] Turfgrass shoots•cm^{-2}.

[y] Traffic applications were applied using the Cady Traffic Simulator.

[x] Data collected after 0, 2, 4, 6 , 8, and 10 fall traffic simulator applications, observed on Oct. 10, 12, 19, 26, Nov. 2, and 10, 2007, respectively.

[w] NS = not significant at $P > 0.05$.

Table 34: Effects of topdressing depth and traffic on turfgrass shoot density following fall traffic simulator applications, East Lansing, Mich. (data collected in 2007).

	Fall Traffic Applications[z]					
	0	2	4	6	8	10
Topdressing Depth (cm)[y]	2007 Mean Shoot Density[x]					
0.0[w]	10.5[v]	10.3[v]	15.3[v] a[u]	3.0[v]	1.8[v]	9.2[t]
1.2	10.0	8.3	5.0 b	4.3	3.0	20.5
2.4	11.2	7.7	8.3 b	6.7	1.7	14.8
3.6	10.5	7.8	3.5 b	0.7	2.7	14.3
4.8	9.5	8.8	7.5 b	5.7	2.2	13.5
	ns[s]	ns		ns	ns	ns
Traffic[r]	2007 Mean Shoot Density					
fall traffic only	15.1 a	10.1	9.9 a	4.6	2.9	15.7
summer[q] & fall traffic	5.5 b	7.1	5.9 b	3.5	1.7	13.2
	ns	ns	ns	ns	ns	ns

[z] Data collected after 0, 2, 4, 6, 8, and 10 fall traffic simulator applications, observed on Oct. 10, 12, 19, 26, Nov. 2, and 8, 2007, respectively.

[y] cm of topdressing sand accumulated over a one month period, July 11- Aug. 15, 2007.

[x] Turfgrass shoots•cm^{-2}.

[w] Number of replications for all treatments = 3

[v] Shoots•8.0 cm^{-2}.

[u] Means in a given column with the same letter do not differ using Fisher's least significant difference at $P = 0.05$.

[t] Shoots•86.6 cm^{-2}.

[s] ns = not significant at $P = 0.05$.

[r] Traffic applications were applied using the Cady Traffic Simulator.

[q] Summer traffic treatments received one traffic applications per week from July 11 – Aug. 15, 2007.

Table 35: Analysis of variance results for rooting density[z] collected after ten fall traffic simulator applications[y], collected Nov. 10, 2007, East Lansing, Mich.

Source of Variation	DF Num.	DF Den.	*P*>F
Topdressing Depth (TD)	4	8	NS[x]
Traffic (T)	1	30	NS
TD X T	4	30	NS
Soil Sampling Depth (SSD)	1	30	<0.0001
TD x SSD	4	30	NS
T X SSD	1	30	0.0310
TDX T X SSD	4	30	NS

[z] Dry root weight (g•91.9 cm^{-3}).

[y] Traffic applications were applied using the Cady Traffic Simulator.

[x] NS = not significant at $P > 0.05$.

Table 36: Effects of topdressing depth, traffic, and soil sampling depth on rooting density following ten fall traffic simulator applications collected Nov. 10, 2007, East Lansing, Mich.

Topdressing Depth (cm)[z]	2007 Mean Root Density ($g \bullet 91.9\ cm^{-3}$)
0.0[y]	0.18
1.2	0.25
2.4	0.23
3.6	0.32
4.8	0.25
	ns[x]
Traffic[w]	**2007 Mean Root Density ($g \bullet 91.9\ cm^{-3}$)**
fall traffic only	0.29
summer[v] & fall traffic	0.20
	ns
Soil Sampling Depth (cm)	**2007 Mean Root Density ($g \bullet 91.9\ cm^{-3}$)**
0.0-3.8	0.41 a[u]
3.8-7.6	0.08 b

[z] cm of topdressing sand accumulated over a one month period, July 11- Aug. 15, 2007.

[y] Number of replications for all treatments = 3.

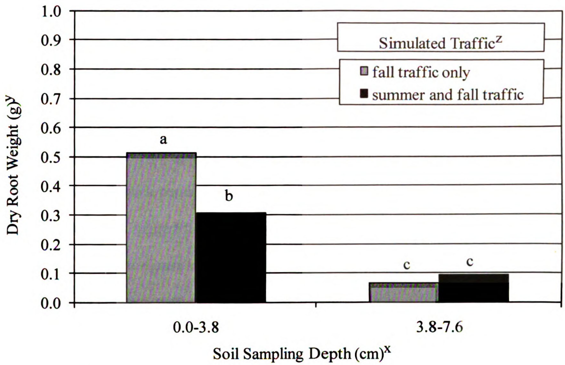
[x] ns = not significant at $P = 0.05$.

[w] Traffic applications were applied using the Cady Traffic Simulator.

[v] Summer traffic treatments received one traffic applications per week from July 11 – Aug. 15, 2007.

[u] Means in a given column with the same letter do not differ using Fisher's least significant difference at $P = 0.05$.

Figure 5: Effects of simulated traffic x soil sampling depth on rooting density collected after ten fall traffic simulator applications, Nov. 10, 2007, East Lansing, Mich.



[z] Traffic applications were applied using the Cady Traffic Simulator, summer traffic treatments received one traffic applications per week from July 11 – Aug. 15, 2007.
[y] Dry root weight ($g \cdot 91.9\ cm^{-3}$).
Columns with the same letter do not differ using Fisher's least significant difference at *P* = 0.05.

Fall Surface Stability Characteristics of a Spring Established Cool-Season Turfgrass Mixture (2007).

Significant main effects of topdressing depth and traffic on the shear vane strength of the spring established turfgrass mixture were observed during the fall data collection period (Table 37). Differences between topdressing depths were noticed after 6, 8 and 10 fall traffic applications (Table 38). In all instances, the control provided the highest mean shear vane strength, while aggressive topdressing depths, 3.6 and 4.8 cm accumulated over a 5 week period in the summer, produced the lowest shear vane strength. These results suggest that as topdressing depths increase the shear vane strength of a newly established turfgrass stand will diminish as the fall athletic season progresses. When differences between traffic were observed, treatments that received only fall traffic had greater mean shear vane strength than those that received summer and fall traffic.

Significant main effects of topdressing depth and traffic on the fall turf shear tester strength were observed (Table 39). A statistically significant topdressing depth x traffic interaction on turf shear tester strength was also noted at this time.

Mean TST strength was greatest in the treatments that received 1.2 cm of cumulative sand topdressing, followed by the 0.0 and 2.4 cm topdressing depths, and finally the 3.6 and 4.8 cm topdressing depths throughout the data collection period (Table 40). These results suggest that conservative topdressing, 1.2 cm of sand topdressing applied over a 5 week period to a newly established turfgrass stand, will provide the greatest overall fall TST strength, while aggressive topdressing, 3.6 and 4.8 cm of sand topdressing applied over a 5 week period, will be detrimental to fall TST strength. Summer traffic was detrimental to mean TST strength prior to the initiation of fall traffic

Table 37: Analysis of variance results for Eijkelkamp shear vane strength[z] collected after fall traffic simulator applications[y], East Lansing, Mich. (data collected in 2007).

			Fall Traffic Applications[x]					
	Num.	Den.	0	2	4	6	8	10
Source of Variation	df	df			P>F			
Topdressing Depth (TD)	4.0	8.0	NS[w]	NS	NS	0.0243	0.0003	0.0243
Traffic (T)	1.0	10.0	0.0170	0.0171	0.0122	NS	NS	0.0413
TD X T	4.0	10.0	NS	NS	NS	NS	NS	NS

[z] Eijkelkamp shear vane strength = Newton meters.

[y] Traffic applications were applied using the Cady Traffic Simulator.

[x] Data collected after 0, 2, 4, 6 , 8, and 10 fall traffic simulator applications, observed on Oct. 10, 12, 19, 26, Nov. 2, and 10, 2007, respectively.

[w] NS = not significant at $P > 0.05$.

Table 38: Effects of topdressing depth and traffic on Eijkelkamp shear vane strength following fall traffic simulator applications, East Lansing, Mich. (data collected in 2007).

	Fall Traffic Applications[z]					
	0	2	4	6	8	10
Topdressing Depth (cm)[y]	2007 Mean Shear Vane Strength (Nm)[x]					
0.0[w]	14.5	10.5	11.5	11.2 a[v]	13.7 a	11.8 a
1.2	12.8	9.5	8.8	9.0 ab	11.0 b	10.3 ab
2.4	13.8	10.0	10.5	7.7 b	8.8 c	8.2 bc
3.6	11.5	8.7	8.2	7.2 b	8.2 d	7.7 bc
4.8	10.0	8.2	8.3	7.0 b	7.3 d	6.7 c
	ns[u]	ns	ns			
Traffic[t]	2007 Mean Shear Vane Strength (Nm)					
fall traffic only	13.5 a	10.5 a	10.5 a	8.7	9.6	9.6 a
summer[s] & fall traffic	11.6 b	8.3 b	8.4 b	8.1	10.0	8.3 b
				ns	ns	

[z] Data collected after 0, 2, 4, 6, 8, and 10 fall traffic simulator applications, observed on Oct. 10, 12, 19, 26, Nov. 2, and 10, 2007, respectively.

[y] cm of topdressing sand accumulated over a one month period, July 11- Aug. 15, 2007.

[x] Eijkelkamp shear vane strength = Newton meters (Nm).

[w] Number of replications for all treatments = 3.

[v] Means in a given column with the same letter do not differ using Fisher's least significant difference at $P = 0.05$.

[u] ns = not significant at $P = 0.05$.

[t] Traffic applications were applied using the Cady Traffic Simulator.

[s] Summer traffic treatments received one traffic applications per week from July 11 – Aug. 15, 2007.

Table 39: Analysis of variance results for Clegg turf shear tester strength[z] collected after fall traffic simulator applications[y], East Lansing, Mich. (data collected in 2007).

			Fall Traffic Applications[x]					
	Num.	Den.	0	2	4	6	8	10
Source of Variation	df	df			*P*>F			
Topdressing Depth (TD)	4.0	8.0	0.0007	0.0390	NS[w]	0.0004	NS	0.0481
Traffic (T)	1.0	10.0	0.0001	NS	NS	NS	NS	NS
TD X T	4.0	10.0	0.0095	NS	NS	NS	NS	NS

[z] Clegg turf shear tester strength = Newton meters.

[y] Traffic applications were applied using the Cady Traffic Simulator.

[x] Data collected after 0, 2, 4, 6 , 8, and 10 fall traffic simulator applications, observed on Oct. 10, 12, 19, 26, Nov. 2, and 10, 2007, respectively.

[w] NS = not significant at $P > 0.05$.

Table 40: Effects of topdressing depth and traffic on Clegg turf shear tester strength following fall traffic simulator applications, East Lansing, Mich. (data collected in 2007).

	Fall Traffic Applications[z]					
	0	2	4	6	8	10
Topdressing Depth (cm)[y]	2007 Mean Turf Shear Tester Strength (Nm)[x]					
0.0[w]	91.3 a[v]	118.2 a	129.4	101.8 a	85.4	60.7 b
1.2	86.7 ab	99.2 abc	102.8	83.7 a	77.5	87.0 a
2.4	74.2 c	100.5 ab	89.3	86.7 a	77.2	63.7 ab
3.6	67.6 bc	93.6 bc	88.3	75.5 ab	76.2	51.2 b
4.8	73.5 bc	75.2 c	89.0	56.8 b	61.7	47.9 b
			ns[u]		ns	
Traffic[t]	2007 Mean Turf Shear Tester Strength (Nm)					
fall traffic only	96.3 a	98.2	103.5	82.5	80.4	67.8
summer[s] & fall traffic	61.1 b	96.4	96.0	79.3	70.8	56.5
		ns	ns	ns	ns	ns

[z] Data collected after 0, 2, 4, 6, 8, and 10 fall traffic simulator applications, observed on Oct. 10, 12, 19, 26, Nov. 2, and 10, 2007, respectively.

[y] cm of topdressing sand accumulated over a one month period, July 11- Aug. 15, 2007.

[x] Clegg turf shear tester strength = Newton meters (Nm).

[w] Number of replications for all treatments = 3.

[v] Means in a given column with the same letter do not differ using Fisher's least significant difference at $P = 0.05$.

[u] ns = not significant at $P = 0.05$.

[t] Traffic applications were applied using the Cady Traffic Simulator.

[s] Summer traffic treatments received one traffic applications per week from July 11 – Aug. 15, 2007.

only. The topdressing depth x simulated traffic interaction was also observed prior to the initiation of fall traffic, with the treatments that received summer traffic producing the lowest TST strength for the 0.0, 2.4 and 4.8 cm topdressing depth, supporting earlier statements that summer traffic is determinant to fall TST strength (Figure 6).

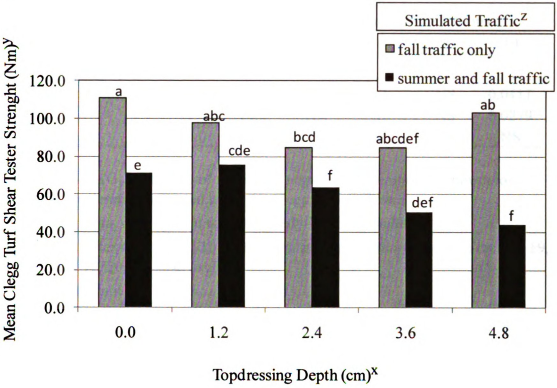
Main effects of topdressing depth and traffic on surface hardness were observed on one occasion only, following 10 fall traffic applications (Table 41). In this instance the 1.2 and 2.4 cm topdressing depths accumulated over a 5 week period, produced the greatest mean surface hardness, while the aggressive topdressing depths, 3.6 and 4.8 cm, produced the lowest surface hardness (Table 42). Summer and fall traffic was shown to increase mean surface hardness in comparison to fall traffic only.

Fall Wear Tolerance Characteristics of an Established Cool-Season Turfgrass Mixture (2008).

Significant main effects of topdressing depth and traffic on the fall ground cover of the same turfgrass stand established in the spring of 2007 and inter-seeded in the spring of 2008 were observed in the fall of 2008 (Table 43). In every instance that differences were observed, topdressing, regardless of depth, provided increased mean turfgrass coverage in comparison to the control (0.0 cm depth) (Table 44). In exception to the overall trend, summer and fall traffic treatment received a greater cover rating than the fall traffic only treatment on one occasion only.

Main effects of topdressing depth on shoot density were observed during the fall, while no differences in traffic were observed (Table 45). When differences were observed, the control produced the lowest mean shoot density in comparison to the other treatment throughout the data collection period (Table 46).

Figure 6: Effects of topdressing depth x simulated traffic on Clegg turf shear tester strength collected prior to fall traffic simulator applications, Oct. 10, 2007, East Lansing, Mich.



[z] Traffic applications were applied using the Cady Traffic Simulator, summer traffic treatments received one traffic applications per week from July 11 – Aug. 15, 2007.

[y] Clegg turf shear tester strength = Newton meters (Nm).

[x] cm of topdressing sand accumulated over a one month period, July 11- Aug. 15, 2007. Columns with the same letter do not differ using Fisher's least significant difference at *P* = 0.05.

Table 41: Analysis of variance results for surface hardness[z] collected after fall traffic simulator applications[y], East Lansing, Mich. (data collected in 2007).

			Fall Traffic Applications[x]			
	Num.	Den.	4	6	8	10
Source of Variation	df	df	*P*>F			
Topdressing Depth (TD)	4.0	8.0	NS[w]	NS	NS	0.0411
Traffic (T)	1.0	10.0	NS	NS	NS	0.0279
TD X T	4.0	10.0	NS	NS	NS	NS

[z] Surface hardness (G_{max}) = ratio of maximum negative acceleration on impact to gravitational acceleration collected using the Clegg Impact Tester.

[y] Traffic applications were applied using the Cady Traffic Simulator.

[x] Data collected after 4, 6 , 8, and 10 traffic simulator applications, observed on Oct. 19, 26, Nov. 2, and 10, 2007, respectively.

[w] NS = not significant at $P > 0.05$.

Table 42: Effects of topdressing depth and traffic on surface hardness following fall traffic simulator applications, East Lansing, Mich. (data collected in 2007).

	Fall Traffic Applications[z]			
	4	6	8	10
Topdressing Depth (cm)[y]	2007 Mean Surface Hardness (G_{max})[x]			
0.0[w]	66.7	67.5	73.2	101.8 ab[v]
1.2	74.0	69.5	76.3	112.2 a
2.4	79.8	62.2	72.8	111.5 a
3.6	68.3	63.2	72.7	96.5 b
4.8	73.7	64.5	72.7	92.7 b
	ns[u]	ns	ns	
Traffic[t]	2007 Mean Surface Hardness (G_{max})			
fall traffic only	70.9	61.8	71.3	98.0 b
summer[s] & fall traffic	74.1	68.9	75.8	107.9 a
	ns	ns	ns	

[z] Data collected after 4, 6, 8, and 10 fall traffic simulator applications, observed on Oct. 19, 26, Nov. 2, and 10, 2007, respectively.

[y] cm of topdressing sand accumulated over a one month period, July 11- Aug. 15, 2007.

[x] Surface hardness (G_{max}) = ratio of maximum negative acceleration on impact to gravitational acceleration collected using the Clegg Impact Tester.

[w] Number of replications for all treatments = 3.

[v] Means in a given column with the same letter do not differ using Fisher's least significant difference at $P = 0.05$.

[u] ns = not significant at $P = 0.05$.

[t] Traffic applications were applied using the Cady Traffic Simulator.

[s] Summer traffic treatments received one traffic applications per week from July 11 – Aug. 15, 2007.

Table 43: Analysis of variance results for cover[z] ratings collected after fall traffic simulator applications[y], East Lansing, Mich. (data collected in 2008).

			Fall Traffic Applications[x]					
	Num.	Den.	0	2	4	6	8	10
Source of Variation	df	df			$P>F$			
Topdressing Depth (TD)	4.0	8.0	NS[w]	0.0094	0.0014	0.0011	0.0130	0.0003
Traffic (T)	1.0	10.0	NS	NS	NS	0.0313	NS	NS
TD X T	4.0	10.0	NS	NS	NS	NS	NS	NS

[z] Living ground cover, 0.0 – 100.0% percent.

[y] Traffic applications were applied using the Cady Traffic Simulator.

[x] Data collected after 0, 2, 4, 6 , 8, and 10 fall traffic simulator applications, observed on Oct. 13, 17, 24, 31, Nov. 7, and 14, 2008, respectively.

[w] NS = not significant at $P > 0.05$.

Table 44: Effects of topdressing depth and traffic on turfgrass cover following fall traffic simulator applications, East Lansing, Mich. (data collected in 2008).

	Fall Traffic Applications[z]					
	0	2	4	6	8	10
Topdressing Depth (cm)[y]	2008 Mean Cover (0-100%)[x]					
0.0[w]	100.0	84.2 b[v]	83.3 b	52.5 b	56.7 b	49.2 b
2.4	100.0	93.3 a	93.3 a	78.3 a	67.5 a	66.7 a
4.8	100.0	91.7 a	92.5 a	72.5 a	73.3 a	71.7 a
7.2	100.0	93.3 a	93.3 a	70.8 a	74.2 a	70.8 a
9.6	100.0	94.2 a	91.7 a	79.2 a	78.3 a	71.7 a
	ns[u]					
Traffic[t]	2008 Mean Cover (0-100%)					
fall traffic only	100.0	90.7	91.3	68.7 b	69.0	65.7
summer[s] & fall traffic	100.0	92.0	90.3	72.7 a	71.0	66.3
	ns	ns	ns		ns	ns

[z] Data collected after 0, 2, 4, 6, 8, and 10 fall traffic simulator applications, observed on Oct. 13, 17, 24, 31, Nov. 7, and 14, 2008, respectively.

[y] cm of topdressing sand accumulated over a two year period, July 11 – Aug. 15, 2007, and July 14 – Aug. 22, 2008.

[x] Living ground cover, 0.0 – 100.0% percent.

[w] Number of replications for all treatments = 3.

[v] Means in a given column with the same letter do not differ using Fisher's least significant difference at $P = 0.05$.

[u] ns = not significant at $P = 0.05$.

[t] Traffic applications were applied using the Cady Traffic Simulator.

[s] Summer traffic treatments received one traffic applications per week from July 14 – Aug. 22, 2008.

Table 45: Analysis of variance results for shoot density[z] collected after fall traffic simulator applications[y], East Lansing, Mich. (data collected in 2008).

			Fall Traffic Applications (2008)[x]					
	Num.	Den.	0	2	4	6	8	10
Source of Variation	df	df	P>F					
Todressing Depth (TD)	4.0	8.0	0.0374	NS[w]	NS	0.0444	NS	0.0050
Traffic (T)	1.0	10.0	NS	NS	NS	NS	NS	NS
TD X T	4.0	10.0	NS	NS	NS	NS	NS	NS

[z] Turfgrass shoots•cm^{-2}.

[y] Traffic applications were applied using the Cady Traffic Simulator.

[x] Data collected after 0, 2, 4, 6 , 8, and 10 traffic simulator applications, observed on Oct. 13, 17, 24, 31, Nov. 7, and 12, 2008, respectively.

[w] NS = not significant at $P > 0.05$.

Table 46: Effects of topdressing depth and traffic on shoot density following fall traffic simulator applications, East Lansing, Mich. (data collected in 2008).

	Fall Traffic Applications[z]					
	0	2	4	6	8	10
Topdressing Depth (cm)[y]	2008 Mean Shoot Density[x]					
0.0[w]	4.8[v] b[u]	6.2[v]	5.0[v]	6.2[v] b	2.3[v]	34.7[t] b
2.4	13.3 a	13.7	6.7	14.2 a	7.5	70.2 a
4.8	15.7 a	10.7	10.3	10.3 ab	8.3	81.5 a
7.2	12.5 a	12.2	10.2	6.2 b	7.3	70.7 a
9.6	13.0 a	16.2	12.2	12.7 a	5.8	66.3 a
		ns[s]				
Traffic[r]	2008 Mean Shoot Density					
fall traffic only	12.5	12.5	8.5	17.8	6.5	60.5
summer[q] & fall traffic	11.3	11.1	9.3	9.4	6.1	68.9
	ns	ns	ns	ns	ns	ns

[z] Data collected after 0, 2, 4, 6, 8, and 10 fall traffic simulator applications, observed on Oct. 13, 17, 24, 31, Nov. 7, and 12, 2008, respectively.

[y] cm of topdressing sand accumulated over a two year period, July 11 – Aug. 15, 2007, and July 14 – Aug. 22, 2008.

[x] Turfgrass shoots•cm^{-2}.

[w] Number of replications for all treatments = 3.

[v] Shoots•8.0 cm^{-2}.

[u] Means in a given column with the same letter do not differ using Fisher's least significant difference at $P = 0.05$.

[t] Shoots•86.6 cm^{-2}.

[s] ns = not significant at $P = 0.05$.

[r] Traffic applications were applied using the Cady Traffic Simulator.

[q] Summer traffic treatments received one traffic applications per week from July 14 – Aug. 22, 2008.

Soil sampling depth produced a main effect on rooting density, while no other main effects or interactions were significant (Table 47). Soil samples collected from the 0.0 – 3.8 cm depth produced greater mean rooting densities than samples collected from the 3.8 – 7.6 cm depth (Table 48).

Fall Surface Stability Characteristics of an Established Cool-Season Turfgrass Mixture (2008).

Significant main effects of topdressing depth on the shear vane strength of a turfgrass mixture, established in the spring of 2007, were observed in the fall of 2008, while traffic was not significant (Table 49). Topdressing depths produced differences in shear vane strength after 2, 6, 8 and 10 fall traffic applications (Table 50). When differences were observed, the overall mean shear vane strength was greatest in treatments that received no topdressing and 4.8 cm of cumulative topdressing, 2.4 cm applied over a 5 week period in the summer of 2007 and 2.4 cm applied over a 6 week period in the summer of 2008. Treatments that received 7.2 and 9.6 cm of topdressing, both accumulated over a 5 week period in 2007 and a 6 week period in 2008, provided the worst overall shear vane strength. These findings suggest that aggressively accumulated topdressing depths, 7.2 and 9.6 cm accumulated over two consecutive summers, are especially detrimental to the fall shear vane strength of an established turfgrass stand.

Significant main effects of topdressing depth and traffic on TST strength were observed during the fall data collection period (Table 51). A significant topdressing depth x traffic interaction on TST strength was also observed at this time.

Table 47: Analysis of variance results for rooting density[z] collected after ten fall traffic simulator applications[y], Nov. 14, 2008, East Lansing, Mich.

Source of Variation	Num. df	Den. df	*P*>F
Topdressing Depth (TD)	4	8	NS[x]
Traffic (T)	1	30	NS
TD X T	4	30	NS
Soil Sampling Depth (SSD)	1	30	<0.0001
TD X SDD	4	30	NS
T X SDD	1	30	NS
TD X T X SDD	4	30	NS

[z] Dry root weight (g•91.9 cm^{-3}).

[y] Traffic applications were applied using the Cady Traffic Simulator.

[x] NS = not significant at $P > 0.05$.

Table 48: Effects of topdressing depth, traffic, and soil sampling depth on rooting density following ten fall traffic simulator applications, collected Nov. 14, 2008, East Lansing, Mich.

Topdressing Depth (cm)[z]	2008 Mean Root Density (g•91.9 cm^{-3})
0.0[y]	0.36
2.4	0.33
4.8	0.46
7.2	0.39
9.6	0.55
	ns[x]
Traffic[w]	**2008 Mean Root Density (g•91.9 cm^{-3})**
fall traffic only	0.43
summer[v] & fall traffic	0.41
	ns
Soil Sampling Depth (cm)	**2008 Mean Root Density (g•91.9 cm^{-3})**
0.0-3.8	0.65 a[u]
3.8-7.6	0.19 b

[z] cm of topdressing sand accumulated over a two year period, July 11 – Aug. 15, 2007, and July 14 – Aug. 22, 2008.

[y] Number of replications for all treatments = 3.

[x] ns = not significant at $P = 0.05$.

[w] Traffic applications were applied using the Cady Traffic Simulator.

[v] Summer traffic treatments received one traffic applications per week from July 14 – Aug. 22, 2008.

[u] Means in a given column with the same letter do not differ using Fisher's least significant difference at $P = 0.05$.

Table 49: Analysis of variance results for Eijkelkamp shear vane strength[z] collected after fall traffic simulator applications[y], East Lansing, Mich. (collected in 2008).

			Fall Traffic Applications[x]					
	Num.	Den.	0	2	4	6	8	10
Source of Variation	df	df				P>F		
Topdressing Depth (TD)	4.0	8.0	NS[w]	0.0166	NS	0.0302	0.0122	0.0007
Traffic (T)	1.0	10.0	NS	NS	NS	NS	NS	NS
TD X T	4.0	10.0	NS	NS	NS	NS	NS	NS

[z] Eijkelkamp shear vane strength = Newton meters.

[y] Traffic applications were applied using the Cady Traffic Simulator.

[x] Data collected after 0, 2, 4, 6, 8, and 10 traffic simulator applications[y], observed on Oct. 13, 17, 24, 31, Nov. 7, and 14, 2008, respectively.

[w] NS = not significant at $P > 0.05$.

Table 50: Effects of topdressing depth and traffic on Eijkelkamp shear vane strength following fall traffic simulator applications, East Lansing, Mich. (data collected in 2008).

	Fall Traffic Applications[z]					
	0	2	4	6	8	10
Topdressing Depth (cm)[y]	2008 Mean Shear Vane Strength (Nm)[x]					
0.0[w]	13.3	9.0 c[v]	9.3	10.7 a	9.0 a	11.7 a
2.4	12.2	12.3 a	9.3	9.3 b	9.0 a	8.3 b
4.8	13.8	10.7 abc	9.7	8.5 abc	7.5 a	6.7 bc
7.2	11.5	9.8 bc	8.0	8.5 bc	6.3 b	5.7 c
9.6	11.7	11.5 ab	9.3	8.0 c	6.3 b	4.7 c
	ns[u]					
Traffic[t]	2008 Mean Shear Vane Strength (Nm)					
fall traffic only	12.7	10.3	9.2	9.2	7.4	7.1
summer[s] & fall traffic	12.3	11.1	9.1	8.8	7.9	7.7
	ns	ns	ns	ns	ns	ns

[z] Data collected after 0, 2, 4, 6, 8, and 10 fall traffic simulator applications, observed on Oct. 13, 17, 24, 31, Nov. 7, and 14, 2008, respectively.

[y] cm of topdressing sand accumulated over a two year period, July 11 – Aug. 15, 2007, and July 14 – Aug. 22, 2008.

[x] Eijkelkamp shear vane strength = Newton meters (Nm).

[w] Number of replications for all treatments = 3.

[v] Means in a given column with the same letter do not differ using Fisher's least significant difference at $P = 0.05$.

[u] ns = not significant at $P = 0.05$.

[t] Traffic applications were applied using the Cady Traffic Simulator.

[s] Summer traffic treatments received one traffic applications per week from July 14 – Aug. 22, 2008.

Table 51: Analysis of variance results for Clegg turf shear tester strength[z] collected after fall traffic simulator applications[y], respectively, East Lansing, Mich. (data collected in 2008).

			Fall Traffic Applications[x]					
	Num.	Den.	0	2	4	6	8	10
Source of Variation	df	df	P>F					
Topdressing Depth (TD)	4.0	8.0	NS[w]	0.0507	NS	0.0445	0.0021	0.0088
Traffic (T)	1.0	10.0	NS	0.0233	NS	NS	NS	NS
TD X T	4.0	10.0	NS	NS	0.0210	NS	NS	NS

[z] Clegg turf shear tester strength = Newton meters.

[y] Traffic applications were applied using the Cady Traffic Simulator.

[x] Data collected after 0, 2, 4, 6 , 8, and 10 fall traffic simulator applications, observed on Oct. 13, 17, 24, 31, Nov. 7, and 14, 2008, respectively.

[w] NS = not significant at $P > 0.05$.

Differences in TST strength between topdressing depths were observed following 2, 6 and 10 fall traffic applications (Table 52). When differences were observed, treatments that received 2.4 cm of sand topdressing, 1.2 cm applied over two 5 week periods in the summer of 2007 and 1.2 cm applied over a 6 week period in 2008, produced the greatest overall mean TST strength. Mean TST strength was the lowest in treatments that received 4.8, 7.2 and 9.6 cm of sand topdressing accumulated over a 5 week period in 2007 and a 6 week period in 2008. This suggests that conservative topdressing depths, 2.4 cm accumulated over two consecutive summers will improve TST strength, while depths greater than this, 4.8, 7.2 and 9.6 cm will be detrimental to TST strength. Inconsistent with tendency, contrary to the overall trend, summer and fall traffic treatment produced a greater TST strength than the fall traffic only treatment on one occasion. The significant topdressing depth x simulated traffic interaction occurred on one occasion only with variable and illogical mean values, possibly indicating a lack in biological significance (Figure 7).

Main effects of topdressing depth and traffic on surface hardness were observed during the fall data collection period (Table 53). A topdressing x traffic interaction was also observed on one occasion only during this data collection period.

The 2.4 cm topdressing depth provided the greatest overall surface hardness, followed by 4.8 and 7.2 cm, then 9.6 cm and finally the control (0.0 cm), all accumulated over a 5 week period in the summer of 2007 and a 6 week period in the summer of 2008 (Table 54). These findings suggest that topdressing, regardless of rate, can be used to improve the surface hardness in comparison to treatments that do not receive topdressing. However, a conservative topdressing depth, 2.4 cm accumulated over two consecutive

Table 52: Effects of topdressing depth and traffic on Clegg turf shear tester strength following fall traffic simulator applications, East Lansing, Mich. (data collected in 2008).

	Fall Traffic Applications[z]					
	0	2	4	6	8	10
Topdressing Depth (cm)[y]	2008 Mean Turf Shear Tester Strength (Nm)[x]					
0.0[w]	102.8	84.1 ab[v]	81.4	120.2 ab	97.8 a	129.4 a
2.4	108.7	101.8 a	92.6	129.4 a	83.4 a	133.6 a
4.8	87.7	82.1 b	85.7	102.4 abc	65.0 b	98.5 b
7.2	76.8	73.2 b	79.5	93.9 bc	54.2 b	92.3 b
9.6	88.0	83.7 b	76.2	90.3 c	62.7 b	83.7 b
	ns[u]		ns			
Traffic[t]	2008 Mean Turf Shear Tester Strength (Nm)					
fall traffic only	91.8	80.1 b	80.2	104.4	74.6	103.1
summer[s] & fall traffic	93.8	89.8 a	85.9	110.1	70.7	111.9
	ns		ns	ns	ns	ns

[z] Data collected after 0, 2, 4, 6, 8, and 10 fall traffic simulator applications, observed on Oct. 13, 17, 24, 31, Nov. 7, and 14, 2008, respectively.

[y] cm of topdressing sand accumulated over a two year period, July 11 – Aug. 15, 2007, and July 14 – Aug. 22, 2008.

[x] Clegg turf shear tester strength = Newton meters (Nm).

[w] Number of replications for all treatments = 3.

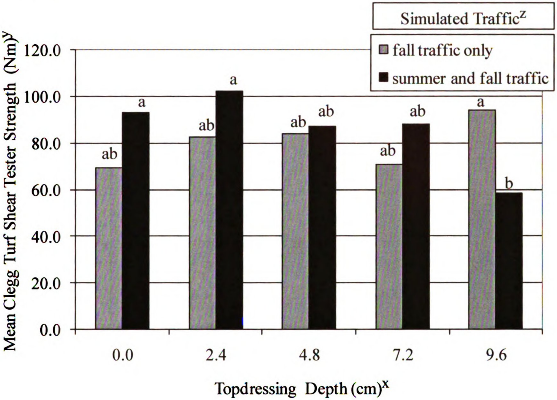
[v] Means in a given column with the same letter do not differ using Fisher's least significant difference at $P = 0.05$.

[u] ns = not significant at $P = 0.05$.

[t] Traffic applications were applied using the Cady Traffic Simulator.

[s] Summer traffic treatments received one traffic applications per week from July 14 – Aug. 22, 2008.

Figure 7: Effects of topdressing depth x simulated traffic on Clegg turf shear tester strength collected after four fall traffic simulator applications, Oct. 24, 2008, East Lansing, Mich.



[z] Traffic applications were applied using the Cady Traffic Simulator, summer traffic treatments received one traffic applications per week from July 14 – Aug. 22, 2008.

[y] Clegg turf shear tester strength = Newton meters (Nm).

[x] cm of topdressing sand accumulated over a two year period, July 11 – Aug. 15, 2007, and July 14 – Aug. 22, 2008.

Columns with the same letter do not differ using Fisher's least significant difference at $P = 0.05$.

Table 53: Analysis of variance results for surface hardness[z] collected after fall traffic simulator applications[y], East Lansing, Mich. (data collected in 2008).

			Fall Traffic Applications[x]					
	Num.	Den.	0	2	4	6	8	10
Source of Variation	df	df	P>F					
Todressing Depth (TD)	4.0	8.0	0.0085	0.0085	0.0420	0.0141	NS[w]	NS
Traffic (T)	1.0	10.0	0.0036	0.0036	0.0048	0.0047	0.0308	NS
TD X T	4.0	10.0	NS	NS	NS	NS	NS	0.0372

[z] Surface hardness (G_{max}) = ratio of maximum negative acceleration on impact to gravitational acceleration collected using the Clegg Impact Tester.

[y] Traffic applications were applied using the Cady Traffic Simulator.

[x] Data collected after 0, 2, 4, 6, 8, and 10 fall traffic simulator applications, observed on Oct. 13, 17, 24, 31, Nov. 7, and 14, 2008, respectively.

[w] NS = not significant at $P > 0.05$.

Table 54: Effects of topdressing depth and traffic on surface hardness following fall traffic simulator applications, East Lansing, Mich. (data collected in 2008).

	Fall Traffic Applications[z]					
	0	2	4	6	8	10
Topdressing Depth (cm)[y]	2008 Mean Surface Hardness (G_{max})[x]					
0.0[w]	75.0 a[v]	43.2 b	46.2 b	54.3 c	64.8	48.3
2.4	73.8 a	60.7 a	51.2 ab	70.0 a	70.0	51.5
4.8	63.2 b	55.8 a	56.7 a	65.3 ab	67.8	47.2
7.2	62.7 b	56.5 a	53.3 a	64.0 ab	61.8	48.3
9.6	58.3 b	56.5 a	54.8 a	60.8 bc	62.3	54.8
					ns[u]	ns
Traffic[t]	2008 Mean Surface Hardness (G_{max})					
fall traffic only	63.6 b	53.0 b	50.1 b	59.1 b	62.8 b	50.5
summer[s] & fall traffic	69.6 a	56.1 a	54.8 a	66.7 a	67.9 a	49.6
						ns

[z] Data collected after 0, 2, 4, 6, 8, and 10 fall traffic simulator applications, observed on Oct. 13, 17, 24, 31, Nov. 7, and 14, 2008, respectively.

[y] cm of topdressing sand accumulated over a two year period, July 11 – Aug. 15, 2007, and July 14 – Aug. 22, 2008.

[x] Surface hardness (G_{max}) = ratio of maximum negative acceleration on impact to gravitational acceleration collected using the Clegg Impact Tester.

[w] Number of replications for all treatments = 3.

[v] Means in a given column with the same letter do not differ using Fisher's least significant difference at $P = 0.05$.

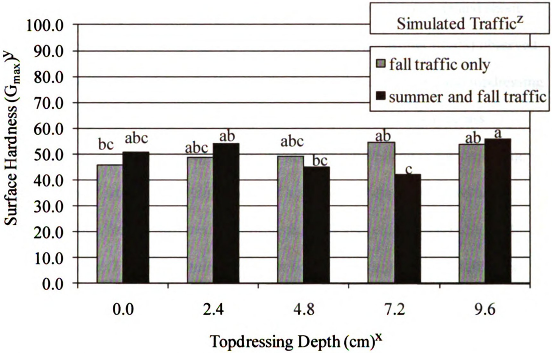
[u] ns = not significant at $P = 0.05$.

[t] Traffic applications were applied using the Cady Traffic Simulator.

[s] Summer traffic treatments received one traffic applications per week from July 14 – Aug. 22, 2008.

summers, will provide the greatest increase in overall fall surface hardness. When differences between traffic levels were observed, the summer and fall traffic treatment produced the greatest mean surface hardness results. The significant topdressing depth x traffic interaction occurred on one occasion only with viable and disorderly means, making the data inconclusive (Figure 8).

Figure 8: Effects of topdressing depth x simulated traffic on surface hardness collected after ten fall traffic simulator applications, Nov. 14, 2008, East Lansing, Mich.



[z] Traffic applications were applied using the Cady Traffic Simulator, summer traffic treatments received one traffic applications per week from July 14 – Aug. 22, 2008.
[y] Surface hardness (G_{max}) = ratio of maximum negative acceleration on impact to gravitational acceleration collected using the Clegg Impact Tester.
[x] cm of topdressing sand accumulated over a two year period, July 11 – Aug. 15, 2007, and July 14 – Aug. 22, 2008.
Columns with the same letter do not differ using Fisher's least significant difference at *P* = 0.05.

DISCUSSION

Effects of cumulative topdressing depths suggest that topdressing, regardless of rate, can be used to improve turfgrass wear tolerance characteristics (cover and shoot density) in comparison to the control. Similar to these findings, Miller (2008) observed increased bermudagrass quality, stand density and rooting as a result of sand topdressing. Barton et al. (2009) observed increased color ratings on topdressed kikuyugrass. Increased turfgrass cover and density as a result of stand topdressing is not surprising, because a variety of work has demonstrated that a sand-based root zone provides a relatively restriction free growth media. For instance, Magni et al. (2004) observed increased tall fescue (*Festuca arundinacea* Schreb.) and perennial ryegrass turfgrass cover and decreased bulk density after a fall traffic period as sand to soil ratios increased from native soil to a sand-based root zone.

However, aggressive topdressing depths, 7.2 and 9.6 cm, accumulated over two consecutive summers, were detrimental to surface stability characteristics (shear vane strength, TST strength and surface hardness) in comparison to the control. Similar to these findings, Miller (2008) observed reduced shear strength as a result of high applications rates, 17.0 mm depth, of crumb rubber and calcined clay topdressing in comparison to low application rates, three applications at 2.0 mm per application providing a 6.0 mm deep sand layer. On the other hand, conservative topdressing rates, 1.2 cm accumulated over a 5 week period in 2007 and 1.2 cm accumulated over a 6 week period in 2008, providing a total depth of 2.4 cm, not only improved turfgrass wear tolerance characteristics, but also improved surface stability characteristics. For instance, in 2007, the 1.2 and 2.4 cm topdressing depth produced shear vane strength greater than 10.0 Nm, a shear vane strength considered to be acceptable for a sand-based sports turf system (Stier et al., 1999), on three of the six dates data were collected, while the 3.6 and 4.8 cm depth provided shear vane strength greater than 10.0 on one occasion only. Miller (2008) also observed increased surface hardness and shear strength as a result of sand topdressing applied at low application rates (6.0 mm). Again, these findings are not totally surprising, because research has revealed that a sand-based rooting media can be used to improve surface stability. For instance, Magni et al. (2004) determined that turfgrass established on a sand-based root zone provided increased shear strength in comparison to turf established on a native soil. These findings suggest that if aggressive topdressing depths are used to develop a sand-based root zone and significant time is allowed for the sand to consolidate or settle, surface shear strength will ultimately be improved. Rogers et al. (1998) determined that crumb rubber topdressed at 44.1 t ha^{-1} (0.95 cm depth) provided the greatest shear strength while a 88.2 t ha^{-1} (1.9 cm depth) provided the greatest turf cover, and suggests a target rate of 60.0 t ha^{-1} (1.4 cm depth), an optimum rate similar to the one derived from this research.

Summer traffic, applied to a recently established turfgrass stand, was detrimental to fall wear tolerance characteristics (cover, shoot density, and rooting density), shear vane strength, and TST strength, but increased surface hardness. Similar to these findings, Rogers and Waddington (1989) determined that bare soil, in comparison to soil covered with turfgrass, decreased shear strength, but increased surface hardness. Vanini et al. (2007) also determined that simulated traffic, applied using the Cady traffic simulator, decreased turf density, and TST strength, while increasing surface hardness. Research conducted by Vanini and Rogers (2008), which evaluated the effects of mowing and fertilization on playing surface characteristics, included a 70-day traffic free re-establishment window, suggesting that a traffic free re-establishment window is crucial to future turfgrass success. Research conducted by Kowalewski et al. (2008) concluded that pre-harvest core cultivation of sod can be performed with minimal effects to sod strength if adequate time (72 days) is allowed for establishment, again suggesting that a traffic free window for turfgrass establishment is critical to future success.

Summer traffic applied to an established turfgrass stand produced inconsequential effects on turfgrass wear tolerance and surface stability characteristic, with the exception of surface hardness. The combination of summer and fall traffic was shown to increase the surface hardness, in comparison to fall traffic only. Similar to these findings, research conducted by Vanini et al., (2007) determined that as the number of weekly traffic applications, applied using the Cady traffic simulator, increased the surface hardness and bulk density of a native loam soil. Rogers and Waddington (1989) also observed a correlation between increased surface hardness and bulk density on a silt loam. It is also important to note that the topdressing material utilized in this research project was a 90% sand – 10% silt/clay mixture. Henderson et al. (2005) determined that soil mixtures containing 10% silt/clay are somewhat susceptible to compaction as water content levels increase, but are still capable of maintaining a relatively high water infiltration rate in comparison to native soil. These findings suggest that the increased surface hardness observed as a result of summer and fall traffic may be the effect of increased bulk density, particularly in the control treatments, a sandy loam which did not receive sand topdressing.

Living ground cover, shoot density and TST strength observed throughout the 2008 data collection period were substantially greater than those observed at the conclusion of the 2007 collection period, while surface hardness decreased from 2007 to 2008. Murphy et al. (2003) observed increased ball mark recovery of creeping bentgrass, regardless of cultivar, after a year of maturation. Kowalewski et al. (2008) observed increased TST strength as Kentucky bluegrass sod matured over time (30 to 72 days after installation). These finding and the results observed in this research suggest that overall turfgrass health, vigor, and strength will increase as a newly established turfgrass system matures over time. Similar to the findings observed in this research, Rogers and Waddington (1989) observed decreased surface hardness as a result of increased turfgrass cover, which would explain the reduction in surface hardness from 2007 to 2008.

CONCLUSIONS

Results obtained from this research suggest that when topdressing is being used to develop a sand layer over an existing native soil athletic field a conservative topdressing regime, 1.2 cm applied over a 5 week period in the summer, will provide field managers the greatest results, wear tolerance and surface stability, in the subsequent fall under Michigan environmental conditions. Results also suggest that if a spring re-establishment prior to the initiation of sand topdressing is required, restricting summer traffic will provide the greatest results in the subsequent fall. Findings from this research also indicate that if spring re-establishment is not required effects of summer traffic will be inconsequential to turfgrass wear tolerance and surface stability characteristics in the ensuing fall.

REFERENCES

Adams, W.A., C. Tanavud and C.T. Springsguth. 1985. Factors influencing the stability of sports turf root zones. Proceedings of the 5th International Turfgrass Research Conference. July 1-5, 1985. Avignon, France.

ASTM. 2006. Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System). American Soc. for Testing and Materials International. D 2487-06:1-11.

ASTM. 2004. Standard guide for construction of high performance sand-based root zones for sports fields. American Soc. for Testing and Materials International. F 2396-04:1-12.

Barton, L. G.G.Y. Wan, R.P. Buck and T.D. Colmer. 2009. Effectiveness of cultural thatch-mat controls for young and mature kikuyu turfgrass. Agron. J. 101:67-74.

Benson, C.H. and D.E. Daniel.1990. Influence of clods on the hydraulic conductivity of compacted clay. J. of Geotechnical Engineering. 116(8):1231-1248.

Bingaman, D.E. and H. Kohnke. 1970. Evaluating sand for athletic turf. Agron. J. 62:464-467.

Brede, A.D. and J.M. Duich. 1984. Establishment characteristics of Kentucky bluegrass-perennial ryegrass turf mixtures as affected by seeding rate and ratio. Agron J 76:875-879.

Carrow, R.N. 1980. Influence of soil compaction on three turfgrass species. Agron J. 72:1038-1042.

Cook, A., S.W. Baker, P.M. Canaway and J.A. Hunt. 1997. Evaluation of turf established using "liquid sod" as compared with establishment using seed and turf. J. Turfgrass Sci. 97:73-83.

Frank, K.W., K.M. O'Reilly, J.R. Crum and R.N. Calhoun. 2005. The fate of nitrogen applied to mature Kentucky bluegrass turf. Crop Sci. 46:209–215.

Fresenburg, B. 2006 a. Synthetic turfgrass concerns: Part I. synthetic turf costs far exceed natural grass fields. TurfNews. 30(2):40.

Goddard, M.J.R., J.C. Sorochan, J.S. McElroy, D.E. Karcher and J.W. Landreth. 2008. The effects of crumb rubber topdressing on hybrid Kentucky bluegrass and bermudagrass athletic fields in the transition zone. Crop Sci. 48:2003–2009.

Harler, C. 2009. Wetness and wealth key foes of native soil fields. SportsTurf. 25(3):15-16,18-19.

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

Henderson, J.J., J.R. Crum, T.F. Wolf and J.N. Rogers. 2005. Effects of particle size distribution and water content at compaction on saturated hydraulic conductivity and strength of high sand content root zone materials. Soil Sci. 170:315-324.

Kowalewski, A.R., J.N. Rogers, III and T.D. Vanloo. 2008. Pre-harvest core cultivation of sod provides an alternative cultivation timing. Appl. Turfgrass Sci. Online. p. 1-9. Retrieved April 23, 2009.(http://www.plantmanagementnetwork.org/sub/ats/research/2008/sod/).

Li, D., D.D. Minner, N.E. Christians and S. Logsdon. 2005. Evaluating the impact of variable root zone depth on the hydraulic properties of sand-based turf systems. International Turfgrass Soc. 10(2): 1100-1107.

Littell, R.C., G.A. Milliken, W.W. Stroup, R.D. Wolfinger and O. Schabenberger. 2007. SAS for mixed models. 2nd edition. SAS Institute, Cary, N.C.

Lunt, O.R. 1956. A method for minimizing compaction in putting greens. Southern Calif. Turfgrass Cult. 6(3):17-20.

Magni, S., M. Volterrani and S. Miele. 2004. Soccer pitches performances as affected by construction method, sand type and turfgrass mixture. Acta Hort. (ISHS). 661:281-285.

Miller, G.L. 2008. An evaluation of crumb rubber and calcined clay for topdressing sports fields. Acta Hort. (ISHS) 783:381-390.

McCarty, L.B., M.F. Gregg, J.E. Toler, J.J. Camberato and H.S. Hill. 2005. Minimizing thatch and mat development in a newly seeded creeping bentgrass golf green. Crop Sci 45:1529-1535.

McNitt, A.S. and P. J. Landschoot. 2003. Effects of soil reinforcing materials on the surface hardness, soil bulk density, and water content of a sand root zone. Crop Sci. 43:957–966.

Murphy, J.A., T.J. Lawson and J. Clark. 2003. Ball Marks on bentgrass. USGA Turfgrass and Environmental Research Online. 2(12):1-6.

National Turfgrass Evaluation Program. 2008. A guide to ntep turfgrass ratings. Retrieved April 24, 2009. Retrieved June 26, 2009. (http://www.ntep.org/reports/ratings.htm).

National Resources Conservation Services. 2005. Web soil survey. Retrieved April 24, 2009. (http://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx).

Ott, R.M. and M. Longnecker. 2001. An introduction to statistical methods and data analysis: 5th edition. Duxbury, Pacific Grove, Calif.

Prettyman, G.W. and E.L. McCoy. 2003. Profile layering, root zone permeability, and slope affect on soil water content during putting green drainage. Crop Sci. 43: 958-994.

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

Rogers, J.N., III, J.T. Vanini and J.R. Crum. 1998. Simulated traffic on turfgrass topdressed with crumb rubber. Agron. J. 90:215-221.

Sherratt, P.J., J.R. Street and D.S. Gardner. 2005. Effects of biomass accumulation on the playing quality of a Kentucky bluegrass stabilizer system used for sports fields. Agron. J. 97:1107-1114.

Sorochan, J.C. and J. N. Rogers, III. 2001. The effect of mulch type for turfgrass establishment within a refined wood fiber mat over plastic. J. Environ. Hortic. 19(2):61-64.

Stier, J.C. and J.N. Rogers, III. 2001. Trinexapac-ethyl and iron effects on supina and Kentucky bluegrasses under low irradiance. Crop Sci. 41:457-465.

Stier. J.C., J.N. Rogers, III, J.R. Crum and P.E. Rieke. 1999. Flurprimidol effects on Kentucky bluegrass under reduced irradiance. Crop Sci. 39:1423-1430.

USGA Green Section Staff. 2004. USGA recommendations for a method of putting green construction. United States Green Association World Wide Web Site. p. 1-11. Retrieved January 17, 2007. (http://www.usga.org/turf/course_construction/green_articles/putting_green_guidelines.html).

Vanini, J.T., J.J. Henderson, J.C. Sorochan and J.N. Rogers, III. 2007. Evaluating traffic stress by the brinkman traffic simulator and cady traffic simulator on a Kentucky bluegrass stand. Crop Sci. 47:780-784.

Vanini, J. T. and J. N. Rogers, III. 2008. Mowing strategies and fertilization improves sports fields during and after 70-day re-establishment window. [Online] Appl. Turfgrass Sci. p. 1-10. Retrieved April 23, 2009. (http://www.plantmanagement network.org/pub/ats/research/2008/70day/).

CHAPTER 3

EFFECTS OF INTERCEPT DRAIN TILE SPACING AND SUBSEQUENT SAND TOPDRESSING ON THE DRAINAGE CHARACTERISTICS AND SURFACE STABILITY OF A COOL-SEASON TURFGRASS SYSTEM.

ABSTRACT

Drain tile installation and subsequent sand topdressing applications can provide a built-up sand-based system. However, there are a number of different drain tile spacing and sand layer depth recommendations. The objectives of this research were to establish optimum drain tile spacing, in combination with sand topdressing, necessary to improve field drainage and stability characteristics. A RCBD field study on a sandy loam soil, in East Lansing, Mich., was seeded May 29, 2007 with a 90.0% *Poa pratensis* L. – 10.0% *Lolium perenne* L. mixture. Factors were drain tile spacing and topdressing depths. Drain tiles were spaced 2.0, 3.0, 4.0 and 6.0 m apart and were compared to an 8.1 m long control without drain tiles. Topdressing applications consisted of a well-graded high sand content material (90.0% sand – 10.0% silt/clay) applied 0, 2, and 4 times within a 5 week period at a rate of 9.8 kg m^{-2}. Simulated traffic was applied to all treatments from October 10 – November 3, 2007. In 2008 topdressing applications and traffic were repeated on the same experimental treatments. Results determined that as topdressing is accumulated from 0.0 to 2.4 cm, a 4.0 m drain spacing can provide adequate drainage and stability. As topdressing depth is accumulated to depths greater than 2.4 cm, minimal wear tolerance and stability differences were observed, suggesting that drain tile spacing can be increased to distances greater than 4.0 m when sand in accumulated over time.

(
f
t
f

s
h
u
2
fa

INTRODUCTION

Sand-based soils maintain structure, macro-porosity, and rapid infiltration rates when exposed to regular foot traffic and heavy rainfall making them ideal for athletic field construction (Bingaman and Kohnke, 1970; Henderson et al., 2005). When constructing sand-based soil systems, drain tiles are often incorporated for the removal of excess subsoil water during periods of heavy rainfall (ASTM, 2004; Daniel, 1969; Davis et al., 1990; USGA, 2004). Research has demonstrated that a sand-based system combined with drain tiles can be used to increase playability and overall surface quality. Magni et al. (2004) observed increased drainage, ground cover, and traction in research plots with pipe drainage, spaced 5.0 m apart, and a 20.0 mm sand carpet over the native soil, in comparison to undrained native soil and native soil amended with sand (80.0% by volume) to a 80.0 mm depth. However, complete field renovation is expensive and renders the field temporarily useless. For instance, the Sports Turf Managers Association (STMA) states that renovations would cost \$75 – 108 m^{-2} for a conventional sand-based field, 20.3 – 30.5 cm sand-based root zone over a 7.6 – 10.2 cm gravel layer with drain tiles (STMA, 2008). Using these figures the renovation of a standard high school football field, 5,351.2 m^2, would cost \$401,340 – 577,930.

In an effort to reduce renovation costs, sand-cap systems, sand over native soil, similar to a California putting green (Davis et al., 1990; Prettyman and Mcoy, 2003), have increased in popularity. However, saturated hydraulic conductivity is limited by the underlying native soil when sand is placed over the native soil (Prettyman and Mcoy, 2003). In this type of system the amount of excess water that can be removed in a timely fashion is dependent on surface slope, root zone depth, and distance to intercepting drains

(Barber and Sawyer, 1952). For example, putting green research conducted by Prettyman and McCoy (2003) observed that after 27 hrs of drainage at a 0.0% slope, research plots constructed to California style putting green specifications had notably more soil water than the USGA style plots (sand over gravel). This research also indicated that as slope increased from 0.0 – 4.0% later water drainage increased. These findings suggest that, when a gravel layer is not included slope plays an important role in soil system drainage. Renovation estimates for a sand-cap system range from \$43 – 70 m^{-2} for a 10.2 – 15.2 cm sand-cap root zone over native soil, totaling \$230,102 – 374,584 for the renovation of a standard high school football field (STMA, 2008).

Creating a built-up sand layer over time is a possible cost effective alternative to complete field renovation. This renovation method entails drain tile installation into the existing field, and cumulative sand topdressing applications, to achieve a sand cap system. Sand topdressing has been recommended as a method to renovate putting green surfaces for a number of years (Beard, 1978; Vavrek, 1995). Athletic field research has also shown that sand topdressing can be used to improve the characteristic of the playing surface. For instance, Miller (2008) observed increased bermudagrass (*Cynodon dactylon* L.) shear strength, cover, and rooting from three sand topdressing applications totaling 6.0 mm.

Currently, specifications regarding drain tile spacing and sand layer depth for construction of a sand-based turfgrass system are various (ASTM, 2004; Daniel, 1969; Davis et al., 1990; USGA Greem Section Staff, 2004) and there is little research to support these recommendations. Therefore, it is critical to determine the optimum drain tile spacing in combination with sand topdressing depth, accumulated over time, required to prevent prolonged saturated surface soil conditions, and provide a low cost renovation procedure for municipalities with minimal budget allocations to athletic field renovation.

Objective:

Establish intercept drain tile spacing, in combination with sand topdressing, necessary to improve drainage characteristic, wear tolerance and surface stability of a cool-season turfgrass mixture established on a sandy loam soil.

Hypothesis:

Decreased intercept drain tile spacing, in combination with sand topdressing, will improve the wear tolerance and stability by preventing saturated surface soil conditions from occurring during periods of simulated athletic field traffic.

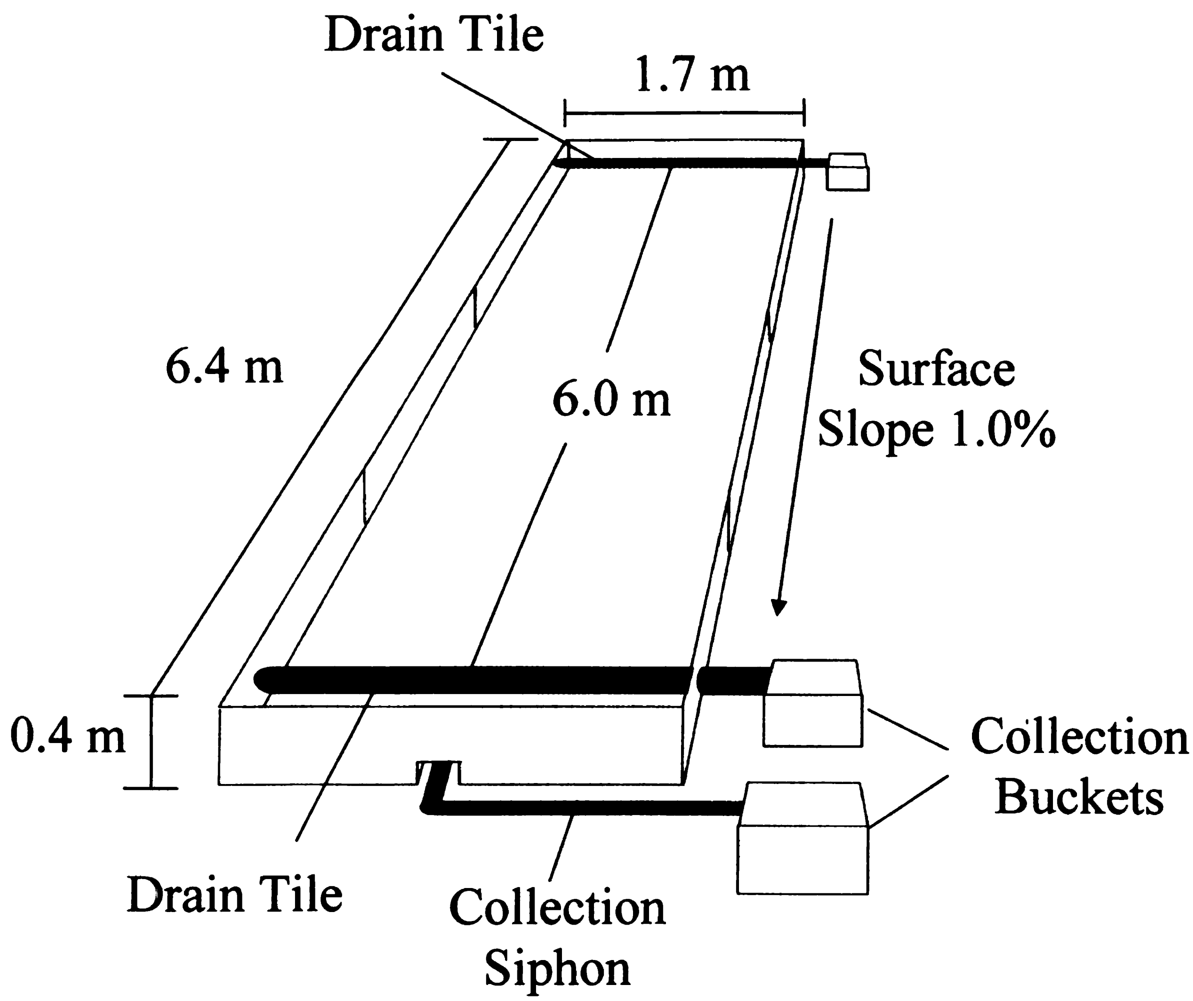
MATERIALS AND METHODS

Field research on intercept drain tile spacing, in combination with sand topdressing, was initiated at the Hancock Turfgrass Research Center (HTRC), April 10, 2007. The total experimental area was 126.9 m^2, divided into three blocks, each containing five treatments (1.7 m wide x 2.4 – 8.1 m long, depending on drain tile spacing). Factors included drain tile spacing (2.0, 3.0, 4.0, and 6.0 m apart, and an 8.1 m control without drain tiles) and topdressing applications (0, 2, and 4, equal to 0.0, 19.6, and 39.2 kg m^{-2} of annually accumulated sand, respectively).

A sandy loam soil, the A horizon of a Colwood series (fine-loamy, mixed, active, mesic Typic Endoaquoll) was excavated and transported to the northern HTRC parking lot where it was thoroughly mixed to ensure even particle distribution and degrade soil structure (National Resources Conservation Services, 2007). Research boxes were constructed out of treated plywood, filled with bird's eye pea gravel to adjust the slope from 2.0% to 1.0%, and then lined with 102.0 μm visqueen plastic sheeting from April 15 – 20, 2007 (Table 25). At this time, subsoil collection siphons, 2.5 cm aluminum pipes, were installed at the bottom end, in relation to the slope, of each treatment. Each siphon was attached to a 5.1 cm slotted, corrugated polyethylene (PE) drain tile, which was laid laterally, in relation to the surface slope across the treatments. The collection siphons were used to quantify the water volume that infiltrates through the sandy loam soil profile.

From April 27 to May 4, 2007, the sandy loam soil described above was placed into individual treatments boxes 1.7 m wide x 2.4 – 8.1 m long x 0.4 m deep (Image 4). Throughout this process, the soil was repeatedly irrigated and compacted in layers using a

Image 4: Constructed research plot 1.7 m (wide) by 6.4 m (long) by 0.4 m (deep), with maximum drain tiles laterally spaced 6.0 m apart and collection buckets, Hancock Turfgrass Research Center, East Lansing, Mich., 2007.



Bartell vibratory compactor (Bartell Industries Inc., Brampton, Canada) to develop a worst case scenario in terms of subsoil drainage. The soil was filled to the top of the research boxes, to a 0.4 m depth over the plastic sheeting. Composite and core soil samples were then collected on May 11, 2007, from locations corresponding to future drain pathways to minimize surface disruption. These samples were then analyzed to determine the existing pH, soil nutrient levels, bulk density, and saturated hydraulic conductivity (pH 7.7, 141.0 ppm phosphorus, 135.0 ppm potassium, bulk density 1.5 g cm^{-3} and saturated hydraulic conductivity 0.2 cm hr^{-1}) (Table 55).

Drain Tile Installation

On May 15, 2007, after the soil boxes were filled and leveled to a 1.0% surface slope, perforated corrugated polyethylene (PE) drain tiles (10.2 cm diameter) were installed at a 30.5 cm depth. Drain lines (15.2 cm wide) were dug by hand then backfilled with a well-graded sand-based root zone material [90.0% sand – 10.0% silt/clay (90/10 sand)] directly on top of the installed PE drain tile in an attempt to reduce the cost of drain tile installation (ASTM, 2006) (Table 27; Figure 4). A 2.0% lateral drain tile slope was established to direct water to the drain tile outlet in each treatment; ASTM International standards suggest a minimum drain tile slope of 0.5% for sand-based sports fields (ASTM, 2004). A 10.2 cm sewage pipe and collection bucket was installed at the output of each drain tile to quantify the volume of water removed from the soil system by the drain tiles. Intercept drain tiles were installed perpendicular to the slope at a variety of spacing ranging from 2.0 – 6.0 m. A control treatment without drain tiles was also included in this study. The control treatment was 8.1 m long, equivalent to the

Table 55: Soil[z] pH, nutrient levels, cation exchange capacity (CEC), particle size analysis, bulk density, and saturated hydraulic conductivity of base soil, Hancock Turfgrass Research Center, East Lansing, Mich.; analysis performed at the MSU Soil and Plant Nutrient Laboratory, and Turfgrass Soil Science Laboratory, East Lansing, Mich., June 20, 2007.

pH	7.7
Soil Nutrients Levels	ppm (mg kg^{-1})
Phosphorus(P)	141.0
Potassium (K)	135.0
Calcium (Ca)	2024.0
Magnesium (Mg)	284.0
	meq $100g^{-1}$
CEC	12.8
Particle Size Analysis	%
Sand (0.05 – 2.00 mm)	73.4
Silt (0.002 – 0.05 mm)	21.2
Clay (<0.002 mm)	5.4
Soil Type	Sandy loam
Bulk Density (P_b)	g cm^{-3}
P_b = Ms/Vt	1.5
Sat. Hydraulic Conductivity (K_s)	cm hr^{-1}
K_s= (V*L)/[A*t*(Hi+L)]	0.2

[z] Prior to excavation the soil was the A horizon of a Colwood series (fine-loamy, mixed, active, mesic Typic Endoaquoll) (NRCS, 2007).

Ms = mass of soil solids (g); Vt = core volume (344.8 cm^3).

V = volume of out flow (cm^3 water); L= core length (7.6 cm); A = core surface area (45.4 cm^2); t = time (hrs); Hi = hydraulic head (1.5 cm).

distance from the crown of a field to the hash makers, where the large majority of football play is concentrated (Cockerham, 1989).

Turfgrass Establishment and Preparation (2007)

Seeding preparation included core cultivation, sand topdressing, and starter fertilizer application. Core cultivation was performed on May 23, 2007, using a Toro Procore 648 (Toro Company, Bloomington, Minn.) with 1.3 cm diameter hollow tines at a 5.0% affected surface area (25.8 cm^2 spacing) and 5.1 cm tine depth. Cores were incorporated back into the soil with hand rakes. 90/10 sand topdressing was applied at a 5.0 mm depth using a Mete-R-Matic self propelled topdresser (Turfco, Minneapolis, Minn.). Starter fertilizer (16-25-13) (Lebanon Turf Products, Lebanon, Pa.) was applied at 48.8 kg ha^{-1} P prior to seeding.

On May 29, 2007, the research plot was seeded with a 90.0% Kentucky bluegrass (*Poa pratensis* L.) (19.7% 'Arcadia', 19.7% 'Odyssey', 19.6% 'America', 19.6% 'SR100' and 19.6% 'Mercury') – 10.0% perennial ryegrass (*Lolium perenne* L.) (34.4% 'Harrier', 34.1% 'Peregrine' and 29.8% 'SR 4600') (Research Seeds, Inc., Fort Dodge, Iowa) mixture at 65.9 kg ha^{-1} and 43.9 kg ha^{-1} by weight, respectively, a common practice on cool-season sports fields (Brede and Duich, 1984). The preemergence herbicide Tupersan®, siduron [1-(2-methylcyclohexyl)-3-phenylurea] (Lebanon Seaboard Corp., Lebanon, Pa.), was also applied at 4.6 kg ha^{-1} a.i. immediately after seeding. Following seeding and preemergence herbicide application, the research area was lightly raked by hand and topdressed again using the 90/10 sand at a 1.0 mm depth to ensure adequate seed to soil contact. At this time, a total of 6.0 mm of nonrestrictive rooting media (90/10 sand) was accumulated over the compacted sandy loam soil.

On June 5, 2007, 2.5 cm PVC pipes, perforated using a 0.6 cm diameter drill bit, were installed laterally across the soil surface at the lower end, in relation to the surface slope, of the research plots and connected to collection buckets to collect and determine the volume of surface water runoff from the various treatments. On June 12, 2007, P3-MR three rod Time-Domain Reflectometers (TDRs) (MESA Systems, Medfield, Mass.), with 16.0 cm wave guides, were installed in the subsoil at a 15.2 cm depth to evaluate possible differences in subsurface moisture contents. These probes were installed horizontally in the center of each treatment in relation to the drain tiles.

Drain Tile Renovation

The 90/10 sand, which was backfilled directly over research plot drain lines, was excavated on June 18, 2007, because standing water was observed over the drain tiles, suggesting that fine soil particles in the sand-based soil were obstructing the drain tile perforations. After the 90/10 sand was excavated, the PE drain tiles were cleaned using an air compressor, and placed back in the drain lines. The drain tiles were then covered with 15.3 cm of bird's eye pea gravel and 15.3 cm of sand (Image 3; Table 26; Figure 3). American Society for Testing and Materials (ASTM) International standards specify slotted, rather than perforated, drain tiles with a D_{85} sand/slit width > 1.5 to prevent particle migration into the drain tile system (ASTM, 2004).

Topdressing

The newly established turfgrass stand received its first 90/10 sand topdressing application July 11, 2007. All sand topdressing applications were applied at the same rate of 9.8 kg m^{-2} (0.6 cm depth), a conservative application rate derived from initial research and consideration of the potential effects of increased atmospheric temperatures typical of summer field conditions. Topdressing applications were made using the Mete-R-Matic self propelled topdresser. All treatments received four annual topdressing applications on July 11, 23, August 3, and 15, 2007.

Turfgrass Maintenance

Initially, during establishment, the turfgrass was mown with a Honda Harmony (American Honda Motor Co, Inc., Alpharetta, Ga.) rotary mulching mower at 3.8 cm from July 3 -7, 2007. On July 8, 2007 the mowing height was raised to 6.4 cm. The newly established turfgrass was then maintained at a regular mowing height of 7.6 cm from July 11 to August 27, 2007, to promote rooting and increase heat stress tolerance, and then reduced to 5.0 cm prior to the fall simulated traffic applications (Vanini and Rogers, 2008). Throughout 2007, the turfgrass received regular applications of a poly coated fertilizer (26-7-14) (Agrium, Sylacauga, AL) and urea (46-0-0) providing a total of 23.7 g m^{-2} N (237.0 kg ha^{-1} N) annually (Table 29). To provide postemergence weed control, Drive® 75 DF, quinclorac (3, 7-dichloro-8-quinolinecarboxylic acid) (BASF Corp., Triangle Park, N.C.)], was applied at 1.1 kg ha^{-1} with methylated seed oil (0.3% v/v) on July 24, 2007, and an application of Trimec® Classic Broadleaf Herbicide, 2,4-D (2,4-dichlorophenoxyacetic acid), propionic acid [2-(2-methyl-4-chlorophenoxy)], and dicamba (3,6-dichloro-o-anisic acid) (PBI/Gordon Corporation, Kansas City, Mo.), was made at a rate of 4.1 L ha^{-1} on July 26, 2007.

Traffic Simulation

At the conclusion of the cumulative 90/10 sand applications, August 15, 2007, traffic was applied to all treatments from October 10 – November 3, 2007, using the Cady traffic simulator (Henderson et al., 2005; Vanini et al., 2007). Traffic simulations included two traffic applications (total of four passes, two forward and two backward) per week.

To ensure a worst case scenario in terms of rain events, rainfall was regularly monitored using the HTRC MAWN weather station (Enviro-weather, 2007) (Table 30). Rainfall data was compared to data collected from the HTRC Rain Bird Maxi Weather Station, Model WS-200 (Rain Bird, Glendora, Cal.) in 2006, a particularly rainy fall in Mid-Michigan. Supplemental irrigation was applied to the research plot in 2007 using Toro® LPS Pop-up spray heads with TVAN 3.7 m adjustable nozzles (Spartan Distributors Inc., Sparta, Mich.), to provide rainfall levels equivalent to fall 2006 levels.

Turfgrass Reestablishment and Maintenance (2008)

On April 22, 2008, treatments were core cultivated at 5.0% affected surface area and inter-seeded with an identical Kentucky bluegrass – perennial ryegrass mixture at the same rate as in 2007. Following inter-seeding, the experimental area received an application of starter fertilizer (16-25-13), at 48.82 kg ha^{-1} P, and Tupersan, at 4.6 kg ha^{-1} a.i.

On June 12, 2008, the research area was core cultivated at 15.0% affected surface area and again inter-seeded with the Kentucky bluegrass – perennial ryegrass mixture at the same rate to ensure adequate turfgrass reestablishment. All turfgrass was maintained at a mowing height of 7.6 cm from April 17 to August 27, 2008, and then reduced to 5.0

cm prior to the fall simulated traffic applications. Throughout 2008, the turfgrass received regular applications of poly coated fertilizer (26-7-14) and urea (46-0-0) providing a total of 28.4 g m^{-2} N (284.0 kg ha^{-1} N) annually (Table 29).

Topdressing Applications and Traffic Simulation

Sand topdressing applications were applied to the reestablished treatments on July 26, August 4, 16, and 22, 2008, at 9.8 kg m^{-2}, to evaluate the effects of two years of cumulative topdressing applications on drainage and surface stability. Following topdressing, traffic was applied to all treatments at a high wear level, two traffic applications per week, simulating in season high school fall athletic field use, from October 14 – November 12, 2008. Again, to ensure a worst case scenario in terms of rain events, rainfall was regularly monitored using the HTRC MAWN weather station and supplemental irrigation was applied to the research plot to provide rainfall levels equivalent to fall 2006 levels (Table 30).

Drainage Characteristics

Rain gauges (10.0 cm x 10.0 cm x 12.5 cm deep), spaced every 1.0 m^2, were used to evaluate differences in irrigation uniformity, and later used to derive volume to volume (v/v) ratios of subsoil drainage, surface runoff and drain tile drainage on a per treatment basis. Collection buckets were used to measure the total volume (L) of drainage from the 2.5 cm subsoil siphons, 2.5 cm surface runoff pipes and the 10.2 cm PE drain tiles after 17.0 minute irrigation events. This data was collected on July 9, prior to topdressing applications, July 26, after two cumulative topdressing applications, and August 18, 2007, after four cumulative applications. In 2008, 17.0 minute irrigation events were applied July 24, prior to the initiation of the 2008 topdressing program, August 6, after six cumulative applications, and August 28, after eight cumulative applications. Surface runoff was also collected following a 34.0 minute irrigation event in 2007 on July 10, prior to topdressing applications, July 31, after two cumulative topdressing applications, August 20, after four cumulative applications, and in 2008 on July 25, prior to the initiation of the 2008 topdressing program, August 8, after six cumulative applications and August 29, after eight cumulative applications.

A portable P3-MR three rod system with 5.1 cm wave guides and the installed P3-MR three rod system, 16.0 cm rods horizontally installed at a 15.2 cm depth, connected to a portable Trime®-FM Mobile moisture meter (MESA Systems Co., Medfield, Mass.) were used to evaluate the surface and subsoil, respectively, wetting and drying cycle over a 4.0 hour period following 17.0 minute irrigation events. Three subsample moisture measurements were taken within each treatment, evenly spaced across the length of the treatment, using the 5.1 cm wave guides horizontally inserted into the soil surface to a 1.3 cm depth. One sample per treatment was recorded from the installed 16.0 cm rods.

Field infiltration rates, determined by saturated hydraulic conductivity (K_{sat}) (cm hr^{-1}), over the drain lines were measured using a double ring infiltrometer, 12.7 cm inner ring and 33.0 cm outer ring (Gregory et al., 2005). Infiltration data were collected July, 11, August 3, 23 and November 16, 2007, and July 26, August 9, September 2 and November 14, 2008. The November 16, 2007, and November 14, 2008, data was collected after the fall traffic period to evaluate potential effects of traffic on intercept drain tile drainage.

Wear Tolerance and Surface Stability

From the initiation of the simulated traffic, October 10, 2007, and October 14, 2008, percent living ground cover (0.0-100.0%), based on the National Turfgrass Evaluation Program (NTEP) system of rating (National Turfgrass Evaluation Program, 2009), and shoot density (shoots $\cdot$ 8.0 cm^{-2}), collected using a 32.0 mm diameter Soil Sampling Probe (Miltona Turf Products, Maple Gove, Minn.), were collected to evaluate the effects of drain spacing on turfgrass wear tolerance. Eijkelkamp shear vane (Eijkelkamp, Giesbeek, the Netherlands) and Clegg turf shear tester (TST), with a 50.0 mm (wide) x 40.0 mm (insertion depth) paddle (Baden Clegg PTY Ltd., Wembley DC, WA, Australia), data were also collected weekly to determine the effects of drain spacing on surface shear strength (Stier and Rogers, 2001; Sherratt et al., 2005). From October 19, 2007, and October 14, 2008, the Clegg Impact Tester, with a 2.25 kg missile, (Lafayette Instrument Co., Lafayette, Ind.) data were collected to determine if drain spacing produced a difference in surface hardness, reported as G_{max}, were present (McNitt and Landschoot, 2003).

After the conclusion of the simulated traffic on November 8, 2007, and November 12, 2008, four shoot density samples (shoots $\cdot$ 86.6 cm^{-2}) per plot were collected using a 10.5 cm diameter Cup Cutter (Miltona Turf Products, Maple Gove, Minn.) in an attempt to reduce density data variability. Two of the four samples were collected 1.0 m into the plots from the bottom of treatment in relation to the slope, and two samples were collect from the center of the treatments in relation to the drain tiles. After turfgrass shoot density was counted the samples were returned to their respective treatments.

Four soil core samples, 7.6 cm deep, per plot were collected using a 32.0 mm diameter soil sampling probe to determine effects on root development. Samples were separated by depth, 0.0 – 3.8 cm and 3.8 – 7.6 cm, bagged and stored at 0.0° C. Root washing was initiated January 13 and concluded January 24, 2008, and initiated January 15 and concluded January 27, 2009. Samples were placed in a 250.0 ml plastic beaker with a screw on cap. Beakers were then filled with a dispersal solution (35.7 g Sodium Metaphosphate, 7. 9 g Sodium Carbonate, and 1 L water) (Frank et al., 2005). Samples were shaken for 24 hrs then washed through a 0.5 mm sieve. Root samples retained on the sieve were then dried for 48 hrs at 100.0° C and weighed using a Mettler PE 3600 Delta Range Balance (Mettler-Toledo Inc., Columbus, Ohio) with a 0.01 g readability to determine the dry root density (g 122.5 cm^{-3}).

Statistical Analysis

Drainage system data (surface and subsoil moisture content, surface runoff and subsoil drainage) were analyzed as a 5x3 randomized factorial, complete split-block design, with three replications, using SAS (version 9.1.3; SAS Institute Inc., Cary, N.C., 2007). Main effects include drain tile spacing (whole-plot) and topdressing depth (sub-plot). Normality of the residuals and homogeneity of variances were examined using PROC UNIVARIATE procedure. When variances were unequal the REPEATED/GROUP = treatment statement was used and treatments with similar variances were grouped accordingly. The Akaike information criterion (AIC) value was used to determine whether a regular analysis with a common variance or an analysis with unequal variance was required (Littell et al., 2007). The analysis that produced the lowest AIC value was selected to make conclusions on significance of factor effects and their interactions. Because cumulative topdressing applications were applied over time, repeated measures (REPEATED treatment/TYPE= variance-covariance structure) were explored. The variance-covariance structure that produced the lowest AIC value was selected to make conclusions on significance of factor effects and their interactions. Mean separations were obtained based on the selected analysis using Fisher's least significant difference (LSD) at a 0.05 level of probability (Ott and Longnecker, 2001).

Drain tile drainage date were analyzed as a 4x3 using the same experimental design as discussed above. Drain tile spacing, the whole-plot factor, has one less level at this time because the control treatments do not have drain tiles and therefore were excluded for the drain tile drainage experimental design.

Infiltration rate data were analyzed as a 4x4 using the same experimental design as discussed above. Infiltration data were collected over the drain tiles, so in terms of drain tiles spacing, again, there are only four levels. However, infiltration data were collected after the three topdressing depths and the fall traffic period, giving the split-plot factor, in this instance, a fourth level.

Wear tolerance and surface characteristic data were analyzed as single factor (drain tile spacing) completely randomized block design, with three replications, using SAS. Normality of the residuals and homogeneity of variances were examined using PROC UNIVARIATE procedure and Levene's test for homogeneous variances (treatment/HOVTEST=LEVENE). In all instances, Levene's test results were not significant ($P > 0.05$); therefore, an equal variance (null) hypothesis was accepted. Mean separations were obtained based on the selected analysis using Fisher's protected LSD at a 0.05 level of probability.

DRAINAGE CHARACTERISTC RESULTS

Drainage Characteristics Following a 17.0 Minute Irrigation Events (2007)

Main effects of drain spacing and topdressing depth on irrigation rates applied to a Kentucky bluegrass – perennial ryegrass mixture established on a loamy sand soil were not statistically significant (Table 56). These findings suggest that all treatments received uniform irrigation rates (Table 57).

Significant main effects of drain spacing on the subsoil drainage were observed, while differences between topdressing depths were not significant (Table 56). The control, an 8.1 m long treatment without drain tiles, and the 6.0 m drain spacing produced mean subsoil drainage values ranking in the highest category, while the 4.0, 3.0 and 2.0 m drain spacing produced subsoil drainage values ranking in the lowest category (Table 57).

Main effects of drain spacing and topdressing depth on surface runoff were significant (Table 56). The control treatment produced the greatest amount of mean surface runoff, followed by the 6.0 m drain spacing, and finally the 4.0, 3.0 and 2.0 m drain spacing (Table 57). These results suggest that drain spacing as far as 4.0 m apart will substantial decrease surface runoff in comparison to a native soil field without drain tiles, and provide the same effects on surface runoff as drains spaced as close as 2.0 m apart. The 0.0 and 1.2 cm topdressing depth produced less surface runoff than the 2.4 cm topdressing depth.

Significant main effects of topdressing depth on drain tile drainage following a 1.3 cm irrigation event were observed, while no differences between drain spacing were observed (Table 58). The 2.4 cm topdressing depth produced the greatest amount of

Table 56: Analysis of variance results for irrigation rates, subsoil drainage and surface runoff, East Lansing, Mich. (data collected in 2007).

		Irrigation Rate (cm)[z]		Subsoil Drainage (v/v)[y]		Surface Runoff (v/v)[x]	
Source of Variation	Num. df	Den. df	*P*>F	Den. df	*P*>F	Den. df	*P*>F
Drain Spacing (DS)	4.0	8.0	NS[w]	13.6	0.0294	8.4	<0.0001
Topdressing Depth (TD)	2.0	3.6	NS	19.2	NS	8.7	0.0037
DS X TD	8.0	14.8	NS	18.9	NS	9.8	NS

[z] Irrigation rates (cm) applied in a 17.0 minute irrigation event.

[y] Volume (L) of subsoil drainage divided by volume of irrigation applied.

[x] Volume (L) of surface runoff divided by volume of irrigation applied.

[w] NS = not significant at $P > 0.05$.

Table 57: Effects of drain spacing and topdressing depth on irrigation rates, subsoil drainage and surface runoff, East Lansing, Mich. (data collected in 2007).

	2007 Mean Values		
Drain Spacing (m)	Irrigation Rate (cm)[z]	Subsoil Drainage (v/v)[y]	Surface Runoff (v/v)[x]
control[w v]	1.3	1.1 a[u]	26.5 a
6.0	1.1	1.6 a	5.2 b
4.0	1.3	0.6 bc	3.3 bc
3.0	1.3	0.6 bc	3.5 bc
2.0	1.3	0.1 c	1.1 c
	ns[t]		
Topdressing Depth (cm)[s]	Irrigation Rate (cm)	Subsoil Drainage (v/v)	Surface Runoff (v/v)
0.0	1.4	1.1	6.1 b
1.2	1.2	0.4	5.5 b
2.4	1.3	1.0	12.2 a
	ns	ns	

[z] Irrigation rates (cm) applied in a 17.0 minute irrigation event.

[y] Volume (L) of subsoil drainage divided by volume of irrigation applied.

[x] Volume (L) of surface runoff divided by volume of irrigation applied.

[w] Control = 8.1 m long treatment, equivalent to the distance from the crown of a field to the hash makers, without drain tiles.

[v] Number of replications for all treatments = 3.

[u] Means in a given column with the same letter do not differ using Fisher's least significant difference at $P = 0.05$.

[t] ns = not significant at $P = 0.05$.

[s] cm of topdressing sand accumulated over a one month period, July 11 – Aug. 15, 2007.

Table 58: Analysis of variance results for drain tile drainage, East Lansing, Mich. (data collected in 2007).

	Drain Tile Drainage (v/v)[z]		
Source of Variation	Num. df	Den. df	*P*>F
Drain Spacing (DS)	3.0	6.0	NS[y]
Topdressing Depth (TD)	2.0	16.0	0.0093
DS X TD	6.0	16.0	NS

[z] Volume (L) of drain tile drainage divided by volume of irrigation applied in a 17.0 minute (1.3 cm) irrigation event.

[y] NS = not significant at $P > 0.05$.

mean drain tile drainage, followed by the 1.2 cm depth and finally the 0.0 cm depth, suggesting a negative correlation between topdressing depth and drain tile drainage (Table 59).

Main effects of drain spacing and topdressing depth on soil surface moisture content were significant throughout the 4 hour data collection period following a 1.3 cm irrigation event (Table 60). In every instance observed throughout the 4.0 hour data collection period, the control and 6.0 m drain spacing resulted in the highest mean surface moisture content, while the 4.0, 3.0 and 2.0 m spacing produced the lowest surface moisture (Table 61). These results suggest that drain tile spacing 4.0 m apart will substantially reduce surface moisture in comparison to a field without drain tiles, while providing the same, statistically insignificant, surface moisture results as a field with drain tiles spaced every 2.0 m. The 0.0 cm topdressing depth produced a greater mean surface moisture content value than the 1.2 and 2.4 cm depth, suggesting that as little as 1.2 cm of sand topdressing can substantially decrease the surface moisture content of a native soil system.

Main effects of drain spacing and topdressing depth on subsoil moisture content were observed throughout the data collection period, while no differences between topdressing depths were observed (Table 62). When differences between drain spacing were observed, the control, 6.0 and 4.0 m drain spacing produced some of the highest mean subsoil moisture content, while the 2.0 m spacing provided the lowest subsoil moisture throughout the 4.0 hour data collection period (Table 63).

Significant main effects of topdressing depth on saturated hydraulic conductivity over an intercept drain line were observed, while drain spacing was not significant (Table

Table 59: Effects of drain spacing and topdressing depth on drain tile drainage, East Lansing, Mich. (data collected in 2007).

Drain Spacing (m)	2007 Mean Drain Tile Drainage (v/v)[z]
6.0[y]	17.1
4.0	20.0
3.0	18.6
2.0	23.7
	ns[x]
Topdressing Depth (cm)[w]	**2007 Mean Drain Tile Drainage (v/v)**
0.0	24.8 a[v]
1.2	19.2 ab
2.4	15.6 b

[z] Volume (L) of drain tile drainage divided by volume of irrigation applied in a 17.0 minute (1.3 cm) irrigation event.

[y] Number of replications for all treatments = 3.

[x] ns = not significant at $P = 0.05$.

[w] cm of topdressing sand accumulated over a one month period, July 11 – Aug. 15, 2007.

[v] Means in a given column with the same letter do not differ using Fisher's least significant difference at $P = 0.05$.

Table 60: Analysis of variance results for surface moisture[z], East Lansing, Mich. (data collected in 2007).

		Time from Initiation of Irrigation (hrs)[y]											
		0:00		0:20		0:40		1:00		2:00		4:00	
	Num.	Den.		Den.		Den.		Den.		Den.		Den.	
Source of Variation	df	df	*P*>F	df	*P*>F	df	*P*>F	df	*P*>F	df	*P*>F	df	*P*>F
Drain Spacing (DS)	4.0	13.1	0.0003	9.1	0.0137	8.0	NS[x]	5.3	0.0007	8.0	0.0052	8.0	0.0061
Topdressing Depth (TD)	2.0	6.0	<0.0001	5.5	<0.0001	20.0	<0.0001	11.7	<0.0001	20.0	<0.0001	20.0	<0.0001
DS X TD	8.0	15.6	NS[x]	15.6	NS	20.0	NS	6.6	NS	20.0	NS	20.0	NS

[z] Surface moisture (v/v to a 1.3 cm depth) collected at various time intervals.

[y] 17.0 minute (1.3 cm) irrigation event.

[x] NS = not significant at $P > 0.05$.

Table 61: Effects of drain spacing and topdressing depth on surface moisture, East Lansing, Mich. (data collected in 2007).

	Time from Initiation of Irrigation (hrs)[z]					
	0:00	0:20	0:40	1:00	2:00	4:00
Drain Spacing (m)	2007 Mean Surface Moisture (v/v)[y]					
control[x w]	29.1 a[v]	40.2 a	38.2	37.9 a	36.5 a	31.1 a
6.0	27.5 a	39.7 a	37.0	37.3 a	33.9 a	30.5 a
4.0	24.6 b	37.4 b	34.8	33.6 b	29.1 b	25.7 b
3.0	25.6 b	36.7 b	35.8	34.5 b	29.5 b	26.1 b
2.0	23.3 b	37.3 b	34.1	31.9 b	28.2 b	24.3 b
			ns[u]			
Topdressing Depth (cm)[t]	2007 Mean Surface Moisture (v/v)					
0.0	39.7 a	47.0 a	46.5 a	46.5 a	43.6 a	40.7 a
1.2	17.5 b	34.5 b	30.4 b	28.8 b	24.6 b	20.7 b
2.4	20.9 b	33.3 b	30.9 b	29.9 b	26.1 b	21.2 b

[z] 17.0 minute (1.3 cm) irrigation event.

[y] Surface moisture (v/v to a 1.3 cm depth) collected at various time intervals.

[x] Control = 8.1 m long treatment, equivalent to the distance from the crown of a field to the hash makers, without drain tiles.

[w] Number of replications for all treatments = 3.

[v] Means in a given column with the same letter do not differ using Fisher's least significant difference at $P = 0.05$.

[u] ns = not significant at $P = 0.05$.

[t] cm of topdressing sand accumulated over a one month period, July 11 – Aug. 15, 2007.

Table 62: Analysis of variance results for subsoil moisture[z], East Lansing, Mich. (data collected in 2007).

		Time from Initiation of Irrigation (hrs)[y]											
		0:00		0:20		0:40		1:00		2:00		4:00	
Source of Variation	Num. df	Den. df	$P>F$	Den. df	$P>F$	Den. df	$P>F$	Den. df	$P>F$	Den. df	$P>F$	Den. df	$P>F$
Drain Spacing (DS)	4.0	10.6	0.0107[x]	8.0	0.0005	9.9	NS	9.0	NS	7.6	0.0454	9.1	0.0146
Topdressing Depth (TD)	2.0	9.0	NS	20.0	NS	8.9	NS	10.1	NS	4.5	NS	5.1	NS
DS X TD	8.0	10.3	NS	20.0	NS	10.2	NS	11.2	NS	15.0	NS	14.4	NS

[z] Subsoil moisture (v/v at 15.2 cm depth) collected at various time intervals.

[y] 17.0 minute (1.3 cm) irrigation event.

[x] NS = not significant at $P > 0.05$.

Table 63: Effects of drain spacing and topdressing depth on subsoil moisture, East Lansing, Mich. (data collected in 2007).

	Time from Initiation of Irrigation (hrs)[z]									
	0:00		0:20		0:40	1:00	2:00		4:00	
Drain Spacing (m)	2007 Mean Subsoil Moisture (v/v)[y]									
control[x w]	35.9	a[v]	35.9	b	35.0	35.1	35.8	ab	35.5	a
6.0	36.5	a	36.7	a	36.8	36.7	36.5	a	36.3	a
4.0	35.4	a	35.4	b	35.4	35.2	35.0	abc	34.8	ab
3.0	33.8	a	32.9	bc	33.0	33.3	33.6	c	33.4	b
2.0	33.6	b	33.8	c	34.2	33.9	33.7	bc	33.4	b
					ns[u]					
Topdressing Depth (cm)[t]	2007 Mean Subsoil Moisture (v/v)									
0.0	35.1		35.2		35.4	35.3	35.1		35.1	
1.2	34.9		35.2		35.3	35.1	34.8		34.6	
2.4	35.2		35.1		33.9	34.2	34.9		34.3	
	ns		ns		ns	ns	ns		ns	

[z] 17.0 minute (1.3 cm) irrigation event.

[y] Subsoil moisture (v/v at a 15.2 cm depth) collected at various time intervals.

[x] Control = 8.1 m long treatment, equivalent to the distance from the crown of a field to the hash makers, without drain tiles.

[w] Number of replications for all treatments = 3.

[v] Means in a given column with the same letter do not differ using Fisher's least significant difference at $P = 0.05$.

[u] ns = not significant at $P = 0.05$.

[t] cm of topdressing sand accumulated over a one month period, July 11 – Aug. 15, 2007.

64). The 0.0 cm topdressing depth produced the greatest mean hydraulic conductivity over an intercept drain line, while the 2.4 cm topdressing depth and 2.4 cm topdressing depth plus fall traffic produced mean hydraulic conductivity values ranking in the lowest category (Table 65).

Surface Runoff Following a 34.0 Minute Irrigation Events (2007)

Significant main effects of drain spacing and topdressing depth on surface runoff collected following a 34.0 minute (2.6 cm) irrigation event were observed (Table 66). A significant drain spacing x topdressing depth interaction was also observed at this time.

The control produced the greatest amount of surface runoff, followed by the 6.0, 4.0 and 3.0 m drain spacing, and finally the 2.0 m spacing (Table 67). This suggests that a 2.0 m spacing will provide the best results, while drain tiles spaced as far as 6.0 m will substantially decrease surface runoff in comparison to the control. The 1.2 and 2.4 cm topdressing depth produced surface runoff ranking in the largest category, while the 0.0 cm topdressing depth resulted in the least amount of runoff. Differences between topdressing depths were observed at the control, 6.0, 4.0 and 3.0 m drain spacing (Figure 9). Surface runoff was reduced by topdressing depth accumulation over the control treatment, but increased by topdressing accumulation over the 6.0, 4.0 and 3.0 m drain spacing.

Drainage Characteristics Following a 17.0 Minute Irrigation Events (2008)

Main effects of topdressing depth on irrigation rate applied to a Kentucky bluegrass – perennial ryegrass mixture were observed, while no differences between drain spacing were observed (Table 68). Significantly more irrigation was applied after 4.8 cm of topdressing had been accumulated over time in comparison to the rates applied

Table 64: Analysis of variance results for saturated hydraulic conductivity, East Lansing, Mich. (data collected in 2007).

	K_{sat} (cm hr^{-1})[z]		
Source of Variation	Num. df	Den. df	*P*>F
Drain Spacing (DS)	3.0	2.5	NS[y]
Topdressing Depth (TD)	3.0	9.9	<0.0001
DS X TD	9.0	12.1	NS

[z] K_{sat} (saturated hydraulic conductivity) over intercept drain lines were determined using double ring infiltrometers.

[y] NS = not significant at $P > 0.05$.

Table 65: Effects of drain spacing and topdressing depth on saturated hydraulic conductivity, East Lansing, Mich. (data collected in 2007).

Drain Spacing (m)	2007 Mean K_{sat} (cm hr^{-1})[z]
6.0[y]	54.9
4.0	45.0
3.0	43.2
2.0	51.1
	ns[x]
Topdressing Depth (cm)[w]	**2007 Mean K_{sat} (cm hr^{-1})**
0.0	98.5 a[v]
1.2	43.2 b
2.4	22.2 c
2.4 + traffic[u]	30.2 bc

[z] K_{sat} (saturated hydraulic conductivity) over intercept drain lines were determined using double ring infiltrometers.

[y] Number of replications for all treatments = 3.

[x] ns = not significant at $P = 0.05$.

[w] cm of topdressing sand accumulated over a one month period, July 11 – Aug. 15, 2007.

[v] Means in a given column with the same letter do not differ using Fisher's least significant difference at $P = 0.05$.

[u] Fall simulator traffic applications were applied using the Cady Traffic Simulator, Oct. 10 – Nov. 10, 2007.

Table 66: Analysis of variance results for surface runoff, East Lansing, Mich. (data collected in 2007).

	Surface Runoff (v/v)[z]		
Source of Variation	Num. df	Den. df	*P*>F
Drain Spacing (DS)	4.0	7.8	<0.0001
Topdressing Depth (TD)	2.0	9.0	0.0252
DS X TD	8.0	10.3	0.0138

[z] Volume (L) of surface runoff divided by volume of irrigation applied in a 34.0 minute (2.6 cm) irrigation event.

Table 67: Effects of drain spacing and topdressing depth on surface runoff, East Lansing, Mich. (data collected in 2007).

Drain Spacing (m)	2007 Mean Surface Runoff (v/v)[z]	
control[y x]	30.8	a[w]
6.0	7.5	b
4.0	10.1	b
3.0	7.8	b
2.0	0.4	c
Topdressing Depth (cm)[v]	**2007 Mean Surface Runoff (v/v)**	
0.0	9.0	b
1.2	13.9	a
2.4	11.1	ab

[z] Volume (L) of surface runoff divided by volume of irrigation applied in a 34.0 minute (2.6 cm) irrigation event.

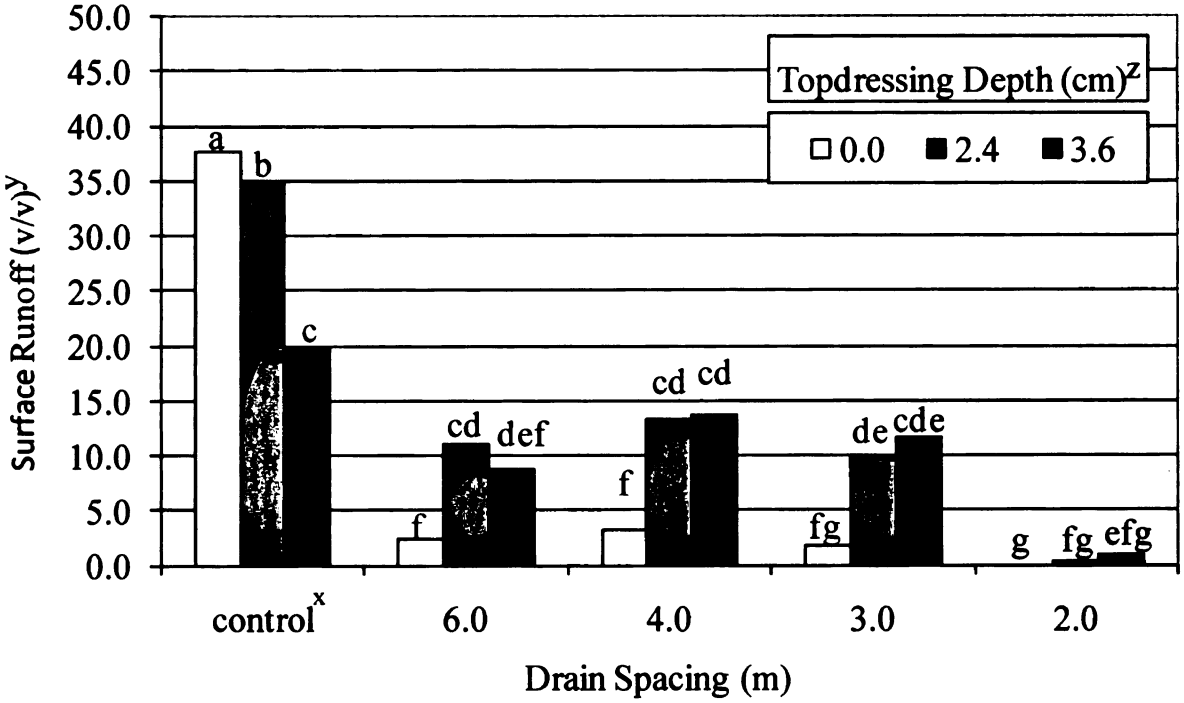
[y] Control = 8.1 m long treatment, equivalent to the distance from the crown of a field to the hash makers, without drain tiles.

[x] Number of replications for all treatments = 3.

[w] Means in a given column with the same letter do not differ using Fisher's least significant difference at $P = 0.05$.

[v] cm of topdressing sand accumulated over a one month period, July 11 – Aug. 15, 2007.

Figure 9: Effects of drain spacing x topdressing depth on surface runoff, East Lansing, Mich. (data collected in 2007).



[z] cm of topdressing sand accumulated over a one month period, July 11 – Aug. 15, 2007.

[y] Volume (L) of surface runoff divided by volume of irrigation applied in a 34.0 minute (2.6 cm) irrigation event.

[x] Control = 8.1 m long treatment, equivalent to the distance from the crown of a field to the hash makers, without drain tiles.

Means in a given column with the same letter do not differ using Fisher's least significant difference at $P = 0.05$.

Table 68: Analysis of variance results for irrigation rates, subsoil drainage and surface runoff, East Lansing, Mich. (data collected in 2008).

		Irrigation Rate (cm)[z]		Subsoil Drainage (v/v)[y]		Surface Runoff (v/v)[x]	
Source of Variation	Num. df	Den. df	*P*>F	Den. df	*P*>F	Den. df	*P*>F
Drain Spacing (DS)	4.0	27.9	NS[w]	9.8	0.0056	8.0	<0.0001
Topdressing Depth (TD)	2.0	17.4	0.0268	12.1	0.0014	20.0	0.0172
DS X TD	8.0	18.4	NS	12.7	0.0012	20.0	0.0301

[z] Irrigation rates (cm) applied in a 17.0 minute irrigation event.

[y] Volume (L) of subsoil drainage divided by volume of irrigation applied.

[x] Volume (L) of surface runoff divided by volume of irrigation applied.

[w] NS = not significant at $P > 0.05$.

prior to the initiation of topdressing that year, at which time a 2.4 cm depth had been accumulated in the previous year, and after the accumulation of a 3.6 cm depth (Table 69).

Significant main effects of drain spacing and topdressing depth on subsoil drainage were observed (Table 68). A significant drain spacing x topdressing depth interaction was also observed.

Contrary to results observed in the previous year, the 3.0 and 2.0 m drain spacing produced mean subsoil drainage values ranking in the highest category, while the control, 6.0 and 4.0 m drain spacing provided the subsoil drainage ranking in the lowest category (Table 69). The 2.4 cm topdressing depth produced the greatest subsoil drainage, followed by the 3.6 cm depth, and finally the 4.8 cm depth, suggesting a negative correlation between sand topdressing depths and subsoil drainage. The significant drain spacing x topdressing depth interaction produced a reduction in subsoil drainage as topdressing depth increased from 2.4 cm to 3.6 cm for the 3.0 m drain spacing only (Figure 10).

Main effects of drain spacing and topdressing depth on surface runoff were observed (Table 68). A drain spacing x topdressing depth interaction was also noted.

Mean surface runoff was greatest from the control, followed by the 4.0 and 3.0 m drain spacing, and finally the 6.0 and 2.0 m spacing (Table 69). Topdressing accumulated to the 3.6 and 4.8 cm depth produced surface runoff values ranking in the greatest category, while the 2.4 cm depth resulted in the least surface runoff. The drain spacing x topdressing depth interaction resulted in less surface runoff at the 2.4 cm

Table 69: Effects of drain spacing and topdressing depth on irrigation rates, subsoil drainage and surface runoff, East Lansing, Mich. (data collected in 2008).

	2008 Mean Values		
Drain Spacing (m)	Irrigation Rate (cm)[z]	Subsoil Drainage (v/v)[y]	Surface Runoff (v/v)[x]
control[w v]	1.5	1.8 bc[u]	16.2 a
6.0	1.5	1.5 c	2.3 c
4.0	1.6	2.1 bc	7.7 b
3.0	1.6	3.2 a	6.1 b
2.0	1.4	2.6 ab	1.6 c
	ns[t]		
Topdressing Depth (cm)[s]	Irrigation Rate (cm)	Subsoil Drainage (v/v)	Surface Runoff (v/v)
2.4	1.4 b	2.7 a	5.1 b
3.6	1.5 b	2.2 ab	8.4 a
4.8	1.7 a	1.8 b	6.8 ab

[z] Irrigation rates (cm) applied in a 17.0 minute irrigation event.

[y] Volume (L) of subsoil drainage divided by volume of irrigation applied.

[x] Volume (L) of surface runoff divided by volume of irrigation applied.

[w] Control = 8.1 m long treatment, equivalent to the distance from the crown of a field to the hash makers, without drain tiles.

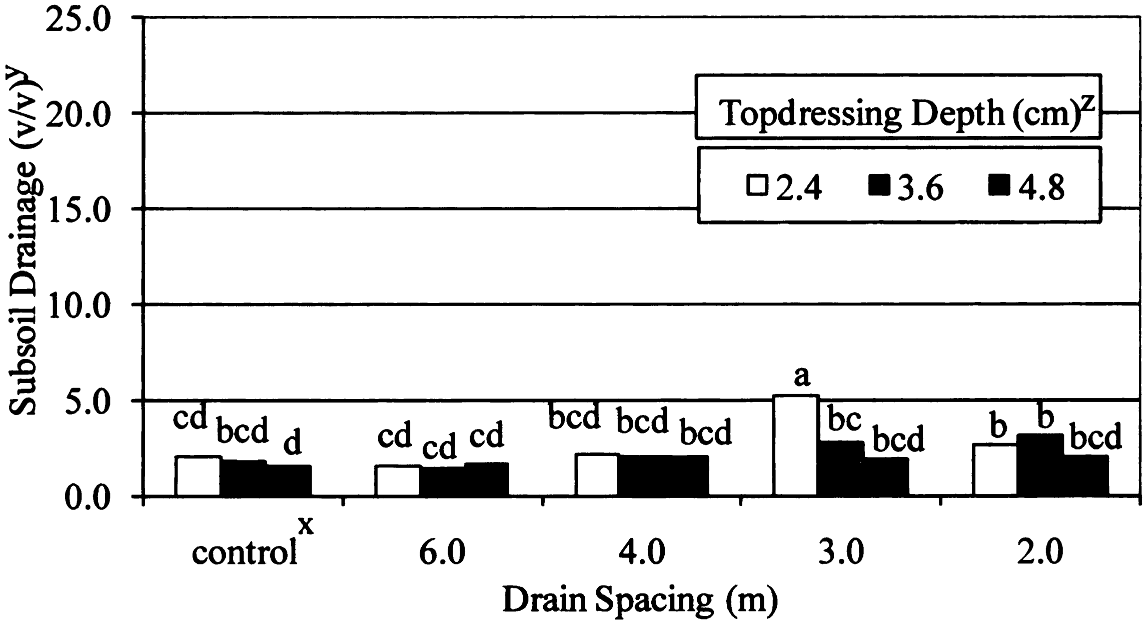
[v] Number of replications for all treatments = 3.

[u] Means in a given column with the same letter do not differ using Fisher's least significant difference at $P = 0.05$.

[t] ns = not significant at $P = 0.05$.

[s] cm of topdressing sand accumulated over a one month period, July 26 – Aug. 22, 2008.

Figure 10: Effects of drain spacing x topdressing depth on subsoil drainage, East Lansing, Mich. (data collected in 2008).



[z] cm of topdressing sand accumulated over a one month period, July 26 – Aug. 22, 2008.
[y] Volume (L) of subsoil drainage divided by volume of irrigation applied in 17.0 minutes.
[x] Control = 8.1 m long treatment, equivalent to the distance from the crown of a field to the hash makers, without drain tiles.
Means in a given column with the same letter do not differ using Fisher's least significant difference at $P = 0.05$.

topdressing depth than at the 3.6 and 4.8 cm depths for the 4.0 m spacing, and the 3.6 cm depth for the 3.0 m spacing (Figure 11).

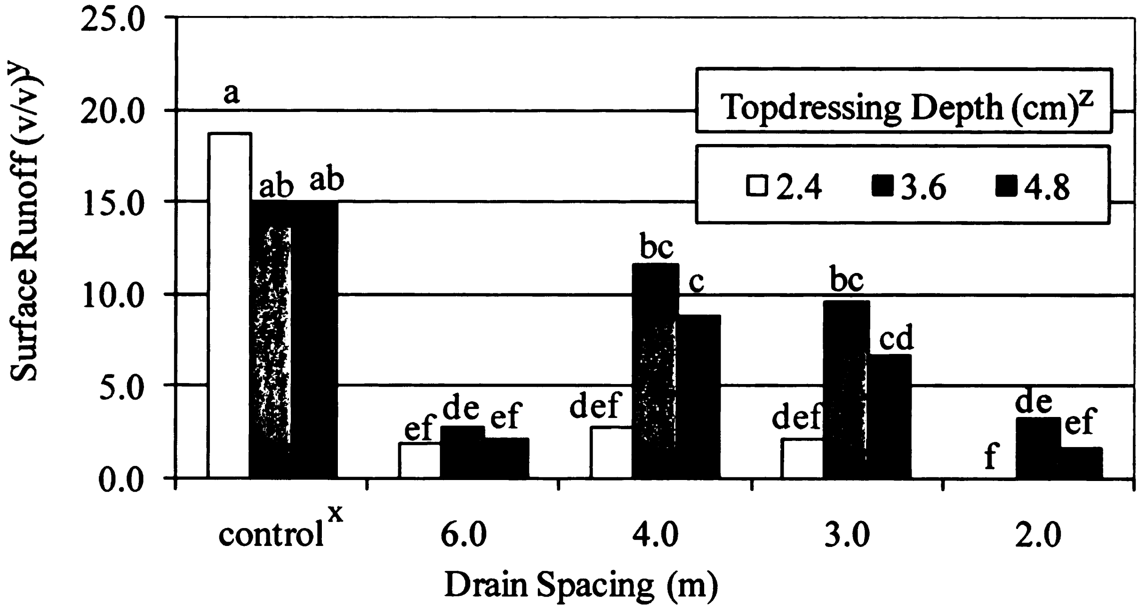
No significant main effects or interactions on drain tile drainage were observed in 2008 (Table 70 and 71).

Significant main effects of drain spacing and topdressing depth on surface moisture were observed throughout the 4.0 hour data collection period (Table 72). Mean surface moisture was highest in the control, while the 2.0 m drain spacing produced the lowest surface moisture throughout the data collection period (Table 73). The 2.4 cm topdressing depth produced the highest mean surface moisture content throughout the data collection period. The significant drain spacing x topdressing depth interaction resulted in significantly less surface moisture at the 3.6 cm topdressing depth in comparison to the 2.4 and 4.8 cm depths regardless of drain tile spacing (Figure 12).

Main effects of drain spacing and topdressing depth on subsoil moisture content were observed throughout the 4 hour data collection period (Table 74). When differences between drain spacing were observed, the 6.0 m drain spacing produced the highest overall subsoil moisture content, while the 3.0 and 2.0 m spacing provided the lowest surface moisture throughout the data collection period (Table 75). Mean subsoil moisture content was highest at the 4.8 cm topdressing depth, followed by the 3.6 cm depth and finally the 2.4 cm depth.

Significant main effects of topdressing depth on saturated hydraulic conductivity were observed, while main effects of drain spacing were not significant (Table 76). The 3.6 cm topdressing depth and 4.8 cm topdressing depth plus fall traffic produced the

Figure 11: Effects of drain spacing x topdressing depth on surface runoff, East Lansing, Mich. (data collected in 2008).



z cm of topdressing sand accumulated over a one month period, July 26 – Aug. 22, 2008.

y Volume (L) of surface runoff divided by volume of irrigation applied in 17.0 minutes.

x Control = 8.1 m long treatment, equivalent to the distance from the crown of a field to the hash makers, without drain tiles.

Means in a given column with the same letter do not differ using Fisher's least significant difference at $P = 0.05$.

Table 70: Analysis of variance results for drain tile drainage, East Lansing, Mich. (data collected in 2008).

Source of Variation	Drain Tile Drainage (v/v)[z] Num. df	Den. df	*P*>F
Drain Spacing (DS)	3.0	3.0	NS[y]
Topdressing Depth (TD)	2.0	9.8	NS
DS X TD	6.0	5.6	NS

[z] Volume (L) of drain tile drainage divided by volume of irrigation applied in a 17.0 minute (1.5 cm) irrigation event.
[y] NS = not significant at $P > 0.05$.

Table 71: Effects of drain spacing and topdressing depth on drain tile drainage, East Lansing, Mich. (data collected in 2008).

Drain Spacing (m)	2008 Mean Drain Tile Drainage (v/v)[z]
6.0[y]	11.8
4.0	15.5
3.0	19.7
2.0	21.2
	ns[x]
Topdressing Depth (cm)[w]	**2008 Mean Drain Tile Drainage (v/v)**
2.4	14.7
3.6	17.1
4.8	19.3
	ns

[z] Volume (L) of drain tile drainage divided by volume of irrigation applied in a 17.0 minute (1.5 cm) irrigation event.

[y] Number of replications for all treatments = 3.

[x] ns = not significant at $P = 0.05$.

[w] cm of topdressing sand accumulated over a one month period, July 26 – Aug. 22, 2008.

Table 72: Analysis of variance results for surface moisture[z], East Lansing, Mich. (data collected in 2008).

		Time from Initiation of Irrigation (hrs)[y]											
		0:00		0:20		0:40		1:00		2:00		4:00	
	Num.	Den.		Den.		Den.		Den.		Den.		Den.	
Source of Variation	df	df	P>F	df	P>F	df	P>F	df	P>F	df	P>F	df	P>F
Drain Spacing (DS)	4.0	10.5	<0.0001	8.0	NS[x]	8.3	0.0245	9.3	0.0078	8.0	0.0023	29.0	NS
Topdressing Depth (TD)	2.0	3.95	NS	19.0	0.0001	18.3	0.0291	19.8	<0.0001	19.0	0.0008	20.2	NS
DS X TD	8.0	14.6	NS	19.0	NS	18.1	NS	19.7	0.0265	19.0	NS	20.2	NS

[z] Surface moisture (v/v to a 1.3 cm depth) collected at various time intervals.

[y] 17.0 minute (1.5 cm) irrigation event.

[x] NS = not significant at $P > 0.05$.

Table 73: Effects of drain spacing and topdressing depth on surface moisture, East Lansing, Mich. (data collected in 2008).

	Time from Initiation of Irrigation (hrs)[z]					
	0:00	0:20	0:40	1:00	2:00	4:00
Drain Spacing (m)	2008 Mean Surface Moisture (v/v)[y]					
control[x w]	26.2 a[v]	34.0	32.3 a	30.4 a	29.2 a	27.3
6.0	24.3 b	33.5	31.1 ab	28.5 ab	28.6 a	26.1
4.0	23.6 b	33.5	32.3 a	29.3 ab	28.0 ab	25.9
3.0	22.1 c	32.8	29.9 bc	27.5 bc	26.1 b	24.5
2.0	20.8 d	31.1	28.6 c	25.9 c	24.0 c	21.5
		ns[u]				ns
Topdressing Depth (cm)[t]	2008 Mean Surface Moisture (v/v)					
2.4	24.7	34.5 a	31.8 a	30.4 a	28.1 a	25.4
3.6	23.5	30.8 b	29.9 b	25.6 c	27.5 a	25.8
4.8	22.0	33.6 a	30.8 ab	28.9 b	26.0 b	24.0
	ns					ns

[z] 17.0 minute (1.5 cm) irrigation event.

[y] Surface moisture (v/v to a 1.3 cm depth) collected at various time intervals.

[x] Control = 8.1 m long treatment, equivalent to the distance from the crown of a field to the hash makers, without drain tiles.

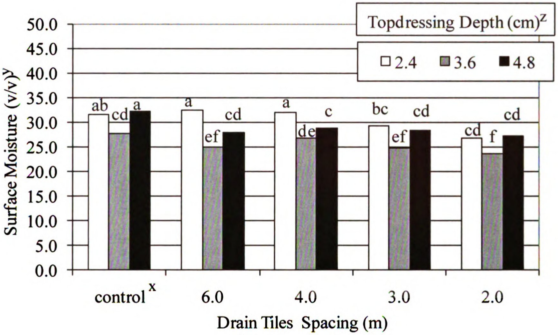
[w] Number of replications for all treatments = 3.

[v] Means in a given column with the same letter do not differ using Fisher's least significant difference at $P = 0.05$.

[u] ns = not significant at $P = 0.05$.

[t] cm of topdressing sand accumulated over a one month period, July 26 – Aug. 22, 2008.

Figure 12: Effects of drain spacing x topdressing depth on surface moisture, East Lansing, Mich. (data collected in 2008).



[z] cm of topdressing sand accumulated over a one month period, July 26 – Aug. 22, 2008.

[y] Surface moisture (v/v) collected 20.0 minutes after the initiation of a 17.0 minutes (1.5 cm) irrigation event.

[x] Control = 8.1 m long treatment, equivalent to the distance from the crown of a field to the hash makers, without drain tiles.

Means in a given column with the same letter do not differ using Fisher's least significant difference at $P = 0.05$.

Table 74: Analysis of variance results for subsoil moisture[z], East Lansing, Mich. (data collected in 2008).

		Time from Initiation of Irrigation (hrs)[y]											
		0:00		0:20		0:40		1:00		2:00		4:00	
Source of Variation	Num. df	Den df	P>F	Den. df	P>F	Den. df	P>F	Den. df	P>F	Den. df	P>F	Den. df	P>F
Drain Spacing (DS)	4.0	10.8	NS[x]	10.0	0.0345	9.9	NS	9.8	0.046	10.6	0.0307	8.0	0.0481
Topdressing Depth (TD)	2.0	5.1	0.0188	9.0	0.0004	9.0	0.0011	9.0	0.0005	12.8	<0.0001	20.0	0.0001
DS X TD	8.0	16.3	NS	10.3	NS	10.3	NS	10.3	NS	13.7	NS	20.0	NS

[z] Subsoil moisture (v/v at 15.2 cm depth) collected at various time intervals.

[y] 17.0 minute (1.5 cm) irrigation event.

[x] NS = not significant at $P > 0.05$.

Table 75: Effects of drain spacing and topdressing depth on subsoil moisture, East Lansing, Mich. (data collected in 2008).

	Time from Initiation of Irrigation (hrs)[z]					
	0:00	0:20	0:40	1:00	2:00	4:00
Drain Spacing (m)	2008 Mean Subsoil Moisture (v/v)[y]					
control[x w]	34.7	35.8 a[v]	35.4	35.5 ab	34.8 b	34.7 abc
6	36.1	36.3 a	36.4	36.4 a	36.2 a	35.8 a
4	35.1	35.5 ab	35.7	35.5 ab	35.2 ab	34.9 b
3	34.1	34.4 b	34.3	34.3 b	34.0 b	33.8 c
2	34.7	35.4 ab	35.5	35.2 ab	34.9 b	34.7 bc
	ns[u]		ns			
Topdressing Depth (cm)[t]	2008 Mean Subsoil Moisture (v/v)					
2.4	34.0 b	34.8 c	34.8 b	34.5 c	34.1 c	33.8 c
3.6	34.9 ab	35.5 b	35.6 ab	35.5 b	35.0 b	34.9 b
4.8	36.0 a	36.1 a	36.1 a	36.2 a	35.9 a	35.7 a

[z] 17.0 minute (1.5 cm) irrigation event.

[y] Subsoil moisture (v/v at a 15.2 cm depth) collected at various time intervals.

[x] Control = 8.1 m long treatment, equivalent to the distance from the crown of a field to the hash makers, without drain tiles.

[w] Number of replications for all treatments = 3.

[v] Means in a given column with the same letter do not differ using Fisher's least significant difference at $P = 0.05$.

[u] ns = not significant at $P = 0.05$.

[t] cm of topdressing sand accumulated over a one month period, July 26 – Aug. 22, 2008.

Table 76: Analysis of variance results for saturated hydraulic conductivity, East Lansing, Mich. (data collected in 2008).

	K_{sat} (cm hr^{-1})^z		
Source of Variation	Num. df	Den. df	*P*>F
Drain Spacing (DS)	3.0	6.9	NS^z
Topdressing Depth (TD)	3.0	6.0	0.0107
DS XTD	9.0	6.9	NS

^{z} K_{sat} (saturated hydraulic conductivity) over intercept drain lines were determined using double ring infiltrometers.

^{y} NS = not significant at $P > 0.05$.

lowest mean hydraulic conductivity rates in comparison to the other topdressing depths (Table 77).

Surface Runoff Following a 34.0 Minute Irrigation Events (2008)

Significant main effects of drain spacing on surface runoff were collected following a 34.0 minute (3.0 cm) irrigation event, while differences between topdressing depths were insignificant (Table 78). The control produced the greatest amount of surface runoff, followed by the 4.0 m drain spacing, then the 6.0 and 3.0 m spacing and finally the 2.0 m spacing (Table 79). Similar to results collected in 2007, these findings suggest the 2.0 m drain tile spacing will provide the least surface runoff, while the 6.0, 4.0 and 3.0 m spacing can substantially reduce surface runoff in comparison to a field without drain tiles.

Table 77: Effects of drain spacing and topdressing depth on saturated hydraulic conductivity, East Lansing, Mich. (data collected in 2008).

Drain Spacing (m)	2008 Mean K_{sat} (cm hr^{-1})[z]
6.0[y]	35.7
4.0	28.6
3.0	34.1
2.0	38.6
	ns[x]
Topdressing Depth (cm)[w]	**2008 Mean K_{sat} (cm hr^{-1})**
2.4	44.2 b[v]
3.6	30.4 c
4.8	42.5 b
4.8 + traffic[u]	20.0 c

[z] K_{sat} (saturated hydraulic conductivity) over intercept drain lines were determined using double ring infiltrometers.

[y] Number of replications for all treatments = 3.

[x] ns = not significant at $P = 0.05$.

[w] cm of topdressing sand accumulated over a one month period, July 26 – Aug. 22, 2008.

[v] Means in a given column with the same letter do not differ using Fisher's least significant difference at $P = 0.05$.

[u] Fall traffic simulator applications were applied using the Cady Traffic Simulator, Oct. 13 – Nov. 14, 2008.

Table 78: Analysis of variance results for surface runoff, East Lansing, Mich. (data collected in 2008).

	Surface Runoff (v/v)[z]		
	Num.	Den.	
Source of Variation	df	df	*P*>F
Drain Spacing (DS)	4.0	9.9	<0.0001
Topdressing Depth (TD)	2.0	9.3	NS[y]
DS X DT	8.0	10.6	NS

[z] Volume (L) of surface runoff divided by volume of irrigation applied in a 34.0 minute (3.0 cm) irrigation event.

[y] NS = not significant at $P > 0.05$.

Table 79: Effects of drain spacing and topdressing depth on surface runoff, East Lansing, Mich. (data collected in 2007).

Drain Spacing (m)	2008 Mean Surface Runoff (v/v)[z]
control[y x]	20.8 a[w]
6.0	6.4 c
4.0	13.1 b
3.0	6.3 c
2.0	2.2 d
Topdressing Depth (cm)[v]	**2008 Mean Surface Runoff (v/v)**
2.4	10.7
3.6	8.7
4.8	9.9
	ns[u]

[z] Volume (L) of surface runoff divided by volume of irrigation applied in a 34.0 minute (3.0 cm) irrigation event.

[y] Control = 8.1 m long treatment, equivalent to the distance from the crown of a field to the hash makers, without drain tiles.

[x] Number of replications for all treatments = 3.

[w] Means in a given column with the same letter do not differ using Fisher's least significant difference at $P = 0.05$.

[v] cm of topdressing sand accumulated over a one month period, July 26 – Aug. 22, 2008.

[u] ns = not significant at $P = 0.05$.

DRAINAGE CHARACTERISTC DISCUSSION

From 2007 to 2008 subsoil drainage increased over two fold, from 1.1 to 2.4 (v/v). Similar to these findings, Arshad et al. (1999) observed a correlation between improved aggregation and water infiltration when soil was undisturbed as a result of continuous no-tillage cropping. Li et al. (2007) also observed consistent reductions in surface runoff and increases in rainfall infiltration as a result of continuous no-tillage cropping over a 6-year period, likely the result of soil aggregation.

Substantial increases in subsoil drainage were observed when drain tiles were spaced up to 4.0 m apart in comparison to the control, and 6.0 m drain spacing. Benefits of aggregation within the control and 6.0 m drain spacing treatment may have been negated by soil compaction due to increased subsoil moisture content levels during the fall traffic period (Mouazen et al., 2002; Rollins et al., 1998; Zhang et al., 2001), which were observed within these treatments throughout the experiment. However, research conducted by Adekalu et al. (2001) determined that the optimum volumetric moisture content necessary to obtain the maximum dry density of a sandy loam soil was 24.0%, which would suggest that all treatments regardless of drain tile spacing were wetter than the optimum moisture content. Lambe (1958) determined that as soil is compacted at moisture content levels progressively greater than the optimum moisture content hydraulic conductivity will continually increase. Therefore, findings by Adekalu et al. (2001) and Lambe (1958) would suggest that the control and 6.0 m drain spacing treatments should produce the greatest subsoil drainage rates.

A negative correlation between sand topdressing depth and subsoil drainage was observed as topdressing was accumulated from 2.4 to 4.8 cm. As sand topdressing was accumulated over time, preferential flow pathways, the result of core cultivation and soil aggregation, were likely filled with sand reducing subsoil drainage rates over time. McCarty et al. (2005) observed substantially greater infiltration rates, 58% greater after the first year of cultivation and 188% greater after the second year of cultivation in comparison to the control, as a result of repeated hollow tine core cultivation of creeping bentgrass throughout the growing season. This suggests that spring core cultivation may have been the factor initially responsible for improving subsoil drainage, but as cumulative sand topdressing applications filled cultivation holes and organic matter accumulation developed subsoil drainage diminished over time.

Drain tiles spacing up to 6.0 m apart substantially reduced the amount of surface runoff across a sloped surface. Minimizing surface runoff will not only prevent saturated soil conditions and standing water from accumulating along athletic field sidelines, but it will also reduce off-site movement of nutrients and pesticides that may otherwise be environmentally harmful (Moss et al., 2007). Conversely, Magni et al. (2004) observed a substantial increase in water infiltration rates, which directly correlates to decreased runoff, only when closely spaced intercept drain tiles, spaced 2.5 m apart, and perpendicular sand slits, spaced 1.0 m apart, were used to improve the drainage characteristics of an un-drained native soil.

Topdressing with a well-graded 90/10 sand-based material increased surface runoff throughout the duration of this experiment. This is likely the direct effect of decreased K_{sat} over intercept drain lines as a result of topdressing applications with a 90/10 sand-based material over a coarse sand (98.0% sand – 2.0% silt/clay) material, which was also an observed response in this experiment. In support of these statements, laboratory findings determined that the coarse sand material placed within the intercept drain lines provided a K_{sat} rate of 117.5 cm hr^{-1} (Table 26), similar to K_{sat} results obtain in the field prior to topdressing applications, while the 90/10 sand-based material produced a K_{sat} rate of 15.4 cm hr^{-1} (Table 27). Similar to these findings, Henderson et al. (2005) determined that a sand/soil mixture containing 2.0% silt/clay, similar to the coarse sand material used in this research, will provide a K_{sat} rate greater than 85.0 cm hr^{-1} when compacted at a 5.0% moisture content, while a mixture containing 10.0% sand/slit, will produce a K_{sat} rate of 19.0 cm hr^{-1} when compacted at the same moisture content.

Drain tile spacing up to 4.0 m apart decreased the overall surface moisture contents in comparison to the 6.0 m drain spacing and the control throughout the 2007 data collection period as topdressing depths were built-up from 0.0 to 2.4 cm. These findings confirm current USGA putting green construction recommendations that drain tile spacing should not exceed 4.6 m (USGA Green Section Staff, 2004). However, ASTM International guidelines for sports field construction suggest drain spacing as far as 6.0 m apart, which according to this research may not be sufficient for maintaining a relatively dry playing surface (ASTM, 2004). Secondly, topdressing depth as shallow as 1.2 cm substantially decreased the overall surface moisture content throughout the 2007 data collected period. These findings are not at all surprising when infiltration rates and field capacity of sand in comparison to native soil is taken into consideration (Rawls et al., 1982; Saxton et al., 1986). It is also important to note that Rogers and Waddington (1989) observed a correlation between increased surface hardness and decreased soil water content, suggesting that a topdressing depth as little as 1.2 cm may improve surface stability. Finally, as topdressing depths increased over a 2 year period, moisture levels continued to decrease, with the 3.6 cm topdressing depth and 2.0 m drain spacing providing the lowest surface moisture contents. Slight increases in surface moisture content observed as topdressing depths increased from 3.6 to 4.8 cm were likely the result of sampling error. It is also important to note that Lunt (1956) determined that a 10.2 cm layer of sand was necessary to prevent the compaction of an underlying moist clay loam soil.

Drain tiles spacing 2.0 and 3.0 m apart produced the lowest overall subsoil moisture content throughout the entire experimental period. However, because drain tiles spaced 4.0 m apart provided surface moisture levels comparable to the 2.0 and 3.0 m spacing and substantially decreased surface runoff this spacing may provide the best cost effective results. Increasing drain tile spacing to 4.0 m apart will not only reduce the cost of drain tile installation, but, as subsoil moisture data has shown, it will increase the plant available water within the rhizosphere. Increased plant available water within the rhizosphere will allow field managers to reduce irrigation requirements, which is of particular interest as water resources become limited (Emekli et al., 2007; Sass and Horgan, 2006). Richie et al. (2002) observed a direct correlation between increased tall fescue (*Festuca arundinacea* Schreb.), visual quality and soil water content observed at a 30.0, 61.0 and 91.0 cm depth, suggesting that increased drain tile spacing may help to conserve water usage while maintaining adequate plant available soil water.

WEAR TOLERANCE AND SURFACE STABILITY RESULTS

Collected After the Accumulation of 2.4 cm of Sand Topdressing (2007)

Main effects of drain spacing on the fall ground cover of a spring established Kentucky bluegrass – perennial ryegrass mixture after the accumulation of a 2.4 cm topdressing depth were observed (Table 80). Differences between drain spacing were observed following 4, 6 and 8 fall traffic simulator applications. When differences were observed throughout the fall data collection period, the 2.0 m drain spacing yielded the greatest overall mean turfgrass cover, followed by the 3.0 and 4.0 m spacing, then the 6.0 m spacing and finally the control, an 8.1 m treatment without drain tiles (Table 81). These findings suggest an inverse correlation between drain tile spacing and living ground cover.

Effects of drain spacing on turfgrass shoot density were insignificant throughout the entirety of the fall data collection period (Table 82 and 83).

Main effects of drain spacing on shear vane strength were observed following 8 and 10 fall traffic simulator applications (Table 84). When these differences were observed, the 2.0, 3.0 and 4.0 m drain tile spacing produced the greatest overall mean shear vane strength, followed by the 6.0 m spacing, and finally the control (Table 85). These findings suggest that as the fall athletic season progresses, a field with drain tiles spaced every 4.0 m apart will provide improved surface shear strength equivalent to a field with drains spaced every 2.0 m apart.

Main effects of drain spacing on TST strength were noted at the conclusion of the fall data collection period only (Table 86). Similar to shear vane results, the 2.0, 3.0 and 4.0 m drain spacing produced TST strength ranking in the highest category in comparison

Table 80: Analysis of variance results for cover[z] ratings collected after fall traffic simulator applications[y], East Lansing, Mich. (data collected in 2007 - 2.4 cm topdressing depth).

			Fall Traffic Applications[x]					
	Num.	Den.	0	2	4	6	8	10
Source of Variation	df	df			*P*>F			
Drain Spacing	4.0	8.0	NS[w]	NS	0.0037	0.0286	0.0007	NS

[z] Living ground cover, 0.0 – 100.0% percent.

[y] Traffic applications were applied using the Cady Traffic Simulator

[x] Data collected after 0, 2, 4, 6 , 8, and 10 fall traffic simulator applications, observed on Oct. 10, 12, 19, 26, Nov. 2, and 10, 2007, respectively.

[w] NS = not significant at $P > 0.05$.

Table 81: Effects of drain spacing on turfgrass cover following fall traffic simulator applications, East Lansing, Mich. (data collected in 2007 - 2.4 cm topdressing depth).

	Fall Traffic Applications[z]					
	0	2	4	6	8	10
Drain Spacing (m)	2007 Mean Cover (0-100%)[y]					
2.0[x]	100.0	95.0	77.5 a[w]	83.3 a	45.0 a	26.7
3.0	100.0	95.0	80.0 a	73.3 abc	38.3 bc	23.3
4.0	100.0	95.0	70.0 bc	76.7 ab	43.3 ab	23.3
6.0	100.0	91.7	75.0 ab	71.7 bc	35.0 c	21.7
control[v]	100.0	93.3	65.0 c	63.3 c	26.7 d	20.0
	ns[u]	ns				ns

[z] Data collected after 0, 2, 4, 6, 8, and 10 fall traffic simulator applications, observed on Oct. 10, 12, 19, 26, Nov. 2, and 10, 2007, respectively, applied using the Cady Traffic Simulator.

[y] Living ground cover, 0.0 – 100.0%.

[x] Number of replications for all treatments = 3.

[w] Means in a given column with the same letter do not differ using Fisher's least significant difference at $P = 0.05$.

[v] Control = 8.1 m long treatment, equivalent to the distance from the crown of a field to the hash makers, without drain tiles.

[u] ns = not significant at $P = 0.05$

Table 82: Analysis of variance results for shoot density[z] collected after fall traffic simulator applications[y], East Lansing, Mich. (data collected in 2007 - 2.4 cm topdressing depth).

			Fall Traffic Applications[x]					
	Num.	Den.	0	2	4	6	8	10
Source of Variation	df	df	P>F					
Drain Spacing	4.0	8.0	NS[w]	NS	NS	NS	NS	NS

[z] Turfgrass shoots•cm^{-2}.

[y] Traffic applications were applied using the Cady Traffic Simulator.

[x] Data collected after 0, 2, 4, 6 , 8, and 10 fall traffic simulator applications, observed on Oct. 10, 12, 19, 26, Nov. 2, and 10, 2007, respectively.

[w] NS = not significant at $P > 0.05$.

Table 83: Effects of drain spacing on turfgrass shoot density following fall traffic simulator applications, East Lansing, Mich. (data collected in 2007 - 2.4 cm topdressing depth).

	Fall Traffic Applications[z]					
	0	2	4	6	8	10
Drain Spacing (m)	2007 Mean Shoot Density[y]					
2.0[x]	12.8[w]	4.5[w]	7.5[w]	4.7[w]	5.8[w]	17.7[v]
3.0	12.3	8.7	7.0	5.2	3.5	16.0
4.0	14.3	7.0	4.7	6.7	4.3	21.0
6.0	13.5	9.2	6.5	4.7	2.8	16.1
control[u]	11.7	5.3	8.8	4.3	3.8	12.3
	ns[t]	ns	ns	ns	ns	ns

[z] Data collected after 0, 2, 4, 6, 8, and 10 fall traffic simulator applications, observed on Oct. 10, 12, 19, 26, Nov. 2, and 10, 2007, respectively, applied using the Cady Traffic Simulator.

[y] Turfgrass shoots•cm^{-2}.

[x] Number of replications for all treatments = 3

[w] Shoots•8.0 cm^{-2}.

[v] Shoots•86.6 cm^{-2}.

[u] Control = 8.1 m long treatment, equivalent to the distance from the crown of a field to the hash makers, without drain tiles.

[t] ns = not significant at $P = 0.05$

Table 84: Analysis of variance results for Eijkelkamp shear vane strength[z] collected after fall traffic simulator applications[y], East Lansing, Mich. (data collected in 2007 - 2.4 cm topdressing depth).

	Num.	Den.	Fall Traffic Applications[x]					
			0	2	4	6	8	10
Source of Variation	df	df	*P*>F					
Drain Spacing	4.0	8.0	NS[w]	NS	NS	NS	0.0031	0.0008

[z] Eijkelkamp shear vane strength = Newton meters.

[y] Traffic applications were applied using the Cady Traffic Simulator.

[x] Data collected after 0, 2, 4, 6 , 8, and 10 fall traffic simulator applications, observed on Oct. 10, 12, 19, 26, Nov. 2, and 10, 2007, respectively,

[w] NS = not significant at $P > 0.05$.

Table 85: Effects of drain spacing on Eijkelkamp shear vane strength following fall traffic simulator applications, East Lansing, Mich. (data collected in 2007 - 2.4 cm topdressing depth).

	Fall Traffic Applications[z]																	
	0	2	4	6	8		10	
Drain Spacing (m)	2007 Mean Shear Vane Strength (Nm)[y]							
2.0[x]	10.7	8.2	9.2	8.8	9.0	a[w]	8.0	a
3.0	10.7	9.7	9.7	7.8	8.3	ab	7.6	a
4.0	11.7	7.7	9.5	8.0	8.8	a	8.6	a
6.0	13.0	9.2	9.0	7.5	6.8	b	6.3	b
control[v]	11.0	10.8	9.5	6.8	4.9	c	4.8	c
	ns[u]	ns	ns	ns				

[z] Data collected after 0, 2, 4, 6, 8, and 10 fall traffic simulator applications, observed on Oct. 10, 12, 19, 26, Nov. 2, and 10, 2007, respectively, applied using the Cady Traffic Simulator.

[y] Eijkelkamp shear vane strength = Newton meters (Nm).

[x] Number of replications for all treatments = 3.

[w] Means in a given column with the same letter do not differ using Fisher's least significant difference at $P = 0.05$.

[v] Control = 8.1 m long treatment, equivalent to the distance from the crown of a field to the hash makers, without drain tiles.

[u] ns = not significant at $P = 0.05$

Table 86: Analysis of variance results for Clegg turf shear tester strength[z] collected after fall traffic simulator applications[y], East Lansing, Mich. (data collected in 2007 - 2.4 cm topdressing depth).

			Fall Traffic Applications[x]					
	Num.	Den.	0	2	4	6	8	10
Source of Variation	df	df			P>F			
Drain Spacing	4.0	8.0	NS[w]	NS	NS	NS	NS	0.0302

[z] Clegg turf shear tester strength = Newton meters.
[y] Traffic applications were applied using the Cady Traffic Simulator.
[x] Data collected after 0, 2, 4, 6 , 8, and 10 fall traffic simulator applications, observed on Oct. 10, 12, 19, 26, Nov. 2, and 10, 2007, respectively.
[w] NS = not significant at $P > 0.05$.

to the other drain spacing levels (Table 87). These findings support earlier statements that drain tiles spaced every 4.0 m apart and 2.4 cm of sand topdressing will increase the surface stability of an athletic field in comparison to a field without drain tiles or sand topdressing.

Significant main effects of drain spacing on surface hardness were observed following 8 fall traffic applications only (Table 88). On this occasion the 2.0 and 3.0 m drain spacing produced mean surface hardness values ranking in the greatest category in comparison to the other drain spacing levels (Table 89).

Significant main effects of soil sampling depth on rooting density collected at the conclusion of the fall traffic period were observed, while differences between drain spacing were not statistically significant (Table 90). The 0.0 to 3.8 cm soil sampling depth yielded greater mean rooting density than the 3.8 to 7.6 sampling depth (Table 91).

Collected After the Accumulation of 4.8 cm of Sand Topdressing (2008)

The effects of drain spacing on the fall ground cover of a Kentucky bluegrass – perennial ryegrass mixture after the accumulation of 4.8 cm of topdressing sand were not statistically significant (Table 92 and 93).

Main effects of drain spacing on turfgrass shoot density were observed after 10 fall traffic simulator applications only (Table 94). In this instance the 6.0 m drain spacing yielded the greatest mean shoot density, while the 2.0, 3.0 and 4.0 m spacing provided the lowest shoot density (Table 95).

Effects of drain spacing on shear vane strength were insignificant throughout the entirety of the fall data collection period (Table 96 and 97).

Table 87: Effects of drain spacing on Clegg turf shear tester strength following fall traffic simulator applications, East Lansing, Mich. (data collected in 2007 - 2.4 cm topdressing depth).

	Fall Traffic Applications[z]					
	0	2	4	6	8	10
Drain Spacing (m)	2007 Mean Turf Shear Tester Strength (Nm)[y]					
2.0[x]	80.1	70.3	83.7	60.1	79.1	81.3 ab[w]
3.0	86.0	77.5	95.9	65.0	77.0	71.7 abc
4.0	88.7	63.4	86.0	70.6	90.5	82.9 a
6.0	82.7	64.7	99.8	55.8	82.7	68.8 bc
control[v]	91.9	62.1	102.1	54.5	60.7	60.6 c
	ns[u]	ns	ns	ns	ns	

[z] Data collected after 0, 2, 4, 6, 8, and 10 fall traffic simulator applications, observed on Oct. 10, 12, 19, 26, Nov. 2, and 10, 2007, respectively, applied using the Cady Traffic Simulator.

[y] Clegg turf shear tester strength = Newton meters (Nm).

[x] Number of replications for all treatments = 3.

[w] Means in a given column with the same letter do not differ using Fisher's least significant difference at $P = 0.05$.

[v] Control = 8.1 m long treatment, equivalent to the distance from the crown of a field to the hash makers, without drain tiles.

[u] ns = not significant at $P = 0.05$.

Table 88: Analysis of variance results for surface hardness[z] collected after fall traffic simulator applications[y], East Lansing, Mich. (data collected in 2007 - 2.4 cm topdressing depth).

			Fall Traffic Applications[x]			
	Num.	Den.	4	6	8	10
Source of Variation	df	df		P>F		
Drain Spacing	4.0	8.0	NS[w]	NS	0.0070	NS

[z] Surface hardness (G_{max}) = ratio of maximum negative acceleration on impact to gravitational acceleration collected using the Clegg Impact Tester.

[y] Traffic applications were applied using the Cady Traffic Simulator.

[x] Data collected after 4, 6 , 8, and 10 traffic simulator applications, observed on Oct. 19, 26, Nov. 2, and 10, 2007, respectively.

[w] NS = not significant at $P > 0.05$.

Table 89: Effects drain spacing on surface hardness following fall traffic simulator applications, East Lansing, Mich. (data collected in 2007 - 2.4 cm topdressing depth).

	Fall Traffic Applications[z]			
	4	6	8	10
Drain Spacing (m)	2007 Mean Surface Hardness (G_{max})[y]			
2.0[x]	60.8	62.5	69.1 a[w]	81.0
3.0	63.3	59.3	66.6 ab	75.4
4.0	63.3	52.7	63.4 b	77.4
6.0	64.0	58.0	63.4 b	79.4
control[v]	64.0	58.3	56.6 c	78.4
	ns[u]	ns		ns

[z] Data collected after 4, 6, 8, and 10 fall traffic simulator applications, observed on Oct. 19, 26, Nov. 2, and 10, 2007, respectively, applied using the Cady Traffic Simulator.

[y] Surface hardness (G_{max}) = ratio of maximum negative acceleration on impact to gravitational acceleration collected using the Clegg Impact Tester.

[x] Number of replications for all treatments = 3.

[w] Means in a given column with the same letter do not differ using Fisher's least significant difference at P = 0.05.

[v] Control = 8.1 m long treatment, equivalent to the distance from the crown of a field to the hash makers.

[u] ns = not significant at P = 0.05

Table 90: Analysis of variance results for rooting density[z] collected after ten fall traffic simulator applications[y], collected Nov. 10, 2007, East Lansing, Mich. (2.4 cm topdressing depth).

Source of Variation	Num. df	Den. df	*P*>F
Drain Spacing (DS)	3.0	1.0	NS[x]
Soil Sampling Depth (SSD)	1.0	8.4	0.0003
DS X SSD	4.0	3.2	NS

[z] Dry root weight (g•122.5 cm^{-3}).

[y] Traffic applications were applied using the Cady Traffic Simulator.

[x] NS = not significant at $P > 0.05$.

Table 91: Effects of drain spacing and soil sampling depth on rooting density following ten fall traffic simulator applications collected Nov. 10, 2007, East Lansing, Mich. (2.4 cm topdressing depth).

Drain Spacing (m)	2007 Mean Root Density ($g \cdot 122.5\ cm^{-3}$)
2.0[z]	0.3
3.0	0.3
4.0	0.4
6.0	0.3
control[y]	0.5
	ns[x]
Sampling Depth (cm)	**2007 Mean Root Density ($g \cdot 122.5\ cm^{-3}$)**
0.0-3.8	0.5 a[w]
3.8-7.6	0.2 b

[z] Number of replications for all treatments = 3.

[y] NS = not significant at $P > 0.05$

[x] Control = 8.1 m long treatment, equivalent to the distance from the crown of a field to the hash makers, without drain tiles.

[w] Means in a given column with the same letter do not differ using Fisher's least significant difference at $P = 0.05$.

Table 92: Analysis of variance results for cover[z] ratings collected after fall traffic simulator applications[y], East Lansing, Mich. (data collected in 2008 - 4.8 cm topdressing depth).

			Fall Traffic Applications[x]					
	Num.	Den.	0	2	4	6	8	10
Source of Variation	df	df			*P*>F			
Drain Spacing	4.0	8.0	NS[w]	NS	NS	NS	NS	NS

[z] Living ground cover, 0.0 – 100.0% percent.

[y] Traffic applications were applied using the Cady Traffic Simulator.

[x] Data collected after 0, 2, 4, 6 , 8, and 10 fall traffic simulator applications, observed on Oct. 13, 17, 24, 31, Nov. 7, and 14, 2008, respectively.

[w] NS = not significant at $P > 0.05$.

Table 93: Effects of drain spacing on turfgrass cover following fall traffic simulator applications, East Lansing, Mich. (data collected in 2008 - 4.8 cm topdressing depth).

	Fall Traffic Applications[z]					
	0	2	4	6	8	10
Drain Spacing (m)	2008 Mean Cover (0-100%)[y]					
2.0[x]	100.0	95.0	90.0	78.3	73.3	66.7
3.0	100.0	95.0	90.0	78.3	73.3	71.7
4.0	100.0	95.0	90.0	78.3	73.3	73.3
6.0	100.0	95.0	88.3	75.0	76.7	73.3
control[w]	100.0	95.0	86.7	75.0	73.3	70.0
	ns[v]	ns	ns	ns	ns	ns

[z] Data collected after 0, 2, 4, 6 , 8, and 10 fall traffic simulator applications, observed on Oct. 13, 17, 24, 31, Nov. 7, and 14, 2008, respectively, applied using the Cady Traffic Simulator.

[y] Living ground cover rating, 0.0 – 100.0%.

[x] Number of replications for all treatments = 3.

[w] Control = 8.1 m long treatment, equivalent to the distance from the crown of a field to the hash makers.

[v] ns = not significant at $P = 0.05$.

Table 94: Analysis of variance results for shoot density[z] collected after fall traffic simulator applications[y], East Lansing, Mich. (data collected in 2008 - 4.8 cm topdressing depth).

			Fall Traffic Applications[x]					
	Num.	Den.	0	2	4	6	8	10
Source of Variation	df	df			*P*>F			
Drain Tile Spacing	4.0	8.0	NS[w]	NS	NS	NS	NS	0.0290

[z] Turfgrass shoots•cm^{-2}.

[y] Traffic applications were applied using the Cady Traffic Simulator.

[x] Data collected after 0, 2, 4, 6 , 8, and 10 fall traffic simulator applications, observed on Oct. 13, 17, 24, 31, Nov. 7, and 14, 2008, respectively.

[w] NS = not significant at $P > 0.05$.

Table 95: Effects of drain spacing on turfgrass shoot density following fall traffic simulator applications, East Lansing, Mich. (data collected in 2008 - 4.8 cm topdressing depth).

	Fall Traffic Applications[z]					
	0	2	4	6	8	10
Drain Tile Spacing (m)	2008 Mean Shoot Density[y]					
2.0[x]	12.5[w] a[v]	13.5[w]	9.0[w]	12.2[w]	9.0[w]	63.3[u] b
3.0	9.2 a	10.3	9.2	8.5	10.7	60.5 b
4.0	13.5 a	13.0	8.7	11.8	11.0	66.4 b
6.0	12.7 a	12.7	7.5	11.3	7.2	82.6 a
control[t]	9.2 a	13.5	12.5	10.2	6.7	71.5 ab
		ns[s]	ns	ns	ns	

[z] Data collected after 0, 2, 4, 6, 8, and 10 fall traffic simulator applications, observed on Oct. 13, 17, 24, 31, Nov. 7, and 14, 2008, respectively, applied using the Cady Traffic Simulator.

[y] Turfgrass shoots•cm^{-2}.

[x] Number of replications for all treatments = 3

[w] Shoots•8.04cm^{-2}.

[v] Means in a given column with the same letter do not differ using Fisher's least significant difference at $P = 0.05$.

[u] Shoots 86.6•cm^{-2}.

[t] Control = 8.1 m long treatment, equivalent to the distance from the crown of a field to the hash makers, without drain tiles.

[s] ns = not significant at $P = 0.05$.

Table 96: Analysis of variance results for Eijkelkamp shear vane strength[z] collected after fall traffic simulator applications[y], East Lansing, Mich. (data collected in 2008 - 4.8 cm topdressing depth).

			Fall Traffic Applications[x]					
	Num.	Den.	0	2	4	6	8	10
Source of Variation	df	df			*P*>F			
Drain Tile Spacing	4.0	8.0	NS[w]	NS	NS	NS	NS	NS

[z] Eijkelkamp shear vane strength = Newton meters.

[y] Traffic applications were applied using the Cady Traffic Simulator.

[x] Data collected after 0, 2, 4, 6 , 8, and 10 fall traffic simulator applications, observed on Oct. 13, 17, 24, 31, Nov. 7, and 14, 2008, respectively,

[w] NS = not significant at $P > 0.05$.

Table 97: Effects of drain spacing on Eijkelkamp shear vane strength following fall traffic simulator applications, East Lansing, Mich. (data collected in 2008 - 4.8 cm topdressing depth).

	Fall Traffic Applications[z]					
	0	2	4	6	8	10
Drain Tile Spacing (m)	2008 Mean Shear Vane Strength (Nm)[y]					
2.0[x]	13.6	12.2	10.8	9.3	8.9	7.5
3.0	14.1	11.3	9.7	9.3	7.9	8.5
4.0	14.4	12.2	10.7	9.8	7.4	9.6
6.0	13.9	12.4	11.0	10.2	8.1	8.9
control[w]	13.9	11.9	10.3	9.9	7.0	9.4
	ns[v]	ns	ns	ns	ns	ns

[z] Data collected after 0, 2, 4, 6, 8, and 10 fall traffic simulator applications, observed on Oct. 13, 17, 24, 31, Nov. 7, and 14, 2008, respectively, applied using the Cady Traffic Simulator.

[y] Eijkelkamp shear vane strength = Newton meters (Nm).

[x] Number of replications for all treatments = 3.

[w] Control = 8.1 m long treatment, equivalent to the distance from the crown of a field to the hash makers, without drain tiles.

[v] ns = not significant at $P = 0.05$.

Main effects of drain spacing on TST strength were observed on one occasion only, prior to the initiation of fall traffic (Table 98). In this instance the 3.0, 4.0 and 6.0 m drain spacing and control treatment produced the greatest turf shear tester strength, while the 2.0 m drain spacing provided the lowest TST (Table 99).

Effects of drain spacing on surface hardness were not significant throughout the entire data collection period (Table 100 and 101).

Main effects of soil sampling depth on rooting density were significant, while differences between drain spacing levels were not significant (Table 102). Similar to rooting density results observed in the previous year, the 0.0 to 3.8 cm soil sampling depth yielded greater mean rooting density than samples collected from the 3.8 to 7.6 cm depth (Table 103).

Table 98: Analysis of variance results for Clegg turf shear tester strength[z] collected after fall traffic simulator applications[y], East Lansing, Mich. (data collected in 2008 - 4.8 cm topdressing depth).

			Fall Traffic Applications[x]					
	Num.	Den.	0	2	4	6	8	10
Source of Variation	df	df	P>F					
Drain Tile Spacing	4.0	8.0	0.0369	NS[w]	NS	NS	NS	NS

[z] Clegg turf shear tester strength = Newton meters.

[y] Traffic applications were applied using the Cady Traffic Simulator.

[x] Data collected after 0, 2, 4, 6 , 8, and 10 fall traffic simulator applications, observed on Oct. 13, 17, 24, 31, Nov. 7, and 14, 2008, respectively.

[w] NS = not significant at $P > 0.05$.

Table 99: Effects of drain spacing on Clegg turf shear tester strength following fall traffic simulator applications, East Lansing, Mich. (data collected in 2008 - 4.8 cm topdressing depth).

	Fall Traffic Applications[z]						
	0		2	4	6	8	10
Drain Tile Spacing (m)	2008 Mean Turf Shear Tester Strength (Nm)[y]						
2.0[x]	88.2	b[w]	99.9	67.5	116.7	137.2	105.4
3.0	105.9	a	96.9	77.0	120.2	110.5	111.3
4.0	115.4	a	118.5	74.5	134.3	121.0	117.2
6.0	107.7	a	95.1	74.2	109.8	114.1	125.8
control[v]	115.1	a	101.5	73.2	121.7	120.0	111.6
			ns[u]	ns	ns	ns	ns

[z] Data collected after 0, 2, 4, 6, 8, and 10 fall traffic simulator applications, observed on Oct. 13, 17, 24, 31, Nov. 7, and 14, 2008, respectively, applied using the Cady Traffic Simulator.

[y] Clegg turf shear tester strength = Newton meters (Nm).

[x] Number of replications for all treatments = 3.

[w] Means in a given column with the same letter do not differ using Fisher's least significant difference at $P = 0.05$.

[v] Control = 8.1 m long treatment, equivalent to the distance from the crown of a field to the hash makers, without drain tiles.

[u] ns = not significant at $P = 0.05$.

Table 100: Analysis of variance results for surface hardness[z] collected after fall traffic simulator applications[y], East Lansing, Mich. (data collected in 2008 - 4.8 cm topdressing depth).

			Fall Traffic Applications[x]					
	Num.	Den.	0	2	4	6	8	10
Source of Variation	df	df			P>F			
Drain Spacing	4.0	8.0	NS[w]	NS	NS	NS	NS	NS

[z] Surface hardness (G_{max}) = ratio of maximum negative acceleration on impact to gravitational acceleration collected using a Clegg Impact Tester.
[y] Traffic applications were applied using the Cady Traffic Simulator.
[x] Data collected after 0, 2, 4, 6 , 8, and 10 fall traffic simulator applications, observed on Oct. 13, 17, 24, 31, Nov. 7, and 14, 2008, respectively.
[w] NS = not significant at $P > 0.05$.

Table 101: Effects drain spacing on surface hardness following fall traffic simulator applications, East Lansing, Mich. (data collected in 2008 - 4.8 cm topdressing depth).

	Fall Traffic Applications[z]					
	0	2	4	6	8	10
Drain Tile Spacing (m)	2008 Mean Surface Hardness (G_{max})[y]					
2.0[x]	64.9	55.0	53.1	67.4	65.3	59.4
3.0	65.2	54.0	53.7	65.1	62.9	59.3
4.0	63.2	51.0	50.9	61.2	66.9	58.7
6.0	64.3	53.5	50.1	61.8	65.6	60.2
control[w]	62.6	54.1	48.5	62.0	67.0	61.0
	ns[v]	ns	ns	ns	ns	ns

[z] Data collected after 0, 2, 4, 6, 8, and 10 fall traffic simulator applications, observed on Oct. 13, 17, 24, 31, Nov. 7, and 14, 2008, applied using the Cady Traffic Simulator.

[y] Surface hardness (G_{max}) = ratio of maximum negative acceleration on impact to gravitational acceleration collected using a Clegg Impact Tester.

[x] Number of replications for all treatments = 3.

[w] ns = not significant at $P = 0.05$.

[v] Control = 8.1 m long treatment, equivalent to the distance from the crown of a field to the hash makers, without drain tiles.

Table 102: Analysis of variance results for rooting density[z] collected after ten fall traffic simulator applications[y], collected Nov. 14, 2008, East Lansing, Mich. (4.8 cm topdressing depth).

Source of Variation	Num. df	Den. df	*P*>F
Drain Spacing (DS)	4.0	10.0	NS[x]
Soil Sampling Depth (SSD)	1.0	10.0	<0.0001
DS X SSD	4.0	10.0	NS

[z] Dry root weight (g•122.5 cm^{-3}).

[y] Traffic applications were applied using the Cady Traffic Simulator.

[x] NS = not significant at $P > 0.05$.

Table 103: Effects of drain spacing and soil sampling depth on rooting density following ten fall traffic simulator applications collected Nov. 14, 2008, East Lansing, Mich. (4.8 cm topdressing depth).

Drain Spacing (m)	2008 Mean Root Density ($g \cdot 122.5\ cm^{-3}$)
2.0[z]	1.1
3.0	0.9
4.0	0.8
6.0	1.0
control[y]	0.7
	ns[x]
Sampling Depth (cm)	**2008 Mean Root Density ($g \cdot 122.5\ cm^{-3}$)**
0.0-3.8	1.3 a[w]
3.8-7.6	0.5 b

[z] Number of replications for all treatments = 3.

[y] ns = not significant at $P = 0.05$.

[x] Control = 8.1 m long treatment, equivalent to the distance from the crown of a field to the hash makers, without drain tiles.

[w] Means in a given column with the same letter do not differ using Fisher's least significant difference at $P = 0.05$.

WEAR TOLERANCE AND SURFACE STABILITY DISCUSSION

After 2.4 cm of topdressing had been accumulated in 2007, the 2.0 m drain spacing yielded the greatest turfgrass cover, while the 6.0 m and control treatment produced the worst cover. Magni et al. (2004) observed increased tall fescue and perennial ryegrass ground cover after traffic was applied using the Brinkman traffic simulator when drain tiles were installed in native soil. This research also observed increased tall fescue ground cover as drain tile spacing was reduced from 5.0 to 2.5 m and perpendicular sand slit drains were incorporated. This work also observed increased water infiltration rates and surface traction as a result of drain tile installation. In 2008 after 4.8 cm of topdressing had been accumulated no differences between drain spacing were observed.

In 2007, drain spacing 2.0, 3.0 and 4.0 m apart produced the greatest overall shear vane strength and turf shear tester strength in comparison to the control and 6.0 m drain spacing. Magni et al. (2004) not only observed increased shear strength as a result of drain tile installation into a native soil, but also observed increasing shear strength as drain spacing was reduced from 5.0 to 2.5 m. These findings confirm USGA putting green construction recommendations that drain tile spacing should not exceed 4.6 m (USGA Green Section Staff, 2004). It is important to note that not only did drain spacing 2.0, 3.0 and 4.0 m apart improve turfgrass cover, and shear (shear vane and TST) strength, but also reduced surface moisture content. Kladivko et al. (2005) observed a direct correlation between increased drain tile spacing and decreased corn (*Zea mays* L.) yield, which was attributed to planting date delays because of wet surface conditions or reduced stability.

Conversely, on only one instance were differences observed in 2008, with the 2.0 m drain spacing providing the worst turf shear tester strength in comparison to the other treatment levels. These findings suggest that as topdressing depth is increased from 2.4 to 4.8 cm the effects of drain tile spacing on surface shear strength are diminished substantially. This suggests that if an adequate sand layer has been accumulated over time, the ASTM International guidelines for sports field construction, which suggest drain spacing as far as 6.0 m apart, may be appropriate (ASTM, 2004).

On one occasion only in 2007 were differences in surface hardness observed. The 2.0 and 3.0 m drain spacing produced the greatest surface hardness, while the control produced the lowest surface hardness. Rogers and Waddington (1990) noted a correlation between increasing surface hardness and decreasing soil water content. Therefore, the findings observed in this research were likely the effects of decreased surface moisture as a result of decreased drain tile spacing.

Differences in rooting density were observed in 2007 and again in 2008, with the 0.0 – 3.8 cm sampling depth yielding the greatest rooting density. While researching the effects of irrigation frequency on creeping bentgrass (*Agrostis palustris* Huds.) rooting characteristics, shoot density and overall plant health/quality, Jordan et al. (2003) also observed decreased creeping bentgrass rooting density as sampling depth increased. Differences in drain tile spacing did not affect rooting density, suggesting that the differences in surface and subsoil moisture content as a result of drain tile spacing observed in this research were not great enough to affect rooting density. Contrary to these findings, Jordan et al. (2003) determined that irrigation applied once every 4 days, which would decrease the average moisture content of the soil, increased turf quality, shoot density and root length of creeping bentgrass, regardless of cultivar, in comparison to irrigation applied daily or every other day. Conversely, Huang and Fry (1998) observed increased specific root length, root/shoot ratio and root hair development, but a reduction in overall root dry weight as a result of drought-stress condition in comparison to well-watered conditions.

Similar to findings observed in chapter 2, living ground cover, shoot density and TST strength observed throughout the 2008 data collection period were substantially greater than those observed in the 2007 collection period, while surface hardness decreased from 2007 to 2008. These results, similar to other findings, suggest that overall turfgrass health, vigor, and strength will increase with turfgrass stand maturation (Murphy et al., 2003; Kowalewski et al., 2008), and surface hardness will decrease because the well established turfgrass is absorbing the impact (Rogers and Waddington, 1989). For instance, results collected in 2008 determined that all treatments, regardless of drain tile spacing, provided shear vane strength greater than 10 Nm, a shear vane strength considered acceptable for sand-based sports turf system (Stier et al., 1999), until the accumulation of six fall traffic simulator applications. Suggesting that a field with a mature turfgrass stand and a 4.8 cm of topdressing accumulated over a 2-year period will provide acceptable shear vane strength within the hash mark for up to 20 football games (Cockerham and Brinkman, 1989; Vanini et al., 2007).

CONCLUSIONS

Results obtained from this research suggest that as little as 1.2 cm of sand topdressing can substantially reduce the surface moisture content of a native soil athletic field, implying that this cultural practice alone could improve the surface characteristics of a native soil athletic field.

As topdressing was being accumulated from a 0.0 to a 2.4 cm depth in 2007, the 2.0 m drain tile spacing provided the greatest overall drainage (surface runoff, and surface moisture), wear tolerance (ground cover) and surface stability (shear vane strength, turf shear tester strength and surface hardness) characteristics. However, the 4.0 m drain spacing provided drainage and surface stability characteristics equivalent to the 2.0 m drain spacing. The only exceptions being surface runoff observed after a 34.0 minute irrigation event and a diminished surface hardness observed on one date only. Advantages of the 4.0 m drain spacing include increased subsoil moisture in comparison to fields with drain tiles spaced 2.0 and 3.0 m apart, which could be utilized to reduce annual irrigation requirements, and increased ground cover and surface hardness in comparison to the control, a field without drain tiles. These findings indicate that a 4.0 m drain spacing can provide a cost effective drainage solution for failing native soil athletic fields.

As topdressing depths were accumulated from 2.4 to 4.8 cm in 2008, minimal wear tolerance and surface stability differences were observed, suggesting that the effects of drain tile spacing on wear tolerance and stability are minimal once 4.8 cm of topdressing has been accumulated. However, substantial surface runoff was still collected from the control treatment, suggesting that drain tiles are still required for the removal of surface runoff from low lying areas while topdressing is being accumulated to the desired 4.8 cm depth.

REFERENCES

Adekalu, K.O. and J.A. Osunbitan. 2001. Compactibility of some agricultural soils in south western nigeria. Soil and Tillage Research. 59:27-31.

Arshad, M.A., A.J. Franzluebbers and R.H. Azooz. 1999. Components of surface soil structure under conventional and no-tillage in northwestern canada. Soil and Tillage Research. 53:41-47.

ASTM. 2006. Standard practice for classification of soils for engineering purposes (United Soil Classification System). American Soc. for Testing and Materials International. D 2487-06:1-11.

ASTM. 2004. Standard guide for construction of high performance sand-based root zones for sports fields. American Soc. for Testing and Materials International. F 2396-04:1-12.

Barber, E.S. and C.L. Sawyer. 1952. Highway subdrainage. Public Roads. 26(12):251–268.

Beard, J. B. 1978. Topdressing overview. 48th Annual Michigan Turfgrass Conference. January 10-11. pp. 36-39.

Bingaman, D.E. and H. Kohnke. 1970. Evaluating sand for athletic turf. Agron. J. 62:464-467.

Brede, A.D. and J.M. Duich. 1984. Establishment characteristics of kentucky bluegrass-perennial ryegrass turf mixtures as affected by seeding rate and ratio. Agron J. 76:875-879.

Cockerham, S.T. 1989. Cleated-shoe traffic concentration on a football field. Calif. Turfgrass Cult. 39(3-4):11-12.

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

Daniel, W.H. 1969. Vertical drainage for compacted turf areas. J. of the Sports Turf Research Institute. 45:41-47.

Davis, W.B., J.L. Paul and D. Bowman. 1990. The sand putting green: construction and management. Publication Number 21488. University of California Division of Agriculture and Natural Resources, Davis, Calif.

Emekli, Y. R. Bastug, D. Buyuktas and N.Y. Emekli. 2007. Evaluation of a crop water stress index for irrigation scheduling of bermudagrass. Agricultural Water Management. 90:205-212.

Enviro-weather. 2007. Weather-based pest, natural resource and production management tools. MAWN weather station, Hanckock Turfgrass Resreach Center, Michigan State University. Last retrieval November 5, 2007. (www.enviroweather.msu.edu).

Frank, K.W., K.M. O'Reilly, J.R. Crum and R.N. Calhoun. 2005. The fate of nitrogen applied to mature Kentucky bluegrass turf. Crop Sci. 46:209–215.

Gregory, J.H., M.D. Dukes, G.L. Miller and P.H. Jones. 2005. Analysis of double-ring infiltration techniques and development of a simple automatic water delivery system. (Online) Applied Turfgrass Science. p. [1-7]. Retrieved March 5, 2009. (http://www.plantmanagementnetwork.org/pub/ats/guide/2005/ring/).

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

Henderson, J.J., J.R. Crum, T.F. Wolf and J.N. Rogers. 2005. Effects of particle size distribution and water content at compaction on saturated hydraulic conductivity and strength of high sand content root zone materials. Soil Sci. 170:315-324.

Huang, B. and J.D. Fry. 1998. Root anatomical, physiological, and morphological responses to drought stress for tall fescue cultivars. Crop Sci. 38:1017-1022.

Jordon, J.E., R.H. White, D.M. Vietor, T.C. Hale, J.C. Thomas and M.C. Engelke. 2003. Effect of irrigation frequency on turf quality, shoot density, and root length density of five bentgrass cultivars. Crop Sci. 43:282-287.

Kladivko, E.J., G.L. Willoughby and J.B. Santini. 2005. Corn growth and yield response to subsurface drain spacing on clermont silt loam soil. Agron. J. 97:1419-1428.

Kowalewski, A.R., J.N. Rogers, III and T.D. Vanloo. 2008. Pre-harvest core cultivation of sod provides an alternative cultivation timing. Appl. Turfgrass Sci. Online. p. 1-9. Retrieved April 23, 2009. (http://www.plantmanagementnetwork.org/sub/ats/research/2008/sod/).

Lambe, T.W. The engineering behavior of compacted clay. Journal of the Soil Mechanics and Foundations Division, ASCE. 84(SM2):1655-1 to 1655-35.

Li, Y.X., J.N. Tullberg and D.M. Freebairn. 2007. Wheel traffic and tillage effects on runoff and crop yield. Soil and Tillage Research. 97:282-292.

Littell, R.C., G.A. Milliken, W.W. Stroup, R.D. Wolfinger and O. Schabenberger. 2007. SAS for mixed models. 2nd edition. SAS Institute, Cary, N.C.

Lunt, O.R. 1956. A method for minimizing compaction in putting greens. Southern Calif. Turfgrass Cult. 6(3):17-20.

Magni, S., M. Volterrani and S. Miele. 2004. Soccer pitches performances as affected by construction method, sand type and turfgrass mixture. Acta Hort. (ISHS). 661:281-285.

McCarty, L.B., M.F. Gregg, J.E. Toler, J.J. Camberato and H.S. Hill. 2005. Minimizing thatch and mat development in a newly seeded creeping bentgrass golf green. Crop Sci. 45:1529–1535.

McNitt, A.S. and P. J. Landschoot. 2003. Effects of soil reinforcing materials on the surface hardness, soil bulk density, and water content of a sand root zone. Crop Sci. 43:957–966.

Miller, G.L. 2008. An evaluation of crumb rubber and calcined clay for topdressing sports fields. Acta Hort. (ISHS) 783:381-390.

Moss, J.Q., G.E. Bell, D.L. Martin and M.E. Payton. 2007. Nutrient runoff from bermudagrass golf course fairways after aerification. Appl. Turfgrass Sci. Online. p. [1-7]. Retrieved June 26, 2009. (http://www.plantmanagementnetwork.org /ats/element/sum2.aspx?id=6011).

Mouazen, A.M., H. Ramon and J.D. Baerdemaeker. 2002. Effects of bulk density and moisture content on selected mechanical properties of sandy loam soil. Biosystems Engineering. 83(2):217-224.

Murphy, J.A., T.J. Lawson and J. Clark. 2003. Ball marks on bentgrass. USGA Turfgrass and Environmental Research Online. 2(12):1-6.

National Resources Conservation Services. 2005. Web soil survey. Retrieved April 24, 2009. (http://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx).

National Turfgrass Evaluation Program. 2008. A guide to ntep turfgrass ratings. Retrieved April 24, 2009. (http://www.ntep.org/reports/ratings.htm).

Ott, R.M. and M. Longnecker. 2001. An introduction to statistical methods and data analysis: 5th edition. Duxbury, Pacific Grove, Calif.

Prettyman, G.W. and E.L. McCoy. 2003. Profile layering, root zone permeability, and slope affect on soil water content during putting green drainage. Crop Sci. 43: 958-994.

Rawls, W.J., D.L. Brakensiek and K.E. Sexton. 1982. Estimation of soil water properties. Transactions of the ASCE. 25(5):1316-1320 and 1328.

Richie, W.E., R.L. Green, G.J. Klein and J.S. Hartin. 2002. Tall fescue performance influenced by irrigation scheduling, cultivar, and mowing height. Crop Sci. 42:2011-2017.

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

Rollins, K.M., S.J. Jorgensen and T.E. Ross. 1998. Optimum moisture content for dynamic compaction of collapsible soils. Journal of Geotechnical and Geoenvironmental Engineering. 124(8):699-708.

Sass, J.F. and B.P. Horgan. 2006. Irrigation scheduling on sand-based creeping bentgrass: evaluating evapotranspiration estimation, capacitance sensors, and deficit irrigation in the upper midwest. Appl. Turfgrass Sci. Online. p. [1-14]. Retrieved June 26, 2009. (http://www.plantmanagementnetwork.org/ats/element/sum2.aspx ?id=5189).

Saxton, K.E., W.J. Rawls, J.S. Romberger and R.I. Papendick. 1986. Estimating generalized soil-water characteristics from texture. Soil Sci. Soc. of America J. 50:1031-1036.

Sherratt, P.J., J.R. Street and D.S. Gardner. 2005. Effects of biomass accumulation on the playing quality of a Kentucky bluegrass stabilizer system used for sports fields. Agron. J. 97:1107-1114.

Stier, J.C. and J.N. Rogers, III. 2001. Trinexapac-ethyl and iron effects on supina and kentucky bluegrasses under low irradiance. Crop Sci. 41:457-465.

Stier. J.C., J.N. Rogers, III, J.R. Crum and P.E. Rieke. 1999. Flurprimidol effects on Kentucky bluegrass under reduced irradiance. Crop Sci. 39:1423-1430.

STMA. 2008. A guide to synthetic and natural turfgrass for athletic fields: selection construction and maintenance considerations: 2nd edition. Sports Turf Managers Association. Lawernce, KS. pp. 5.

USGA Green Section Staff. 2004. USGA recommendations for a method of putting green construction. United States Green Association World Wide Web Site. p. 1-12. Retrieved January 17, 2007. (http://www.usga.org/turf/course_construction/ green_articles/putting_green_guidelines.html).

Vanini, J.T., J.J. Henderson, J.C. Sorochan and J.N. Rogers, III. 2007. Evaluating traffic stress by the brinkman traffic simulator and cady traffic simulator on a Kentucky Bluegrass Stand. Crop Sci. 47:780-784.

Vanini, J.T. and J.N. III Rogers. 2008. Mowing strategies and fertilization improves sports fields during and after 70-day re-establishment window. Appl. Turfgrass Sci. Online. p. [1-10]. Retrieved June 26, 2009. (http://www.plantmanagementnetwork.org/ats/element/sum2.aspx?id=6902).

Vavrek, R.C. 1995. A successful topdressing program requires consistency, commitment, and communication. USGA Green Sec. Rec. 33(5):8-10.