IMPACT AND CONTROL OF ORGANIC MATTER IN USGA ULTRADWARF BERMUDAGRASS GOLF GREENS

By

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A THESIS PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

UNIVERSITY OF FLORIDA

2008

To my parents who always believed in, and supported me.

ACKNOWLEDGMENTS

I would like to thank Dr. John Cisar for making it possible to pursue a graduate degree in turfgrass management, and Dr. George Snyder who agreed to be my committee chair, even though he was already retired. I would like to thank Pamela Michels for her never-ending support, and unequaled editing prowess. Also, the moral support provided by Shamus McBooty was more than welcome. I would also like to thank all at Fort Lauderdale Research and Education Center (FLREC) and Everglades Research and Education Center (EREC) who helped my research project come together, as well as Fort Lauderdale Country Club and SISIS Equipment for their generous donation of equipment.

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LIST OF ABBREVIATIONS

AWHC	Available water holding capacity
CEC	Cation exchange capacity
CV	Cultivar
Db	Bulk density
Dp	Particle density
EREC	Everglades Research and Education Center
FLREC	Fort Lauderdale Research and Education Center
Ggg	*Gaeumannomyces graminis* var. *graminis*
GMAX	Peak deceleration
HTA	Hollow tine aerification
KSAT	Saturated hydraulic conductivity
LDS	Localized dry spot
MAPS	Macro pore space
MIPS	Micro pore space
ODR	Oxygen diffusion rate
OM	Organic matter
PS	Pore space
PVC	Poly vinyl chloride
REC	Research and education center
SBD	Summer bentgrass decline
SF	Summer-fall study
SOM	Soil organic matter
SS	Spring-summer study
STA	Solid tine aerification

TPS	Total pore space
UF	University of Florida
UG	University of Georgia
USGA	Unites States Golf Association
VWC	Volumetric water content
WAT	Weeks after treatment
WHC	Water holding capacity

Abstract of Thesis Presented to the Graduate School
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Requirements for the Degree of Master of Science

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August 2008

Chair: George H. Snyder
Major: Soil and Water Science

Ultradwarf bermudagrasses [*Cynodon dactylon* (L.) Pers. x *C. transvaalensis* Burt Davy] are commonly used for golf course putting greens in Florida due to their ability to tolerate high temperatures and low mowing heights for fast green speeds. Their dense growth habits can cause excessive organic matter build-up above and below the soil line, negatively affecting surface and soil characteristics. This experiment was conducted to evaluate seasonal impacts of commonly used cultural management practices on United States Golf Association ultradwarf bermudagrass putting green properties to determine optimum timing and effectiveness of treatments. Three ultradwarf varieties ('FloraDwarf', 'TifEagle', and 'Champion') were subjected to six cultural management treatments: Hollow tine aerification (one, two, or three times yearly), deep verticutting (three times yearly), solid tine aerification (five times yearly), and an untreated control. Treatments were applied over Spring-Summer (SS) and Summer-Fall (SF) studies with organic matter (OM), soil organic matter (SOM), soil physical properties, and turfgrass characteristics being analyzed. Soil organic matter and physical properties were determined from 5.1 cm diameter, by 9.5 cm deep soil cores. Saturated hydraulic conductivity (Ksat) was determined on a constant head permeameter with, and without verdure.

Using mixed model analysis, we found no reduction of OM or SOM due to treatments. Saturated hydraulic conductivity was increased by three-time yearly hollow tine aerification (HTA 3x) in both studies; removing verdure resulted in an average reduction of 3.2 cm hr^{-1}. Average final Ksat of all treatments was 20 cm hr^{-1} slower in the SF study. Bulk density (Db) was not reduced below control levels by treatments. An overall increase in Db of 0.2 g cm^{-3} occurred in the SF study. Champion had lower Db in both studies. Relative density (Dp) was increased by HTA 3x in the SS study. An overall decrease in Dp of 0.4 g cm^{-3} occurred in the SF study. Hollow tine aerification 3x produced more total pore space (TPS), than the control and verticutting in the SS study, but only more than verticutting in the SF study. Champion had the highest TPS in the SS study. Macropore space was increased more by HTA 3x than verticutting in both studies. All pore space fractions reduced substantially in the SF study. Average turf quality ratings were highest for the control in both studies. Champion had lower turf quality than TifEagle in the SS study. Surface compressibility was reduced least by the control, while HTA 3x provided a firmer surface than HTA 2x, which was firmer than HTA 1x. Champion scalped more than FloraDwarf, which scalped more than TifEagle in the SS study. Verticutting and HTA 3x reduced shoot counts in the SS study. Verticutting had higher volumetric water content than HTA 3x in the SS and SF studies. Since verticutting had the firmest surface, least mower scalping and localized dry spot, and eventually had higher quality, water-holding capacity, and fewer clippings it was the most beneficial treatment, particularly since no other treatment significantly reduced OM or SOM. Reduced Ksat, increased Db, and reduced pore space in the SF study showed that this seasonal treatment timing was least effective in managing soil properties. Due to higher overall quality, reduced scalping and LDS, TifEagle stood out as the best overall grass studied.

CHAPTER 1
INTRODUCTION

Ultradwarf Bermudagrass History and Characteristics

Hybrid bermudagrasses for golf course putting greens have been available since 1953, when 'Tiffine' was released from the United States Department of Agriculture, Coastal Plain Experiment Station in Tifton, GA (Burton, 1991). 'Tifgreen' was released shortly after in 1956, and was touted for having finer leaves and the ability to withstand daily mowing at 6.4 mm (Burton, 1991). Tifgreen sprigs sent to golf courses for early evaluation contained a natural mutation that was later isolated and increased for evaluation (Burton, 1991). This selection, now known as 'Tifdwarf' due to its smaller, shorter leaves, stems, and internodes, was released in 1965 (Burton, 1991). Tifdwarf tolerated lower mowing heights and provided the faster green speeds that golfers demanded (Burton, 1991). The United States Golf Association (USGA) introduced its version of the stimpmeter in 1977 to measure golf ball roll as a means of estimating a greens 'speed' (Beard, 1982; Gaussoin, 1995; Oatis, 1990). Wide spread use of the USGA stimpmeter brought about a green speed war and the motto was "the faster, the better" (Vermeulen, 1995). Golfers and superintendents preference for faster green speeds, and advances in greens maintenance technology, eventually necessitated improved greens grass varieties (Vermeulen, 1995). In 1995, A.E. Dudeck of the University of Florida (UF) released 'FloraDwarf', which had a lower vertical growth characteristic, finer texture, and increased shoot density (Busey and Dudeck, 1999). Soon afterwards, 'TifEagle' and 'Champion', which had similar characteristics to FloraDwarf, were released from Tifton, GA and Bay City, TX, respectively (Busey and Dudeck, 1999). These denser, lower growing varieties, named 'Ultradwarfs' by P. Busey of UF, can easily withstand regular mowing below 3 mm (Foy, 1997; Foy, 2000, Unruh and Elliott 1999), and produce green speeds (i.e., ball roll distance) in excess of 3.35 m, as measured with a stimpmeter. These improved qualities rival bentgrass (Hartwiger, 2000), which cannot be grown year-round in south Florida due to an inability to tolerate persistent heat (Foy, 1988), in quality of putting surface and green speed (McCarty and Miller, 2002; Unruh and Davis, 2001). Unfortunately, organic matter levels within ultradwarfs can quickly reach detrimental levels if incorrectly managed due to the faster rate of thatch/biomass accumulation, shoot density, and stoloniferous growth habit (Foy, 2000; McCarty and Miller, 2002; White et al., 2004).

USGA Putting Green History and Characteristics

United States Golf Association green construction methods have been used for more than 40 years due to their successful scientifically-tested guidelines (USGA Green Section Staff, 2004). Their recommendation for particle size distribution in root zone media is a major reason why these greens are so successful, as these profiles provide physical properties that can withstand continuous traffic (Carrow, 2003). Particle diameter ranges from fine gravel (≤3.4mm) to clay, which is smaller than 0.002 mm (USGA Green Section Staff, 2004). Limiting fine gravel and very coarse sand (1.0-2.0 mm) to ≤10% helps limit saturated hydraulic conductivity (Ksat), so sufficient water can be held in the root zone (USGA Green Section Staff, 2004). Total fines (i.e., very fine sand, silt, and clay) are also limited to ≤10% to control excessive moisture and ensure that Ksat will not be below 15 cm hr^{-1} in newly constructed greens (USGA Green Section Staff, 2004). Compaction is also controlled by limiting total fines, as they can fill micropores that sand size particles cannot fill (Gaussoin et al., 2006). These USGA guidelines produce a total pore space range of 35-55%, which provides optimum air-filled and capillary porosity for plant growth and drainage (Brady and Weil, 1999). Some consider USGA greens a relatively sterile environment, free of microorganisms capable of organic matter breakdown, since they are composed primarily of sand (Habeck and Christians, 2000). This has been proven incorrect, as sand-based greens were found to contain microbial populations with considerable taxonomic diversity similar to native soils, within 24 months after construction (Bigelow, et al., 2000; Elliott et al., 2007; Gaussoin, 2003).

Organic Matter

Organic matter (OM) and soil organic matter (SOM) impact USGA putting greens in various ways both positive and negative (Beard, 1973; Carrow, 2004a, b, c; Christians, 1998; Hartwiger, 2004). One-quarter inch of OM, in the way of thatch-mat, is required to protect crowns and roots of turfgrass from foot traffic and mowing (Moore, 2007). Organic matter has also been shown to hold pesticides until they are broken down by microorganisms (Snyder and Cisar, 1995). This microbial process can limit environmental contamination in the form of ground water pollution (Snyder and Cisar, 1995). Excessive thatch can affect putting surface quality, as mower scalping can become more prevalent when greens are “puffy”. (Carrow, 2003; McCarty and Miller, 2002).

Soil Organic Matter

Without adequate SOM, excessive Ksat and reduced cation-exchange capacity (CEC) allow water and nutrients to move quickly through the root zone (Beard, 1973; Guertal, 2007). Inadequate SOM can cause greens to dry out quickly, requiring more frequent irrigation (McCoy and McCoy, 2005). Increased fertilizer applications may also be necessary in order to maintain acceptable turf quality due to low CEC and excessive leaching of nutrients (Carrow, 2004b; McCarty and Miller, 2002). Nutrient and pesticide leaching could become problems in the form of nonpoint-source pollution, as only limited amounts can remain in the soil while the remainder enter groundwater or move off site (FDEP Staff, 2007). Soil organic matter provides many other benefits to the soil environment including providing C for microorganisms, pH buffering capacity, enhanced chelation of trace elements, increased N, CEC, and porosity (Noer, 1928;

Wolf and Snyder, 2003). In contrast, greens with excessive SOM may have reduced Ksat and infiltration rates, and decreased pesticide efficacy (Carrow, 2004a, b, c; McCarty et al., 2007). Reduced Ksat can cause soils to become waterlogged and create anaerobic conditions (Carrow, 2004a, b, c). Prolonged anoxic conditions can rapidly cause turfgrass quality to decline (Carrow, 2004a, b, c; Hartwiger, 2004).

History of Turfgrass Decline

Bentgrass. Most research related to SOM in golf greens has been conducted on bentgrass [*Agrostis stoloniferous* L. var. *palustris* (Huds.)] greens, due to the phenomenon of Summer Bentgrass Decline (SBD). Initially, SBD was thought to be caused by fungal pressure associated with extended periods of high temperature (Carrow, 2004a, c; Hartwiger, 2004). Presently, researchers have focused on SOM content in the root zone in relation to oxygen diffusion rates (ODR) and Ksat (Carrow, 2004a, c). When SOM accumulates to 3-4% (by weight), macropores (>0.075 mm), which facilitate oxygen diffusion, can become clogged with SOM, resulting in reductions of Ksat and ODR (Carrow, 2004a, c). Extended high temperatures (>32.2ºC), SOM concentrations greater than 4% (by weight), and ODR below 0.20 μg oxygen cm^{-2} min^{-1} in the surface 1.3 cm, are now believed to trigger the decline of bentgrass greens (Carrow, 2004a, c; Hartwiger, 2004; Huang, 2002).

Bermudagrass. Ultradwarf bermudagrass is well suited for Florida's subtropical climate, as optimum bermudagrass shoot growth occurs at air temperatures between 29 and 38º C, and reduced root growth is not expected to occur until soil temperatures exceed 38º C (McCarty and Miller, 2002). Due to buffering effects from the Gulf of Mexico and the Atlantic Ocean, Florida's air temperatures rarely exceed 35º C. In addition, Florida's soil pH (≥5.5) and average annual high temperatures (≥13º C) are more conducive to microbial degradation of OM and SOM (Brady and Weil, 1999; Christians, 1998). Even though growing conditions seem ideal ultradwarf bermudagrass greens still exhibit decline, as golf course superintendents regularly experience reduced turfgrass quality during summer months (Elliott, 1991; Foy, 2005; White, 2004).

Monica Elliott, of the Fort Lauderdale Research and Education Center (FLREC), confirmed that an etiological agent [*Gaeumannomyces graminis* var. *graminis* (Ggg)], when associated with host-predisposing abiotic stresses, caused bermudagrass decline (Elliott, 1991). USGA ultradwarf bermudagrass greens usually experience this decline in summer or early fall, during prolonged periods of high humidity, cloudiness, rainfall, and excessive soil moisture (Elliott, 1991; White, 2004). Another hypothesis is that excessive SOM causes primary stresses such as Ggg and *Curvularia* spp (Carrow, 2004b). Recent research conducted at the University of Florida has also associated *Bipolaris* spp. and *Curvularia* spp. with bermudagrass decline syndrome (Cisar and Snyder, 2003; Datnoff, et al., 2005; Unruh and Davis, 2001).

Although significant research has been conducted to define optimum levels of SOM in bentgrass greens, very little has been conducted for ultradwarf bermudagrass greens, especially in south Florida (Cisar, et al. 2005). Recommended SOM levels for USGA bentgrass greens may be irrelevant for USGA ultradwarf bermudagrass greens, particularly in south Florida's subtropical climate. Growth characteristics of ultradwarf bermudagrass differ from those of creeping bentgrass and may have varied SOM requirements and tolerances. Year-round growing conditions, optimal conditions for soil microbes, and annual rainfall exceeding 150 cm differentiate south Florida from most areas of the United States (Cisar and Snyder, 2003). Similarities of bermudagrass decline to SBD reinforce the need for research investigating the affects of OM and SOM on USGA ultradwarf bermudagrass greens in subtropical Florida. Therefore, we conducted an experiment which incorporated commonly used cultural practices in an attempt to manage levels of OM and SOM. Cultural practices were applied in two separate seasonal studies to determine seasonal affects on OM, SOM, qualitative turfgrass characteristics, soil physical properties and surface characteristics.

CHAPTER 2
LITERATURE REVIEW

Composition and Breakdown of Organic Matter

Organic matter (OM) consists of living plant tissue and recently-deposited plant and animal residues (Wolf and Snyder, 2003), and is represented as thatch and mat layers on the soil surface (McCarty et al., 2007). Thatch, which is found between the soil surface and verdure (i.e., green turfgrass leaves) contains: stolons, rhizomes, sloughed roots, mature leaf sheaths, and stems (Christians, 1998; McCarty et al., 2007; Turgeon, 1978). Thatch that is not completely decomposed, and is surrounded by the soil matrix, is considered to be mat (McCarty et al., 2007). Thatch and mat combine to form the thatch-mat layer.

The rate of OM decomposition by microorganisms is predicated on its age, chemical makeup, C:N ratio, and environmental factors such as aeration, moisture, pH, and temperature (Carrow, 2004a, c; Wolf and Snyder, 2003). Organic matter with higher N concentrations will tend to decompose more rapidly, as it provides a nutrient source for microorganisms (Wolf and Snyder, 2003). Proper soil aeration and moisture provide an environment where microorganisms can thrive, and readily decompose OM, SOM, and applied materials such as fertilizers and pesticides (Carrow, 2003; Cooper, 1996; Waltz and McCarty, 2001). Acidic soil pH (<5.5) can decrease the breakdown of OM and SOM as it is injurious to actinomycete and bacteria populations (Cooper, 1996; Waltz and McCarty, 2001). Cool, humid, temperate climates are known to create extreme cases of OM and SOM accumulation (Carrow, 2003).

Composition and Breakdown of Soil Organic Matter

Soil organic matter (SOM) originated from plant and animal residue deposition from grass and soil organisms (Wolf and Snyder, 2003). This decomposed material is composed of humic and nonhumic compounds, lignins, proteins, and polysaccharides, which are deposited from living tissue and soil microorganisms (Wolf and Snyder, 2003). Humus makes up the largest fraction of SOM, and soil microbial and fungal biomass make up the remainder (Brady and Weil, 1999; Wolf and Snyder, 2003). Decomposition of SOM is much slower than recently-deposited OM found in the thatch-mat (Wolf and Snyder, 2003).

Organic Matter Levels

Thatch-Mat

Turfgrass requires a minimum thatch-mat depth of 0.6 cm in order to properly tolerate wear stress (Moore, 2007), while a depth greater than 2.5 cm is considered excessive (McCarty et al., 2007). Moderate OM provides a desirable cushioning effect for traffic and incoming shots (Vermeulen and Hartwiger, 2005), and prevents volatilization of ammonia (Petrovic, 1990), leaching of pesticides into groundwater (Horst et al., 1996; Snyder and Cisar, 1995) and reduces summer heat stress (Christians, 1998). Excessive thatch-mat, which can occur even under excellent management (Carrow, 2000), can cause numerous problems including excessive ball marks, inconsistent ball roll (Vermeulen and Hartwiger, 2005), increased pathogens and insects (Christians, 1998; Bevard, 2005; Vermeulen and Hartwiger, 2005), reduced infiltration and percolation (Bevard, 2005; McCarty, 2007), scalping (McCarty, et al., 2007; Vermeulen and Hartwiger, 2005) and pesticide efficacy (McCarty et al., 2007).

Soil Organic Matter

Soil organic matter improves turfgrass quality by increasing aeration, structure, water and nutrient-holding capacity in highly mineral soils (Beard, 1973; Brady and Weil, 1999). Soil organic matter, which has a particle density range of 0.9 to 1.3 g cm^{-3}, can reduce mineral soils with an initial particle density of 2.60 to 2.75 g cm^{-3} to levels below 2.40 g cm^{-3} (Brady and Weil, 1999). This reduction in particle density will translate into reduced bulk density, which can improve environmental conditions for turfgrass roots in compacted high density soils (Brady and Weil, 1999). Excessive SOM can impede water flow, oxygen diffusion rates and negatively affect turfgrass growth, especially under stressful environmental conditions (Carrow, 2003; Hartwiger, 2004).

Recommendations for SOM (by weight) in golf greens range from 1.5 to 8% (Vermeulen and Hartwiger, 2005). This wide range can be due in part to sampling and testing methods used to measure SOM (Vermeulen and Hartwiger, 2005). Sampling depths used to determine the SOM range from 0.6 cm to over 15 cm (Vermeulen and Hartwiger, 2005). The shallower samples (e.g., 2.5-5.0 cm) mostly analyze the thatch-mat layer (Carrow, 2004a, b, c, McCarty et al., 2007), while the deeper samples can include the thatch-mat, root-zone SOM, and unadulterated subsoils. Soil testing labs do not have a universally-accepted protocol for testing SOM, so any of a number of procedures may be used with each giving potentially different results (Vermeulen and Hartwiger, 2005). Other reasons for the wide range of recommendations include geographic location and turfgrass variety (Vermeulen and Hartwiger, 2005). Climatic zones also seem to have an effect on SOM build up (Carrow, 2003), as levels along the Gulf coast from Florida to Louisiana were found to have less than 2% SOM (Carrow, 2004b) in comparison to levels found in Griffin GA, which were in excess of 9% in the surface 3 cm (Carrow, 2003).

University of Georgia (UG) turfgrass stress physiologist Robert N. Carrow conducted a five-year research project on bentgrass greens, and determined that once SOM rises above 4% (by weight) in the first 5 cm of the surface soil, bentgrass greens are at high risk of decline (Carrow, 2004a, c). Others have stated that once OM levels get higher than 5% (by weight), there is immediate concern for bentgrass greens found in or near the transition zone, even if they seem healthy at the time (O'Brien and Hartwiger, 2005). In cooler regions of bentgrass adaptation, 5% SOM (by weight) is usually not as much of a concern, as they have fewer prolonged periods of excessive heat to contend with (Hartwiger, 2004).

Control Options for OM and SOM

Since conventional tillage cannot be used on turfgrass without destroying performance characteristics (Beard, 1973; McCarty and Brown, 2004), cultural practices used to control OM accumulation include: solid and hollow tine aerification, vertical mowing, slicing, topdressing, and grooming (Beard, 1973; Christians, 1998; Cisar, 1999a; Hanna, 2005; McCarty and Miller, 2002; Vavrek, 2006). These practices are used in an attempt to increase soil aeration, rooting, water movement, improve soil physical properties, and physically remove OM and SOM (Beard, 1973; Bevard, 2005; Cisar, 1999a; McCarty and Miller, 2002; Unruh and Elliott, 1999). When multiple cultural practices were combined in accelerated programs, they caused unacceptable damage to the putting green surface for extended periods of time (Hollingsworth et al., 2005; Landreth, et al., 2007). Seasonal timing of cultural practices can also be important, as OM and SOM tend to accumulate more rapidly during times of maximum growth (Carrow, 2000), and turfgrass recovery is impeded when growth is limited by environmental affects. Cultural practices may be somewhat effective at reducing organic matter accumulation but results are variable (McCarty et al., 2007).

Control of Thatch-Mat

Wayne Hanna, who bred, developed and released TifEagle ultradwarf bermudagrass at UG, conducted a study which analyzed the effectiveness of verticutting on OM removal (Hanna, 2005). Verticutting to a depth of 2.5 cm was effective in removing OM, while 0.6 cm was insufficient (Hanna, 2005). Blade width also had an impact on OM removal, as increasing the blade width from 1.6 mm to 3.2 mm increased OM removal (Hanna, 2005; Landreth et al., 2007). A recent two-year study performed in Arkansas showed verticutting at a 2.5 cm depth was more effective in removing OM in the surface inch than HTA, although it took 60 days to recover (Landreth, et al., 2007). Another study found that verticutting and HTA used in combination were effective in reducing thatch levels when used at least four times annually for two consecutive years (McCarty et al., 2007). Topdressing alone has also been found to decrease thatch levels (Callahan et al., 1998). Cultural practices such as verticutting and HTA have also been found to reduce shoot counts, a component of thatch, which may positively enhance putting green quality (Hollingsworth et al., 2005).

A two-year study that used grooming, HTA, a biological thatch control agent, topdressing, and verticutting (alone and in combinations) found that none of the treatments reduced thatch-mat levels when compared to the control in the first year (McCarty et al., 2007). After the second year they found topdressing with 9.6 mm sand yr^{-1} increased thatch-mat depth 15% compared to the control, while HTA combined with grooming and verticutting reduced surface OM concentration more than the control (McCarty et al., 2007). Another study that used varied levels of HTA and verticutting showed a lack of differences in thatch levels from treatments (White and Dickens, 1984).

Slow-release N has been noted to reduce thatch levels when compared to quick-release sources (Sartain, 1985). Also, fertilizing with N at rates needed to maintain only minimally desired turf quality has successfully managed thatch accumulation (Hanna, 2005). Others have noted no affect on thatch depth, regardless of N source (Hollingsworth et al., 2005; White and Dickens, 1984). Soluble N can be beneficial due to its ability to speed up turf recovery after cultivation (Hollingsworth et al., 2005).

Differences in thatch levels among bermudagrass cultivars have also been found (Hollingsworth et al., 2005; White et al., 2004). Tifdwarf (cv.) was found to have less thatch than ultradwarf (cvs.) in one study (Hollingsworth et al., 2005), while others showed Tifdwarf had equal or greater thatch depth than ultradwarfs a year after planting (Cisar, 1999b; McCarty and Canegallo, 2005). The ultradwarfs used in our study had similar thatch depths (National Turfgrass Evaluation Program, 1998; White, 2004).

Control of Soil Organic Matter

Hollow tine aerification three times yearly, using 1.3 cm or greater tines, is considered adequate for managing root zone physical characteristics in Florida (Foy, 2000), although four or more HTA may be needed to improve highly-trafficked greens (Unruh and Elliott 1999). Dr. Carrow found HTA two times yr^{-1}, with 45.6-60.9 m^3 USGA sand ha^{-1} used to fill aerification holes effectively diluted soil organic matter, and increased macropore space in a creeping bentgrass green (O'Brien and Hartwiger, 2003). He also found STA, HTA and slicing improved Ksat for three to eight weeks (Carrow, 2003). When hydraulic conductivity samples were taken soon after aerification, before turf was completely healed, field readings were found to be similar to lab readings whether or not verdure was removed (Carrow, 2004a). Once the bentgrass green had recovered, field readings with verdure intact were slower than lab results, which again had verdure removed (Carrow, 2004a). Decreased Ksat was also found to occur in cooler months when leaf tissue growth was limited, and root growth was accelerated, as macropores (>0.12 mm diameter) became clogged with new root growth (Carrow, 2004a, c). A study conducted in Arkansas on bentgrass greens showed that, although not as effective in penetrating the entire thatch-mat layer, verticutting 2.5 cm deep with 3mm wide blades was more effective than HTA in removing SOM in the first inch of the root zone (Landreth, et al., 2007). Their most aggressive HTA treatment impacted less than 10% surface area compared to >20% impacted by verticutting. Since the upper 10 cm of a USGA green changes most over time, particularly from OM deposition (White, 2006), it is this region that is normally targeted by cultural practices.

Although verticutting and HTA are routinely used in cultural management programs to control SOM, the pros and cons of these practices may not be entirely understood, as published results are highly variable. Some researchers note the ability of these practices to reduce SOM, while others have found little or no reduction. One agronomist claims aerification will help prolong a greens life span, but SOM can still build up to detrimental levels and require renovation of the top four inches (White, 2006).

Cultural practices are looked upon negatively by most of the golfing public (Hartwiger and O'Brien, 2001; Vavrek, 2002), and when golfers hear that greens have been "ripped up" they will usually shun the course, and play elsewhere until damage has recovered. Since this can cause an 18-hole facility to lose $100,000 a week in lost revenue, much thought needs to be put into developing a cultural program that allows greens to remain in optimum playing condition, while at the same time satisfying the physiological needs of turfgrass. This is especially true in geographical locations where a single HTA impacts a substantial part of their growing season (Bevard, 2005). Many superintendents have foregone the 'Big Holes, Big Spacing' program recommended by USGA for less disruptive solid deep-tine, hydroject, or 6 mm hollow tine programs (Vavrek, 2007).

The objectives of this experiment were to evaluate seasonal impacts of commonly used cultural management practices on United States Golf Association ultradwarf bermudagrass putting green properties to determine optimum timing and effectiveness of treatments.

CHAPTER 3
EFFECTS OF TURFGRASS CULTIVATION PRACTICES ON ORGANIC MATTER, SOIL PHYSICAL PROPERTIES, AND TURFGRASS CHARACTERISTICS

Materials and Methods

Experimental Background

This study was performed on the FLREC ultradwarf bermudagrass research green from 2007 to 2008. The research green was established in 1999 using a 90:10 (sand:sphagnum peat, v/v), USGA specified green soil mix (USGA Green Section Staff, 2004). FloraDwarf, TifEagle, and Champion ultradwarf bermudagrass varieties were planted due to their availability and popularity at the time (Cisar, et al., 2003; Foy, 2000). After eight years of growth, and a two-year period of minimal cultural management practices prior to initiation, the ultradwarf research green had 1.6 cm of thatch-mat, and a 6 cm deep dark organic layer. Below the deep thatch-mat and dark organic layers was a noticeably lighter layer which appeared to be stained by inorganic and organic acid leachate. Below this layer was the unadulterated original greens mix. The dark organic layer averaged 40 g kg^{-1} SOM with no significant differences among treatments or grasses, while the lighter layer had approximately 5 g kg^{-1} SOM.

The green was mowed daily at 3 mm height, and fertilized annually with 100 g N m^{-2}, 26 g P m^{-2}, and 91 g K m^{-2}. Pesticides (i.e., fungicides, and insecticides) were applied only when turfgrass decline due to biotic factors became unacceptable. Chlorothalonil, and bifenthrin were used to control surface algae and sod webworms on an as needed basis at label rates.

Experimental Design and Statistical Analysis

A split-plot, randomized complete block design was used for the ultradwarf bermudagrasses in order to increase treatment effect precision (Littell et al., 2006). Grasses were oriented in east-west rows as whole plot units, with six cultural management treatments randomly assigned to each row as sub-plot units (Littell et al., 2006). Each row received all six treatments, which included hollow tine aerification (HTA): one, two, and three times yearly, solid tine aerification (STA) five times yearly, deep verticutting three times yearly, and an untreated control. To reduce spatial variability the experimental area was further separated into randomized blocks and each block contained a complete replication (Littell et al., 2006). SAS® PROC MIXED, and SAS® PROC GLIMMIX (SAS, 2004), both using Tukey's multiple-comparison procedure, were used to determine significant differences ($P<0.05$).

Two completely separate studies were conducted. One started in March 2007, the Spring-Summer study, and one started in July 2007, the summer-fall study. Spring-Summer treatments were applied to eighteen rows of FloraDwarf, TifEagle, and Champion, making up six complete replications. Summer-Fall treatments were applied to a separate area of the green, and consisted of five rows each of FloraDwarf and TifEagle, and three rows of Champion.

Turfgrass Cultivation Treatments

Hollow tine aerification. Hollow tine aerification was performed with a walking core aerator (model ProCore 648, The Toro Company, Bloomington, MN) one, two, or three times yearly. Putting green surface area and volumetric soil impact, to a depth of three inches, was 7.7, 15.4, and 23.1%, respectively, for each level of HTA. Cores were removed with 1.6 cm inner diameter hollow tines, on 5.1 cm centers (O'Brien and Hartwiger, 2003), and set to a 7.6 cm depth. Ejected cores were picked up with a scoop shovel and discarded. Each HTA application required 47.2 m^3 (4.7 mm) USGA sand ha^{-1} to fill the aerification holes and smooth the surface (Hartwiger 2004). In addition, 42.7 m^3 (4.3 mm) USGA sand ha^{-1} yr^{-1}, applied as surface topdressing (O'Brien and Hartwiger, 2003), was uniformly applied over all HTA treatments. This combination added 89.9, 137.1, and 184.3 m^3 (8.9, 13.7, and 18.4 mm) USGA sand ha^{-1} yr^{-1} for the one, two, and three-time HTA treatments, respectively. This methodology provided suboptimal, optimal, and supraoptimal treatments when compared to USGA guidelines for yearly surface impact and topdressing. Our optimal HTA treatment (i.e., two-time yearly) mimicked the USGA's 'Big Holes, Big Spacing' approach (O'Brien and Hartwiger, 2003).

The Spring-Summer study HTA treatments started in March 2007 with the first application of the three-time a year treatment (Table 3-1). Two months later, in May, all HTA treatments were performed. In July the last application of the two, and three-time yearly HTA were performed. The Summer-Fall study treatments started in July 2007 with all HTA treatments being performed (Table 3-2), since it was the peak of the growing season. Two months later, in September, the two, and three-time yearly HTA were performed. In November, the last three-time yearly HTA was performed.

Verticutting. A deep (2.5 cm) vertical mowing treatment (i.e., verticutting) was performed three times yearly with a commercial scarifier (model 117462, Sisis Equipment (Macclesfield) Ltd., Cheshire, England). Yearly putting green surface area and volumetric impact, to a depth of three inches, was 46.8, and 15.6%, respectively. The two mm wide steel blades were set 2.5 cm deep, and an average of 21.4 m^3 (2.2 mm) USGA sand ha^{-1} was used to fill in grooves and smooth the surface after each treatment. In addition, 42.7 m^3 (4.3 mm) USGA sand ha^{-1} yr^{-1} was applied as surface topdressing for an average total of 106.9 m^3 (10.7 mm) ha^{-1} yr^{-1}. Debris was swept up with a push broom, collected with a scoop shovel and discarded.

Spring-Summer verticutting treatments were applied in March, May and July 2007 (Table 3-1). Summer-Fall verticutting treatments were applied in July, September and November 2007 (Table 3-2).

Solid tine aerification. Solid tine aerification was performed with the same Toro aerator used for HTA treatments. This procedure was implemented monthly in an attempt to increase decomposition of OM, SOM, infiltration, oxygen flow, Ksat and encourage root growth with less surface disruption than HTA and verticutting (Carrow, 2003; Vavrek, 2002). Initially, 10.2 cm long tines were used in an attempt to reach below the dark organic layer, but since considerable turf damage was observed we changed to shorter (7.6 cm) tines for the Summer-Fall treatments. Since damage was excessive in the Spring-Summer treatments, it required 39.6 m^3 (4.0 mm) USGA sand ha^{-1} yr^{-1} to fill in holes and smooth the surface. Summer-Fall treatments required only 21.4 m^3 (2.1 mm) USGA sand ha^{-1} yr^{-1} to fill in holes and smooth the surface, as turfgrass damage was less severe with the shorter tines. In addition, 42.7 m^3 (4.3 mm) USGA sand ha^{-1} yr^{-1} was applied to each study as surface topdressing. Results for the Spring-Summer applied solid tine treatments will be shown in figures and tables but not discussed in the text, as results were irregular.

Control. The control treatment and all other treatments, received 42.7 m^3 (4.3 mm) USGA sand ha^{-1} yr^{-1} applied as a surface topdressing and light vertical mowing (i.e., grooming). Topdressing was applied using a calibrated rotary spreader (The Scotts Company, Marysville, OH) with rates and timings dependent on turfgrass growth (Carrow, 2003; O'Brien and Hartwiger, 2003), and ranged from 1.52-3.05 m^3 (0.15-0.30 mm) USGA sand ha^{-1} for each application. Grooming was performed 32 times annually using a commercial walk mower (model 522, Jacobsen, A Textron Company, Charlotte, NC) with grooming attachment. The walk mower was set to a 3.2 mm height, and grooming blades reached 1.6 mm below the bedknife. This allowed grooming blades to cut lateral growth with only minimal disturbance to the underlying soil matrix. Each grooming was performed in a direction different from the last in order to impact directional growth (i.e., grain) from a variety of angles (Foy, 2005), and allow incorporation of topdressing through the dense turfgrass surface (Carrow, 2004b; Foy, 1999; Vavrek, 2006).

Physical Measurements

Thatch depth. Thatch depth was determined by direct physical measurement and a 'Volkmeter', which is a weight-based thatch displacement instrument (Volk, 1972). Direct physical thatch measurements were taken at experiment initiation and after all treatments recovered. An open sided, 1.9 cm diameter soil probe was used to provide a clear view of the entire soil profile. Non-destructive, rapidly repeated thatch measurements were taken with the Volkmeter (Cisar and Snyder, 2003; Volk, 1972). The device had a cylinder with 7.92 cm^2 of surface area which provided a load of 570 g cm^{-3} (Volk, 1972). A 10 time multiplication of compression gauge was used to increase ease of measurement (Volk, 1972). Readings showed a highly significant ($p < 0.001$) positive regression between surface compressibility and thickness of thatch (Volk, 1972). The resultant regression line ($Y=2.72+2.64X$) was used to determine thatch depth and measure surface compressibility (Volk, 1972). Three readings were taken in each 2.4 m^2 plot and each was used separately in statistical analysis.

Organic matter content. Organic matter content in the thatch layer was determined from 10 cm diameter by approximately 15 cm deep cup cutter cores. Thatch was separated from the core with a long knife and then oven dried at 105ºC for 24 hours before weighing. The "pelts" were then put into a 550ºC muffle furnace for four hours to oxidize OM, and re-weighed to determine OM (by weight) lost on ignition.

Soil organic matter content. SOM levels were established from 5.1 cm wide and 9.5 cm soil cores. A handheld soil sampler 1.9 cm wide, with an open-side profile, was inserted 15 cm deep in order to collect only the dark organic layer, which was located below thatch-mat, and above the unconsolidated lightly stained layer. This sampling method was used to determine the worse case scenario for SOM, as the other method sometimes included portions of the lightly stained layer. In less mature greens, an even larger portion of the lightly stained layer would be included and actual SOM levels may be diluted. Samples were oven-dried at 105ºC for 24 hours to accommodate the removal of contaminants (e.g., stems, and gravel) with a 2 mm (#10) sieve. Samples were weighed and put into a 550ºC muffle furnace for four hours to oxidize OM. The soil samples were then re-weighed to determine SOM loss on ignition. We also compared three separate sieving methods to determine their affects on SOM levels. A #10 (2 mm) sieve, which is the one most commonly used in soil testing labs, was compared to a smaller #35 (0.5 mm) sieve and no sieve at all.

Root weights. Root weights were determined from 10 cm diameter by approximately 15 cm deep cup cutter cores in order to obtain more measureable weights and reach below the root zone. Thatch was removed from the core with a long knife, while the rest of the core was washed through a 2 mm screen to remove the mineral fraction. Samples were then oven dried at 105ºC for 24 hours before weighing.

Soil physical properties. Ksat, bulk density, pore space and water- holding capacity were established using ASTM F method 1815-97, minus the cylinder loading step. Weight of the pycnometer [i.e., poly vinyl chloride (PVC) rings] when filled with water for relative density (i.e., particle density) determination was obtained from saturated Ksat soil cores. Calculations for ASTM D 854-83[1] methods were used. A 5.1 cm diameter by 7.6 cm deep soil core was used in all cases except for Ksat with verdure intact. For Ksat with verdure there was an additional 1.8 cm deep ring on top, making the total sample 9.4 cm deep.

Ksat was determined both with verdure intact and removed. Soil cores were first inundated in water with verdure intact to remove gas bubbles, then placed onto a constant head permeameter for four hours before measurements were recorded. Verdure was then removed by cutting off the 1.8 cm top ring with a long knife. Cores were then re-saturated from underneath and placed onto the constant head permeameter for an additional hour before sampling.

Qualitative Measurements

Golf course greens are composed of many factors that influence quality and playability. These include denseness and color of canopy, rate of recovery, ball roll speed, surface compressibility, extent of scalping, localized dry spot, disease, and rate of recovery. Shoot counts from 20 cm^2 cores were manually counted. Visual denseness, and color of canopy were rated weekly as quality on a 1-10 scale; 1 = dead, 6 = minimally acceptable, and 10 = best possible turf quality. Recovery was rated weekly on a 1-10 scale; 10= completely recovered. Ball roll speed was obtained by averaging the distance of two golf balls, rolled in two opposite directions, using a 19-cm modified USGA stimpmeter (Gaussoin et al., 1995). Surface compressibility was measured weekly with the Volkmeter. Mower scalping was rated on a 1-10 scale; 10 = complete loss of turfgrass cover. Localized dry spot, and fungus were rated on a 1-10 scale; 10 represented complete plot coverage. Recovery from treatments was rated on a 1-10 scale; 10 = completely recovered.

Results and Discussion

Surface Compressibility

Although effects of cultural practice treatments on SOM were the main focus of this project, many other peripheral factors were analyzed. One of the most interesting results was the cultural practice treatments' effect on surface compressibility. The Volkmeter, developed by Gaylord Volk of UF for determination of thatch depth, uncovered notable differences in surface compressibility among treatments and grasses (Figures 3-1 to 3-6). The control treatment was consistently "spongier" as indicated by higher Volkmeter readings (Figures 3-1 to 3-4), which indicated the weight used to measure surface compression sunk further down into the thatch layer. Verticutting had lower Volkmeter readings, indicative of a firmer surface (Figures 3-1 to 3-4). When analyzed as repeated measures over the entire study, a clear indication of effectiveness of treatments on surface compressibility became apparent (Figures 3-3, 3-4). One-time HTA had less surface compressibility than the control, which was spongiest (Figures 3-3, 3-4). Each additional HTA further reduced surface compressibility, and verticutting was more effective than all HTA treatments for both studies (Figures 3-3, 3-4). Although verticutting produced the firmest surface during each 35 week study, HTA 3x had an as firm, and sometimes firmer surface after this time frame due to its larger volumetric impact. On several occasions, particularly after September 14, 2007 during the Spring-Summer study, TifEagle had the least surface compressibility (Figure 3-5). The Summer-Fall study showed Champion was firmer on most occasions up to week 15 (i.e., November 12, 2007), when TifEagle started to become firmer (Figure 3-6). The firmness of Champion in the second study was because plots were near the edge of green. This was unavoidable as there were only three plots of Champion available.

Thatch Levels

The Volkmeter assessed physical thatch depth rather accurately at the initiation of both studies, as initial readings were 1.65 and 1.69 cm, versus direct physical thatch measurements of 1.67 and 1.66 cm for the Spring-Summer, and Summer-Fall studies, respectively (Table 3-3). Volkmeter readings quickly became varied among treatments after the first application of cultural practices, although physical thatch depth had not necessarily changed and ashed organic matter weights were statistically similar. A final physical thatch depth of 1.62 cm in the Spring-Summer study was only 0.05 cm less than the initial measurement (Table 3-3). Volkmeter readings for the control and verticutting treatments taken at the same time (i.e., week 21, Figure 3-1) were 1.79, and 1.42 cm, respectively. Increased Volkmeter readings above direct physical measurements for the control could be due to aggressive summer top growth, and lack of appreciable impact on the thatch layer, while reduced Volkmeter readings for the verticutting are probably due to a substantial impact on the thatch layer, and the incorporation of sand into treatment openings.

Since direct physical measurement of thatch was not necessarily being represented after the initiation of treatments, Volkmeter readings were considered to represent the “effective thatch depth”. For example, although actual thatch depth may still be in excess of 1.6 cm, changes brought about by verticutting reduced its impact to 1.4 cm. Another interesting note was that HTA and verticutting firmed up our soft ‘spongy’ green, while other research has shown that HTA actually softened up firm greens (McCarty et al., 2007). This demonstrates the potential of cultural practices to adjust surface compressibility to a moderate level depending on whether preexisting surface conditions are either too firm, or too soft. The surface firming observed in this experiment could be tied to reduced organic matter concentration in the thatch layer, as verticutting had lower levels than the control in both studies and HTA 3x was lower in the Summer-Fall study. TifEagle had least among grasses in the Spring-Summer study and exhibited the least mower scalping.

An overall surface firming trend occurred from September to November in both studies (Figures 3-1, 3-2, 3-5, 3-6). This could be due to either a firming effect from grooming and topdressing, or a physiological turfgrass response to declining temperatures and resultant changes in soil and surface characteristics. The grooming and topdressing hypothesis is less likely because although they were both applied to the Summer-Fall study for four months prior to initiation, compressibility was still very close to initial Spring-Summer readings (Table 3-3). A noticeable increase in surface firmness started in September for both studies as air and soil temperatures declined. This transition period from maximum to moderated growth brings about distinct changes in surface characteristics that are known to provide optimum putting conditions in southern regions where bermudagrass is grown (O'Brien and Hartwiger, 2007). Although ultradwarf bermudagrasses can tolerate appreciably lower cutting heights during this period, superintendents will actually increase their height of cut to slow down excessive green speeds that can occur (O'Brien and Hartwiger, 2007). These increased green speeds are due to a combination of decreased turfgrass top growth that reduces friction from leaf surface and surface firming brought about by increased production of roots (O'Brien and Hartwiger, 2007).

Soil Organic Matter

USGA agronomists recommend impacting 15-20% of the putting green surface each year with hollow tine aerification, and topdressing with 121.9-152.4 m^3 (12.2-15.2 mm) USGA sand ha^{-1} yr^{-1} to dilute SOM (Obrien and Hartwiger, 2003). Even though our treatments exceeded the USGA's recommendations, there was no significant reduction of SOM concentration among grasses or treatments in either study (Table 3-4, 3-5). There was a notable increase in SOM between initial and final levels in the Summer-Fall study (Table 3-4, 3-5). Soil organic matter in the Ksat core samples increased 22.3% (i.e., 0.6 g cm^{-3}), while it increased 19.6% (i.e., 0.8 g cm^{-3}) in the dark layer. This seasonal increase in SOM could have caused a reduction in pore space, Ksat, and Dp, and increased Db (Tables 3-11 to 3-16). Since Summer-Fall study root weights were 167% greater than those in the Summer-Fall study (Table 3-8), it would be reasonable to assume that there was substantial root production between November and February. These new roots would have filled in previously open pores, reducing pore space. If that was the case, Ksat would be expected to decrease as naturally occurring drainage channels became filled with new growth. Relative density could also decrease with increased SOM concentration because SOM has lower density than mineral particles. Bulk density could increase as previously empty pores fill with roots, increasing the overall mass of a sample.

Scalping

Scalping, which is the excessive removal of leaf tissue from mowing (Christians, 1998), had occurred frequently on the research green due to excessive sponginess of the thatch layer (McCarty and Canegallo, 2005). Scalping was most severe in the heat of the summer when top growth was accelerated. Scalping was especially severe when mowing was performed from south to north, against the grain (Foy, 2006). When ratings were taken after a notable incidence of scalping, verticutting treatments showed significantly less ($P<0.01$) overall scalping than all other treatments in the Spring-Summer study (Figures 3-7 to 3-9). This is due to the removal of 'spongy' thatch matter, and surface firming brought about by incorporation of topdressing into grooves. Results were similar in the Summer-Fall study when verticutting again scalped least, but it was only significantly less than HTA 2x, HTA 3x, and solid tine aerification (Figures 3-10, 3-11). A shallower (i.e., one cm deep) verticutting performed over the Summer-Fall study area prior to initiation may have reduced scalping for the other treatments, making them more similar to verticutting (Figures 3-7 to 3-11). Note also that although shorter solid tines were used for the Summer-Fall study scalping was still appreciable (Figure 3-10). Solid and HTA treatments caused mower scalping due to surface disruption, while the control plots scalped due to increased sponginess of the thatch layer.

TifEagle exhibited least overall scalping during the Spring-Summer study, while FloraDwarf scalped less than Champion (Figures 3-12, 3-13). Overall scalping results in the Summer-Fall study were similar, although not as significant ($P=0.09$, Figures 3-14, 3-15). Again, this was probably due to the prior shallow verticutting that alleviated scalping symptoms. Results obtained among treatments and grasses for mower scalping shows a relationship between scalping and surface firmness, as verticutting and TifEagle were usually firmer, and scalped the least.

Physical Turfgrass Characteristics

Shoot counts. Shoot counts were reduced more by verticutting than one-time HTA, two-time HTA, and the control in the Spring-Summer study (Figure 3-16, Table 3-6). Reduction in shoot counts may actually reduce sponginess and scalping as verticutting scalped the least over the Spring-Summer study (Figures 3-7 to 3-9). Although Champion had most shoots after both studies, there were no statistical differences among grasses during either study (Table 3-6). This shows a possible correlation between shoots and scalping as Champion scalped most severely over the Spring-Summer study (Figures 3-12, 3-13).

Grass clippings. Verticutting had fewer clippings after Spring-Summer treatments were applied, and allowed to recover (Figure 3-17). After the Summer-Fall study verticutting, and HTA 3x had fewer clippings than solid tine aerification (Figure 3-18). Clippings among grasses were only significantly affected in the Spring-Summer study when Champion had fewest (Figure 3-19). This could be due to the damage Champion incurred from mower scalping, which could have affected tissue production or reduced the number of shoots.

Ball roll. Although verticutting was slightly faster than other treatments in the Spring-Summer study, and equal to the fastest treatment in the Summer-Fall study, no significant differences among grasses or treatments were found for ball roll when treatments were allowed to recover (Table 3-7). A notable 22.4% overall average increase in ball roll was realized in the Summer-Fall study due to previously mentioned changes in surface characteristics brought about by cooler temperatures (Table 3-7).

Root weights. No significant differences among grasses or treatments were found for oven dry root weights in either study, though average Summer-Fall study root weights were over twice that, 19.2 versus 7.2 g, of the Spring-Summer study (Table 3-8). This increase in root zone biomass can possibly be correlated to the decreased Ksat, pore space and relative density, and increased bulk density that occurred in the Summer-Fall study.

Localized dry spot. A dry-down of the research green produced substantial localized dry spot (LDS) symptoms and verticutting exhibited less LDS than HTA 3x in both studies (Figures 3-20, 3-21, Table 3-9). TifEagle exhibited the lowest ($P<0.10$) LDS symptoms among grasses in the Spring-Summer study (Figure 3-22, Table 3-9). Verticutting also had higher volumetric water content (VWC) than HTA 3x in both studies (Figures 3-23, 3-24, Table 3-10), while TifEagle had highest VWC among grasses in the Spring-Summer study (Figure 3-25, Table 3-10). This would help explain why LDS symptoms were reduced for TifEagle over the Spring-Summer study (Figure 3-22, Table 3-9). This reduction in VWC and subsequent increase in LDS for HTA 3x was due to removal of cores that contain appreciable SOM and water-holding capacity. Hollow tine aerification can also create fast draining channels, especially when side walls become sealed due to mechanical friction. These channels do not allow water to move sideways into the root zone so water can quickly percolate below the root zone and become unavailable to the turfgrass. TifEagle exhibited fewest ($P<0.10$) LDS symptoms (Figure 3-22, Table 3-9) and highest VWC among grasses (Figure 3-25, Table 3-10), most probably due to inherent growth characteristics.

Qualitative Turfgrass Characteristics

Quality. All cultural practices negatively affected turfgrass quality due to a disruption of the putting surface. Hollow tine aerification and verticutting negatively impacted 7.7, and 15.6% of a greens surface with each application caused the greens surface to become uneven, increased mower scalping and caused ball roll to slow for two weeks (McCarty et al., 2007). When analyzed as repeated measures, the control had the highest average quality in both studies (Figures 3-26, 3-27; Table 3-11). Although the control had higher overall quality ratings, verticutting had higher ratings on eight occasions during the Spring-Summer study (Figure 3-26). This was a result of reduced scalping due to a firmer surface and a greening effect possibly brought about by the release of N from disturbed organic matter (Figure 3-28). Verticutting and HTA 3x had statistically similar quality in the Spring-Summer study (Figure 3-26), but HTA 3x had higher overall quality in the Summer-Fall study (Figure 3-27; Table 3-11). The reduction of quality in verticutting plots over the Summer-Fall study occurred due to the shallow verticutting that was performed prior to initiation of study. Since turf had not completely recovered, damage was worse than expected and ratings suffered throughout the study. Hollow tine aerification 1x, HTA 2x and solid tine aerification exhibited statistically similar overall quality, which was lower than the control but higher than HTA 3x and verticutting in the Summer-Fall study (Figure 3-27; Table 3-11).

Champion had lower quality than TifEagle over the Spring-Summer study (Figure 3-29; Table 3-11). Champion seemed to have aggressive top growth that increased mower scalping during hot summer months (Figure 3-12), as that is when its quality was lowest (Figure 3-29; Table 3-11). Grasses had statistically similar quality ratings in the Summer-Fall study (Figure 3-30; Table 3-11). This was probably due to the location of Champion plots near edge of treatment area, which was firmer and subsequently scalped less.

Recovery. Hollow tine aerification and verticutting took a similar amount of time to recover in both studies although verticutting was at times more damaging (Figures 3-31, 3-32; Table 3-12). They both took five weeks longer to recover after final treatments were applied in the Summer-Fall study compared to the Spring-Summer study (Figure 3-31, 3-32; Table 3-12). This was due to cooler air and soil temperatures, which slowed bermudagrass growth. Overall recovery ratings for HTA 1x, and the control were statistically similar in both studies. Solid tine aerification joined them in the Summer-Fall study, as it also had highest average recovery ratings after tine length was reduced 2.5 cm (Figure 3-32; Table 3-12). Hollow tine aerification 2x, HTA 3x, and verticutting had lower recovery ratings in both studies (Figure 3-31, 3-32; Table 3-12). This meant that damage was more extensive over the course of both studies from these treatments compared to the control. Champion was slightly slower ($P<0.15$) to recover in the Spring-Summer study due to regularly observed mower scalping (Figure 3-12).

Soil Physical Properties

Saturated hydraulic conductivity. Hollow tine aerification 3x had the fastest Ksat (41.7 cm hr^{-1}) after the Spring-Summer study ($P<0.01$), while verticutting and control were slowest (18.9, and 20.2 cm hr^{-1}); all treatments averaged 31.5 cm hr^{-1} (Figure 3-33; Table 3-13). Although 30% slower than Spring-Summer Ksat, HTA 3x had fastest (29.2 cm hr^{-1}) Ksat of the Summer-Fall study (Figure 3-34; Table 3-13). Hollow tine aerification 2x, which was approximately 50% slower than HTA 3x, was second fastest in the Summer-Fall study. All treatments in the Summer-Fall study averaged 11.4 cm hr^{-1}, which was 64% slower than the Spring-Summer study Ksat (Figures 3-33, 3-34; Table 3-13). Champion had slower ($P=0.13$, and $P=0.13$) Ksat in Spring-Summer, and Summer-Fall studies, respectively (Table 3-13). Verdure did not seem to affect Ksat negatively. Saturated hydraulic conductivity was actually 15% slower after verdure was removed in both studies. This may have been due to sealing of naturally occurring flow channels after verdure was removed from the moist soil core with a long knife. Overall Spring-Summer Ksat increased 10.44 cm hr^{-1}, while overall Summer-Fall Ksat decreased 2.46 cm hr^{-1} after all treatments were applied and allowed to recover (Table 3-13). This notable decrease in Summer-Fall Ksat can be associated with the dramatically increased root weights observed (Table 3-8).

Bulk density. Bulk density (Db) was not reduced (P=0.29) by any treatment in the Spring-Summer study (Table 3-14). Hollow tine aerification 2x (1.37 g cm^{-3}) had lower Db than verticutting (1.43 g cm^{-3}) in the Summer-Fall study (Figure 3-35; Table 3-14). Champion had the lowest Db among grasses in both studies (Figures 3-36, 3-37; Table 3-14). This could be due to Champions' growth characteristics, which may also produce more total pore space. Bulk density decreased only marginally from an initial 1.31 g cm^{-3} to a final 1.24 g cm^{-3} in the Spring-Summer study, while the Summer-Fall study increased substantially from an initial 1.20 g cm^{-3} to a final 1.40 g cm^{-3} (Table 3-14). This increase of Db in the Summer-Fall study seemed to be linked to the same seasonal changes that increased surface firmness and ball roll in the fall. When air and soil temperatures started falling in September, Volkmeter readings showed a surface firming trend that may have been indicative of similar changes in root-zone characteristics.

Reduced Ksat is one indicator of increased Db (McCarty and Brown, 2004). Bulk density decreased 0.07 g cm^{-3} in the Spring-Summer study and overall Ksat increased 10.4 cm hr^{-1} (Tables 3-13, 3-14). Bulk density in the Summer-Fall study increased 0.2 g cm^{-3}, and overall Ksat was reduced by 3.2 cm hr^{-1} (Tables 3-13, 3-14). The reason for this seasonal phenomenon is not completely understood, although it may be due to seasonal changes in soil characteristics, microbial activity, and plant physiology. Naturally occurring fluctuations in organic matter may also be a factor, as relative density and root weights were affected in the Summer-Fall study. Also, compaction (i.e., increased bulk density) caused by HTA could be a factor, as Petrovic (1979) found zones of compaction along side walls, and bottoms of aerification holes. This compaction found at the bottom of aerification holes is similar to the plow pan that can occur during farming (Vavrek, 2002). The impact of this compaction is debatable as varied results have been obtained (Vavrek, 2002).

Relative density. Relative density (Dp), which is the ratio of the weight of the soil to the weight of an equal volume of water (Liu and Evett, 1990), increased only slightly (2.68 to 2.70 g cm^{-3}) in the Spring-Summer study, while it decreased from 2.56 to 2.17 g cm^{-3} in the Summer-Fall study (Table 3-15). Verticutting had lowest Dp in the Spring-Summer study, while HTA 2x and 3x had higher Dp due to incorporation of sand into the root-zone (Figure 3-38). There were no Dp treatment differences in the Summer-Fall study (Table 3-15), although overall Dp decreased substantially (0.39 g cm^{-3}) from initial levels. The Summer-Fall study decrease in Dp is probably because of the aforementioned seasonal changes, which in this case overrode any effects of HTA because underground turfgrass production increased substantially. There were no differences in Dp among grasses in the Spring-Summer study, although Champion had lowest and FloraDwarf had highest after the Summer-Fall study (Table 3-15). The decrease in Dp for grasses in the Summer-Fall study may be due to physiological changes that increased SOM in the form of roots and underground plant parts.

Total pore space. Overall total pore space (TPS) increased slightly from 51.2 to 54.1 % in the Spring-Summer study after treatments were applied and allowed to recover, while it decreased substantially from 53.1 to 35.3 % in the Summer-Fall study (Figure 3-39, 3-40; Table 3-16). All treatments, including the control had more TPS at the end of the Spring-Summer study, while Summer-Fall TPS decreased substantially from initial levels, regardless of treatment (Table 3-16). Hollow tine aerification 3x had most TPS, while HTA 1x, verticutting and the control had least TPS in the Spring-Summer study (Figure 3-39). After the Summer-Fall study HTA 2x and HTA 3x had most TPS, while verticutting had the least (Figure 3-40). All HTA treatments were statistically similar to each other in both studies. Champion had more TPS than both FloraDwarf and TifEagle in the Spring-Summer study (Table 3-16), which could be indicative of an aggressive summer top-growth habit that limits root production. No grass TPS differences were found in the Summer-Fall study (Table 3-16).

Macropore space. Overall macropore space (MAPS) increased from 12.4 to 17.7 % in the Spring-Summer study (Figure 3-41; Table 3-17), while it decreased from 18.0 to 9.8 % in the Summer-Fall study (Figure 3-42; Table 3-17). Verticutting had least MAPS after Spring-Summer treatments were applied and allowed to recover (Figure 3-41; Table 3-17). Hollow tine aerification 3x had most MAPS, while HTA 1x, verticutting and the control had least in the Summer-Fall study (Figure 3-42; Table 3-17).

Micropore space. Micropore space (MIPS) decreased slightly from 38.8 to 36.4 % after Spring-Summer treatments were applied and allowed to recover (Table 3-18), while it decreased substantially from 35.1 to 25.5 % in the Summer-Fall study (Table 3-18). There were no treatment differences in the Spring-Summer, or Summer-Fall studies (Table 3-18).

Water holding capacity. Overall water holding capacity by weight (WHC) decreased very slightly from 29.8 to 29.7 % in the Spring-Summer study (Table 3-19), while it decreased substantially from 29.5 to 18.3 % in the Summer-Fall study (Table 3-19). There were no treatment differences in the Spring-Summer, or Summer-Fall studies (Table 3-19). Champion had most WHC among grasses in the Spring-Summer study, while TifEagle had least (Table 3-19). No grass differences were found in either study (Table 3-19).

Conclusions

Treatments used in this experiment, even though meeting and exceeding USGA recommendations for surface impact and topdressing, did not impact enough of the root-zone to significantly reduce SOM. If HTA treatments were performed more frequently (e.g., four or five times) or repeated for another year, there may have been an appreciable reduction of SOM. McCarty et al. (2007) used similar treatments in a two-year study and found no reduction of organic matter in the top 5.1 cm the first year, while a reduction was noted in the second year for the HTA 4x combined with verticutting 2x treatment. Another thing to consider is that their green was only three years old with 1.4% (wt) SOM and ours was eight years old and had an average of 4% (wt) SOM. It may be more difficult to dilute SOM in a more mature green.

Since verticutting eventually had higher quality, fewer clippings, firmest surface, least mower scalping, and localized dry spot it seemed to be the most beneficial treatment in our experiment, especially since no other treatment significantly reduced OM or SOM. Due to its higher overall quality and reduced scalping, TifEagle stood out as the best overall grass studied.

Naturally-occurring seasonal changes in turfgrass growth appeared to supplant the impact of cultural practices on most USGA green soil properties, particularly when applied later in the year. Bulk density increased, while pore space and Ksat decreased substantially in the Summer-Fall study, regardless of treatment. Since cultural practices are much less effective when applied later in the year, it is best to start them in the spring. This timing would also allow extra aerification or verticutting applications to be made in the summer when golfer play is at a minimum. When play is at its peak in the winter, all treatments would be fully recovered and the greens will be at their best.

Table 3-1. Specifications and timings of "spring-summer" cultural practices used on ultradwarf bermudagrass research putting green, 2007.

Treatment	Timing	Tine Spacing (cm)	Tine Depth (cm)	Tine Width (cm)	Surface Area Impacted (%)	Volumetric Area Impacted* (%)	Sand Applied (m^3)
Control	-	-	-	-	-	-	-
Hollow tine	One time: May	5.1	7.6	1.6	7.7	7.7	47.3
Hollow tine	Two times: May, July	5.1	7.6	1.6	15.4	15.4	94.6
Hollow tine	Three times: March, May, July	5.1	7.6	1.6	23.1	23.1	141.9
Verticut	Three times: March, May, July	1.3	2.5	0.2	46.8	15.6	48.8
Solid tine	Five times: March-July	5.1	10.2	1.0	15.7	15.7	39.6

All treatments received grooming 32 times yearly, and an additional 42.7 m^3 (4.3 mm) USGA sand ha^{-1} $year^{-1}$. *Volumetric area impacted is based on a 7.6 cm depth.

Table 3-2. Specifications and timings of "summer-fall" cultural practices used on ultradwarf bermudagrass research putting green, 2007.

Treatment	Timing	Tine Spacing (cm)	Tine Depth (cm)	Tine Width (cm)	Surface Area Impacted (%)	Volumetric Area Impacted* (%)	Sand Applied (m^3)
Control	-	-	-	-	-	-	-
Hollow tine	One time: May	5.1	7.6	1.6	7.7	7.7	47.3
Hollow tine	Two times: May, July	5.1	7.6	1.6	15.4	15.4	94.6
Hollow tine	Three times: March, May, July	5.1	7.6	1.6	23.1	23.1	141.9
Verticut	Three times: March, May, July	1.3	2.5	0.2	46.8	15.6	79.3
Solid tine	Five times: March-July	5.1	7.6	1.0	15.7	15.7	21.4

All treatments received grooming 32 times yearly, and an additional 42.7 m^3 (4.3 mm) USGA sand ha^{-1} $year^{-1}$. *Volumetric area impacted is based on a 7.6 cm depth.

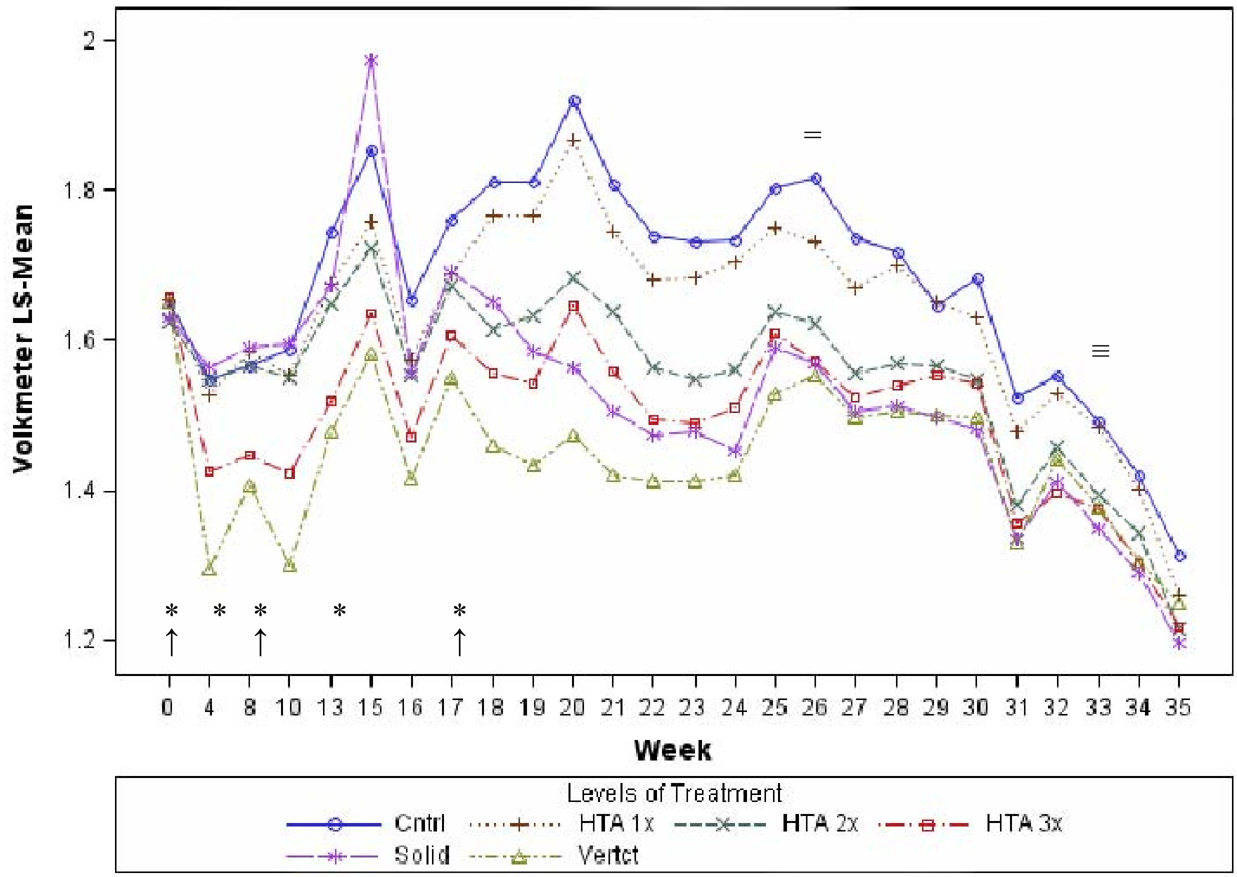

Figure 3-1. Comparison of spring-summer applied cultural practices on surface compressibility (cm). Readings were taken from March 10 to November 16, 2007. Verticutting and hollow tine aerification (HTA) 3x yr^{-1} became statistically similar (P>0.05) at week 26 (=); all treatments became statistically similar (P>0.05) at week 33 (≡). Note firming trend from weeks 26-35 (September 14-November 16). Arrows (↑) indicate HTA and verticutting, while (*) indicate solid tine applications. Table 3-1 shows complete breakdown of treatments.

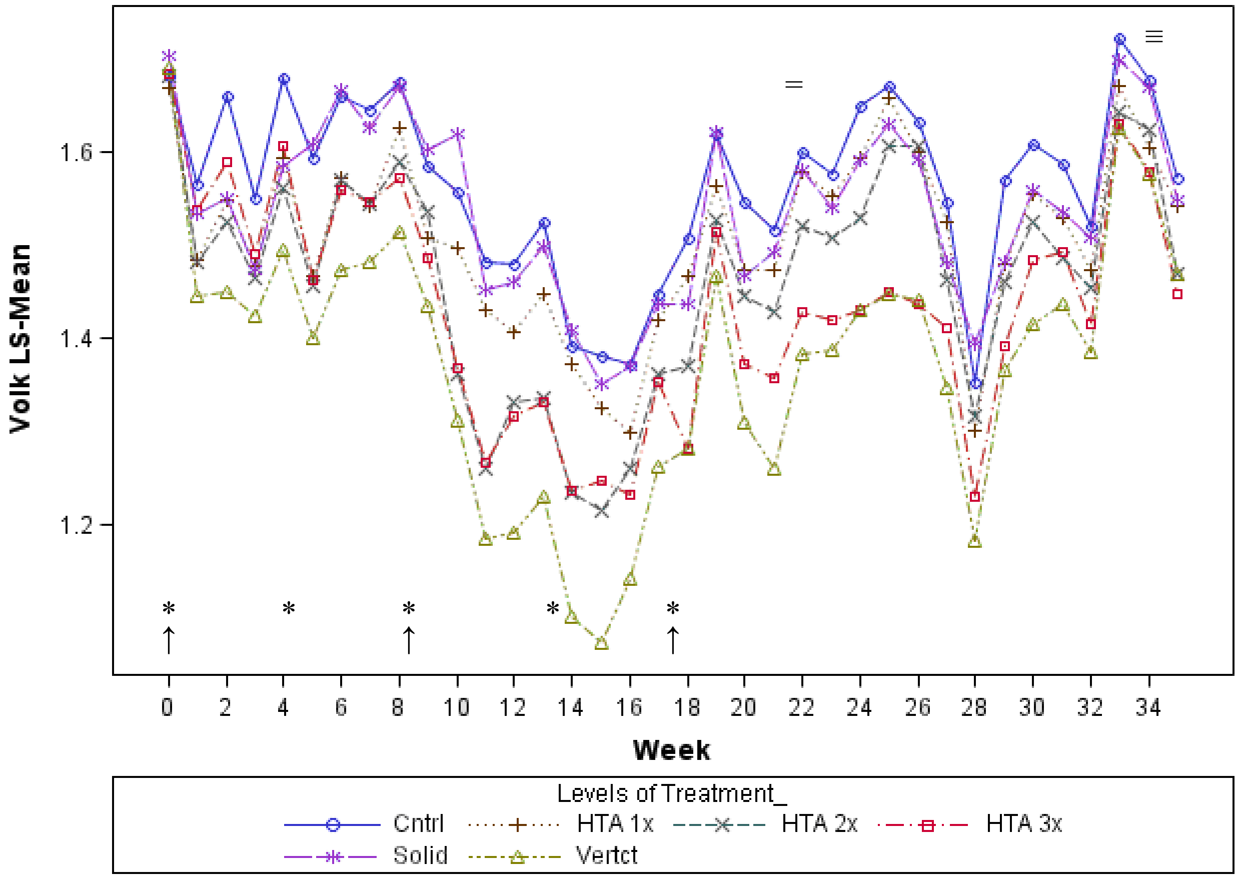

Figure 3-2. Comparison of summer-fall applied cultural practices on surface compressibility (cm). Readings were taken from July 30 to March 31, 2008. Verticutting and hollow tine aerification (HTA) 3x yr^{-1} became statistically similar ($P>0.05$) at week 22 (=); all treatments became statistically similar ($P>0.05$) at week 33 (≡). Note overall firming trend from weeks 6-16 (September 10-November 19). Arrows (↑) indicate HTA and verticutting, while (*) indicate solid tine applications. Table 3-2 shows complete breakdown of treatments.

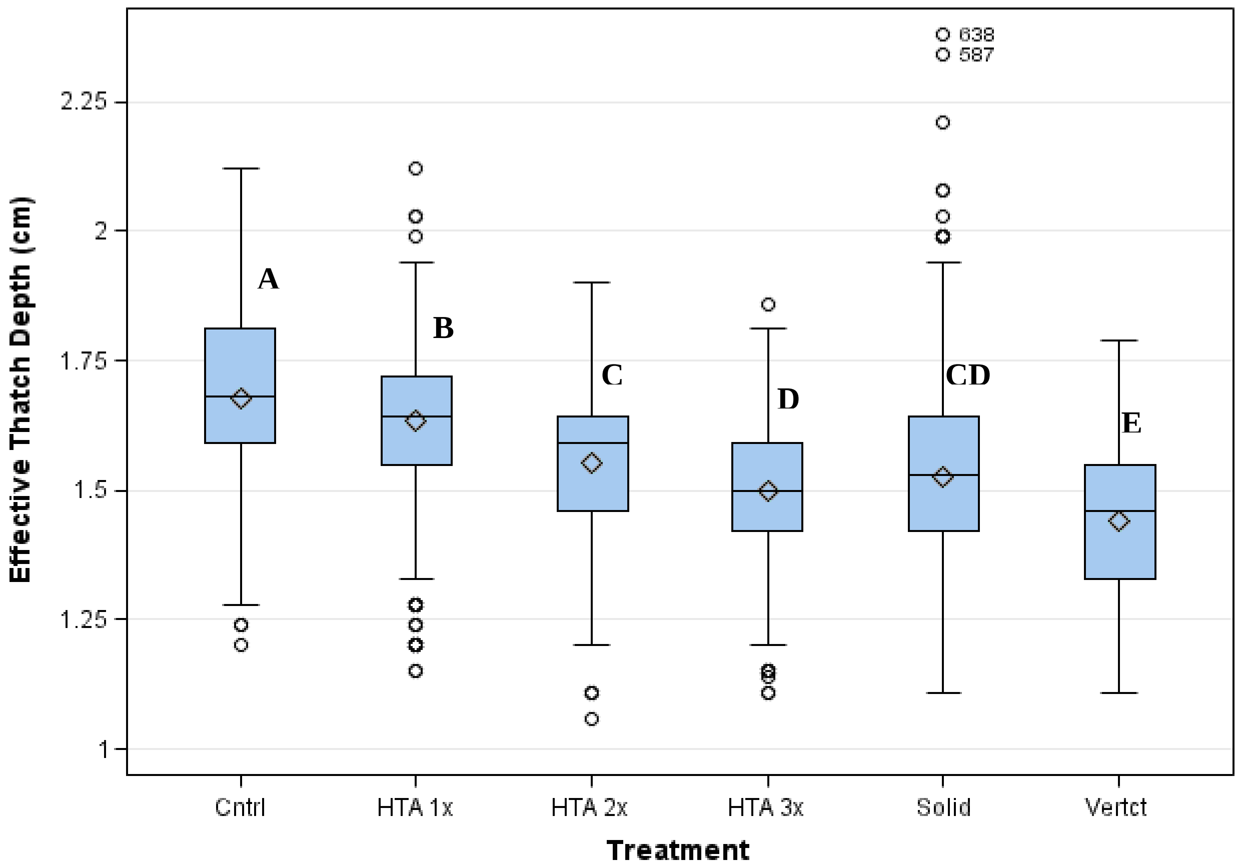

Figure 3-3. Effects of spring-summer applied cultural practices on surface compressibility (cm) determined from average Volkmeter readings over entire study (P<0.05).

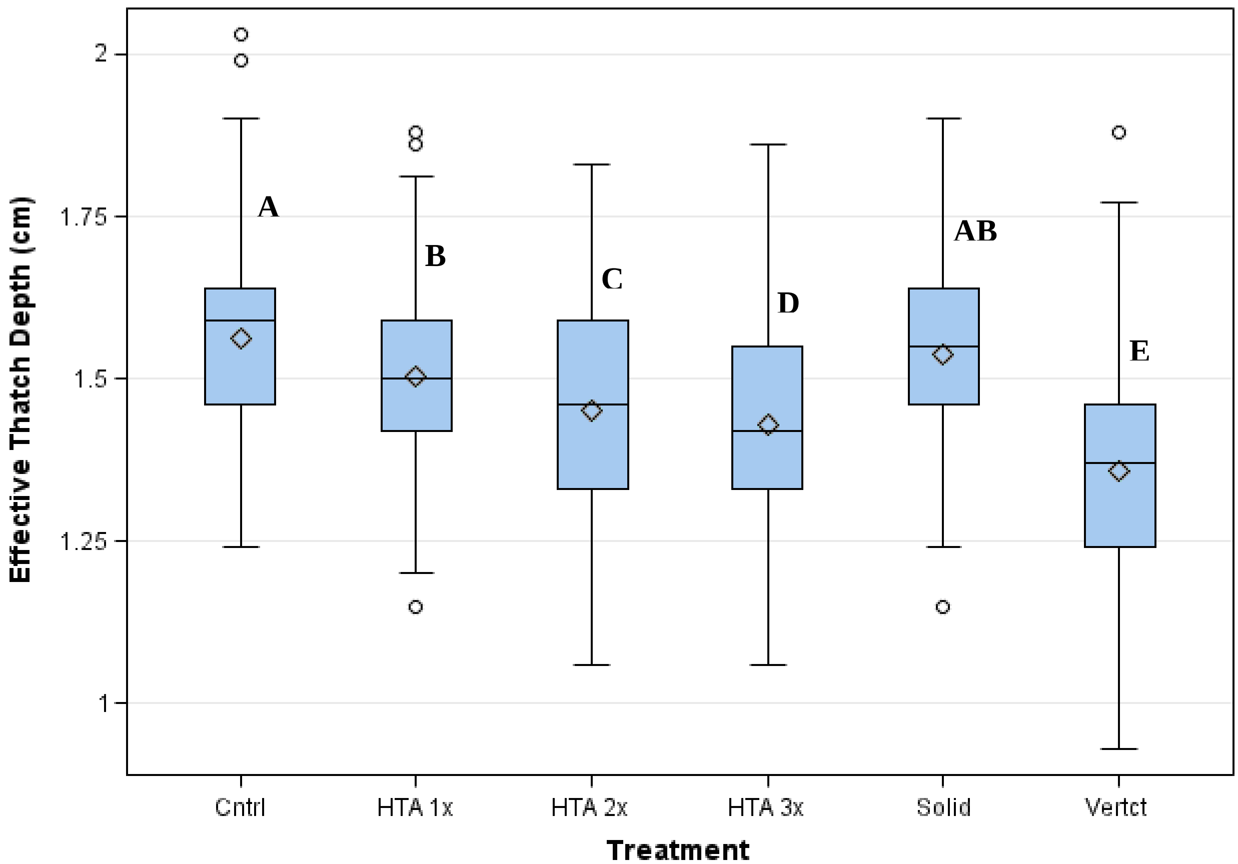

Figure 3-4. Effects of summer-fall applied cultural practices on surface compressibility (cm) determined from Volkmeter readings averaged over entire study (P<0.05).

Table 3-3. Thatch measurements for “spring-summer” and “summer-fall” studies.

Method	Spring-summer		Summer-fall	
	Thatch Depth (cm)			
	Initial	Final	Initial	Final
Volkmeter	1.65	1.61	1.69	1.58
Direct	1.67	1.62	1.66	1.37

Thatch was measured prior to cultural practice treatments and after all treatments were applied and allowed to recover. A weight-based thatch displacement instrument (i.e., Volkmeter) was used along with direct physical measurement.

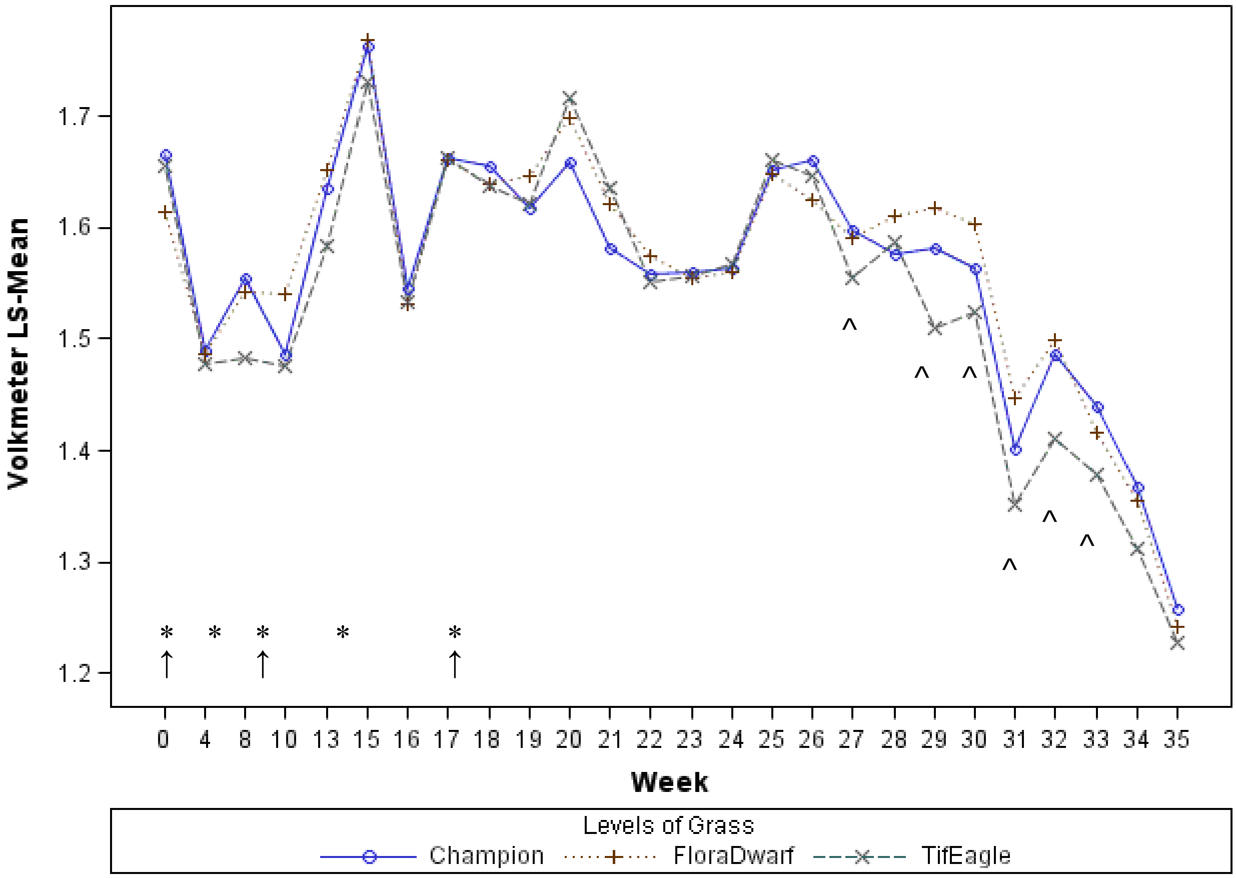

Figure 3-5. Comparison of spring-summer applied cultural practices on surface compressibility (cm) among grasses. Readings were taken from March 10 to November 16, 2007. TifEagle was notably firmer ($P<0.05$) on six occasions (^) after September 14 (week 26), and several times thereafter (data not shown). Note overall firming trend from weeks 26-35 (September 14-November 16). Arrows (↑) indicate hollow tine aerification and verticutting, while (*) indicate solid tine applications. Table 3-1 shows complete breakdown of treatments.

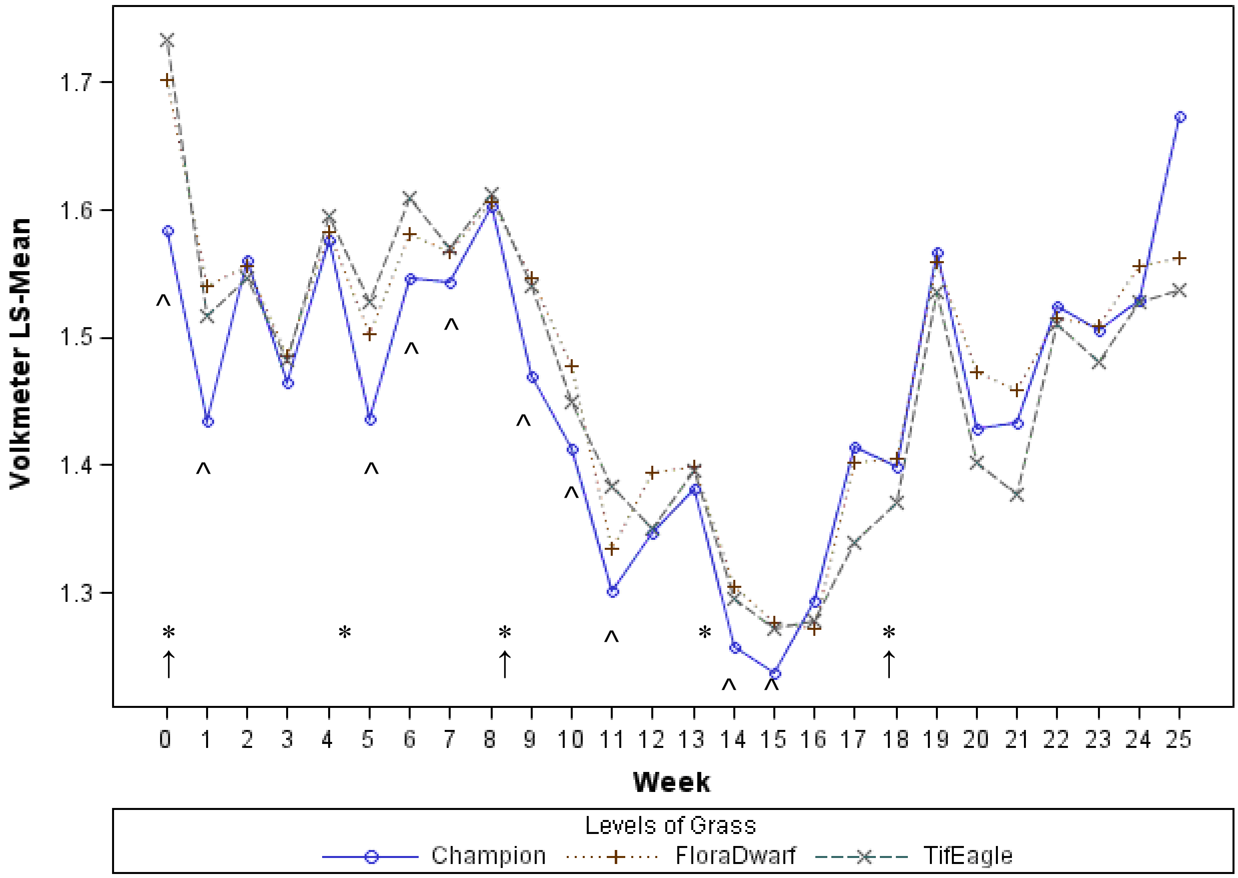

Figure 3-6. Comparison of summer-fall applied cultural practices on surface compressibility (cm) among grasses. Readings were taken from July 30 to March 31, 2008. Champion was notably firmer (P<0.05) on 10 occasions (^) prior to November 12 (week 15) due to plot locations near end of research area. Afterwards TifEagle started to become firmer, as was the case in the Spring-Summer study. Note overall firming trend from weeks 6-16 (September 10-November 19). Arrows (↑) indicate hollow tine aerification and verticutting, while (*) indicate solid tine applications. Table 3-2 shows complete breakdown of treatments.

Table 3-4. Soil organic matter concentration in Ksat cores for "spring-summer" and "summer-fall" studies.

Treatment	Spring-summer		Summer-fall	
	g cm^{-3}			
	Initial	Final	Initial	Final
Hollow Tine Aerification (1x yr^{-1})	3.49 a	3.19 a	2.52 a	3.40 a
Hollow Tine Aerification (2x yr^{-1})	3.32 a	3.15 a	2.75 a	3.40 a
Hollow Tine Aerification (3x yr^{-1})	3.45 a	3.38 a	2.72 a	3.34 a
Control	3.29 a	3.31 a	2.79 a	3.35 a
Verticutting (3x yr^{-1})	3.39 a	3.56 a	2.89 a	3.32 a
Solid Tine Aerification (5x yr^{-1})	3.36 a	3.03 a	2.80 a	3.30 a
	P=0.67	P=0.31	P=0.87	P=0.89
Grass				
Champion	3.58 a	3.52 a	2.89 a	3.36 a
FloraDwarf	3.24 b	3.10 a	2.70 a	3.32 a
TifEagle	3.33 b	3.19 a	2.65 a	3.37 a
	P=0.001	P=0.11	P=0.60	P=0.88

Mean estimates with same letter within column are not statistically different, at 0.05 significance level, using Tukey-Kramer method.

Table 3-5. Soil organic matter concentration in dark layer cores for “spring-summer” and “summer-fall” studies.

Treatment	Spring-summer		Summer-fall	
	$g\ cm^{-3}$			
	Initial	Final	Initial	Final
Hollow Tine Aerification ($1x\ yr^{-1}$)	5.11 a	3.75 a	4.22 a	4.95 a
Hollow Tine Aerification ($2x\ yr^{-1}$)	4.69 a	3.95 a	4.28 a	5.03 a
Hollow Tine Aerification ($3x\ yr^{-1}$)	4.29 a	3.42 a	4.51 a	4.75 a
Control	4.69 a	4.10 a	4.56 a	5.13 a
Verticutting ($3x\ yr^{-1}$)	4.29 a	3.86 a	3.98 a	5.12 a
Solid Tine Aerification ($5x\ yr^{-1}$)	5.11 a	4.00 a	4.21 a	5.75 a
	P=0.38	P=0.53	P=0.10	P=0.23
Grass				
Champion	4.71 a	3.83 a	4.74 a	5.39 a
FloraDwarf	4.42 a	3.85 a	3.97 a	4.98 a
TifEagle	4.96 a	3.86 a	4.17 a	5.00 a
	P=0.11	P=0.99	P=0.08	P=0.50

Mean estimates with same letter within column are not statistically different, at 0.05 significance level, using Tukey-Kramer method.

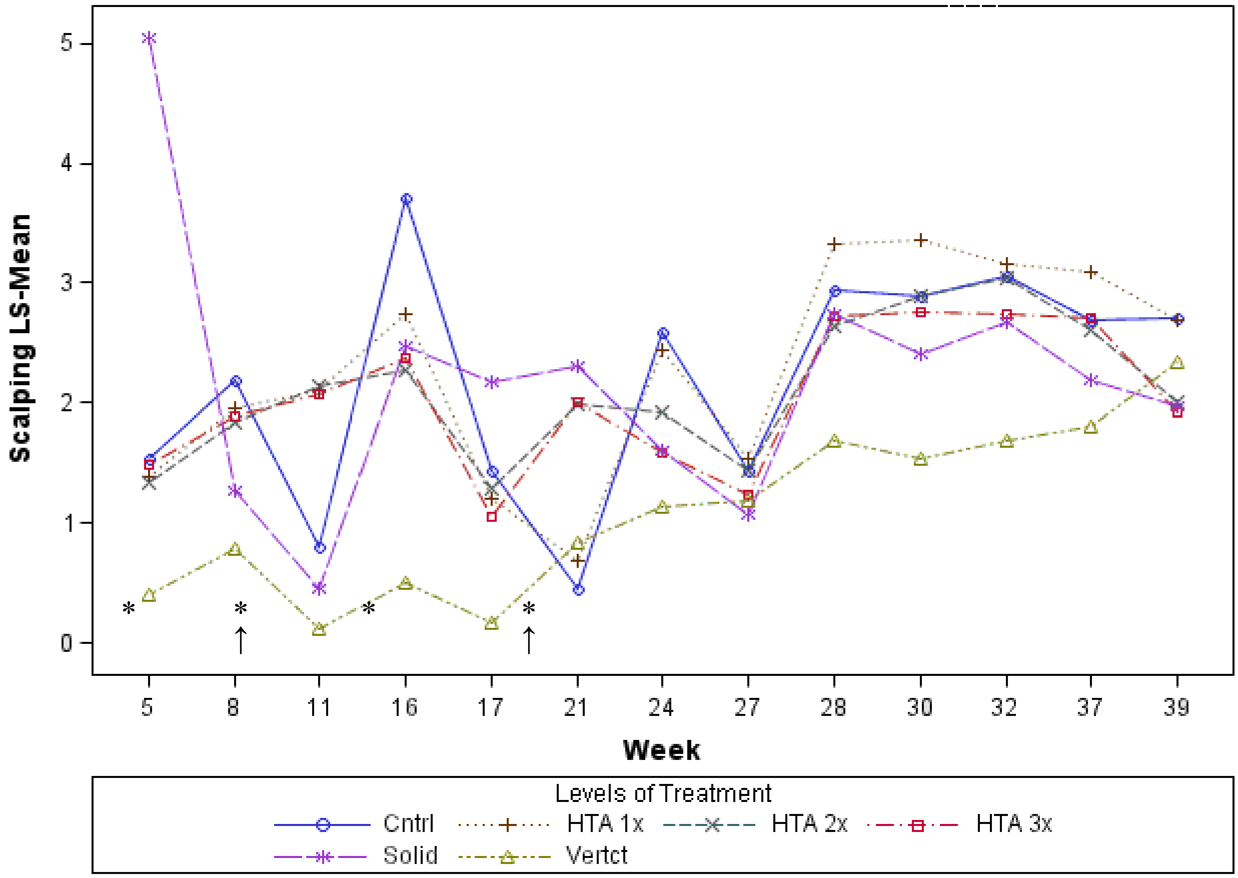

Figure 3-7. Comparison of spring-summer applied cultural practices on mower scalping (tissue loss). Ratings 0-9 (0 = no scalping, and 9 = completely scalped) were taken from April 15 to December 14, 2007. Arrows (↑) indicate hollow tine aerification and verticutting, while (*) indicate solid tine applications. Table 3-1 shows complete breakdown of treatments.

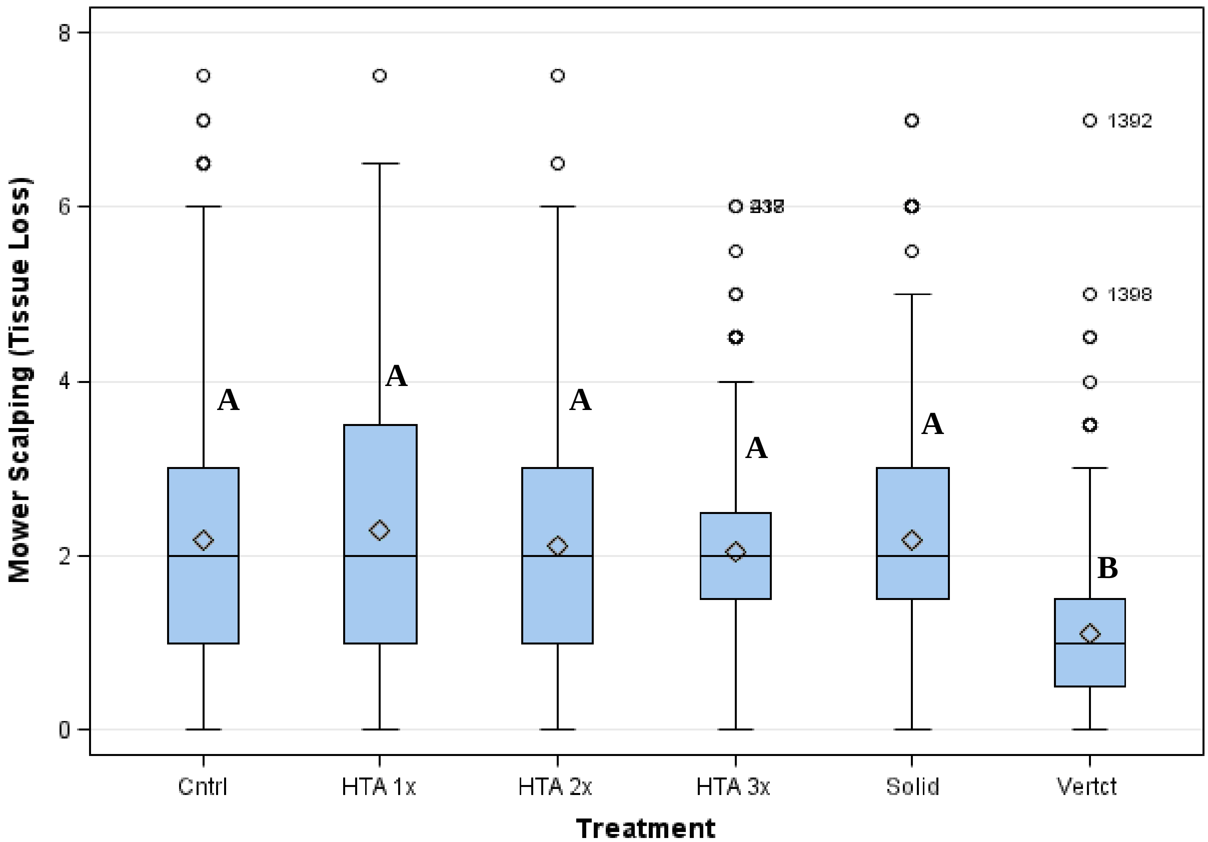

Figure 3-8. Effects of spring-summer applied cultural practices on mower scalping (tissue loss). Ratings 0-9 (0 = no scalping, and 9 = completely scalped) indicate average mower scalping from April 15 to December 14, 2007. Verticutting scalped least (P<0.01).

Figure 3-9. Severe mower scalping on all cultural treatment plots except verticutting.

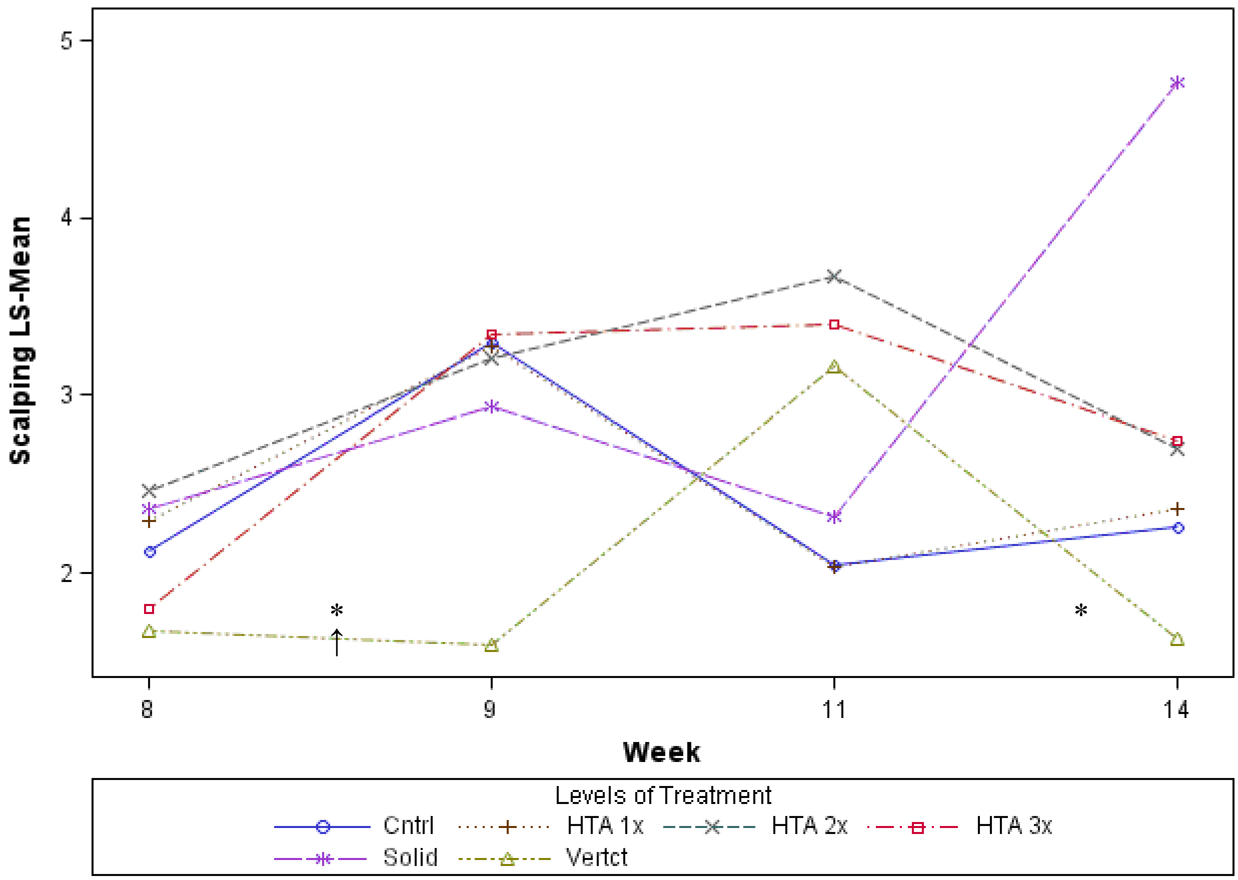

Figure 3-10. Comparison of summer-fall applied cultural practices on mower scalping (tissue loss). Ratings 0-9 (0 = no scalping, and 9 = completely scalped) were taken from September 24 to November 5, 2007. Arrows (↑) indicate hollow tine aerification and verticutting, while (*) indicate solid tine applications. Table 3-2 shows complete breakdown of treatments.

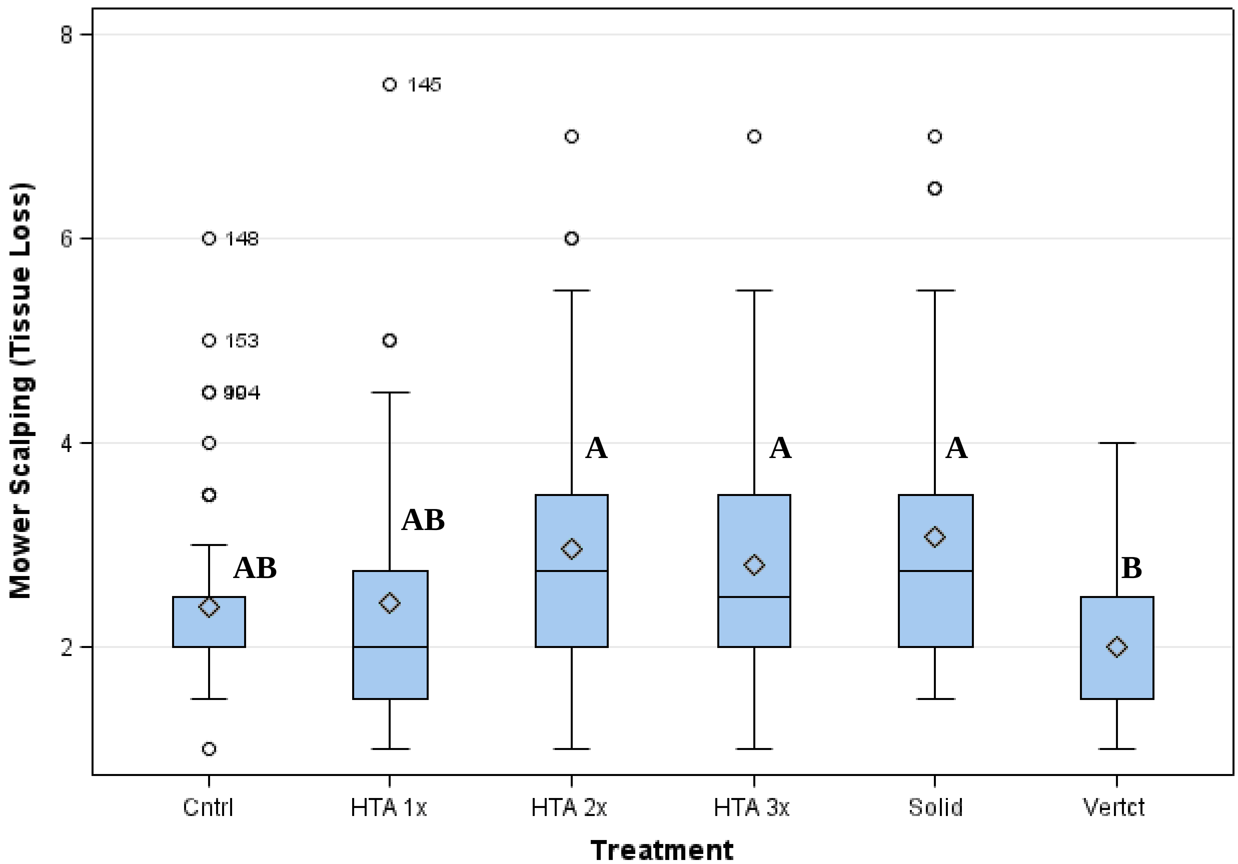

Figure 3-11. Effects (P<0.05) of summer-fall applied cultural practices on mower scalping (tissue loss). Ratings 0-9 (0 = no scalping, and 9 = completely scalped) indicate average mower scalping from September 24 to November 5, 2007.

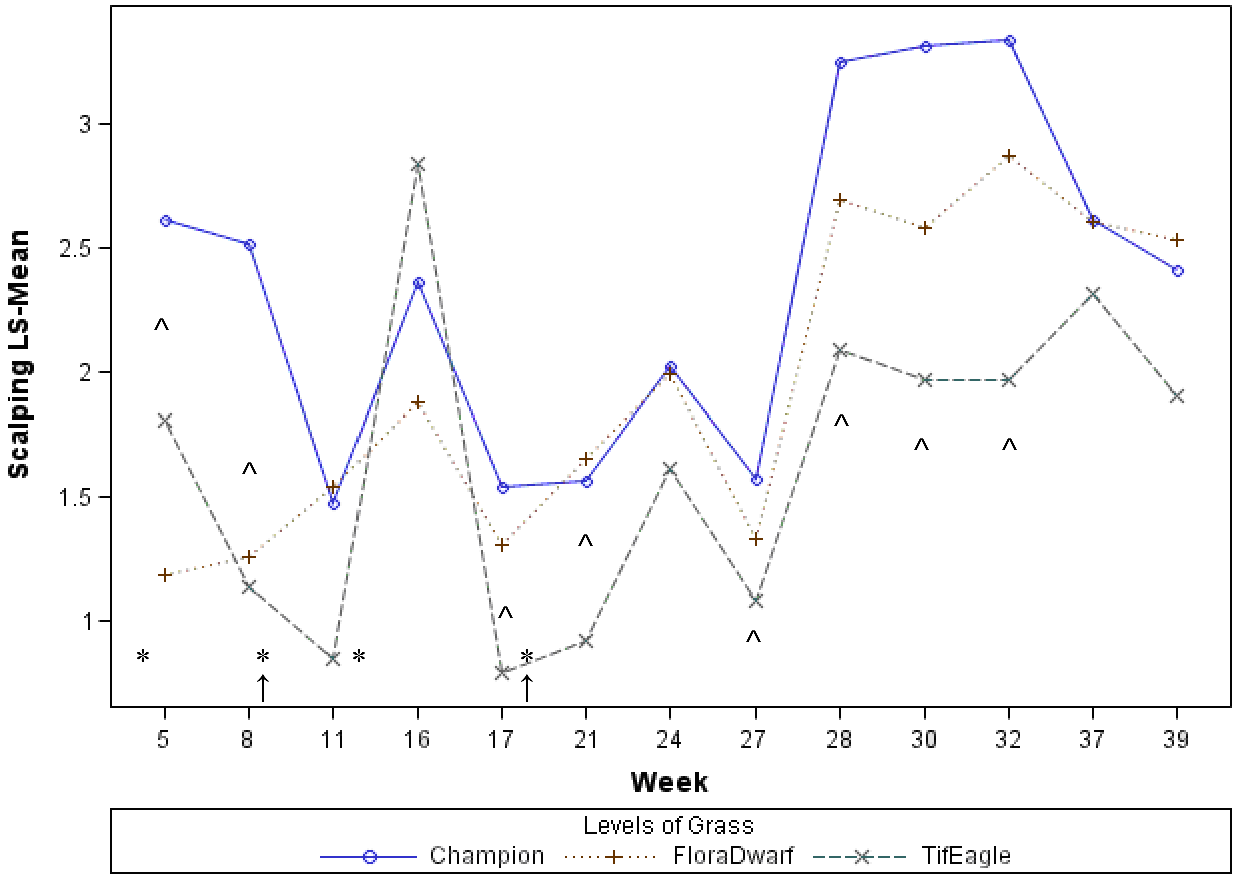

Figure 3-12. Comparison of spring-summer applied cultural practices on scalping (tissue loss) among grasses. Ratings 0-9 (0 = no scalping, and 9 = completely scalped) were taken from April 15 to December 14, 2007. Champion and TifEagle were significantly different (P<0.05) on eight occasions as indicated by (^). Arrows (↑) indicate hollow tine aerification and verticutting, while (*) indicate solid tine applications. Table 3-1 shows complete breakdown of treatments.

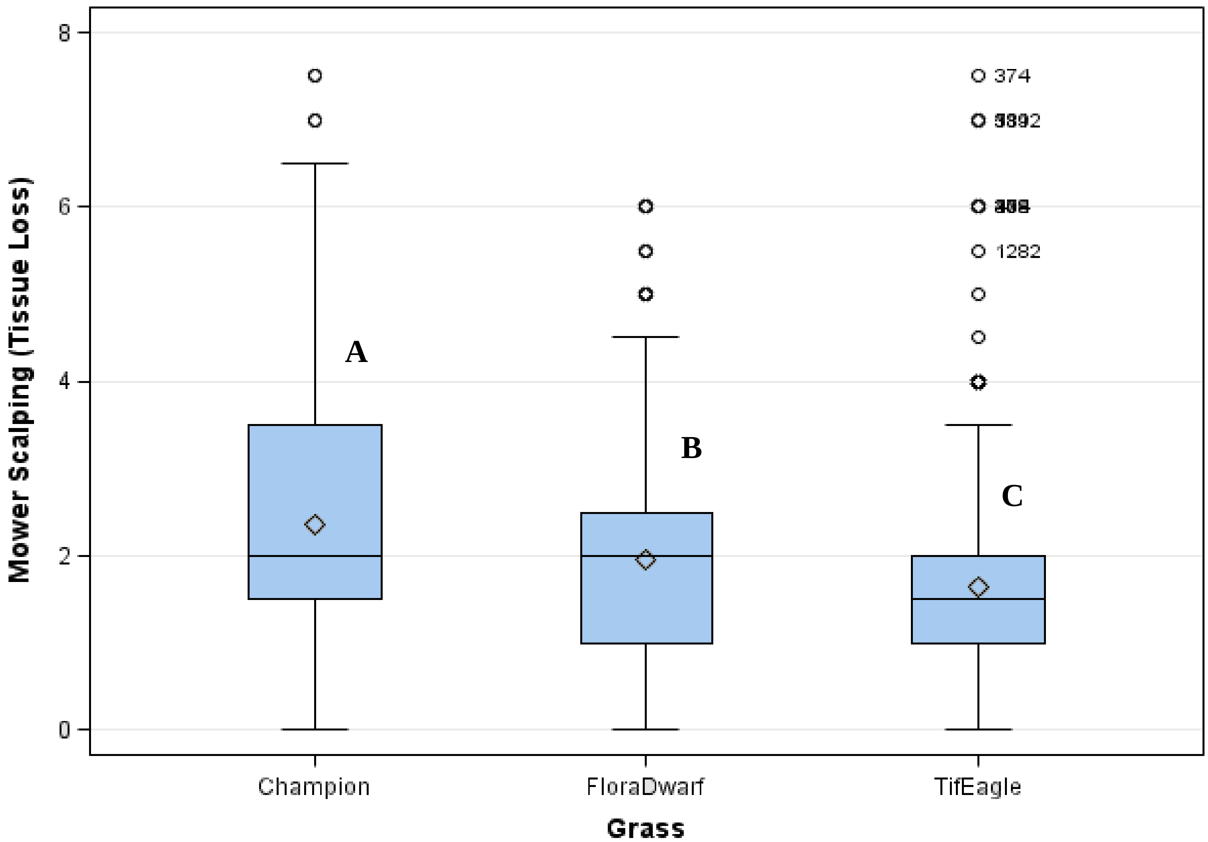

Figure 3-13. Effects of spring-summer applied cultural practices on mower scalping (tissue loss) among grasses. Ratings 0-9 (0 = no scalping, and 9 = completely scalped) indicate average mower scalping from April 15 to December 14, 2007. TifEagle had less (P<0.05) mower scalping than FloraDwarf, which had less (P<0.05) than Champion.

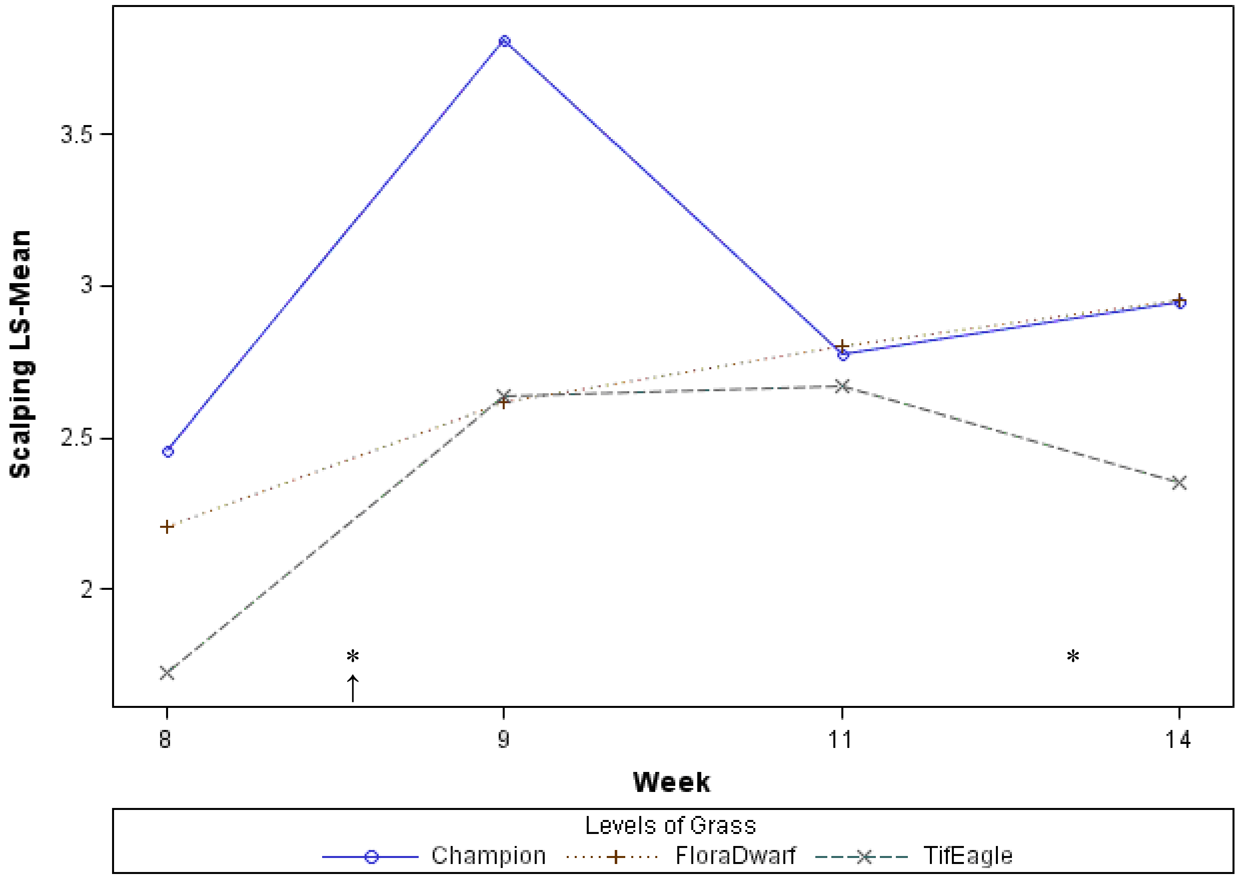

Figure 3-14. Comparison of summer-fall applied cultural practices on mower scalping (tissue loss) among grasses. Ratings 0-9 (0 = no scalping, and 9 = completely scalped) were taken from September 24 to November 5, 2007. TifEagle scalped least (P<0.10) on weeks 8, and 14. Arrows (↑) indicate hollow tine aerification and verticutting, while (*) indicate solid tine applications. Table 3-2 shows complete breakdown of treatments.

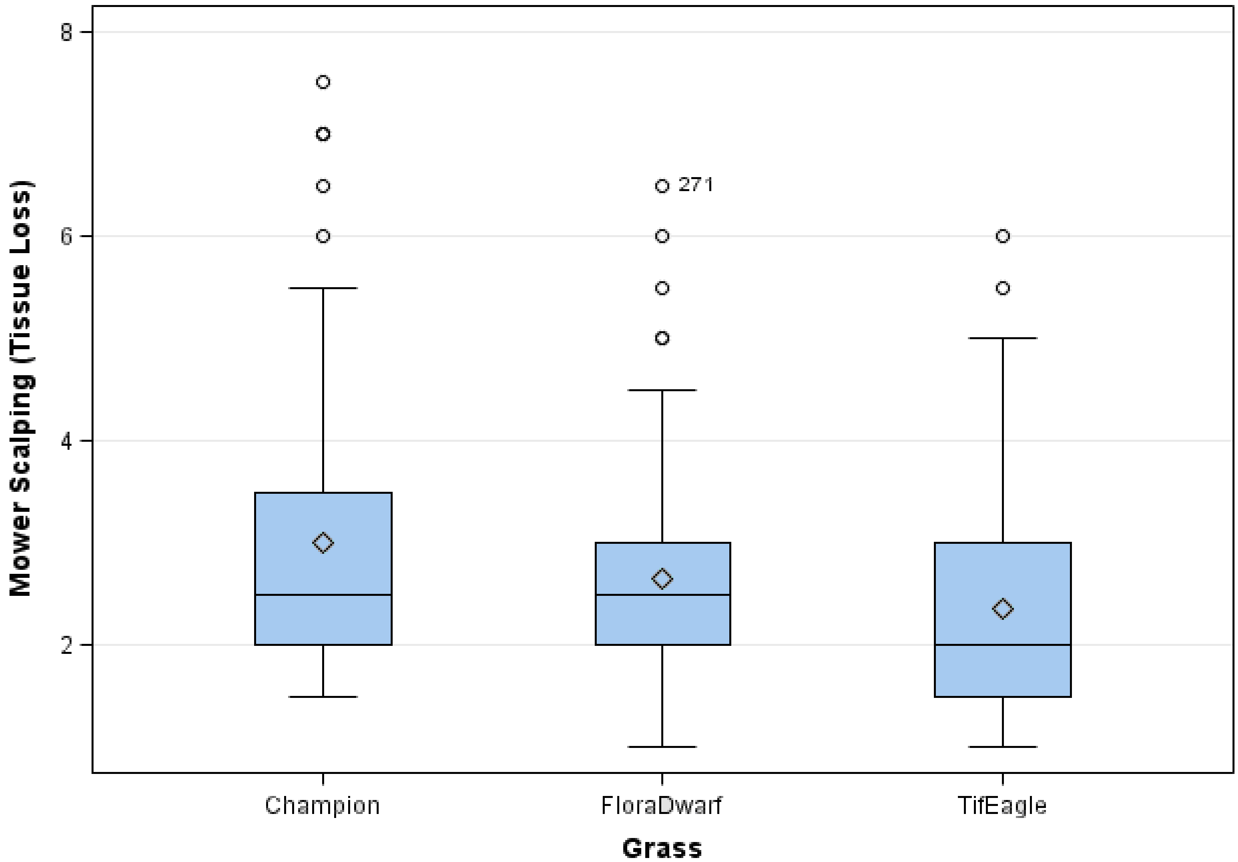

Figure 3-15. Effects of summer-fall applied cultural practices on scalping (tissue loss) among grasses. Ratings 0-9 (0 = no scalping, and 9 = completely scalped) indicate mower scalping averaged from September 24 to December 5, 2007 (P=0.09).

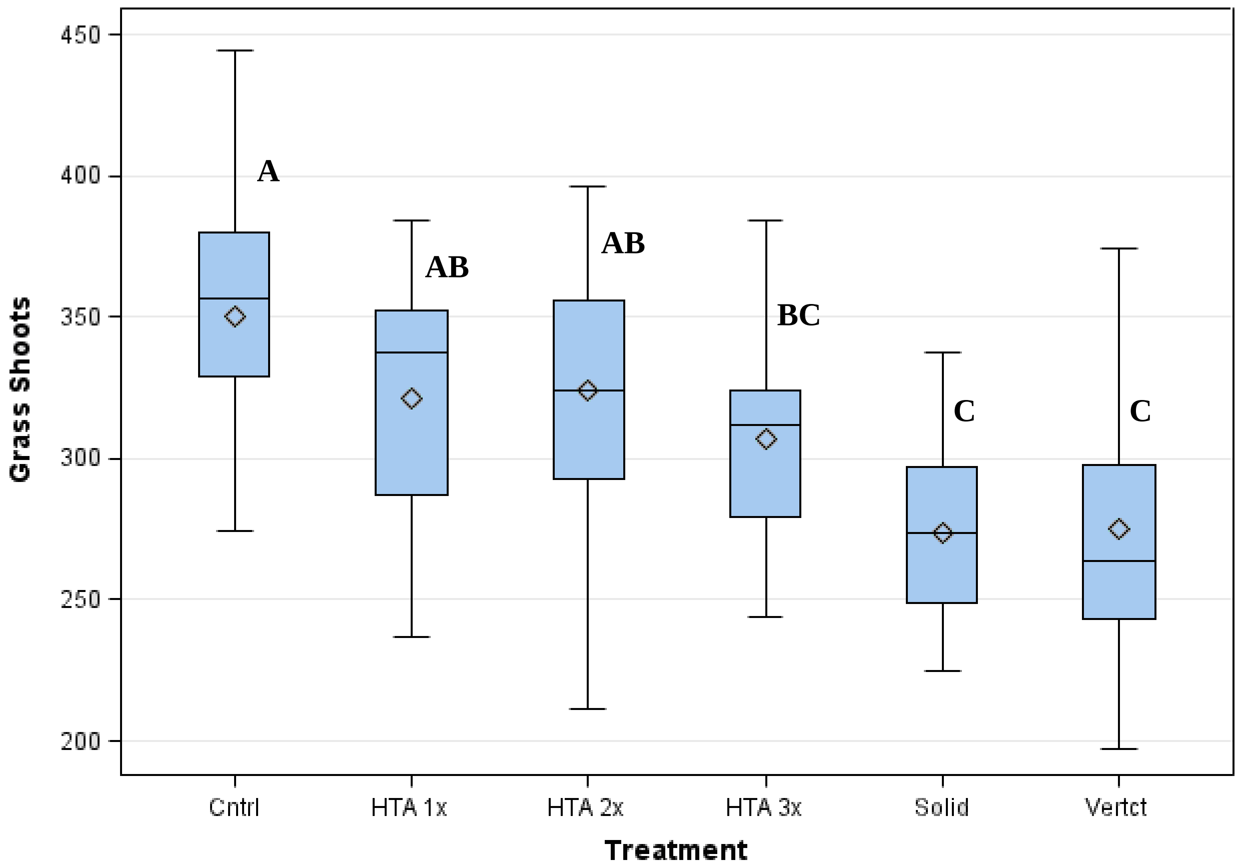

Figure 3-16. Bermudagrass shoots counted from 20 cm^{-2} cores after spring-summer cultural practices were applied, and allowed to recover ($P<0.01$).

Table 3-6. Shoot counts for “spring-summer” and “summer-fall” studies.

Treatment	Spring-Summer	Summer-Fall
Hollow Tine Aerification (1x yr^{-1})	321 ab	312 a
Hollow Tine Aerification (2x yr^{-1})	324 ab	347 a
Hollow Tine Aerification (3x yr^{-1})	307 bc	342 a
Control	350 a	325 a
Verticutting (3x yr^{-1})	275 c	342 a
Solid Tine Aerification (5x yr^{-1})	273 c	317 a
	$P<0.0001$	$P=0.55$
Grass		
Champion	321 a	341 a
FloraDwarf	300 a	320 a
TifEagle	304 a	331 a
	$P=0.24$	$P=0.35$

Bermudagrass shoot counts taken from 20 cm^{-2} cores. Mean estimates with same letter within column are not statistically different at 0.05 significance level using Tukey-Kramer method.

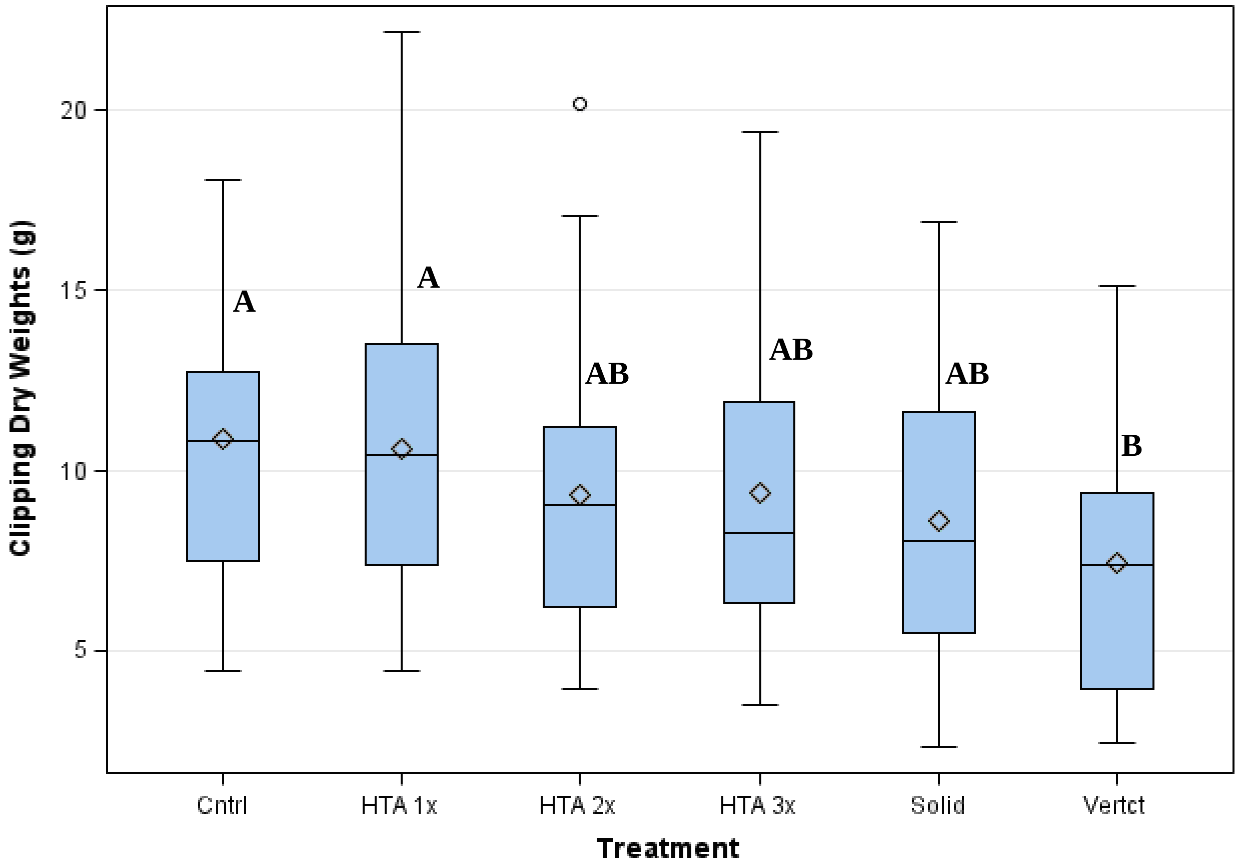

Figure 3-17. Effects of spring-summer applied cultural practices on bermudagrass clipping oven dry weights (P<0.05).

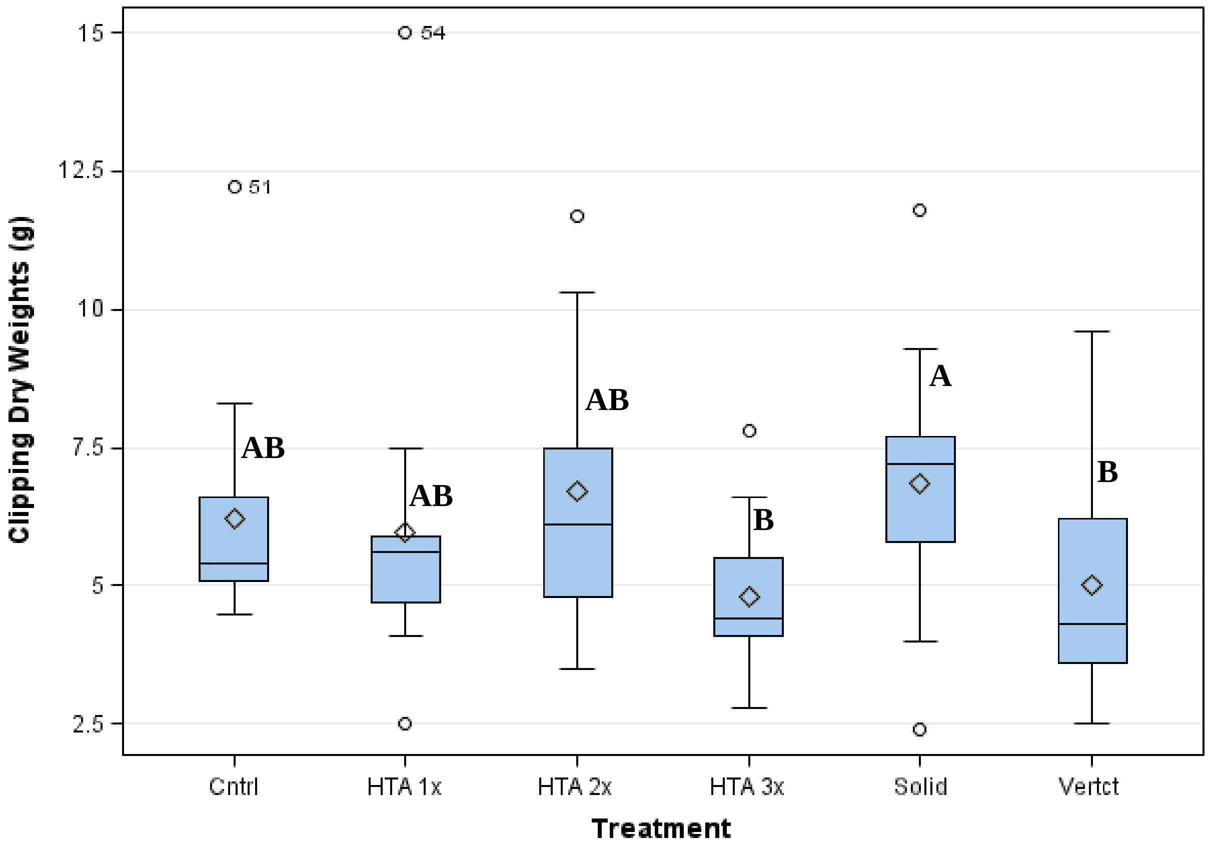

Figure 3-18. Effects of summer-fall applied cultural practices on bermudagrass clipping oven dry weights (P<0.05).

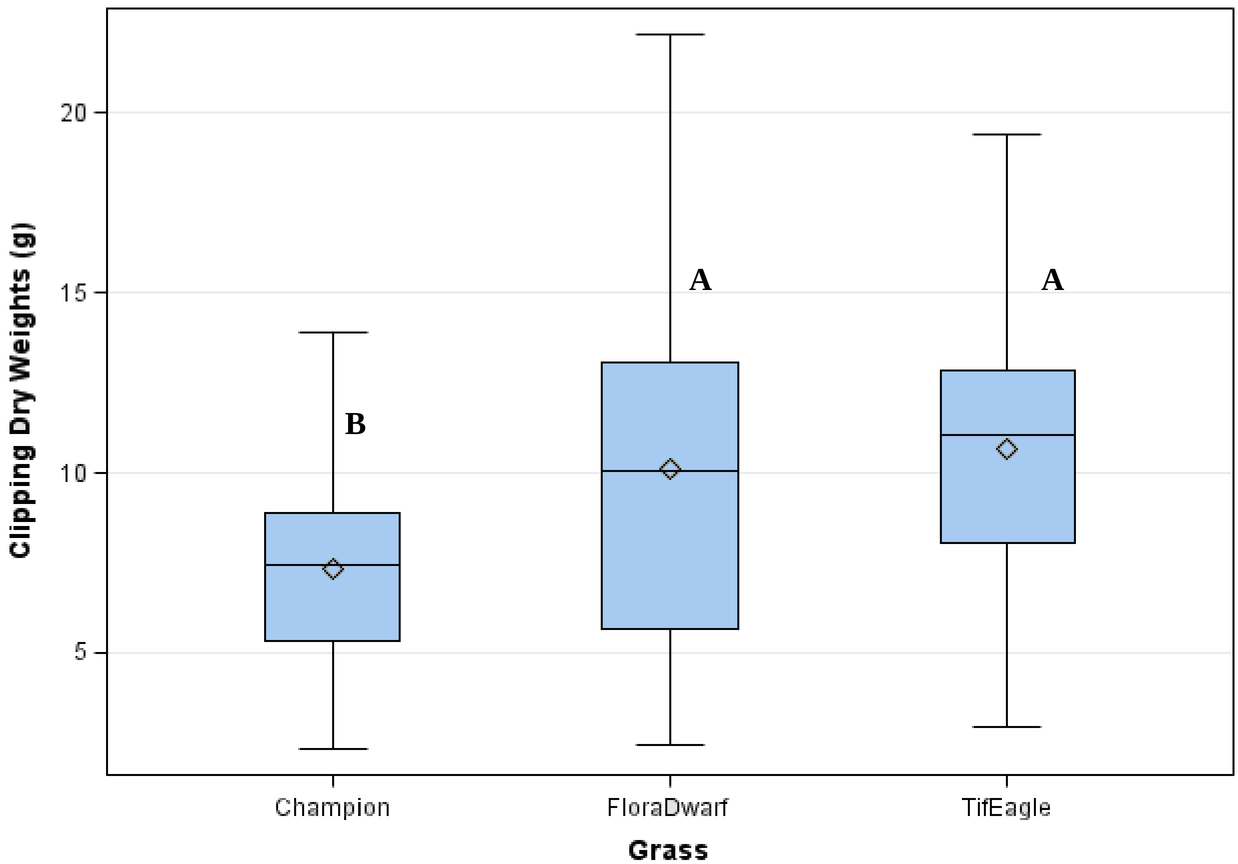

Figure 3-19. Effects of spring-summer applied cultural practices on bermudagrass clipping oven dry weights among grasses (P<0.05).

Table 3-7. Ball roll (cm) for "spring-summer" and "summer-fall" studies.

Treatment	Spring-summer	Summer-fall
	cm	
Hollow Tine Aerification (1x yr^{-1})	53 a	69 a
Hollow Tine Aerification (2x yr^{-1})	56 a	67 a
Hollow Tine Aerification (3x yr^{-1})	55 a	68 a
Control	56 a	68 a
Verticutting (3x yr^{-1})	57 a	69 a
Solid Tine Aerification (5x yr^{-1})	54 a	67 a
	P=0.20	P=0.90
Grass		
Champion	54 a	68 a
FloraDwarf	57 a	68 a
TifEagle	55 a	67 a
	P=0.29	P=0.89

Ball roll distances (cm) taken with a 19-cm modified USGA stimpmeter. Mean estimates with same letter within column are not statistically different at 0.05 significance level using Tukey-Kramer method.

Table 3-8. Root weights (g) for “spring-summer” and “summer-fall” studies.

Treatment	Spring-summer	Summer-fall
	g	
Hollow Tine Aerification (1x yr^{-1})	6.7 a	18.8 a
Hollow Tine Aerification (2x yr^{-1})	6.8 a	18.0 a
Hollow Tine Aerification (3x yr^{-1})	7.0 a	19.2 a
Control	7.7 a	19.2 a
Verticutting (3x yr^{-1})	8.3 a	21.2 a
Solid Tine Aerification (5x yr^{-1})	6.2 a	18.7 a
	P=0.05	P=0.18
Grass		
Champion	8.0 a	26.3 a
FloraDwarf	6.9 a	14.7 a
TifEagle	6.6 a	16.5 a
	P=0.30	P=0.15

Oven dry root weights (g) taken from cup cutter cores. Mean estimates with same letter within column are not statistically different at 0.05 significance level using Tukey-Kramer method.

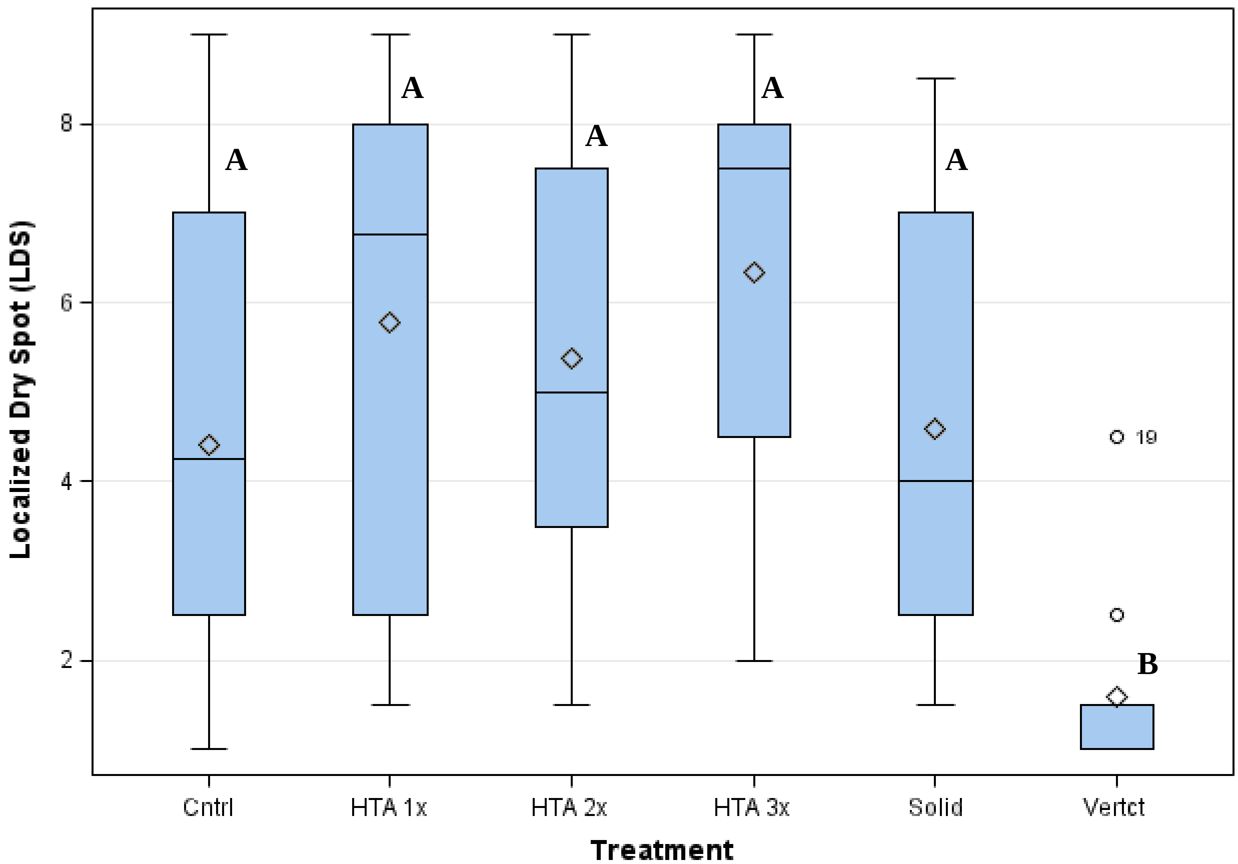

Figure 3-20. Effects of spring-summer applied cultural practices on localized dry spot (P<0.01). Ratings: 1-10 (1 = least symptoms, and 10 = most symptoms).

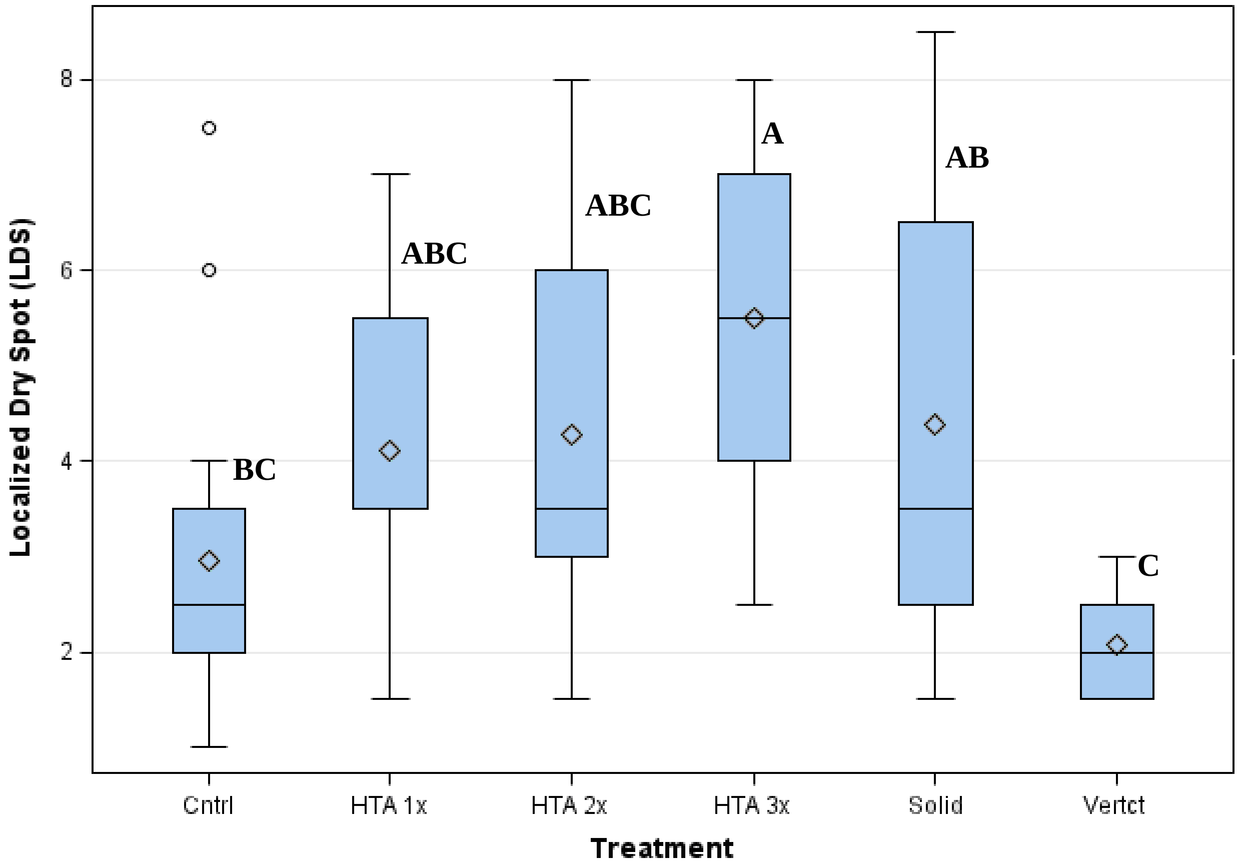

Figure 3-21. Effects of summer-fall applied cultural practices on localized dry spot (P<0.01). Ratings: 1-10 (1 = least symptoms, and 10 = most symptoms).

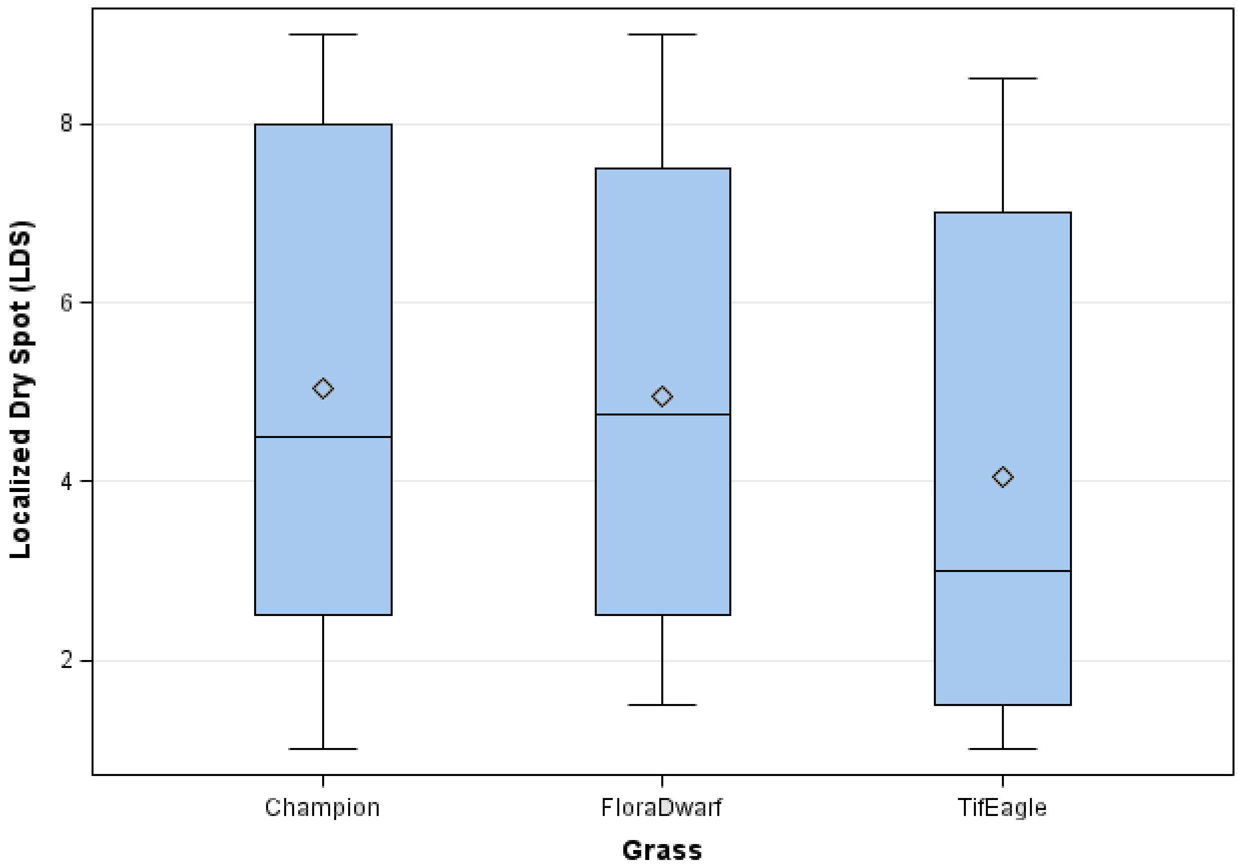

Figure 3-22. Effects of spring-summer applied cultural practices on localized dry spot among grasses (P<0.10). Ratings: 1-10 (1 = least symptoms, and 10 = most symptoms).

Table 3-9. Localized dry spot for “spring-summer” and “summer-fall” studies.

Treatment	Spring-summer	Summer-fall
	g	
Hollow Tine Aerification (1x yr^{-1})	5.8 a	4.0 ab
Hollow Tine Aerification (2x yr^{-1})	5.4 a	4.2 ab
Hollow Tine Aerification (3x yr^{-1})	6.3 a	5.4 a
Control	4.4 a	3.0 ab
Verticutting (3x yr^{-1})	1.6 b	2.2 b
Solid Tine Aerification (5x yr^{-1})	4.6 a	4.3 ab
	$P<0.0001$	$P=0.008$
Grass		
Champion	5.0 a	3.6 a
FloraDwarf	4.9 a	4.2 a
TifEagle	4.0 a	3.8 a
	$P=0.09$	$P=0.66$

Localized dry spot ratings: 1-10 (10 = Complete Plot Coverage). Mean estimates with same letter within column are not statistically different at 0.05 significance level using Tukey-Kramer method.

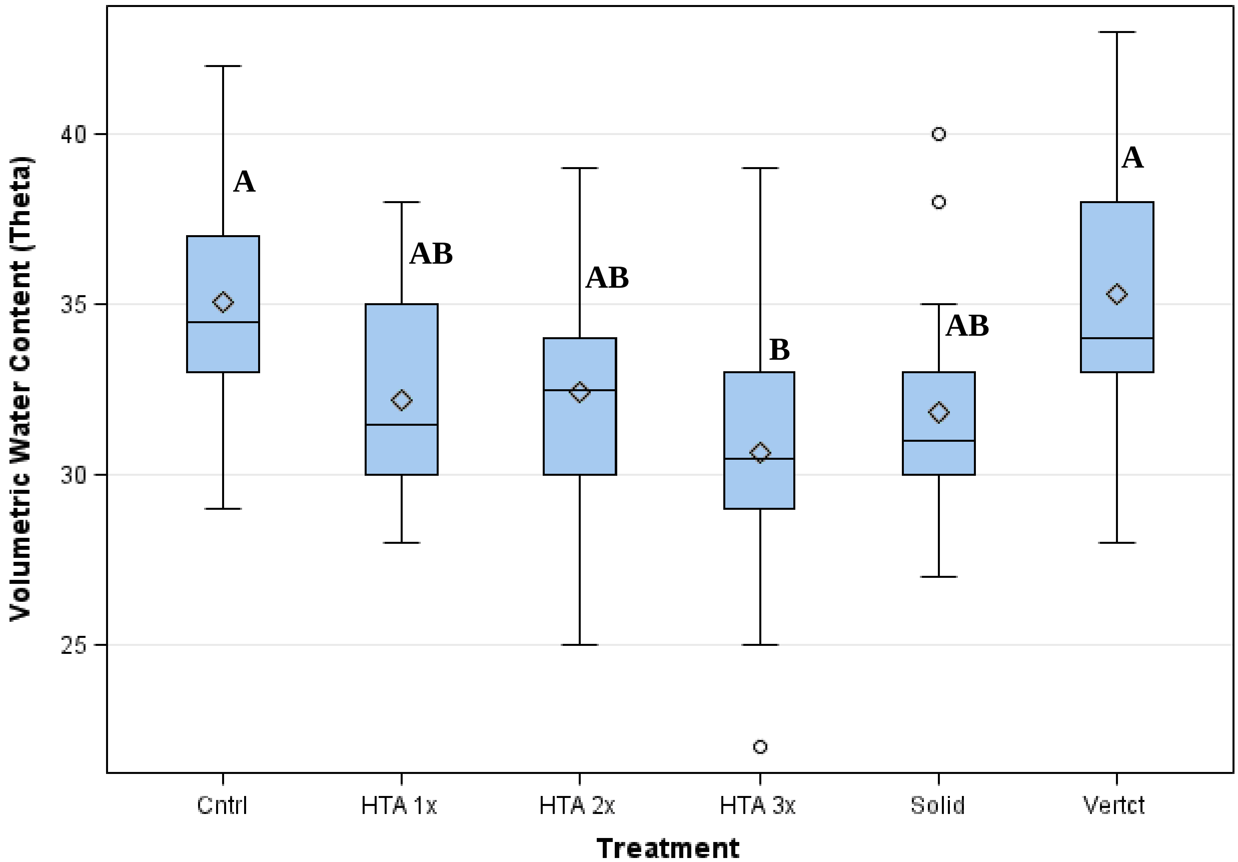

Figure 3-23. Effects of spring-summer applied cultural practices on volumetric water content (P<0.01). Ratings: 1-10 (1 = least symptoms, and 10 = most symptoms). Readings taken on November 9, 2007.

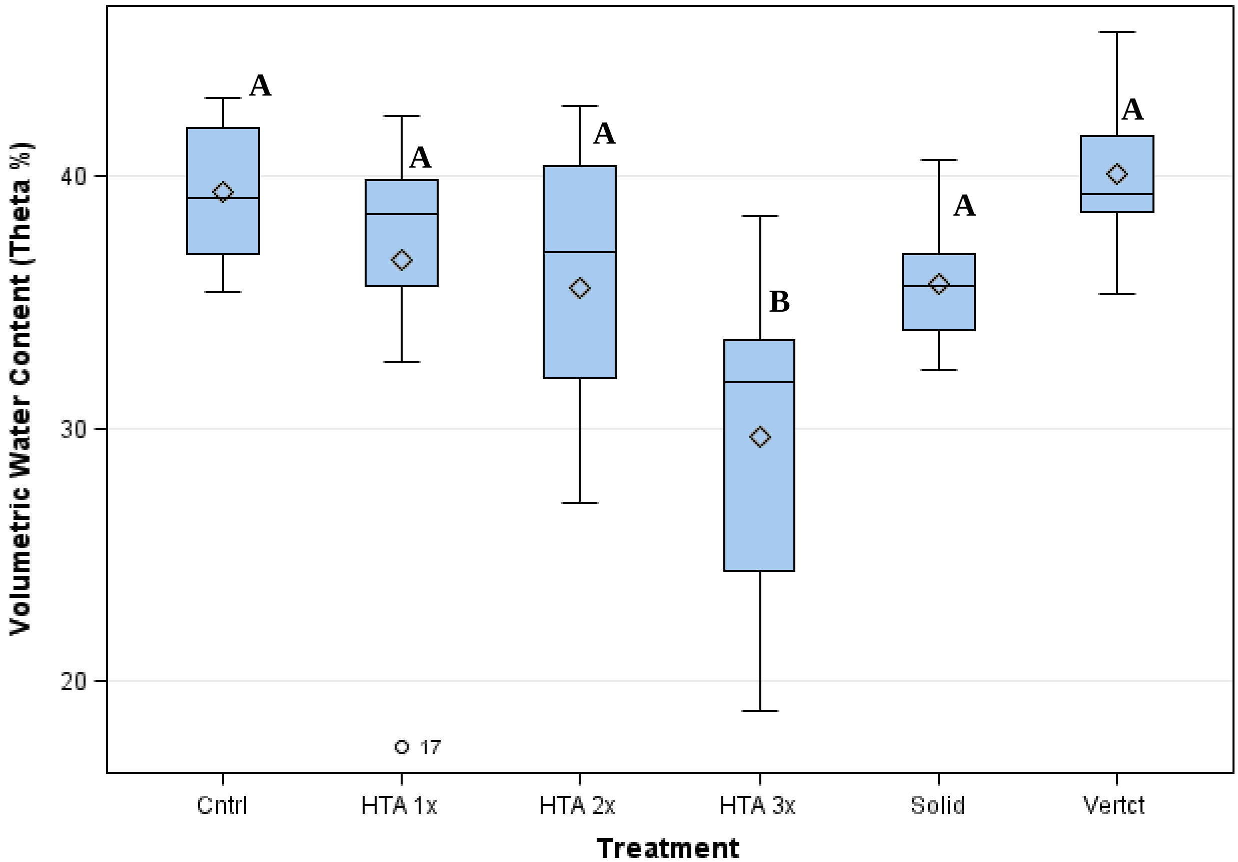

Figure 3-24. Effects of summer-fall applied cultural practices on volumetric water content (P<0.01). Readings taken on February 4, 2008.

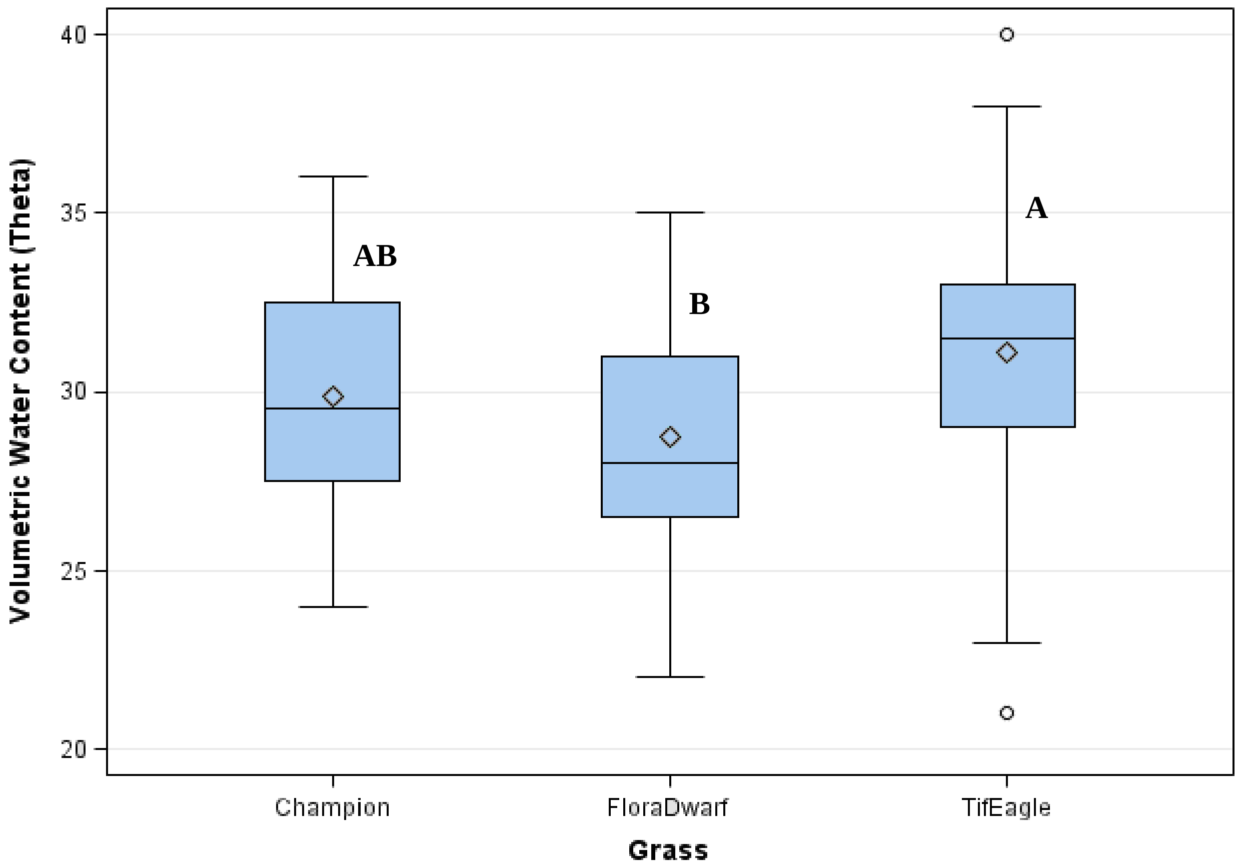

Figure 3-25. Effects of spring-summer applied cultural practices on volumetric water content among grasses (P<0.05). Readings taken on November 21, 2007.

Table 3-10. Volumetric water content (Theta) readings for “spring-summer” and “summer-fall” studies.

Treatment	Spring-summer	Summer-fall
	g	
Hollow Tine Aerification (1x yr^{-1})	32.2 ab	36.8 a
Hollow Tine Aerification (2x yr^{-1})	32.4 ab	35.5 a
Hollow Tine Aerification (3x yr^{-1})	30.7 b	29.1 b
Control	35.1 a	39.3 a
Verticutting (3x yr^{-1})	35.3 a	39.6 a
Solid Tine Aerification (5x yr^{-1})	31.8 ab	35.4 a
	P=0.002	P=0.0002
Grass		
Champion	29.9 ab	36.3 a
FloraDwarf	28.7 b	36.3 a
TifEagle	31.1 a	35.2 a
	P=0.03	P=0.72

Volumetric water content (Theta) readings: % soil saturation. Mean estimates with same letter within column are not statistically different at 0.05 significance level using Tukey-Kramer method.

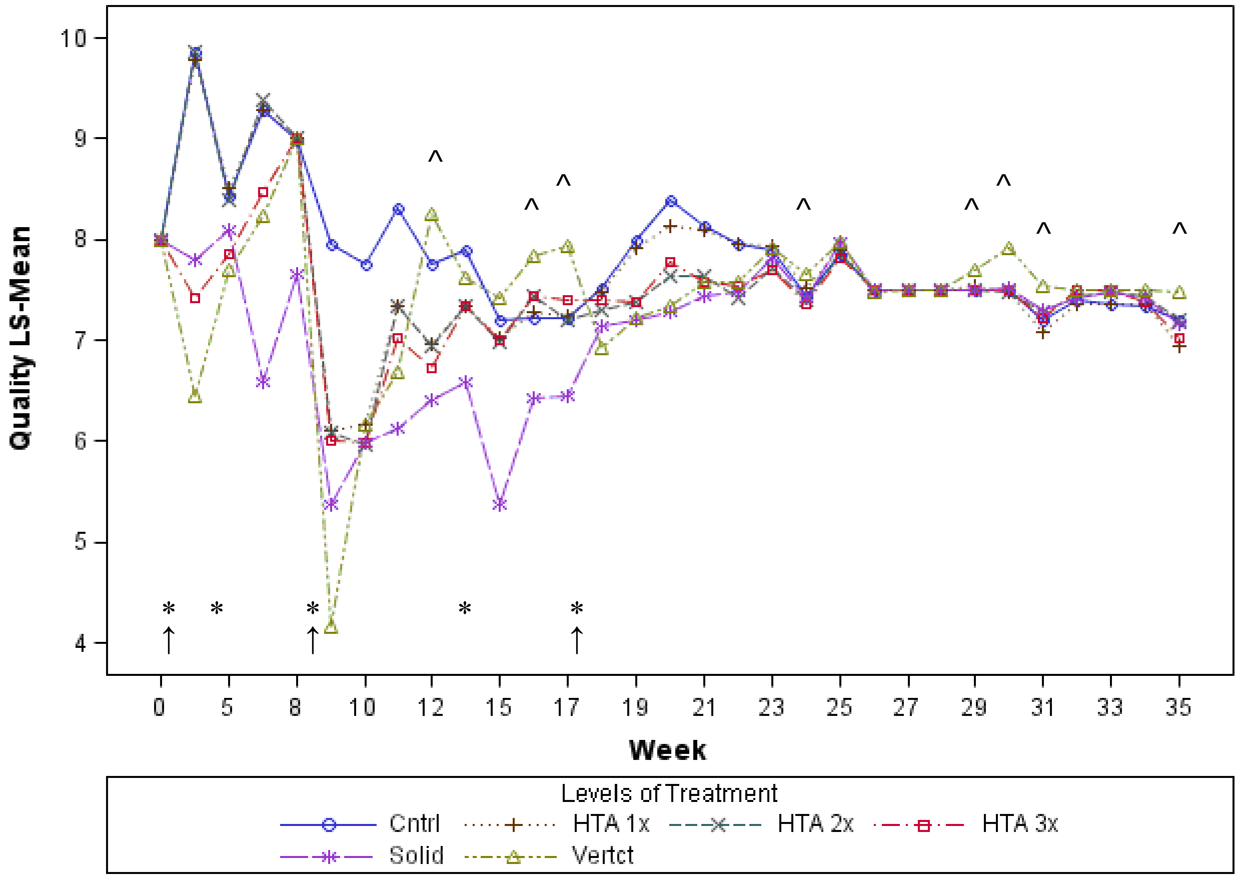

Figure 3-26. Effects of spring-summer applied cultural practices on quality. Ratings 1-10 (1 = Dead, 6 = Minimum Acceptable, and 10 = Best) were taken from March 10 to November 16, 2007. Arrows (↑) indicate hollow tine aerification and verticutting, while (*) indicate solid tine applications. Verticutting had highest (P<0.05) quality on eight occasions as indicated by (^). Table 3-1 shows complete breakdown of treatments.

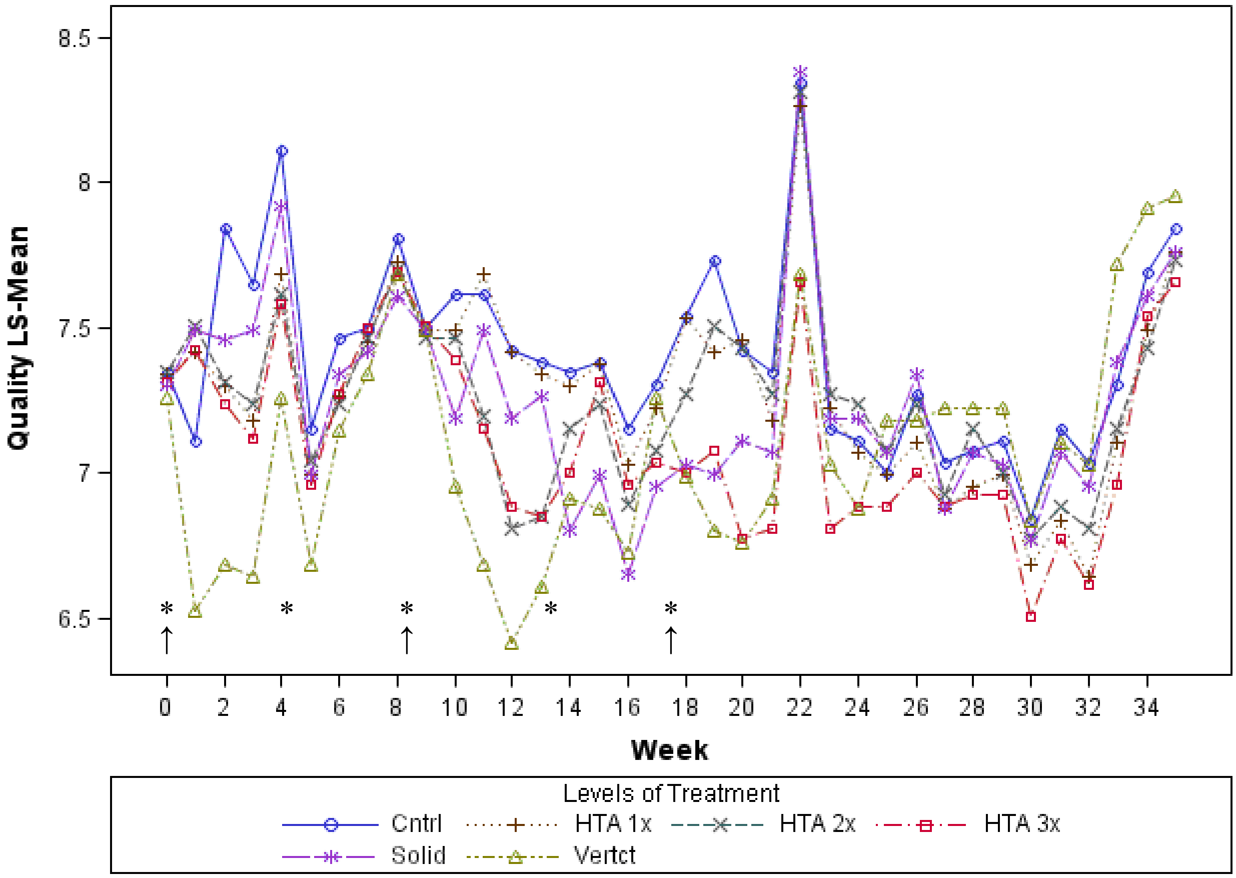

Figure 3-27. Effects of summer-fall applied cultural practices on quality. Ratings 1-10 (1 = Dead, 6 = Minimum Acceptable, and 10 = Best) were taken from 30 July 2007 to March 31, 2008. Arrows (↑) indicate hollow tine aerification and verticutting, while (*) indicate solid tine applications. Table 3-2 shows complete breakdown of treatments.

Figure 3-28. Verticutting treatment showed increased quality due to a release of nitrogen from soil organic matter, and a firmer surface that reduced scalping.

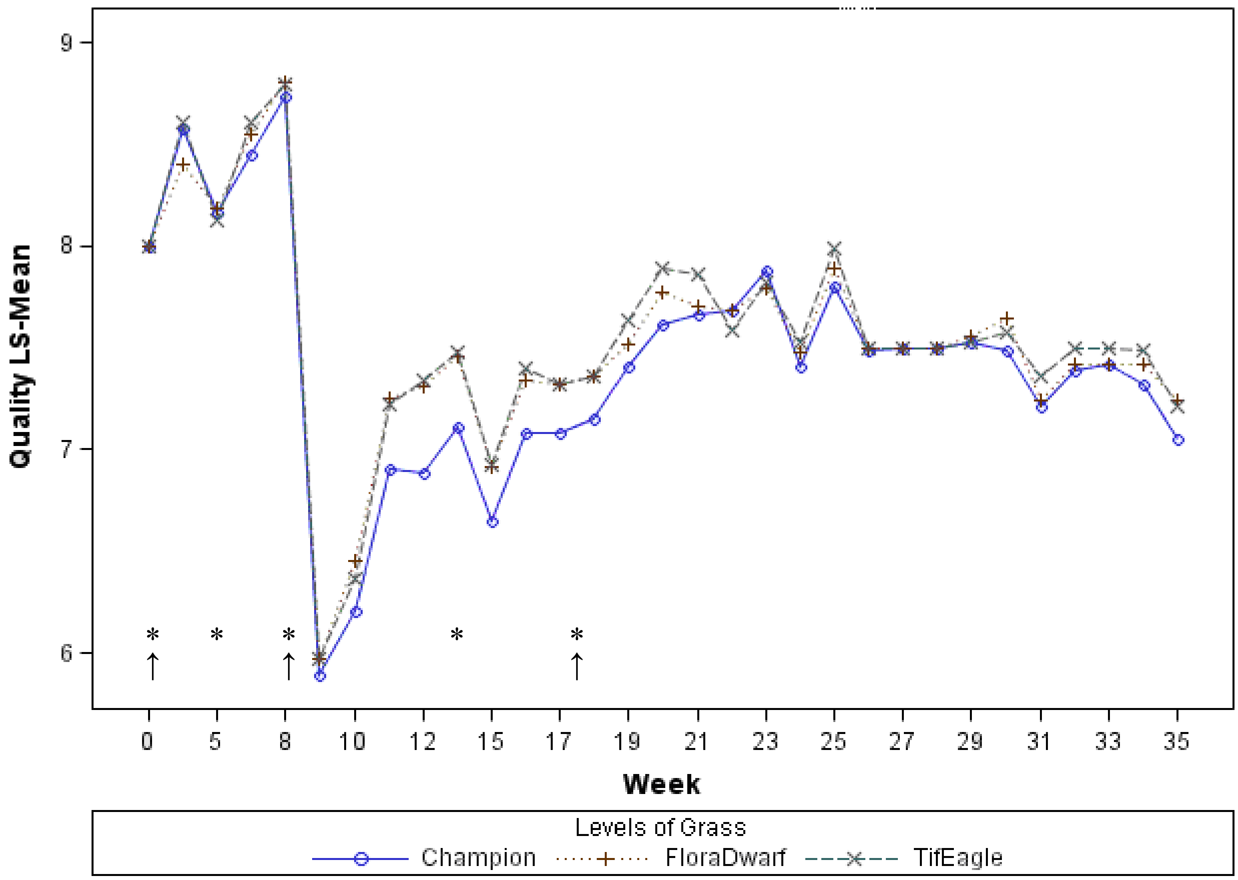

Figure 3-29. Comparison of spring-summer applied cultural practices on quality among grasses. Ratings 1-10 (1 = Dead, 6 = Minimum Acceptable, and 10 = Best) were taken from March 10 to November 16, 2007. Arrows (↑) indicate hollow tine aerification and verticutting, while (*) indicate solid tine applications. Table 3-1 shows complete breakdown of treatments.

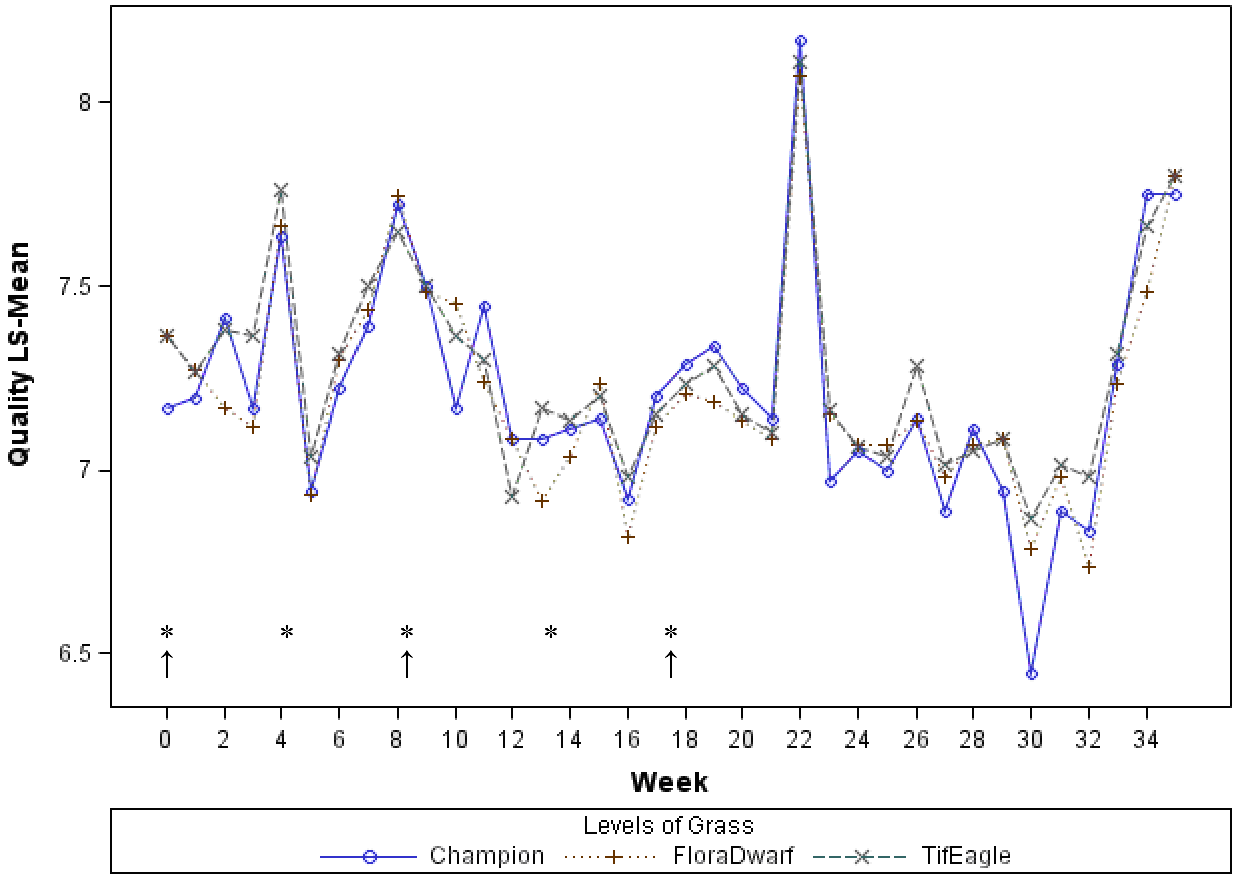

Figure 3-30. Comparison of summer-fall applied cultural practices on quality among grasses. Ratings 1-10 (1 = Dead, 6 = Minimum Acceptable, and 10 = Best) were taken from 30 July 2007 to March 31, 2008. Arrows (↑) indicate hollow tine aerification and verticutting, while (*) indicate solid tine applications. Table 3-2 shows complete breakdown of treatments.

Table 3-11. Quality ratings for “spring-summer” and “summer-fall” studies.

Treatment	Spring-summer	Summer-fall
Hollow Tine Aerification (1x yr^{-1})	7.63 b	7.30 b
Hollow Tine Aerification (2x yr^{-1})	7.57 bc	7.26 b
Hollow Tine Aerification (3x yr^{-1})	7.43 c	7.11 c
Control	7.83 a	7.41 a
Verticutting (3x yr^{-1})	7.46 bc	7.00 d
Solid Tine Aerification (5x yr^{-1})	7.13 d	7.23 b
	P<0.0001	P<0.0001
Grass		
Champion	7.43 b	7.20 a
FloraDwarf	7.54 ab	7.21 a
TifEagle	7.56 a	7.25 a
	P=0.02	P=0.30

Quality ratings: 1-10 (1 = Dead, 6 = Minimum Acceptable, and 10 = Best). Mean estimates with same letter within column are not statistically different, at 0.05 significance level, using Kenward-Roger method for repeated measures.

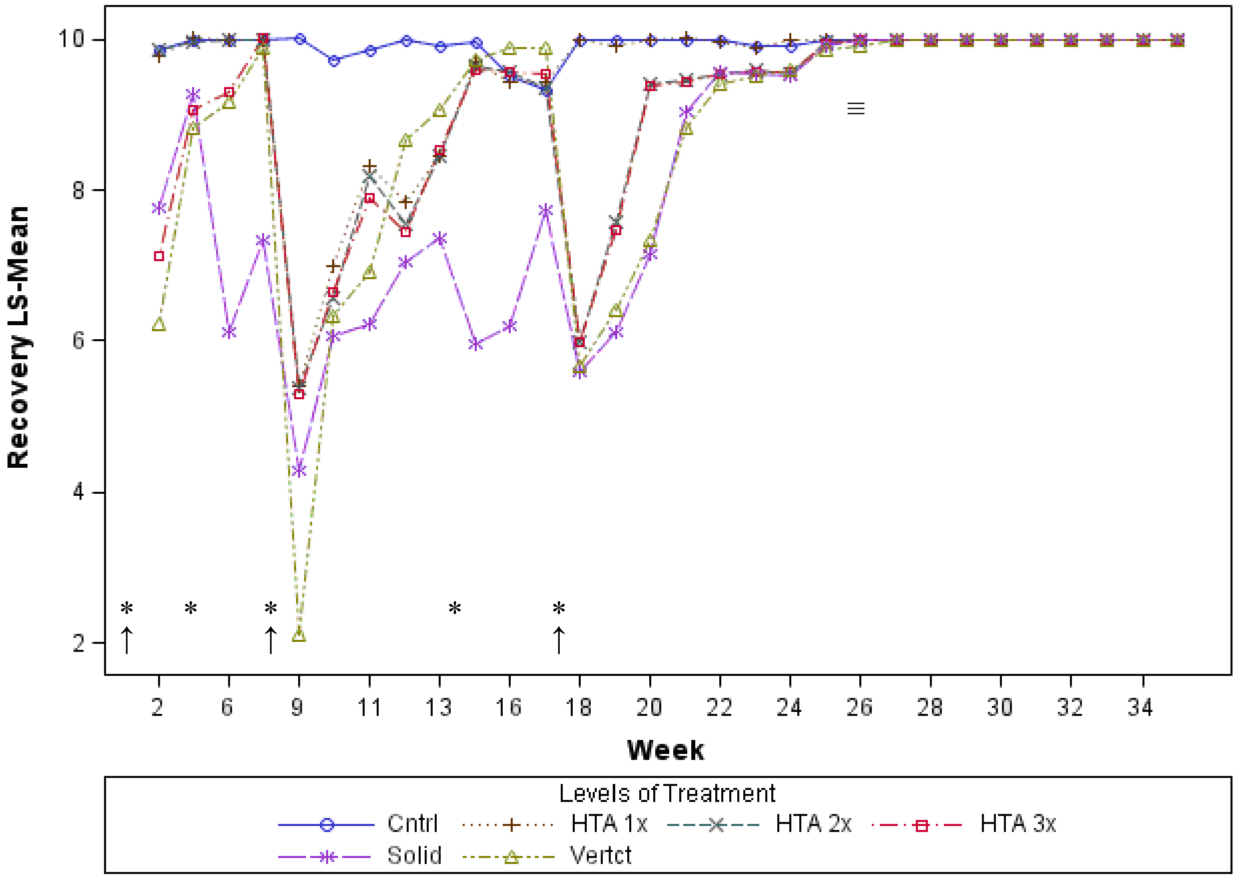

Figure 3-31. Comparison of spring-summer applied cultural practices on recovery. Ratings: 1-10 (10 = Recovered) were taken from March 26 to November 16, 2007. Treatments became statistically similar (P>0.05) at week 26. Arrows (↑) indicate hollow tine aerification and verticutting, while (*) indicate solid tine applications. All treatments became statistically similar (P>0.05) at week 26 as indicated by (≡). Table 3-1 shows complete breakdown of treatments.

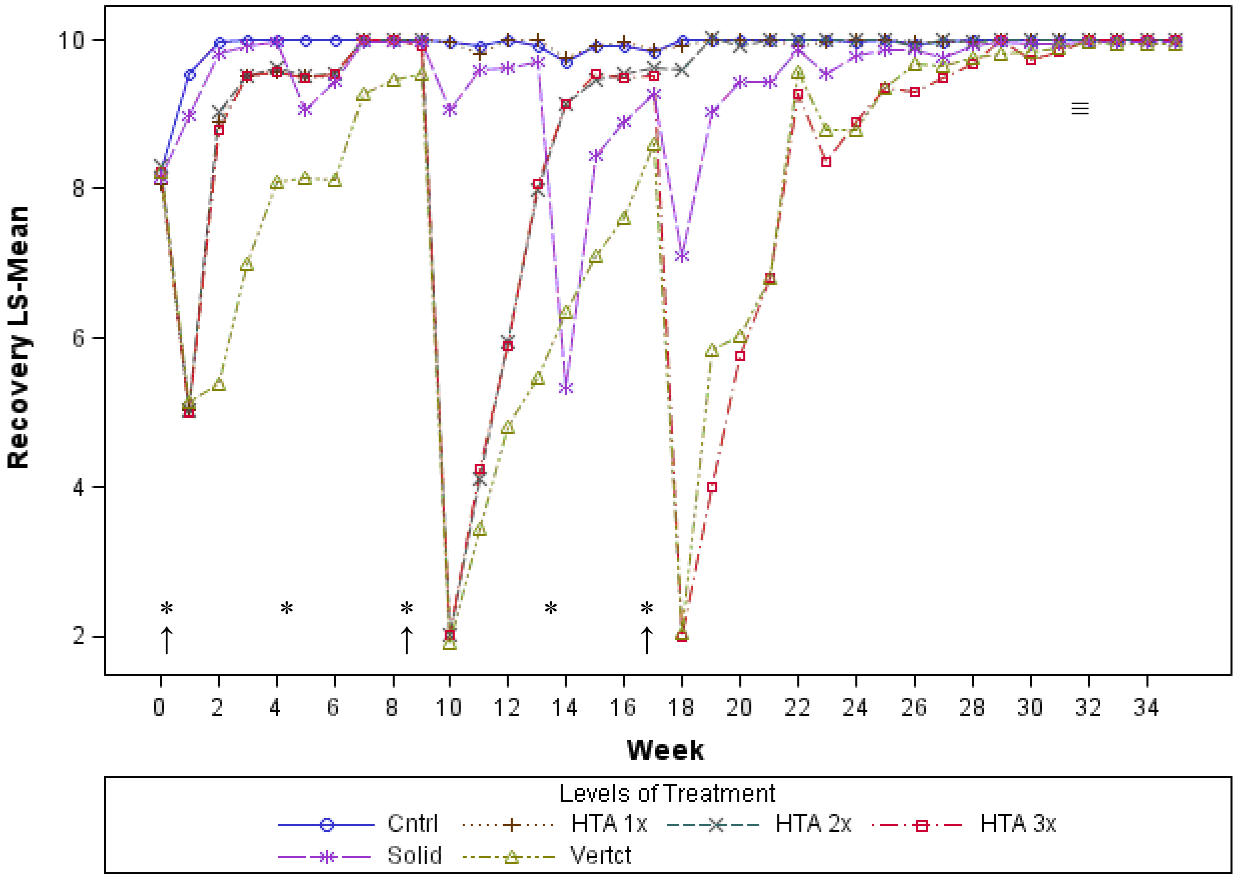

Figure 3-32. Comparison of summer-fall applied cultural practices on recovery. Ratings: 1-10 (10 = Recovered) were taken from 30 July, 2007 to March 31, 2008. All treatments became statistically similar ($P>0.05$) at week 31 (≡). Arrows (↑) indicate hollow tine aerification and verticutting, while (*) indicate solid tine applications. Table 3-2 shows complete breakdown of treatments.

Table 3-12. Recovery ratings for "spring-summer" and "summer-fall" studies.

Treatment	Spring-summer	Summer-fall
Hollow Tine Aerification (1x yr^{-1})	9.52 ab	9.58 a
Hollow Tine Aerification (2x yr^{-1})	9.21 bc	8.97 ab
Hollow Tine Aerification (3x yr^{-1})	9.01 cd	8.12 bc
Control	9.93 a	9.81 a
Verticutting (3x yr^{-1})	8.73 de	7.50 c
Solid Tine Aerification (5x yr^{-1})	8.29 e	9.25 a
	$P<0.0001$	$P<0.0001$
Grass		
Champion	8.99 a	8.77 a
FloraDwarf	9.18 a	8.93 a
TifEagle	9.18 a	8.92 a
	$P=0.15$	$P=0.76$

Recovery ratings: 1-10 (1 = no recovery, and 10 = completely recovered). Mean estimates with same letter within column are not statistically different, at 0.05 significance level, using Kenward-Roger method for repeated measures.

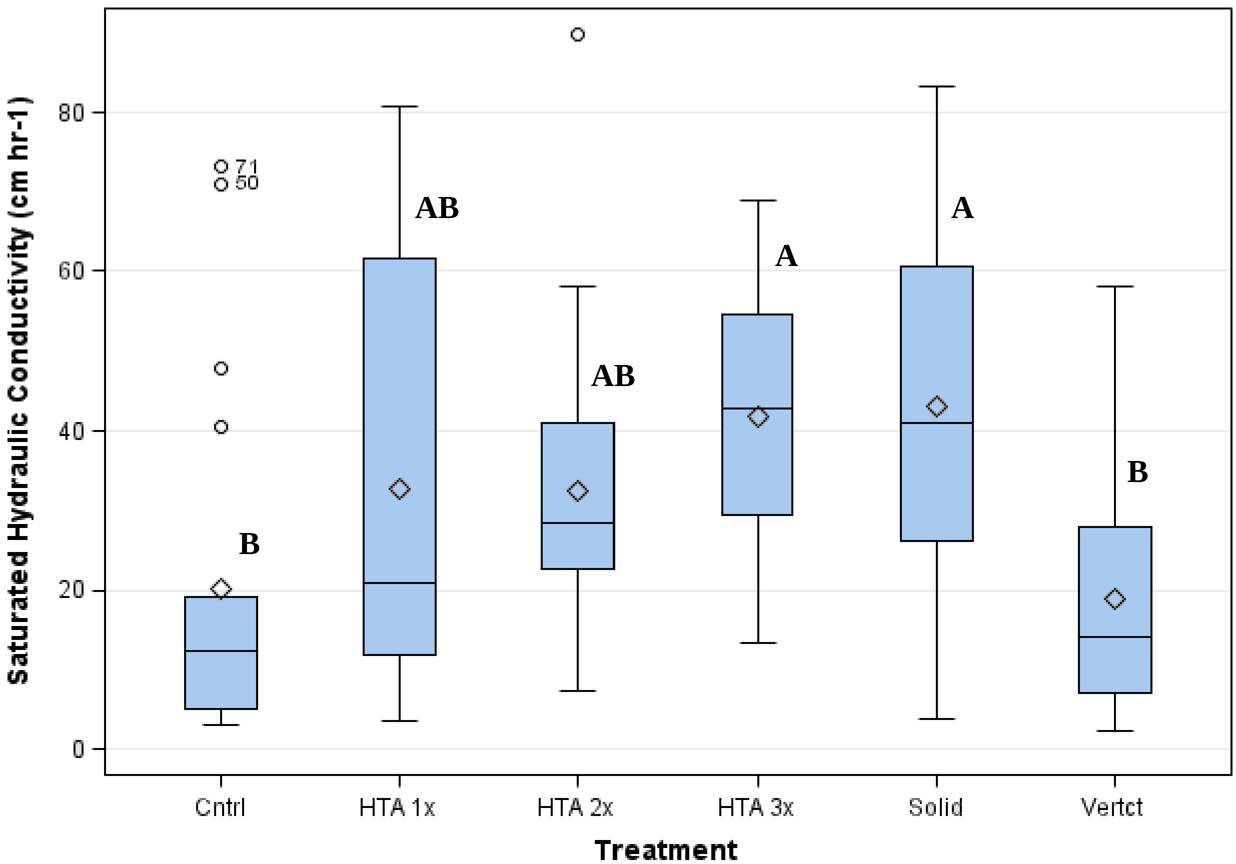

Figure 3-33. Effects of spring-summer applied cultural practices on saturated hydraulic conductivity (P<0.01).

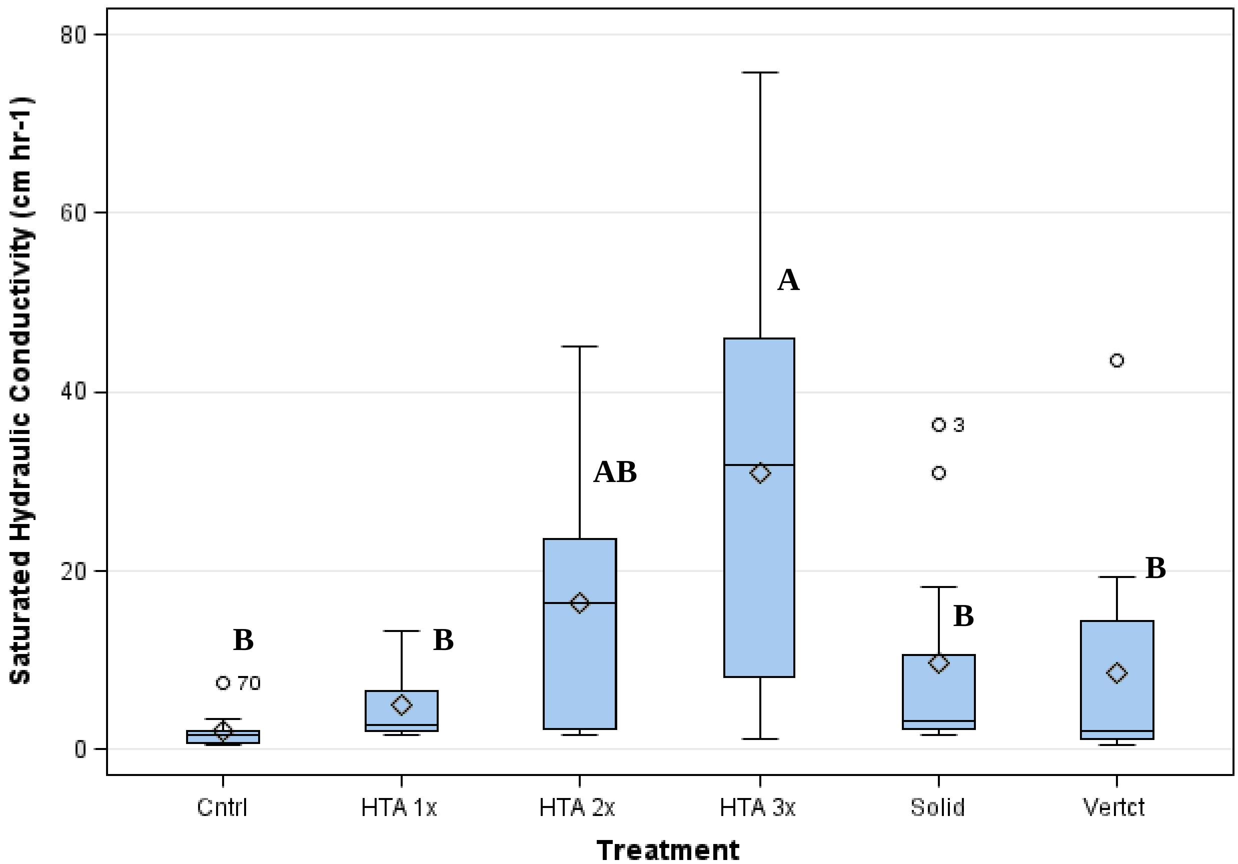

Figure 3-34. Effects of summer-fall applied cultural practices on saturated hydraulic conductivity (P<0.01). There was an overall reduction of 20 cm hr^{-1} compared to the spring-summer study.

Table 3-13. Saturated hydraulic conductivity (Ksat) for “spring-summer” and “summer-fall” studies.

Treatment	Spring-summer		Summer-fall	
	cm hr^{-1}			
	Initial	Final	Initial	Final
Hollow Tine Aerification (1x yr^{-1})	18.8 a	32.8 ab	18.4 a	4.6 b
Hollow Tine Aerification (2x yr^{-1})	20.9 a	32.4 ab	10.2 a	15.4 ab
Hollow Tine Aerification (3x yr^{-1})	24.9 a	41.7 a	18.5 a	29.3 a
Control	22.6 a	20.3 b	12.6 a	2.2 b
Verticutting (3x yr^{-1})	16.8 a	18.9 b	16.7 a	7.7 b
Solid Tine Aerification (5x yr^{-1})	22.4 a	43.1 a	11.3 a	9.2 b
P Value	P=0.60	P=0.0005	P=0.81	P<0.0001
Grass				
Champion	25.1 a	26.7 a	10.7 a	6.9 a
FloraDwarf	22.1 a	33.4 a	21.3 a	14.6 a
TifEagle	16.1 a	34.5 a	11.8 a	12.7 a
P Value	P=0.13	P=0.35	P=0.13	P=0.19

Mean estimates with same letter within column are not statistically different, at 0.05 significance level, using Tukey-Kramer method.

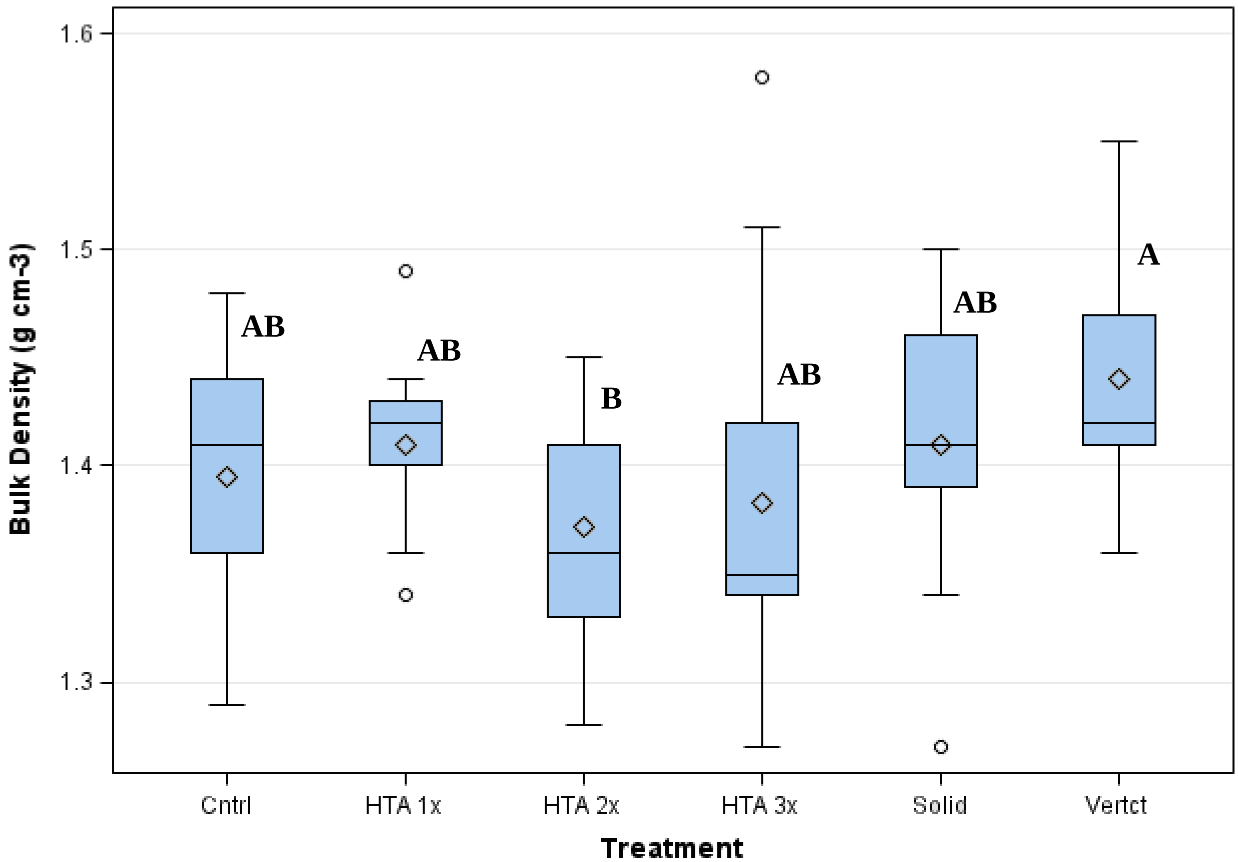

Figure 3-35. Effects of summer-fall applied cultural practices on bulk density (P<0.05). There was an overall increase in Db of 0.2 g cm^{-3} compared to the spring-summer study.

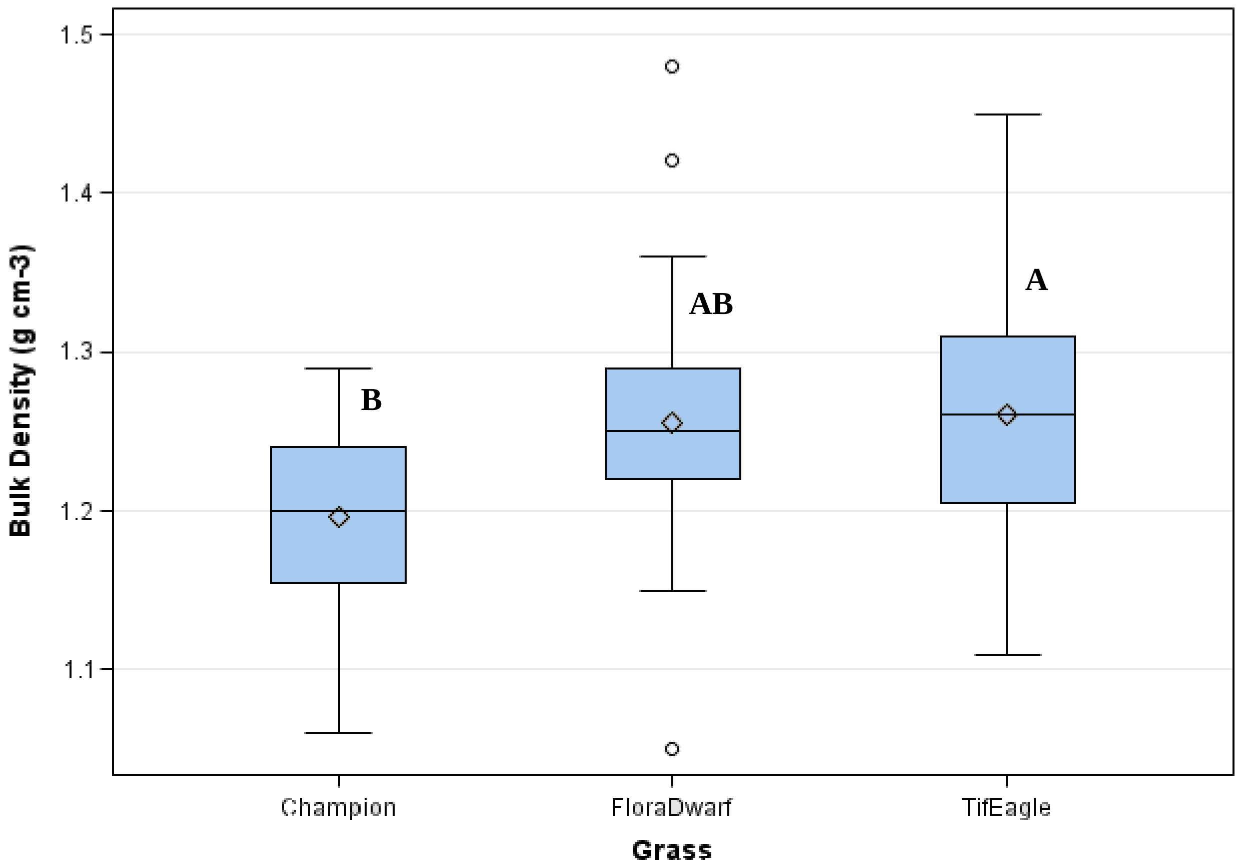

Figure 3-36. Effects of spring-summer applied cultural practices effects on bulk density (Db) among grasses ($P<0.05$).

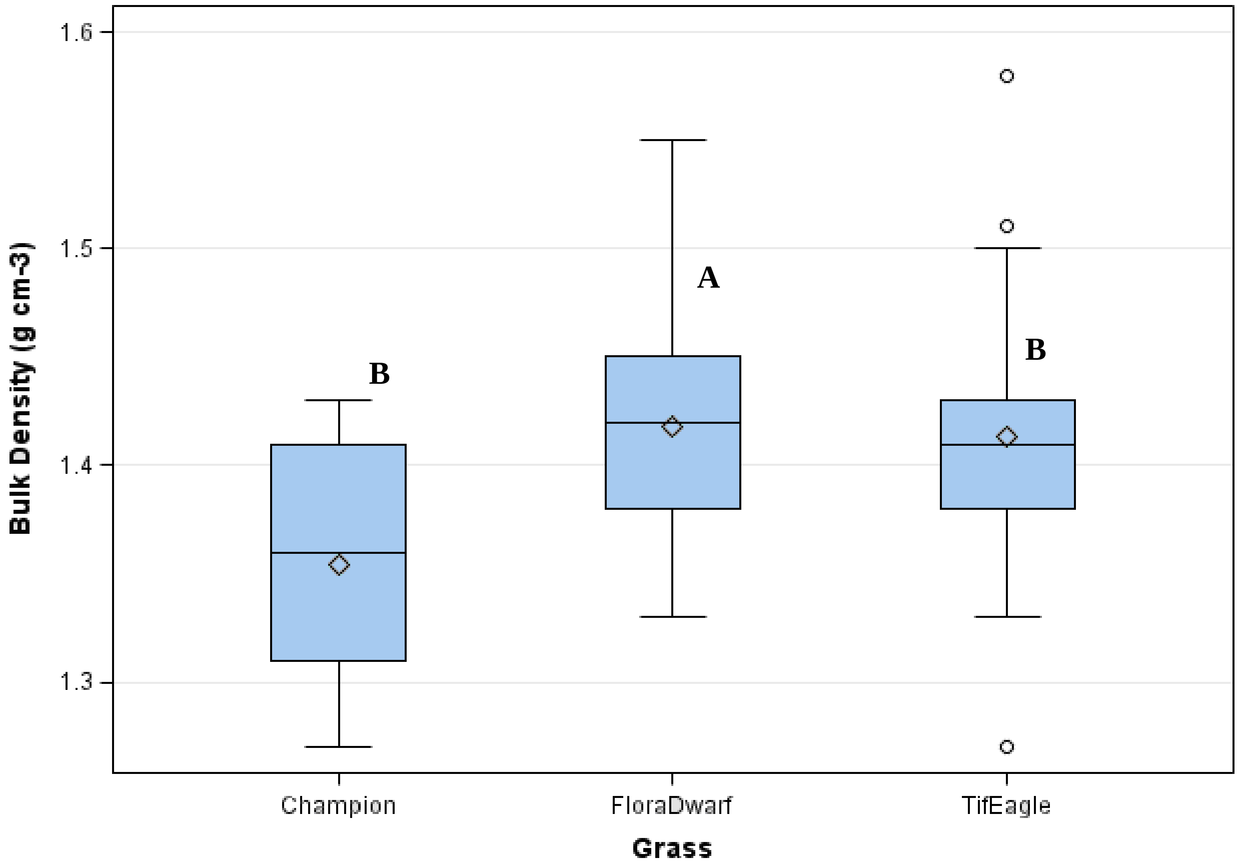

Figure 3-37. Effects of summer-fall applied cultural practices on bulk density (Db) among grasses ($P<0.05$). There was an overall increase in Db of 0.2 g cm^{-3} compared to the spring-summer study.

Table 3-14. Bulk density (Db) for “spring-summer” and “summer-fall” studies.

Treatment	Spring-summer		Summer-fall	
	g cm^{-3}			
	Initial	Final	Initial	Final
Hollow Tine Aerification (1x yr^{-1})	1.30 a	1.24 a	1.21 a	1.40 ab
Hollow Tine Aerification (2x yr^{-1})	1.31 a	1.25 a	1.20 a	1.37 b
Hollow Tine Aerification (3x yr^{-1})	1.30 a	1.22 a	1.19 a	1.37 ab
Control	1.31 a	1.23 a	1.19 a	1.39 ab
Verticutting (3x yr^{-1})	1.29 a	1.22 a	1.21 a	1.43 a
Solid Tine Aerification (5x yr^{-1})	1.33 a	1.27 a	1.17 a	1.41 ab
	P=0.59	P=0.29	P=0.72	P=0.04
Grass				
Champion	1.27 b	1.20 b	1.17 a	1.35 b
FloraDwarf	1.32 a	1.26 ab	1.21 a	1.42 a
TifEagle	1.32 a	1.26 a	1.21 a	1.41 a
	P<0.0001	P=0.03	P=0.19	P=0.02

Mean estimates with same letter within column are not statistically different, at 0.05 significance level, using Tukey-Kramer method.

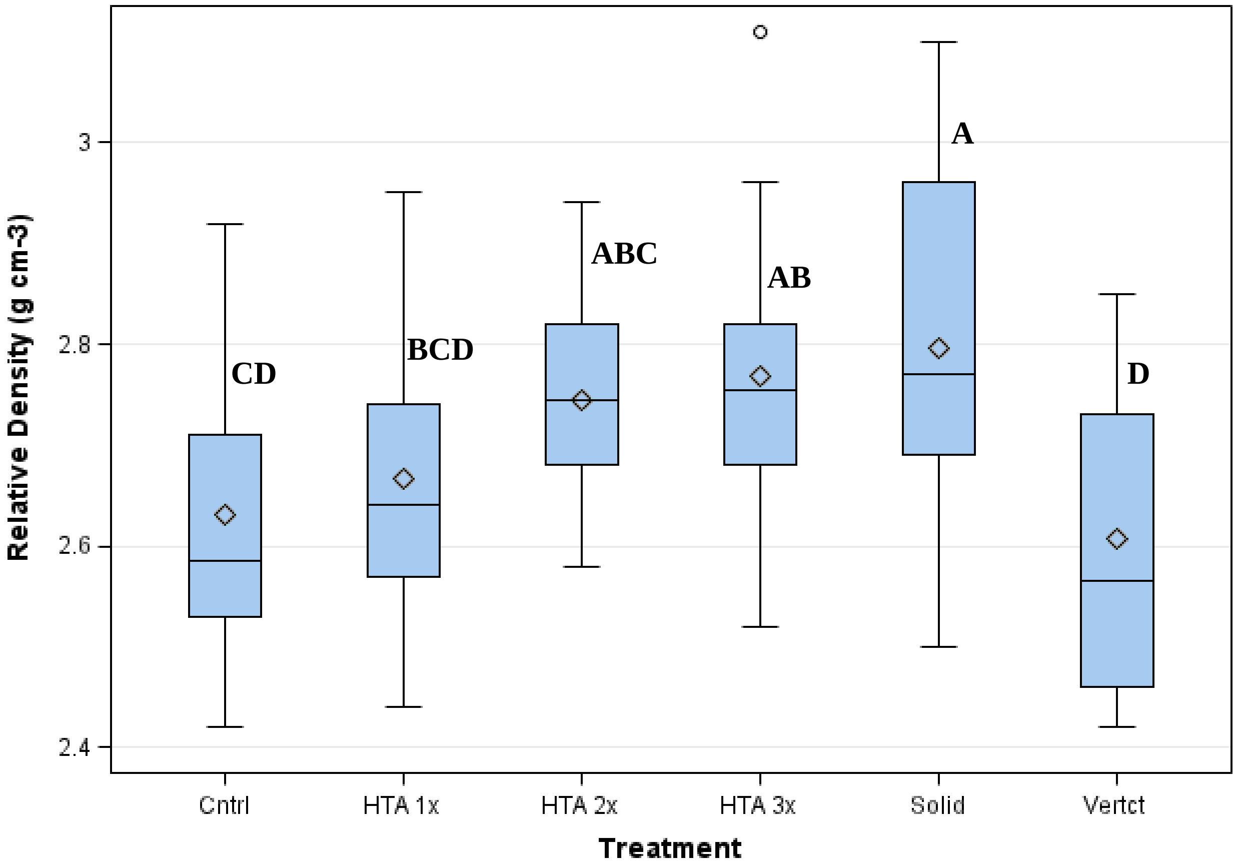

Figure 3-38. Effects of spring-summer applied cultural practices on relative density (P<0.01).

Table 3-15. Relative density (Dp) for "spring-summer" and "summer-fall" studies.

Treatment	Spring-summer		Summer-fall	
	g cm^{-3}			
	Initial	Final	Initial	Final
Hollow Tine Aerification (1x yr^{-1})	2.61 b	2.67 bcd	2.57 a	2.17 a
Hollow Tine Aerification (2x yr^{-1})	2.69 ab	2.74 abc	2.53 a	2.17 a
Hollow Tine Aerification (3x yr^{-1})	2.69 ab	2.77 ab	2.58 a	2.18 a
Control	2.70 ab	2.63 cd	2.55 a	2.14 a
Verticutting (3x yr^{-1})	2.64 ab	2.61 d	2.60 a	2.13 a
Solid Tine Aerification (5x yr^{-1})	2.73 a	2.80 a	2.50 a	2.17 a
	P=0.03	P<0.0001	P=0.52	P=0.56
Grass				
Champion	2.73 a	2.70 a	2.50 a	2.11 b
FloraDwarf	2.64 a	2.70 a	2.60 a	2.21 a
TifEagle	2.66 a	2.70 a	2.56 a	2.15 ab
	P=0.11	P=0.99	P=0.46	P=0.04

Mean estimates with same letter within column are not statistically different, at 0.05 significance level, using Tukey-Kramer method.

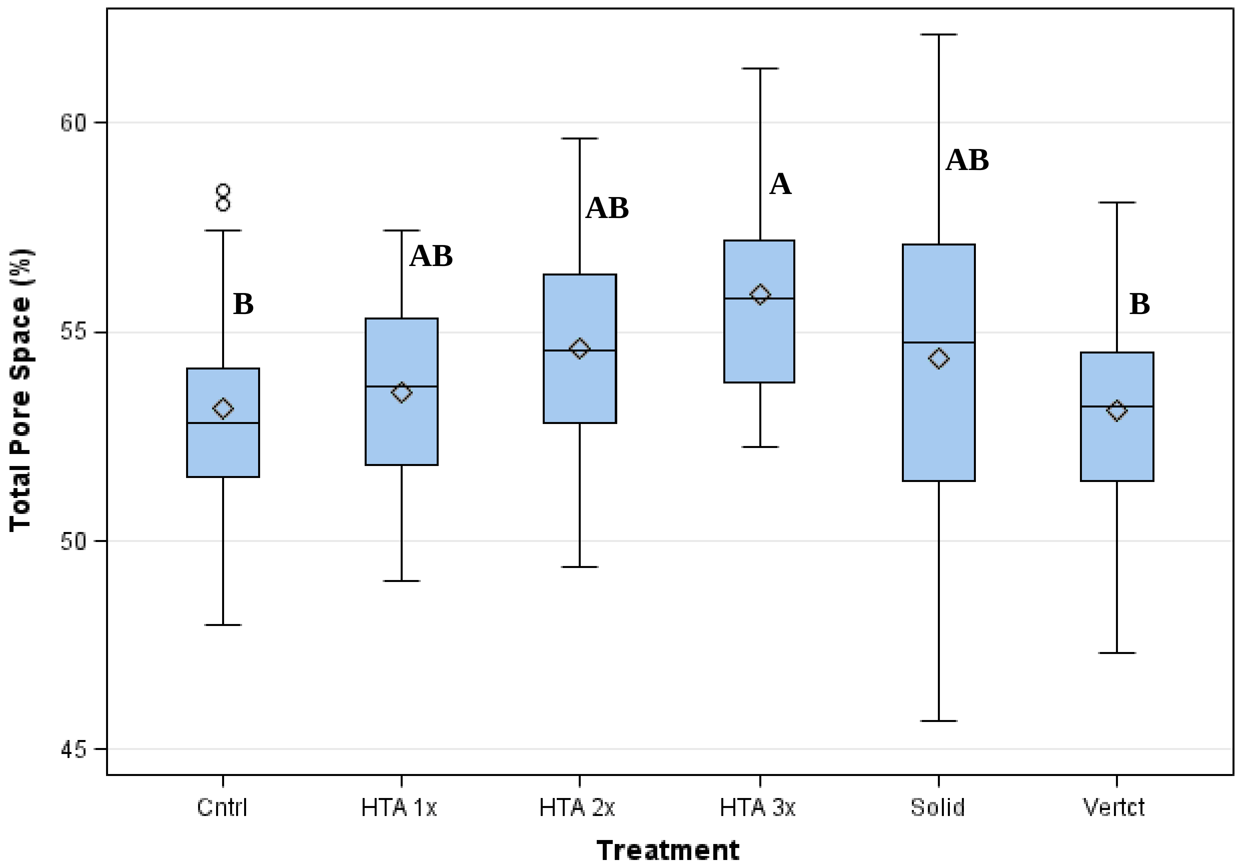

Figure 3-39. Effects of spring-summer applied cultural practices on total pore space (P<0.05).

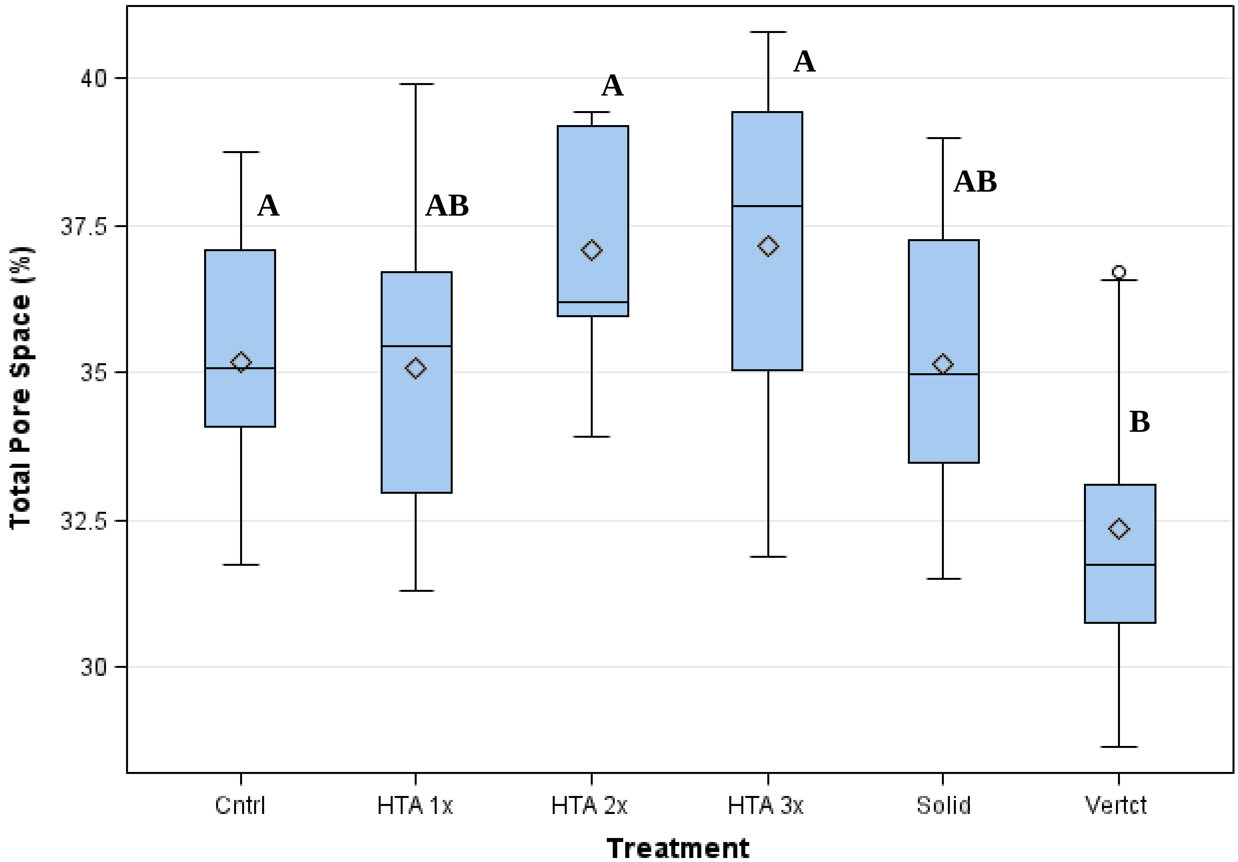

Figure 3-40. Effects of summer-fall applied cultural practices on total pore space (P<0.01).

Table 3-16. Total pore space (TPS) for "spring-summer" and "summer-fall" studies.

Treatment	Spring-summer		Summer-fall	
	Percent (%)			
	Initial	Final	Initial	Final
Hollow Tine Aerification (1x yr^{-1})	50.3 a	53.5 ab	52.7 a	35.1 ab
Hollow Tine Aerification (2x yr^{-1})	51.1 a	54.6 ab	52.6 a	37.1 a
Hollow Tine Aerification (3x yr^{-1})	51.6 a	55.9 a	53.7 a	37.2 a
Control	51.5 a	53.2 b	53.3 a	35.3 a
Verticutting (3x yr^{-1})	51.1 a	53.1 b	53.4 a	32.7 b
Solid Tine Aerification (5x yr^{-1})	51.4 a	54.4 ab	53.0 a	34.9 ab
	P=0.49	P=0.02	P=0.72	P<0.0001
Grass				
Champion	53.3 a	55.6 a	53.2 a	36.1 a
FloraDwarf	49.9 b	53.4 b	53.6 a	35.9 a
TifEagle	50.2 b	53.3 b	52.5 a	34.2 a
	P=0.002	P=0.04	P=0.55	P=0.21

Mean estimates with same letter within column are not statistically different, at 0.05 significance level, using Tukey-Kramer method.

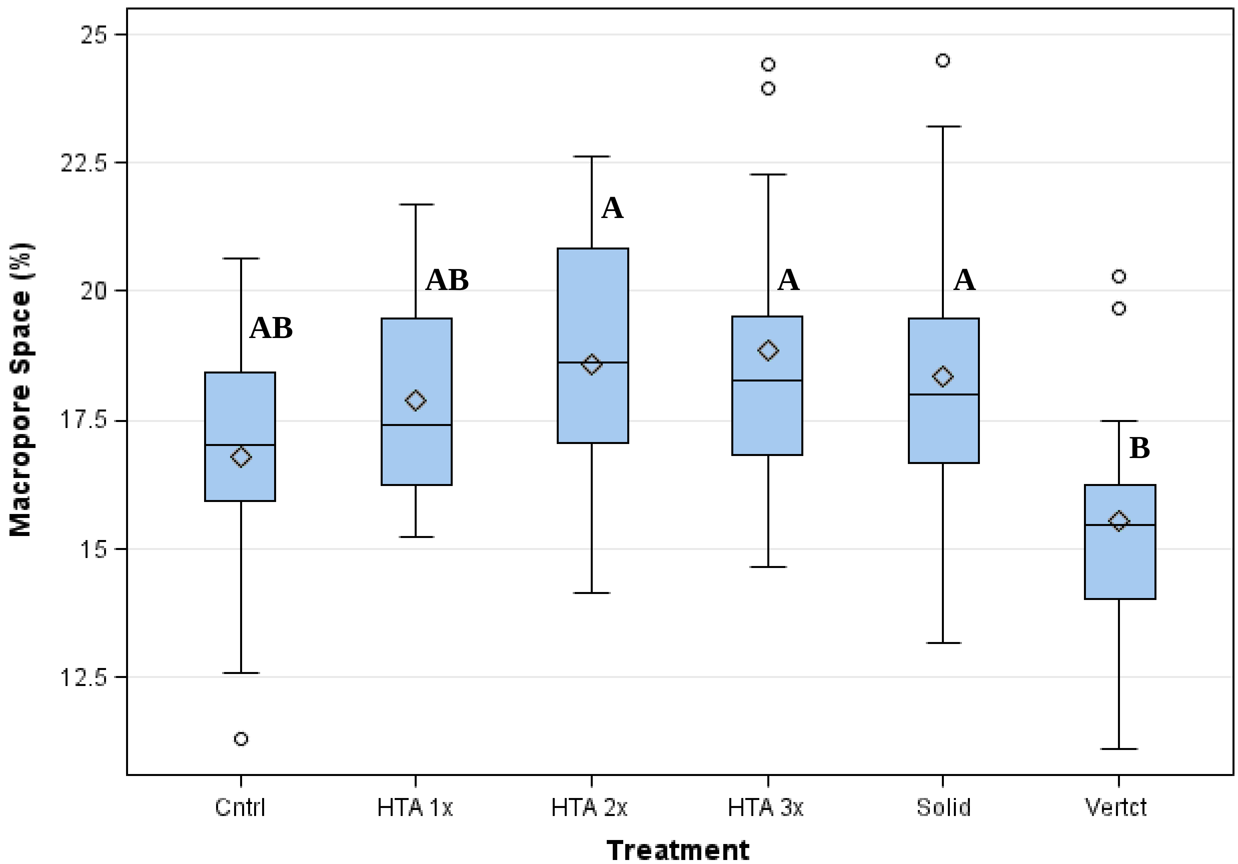

Figure 3-41. Effects of spring-summer applied cultural practices effects on macropore space (P<0.01).

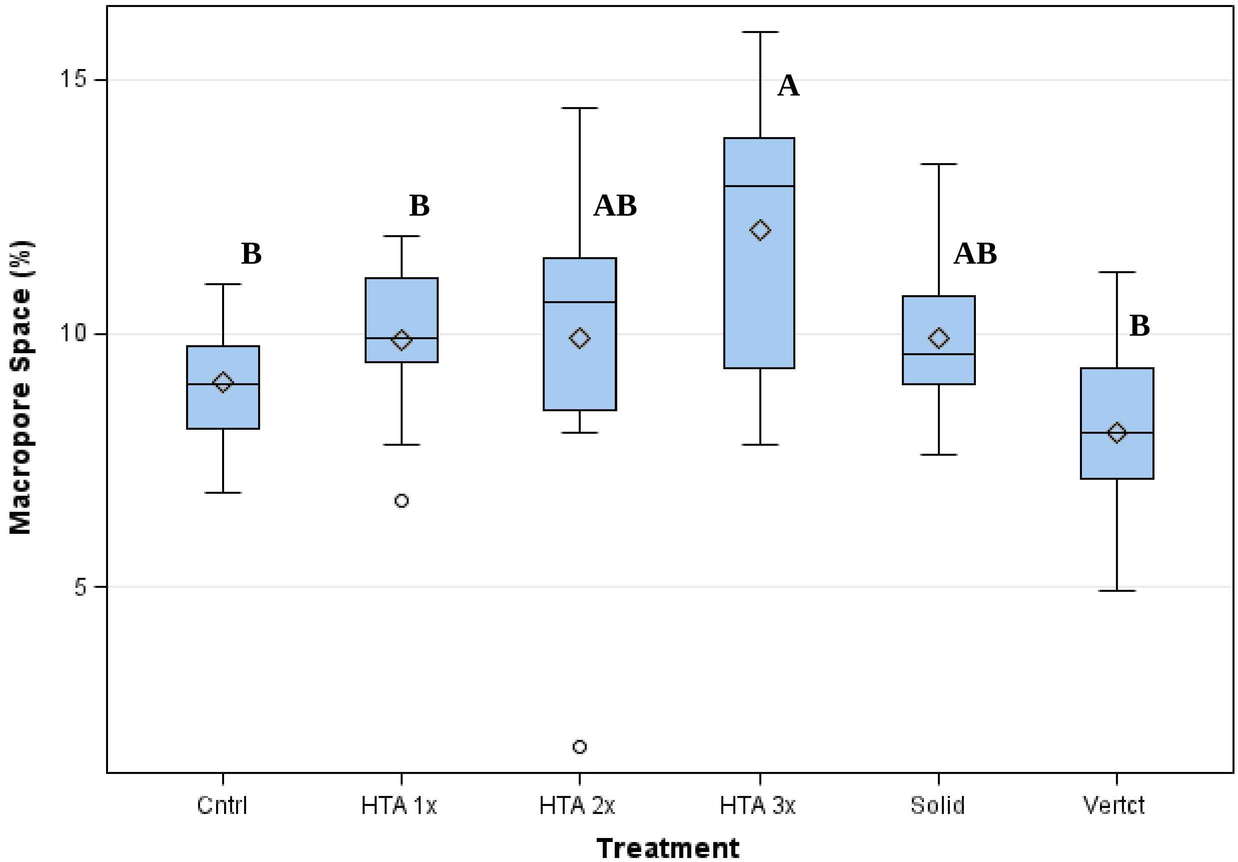

Figure 3-42. Effects of summer-fall applied cultural practices on macropore space (P<0.01).

Table 3-17. Macropore space (MPS) for “spring-summer” and “summer-fall” studies.

Treatment	Spring-summer		Summer-fall	
	Percent (%)			
	Initial	Final	Initial	Final
Hollow Tine Aerification (1x yr^{-1})	12.2 a	17.9 ab	18.8 a	9.7 b
Hollow Tine Aerification (2x yr^{-1})	11.7 a	18.6 a	17.6 a	10.0 ab
Hollow Tine Aerification (3x yr^{-1})	12.4 a	18.8 a	19.7 a	11.9 a
Control	12.9 a	16.8 ab	18.6 a	9.0 b
Verticutting (3x yr^{-1})	12.0 a	15.5 b	19.2 a	8.2 b
Solid Tine Aerification (5x yr^{-1})	13.1 a	18.4 a	18.7 a	9.9 ab
	P=0.31	P=0.002	P=0.78	P=0.0003
Grass				
Champion	13.8 a	18.2 a	18.0 a	9.5 a
FloraDwarf	10.7 a	17.2 a	20.2 a	9.9 a
TifEagle	12.7 a	17.5 a	18.0 a	9.8 a
	P=0.06	P=0.15	P=0.18	P=0.94

Mean estimates with same letter within column are not statistically different, at 0.05 significance level, using Tukey-Kramer method.

Table 3-18. Micropore space [i.e., water holding capacity (volume)] for “spring-summer” and “summer-fall” studies.

Treatment	Spring-summer		Summer-fall	
	Percent (%)			
	Initial	Final	Initial	Final
Hollow Tine Aerification (1x yr^{-1})	38.0 a	35.6 a	35.2 a	25.4 a
Hollow Tine Aerification (2x yr^{-1})	39.4 a	36.0 a	34.9 a	27.2 a
Hollow Tine Aerification (3x yr^{-1})	39.2 a	37.0 a	34.9 a	25.6 a
Control	38.6 a	36.4 a	34.7 a	26.4 a
Verticutting (3x yr^{-1})	39.1 a	37.6 a	35.5 a	24.5 a
Solid Tine Aerification (5x yr^{-1})	38.3 a	36.0 a	35.2 a	25.2 a
	P=0.51	P=0.60	P=0.99	P=0.21
Grass				
Champion	39.5 a	37.4 a	35.2 a	26.8 a
FloraDwarf	39.3 a	36.2 a	35.3 a	25.9 a
TifEagle	37.5 a	35.8 a	34.7 a	24.4 a
	P=0.34	P=0.19	P=0.95	P=0.41

Mean estimates with same letter within column are not statistically different, at 0.05 significance level, using Tukey-Kramer method.

Table 3-19. Water holding capacity (weight) for "spring-summer" and "summer-fall" studies.

Treatment	Spring-summer		Summer-fall	
	Percent (%)			
	Initial	Final	Initial	Final
Hollow Tine Aerification (1x yr^{-1})	29.4 a	29.1 a	29.2 a	18.1 a
Hollow Tine Aerification (2x yr^{-1})	30.0 a	29.1 a	29.4 a	19.9 a
Hollow Tine Aerification (3x yr^{-1})	30.3 a	30.5 a	29.6 a	18.9 a
Control	29.7 a	29.9 a	29.6 a	19.1 a
Verticutting (3x yr^{-1})	30.4 a	31.0 a	29.6 a	17.1 a
Solid Tine Aerification (5x yr^{-1})	28.8 a	28.5 a	30.2 a	17.9 a
	P=0.69	P=0.50	P=0.99	P=0.06
Grass				
Champion	31.1 a	31.4 a	30.5 a	19.8 a
FloraDwarf	29.7 a	29.0 a	29.6 a	18.3 a
TifEagle	28.4 a	28.6 a	28.7 a	17.4 a
	P=0.14	P=0.05	P=0.73	P=0.27

Mean estimates with same letter within column are not statistically different, at 0.05 significance level, using Tukey-Kramer method.

LIST OF REFERENCES

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

Beard, J.B. 1982. Turf Management for Golf Courses. Burgess Publishing Co., Minneapolis, MN.

Bevard, D.S. 2005. Basic Training. USGA Green Section Record 43(2):1-6.

Bigelow, C.A., A.G. Wollum, and D.C. Bowman. 2000. Soil Microbial Populations in Sand-Based Root Zones. Golf Course Management 68(10):65-69. TGIF Record: 68879.

Brady N.C., and R.R. Weil. 1999. The Nature and Properties of Soils. Prentice Hall, Upper Saddle River, NJ.

Burton, G.W. 1991. A History Of Turf Research At Tifton. USGA Green Section Record 29(3):12-14.

Busey, P., and S.E. Boyer. 1997. Golf Ball Roll Friction of Cynodon Genotypes. Int. Turfgrass Soc. Research J. 8:59-63.

Busey, P., and A.E. Dudeck. 1999. Bermudagrass Varieties. P. 97-99. *In* Unruh, J.B., and M.L. Elliott (ed.) Best Management Practices for Florida Golf Courses. 2nd ed. University of Florida, Institute of Food and Agricultural Sciences.

Callahan, L.L., W.L. Sanders, J.M. Parham, C.A. Harper, L.D. Lester, and E.R. McDonald. 1998. Cultural and Chemical Controls of Thatch and Their Influence on Rootzone Nutrients in a Bentgrass Green. Crop Sci. 38:181-187.

Carrow, R.N. 2003. Surface Organic Matter in Bentgrass Greens. USGA Turfgrass and Environmental Research Online. 2(17):1-12. TGIF Record: 91781.

Carrow, R.N. 2004a. Surface Organic Matter in Bentgrass Greens. USGA Green Section Record 42(1):11-15.

Carrow, R.N. 2004b. Surface Organic Matter in Bermudagrass Greens: A Primary Stress? Golf Course Management 72(5):102-105.

Carrow, R.N. 2004c. Surface Organic Matter in Creeping Bentgrass Greens. Golf Course Manage. 72(5):96-101.

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

Cisar, J. 1999a. Processing Cores After Aeration. Grounds Maintenance. 34(11):1-8.

Cisar, J. 1999b. Ultradwarf Evaluation Hits the One Year Mark. NTEP Evaluation Report.

Cisar, J. L., J. E. Erickson, G. H. Snyder, J. J. Haydu, and J. C. Volin. 2004. Documenting nitrogen leaching and runoff losses from urban landscapes. p. 266-269 *In* Environmental impact of fertilizer on soil and water. ed. W. L. Hall and W.P. Robarge. Oxford University Press. Cary, N.C.

Cisar, J., and G. Snyder. 2003. Evaluation of Ultradwarf Bermudagrass Cultural Management Practices. TPI Turf News Jan./Feb. 2003.

Cisar, J., G. Snyder, and D. Park. 2005. The Effect of Nitrogen Rates on Ultradwarf Bermudagrass Quality. USGA Turfgrass and Environmental Research Online 4(17):1-6. TGIF Record: 107580.

Cooper, R.J. 1996. It's Dark Down There: Soils Teem with Tiny Organisms. Golf Course Management 27(6):7-9.

Datnoff L., C. Stiles, J. Cisar, and S. Kammerer. 2005. Influence of Mowing Heights and Fungicides on the Decline of Ultradwarf Bermudagrass. Florida Turf Digest March/April 2005.

Elliott, M.L. 1991. Determination of an Etiological Agent of Bermudagrass Decline. Phytopathology 81:1380-1384.

Elliott, M.L., J.A. McInroy, K. Xiong, J.H. Kim, H.D. Skipper, and E.A. Guertal. 2007. Diversity of Rhizosphere Bacteria in USGA Putting Greens. USGA Turfgrass and Environmental Research Online 6(20):1-8. TGIF Record: 128929.

Engel, R.E. 1998. The Six Seasonal Stages of Bentgrass Nitrogen Fertilization. USGA Green Section Record 26(4):10-12.

Florida Department of Environmental Protection. 2007. Best Management Practices for the Enhancement of Environmental Quality on Florida Golf Courses. FDEP Publications. dep.state.fl.us/water/nonpoint/pubs.htm

Foy, J.H. 1988. Bentgrass or Bermudagrass Greens-What is Right for Florida? USGA Green Section Record 26(1):1-5.

Foy, J.H. 1997. The Hybrid Bermudagrass Scene. USGA Green Section Record 35(6):1-4.

Foy, J.H. 1999. May the Force be with You. USGA Green Section Record 37(3):27.

Foy, J.H. 2000. Going for the Gold with Bermudagrass Greens: Part II. USGA Green Section Record 38(6):1-5.

Foy, J.H. 2005. Bermudagrass Decline: Disease or Simply Declining Bermudagrass. USGA Green Section Record Regional Update http://www.usga.org/turf/regional_updates/regional_reports/florida/08-05-2005.html

Foy, J.H. 2006. Grain on the Brain. USGA Green Section Record 43(6):36.

Gaussoin, R., J. Nus, and L. Leuthold. 1995. A modified stimpmeter for small-plot turfgrass research. HortScience 30(3):547-548.

Gaussoin, R., R. Shearman, L. Wit, T. McClellan, J. Lewis. 2006. Soil Physical and Chemical Characteristics of Aging Golf Greens. USGA Turfgrass and Environmental Research Online 5(14):1-11. TGIF Record: 113214.

Gaussoin, R.E. 2003. Soil Microbial Characteristics of Aging Golf Greens. USGA Turfgrass and Environmental Research Online 2(3):1-6. TGIF Record: 85613.

Guertal, B. 2007. Phosphorous Leaching from Sand-Based Putting Greens. USGA Green Section Record 45(6):14-18.

Habeck, J., and N. Christians. 2000. Time Alters Greens' Key Characteristics. Golf Course Management 68(5):54-60. TGIF Record: 64765.

Hanna, W. 2005. USGA Turfgrass and Environmental Research Online. 4(5):1-6. TGIF Record: 102599.

Hartwiger, C. 2000. Give Me Your Poor, Your Tired, Your dead Bentgrass Greens. USGA Green Section Record 38(3):7.

Hartwiger, C. 2001. Opportunity Knocks with the Ultradwarfs. USGA Green Section Record 39(5):1-5.

Hartwiger, C. 2004. The Importance of Organic Matter Dynamics. USGA Green Section Record 42(3):9-11.

Hartwiger, C., and P. O'Brien. 2001. Core Aeration by the Numbers. USGA Green Section Record 39(4):8-9.

Holl, B.F. 2004. Rhizospheric Pressure: Are Soil Microbial Practices Taking Root? Green Master. 39(2):24-27.

Hollingsworth, B.S., E.A., Guertal, and R.H. Walker. 2005. Cultural Management and Nitrogen Source Effects on Ultradwarf Bermudagrass Cultivars. Crop Sci. 45:486-493.

Horst, G.L., P.J. Shea, N. Christians, D.R. Miller, C. Stuefer-Powell and S.K. Starrett. 1996. Pesticide Dissipation under Golf Course Fairway Conditions. Crop Sci. 36:362-370

Huang, B. 2002. Getting to the Root of Summer Bentgrass Decline. USGA Green Section Record 40(4):21-23.

Landreth, J., D. Karcher, and M. Richardson. 2007. Cultivating to Manage Organic Matter in Sand-Based Putting Greens. USGA Turfgrass and Environmental Research Online 6(19):1-7. TGIF Record Number: 128563.

Littell, R.C., G.A. Miliken, W.W. Stroup, R.D. Wolfinger, and O. Schabenberger. 2006. *SAS for Mixed Models*, *2nd Ed.* Cary, NC: SAS Institute Inc.

Liu, C, and J. Evett. 1990. Soil Properties: Testing, Measurement, and Evaluation. Prentice Hall, Englewood Cliffs, NJ.

McCarty, B., and P. Brown. 2004. Curing Soil Compaction Means Knowing the Causes. Turfgrass Trends. April 1, 2004.

McCarty, B., and A. Canegallo. 2005. Tips for Managing Ultradwarf Bermudagrass Greens. Golf Course Management. June 2005:90-95.

McCarty, L.B., M.F. Gregg, and J.E. Toler. 2007. Thatch and Mat Management in an Established Creeping Bentgrass Golf Green. Agron. J. 99:1530-1537

McCarty, L.B., and G. Miller. 2002. Managing Bermudagrass Turf. Ann Arbor Press, Chelsea, MI.

McCoy, E., K. McCoy. 2005. Geography Affects How Rootzone Amendments Conserve Irrigation Water. USGA Green Section Record 43(5):11-15.

Moore, J.F. 2007. A Troubleshooting Checklist for New USGA Greens. USGA Green Section: Greens Articles http://www.usga.org/turf/articles/construction/greens/troubleshooting.html

National Turfgrass Evaluation Program. 1998. On-Site Testing of Bentgrass and Bermudagrass Cultivars for Golf Course Putting Greens. 1998-2001 Data. NTEP, Beltsville, MD. http://www.ntep.org/data/bg98o/bg98o_02-8/bg98o_02-8.pdf

Noer, O.J. 1928. Physical Soil Factors Affecting Turf Growth. The Bulletin of the United States Golf Association Green Section. 8(1):6-10.

Oatis, D.A. 1990. It's time to put the green back in green speed. USGA Green Section Record 28(6)1-6.

O'Brien, P., and C. Hartwiger. 2003. Aeration and Topdressing for the 21st Century. USGA Green Section Record. 41(2):1-7.

O'Brien, P., and C. Hartwiger. 2005. Worst Summer Bentgrass Putting Green Turf Loss in 10 Years Occurs in SE Region. USGA Green Section Record. 41(2):1-7.

O'Brien, P., and C. Hartwiger. 2007. Ultradwarfs in the Off-Season–A Winter Wonderland. USGA Green Section Record 45(6)1-7.

Petrovic, A.M. 1979. The effects of vertical operating hollow tine cultivation on turfgrass soil structure. *Ph.D. dissertation*. Michigan State University

Petrovic, A.M. 1990. The Fate of Nitrogenous Fertilizers Applied to Turfgrass. Journal of Environmental Quality 19(1):1-14.

Sartain, J.B. 1985. Effect of Acidity and N Source on the Growth and Thatch Accumulation of Tifgreen Bermudagrass and on Soil Nutrient Retention. Agron. J. 77:33-36.

SAS Institute. 2004. SAS/STAT User's Guide. Version 9.0. SAS Institute, Cary, NC.

Snyder, G. H., and J. L. Cisar. 1995. Pesticide Mobility and Persistence in a High-Sand-Content Green. USGA Green Section Record. 33(1):15-18.

Turgeon, A.J. 1978. Influence of Thatch on Soil is both Positive and Negative. Weeds, Trees, and Turf 18(4):48-50

Unruh, J.B., and S. Davis. 2001. Diseases and Heat Besiege Ultradwarf Bermudagrasses. Golf Course Management 69(4):49-54.

Unruh, J.B., and M. Elliott. 1999. Best Management Practices for Florida Golf Courses: Putting Green Construction, Water Management, Fertilization, Cultural Practices and Pest Management. UF/IFAS Publications, Gainesville, FL.

USGA Greens Section Staff. 2004. USGA Recommendations for a method of putting green construction. USGA Green Section Record. 31(2):1-3.

Vavrek, B. 2002. Quit Fooling Yourself. USGA Green Section Record. 45(1):28.

Vavrek, B. 2006. Customized Cultivation. USGA Green Section Record. 44(5):9-13.

Vavrek, B. 2007. Traffic…How Much Can You Bear? USGA Green Section Record. 40(4):1-6.

Vermeulen, P. 1995. S.P.E.E.D. – Consider What's Right for Your Course. USGA Green Section Record 43(3):18-19.

Vermeulen, P., and C. Hartwiger. 2005. Strategies for Organic Matter Control. USGA Green Section Record 33(6):1-5.

Volk, G.M. 1972. Compressibility of Turf as a Measure of Grass Growth and Thatch Development on Bermudagrass Greens. Agron. J. July-August 1972.

Waltz, S.H., and B. McCarty. 2001. The Living Earth. Grounds Maintenance: Golf Edition. 36(5)1-2,6.

White, B. 2006. Rebuild or Resurface. USGA Green Section Record 44(1):1-6.

White, R.H. 2004. Environment and Culture Affect Bermudagrass Growth and Decline. USGA Green Section Record 42(6):21-24. NTEP No. 02-10. TGIF Record: 84150.

White, R.H., and R. Dickens. 1984. Thatch Accumulation in Bentgrass as Influenced by Cultural Practices. Agron. J. 76:19-22.

White, R.H., T.C. Hale, D.R. Chalmers, M.H. Hall, J.C. Thomas, and W.G. Menn. 2004. Cultural Management of Selected Ultradwarf Bermudagrass Cultivars. Online Crop Management. DOI: 10.1094/CM-2004-0514-01-RS. TGIF Record: 104646.

Wolf, B., and G.H. Snyder. 2003. Sustainable Soils. Food Products Press, Binghamton, NY.

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John Rowland was born in Neptune City, NJ, on July 15, 1966. He attended elementary school in Neptune City, NJ and high school in Neptune, NJ. After taking some turfgrass management courses at Rutgers University, he obtained a B.S. degree in turfgrass science at the University of Florida. He then began work on his Master of Science degree at the University of Florida in soil and water science with a focus on turfgrass. After graduation he plans to stay at the University of Florida to pursue a Doctor of Philosophy degree.