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PHYSIOLOGICAL EFFECTS OF LOW MOWING HEIGHTS, ROLLING, AND FOOT TRAFFIC ON CREEPING BENTGRASS PUTTING GREENS

PHYSIOLOGICAL EFFECTS OF LOW MOWING HEIGHTS, ROLLING, AND FOOT TRAFFIC ON CREEPING BENTGRASS PUTTING GREENS

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy in Plant Sciences

By

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May 2013
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ABSTRACT

Golf course superintendents are managing creeping bentgrass (*Agrostis stolonifera* L.) putting greens throughout the transition zone where temperatures can exceed optimum levels for consecutive days in the summer. The stress of creeping bentgrass associated with these supraoptimal temperatures has been well documented, but the management practices implemented on putting greens to increase green speeds may exacerbate these environmental stresses. To date, the physiological effects of these management practices in combination have not been evaluated for putting green turf. The objective of this dissertation project was to determine the effect of mowing heights, light-weight rolling, and foot traffic on performance and physiological parameters of 'SR 1020' and 'Penn G2' creeping bentgrass. Both above and below ground performance characteristics were evaluated in this project including: wear tolerance, turf quality, turf coverage, turf color, rooting characteristics, ball roll distance, ball mark severity, and ball mark recovery. Physiological data were collected with a custom photosynthesis chamber, and carbohydrate analysis was performed for all mowing and rolling treatments. Individual carbohydrates (total ethanol soluble sugars, glucose, sucrose, fructans, and average degree of polymerization) were determined for foliage, crown, and root material of each sample. Both performance characteristics and physiological parameters reached poorest levels in July or August each year as environmental stresses increased. Plots maintained at higher mowing heights and reduced rolling frequencies maintained better wear tolerance, turf quality, coverage, and color compared to lower mowing heights with frequent rolling. Net photosynthesis increased slightly as mowing heights were increased, but few significant differences were observed for these treatment combinations. Few consistent differences were observed for carbohydrate analysis with lower mowing heights or increased rolling frequencies, but increased mowing height generally resulted in higher carbohydrate concentrations in foliage and crown material following heat stress. Ball mark severity was rarely affected by these treatment combinations, but increased rolling frequencies increased maximum ball mark injury and extended recovery time. Fewer significant differences were observed for these parameters compared to initial expectations, but increased mowing heights and reduced rolling frequencies generally created healthier turf.

This dissertation is approved for recommendation
to the Graduate Council.

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ACKNOWLEDGEMENTS

I have greatly appreciated the leadership of my major professor, Dr. Michael Richardson, throughout my career at the University of Arkansas. Dr. Richardson has stood behind me and expressed confidence in my abilities through the good and bad times doctorial students experience. I am also grateful for my dissertation committee, Drs. Douglas Karcher, Aaron Patton, Derrick Oosterhuis, Kristofor Brye, and Rick Bennett. Each of these professors has been inspirational in defining the methodology used in this study. I also appreciated them challenging me to expand my knowledge through my comprehensive exams and classroom activities. Dr. Karcher has been extremely helpful with determining appropriate statistical methods used for data analysis, and Dr. Patton's assistance with carbohydrate analysis procedures was highly valued.

I am also thankful for all the technicians, graduate students, and student workers who have helped me with various portions of this research. Many of these people walked in plots multiple times per summer when foot traffic was applied. Dr. Richardson's technician, John McCalla, was always willing to lend a helping hand no matter how big or small the task. John's ability to construct items used in this research and the countless hours of separating plant parts for carbohydrate analysis were greatly appreciated. Dr. Karcher's former technician and doctorial student, Dan Strunk, was always helpful with teaching me the mechanics of maintaining the mowers, fixing mechanical problems when they arose, and maintaining fertilization and chemical applications on the plot area.

We have had multiple student workers each summer that helped with data collection, treatment application, and sample processing throughout the study. Many aspects of this project could not have been completed without their unending assistance. One student worker in

particular, Raven Bough, was incredibly helpful with quantifying carbohydrates in this study. Raven helped with all aspects of quantifying these sugars and showed great strides throughout the entire process. She was an excellent student and worked diligently to grasp the techniques of performing carbohydrate analysis. I have appreciated all the assistance from all parties throughout my doctorial work.

I must express my appreciation to those that helped with the construction and use of the photosynthesis chamber in this research project. All the members of Dr. Bremer's lab from Kansas State University have been a tremendous help to me throughout this project. Kenton Peterson and Kira Shonkwiler Arnold helped with construction and connecting all electrical components of the chamber and were always available when assistance was needed. I also appreciated Leland Schrader of the University of Arkansas' Agricultural Engineering group for welding the frames together that were used during photosynthetic measurements.

In addition to the personnel required to do this project, financial support and equipment donations allowed us to conduct high quality research. The O.J. Noer Foundation partially funded this research project providing funds to purchase materials for carbohydrate analysis and other research necessities. I am also grateful that the Toro Company and DMI Speed Roller donated equipment for use in this project. This newer equipment was more reliable and parallels the equipment used on many golf courses today.

DEDICATION

I would like to dedicate this dissertation to my loving parents, Paul and Dianne Young, for their continual support throughout my entire educational career. I would also like to dedicate this document to Scott McNeer, a former boss at Spring Creek Ranch in Collierville, TN. Scott lost a battle with colon cancer in January 2012, but he was an excellent teacher. Scott had an exceptional way of teaching us why we were performing tasks and a tremendous eye for detail. The lessons I learned from Scott led me on the educational path I have taken, and I hope to be able to pass this enthusiasm and knowledge on to students I teach in the future.

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INTRODUCTION

The popularity of the game of golf increased from the 1950's through the early 2000's in the United States, but growth has leveled over the past decade. The increased popularity of golf over those decades combined with many technological advances greatly improved the coverage and information available to fans of professional golf tournaments. These golf courses are managed to reach their peak potential just as the golf tournament is about to begin, but management practices are generally eased following the golf tournament to allow time for recovery. The precise conditions of course setup, including Stimpmeter readings (ball roll distances) are reported to viewers during these events. Although the original purpose of the Stimpmeter was to maintain consistent green speeds throughout a single golf course, the publicity of these values and competition among golf courses has altered the mindset to create the fastest greens possible. Avid golfers all over the world expect to play golf under the same conditions they see at these events on a week to week basis, so golf course superintendents are challenged to push putting green grasses to their limits to deliver the fast, firm conditions desired by golfers.

Many management practices can be altered to increase green speeds, but some of the most commonly used practices are reducing mowing heights and incorporating light-weight rolling. In addition to the mechanical stress imposed by these management practices, many golf courses throughout the transition zone (Fry and Huang, 2004) have creeping bentgrass (*Agrostis stolonifera* L.) putting greens, a cool-season grass being grown in areas experiencing supraoptimal temperatures for consecutive days during summer months. The effect of heat stress on quality and physiological health of the putting green has been well established through controlled environment and field studies; however, studies have not been conducted to determine the physiological effect of altering mowing and rolling practices to increase green speeds.

Previous mowing and rolling studies have demonstrated the ability of a putting green to maintain increased green speeds at higher mowing heights when light-weight rolling was applied compared to plots mowed at lower mowing heights (Hartwiger et al., 2001; Nikolai, 2005; Richards, 2010). The increased leaf area in plots maintained at higher mowing heights with rolling is expected to be physiologically healthier, producing greater photosynthetic rates and maintaining greater carbohydrate concentrations. In addition to the environmental and mechanical stresses previously discussed, putting greens also experience significant stress from foot traffic of golfers. Generally, golfers wear special shoes with a rubber spiked sole or individual rubber cleats that help minimize slipping when swinging the club. The tread of the shoe combined with the high level of golf rounds at many golf courses create added stress that is more difficult to manage or control.

The management practices described have been evaluated in previous studies, but no studies have evaluated these three individual stresses in combination. Furthermore, this will be the first study to determine the physiological effects of light-weight rolling on creeping bentgrass. Lastly, ball marks, depressions created when high arching golf shots strike the putting surface, are a major concern for golf course superintendents. Previous ball mark studies have evaluated recovery time between repaired or non-repaired ball marks (Fry et al., 2005), various ball mark repair tools (Munshaw et al., 2007; Nemitz et al., 2008), or different bentgrass cultivars (Murphy et al., 2003). No studies have evaluated the effect of these common putting green management strategies on the severity or recovery of ball marks. A unique methodology was derived for this study to incorporate digital image analysis techniques to collect objective data for both ball mark severity and recovery in an efficient, reliable manner.

OBJECTIVES

1. Determine the quality and agronomic aspects of the turf to ensure the playing surface maintains acceptable conditions appropriate for a golf course putting green while being mowed, rolled, and trafficked.
2. Investigate net photosynthetic rates of treatments to determine stress levels.
3. Identify and quantify fractions of nonstructural carbohydrates in foliage, crown, and root material of creeping bentgrass putting green turf undergoing these treatment combinations.
4. Evaluate ball mark severity and recovery based on the different treatment combinations.

HYPOTHESES

It was hypothesized that putting greens maintained at the lowest mowing height throughout summer months will experience the highest level of stress, possibly to the point of turf loss. The increased stress level of this mowing treatment would result in lower turf quality, coverage, color, rooting, photosynthetic rate, carbohydrate level, and ball mark recovery; however, putting green speed would be increased with the lowest mowing height. The rolling treatments may have a slightly negative effect when performed daily, but rolling should not have a tremendous effect on the performance or physiological factors based on previously published research. However, ball roll distance should be increased with increased rolling frequencies. The negative effects of wear from foot traffic are expected at all mowing heights and rolling frequencies; however, these negative effects should be exacerbated at the lowest mowing height with daily rolling.

LITERATURE REVIEW

The game of golf was believed to have started around the 16th century in England. Initially, the vegetation was maintained by grazing animals and little effort or thought was placed on growing conditions. The natural maintenance of the land continued until 1830, when Englishman, Edwin Beard Budding, developed the first mechanical mowing device (Beard, 2002). Nearing the turn of the 20th century, turfgrass research stations were being established throughout the United States (Beard, 1973). Researchers were evaluating improved turfgrass varieties, fertilization schedules, and establishment techniques. The creation of the Green Section through funding from United States Department of Agriculture and continual expansion of turfgrass research stations across the United States helped educate turfgrass managers to improve growth and development factors. As technology advanced, vast improvements were realized for turfgrass management. Advancements in machinery allowed for more precise application of pesticides, fungicides, and irrigation (Beard, 1973). In addition, new mower technology was developed that was capable of cutting vast areas of grass more efficiently and at lower mowing heights. These advancements and others caused the game of golf to grow exponentially in the 1950's.

The premier of professional golf tournaments on television created more exposure for the game itself, and the turfgrass surface golf was played on as well. As the game was delivered into homes across the United States, increased enthusiasm created a new, higher standard desired by golfers. Educational information provided by research facilities and colleges in relation to management strategies and their affect on turfgrass health helped golf course superintendents provide the highest quality conditions daily (Gross, 2010). The second development that significantly impacted management practices, especially on putting greens, was the Stimpmeter, which was designed by Edward Stimpson in the 1970's (Zontek, 2006). The initial desire for the instrument was to measure the distance a golf ball would roll along the putting green surface when released from an incline to ensure consistent green speeds among the putting greens at a single golf course. Unfortunately, the competition among golf courses and the desire of golfers to have conditions similar to those seen in televised golf tournaments resulted in Stimpmeter readings being equated to quality of putting greens. Golf courses with higher Stimpmeter measurements were viewed as higher quality golf courses. The desire to have faster green speeds led many golf course superintendents to manipulate management strategies in a way to maximize Stimpmeter measurements.

In an attempt to increase green speeds, the most logical and first practice altered was the mowing height of the grass. Over the years, mowing heights trended in a downward direction. As late as the 1970's, it was common for putting greens to be mowed at 6 mm, but this mowing height was trimmed by half to 3 mm by the 1990's. Many researchers have demonstrated the negative effects of these low mowing heights on quality and physiological factors of putting green turf (Huang and Gao, 2000; Stier, 2006; Zontek, 2006). Extensive studies on the effects of low mowing heights on creeping bentgrass (*Agrostis stolonifera* L.) putting greens were performed at the University of Wisconsin-Madison. Mowing treatments consisted of 2.6, 3.7, or 5.6 mm. The lowest mowing height resulted in the highest green speed, but reduced turf quality and density led to increased algae formation (Kussow, 1998). Roots were also affected by mowing height with reduced total root mass at the lowest mowing height. Liu and Huang (2002) demonstrated the effects of mowing at 3 or 4 mm had on root production, growth, and mortality in more detail than previous studies. They used minirhizotron technology to photograph root activity at both 3 and 9 cm depths to quantitatively determine rooting response to the two mowing heights. These researcher's data follow the seasonal growth pattern of cool-season turfgrasses with root growth decreasing in the summer months for both mowing heights; however, the effects of reduced rooting were greater at the low mowing height (3 mm) during summer heat stress.

Creeping bentgrass is a cool-season (C_3) plant, and all plants undergoing photosynthesis in the Calvin cycle have similar seasonal growth patterns. The peaks and valleys of the annual growth curve are exacerbated throughout the transition zone (Fry and Huang, 2004) and southeastern regions of the United States due to excess temperatures throughout summer months in these regions. Cool-season plants have two peak growth periods within the annual cycle where both shoot and root growth are maximized; first in the spring and the second in the fall when air temperatures are between 15 and 24°C and soil temperatures are between 10 and 18°C. During the summer months as temperatures increase, both shoot and root growth of cool-season grasses are reduced due to the inefficiency of rubisco (Ribulose 1,5-bisphosphate carboxylase/oxygenase), the enzyme responsible for carbon dioxide (CO_2) fixation in C_3 photosynthesis. Carbon dioxide levels in the plant are further reduced during the summer due to stomatal closure, reducing photosynthate production. In contrast, respiration, the process of using stored carbohydrates to create energy for growth, continually increases during warmer weather. If temperatures remain above 30ºC and stomata are closed, reducing CO_2 concentrations in the plant, rubisco will begin fixing oxygen (O_2), magnifying the inefficiency of the photosynthetic process (Fry and Huang, 2004; Gardner et al., 1985). The contradictory aspects of these metabolic pathways result in a physiologically weakened plant because the plant is incapable of producing the amount of food necessary for normal growth and maintenance. This concept has been proven to be true for many creeping bentgrass cultivars grown in controlled environment studies (Huang et al., 1998a; Huang et al., 1998b; Huang and Gao, 2000; Xu and Huang, 2000) and in natural environments managed as putting greens (Liu and Huang, 2001; Xu and Huang, 2003). This physiological stress led turfgrass breeders to develop creeping bentgrass cultivars better adapted to grow in warmer environments.

As previously mentioned, the optimum temperature range for creeping bentgrass growth is between 15° and 24°C, but creeping bentgrass is being grown and managed as a putting green in USDA Plant Hardiness zones 7a and 7b (Kaplan, 2012). Temperatures in these regions may remain above the optimum temperature for long periods during the summer. As the plants weaken due to environmental conditions, they are also being mowed at excessively low heights, reducing the leaf area available to produce more photosynthates. Based on these factors, turfgrass breeders worked to develop cultivars with increased heat tolerance and shoot densities, especially when maintained at very low mowing heights. Many higher density creeping bentgrass cultivars have been released in the last 15 years that exhibit greater heat tolerance and disease resistance (Beard et al., 2001; Moeller et al., 2008; Sifers et al., 2001). Sweeney et al. (2001) compared various standard and high density bentgrasses maintained at 3.1 mm height-of-cut based on root dry weights over two seasons and verified differences in shoot densities among cultivars. There were no significant differences in root dry weight for standard or high shoot density creeping bentgrasses, and both types followed the trend discussed earlier with highest root dry weights in spring/fall then reduced weights in summer. Sweeney et al. (2001) determined that higher density bentgrasses had greater tillers/dm^2 than standard cultivars even in the middle of summer, suggesting the higher density cultivars may have greater leaf area available to intercept light and maximize photosynthetic production. Many other studies have demonstrated increased photosynthetic rates and decreased respiration rates when comparing newer, high density cultivars to the standard bentgrass cultivars (Liu and Huang, 2001; Liu and Huang, 2002; Xu and Huang, 2000). The ratio of carbohydrates produced to carbohydrates consumed by the plant during various seasons is an important response variable when studying physiological effects of different practices on plants.

Many researchers have used total nonstructural carbohydrate levels as a basis to understand energy reserves the plant could use for coming out of dormancy (Davis and Gilbert, 1970; Munshaw et al., 2001), identifying stressed plants (Huang, 2003; Huang and Gao, 2000; Sweeney et al., 2001; Xu and Huang, 2000), or determining recuperative ability (Donaghy and Fulkerson, 1998; Fu and Dernoeden, 2009a; Goss et al., 2002). Carbohydrate reserves are also necessary for shoot regrowth after mowing. This role of carbohydrate reserves has been studied vastly in forages when determining physiological factors of grazing and defoliation (Ritsema and Smeekens, 2003; Smouter and Simpson, 1989; Sullivan and Sprague, 1943). The type and quantity of carbohydrates stored play a significant role in the plant's ability to withstand stress conditions. Total nonstructural carbohydrate data are sufficient to produce a general idea of the amount of carbohydrates in the plant, but recent studies have gone more in depth with improved techniques to identify and quantify the individual carbohydrates in shoots and roots.

Cool-season grasses contain four main nonstructural carbohydrates: glucose, fructose, sucrose, and fructans. The first three of these are readily available as long as the plant is actively photosynthesizing. Glucose is the main sugar produced through photosynthesis and the combination of two glyceraldehyde 3-phosphate molecules. Fructose is also produced with glyceraldehyde 3-phosphate combining with fructose 1,6-bisphosphate. The availability and production of these two reducing sugars regulates the production of the non-reducing sucrose, the main sugar transported throughout the plant from sources to sinks. Fructans are the main storage carbohydrate of cool-season grasses and are fructose polymers formed by sucrose (Ritsema and Smeekens, 2003). Fructans are produced in the vacuoles and are positively correlated with light interception by the plant (Hull, 1992). Sucrose is initially formed in the cytosol and transported to the vacuole where sucrose-sucrose-fructosyltransferase (SST) catalyzes the addition of a fructose molecule to another sucrose forming a trisaccharide. A second enzyme fructan-fructan-fructosyltransferase (FFT) helps add another fructose molecule from sucrose to the trisaccharide forming a fructan with degree of polymerization (DP) equal to four (Hull, 1992). The activity of SST is light-dependent, so fructans stored in vacuoles during the day are hydrolyzed to sucrose and transported to sinks or storage organs in the evening. Most fructans identified from Gramineae (Poaceae) plants are levan type [β(2-6)-linked fructose polymer] (Pollock and Cairns, 1991; Ritsema and Smeekens, 2003). Although these individual sugars have pivotal roles in determining the health of turf, few studies have demonstrated the effects of treatments on these individual nonstructural carbohydrates.

More recent studies have begun to explain seasonal trends and the effects of cultural practices and mowing on carbohydrate levels. Xu and Huang (2000) identified differences in carbohydrate accumulation over seasons for a standard and newer, heat tolerant cultivar of creeping bentgrass. Carbohydrate levels were high in spring and fall, but declined to the lowest levels when temperatures increased above optimum. There were a few dates where significant differences between cultivars were observed, but the observations were not persistent enough to make a definitive conclusion that the heat tolerant cultivar had more favorable carbohydrate levels. Fu and Dernoeden (2009a) studied carbohydrate levels in shoots and roots of creeping bentgrass that was aerified in the spring only and spring/summer compared to a non-aerified control to determine if aerification treatments influenced carbohydrate reserves, which may lead to healthier turf. There were few consistent treatment differences identified over the two year study, but carbohydrate levels in shoots and roots followed the trend previously mentioned. These studies demonstrate the natural progression of carbohydrate levels throughout seasons and with aerification regimes, but it is unclear if mowing frequency and height would have a similar effect on carbohydrate levels.

A study was conducted in a controlled environment by Howieson and Christians (2008) to determine the effect of a single mowing, double-cutting, and rolling on the carbohydrate content of creeping bentgrass maintained at putting green height. Fructan levels were significantly lower in mown treatments than the rolled and non-mown control. The double-cutting treatment required much more time than the single mowing treatment to rebound to fructan levels observed in non-mown treatments. Fructose, glucose, and sucrose levels were also determined for the various treatments in the study, but glucose was the only carbohydrate that exhibited differences among treatments with double-cutting having significantly less glucose concentration than non-mown treatments, and single cut treatments having reduced concentrations (Howieson and Christians, 2008).

Narra et al. (2004) extracted and quantified total nonstructural carbohydrates from shoots of creeping bentgrass maintained as a golf course fairway mown at three mowing heights (0.64, 1.27, and 1.90 cm) in Urbana, IL to determine if carbohydrate levels could be used to predict the onset of stress, and if lower mown turf would exhibit lower carbohydrate levels due to decreased leaf area. Total nonstructural carbohydrate levels at the three mowing heights all followed the trend discussed previously with highest levels in the spring/fall and lowest values in summer. Fructans were the major nonstructural carbohydrate found in the grasses and were highly correlated with total nonstructural carbohydrate data. Surprisingly, the lowest mowing height

(0.64 cm) had significantly higher fructan concentration on 11 of 29 collection dates. The medium mowing height (1.27 cm) had the highest fructan concentration on one date with the highest mowing height (1.90 cm) never being highest. These findings were in contrast to original expectations, but the authors hypothesized the increased carbohydrate concentration at lower mowing heights was due to removing more sheath and stem material that would contain higher fructan levels than removing leaf material only at the higher mowing heights (Narra et al., 2004). If this trend were true, there may be an optimum mowing height that would result in a peak carbohydrate level before diminishing again.

Besides being the main storage carbohydrate for cool-season plants, increased fructan concentrations have been observed during acclimation periods prior to stress. Previous research has demonstrated the role of fructans as plants respond to salinity, drought, or cold stress conditions (Livingston et al., 2005; Qian and Fu, 2005; Ritsema and Smeekens, 2003; Smouter and Simpson, 1989). The soluble nature of these fructans allows them to adjust osmotic potential and protect membrane phospholipids and proteins under environmental stress conditions (Qian and Fu, 2005). According to Hull (1992), fructan synthesis is favored by conditions of minimal plant growth with little effect on photosynthetic rate, such as cool temperatures. In contrast, Duff and Beard (1974) identified significant increases in fructans and reducing sugars when creeping bentgrass was grown at day/night temperatures of 40°/30° C compared to cooler temperatures. The majority of research identifying and quantifying DP fractions of fructans have come from forage or native grasses using thin layer chromatography (TLC) (Smouter and Simpson, 1989; Spollen and Nelson, 1988), high performance liquid chromatography (HPLC) (Livingston et al., 2005; Livingston, 1991; Livingston and Henson, 1998), or a combination of both methods (Cairns and Pollock, 1988). Some of these studies evaluated the effect of defoliation on these grasses, but daily mowing below the optimum height may have a more drastic effect on the carbohydrates levels within the plant.

The previous information discusses some of the physiological effects that may be observed as putting green mowing heights are lowered to increase green speeds. A second management practice that has been used to increase green speeds is rolling. This practice was commonly performed in the early 1900’s, but began to decrease in the 1920’s due to the potential negative effects of soil compaction. Many years later, a couple of new developments revitalized rolling as a management strategy to increase green speeds and improve smoothness of putting greens. First, the development of USGA-style putting greens that contain high percentages of sand reduced the potential for soil compaction. Secondly, a new generation of light-weight rollers were introduced that had reduced surface pressure compared to previous rollers used on putting greens. These rollers were also much faster with speeds approaching 2.68 m/s (6 mph) (Nus, 1992). Throughout the past 20 years, researchers have studied the effects of rolling on soil and plant properties.

A research project conducted at North Carolina State University investigated the impact of rolling frequency and mowing height on both a sand-based and native soil putting green (Hartwiger et al., 2001). Rolling frequencies consisted of 0, 1, 4, and 7 times per week, but single treatments were rolled in both the forward and reverse directions; therefore, treatments were actually rolled 0, 2, 8, or 14 times per week. These rolling frequencies were performed on putting greens maintained at 4 and 6.5 mm height-of-cut. Hartwiger et al. (2001) measured soil properties, turf quality, and ball roll distance to determine an optimum rolling frequency to maximize green speed and minimize negative effects on soil and turfgrass characteristics. Ball roll distances had a direct relationship with rolling frequencies and all plots that were rolled had greater ball roll distances than the control. As the rolling frequency was increased, ball roll distances increased (Hartwiger et al., 2001). However, there were negative effects observed at higher frequencies of rolling. Soil bulk density in the top 3 cm increased on native soils when plots were rolled 8 or 14 times per week, but levels never exceeded the USGA's recommendations for bulk density measurements (Hummel, 1993). Turf quality followed a similar trend with the two higher rolling frequencies having reduced turfgrass quality ratings. The reduction in turf quality was similar at both mowing heights and on both soil types (Hartwiger et al., 2001). This research demonstrated both positive and negative effects of rolling putting greens and confirms a rolling frequency must exist that maximizes beneficial effects and minimizes detrimental effects of rolling.

A thorough study on mowing height, mowing frequency, and rolling frequency was recently completed at the University of Arkansas (Richards, 2010). The main objective of the study was to determine a short-term mowing height and mowing/rolling frequency that would maximize green speeds and maintain an acceptable putting surface. Similar to previous studies, ball roll distances increased as rolling frequencies increased; furthermore, turf quality was reduced with the highest frequency rolling treatments. Although turf quality was reduced, quality never dropped below acceptable until greens were rolled 4 to 8 times a day. Even at this frequency, it took 30 and 11 days, respectively, for turf quality values to be reduced below acceptable values. Reduced turf quality was due to thinning, which predisposes the area to algae growth. Percent algae coverage data was obtained following heavy rain activity, and most plots mowed at 3.2 mm had significantly greater algae coverage than plots mowed at 4.0 mm. Rolling treatments did not significantly affect algae coverage. Surface hardness measurements were recorded for the treatment combinations with a Clegg Soil Impact Tester. The resultant data in

Gmax ranged from 40 to 62.8 over two studies. Few conclusions could be drawn from the values because the authors were unsure of how to interpret the data, but increasing rolling frequency led to firmer surfaces (Richards, 2010).

Researchers at Michigan State University have performed extensive rolling studies to determine the effects of season-long rolling programs on putting greens. One of these studies consisted of various treatment combinations that included mowing heights (4.0 and 4.8 mm), mowing frequency, (single- and double-cut), rolling frequencies (3 and 5 times per week), and rolling equipment (Olathe and Jacobson) (Nikolai et al., 1997). As with the previous studies, rolling increased green speeds by approximately 30 cm compared to unrolled plots. Interestingly, when rolling was incorporated with mowing three times per week at the higher mowing height (4.8 mm), green speeds were similar to the lower mowing height (4.0 mm) with no rolling. Other interesting data observed with rolling three times per week included a reduction in dollar spot (*Sclerotinia homoeocarpa* F.T. Bennett) incidence, decreased algae growth, and minimized occurrence of localized dry spot; however, pink snow mold (*Fusarium nivale* Ces. ex Berl. & Voglino) incidence increased with rolling at this frequency (Nikolai, 2002). Based on this research, it appears rolling putting greens three times per week in combination with mowing six times per week can maximize green speeds, while not reducing turf quality to unacceptable limits.

The practice of rolling putting greens has become common with the new research that has been produced over the last 20 years. This research disproved some of the fears associated with rolling putting greens. For instance, rolling putting greens on a regular basis was not going to affect turf quality or soil compaction in a significant manner. The improved technology devised specifically for golf course putting greens greatly reduced these negative effects. In addition, rolling putting greens can increase ball roll distances or maintain green speeds when putting greens are managed at higher mowing heights during environmental stress. To date, the main objectives of rolling studies have been to disprove the negative effects and ensure ball roll distances were indeed increased with rolling treatments. No research has been conducted to determine the physiological effect of increased rolling during summer heat stress. Both mowing and rolling, along with many other management practices performed on putting greens, can be injurious to turf due to wear, but golf course putting greens may undergo more wear due to foot traffic.

Traffic on turf can be detrimental to the overall health of the turfgrass stand due to the associated compaction and wear (Beard, 1973). The effects of compaction will typically take time to become evident in turf. Compaction is more problematic in fine textured soils that undergo continual traffic, especially when moisture is adequate. These conditions raise bulk density and minimize pore space, reducing available oxygen in the rootzone. The main traffic on golf course putting greens that may lead to compaction is the equipment used to maintain the area and foot traffic throughout the green, but especially around the hole location. Based on the information previously discussed on rolling, compaction is not a major concern on newer sand-based putting greens due to the larger percentage of coarse particles. Previous studies concluded that bulk density and pore space were not significantly reduced on sand-based putting greens (Hartwiger et al., 2001, Samaranayake et al., 2008). For this reason, the main effect of traffic on a putting green will come from wear. Wear is the result of pressure, tearing, or scraping actions causing physical injury to turfgrass resulting in immediate damage of plants (Beard, 1973; Carrow, 1995). Wear could be caused by mowers or other cultivation equipment, but is more likely caused by foot traffic in highly traversed areas of the putting green. These areas consist of the turf in vicinity of the golf hole and any walk-on areas that are used consistently by golfers due to terrain or hazards impeding alternate paths.

Samaranayake et al. (2008) conducted a study in New Brunswick, NJ to determine the effect of wear and compaction or the interaction of both on soil properties and turf quality of multiple creeping bentgrass cultivars maintained as a putting green or fairway. Both wear and compaction treatments were applied using simulators to get consistent treatments on each cultivar and management level. Neither wear nor compaction alone significantly affected bulk density or porosity of the top 5.1 cm in the sand-based putting green similar to previous rolling research. However, there was an interaction effect that increased bulk density and decreased air porosity on the sand-based surface. This response was thought to be the result of applying treatments over a season rather than one time at a high frequency. Variations in turf quality were mostly explained by cultivar and wear; compaction did not play a major factor in differentiating treatments on the sand-based putting green (Samaranayake et al., 2008). Since wear on sand-based putting greens appears to be more injurious to turf, the damage of foot traffic from various sole and spike types may exacerbate stress.

In 1983, the United States Golf Association (USGA) published data that demonstrated differences in wear damage from golf shoe spike type and sole design. The concept of wearing specialized shoes with some form of traction protection dates back to 1893 and became a standard practice in 1919 (Gibeault et al., 1983). The traction protection for most of these shoes was metal spikes, approximately 8 mm in length, which would stabilize the golfer's feet in the ground and reduce slippage. There was much debate by groups that these metal spikes were deleterious to putting green quality. Metal spikes can result in raised tufts of grass (spike marks) that reduce smoothness of putting greens, and by rule cannot be repaired by golfers prior to striking a putt. Multiple studies in the 1990's and prior to concluded that shoes with metal spikes created greater wear on putting greens than did non-metal spikes or spikeless treads (Carrow, 1995; Gibeault et al., 1983; Morrow and Danneberger, 1995; Nikolai and Rieke, 1998), leading the majority of golf courses in the United States to ban metal spikes. In contrast, a research project conducted at Clemson University on a heat stressed creeping bentgrass putting green demonstrated that non-metal spikes exhibited unacceptable wear stress under human foot traffic (Waltz and McCarty, 1999). As such, foot traffic in extreme environmental conditions may be destructive regardless of the spike type; however, the previously cited research demonstrated that metal spikes increase wear stress under all conditions.

Another lesser form of traffic that can still be extremely destructive on creeping bentgrass putting greens are ball marks. Ball marks occur when high arching golf shots contact the putting green creating an impression in the putting surface. The golf ball is not only coming in from a high trajectory, but likely has backspin, which causes turfgrass and possibly soil material to be removed. There are tools that can be used to repair these marks, but many golfers fail to repair ball marks, increasing their detrimental effect (Munshaw et al., 2007). Even when repaired properly, it has been reported to take two weeks for ball marks to heal completely and upwards of 6 weeks for unrepaired ball marks to heal (Murphy et al., 2003). The majority of ball mark studies conducted have evaluated recovery time with various repair techniques or tools (Fry et al., 2005; Munshaw et al., 2007; Nemitz et al., 2008)

Management practices can improve surface conditions and reduce the magnitude of ball marks on creeping bentgrass putting greens. The cultivar selected, age of the putting green, and surface firmness have been shown to have a significant effect on ball marks. A USGA study evaluated initial ball mark size on 15 creeping bentgrass cultivars, and how quickly unrepaired ball marks recovered under compaction and wear treatments (Murphy et al., 2003). The higher density creeping bentgrasses had smaller ball marks that recovered quicker. As expected, plots receiving compaction and wear had larger ball marks that took much longer to recover; however, in plots with just compaction, this result was not observed (Murphy et al., 2003). Similar to previous studies, wear must decrease the recuperative ability to a greater extent than compaction on sand-based putting greens. Nemitz et al. (2008) evaluated the effect of surface firmness on ball mark severity. The Clegg Soil Impact Tester was used to evaluate surface hardness prior to experimental data collection. The "soft" putting green had Clegg Impact value of 100 Gmax, whereas the "firm" putting green measured 145 Gmax (Nemitz et al., 2008). The softer putting green had significantly larger ball marks than the firm surface, and unrepaired ball marks on the softer green had a significantly larger scar area 21 days after occurrence (Nemitz et al., 2008). This research demonstrates the potential benefit of firmer surfaces by reducing the negative effects of ball marks.

The previous information discusses some of the research that has been performed based on mowing heights, rolling frequency, and foot traffic. Many of these studies evaluated treatments by visual turf quality ratings, root masses, or ball roll distances. All of this information is important and gives golf course superintendents guidelines to follow that should result in a high quality turf with improved playability. To date, no research has measured the physiological effects of extremely low mowing heights, season long rolling, and standard foot traffic of creeping bentgrass putting greens in a simultaneous study.

MATERIALS AND METHODS

Treatment design and application

This experiment was conducted at the University of Arkansas Research and Extension Center in Fayetteville from May to September in the 2010 and 2012 growing seasons and May to October in the 2011 growing season. Creeping bentgrass cultivars, SR 1020 and Penn G2, were evaluated through this study, but these cultivars were not replicated. Both of these cultivars were improved type cultivars, but Penn G2 was a high-density, fine-textured cultivar better adapted for lower mowing heights (Fraser, 1998; Samples and Sorochan, 2007). Previous research has also differentiated these cultivars based on turf quality, shoot density, and rooting potential (Sifers et al., 2001). The experimental design within each cultivar consisted of a randomized complete block with three replications in a strip-split plot treatment arrangement. The main plot factor was mowing height at bench height settings of 2.5, 3.2, or 4.0 mm. Main plots (3.6 x 5.5 m) were mowed six days per week in three alternate directions using a walk-behind mower (Toro Flex 21, The Toro Company, Bloomington, MN), while alleyways were mowed at 4.0 mm three days per week. The main plot was divided into three strips (1.2 x 5.5 m) for applying rolling treatments of zero, three, or six times per week. A commercially available roller (Speed Roller, DMI/IPAC Group, Amherst, NY) was used throughout this project. The strip plots were further split (1.2 x 2.7 m), and foot traffic was applied by five researchers walking within each plot for two minutes every two weeks from June to August in 2010 and 2011. The frequency of foot traffic application was increased in 2012 to weekly and was administered from July to mid-August. A preliminary study estimated an average of 250 steps within each sub-sub-plot over a two minute period. Comparing this information to the data discussed by Hathaway and Nikolai (2005), this level of foot traffic should be similar to traffic around the hole location following 200 rounds of golf at an average golf facility, which on average will receive 32,000 rounds of golf per year (NGF, 2003). Weather data were collected from a weather station located at the research farm to document general weather conditions while treatments were applied.

All other management practices generally applied to a creeping bentgrass putting green in the transition zone were followed. The entire area was aerified (aerifier type, The Toro Company, Bloomington, IL) once in the fall and spring followed by sand topdressing to fill aerification holes. Sand was applied as a light topdressing every two weeks throughout the growing season. Trinexapac ethyl (Primo Maxx, Syngenta Crop Protection, Greensboro, NC) was applied at 0.05 kg ai/ha monthly to regulate shoot growth along with wetting agents [Revolution ® (Aquatrols, Paulsboro, NJ) at 9.4 liters/ha; Cascade Plus (Precision Laboratories, Waukegan, IL) at 51 liters/ha] to maintain adequate soil moisture and reduce localized dry spot. The study area was fertilized with 196 kg N/ha each year including foliar feeding 9.9 kg N/ha biweekly throughout the summer months. Fungicides and insecticides were applied curatively when symptoms became apparent on any creeping bentgrass putting green turf at the research facility to minimize disease or insect symptoms from becoming apparent in the study area. Irrigation and syringing was applied to the study area to prevent drought stress.

Performance data collection

Various forms of performance data were evaluated throughout this study including: turfgrass wear from foot traffic, quality, coverage, color, and ball roll distance. Immediately following foot traffic application, visual wear was rated using a 1 to 9 scale with 9 being no visible evidence of foot traffic within the plot and 1 being complete destruction of turf with spike marks, chlorosis, and thinning. Turfgrass quality was determined on a 1 to 9 scale (9 = best quality, 6 = minimum acceptability, and 1 = poor quality). Turf quality ratings were not recorded in conjunction with wear ratings. Following this visual turf quality rating, two digital images were captured of each plot to determine turfgrass coverage and color. Images of the plots were obtained using an Olympus SP-510UZ digital camera (Olympus Optical Co., Center Valley, PA) mounted to a light box (NexGen Turf Research, Albany, OR) to ensure consistent light conditions. The digital camera was manually set at shutter speed 1/50 s, aperture of F2.8, and 100 ISO. Each jpeg image (1024 x 768 pixels) was analyzed in SigmaScan Pro (v. 5.0, SPSS, Inc., Chicago, IL) for percent turf coverage (Richardson et al., 2001) and color (Karcher and Richardson, 2003). Both percent turf coverage and color were analyzed with threshold parameters (Hue 65-120 and Saturation 15-100). Threshold parameters were incorporated into the color analysis to ensure that only green tissue was evaluated. The color analysis consisted of four separate evaluations including hue, saturation, brightness, and dark green color index (DGCI). The values determined for the first three parameters are used to calculate DGCI (Karcher and Richardson, 2003).

Ball roll data were collected twice within both 2010 and 2011. Ball roll evaluations were only conducted on mowing and rolling treatments without foot traffic. Individual collection dates consisted of measuring ball roll on sequential days to obtain a data set with and without rolling for the 3 times per week treatment. A standard USGA Stimpmeter was modified with a new notch etched at 38 cm (Gaussoin et al., 1995) to ensure ball roll was evaluated within each sub-sub-plot. Three individual measurements were recorded following the release of the golf ball from the notch in a single direction. An additional set of three measurements were recorded for the opposite direction. The average distance for each direction was normalized to a standard 76 cm Stimpmeter using the equation derived by Gaussoin et al. (1995). The normalized data were incorporated into the Brede formula (Brede, 1991) to determine ball roll distance.

Rooting parameters

Rooting parameters were evaluated in late-May and mid-August each year. Each year, the May sampling was performed prior to the initiation of foot traffic treatments, so only mowing and rolling treatments were evaluated. Two random samples were collected from each plot using a profile sampler (Turf-Tec International, Tallahassee, FL) (7.6 cm x 1.3 cm) at a 10 cm depth. Sand and organic matter were washed from each sample. The top two cm of verdure and thatch/mat layer were removed from each sample, and a second rinse ensued to ensure that all sand was removed from the root sample. The root material was carefully spread out in a 15 x 20 cm clear dish containing water to ease separation of root material in preparation for scanning. The dish was placed on an Epson Perfection V700 Photo Scanner (Epson America, Inc., Long Beach, CA). The scanned image was analyzed by WinRhizo software (Regent Instruments Inc., Quebec, Canada) resulting in cumulative root length, surface area, and average root diameter along with numerous parameters that were not reported. Following image analysis, the two root samples were combined, dried in an oven at 100°C for 48 hours, and weighed to obtain root mass data.

Photosynthetic measurements

A closed-system photosynthesis chamber was constructed similar to the design previously described by Lewis (2010) and Murphy (2007) (Fig. 1). Two pieces of clear acrylic FF plastic (0.48 x 112 x 30.5 cm) were bent to 90 degree angles, and the two pieces were glued together by Regal Plastics Supply (San Antonio, TX) to prevent leakage at seams. The top of the chamber was covered with transparent, heat shrink plastic (0.0012 mm clear oriented polypropylene, Product no. 001051, Professional Plastics, Fullerton, CA). The heat shrink plastic was replaced before each year of photosynthetic measurements. Four small (92 x 92 x 25 mm), DC fans (Allied Stock # 997-0439, Allied Electronics, Fort Worth, TX) and perforated electrical conduit (Lewis, 2010) were attached to the interior of the chamber and electrical conduit was connected to a larger 12 VDC Blower (Prod. # 259-1363-ND, Digi-Key Corp., Thief River Falls, MN) to increase air mixing within the chamber.

An infrared gas analyzer (LI-840 CO_2/H_2O Analyzer, Li-Cor Biosciences, Lincoln, NE) was attached to a PVC shield on the back of the plastic chamber (Fig. 2). A rotary vane pump (Thomas 50095 pump, Wilson Company, Addison, TX) circulated mixed air from electrical conduit to the infrared gas analyzer and back into the chamber. A vent was installed to help maintain pressure within the chamber similar to outside pressure. A bidirectional pressure transducer (Prod # 2641R05WB2DT1C, Setra Systems, Inc., Boxborough, MA) was attached to the shield to monitor differences in pressure within and outside the photosynthesis chamber.

In addition to carbon dioxide levels being evaluated, other instruments were installed to measure environmental parameters. A quantum light sensor (LI-190SZ-50, Li-Cor Biosciences, Lincoln, NE) was attached to the top of the PVC shield to quantify photosynthetically active radiation (PAR). Turfgrass canopy temperatures were determined using an infrared radiometer with thermistor (SI-111, Apogee Instruments, Inc., Logan, UT). Air temperature within the chamber was obtained with a thermocouple wire (Type T Thermocouple Wire, Grainger, Lake Forrest, IL) that was secured within the electrical conduit. All these instruments and peripherals were powered by a rechargeable 12 volt battery (P078-ND, Digi-Key Corp., Thief River Falls, MN). All data were collected and stored on a CR10x datalogger (Campbell Scientific, Logan, UT) using a program written by researchers at Kansas State University (D. J. Bremer, personal communication, 2010).

Photosynthesis measurements were only performed on completely sunny days between 1100 and 1400 hours. Aluminum T-bar (Alloy 6061, McMaster-Carr, Robbinsville, NJ) was welded together to form square frames to hold the chamber when collecting data. Foam weather stripping was placed around the base of the chamber to ensure a good seal between the chamber and metal frames. Because measurements were taken on a putting green, the frames were placed on the putting green surface instead of inserting the frames into the soil. Once the datalogger program was initiated, there was a 20 s period when the chamber was held in the air to acquire ambient levels within the chamber. A chime would sound following this time period, and the chamber was quickly set on the square T-frames. Each response variable being evaluated was stored on the datalogger every second for 40 s. Once the chime sounded a second time, the chamber was removed and allowed to equilibrate before measuring the next treatment combination. A single measurement in full sun was obtained for each sub-sub-plot. At the completion of a single replication, a dark measurement was recorded using the methods discussed, but the chamber was covered with a cardboard box to eliminate all light to the turf canopy. This measurement results in a soil and canopy respiration value that is subtracted from the CO_2 flux to determine net photosynthetic rate (Bremer and Ham, 2005). These computations were performed by running a separate program written by researchers at Kansas State University in MatLab (MathWorks, Natick, MA) (D. J. Bremer, personal communication, 2010).

Carbohydrate analysis

Samples were collected three times throughout the summer months in 2011 and 2012 to quantify carbohydrate levels. Carbohydrate analysis was only performed on non-trafficked treatments. Foot traffic was not evaluated in this portion of the study. Two random samples were obtained using a slide hammer (3.8 cm diameter) to a depth of 5 cm and placed on ice immediately. Samples were held at 4°C until processed. The majority of foliage was removed from each sample using scissors. The top 5 mm of crown and stem tissue were removed with a knife, and the remaining root material was replaced in a 4°C refrigerator. Individual crown and stem material was picked out of samples using forceps and dipped in water to remove any sand and soil from the material. Approximately 2 g of fresh material was extracted from the samples and combined. The crown and stem material was submerged in liquid nitrogen and stored at -20°C until further sample processing.

Root material was obtained from the remaining soil material after removing the top 5 mm. An additional 15 mm of thatch/mat was later removed from each of the soil samples. The sand and organic matter remaining was washed from the root material. Roots collected from the two samples were combined, submerged in liquid nitrogen, and stored at -20°C until further sample processing.

Foliage samples were obtained by collecting clippings from each strip-split plot. Two passes were made using a walk-behind mower (Toro Flex 21, The Toro Company, Bloomington, MN). Because the area for clipping harvest was relatively small, clippings were collected following two days of no mowing to guarantee enough foliage was collected for analysis. Foliage was placed on ice immediately until clipping collection was completed. Samples were submerged in liquid nitrogen and stored at -20°C until further sample processing.

All the procedures used in processing samples, extracting carbohydrates, and quantifying individual sugars were the same for foliage, crown, and root samples. Tissue samples were dried at 90°C for approximately 48 hr, or until mass of samples were no longer reduced. The dried samples were frozen in liquid nitrogen before being ground with mortar and pestle. The ground tissue was stored at room temperature in dark vials (Capitol Vial Inc., Auburn, AL) to prevent light degradation.

Ethanol soluble sugars [glucose, fructose, sucrose, and low degree of polymerization (DP) fructans] were extracted from approximately 60 mg of ground tissue using 1 ml of 92% ethanol. The samples were incubated for 15 min at room temperature vortexing three times. The tissue and ethanol solution were centrifuged at 11,500 rpm for 7 min to separate tissue from supernatant containing sugars. The supernatant was carefully removed, and this process was repeated two more times. There was high variation in sugar concentration for plant parts as well as time of year samples were collected. For this reason, some sugar extractions required further dilution in 92% ethanol to be able to more consistently quantify nonstructural carbohydrates from samples. The ethanol solution containing sugars was stored at -20°C until quantification procedures were performed.

The residue remaining after the third wash was used for fructan extraction in double distilled water (ddH_2O). Tissue residue was vortexed with 1 ml of ddH_2O, incubated for 15 min, followed by centrifugation at 11,500 rpm for 7 min. Supernatant containing the water soluble fructans was decanted into a separate tube. Some samples required dilution in ddH_2O based on reasoning previously described. The fructan solution was stored at 4°C until hydrolysis and quantification were performed.

Total ethanol soluble sugars were determined using a hot anthrone method previously described by Koehler (1952). Briefly, 200 µl of sugar extract was diluted in 300 µl of 92% ethanol and mixed with 3.5 ml of 0.2% anthrone (Prod. No. A19118-22, Alfa Aesar, Ward Hill, MA) in 95% sulfuric acid in a cold water bath. Test tubes were then incubated in a boiling water bath for 8 min. Spectrophotometer (UV 160 UV-Visible Recording Spectrophotometer, Shimadzu Corp., Kyoto, Japan) readings were obtained at 625 nm and compared to values for a standard glucose curve.

Glucose and sucrose quantification was performed simultaneously with three replicates per sample. For glucose quantification, 200 µl of ethanol sugar extract was diluted in 200 µl of ddH_2O and 600 µl of 5 mM sodium acetate solution [2 g sodium acetate (Fisher Scientific, Pittsburgh, PA) in 500 ml of ddH_2O]. Sucrose reactions were prepared with the same material, but 200 µl of invertase (Cat. No. E-INVRT, Megazyme International, Bray, Co. Wicklow, Ireland) mixture containing 100 U of invertase was substituted for ddH_2O. All tubes were incubated at 50°C for 1 hr to hydrolyze the disaccharide, sucrose. Total glucose in each sample was quantified by incorporating 1 ml of glucose oxidase reagent (Glucose Assay, Cat. No. 220-32, Diagnostic Chemicals Limited, Charlottetown, PE, Canada). All tubes were incubated at 37°C for 5 min, allowed to cool to room temperature, and spectrophotometer readings were conducted at 505 nm. Glucose concentration was determined based on a standard glucose curve. Sucrose quantification was determined by subtracting the value determined without invertase from the glucose value calculated with invertase.

Fructans were initially hydrolyzed to calculate total fructans and average DP size from the extracted sample. One or two milliliters of water soluble sugar extract containing fructans, depending on tissue type and month, was mixed with 1 ml of 1 N sulfuric acid (H_2SO_4) (Cat. no. MK287646, VWR, Radnor, PA). The mixture was placed in boiling water for 15 min to hydrolyze fructans into monosaccharides, glucose and fructose. Once the solution cooled to room temperature, 1 ml of 1 N sodium hydroxide (NaOH) (Cat no. BDH3222-1, VWR, Radnor, PA) was added to neutralize the solution. Glucose was quantified using the glucose oxidase reagent as previously described. The value determined by glucose standard curve represented the total number of fructans extracted from tissue samples. A separate procedure was completed to determine fructose concentration in the hydrolyzed solution. Five hundred microliters of digested fructan solution was added to 500 µl of alcoholic resorcinol [1 g Resorcinol (Prod. No. A13080-30, Alfa Aesar, Ward Mill, MA) in 1 L 95% ethanol] and 1.5 ml of 30% hydrochloric acid (HCl) solution. The mixture was incubated at 80°C for 20 min, allowed to cool, and analyzed on a spectrophotometer at 540 nm. Fructose levels were determined based on a fructose standard curve. The value obtained for total fructose in the sample was divided by the amount of glucose in the solution to determine average DP fraction from tissue.

Ball mark severity and recovery

Ball marks were created once per growing season in 2010 and 2011 and evaluated until completely healed. Volumetric water content of each plot was determined prior to making ball marks with a time domain reflectance (TDR) meter (FieldScout TDR 300 Soil Moisture Meter, Spectrum Technologies, Inc., Plainfield, IL) equipped with 3.8 cm rods. A pneumatic golf ball launcher modeled after the device previously described by Murphy et al. (2003) was attached to a tripod to ensure consistent firing height and angle each time. Two ball marks were produced by firing golf balls at 275 kPa. Digital images of golf balls in the impression were used to determine the severity (volume) of the ball mark (Young et al., 2012a). SigmaScan Pro (v. 5.0, SPSS, Inc., Chicago, IL) was used to determine the percent of golf ball visible by dividing pixels selected from red golf ball in the ball mark by the number of pixels of a red golf ball sitting on the putting green surface. The resulting value was subtracted from 100 to determine the percent of golf ball below the putting green surface, or ball mark severity. All ball marks were repaired using a standard ball mark repair tool and the method recommended by the Golf Course Superintendents Association of America (GCSAA) (GCSAA, 2008).

One to two days following ball mark repair, the area became completely necrotic, showing general injury symptoms observed on golf course putting greens from ball mark damage. Digital images of the injury area were obtained using a Canon PowerShot G12 digital camera (Canon USA Inc., Lake Success, NY), and a light box once necrotic symptoms were visible. The camera settings were manually set at shutter speed 1/15 s, aperture of F3.5, and 100 ISO. The zoom position was also maintained by this camera to ensure the same focal distance and size each time images were obtained. Images were taken daily until the injury area began to decrease, and then pictures were collected two times per week until ball marks had healed completely. The light box was attached to a piece of purple foam board with a 10 cm diameter cut-out in the center. Golf tees were placed in the ground at two of the foam board corners to verify that images were collected at the same location each time, and to ensure that the area could be photographed once the ball mark had healed. Each image was analyzed using a cover analysis (Stier et al., In Press) with frame in SigmaScan Pro that was modified to reduce noise within the image by selecting pixels within small holes caused by necrotic grass blades or sand particles outside the ball mark injury area. Based on the number of pixels within the cut-out, the area of turf per pixel was calculated. This value was multiplied by the number of pixels not selected (non-green) within the cut-out to determine the injury area (mm^2) of the ball mark.

Statistical analysis

All statistical analysis was performed in SAS 9.2 (SAS Institute, Inc., Cary, NC) using the Proc Mixed procedure. The model statement for each response variable included all the main factors evaluated and all possible interactions with those main treatment factors. Mean separation was conducted at alpha = 0.05 using least significant difference values for all analyses except rooting parameters. An alpha value of 0.1 was used for rooting parameters due to the probability of higher variation in these data. All of these data with the exception of the rooting characteristics were analyzed separately within years because the number of ratings or sampling dates varied each year as well as time frames between rating dates. The two root sampling timings, May and August, were analyzed separately, but all years were included in the analysis because sampling number and time were consistent for all three years. The random terms included with each analysis were dependent on the inclusion of foot traffic data within the analysis. Visual wear, ball roll distance, and carbohydrate analysis data were the response variables that did not include the main factor, foot traffic. These three parameters included all the same random terms as other analyses with the exception of the Replication*Cultivar*Mowing height*Rolling frequency*Foot traffic term. When evaluations were conducted on the entire study area within a single day, cultivars were treated as locations and data pooled if there was not a significant cultivar by treatment interaction. The majority of the parameters evaluated throughout this study were analyzed in this manner, but a few response variables required a modified analysis.

Net photosynthetic rates were analyzed separately for each cultivar and year because all plots for both cultivars were not always measured on the same day. Time constraints or cloudy conditions interfered with the ability to conduct measurements on both cultivars each collection date. Furthermore, the number of collection dates and timings varied in 2011 and 2012 requiring the separation of years. The carbohydrate analysis included an extra parameter for each tissue evaluated to statistically differentiate individual sugar concentrations within foliage, crown, and root material. Although this extra parameter was included in the model and mean separation statements, no change was required to the random statement compared to other response variables that excluded foot traffic treatments.

Finally, the analysis of ball mark recovery was determined using alternative methods to those discussed for all other parameters. Ball mark injury area was averaged for the two ball marks within each sub-sub-plot and imported into GraphPad Prism (GraphPad Software, Inc., La Jolla, CA). The recovery of ball marks followed a one phase experimental decay model [Y = (Yo – plateau)*exp(-K*X) + plateau] (GraphPad Software, 2007) with three main parameters for each set of ball marks including: theoretical maximum injury (Yo), slope of recovery (K), and days to 50% recovery [ln(2)/K]. When evaluating recovery of all the ball marks, R^2 values ranged from 0.66 to 0.99 with a mean of 0.91. The combination of heat and drought stress along with possible mechanical injury from scalping caused necrosis around the ball mark that would erroneously increase ball mark injury area. Due to this potential variability with some of these data, plots with R^2 values less than 0.75 were removed before statistical analysis. The theoretical maximum, slope, and days to 50% recovery data from each plot exceeding R^2 values of 0.75 were analyzed using the Proc Mixed procedure in SAS as previously described. Main treatment factors or interactions with significant F-tests (P value < 0.05) were combined and graphed in GraphPad Prism to determine significant differences among treatments. Confidence intervals (95%) were constructed by the software to demonstrate significant differences among treatments.

Figure 1. Custom built photosynthesis chamber connected to datalogger to collect all carbon dioxide fluxes and other internal chamber parameters.

Figure 2. Infrared gas analyzer attached to the PVC shield to reduce sunlight and heat to the gas analyzer.

RESULTS AND DISCUSSION

Weather data were compiled for each year from 1 May thru 15 September. Air temperatures exceeded optimal (15 to 24°C) for creeping bentgrass growth each summer this research was conducted. Furthermore, an all-time record high temperature was recorded in 2011 of 43°C (Figs. 3-5). As temperatures increase above 30°C, the potential for photorespiration increases and plant respiration rates will surpass photosynthetic production magnifying the inefficiencies associated with the Calvin cycle (Fry and Huang, 2004; Gardener et al. 1985). In 2010, daily maximum temperature surpassed 30°C on 24 May and exceeded this critical value on 82 days (Fig. 3). Maximum daily air temperature crossed this threshold on 9 May 2011 and more persistent heat stress was prevalent with maximum air temperatures above 30°C for 95 days (Fig. 4). Heat stress was prevalent early in 2012 as well with 6 May providing the initial date maximum air temperatures exceeded 30°C, but maximum daily air temperatures only topped 30°C for 89 days in 2012 (Fig. 5). Although record breaking heat was experienced the last two years of the study, precipitation levels were decreased (Figs. 3-5). The reduction in precipitation lowered relative humidity levels, so soil moisture levels were more easily managed with irrigation frequency to promote evaporational cooling and minimize the effects of severe heat stress (Fry and Huang, 2004).

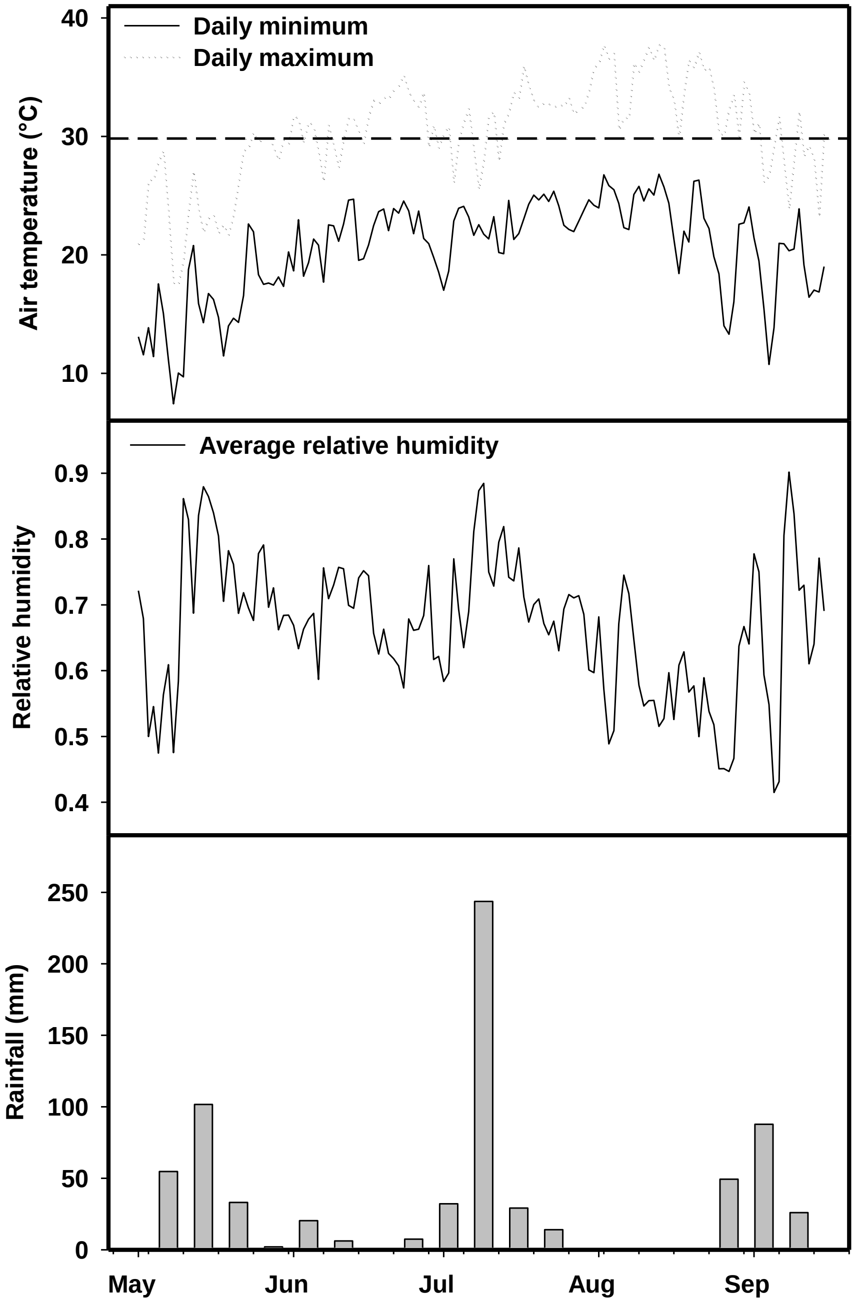

Figure 3. Weather data collected from the University of Arkansas Research and Extension Center in Fayetteville from 1 May to 15 September 2010. The horizontal, dashed line represents the critical temperature where respiration rates exceed photosynthetic rates increasing physiological stress.

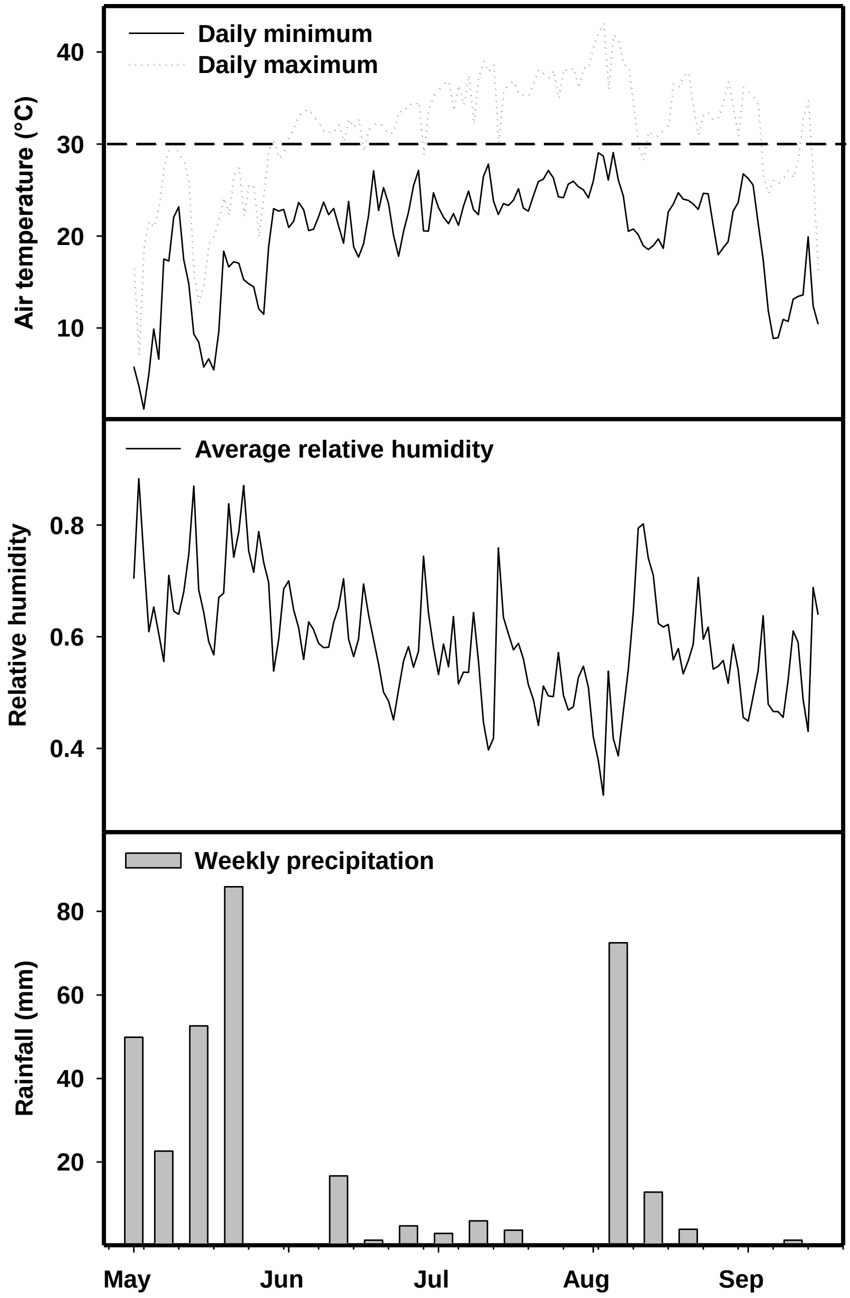

Figure 4. Weather data collected from the University of Arkansas Research and Extension Center in Fayetteville from 1 May to 15 September 2011. The horizontal, dashed line represents the critical temperature where respiration rates exceed photosynthetic rates increasing physiological stress.

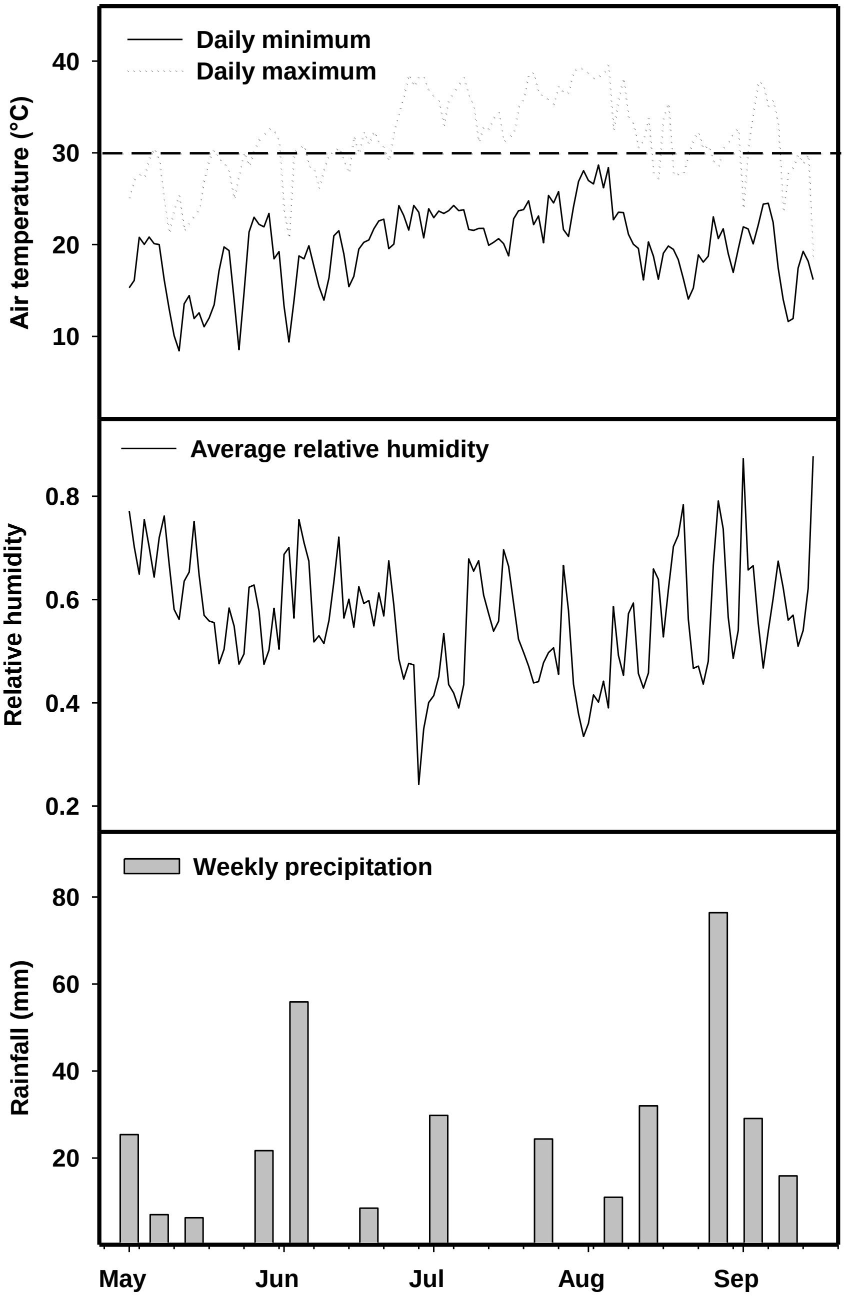

Figure 5. Weather data collected from the University of Arkansas Research and Extension Center in Fayetteville from 1 May to 15 September 2012. The horizontal, dashed line represents the critical temperature where respiration rates exceed photosynthetic rates increasing physiological stress.

Wear tolerance

Both mowing and rolling treatments significantly affected wear in all three summers (Table 1). As foot traffic continued with higher temperatures throughout the summer months, wear was increased for both cultivars and treatments. In all three summers, daily rolling significantly increased wear injury from foot traffic when compared to non-rolled treatments, and plots rolled three times per week had increased wear injury over non-rolled treatments in 2010 and 2011 (Fig. 6). A significant interaction between date and rolling frequency occurred in 2011 with daily rolling treatments exhibiting significantly greater wear injury following all applications of traffic (Fig. 7). In addition, the effects of rolling on wear from foot traffic were more severe in the hottest part of the summer (Fig. 7). Furthermore, when foot traffic was applied every week, all rolling treatments exhibited increased wear damage compared to data collected when traffic was applied every two weeks (Fig. 6). These results demonstrate the negative effects associated with increased foot traffic on creeping bentgrass putting greens under summer heat stress, regardless of management practices implemented. Wear injury increased significantly throughout the summer months for all mowing heights (Figs. 8 and 9); however, 4.0 mm treatments appeared to have greater traffic tolerance later in the summer as traffic stress accumulated.

On 11 Aug 2010, treatments mowed at 2.5 mm exhibited greater wear injury than those mown at 4.0 mm; however, 2.5 mm treatments had significantly greater wear injury compared to higher mowing heights on 25 Aug 2010 (Fig. 8). Similar results were observed in 2011 with significantly less wear damage occurring on treatments maintained at 4.0 mm compared to lower mowing heights on 21 Jul and 10 Aug (Fig. 8). Foot traffic being applied weekly in 2012 resulted in greater wear injury compared to other years for both cultivars. Significant differences among mowing heights were only observed on SR 1020 treatments on 30 Jul and 10 Aug 2012 (Fig. 9). Unlike the previous years, treatments maintained at 3.2 mm exhibited significantly greater wear injury than the other mowing heights. Significant reductions in turf quality and coverage may have led to diminished wear tolerance in these plots. Similar reductions in turf quality and coverage were observed for treatments maintained at 2.5 mm, but the increased foliage from 3.2 mm mown treatments may have increased visual wear damage following foot traffic under extreme heat stress (Young, 2013).

Traffic from equipment and foot traffic can have a significant effect on turfgrass quality, but some creeping bentgrass cultivars have demonstrated increased wear tolerance compared to others. The two cultivars evaluated in this study, SR 1020 and Penn G2, were among the most wear tolerant creeping bentgrass putting green cultivars in previous research (Bonos et al., 2001). Minimal research has been published on the effect of foot traffic to putting greens. The majority of the published research evaluated wear and compaction with traffic simulators (Bonos et al., 2001; Kohlmeier and Eggens, 1983; Samaranayake et al., 2008). Samaranayake et al. (2008) demonstrated increased bulk density that resulted from a decrease in air-filled porosity, but they did not observe a significant difference in saturated conductivity. This research was performed on a putting green with higher organic matter content than previous research, and traffic simulations were applied continuously over a season. These factors may have resulted in greater interaction between wear and compaction treatments. Previous studies conducted on sand-based putting greens have not detected compaction problems, so wear injury has been associated with greater damage from equipment and foot traffic (Baldwin et al., 2008; Bonos et al., 2001; Kohlmeier and Eggens, 1983). Bulk density evaluations were not performed in the current study due to the numerous reports of compaction not having a negative effect on sand-based putting greens.

Baldwin et al. (2008) evaluated the effect of equipment and foot traffic during winter stress on creeping bentgrass putting greens in the transition zone. Greater wear injury was observed with equipment compared to foot traffic. The authors stated that more aggressive pressure from equipment likely generated increased wear; however, no differences in soil compaction were observed through their study. In that study, foot traffic consisted of approximately 75 steps within a plot area 45 cm by 120 cm, and exhibited little turning that would increase wear of turf (Baldwin et al., 2008). In the current study, walking in a small area over two minutes consisted of much more turning, which likely led to greater wear injury of creeping bentgrass. The previous study on winter stress did not evaluate both foot and equipment traffic in combination, but the current study demonstrates greater wear on putting greens when foot traffic is combined with daily rolling.

This research indicates the effect of foot traffic on creeping bentgrass putting greens during heat stress in the transition zone. Foot traffic applications in this study were intense, simulating 200 rounds of golf near the hole location (Hathaway and Nikolai, 2005). The increased stress observed under these management regimes demonstrate the importance of changing hole locations on a regular basis. This practice will disperse traffic throughout the putting green to minimize stress in a single location over multiple days. It may also be important to alter walk-on areas as much as possible to manage summer stress on creeping bentgrass putting greens as these areas will experience significantly more wear from foot traffic. This research also validates increasing mowing heights during summer months to increase wear tolerance of creeping bentgrass putting greens. The greater amount of leaf tissue at higher mowing heights may have masked visual wear injury from abrasion of leaf tissue.

A United States Golf Association publication described the process of “target” rolling practices to minimize stress on a putting green (Gilhuly, 2006). Target rolling consists of rolling a portion of the green around the hole location, but not the entire green. The author referenced two golf courses with annual bluegrass (*Poa annua* L.) and hybrid bermudagrass (*Cynodon dactylon* (L.) Pers. × *C. transvaalensis* Burtt-Davy) putting greens that implemented this practice as a means to reduce stress and save time prior to golf tournaments. The article mentions that golfer’s surveyed did not notice inconsistencies in green speed when increasing mowing heights by 0.7 mm and target rolling. At the time this article was published, rolling putting greens more than three times per week was thought to be injurious to putting greens, so these practices would allow for more frequent rolling without exceeding three rolls per week on any portion of the putting green. More recent research has demonstrated that putting greens can be rolled daily with few negative visual effects (Hartwiger et al., 2001; Richards, 2010). The results from this research indicate that increasing rolling frequencies reduces the wear tolerance of creeping bentgrass putting greens. The reduction in wear tolerance was increased under supraoptimal temperatures, so these conditions may warrant implementing target rolling, especially during summer stress conditions. As temperatures rise during summer months and golfer foot traffic is high, this research indicates that increasing mowing heights and applying target rolling will increase wear tolerance and maintain a higher quality putting surface.

Table 1. ANOVA table of visual wear injury from 2010 to 2012.

	P-value for all interaction and main factors evaluated		
Effect	2010[y]	2011[y]	2012[z]
Rep	0.9085	0.5160	0.7181
Cultivar	0.7535	0.2986	0.9569
Mow	0.2288	0.0921	0.0683
Cultivar*Mow	0.7852	0.1152	0.1335
Roll	0.0020	0.0026	0.0470
Cultivar*Roll	0.1192	0.8747	0.8807
Mow*Roll	0.5080	0.2822	0.5925
Cultivar*Mow*Roll	0.9278	0.5343	0.5077
Date	<0.0001	<0.0001	<0.0001
Cultivar*Date	0.2365	0.0020	<0.0001
Date*Mow	<0.0001	0.0297	<0.0001
Cultivar*Date*Mow	0.0700	0.4682	0.0047
Date*Roll	0.0539	0.0194	0.4635
Cultivar*Date*Roll	0.9235	0.2319	0.8439
Date*Mow*Roll	0.0595	0.5032	0.5911
Cultivar*Date*Mow*Roll	0.7152	0.4354	0.8872

[y] Foot traffic applied every other week with 5 total applications

[z] Foot traffic applied once per week with 6 total applications

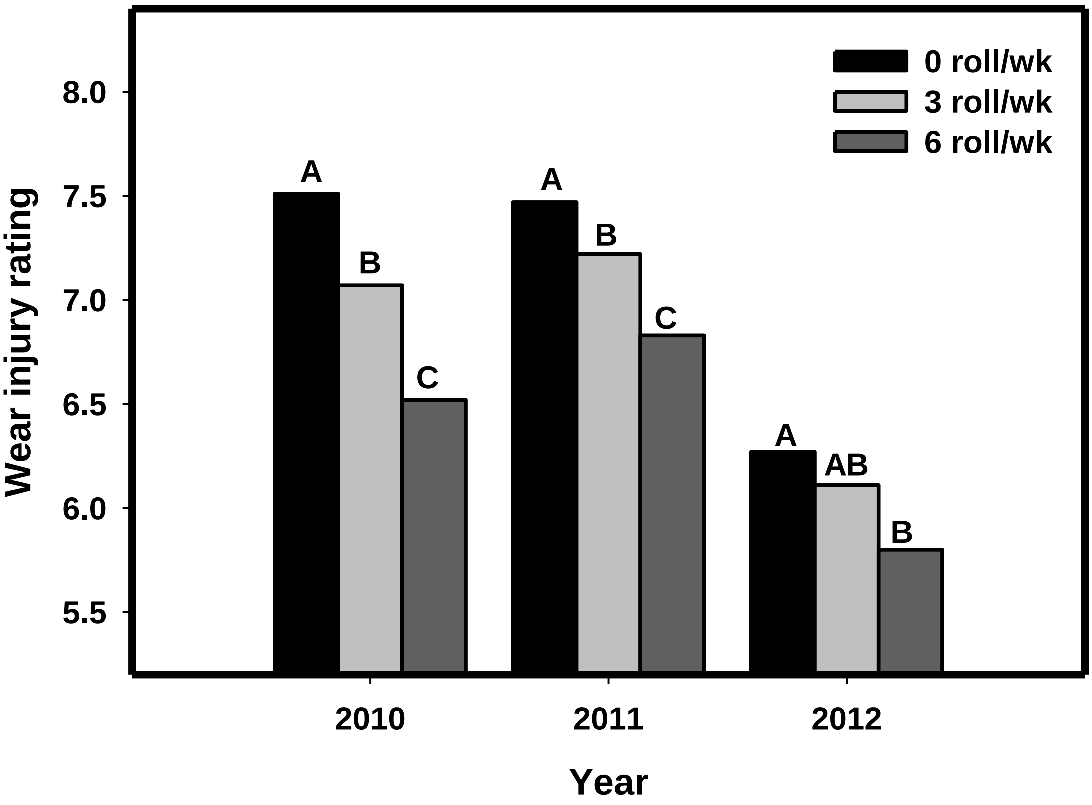

Figure 6. Average visual wear injury ratings for the main effect of rolling over summers from 2010 to 2012. Wear was visually rated following foot traffic on a 1-9 scale with 9 = no visual evidence of foot traffic and 1 = complete destruction of turf. Foot traffic was applied every other week in 2010 and 2011 a total of five times, and every week in 2012 at total of six times. Bars sharing the same letter within year are statistically similar at α = 0.05.

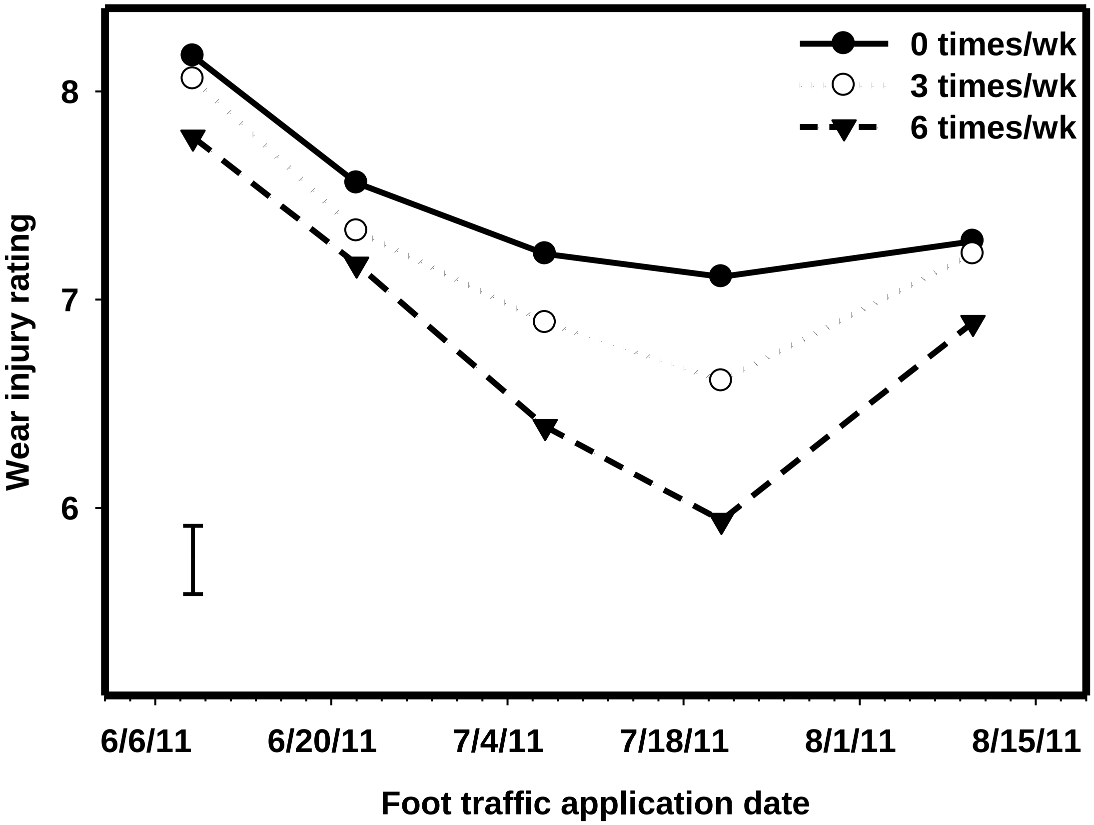

Figure 7. Visual wear ratings for rolling frequency averaged across cultivars and mowing treatments following foot traffic applications in 2011. Error bar represents LSD (α = 0.05) for the date by rolling frequency interaction for all data points.

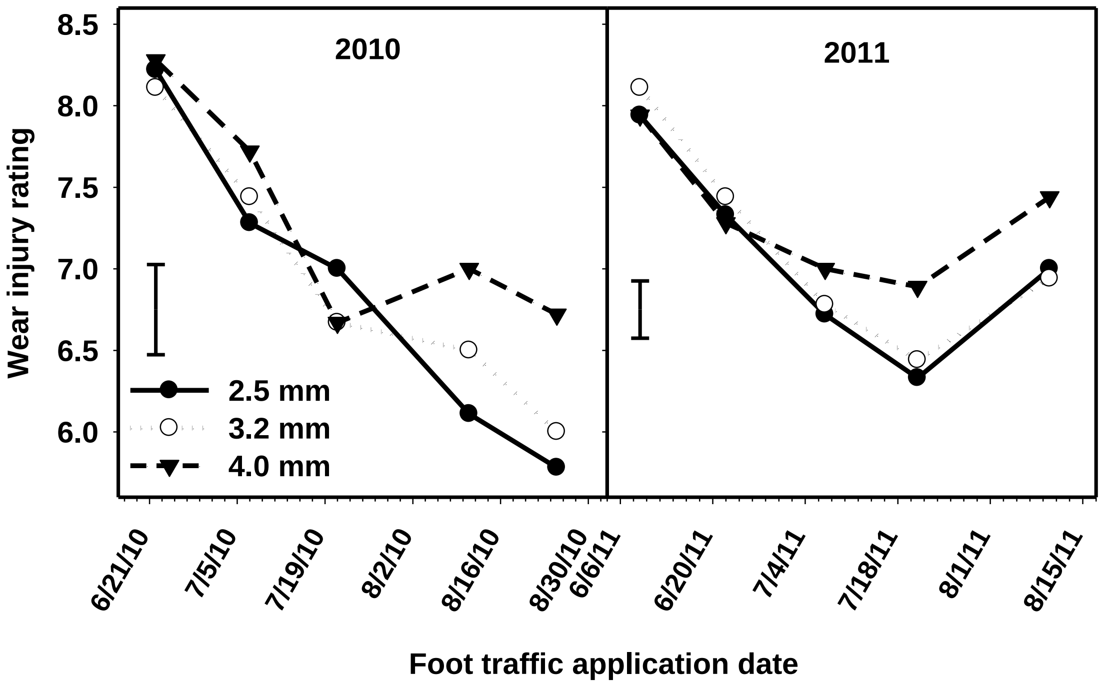

Figure 8. Visual wear ratings for mowing heights averaged across cultivars and rolling treatments following foot traffic applications in 2010 and 2011. Error bars represent LSD (α = 0.05) for the date by mowing height interaction for all data points within a single year.

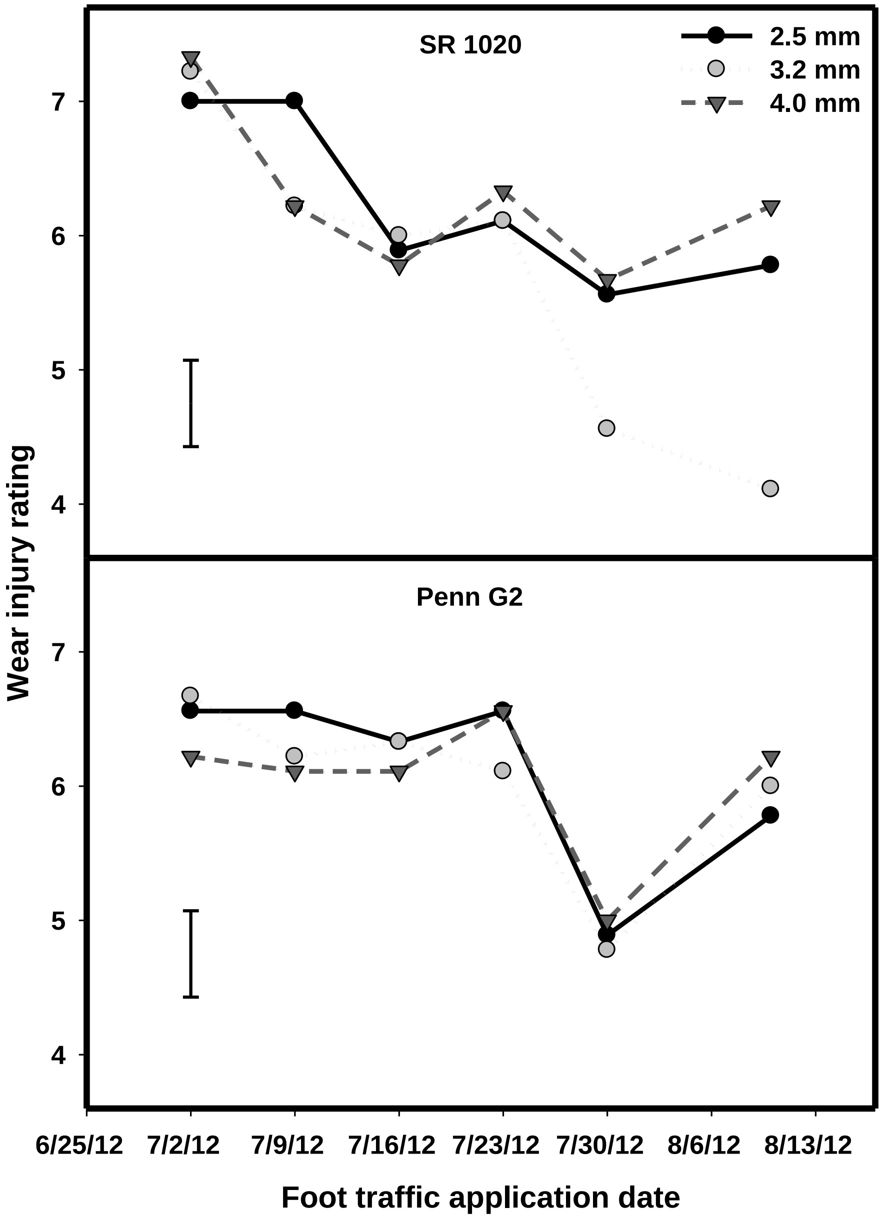

Figure 9. Visual wear rating for mowing height of SR 1020 and Penn G2 creeping bentgrass averaged over rolling frequencies in 2012. Error bars represent LSD (α = 0.05) for the cultivar by date by mowing height interaction for all data points.

Turfgrass quality

Visual turf quality ratings diminished significantly throughout summer months in all three growing seasons (2010 – 2012) before recovering in September once environmental stresses decreased. The treatment factors evaluated in this study significantly affected visual turf quality each year (Table 2). In 2010, the main factors, rolling frequency and foot traffic, significantly affected visual turf quality ratings. When averaged over all other parameters, increasing rolling frequency or applying foot traffic significantly reduced visual turf quality (Table 3). Although there were significant reductions in turf quality observed, quality was never reduced below acceptable levels.

Visual turf quality ratings in 2011 resulted in significant differences among treatments with interactions including mowing and rolling, but no foot traffic affects were observed (Table 2). Plots maintained at 4.0 mm had lower quality ratings on the initial rating date for both cultivars because of the lack of uniformity observed when mowed at the highest mowing height. However, both cultivars were able to maintain more consistent quality ratings throughout summer months when maintained at 4.0 mm. SR 1020 managed at 2.5 or 3.2 mm exhibited significant declines in turf quality on 23 Jul (Fig. 10). The continual mechanical and environmental stresses on SR 1020 managed at the lowest mowing height reduced turf quality below acceptable levels on 12 Aug. Penn G2 mowed at 2.5 mm exhibited significant reductions in visual turf quality until 23 Jul, but gradually recovered the remainder of the summer (Fig. 10). In contrast to SR 1020, Penn G2 at 3.2 mm maintained higher turf quality throughout summer. Turf quality ratings for Penn G2 never fell below acceptable values for any of the mowing heights, and all the mowing heights returned to similar ratings by 1 Sep (Fig. 10). Rolling frequencies also affected turf quality ratings throughout summer 2011. Increased wear injury from daily rolling significantly reduced turf quality on 12 Aug and 1 Sep, but recovered to similar ratings of lower rolling frequencies by 16 Sep (Fig. 11). Although significant declines in turf quality were observed with increased rolling, these ratings never declined below acceptable levels.

Similar to 2011, there was a significant cultivar by rating date by mowing height interaction in 2012 (Table 2). Both SR 1020 and Penn G2 followed similar trends with turf quality diminishing significantly from 10 Jul to 8 Aug before recovering significantly by 30 Aug following more conducive weather and 20 days of no foot traffic. SR 1020 mowed at 4.0 mm maintained significantly higher turf quality ratings throughout the summer compared to the lower mowing heights (Fig. 12). Although Penn G2 quality was reduced for all mowing heights through mid-August, turf quality ratings were never significantly different for any of the mowing heights on any rating date. All mowing heights for both cultivars dropped below acceptable levels on 8 Aug (Fig. 12). There was significant drought and heat stress on 2 Aug because irrigation did not run for a few days resulting in large areas of necrotic turf that resulted in unacceptable turf quality ratings. All treatment combinations exhibited significant increases in turf quality back to acceptable levels on the final rating date with the exception of SR 1020 at the two lower mowing heights (Fig. 12).

When cultivars were combined in 2012, there was a significant interaction among rating date, mowing height, rolling frequency, and foot traffic (Table 2). The general trend observed for all combinations was a reduction in quality through 8 Aug followed by recovery on 30 Aug (Fig. 13). The downward trend in quality ratings was least pronounced for treatments mowed at 4.0 mm, rolled zero or three times per week, and not receiving foot traffic. These treatment combinations represent the only group that did not decline below acceptable levels in 2012, demonstrating a visually healthier turf at the highest mowing height maintained with minimal wear traffic. As mowing heights were decreased and rolling frequencies increased, weekly foot traffic applications did not further reduce turf quality significantly compared to non-trafficked treatments. Regardless if foot traffic was applied or not, turf quality ratings declined below acceptable levels by 8 Aug.

The trends of visual turf quality ratings throughout each evaluation period followed the expected trend with significant decreases in turf quality during the hottest portions of the summer. Similar to previous studies, lower mowing heights experienced greater reductions in turf quality than higher mown turf (Huang and Gao, 2000; Liu and Huang, 2001). The wear of turf from daily rolling during these extreme environmental conditions was demonstrated throughout this study. The effect of increased wear from rolling did not become evident until July each year, which indicates the extended period of mechanical and environmental stress that would be required to cause a significant decline in turf quality similar to results discussed by Hartwiger et al. (2001) and Richards (2010). Many of the previous rolling studies have established reductions in visual turf quality with increased rolling frequency, but few of these studies have observed turf quality ratings that fall below acceptable levels. The results from this study were similar in 2010 and 2011. However, the combination of low mowing heights with increased rolling frequencies during extreme environmental stress resulted in unacceptable turf quality in Jul 2012. Previous studies have not evaluated the effect of foot traffic in combination with mowing and rolling practices. Foot traffic did not affect visual quality as significantly as hypothesized prior to the study. Although turf quality ratings fell below acceptable levels in 2012, foot traffic rarely reduced visual turf quality greater than mowing height and rolling frequency combinations.

Turfgrass Coverage

Turfgrass coverage was never significantly different for any main treatment factors in 2010, but increased heat stress in 2011 and 2012 helped differentiate treatments based on turfgrass coverage (Table 4). Percent turfgrass coverage averaged over cultivars, mowing heights, rolling frequencies, and foot traffic on 14 Jul 2010 was 90% as determined by DIA. By 3 Sep, percent turfgrass coverage had increased back to 99%, similar to coverage values observed prior to foot traffic application and only four weeks of mowing and rolling (*data not shown*). The frequency of data collection was increased in 2011 and 2012 to better demonstrate the change in percent turfgrass coverage with increased mechanical and environmental stress throughout the study periods.

There was a significant interaction among cultivar, rating date, and mowing height for percent turfgrass coverage in 2011 (Table 4). Percent turfgrass coverage remained steady through mid-July, maintaining greater than 98% coverage for all mowing heights in 2011 (Fig. 14). On 23 Jul, there was a significant decrease in turf coverage for both SR 1020 mowed at 2.5 or 3.2 mm and Penn G2 maintained at 2.5 mm (Fig. 14). SR 1020 mowed at the two lower mowing heights slowly recovered the remainder of the summer, but these treatments never reached similar percent turfgrass coverage compared to treatments maintained at 4.0 mm. There was a significant reduction in turfgrass coverage for SR 1020 at 4.0 mm from 17 Jun to 23 Jul, but these treatments recovered quickly and were able to maintain significantly greater percent turfgrass coverage under these intensive management practices and high environmental stress. In contrast to SR 1020, Penn G2 maintained at either 3.2 or 4.0 mm maintained similar percent turfgrass coverage on every rating date (Fig. 14). Penn G2 differed from SR 1020 in its recovery from the reduction in turfgrass coverage following 23 Jul. Penn G2 recovered significantly by

12 Aug reaching statistically similar levels as the higher mowing heights before dropping significantly again on 1 Sep. All of these treatments returned to similar turfgrass coverage values by 16 Sep (Fig. 14).

Light-weight rolling also significantly affected percent turfgrass coverage in 2011 (Table 4). When combining data for cultivars, mowing heights, and foot traffic; rolling treatments significantly reduced turfgrass coverage on 23 Jul (Fig. 15). All of these plots had improved turfgrass coverage on 12 Aug, but daily rolled treatments remained significantly lower than non-rolled treatments on this date. Daily rolled treatments were not similar to non-rolled treatments with regards to percent turfgrass coverage until the final rating date in mid-September (Fig. 15).

In 2012, there was a significant interaction among cultivar, rating date, mowing height, rolling frequency, and foot traffic with respect to percent turfgrass coverage (Table 4). The general trend for both cultivars in 2012 illustrates a larger reduction in percent turfgrass coverage as mowing heights were lowered, rolling frequencies increased, and foot traffic was applied (Fig. 16a and 16b). The lowest coverage values were observed for Penn G2 on 24 Jul; whereas, SR 1020 reached lowest levels on 8 Aug. The reduction in percent turf coverage was greater for all SR 1020 plots than Penn G2 (Fig. 16a and 16b). The extreme drought and heat stress previously mentioned exacerbated reductions in percent turfgrass coverage observed on SR 1020. The areas most affected by the heat and drought stress were not specific to certain treatments; hence, the variation in foot traffic treatments for the highest mowing height rolled three or six days per week. SR 1020 mowed at 4.0 mm and rolled three days per week with foot traffic had a significant reduction in turf coverage, while a similar decrease was observed for non-trafficked treatments with daily rolling (Fig. 16a). Although there was greater variation in turfgrass coverage due to heat and drought stress, the trends still indicate greater reductions in turfgrass coverage with lower mowing heights, increased rolling frequencies, and foot traffic. SR 1020 maintained at 2.5 mm, rolled daily, and receiving foot traffic had the lowest turf coverage on 8 Aug (Fig. 16a). The reduction of turfgrass coverage with daily rolling was also evident when looking at all mowing heights. As mowing height decreased, turf coverage was significantly decreased with foot traffic (Fig. 16a). Despite the significant reductions associated with SR 1020 on 8 Aug, the majority of treatments regained significant coverage by 30 Aug following more favorable environmental conditions and 22 days with no foot traffic (Fig. 16a). The trends for Penn G2 were more consistent and follow the expected progression with greater reductions at the lowest mowing height, highest rolling frequency, and foot traffic. Few significant differences were observed on specific dates, but coverage was reduced significantly for daily rolled treatments as mowing height was decreased. Similarly, all plots at the lowest mowing height receiving foot traffic, regardless of rolling frequency, had significantly less turf coverage than higher mown treatments (Fig. 16b). All treatment combinations recovered to similar levels by 8 Aug and remained similar the remainder of the summer.

As environmental stresses increased during summer months of each year, percent turfgrass coverage was significantly reduced. However, all treatments rebounded back to nearly full coverage each year following more conducive environmental conditions. As mechanical stresses increased either with lower mowing heights or daily rolling, percent turfgrass coverage was reduced significantly. In contrast, treatments maintained at 4.0 mm appeared to maintain higher turf coverage under stresses associated with rolling and foot traffic for both cultivars.

Turfgrass color

All of the treatments evaluated in this study resulted in significant differences in turfgrass hue from 2010 to 2012 (Table 5). Hue measurements are measured in degrees using a color wheel with yellow at 60° and green at 120° (Karcher and Richardson, 2003), so the closer numbers are to 120° the greener they appear. There was a significant interaction among mowing height, rolling frequency, and foot traffic treatments when averaged over rating dates and cultivars in 2010 (Table 5). When daily rolling and foot traffic were applied to the plots, the highest mowing height had significantly higher turfgrass hue than the two lower mowing heights (Fig. 17). In addition, daily rolling and foot traffic significantly reduced turfgrass hue when mowed at 2.5 mm compared to non-rolled and non-trafficked treatments (Fig. 17). Similar to turfgrass coverage, digital images were obtained more frequently in 2011 and 2012 to better quantify the change in hue throughout the season with various mowing heights, rolling frequencies, and foot traffic.

Turfgrass hue exhibited a significant interaction among all of the main treatment factors over rating dates when cultivars were pooled in 2011 (Table 5). Turfgrass hue followed similar trends for each treatment combination with the highest levels observed on 17 Jun and diminishing to lowest levels on 23 Jul (Fig. 18). Turfgrass hue of all the treatment combinations proceeded to increase until 1 Sep and hue remained similar through 16 Sep. Few significant differences in turfgrass hue were observed among treatments on individual rating dates. Treatments mowed at 4.0 mm, rolled three days per week, and receiving foot traffic had significantly lower turfgrass hue than non-trafficked treatments on 23 Jul and remained significantly lower throughout the remainder of 2011 (Fig. 18). In contrast, treatments maintained at 3.2 mm without rolling or foot traffic exhibited significantly lower turfgrass hue than trafficked treatments from 12 Aug through the rest of the summer (Fig. 18).

Similar to percent turfgrass coverage, there was a significant interaction with all five factors included in the evaluation in 2012 (Table 5). SR 1020 displayed greater variability in turfgrass hue; whereas, Penn G2 maintained similar trends over each rating date in 2012 (Figs. 19a and 19b). Few significant differences were observed for either cultivar on a single rating date. All treatment combinations applied to SR 1020 resulted in a significant reduction in turfgrass hue from 10 Jul to 24 Jul, but no significant differences in treatments were observed on either rating date (Fig. 19a). On 8 Aug, foot traffic treatments significantly reduced turfgrass hue on plots mowed at 4.0 mm and rolled three days per week as well as plots mowed at 2.5 mm without rolling. However, turfgrass hue was significantly lower in non-trafficked treatments that were mowed at 4.0 mm with daily rolling on 8 Aug. All treatment combinations on SR 1020 demonstrated a significant increase in turfgrass hue from 8 Aug to 30 Aug (Fig. 19a). On the final rating date, SR 1020 maintained at 2.5 and 4.0 mm with daily rolling and no foot traffic had significantly higher turfgrass hue than trafficked treatments (Fig. 19a). In contrast, SR 1020 mowed at 4.0 mm without rolling or foot traffic displayed significantly lower turfgrass hue than trafficked treatments (Fig. 19a). There were no differences observed in turfgrass hue for any of the treatment combinations on individual rating dates for Penn G2 (Fig. 19b). Turfgrass hue was significantly reduced for all treatment combinations from 10 Jul to 24 July, but steadily increased the remainder of the summer (Fig. 19b).

Neither saturation nor brightness resulted in significant differences in the main treatment factors evaluated in this study, but these parameters were incorporated in an equation with turfgrass hue to determine dark green color index (DGCI) (Karcher and Richardson, 2003).

Combining all the color parameters in the DGCI calculations produced significant interactions with all the main factors during these evaluation periods (Table 6). Similar to turfgrass hue evaluations, DGCI exhibited a significant mowing height by rolling frequency by foot traffic interaction when combining data for cultivars and rating dates in 2010 (Table 6). Dark green color index was significantly higher at the highest mowing height under daily rolling and foot traffic (Fig. 20). When plots were mown at 2.5 mm and rolled daily, DGCI was significantly reduced when foot traffic was applied (Fig. 20). Increasing the number of rating dates in 2011 and 2012 helped demonstrate the change in DGCI under intensive management practices.

Two lower order interactions encompassing all main treatment factors were identified for DGCI in 2011 (Table 6). Mowing heights and rolling frequencies interacted over rating dates to affect DGCI when pooling cultivar and foot traffic data in 2011 (Table 6). Dark green color index followed similar trends to those discussed for turfgrass hue in 2011. All treatment combinations were reduced significantly on each rating date from 17 Jun to lowest levels on 23 Jul (Fig. 21). Dark green color index did not rebound until 1 Sep, but all treatment combinations were reduced significantly between 1 Sep and 16 Sep. Few significant differences among treatment combinations were observed on individual rating dates, but treatments mowed at 3.2 mm and rolled three days per week had significantly greater DGCI than treatments maintained at 3.2 mm with no rolling and daily rolling (Fig. 21). In addition, DGCI was significantly lower on 1 Sep when treatments mowed at 2.5 mm were rolled daily compared to non-rolled treatments (Fig. 21). On the final rating date, a more expected separation was observed with treatments mowed at 4.0 mm and no rolling displaying significantly higher DGCI than 2.5 mm treatments with daily rolling. Rolling frequencies also interacted with foot traffic treatments over rating dates to significantly affect DGCI when averaging cultivars and mowing heights in 2011 (Table

6). This interaction followed the trend established for the previous interaction previously discussed (Figs. 21 and 22). On 9 Jul, foot traffic significantly reduced DGCI on daily rolled treatments (Fig. 22). Similarly, foot traffic significantly reduced DGCI on treatments rolled three days per week on each of the last four rating dates in 2011. In contrast to these data but similar to turfgrass hue in 2011, treatments receiving no rolling with foot traffic maintained significantly higher DGCI than treatments that were not rolled or exposed to foot traffic (Fig. 22).

All five of the parameters evaluated significantly interacted to affect DGCI in 2012 (Table 6). The trends observed for both cultivars with respect to DGCI followed similar trends to those discussed for turfgrass hue in 2012. Dark green color index of SR 1020 was reduced significantly from 10 Jul to 24 Jul, remained statistically similar on 8 Aug before recovering DGCI on 30 Aug for all treatment combinations (Fig. 23a). Foot traffic significantly reduced DGCI on 8 Aug for treatments mowed at 4.0 mm and rolled three days per week as well as treatments mowed at 2.5 mm and rolled daily. In contrast, treatments mowed at 4.0 mm and rolled daily exhibited significantly higher DGCI when foot traffic was applied on 8 Aug. Following the significant increase in DGCI on 30 Aug, treatments mowed at 4.0 mm with daily rolling, 3.2 mm without rolling, and 2.5 mm with daily rolling had significantly lower DGCI under foot traffic (Fig. 23a). However, foot traffic significantly increased DGCI on treatments mowed at 4.0 mm without rolling on 30 Aug (Fig. 23a). There were no significant differences in DGCI identified for any treatment combination on a single rating date for Penn G2 (Fig. 23b). Dark green color index declined significantly from 10 Jul to 24 Jul, but significantly increased the remainder of the summer (Fig. 23b).

The results observed in this study for visual turf quality, coverage, and color all followed similar trends to previous research with significant reductions in each parameter during the peak of environmental stress, but all recovered significantly by the end of the summer (Hartwiger et al., 2001; Huang and Gao, 2000; Liu and Huang, 2001; Richards, 2010). The majority of these studies only evaluated visual turf quality, while the current research utilized objective data to confirm the changes in visual turf quality. Visual quality ratings take turf density, uniformity, and color into account when determining quality of a single plot, so the digital image analysis parameters help distinguish the individual parameters embedded in quality ratings. Regardless of treatment combinations applied, turf quality was reduced during July and August each year. The increased temperatures during this time period reduced turf coverage and color, which caused the decline in turf quality. Although antioxidant enzyme activity was not evaluated in this study, previous research has demonstrated increased electrolyte leakage and reduced enzyme activity in cool-season grasses under heat stress (Du et al., 2009; Liu and Huang, 2000). The reductions in turf quality, coverage, and color were likely affected by these changes at the cellular level. There is no way to avoid heat stress when managing cool-season grasses in the transition zone, but management practices and the level of traffic significantly affected turf quality, coverage, and color each year.

The trends from each year indicate that creeping bentgrass at higher mowing heights, reduced rolling frequencies, and no foot traffic results in higher turf quality ratings, percent turf coverage, and color during environmental stress periods. In 2010 and 2011, the reductions in turf quality remained above acceptable levels with the exception of SR 1020 plots mowed at 2.5 mm in 2011. In contrast, plots maintained at 4.0 mm with no rolling or three rolls per week and no foot traffic were the only treatments to remain above acceptable in 2012. The main reason turf quality was reduced for all these treatments was the affect of severe drought and heat stress on the plot area in early August. Large areas of necrotic turf were present that significantly affected turf quality and coverage. These drought and heat stress effects were not consistent to certain treatment combinations, so the variability among treatment combinations was increased making it more challenging to distinguish treatment differences. These findings indicate the importance of proper soil moisture management, especially during heat stress. The rooting characteristics evaluated in this study demonstrated the effect of environmental stress on the root system of creeping bentgrass putting greens (Young, 2013). The compromised root system will require more precise water management to maintain high visual turf quality, and the use of time-domain reflectometers (TDR's) to monitor soil moisture levels is increasing among golf course superintendents (Young et al., 2000). Fu and Dernoeden (2009b) demonstrated differences in creeping bentgrass quality and color under two common irrigation schedules. Light and frequent irrigation maintained similar or better turf quality and color than deep and infrequent irrigation practices throughout summer months in their study (Fu and Dernoeden, 2009b). Light, frequent irrigation will help maintain soil moisture in the upper level of the soil surface where roots are positioned during the severe heat stress, but excess moisture in the root zone can increase disease, algae, and turf thinning. The use of TDR technology allows golf course managers to quickly determine soil moisture levels in the upper soil surface. If small areas on the putting green have a greater propensity to dry out during the day, hand watering can be implemented to more precisely apply water to trouble areas (Dernoeden, 2013).

Turf quality, coverage, and color were significantly affected by the main factors evaluated in this study each year. As putting greens experienced reduced coverage, ball roll distance may not be affected negatively because reduced leaf material will limit friction that would lower ball roll distance (Richards, 2010); however, the trueness of ball roll would likely be affected by thin areas on putting greens. The performance (i.e. ball roll distance and ball roll trueness) of the putting green is of utmost importance when evaluating putting green quality. Putting green color would generally not be included in the performance parameters, but color plays an integral part of turf quality ratings and likely is a good indicator of overall plant health. It has been well established that wear from equipment and golfer foot traffic reduces turf quality (Samaranayake et al., 2008), but most of the visual changes appear as chlorosis as mechanical stresses are increased. There was variation observed in turfgrass hue and DGCI for the treatment combinations evaluated, but plots maintained at the highest mowing heights or with minimal wear traffic were generally capable of producing darker green color. The darker green color indicates that these plots would also result in physiologically healthier turf, but this has not been evaluated extensively.

There is no way to completely remove mechanical stresses from putting greens, and different golf courses may experience much higher rounds that increases these mechanical stresses. These results demonstrate the importance of changing the hole location regularly to disperse the heaviest foot traffic throughout the green (Hathaway and Nikolai, 2005). If common walk-on areas are used consistently on a specific green, ropes may need to be added to divert traffic into various locations. As temperatures rise in summer and putting greens experience increased wear stress, mowing heights should be increased to minimize turf quality reductions, lost turf coverage, and yellowing of turf.

Table 2. ANOVA table of visual turf quality ratings from 2010 to 2012.

	P-values for all the main factors and interactions evaluated		
Effect	2010	2011	2012
Rep	0.7433	0.9914	0.3759
Cultivar	0.7128	0.0871	0.3410
Mow	0.1475	0.0759	0.2835
Cultivar*Mow	0.4635	0.0070	0.1566
Roll	0.0029	0.3578	0.0295
Cultivar*Roll	0.9495	0.5833	0.9045
Mow*Roll	0.2241	0.2277	0.3319
Cultivar*Mow*Roll	0.9545	0.4001	0.7528
Foot	0.0009	0.8824	<0.0001
Cultivar*Foot	0.1767	0.0518	0.0503
Mow*Foot	0.2387	0.7509	0.1969
Cultivar*Mow*Foot	0.1611	0.4501	0.5505
Roll*Foot	0.2935	0.2109	0.8635
Cultivar*Roll*Foot	0.7615	0.6336	0.3286
Mow*Roll*Foot	0.8381	0.1556	0.5179
Cultivar*Mow*Roll*Foot	0.2232	0.7644	0.7447
Date	<0.0001	<0.0001	<0.0001
Cultivar*Date	0.0133	0.3413	0.1844
Date*Mow	0.7453	<0.0001	0.0523
Cultivar*Date*Mow	0.9905	0.0307	0.0416
Date*Roll	0.1024	0.0039	0.0011
Cultivar*Date*Roll	0.7042	0.9067	0.7372
Date*Mow*Roll	0.6571	0.8674	0.2325
Cultivar*Date*Mow*Roll	0.9837	0.6832	0.4402
Date*Foot	0.5600	0.0846	0.0004
Cultivar*Date*Foot	0.2454	0.1290	0.7680
Date*Mow*Foot	0.4169	0.9207	0.6671
Cultivar*Date*Mow*Foot	0.9718	0.4569	0.8800
Date*Roll*Foot	0.8192	0.8721	0.0643
Cultivar*Date*Roll*Foot	0.9718	0.7519	0.6701
Date*Mow*Roll*Foot	0.6842	0.9713	0.0404
Cultivar*Date*Mow*Roll*Foot	0.6842	0.8542	0.3724

Table 3. Effect of rolling frequency and foot traffic on visual turf quality in 2010.

Effect	Treatment	Turf quality[y]
Rolling frequency	0 times/wk	7.46a[z]
	3 times/wk	6.85b
	6 times/wk	6.36c
Foot traffic	No foot traffic	7.08a
	Foot traffic	6.69b

[y] Turf quality was rated visually on a 1 to 9 scale with 9 = best, 1 = worst, and 6 = minimum acceptability.

[z] Values sharing the same letter within treatment effects are statistically similar at $\alpha = 0.05$.

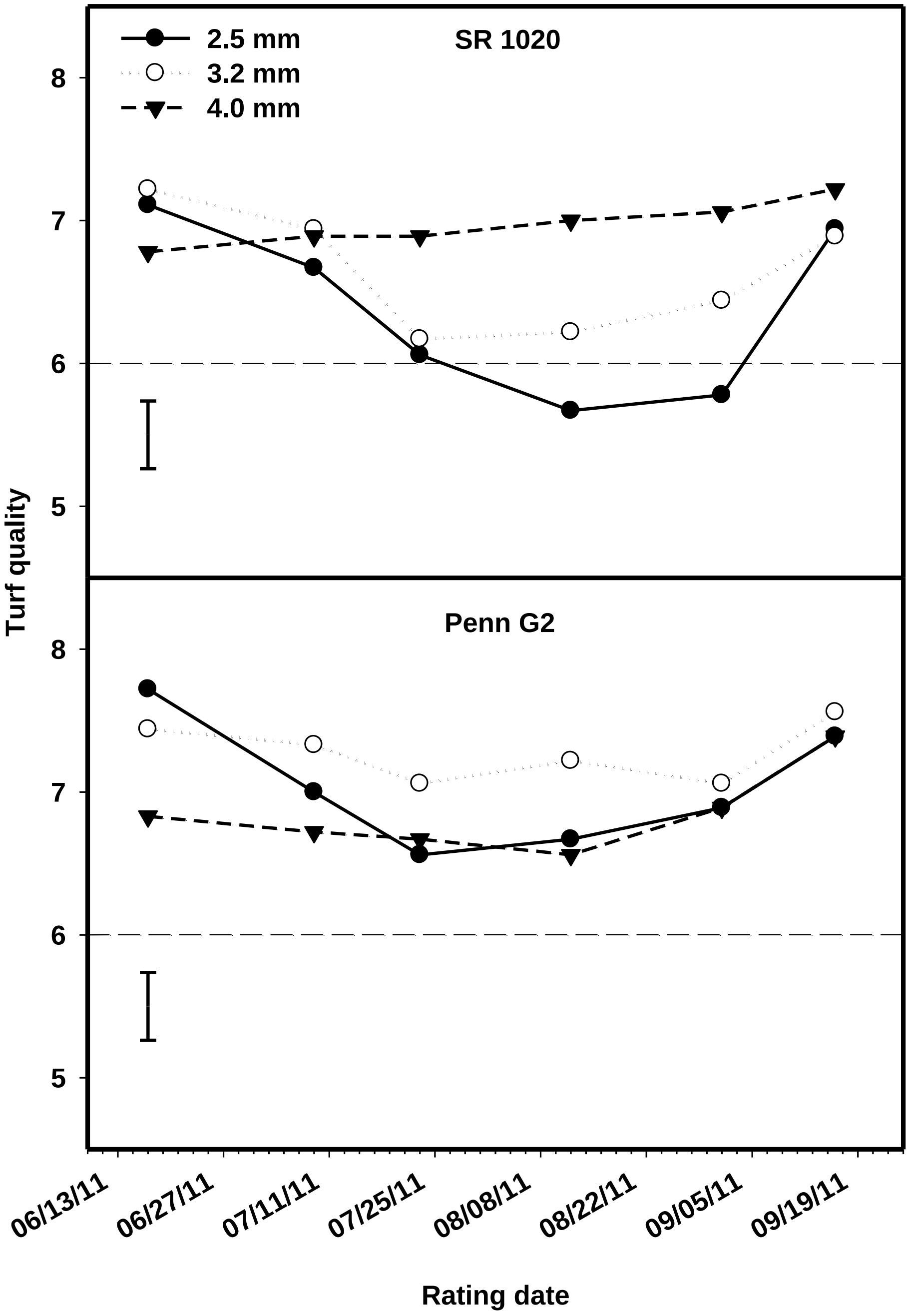

Figure 10. Cultivar by date by mowing height interaction for visual turf quality in 2011. Data were averaged over rolling frequencies and foot traffic treatments. The horizontal, dashed line represents the minimal acceptable turf quality rating. Error bars represent LSD ($\alpha = 0.05$) for the cultivar by date by mowing height interaction.

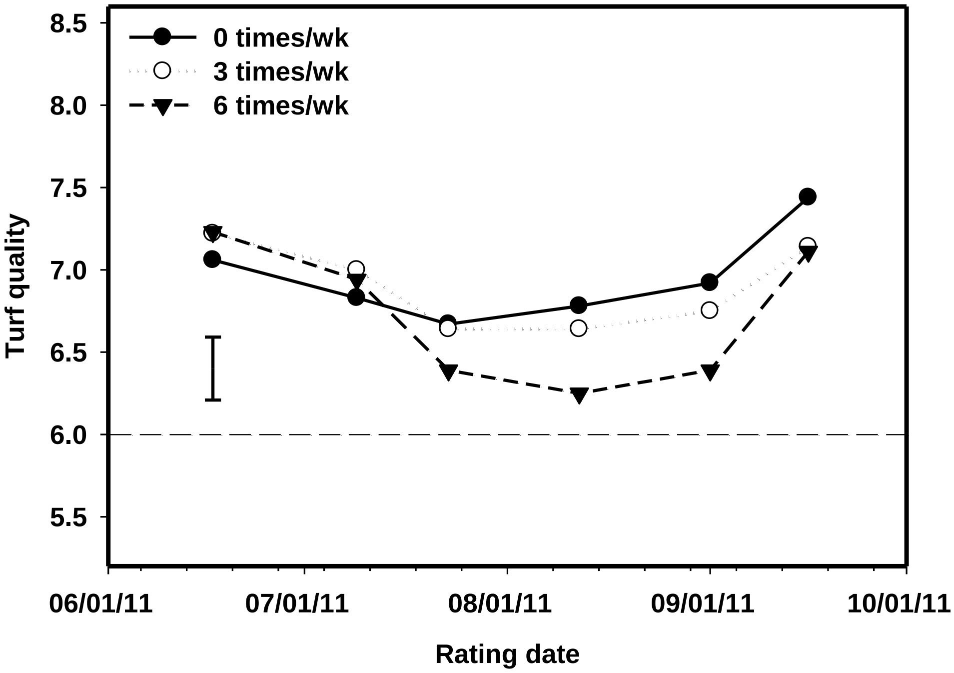

Figure 11. Date by rolling frequency interaction for visual turf quality in 2011. Data were averaged over cultivars, mowing heights, and foot traffic treatments. The horizontal, dashed line represents the minimal acceptable turf quality rating. Error bar represents LSD (α = 0.05) for the date by rolling frequency interaction.

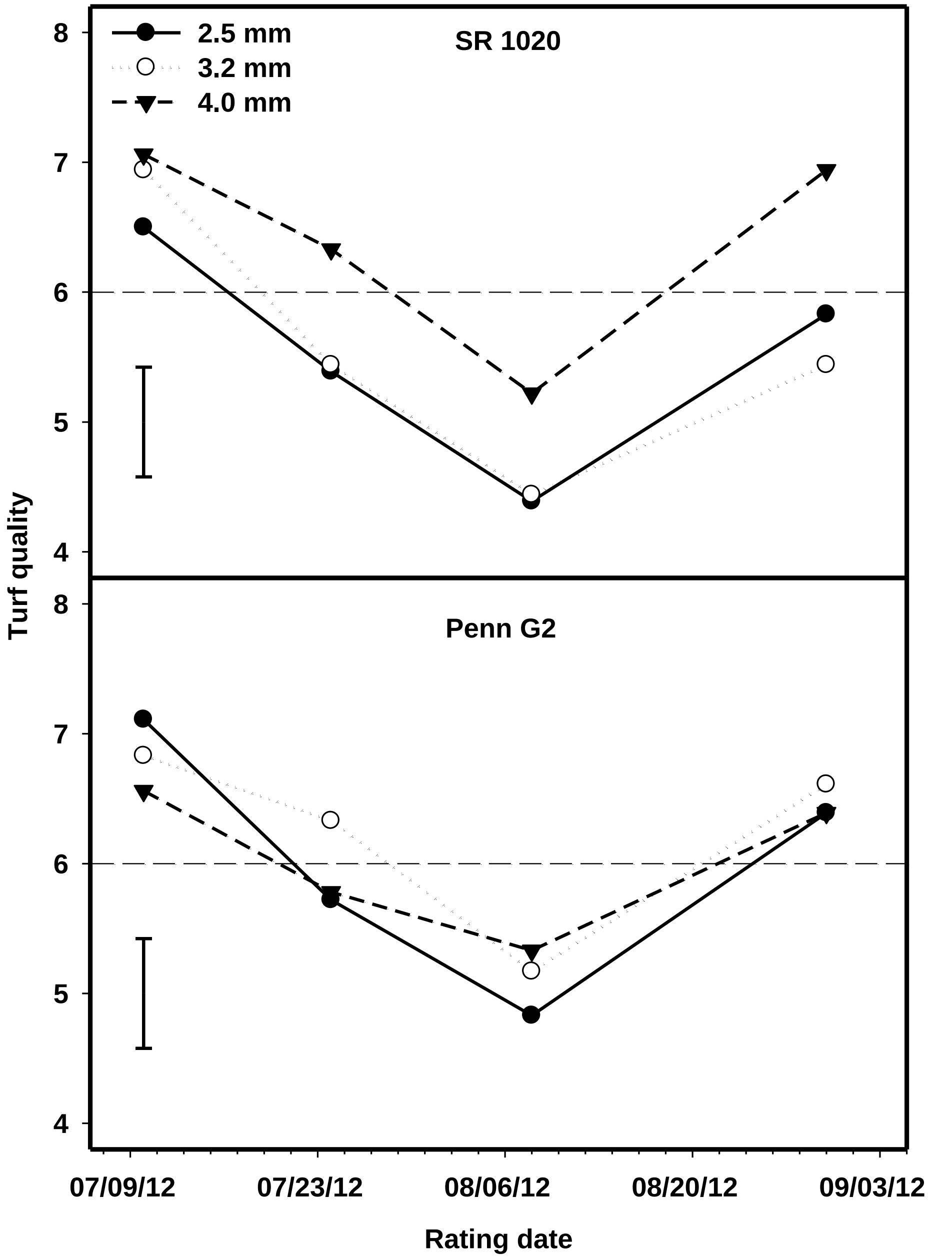

Figure 12. Cultivar by date by mowing height interaction for visual turf quality in 2012. Data were averaged over rolling frequencies and foot traffic treatments. The horizontal, dashed line represents the minimal acceptable turf quality rating. Error bars represent LSD ($\alpha = 0.05$) for the cultivar by date by mowing height interaction.

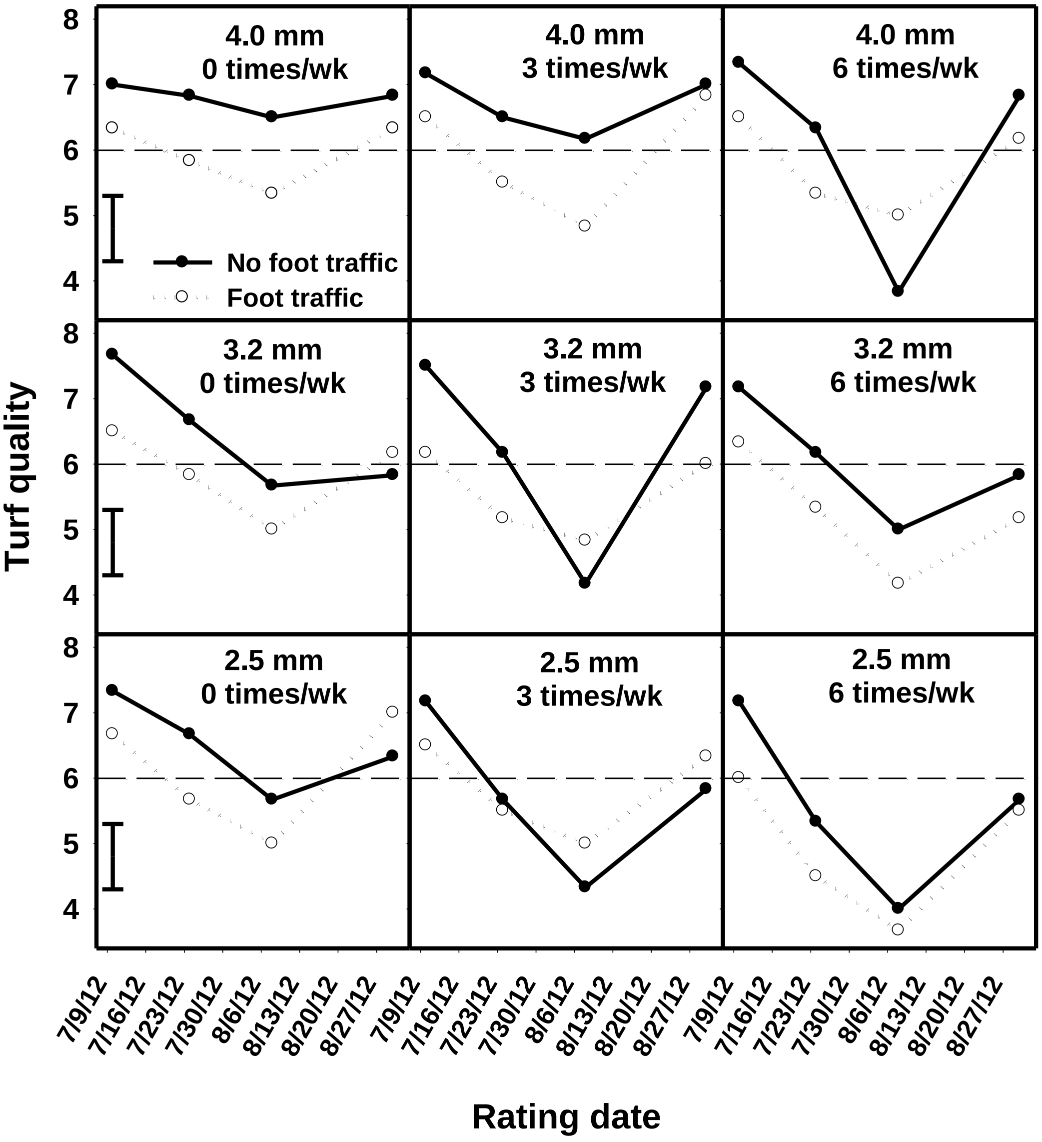

Figure 13. Date by mowing height by rolling frequency by foot traffic interaction for visual turf quality in 2012. Data were averaged over cultivars. The horizontal, dashed line represents the minimal acceptable turf quality rating. Error bars represent LSD (α = 0.05) for the date by mowing height by rolling frequency by foot traffic interaction.

Table 4. ANOVA table of percent turf coverage determined by digital image analysis from 2010 to 2012.

	P-values for all the main factors and interactions evaluated		
Effect	2010	2011	2012
Rep	0.3507	0.3702	0.2755
Cultivar	0.6581	0.1806	0.0714
Mow	0.3336	0.0048	0.4436
Cultivar*Mow	0.9393	0.1156	0.8276
Roll	0.5628	0.1344	0.1297
Cultivar*Roll	0.7810	0.1152	0.8430
Mow*Roll	0.5334	0.3620	0.4790
Cultivar*Mow*Roll	0.9852	0.3412	0.9765
Foot	0.1797	0.8252	0.0060
Cultivar*Foot	0.2784	0.2954	0.6405
Mow*Foot	0.1108	0.7954	0.6437
Cultivar*Mow*Foot	0.8599	0.1342	0.8829
Roll*Foot	0.3260	0.6110	0.2070
Cultivar*Roll*Foot	0.6536	0.2232	0.2953
Mow*Roll*Foot	0.6820	0.7707	0.0117
Cultivar*Mow*Roll*Foot	0.9662	0.7884	0.0141
Date	<0.0001	<0.0001	<0.0001
Cultivar*Date	0.8181	<0.0001	<0.0001
Date*Mow	0.9585	<0.0001	0.0477
Cultivar*Date*Mow	0.9775	0.0040	0.5070
Date*Roll	0.0840	0.0015	0.4472
Cultivar*Date*Roll	0.9580	0.5588	0.8146
Date*Mow*Roll	0.7939	0.8762	0.9982
Cultivar*Date*Mow*Roll	0.9831	0.5926	0.9727
Date*Foot	0.6813	0.4406	0.0005
Cultivar*Date*Foot	0.1918	0.4466	0.1422
Date*Mow*Foot	0.3990	0.5744	0.5704
Cultivar*Date*Mow*Foot	0.8530	0.1152	0.8859
Date*Roll*Foot	0.6044	0.7801	0.4027
Cultivar*Date*Roll*Foot	0.7450	0.8766	0.9127
Date*Mow*Roll*Foot	0.8595	0.9230	0.0004
Cultivar*Date*Mow*Roll*Foot	0.9536	0.9813	<0.0001

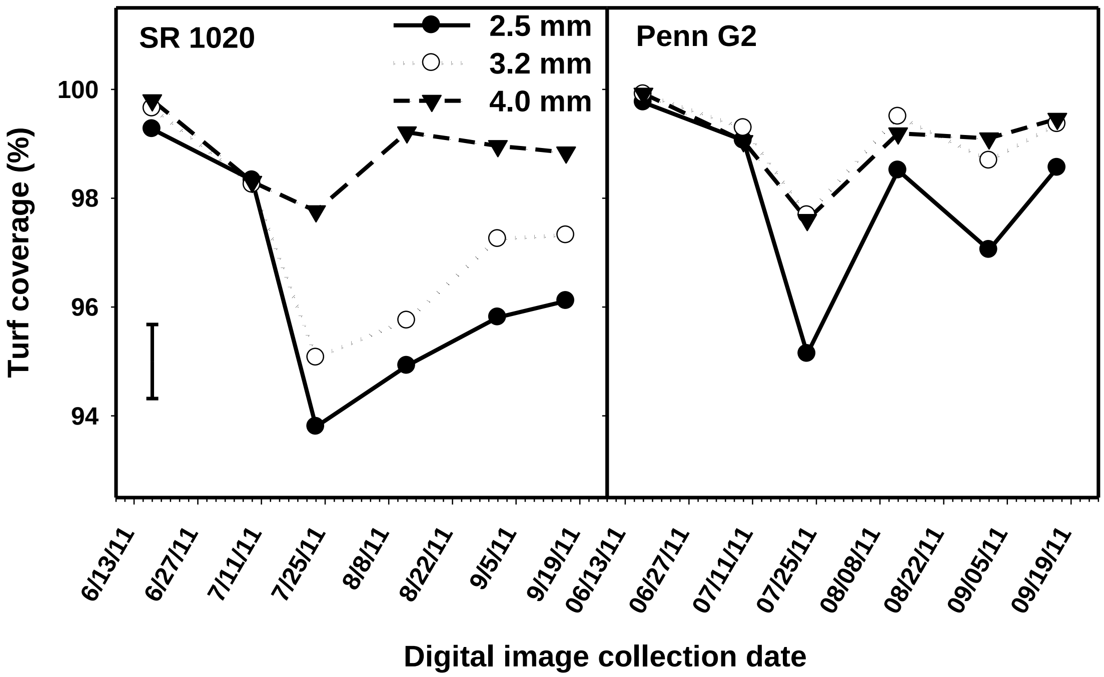

Figure 14. Cultivar by date by mowing height interaction for percent turf coverage in 2011. Data were averaged over rolling frequencies and foot traffic treatments. Error bar represents LSD (α = 0.05) for the cultivar by date by mowing height interaction.

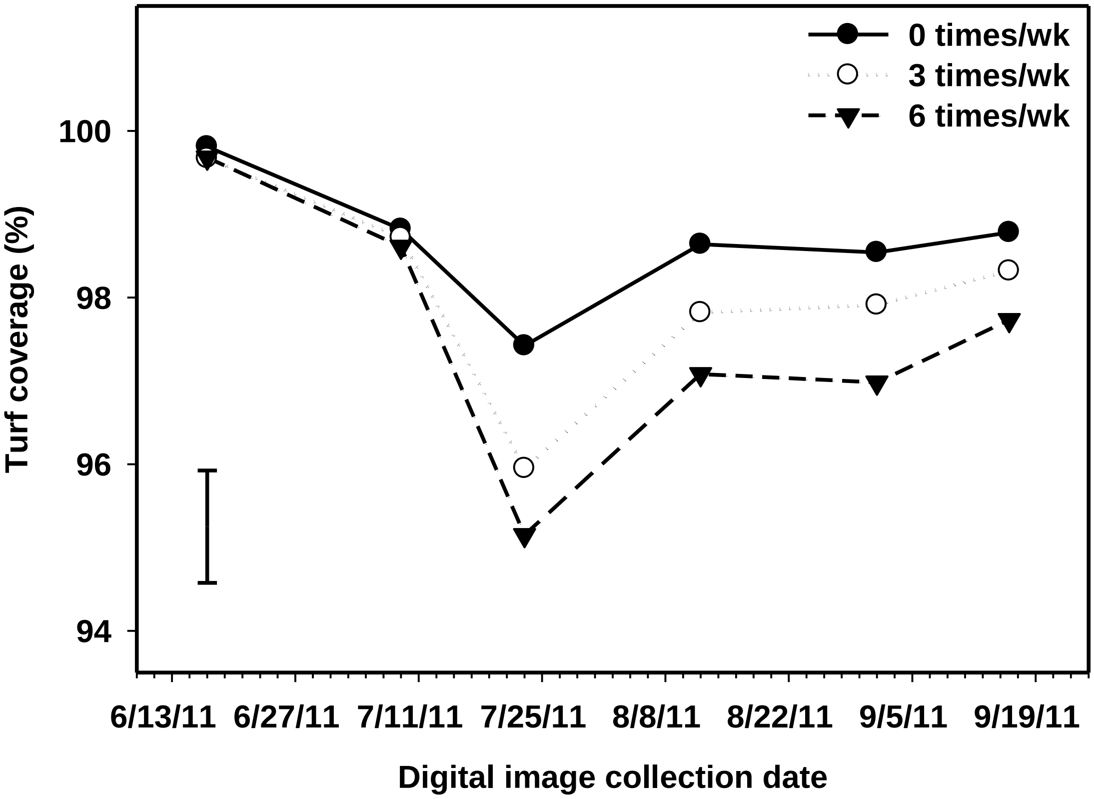

Figure 15. Date by rolling frequency interaction for percent turf coverage in 2011. Data were averaged over cultivars, mowing heights, and foot traffic treatments. Error bar represents LSD (α = 0.05) for the date by rolling frequency interaction.

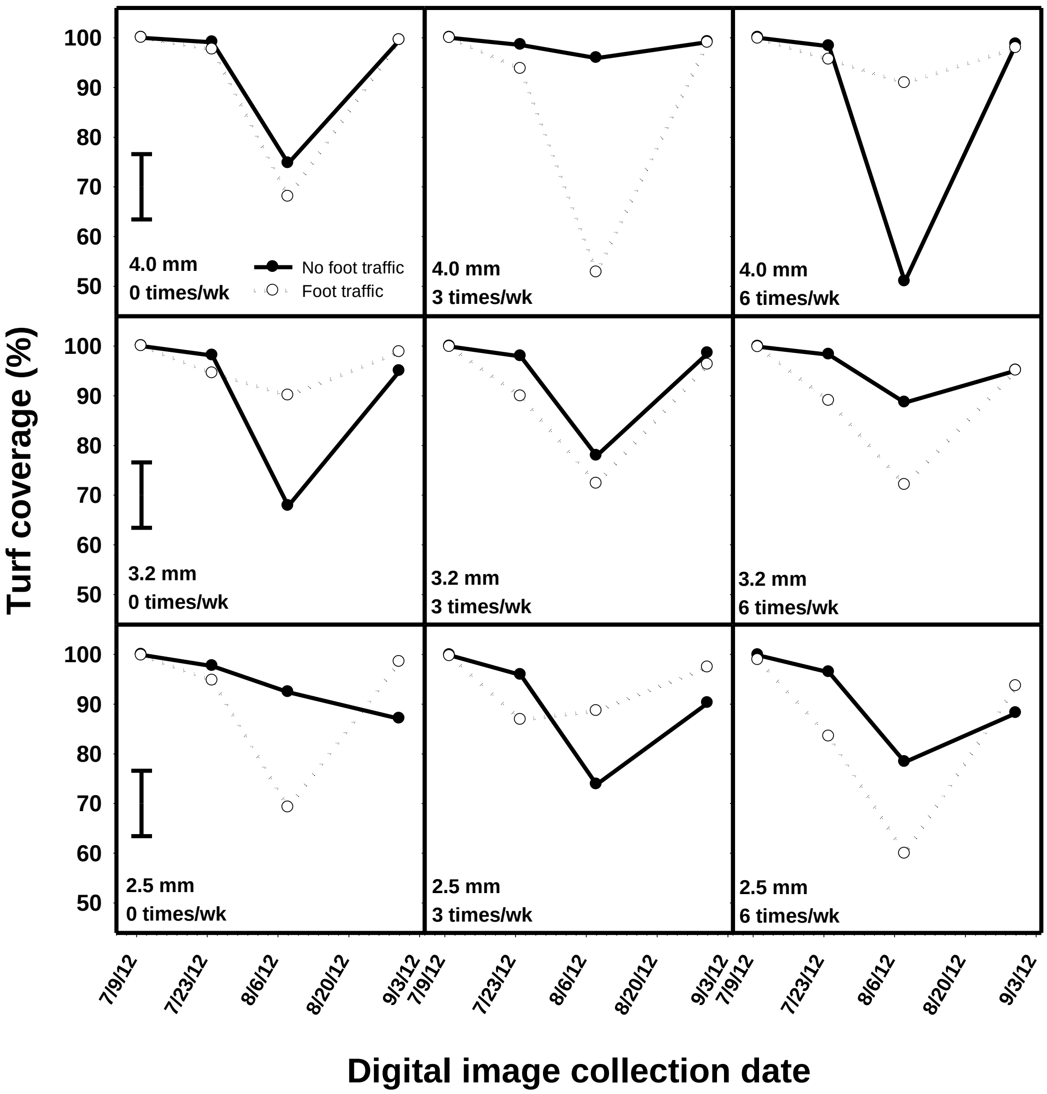

Figure 16a. Cultivar by date by mowing height by rolling frequency by foot traffic interaction for percent turf coverage for SR 1020 in 2012. Error bars represent LSD (α = 0.05) for the cultivar by date by mowing height by rolling frequency by foot traffic interaction.

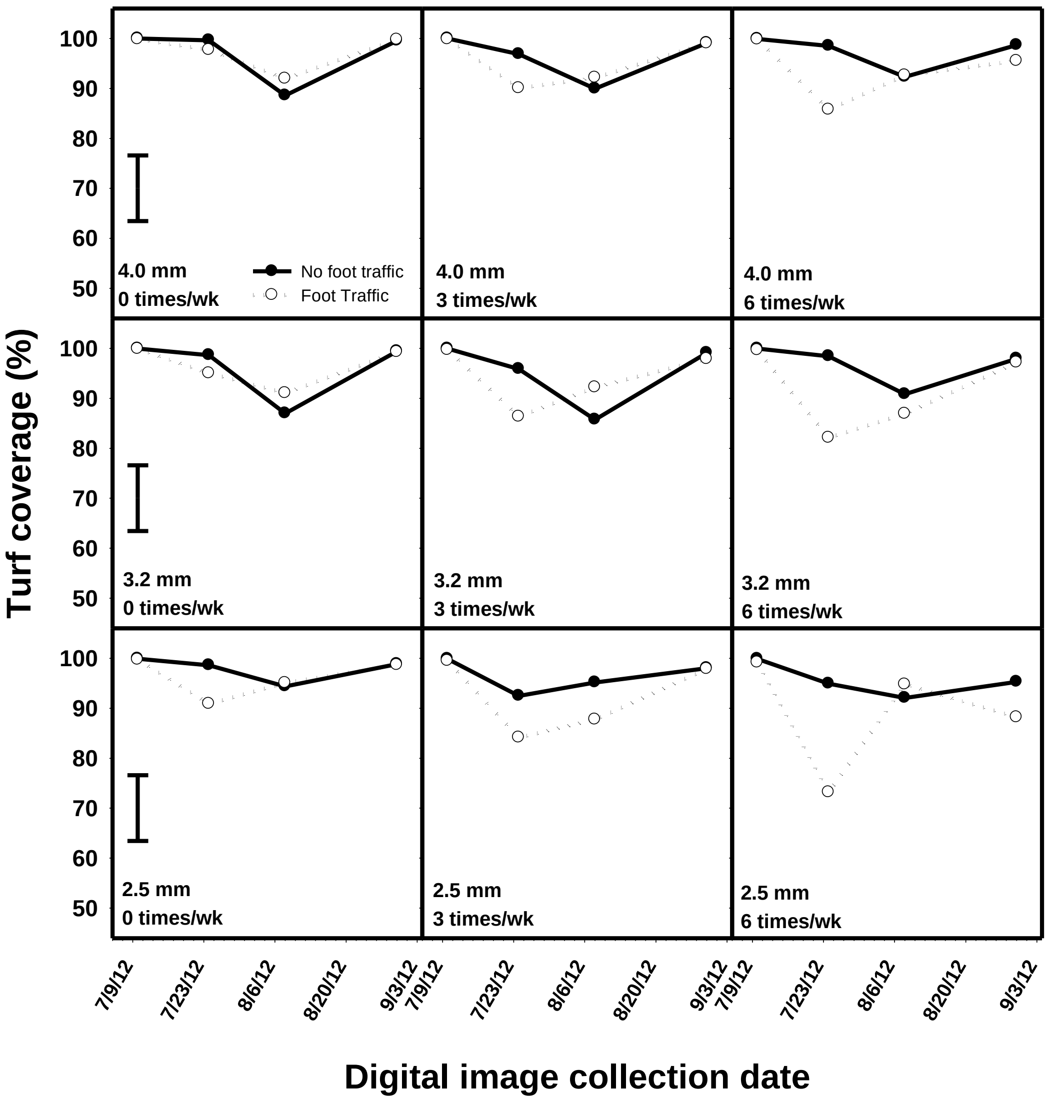

Figure 16b. Cultivar by date by mowing height by rolling frequency by foot traffic interaction for percent turf coverage for Penn G2 in 2012. Error bars represent LSD (α = 0.05) for the cultivar by date by mowing height by rolling frequency by foot traffic interaction.

Table 5. ANOVA table of turfgrass hue in degrees determined by digital image analysis from 2010 to 2012.

	P-values for all the main factors and interactions evaluated		
Effect	2010	2011	2012
Rep	0.9415	0.3850	0.3408
Cultivar	0.0387	0.2260	0.7397
Mow	0.9132	0.3900	0.1119
Cultivar*Mow	0.4576	0.5293	0.2281
Roll	0.7386	0.4315	0.8642
Cultivar*Roll	0.8060	0.6621	0.7488
Mow*Roll	0.2605	0.7129	0.5703
Cultivar*Mow*Roll	0.6426	0.9254	0.8543
Foot	0.3866	0.5313	0.1783
Cultivar*Foot	0.0317	0.0435	0.0485
Mow*Foot	0.1002	0.5111	0.3221
Cultivar*Mow*Foot	0.6676	0.6576	0.7879
Roll*Foot	0.0434	0.0074	0.1438
Cultivar*Roll*Foot	0.9617	0.3855	0.9494
Mow*Roll*Foot	0.0194	0.1469	0.0721
Cultivar*Mow*Roll*Foot	0.2504	0.2520	0.0562
Date	<0.0001	<0.0001	<0.0001
Cultivar*Date	0.2365	0.0026	<0.0001
Date*Mow	0.0009	0.2930	0.4510
Cultivar*Date*Mow	0.1577	0.8874	0.7572
Date*Roll	0.9265	0.9666	0.9533
Cultivar*Date*Roll	0.5885	0.9989	0.9281
Date*Mow*Roll	0.9497	0.4350	0.9814
Cultivar*Date*Mow*Roll	0.9862	0.9999	0.9827
Date*Foot	0.4674	0.9876	0.9814
Cultivar*Date*Foot	0.9197	0.5184	0.8541
Date*Mow*Foot	0.8103	0.6282	0.9994
Cultivar*Date*Mow*Foot	0.5414	0.9978	1.0000
Date*Roll*Foot	0.6053	<0.0001	0.4588
Cultivar*Date*Roll*Foot	0.3460	0.2365	0.2588
Date*Mow*Roll*Foot	0.4548	0.0031	0.0003
Cultivar*Date*Mow*Roll*Foot	0.2332	0.2516	0.0001

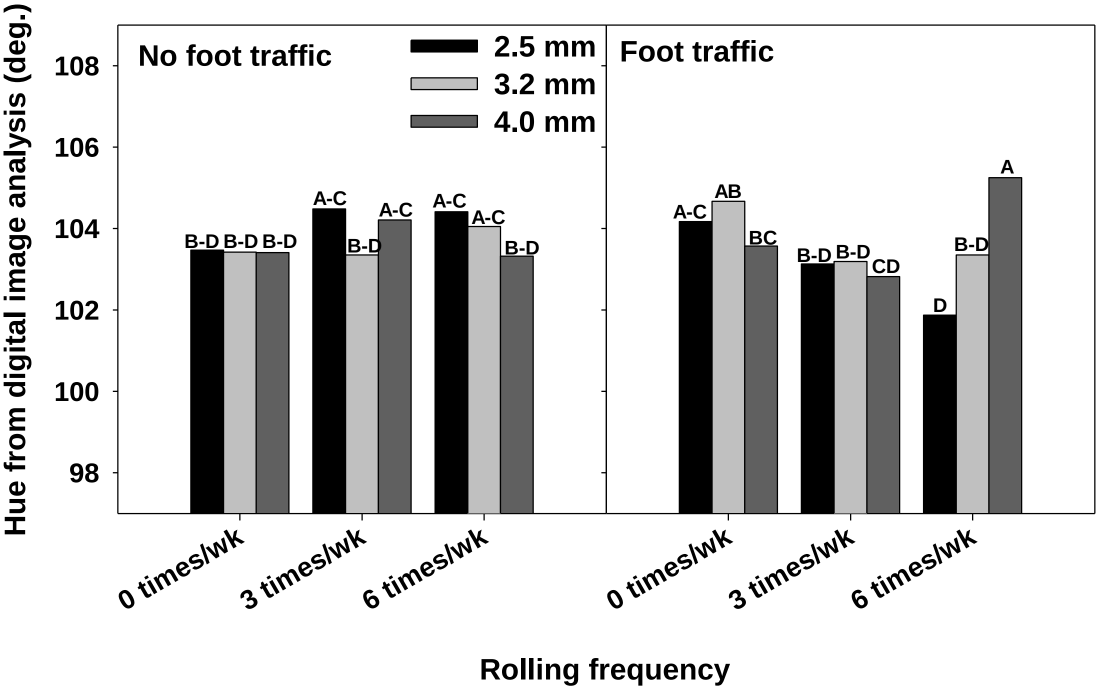

Figure 17. Mowing height by rolling frequency by foot traffic interaction for turfgrass hue in 2010. Data were averaged over cultivars and rating dates. Bars sharing the same letter are statistically similar at α = 0.05.

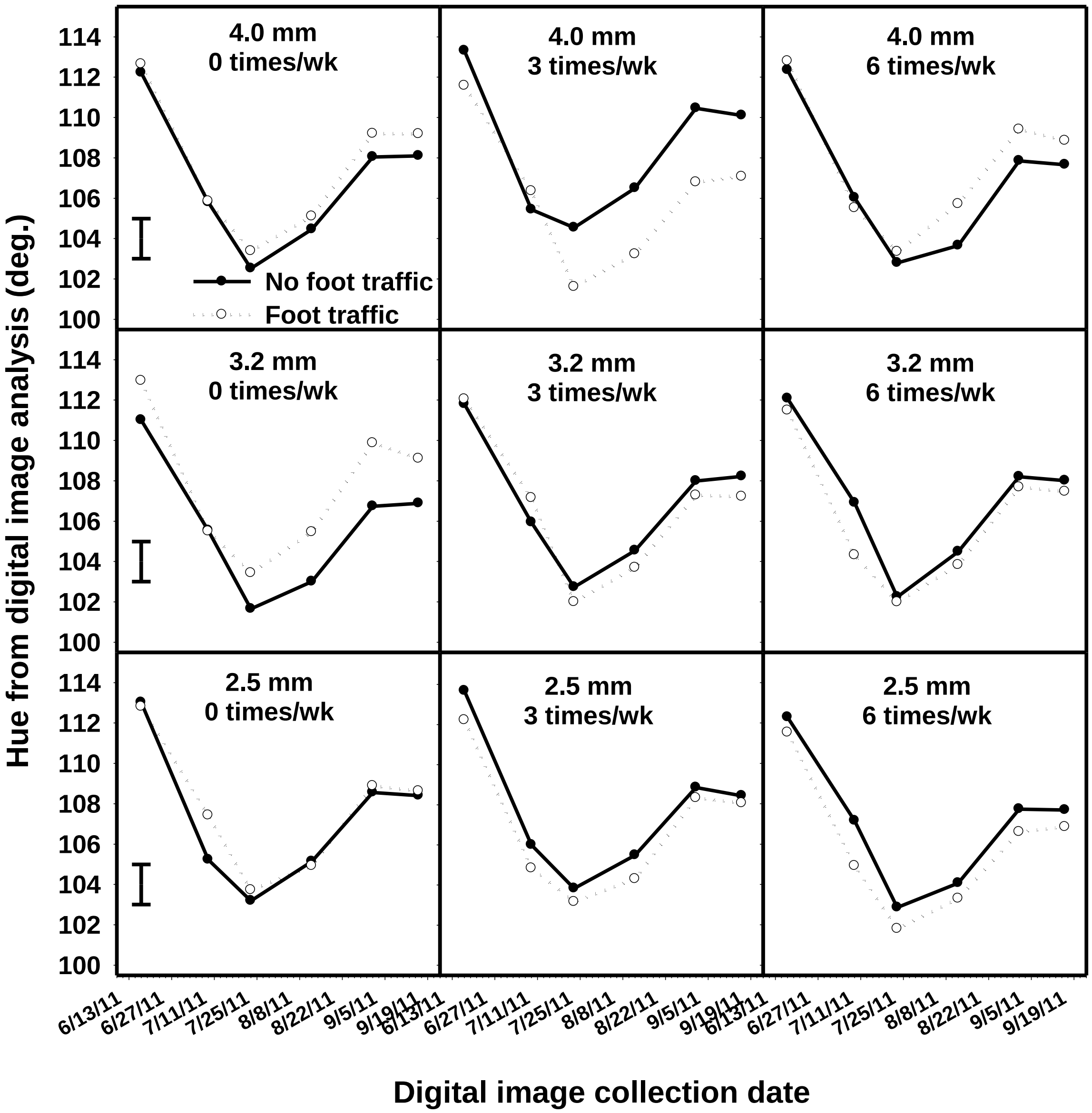

Figure 18. Date by mowing height by rolling frequency by foot traffic interaction for turfgrass hue in 2011. Data were averaged over cultivars. Error bars represent LSD (α = 0.05) for the date by mowing height by rolling frequency by foot traffic interaction.

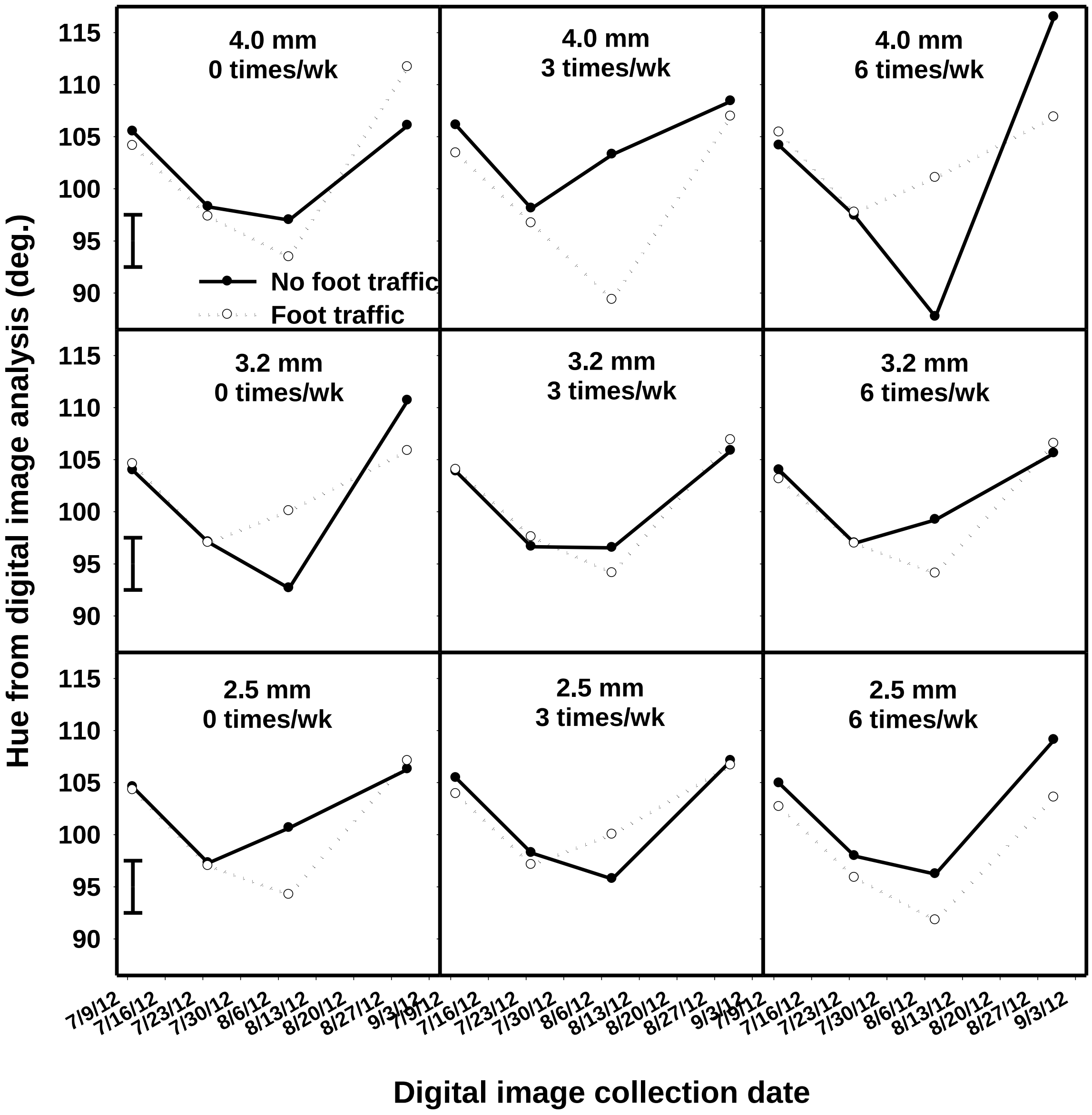

Figure 19a. Cultivar by date by mowing height by rolling frequency by foot traffic interaction for turfgrass hue of SR 1020 in 2012. Error bars represent LSD (α = 0.05) for the cultivar by date by mowing height by rolling frequency by foot traffic interaction.

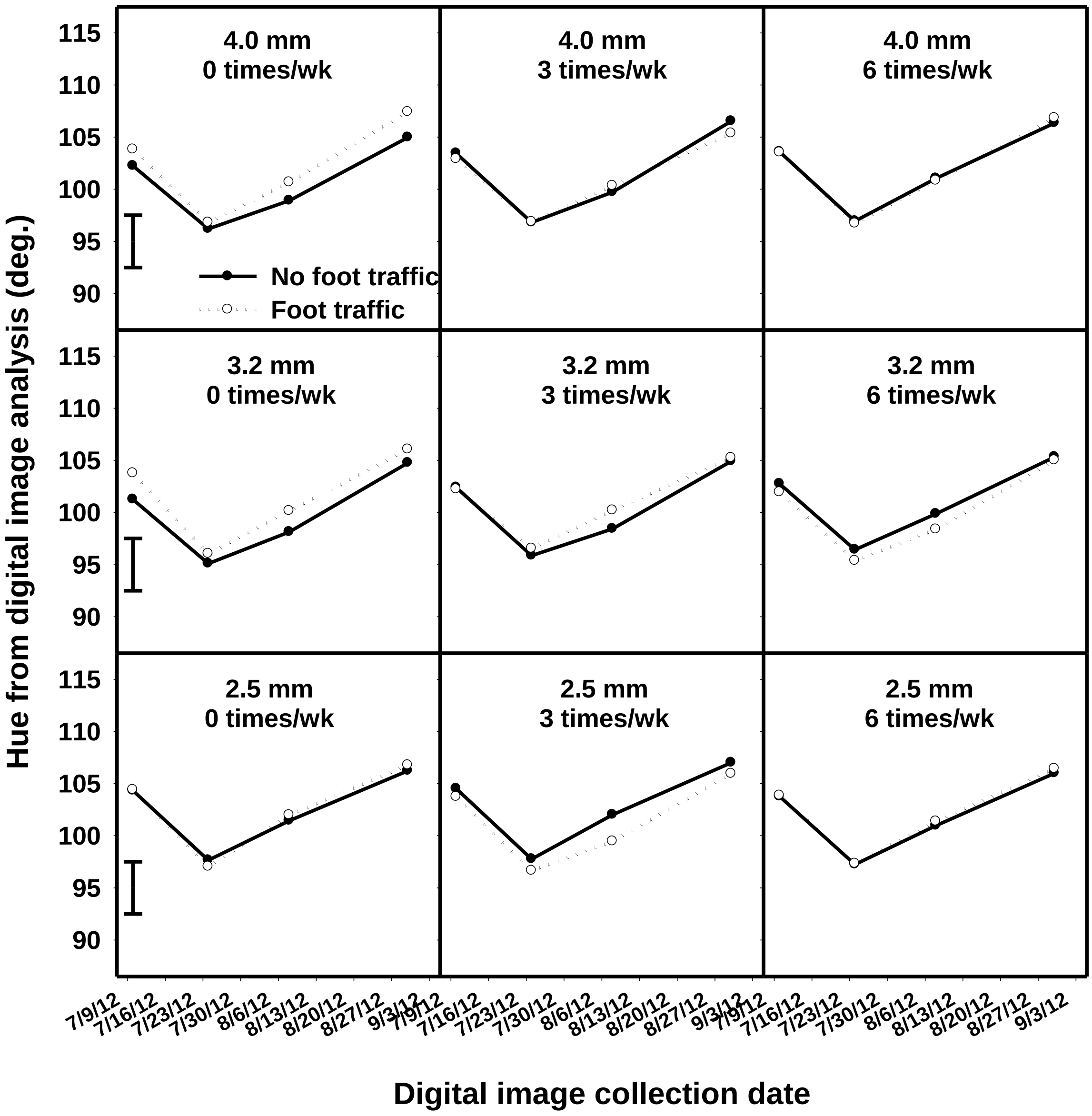

Figure 19b. Cultivar by date by mowing height by rolling frequency by foot traffic interaction for turfgrass hue of Penn G2 in 2012. Error bars represent LSD (α = 0.05) for the cultivar by date by mowing height by rolling frequency by foot traffic interaction.

Table 6. ANOVA table of dark green color index determined by digital image analysis from 2010 to 2012.

	P-values for all the main factors and interactions evaluated		
Effect	2010	2011	2012
Rep	0.9722	0.4102	0.4021
Cultivar	0.0549	0.0999	0.2953
Mow	0.8924	0.3970	0.1700
Cultivar*Mow	0.6931	0.7072	0.2564
Roll	0.7413	0.6106	0.9313
Cultivar*Roll	0.8756	0.7836	0.9936
Mow*Roll	0.2203	0.5837	0.4427
Cultivar*Mow*Roll	0.7742	0.9599	0.7839
Foot	0.4415	0.7926	0.2986
Cultivar*Foot	0.1018	0.0807	0.0594
Mow*Foot	0.1086	0.4146	0.1920
Cultivar*Mow*Foot	0.8092	0.7299	0.5616
Roll*Foot	0.1653	0.0054	0.0361
Cultivar*Roll*Foot	0.7295	0.3753	0.7121
Mow*Roll*Foot	0.0215	0.4276	0.5044
Cultivar*Mow*Roll*Foot	0.0831	0.5231	0.1682
Date	<0.0001	<0.0001	<0.0001
Cultivar*Date	0.2769	<0.0001	<0.0001
Date*Mow	0.0022	0.4901	0.2591
Cultivar*Date*Mow	0.2427	0.5979	0.5891
Date*Roll	0.8304	0.9441	0.9566
Cultivar*Date*Roll	0.8700	0.9909	0.9691
Date*Mow*Roll	0.9414	0.0240	0.9810
Cultivar*Date*Mow*Roll	0.8666	1.0000	0.9943
Date*Foot	0.4450	0.9665	0.8623
Cultivar*Date*Foot	0.8784	0.1381	0.8078
Date*Mow*Foot	0.9436	0.7629	0.9906
Cultivar*Date*Mow*Foot	0.6799	0.9855	0.9986
Date*Roll*Foot	0.5250	0.0002	0.4811
Cultivar*Date*Roll*Foot	0.4348	0.3556	0.2162
Date*Mow*Roll*Foot	0.1738	0.1235	0.0017
Cultivar*Date*Mow*Roll*Foot	0.0819	0.0914	0.0028

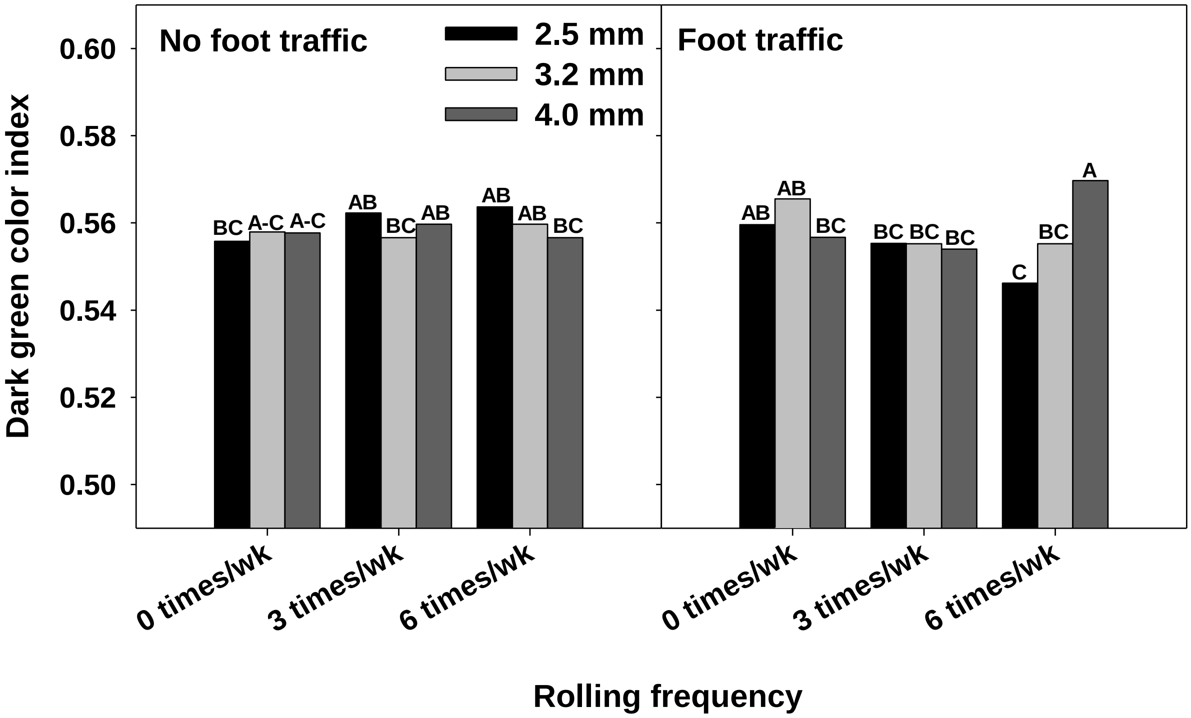

Figure 20. Mowing height by rolling frequency by foot traffic interaction for dark green color index in 2010. Data were averaged over cultivars and rating dates. Bars sharing the same letter are statistically similar at α = 0.05.

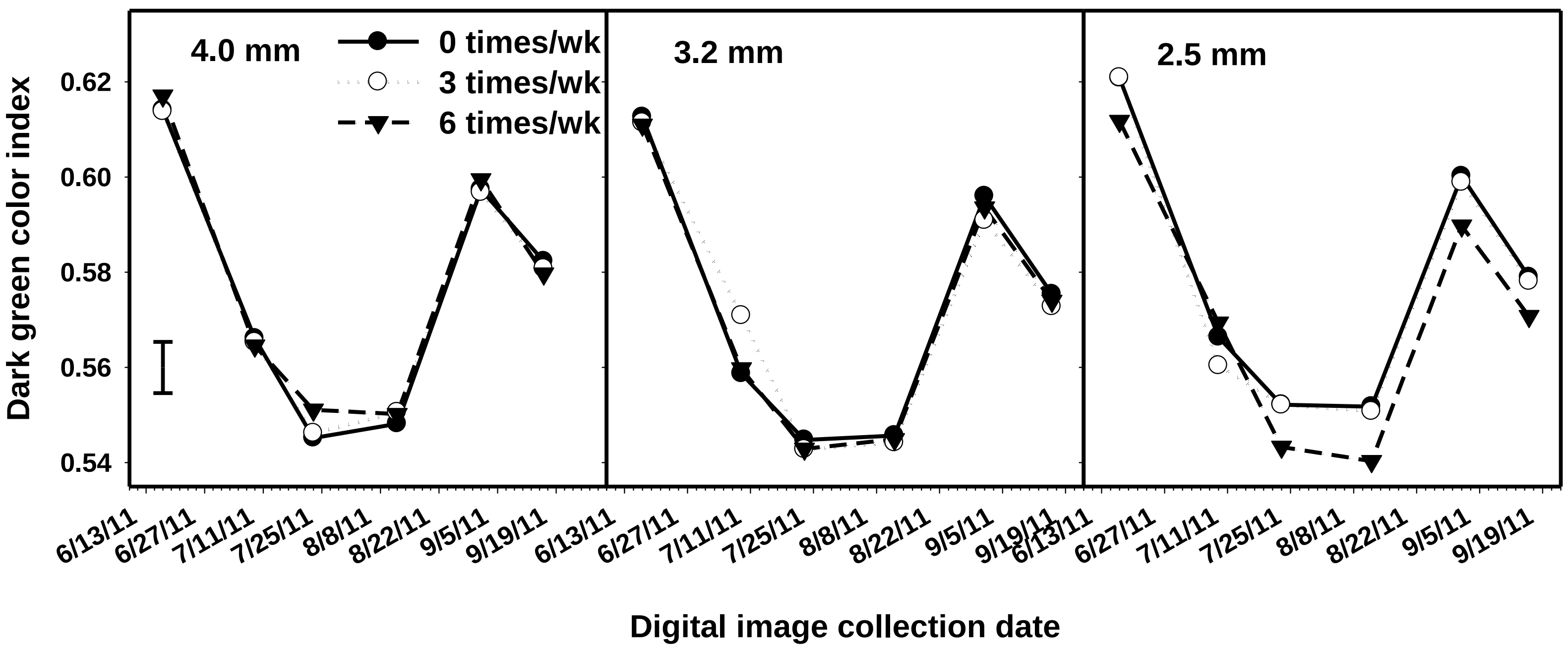

Figure 21. Date by mowing height by rolling frequency interaction for dark green color index in 2011. Data were averaged over cultivars and foot traffic treatments. Error bar represents LSD (α = 0.05) for the date by mowing height by rolling frequency interaction.

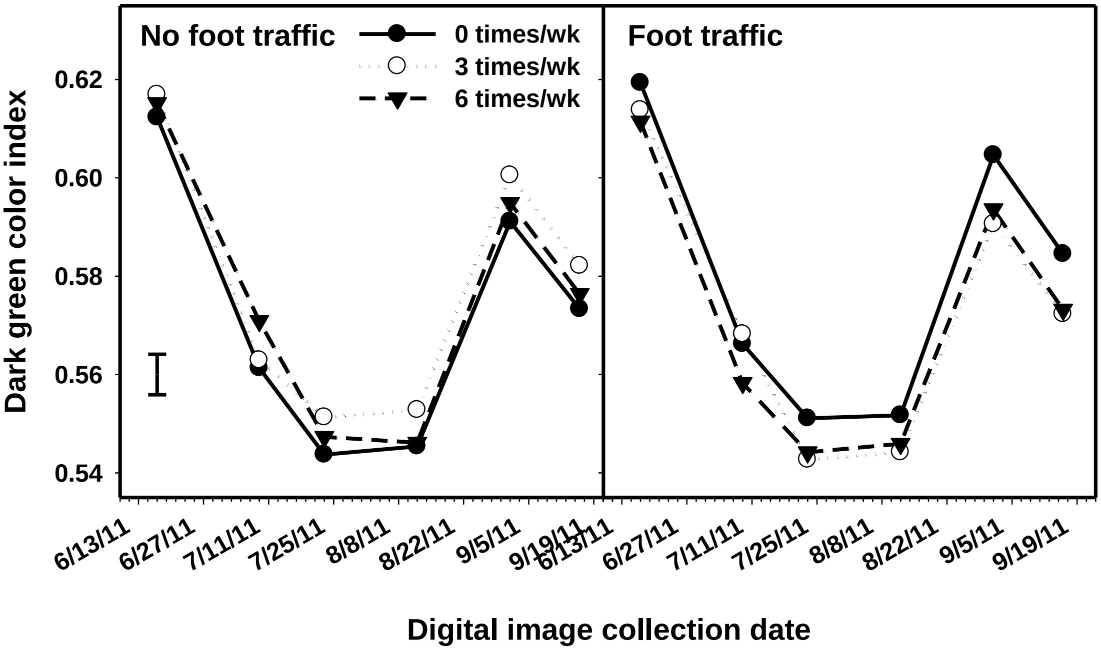

Figure 22. Date by rolling frequency by foot traffic interaction for dark green color index in 2011. Data were averaged over cultivars and mowing heights. Error bar represents LSD ($\alpha = 0.05$) for the date by rolling frequency by foot traffic interaction.

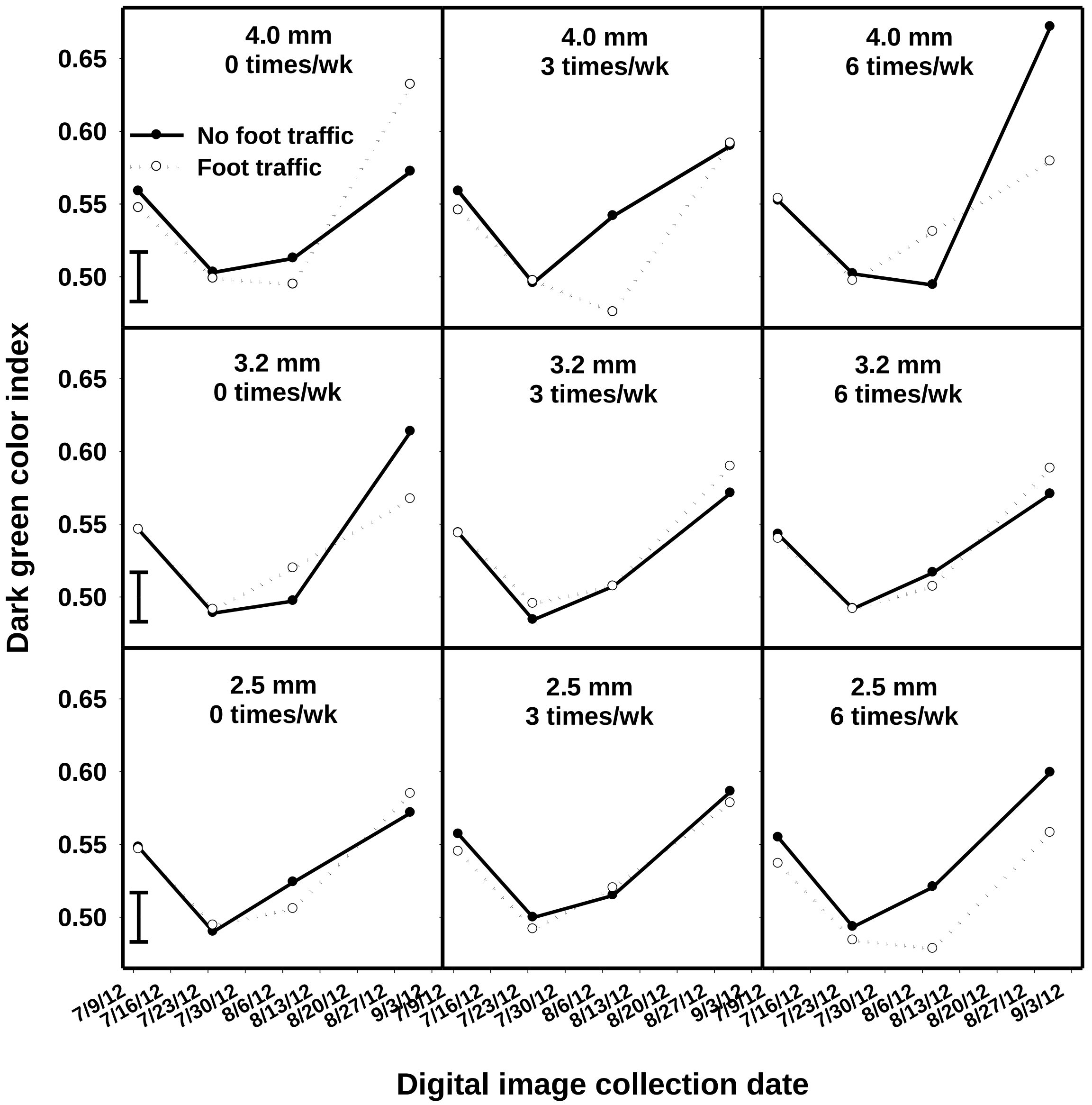

Figure 23a. Cultivar by date by mowing height by rolling frequency by foot traffic interaction for dark green color index for SR 1020 in 2012. Error bars represent LSD (α = 0.05) for the cultivar by date by mowing height by rolling frequency by foot traffic interaction.

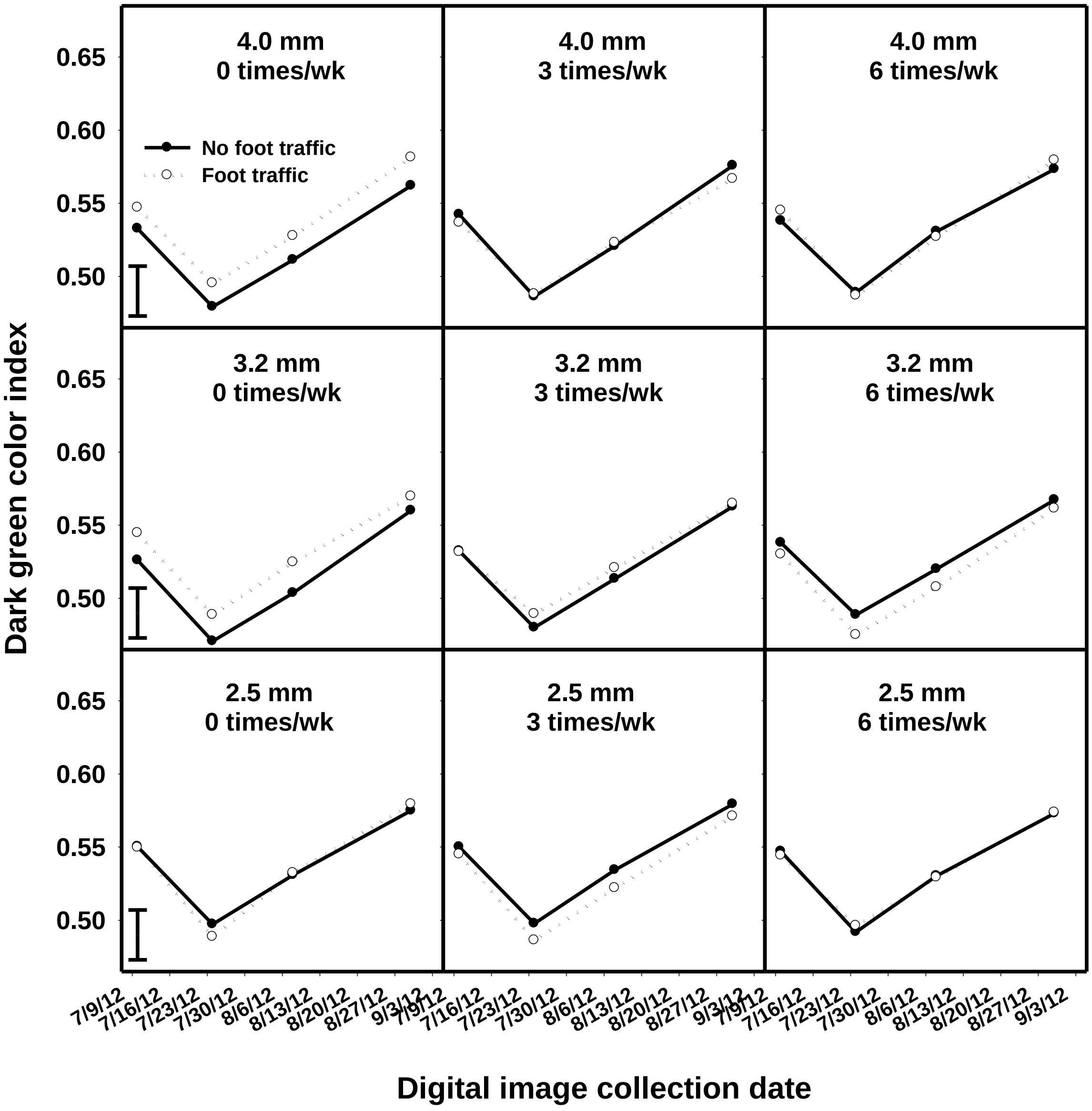

Figure 23b. Cultivar by date by mowing height by rolling frequency by foot traffic interaction for dark green color index for Penn G2 in 2012. Error bars represent LSD (α = 0.05) for the cultivar by date by mowing height by rolling frequency by foot traffic interaction.

Ball roll distance

Mowing heights and rolling frequencies significantly affected ball roll distance in 2010 and 2011. In 2010, mowing heights and rolling frequencies interacted with dates to significantly affect ball roll distance (Table 7). Data obtained from 28 May and 19 Jun 2010 were collected after all rolling treatments were applied, but only plots rolled six times per week were rolled when data were obtained for 18 Jun 2010. As mowing heights were increased, ball roll distance was decreased significantly on all dates except 28 May when cultivars and rolling frequencies were averaged (Fig. 24). The one exception was treatments maintained at 3.2 mm having statistically similar ball roll distance to 2.5 mm treatments on 28 May. Nikolai (2005) found that ball roll differences between treatments must be greater than 15.2 cm for the golfer to be able to distinguish various green speeds. When using this value to differentiate mowing heights in 2010, the two lower mowing heights maintained similar ball roll distances with the exception of 3.2 mm mowing heights on 18 Jun; however, treatments rolled three times per week were not rolled that day likely reducing ball roll distance at this mowing height.

Increasing rolling frequency also significantly increased ball roll distances on each rating date in 2010 when data were averaged over cultivars and mowing heights (Fig. 25). On the initial data collection date, each increase in rolling frequency resulted in a significantly greater ball roll distance that could be distinguished by golfers. On 19 June when all rolling treatments were applied, golfers would only have been able to differentiate daily and non-rolled treatments. When evaluating residual ball roll distance on 18 June (Nikolai, 2005), all treatments receiving rolling maintained ball roll differences that could have been identified by golfers when comparing non-rolled plots. The residual effect of rolling three times per day only decreased ball roll distance by 3.7% on 18 Jun compared to ball roll distances determined on 19 Jun when all rolling treatments were applied.

Mowing heights and rolling frequencies differentiated ball roll distances in 2011 as well. The main treatment factor, mowing height, resulted in significant differences with regards to ball roll distance when pooling cultivars, dates, and rolling frequencies (Table 7). Following the same trend previously discussed, ball roll distances were increased significantly as mowing heights were reduced (Fig. 26). Both of the lower mowing heights could be distinguished by golfers (> 15.2 cm) from plots mowed at 4.0 mm, but golfers could not distinguish a change in green speed between the two lower mowing heights.

Rolling frequency and date interacted significantly in 2011 with regards to ball roll distance (Table 7), but the data contrasted the data collected in 2010. Ball roll distances determined for 1 Jun and 22 Jul were obtained when all rolling treatments were applied. The data collected on 2 Jun and 21 Jul allowed for determination of residual rolling effect from rolling three days per week. Data collected early in the summer followed well established trends with rolling treatments exhibiting significantly greater ball roll distance than non-rolled treatments when all rolling treatments were applied (Fig. 27). All the rolling treatments were statistically different when rolling treatments were applied in June (Fig. 27). The residual effect of rolling three days per week only decreased ball roll distance by 1.6% on 2 Jun. From the golfer’s perspective, all rolling treatments would have been distinguishable from the non-rolled treatment each rating date. There were no differences observed for rolling frequencies later in the summer of 2011 (Fig. 27), which contrasts previous studies (Hartwiger et al., 2001; Richards, 2010). These final ball roll data coincided with significant reductions in turf coverage observed on 23 Jul (Young, 2013). Richards (2010) stated that reductions in ball roll distance observed in his study were a result of changes in environmental conditions, which has been discussed thoroughly by Nikolai (2005). In the current study, it appears the reduction in turf coverage from environmental and mechanical stress may have affected ball roll distance. The reduction in turfgrass coverage may have resulted in greater friction from the putting green surface that reduced ball roll distance, creating similar green speeds for all rolling frequencies. In contrast, increased rolling with high percent turf coverage always significantly increased ball roll distance in this study. The increase in rolling frequency with full turf coverage likely created a smoother surface that minimized friction on the golf ball; especially on the day rolling treatments were applied.

The effect of lowering mowing heights and increasing rolling frequencies on ball roll distance have been well established through previous research (Hartwiger et al., 2001; Nikolai, 2005; Richards, 2010), so evaluating ball roll distance was not a major objective for this project. Similar to previously published studies, lowering mowing heights resulted in significantly greater ball roll distances in both years. Nikolai (2005) discusses in great detail "the law of diminishing returns" with respect to mowing heights and increasing green speed. The author illustrates the minimal increase in putting green speed when decreasing mowing heights below 3.2 mm, similar to the results observed in the current study. Although statistically significant differences in ball roll distance were observed between 2.5 and 3.2 mm mowing heights, plots mowed at 3.2 mm and rolled three days per week were only distinguishable by golfers when residual rolling affects were evaluated.

As long as turf coverage was high, light-weight rolling resulted in significantly greater ball roll distance as observed in previous studies (Hartwiger et al., 2001; Nikolai, 2005; Richards, 2010). However, the similarities in ball roll distance observed in July 2011 when percent turfgrass coverage was reduced contrasted the previous studies. In previous studies, when plots were rolled multiple times per day, ball roll distances were increased significantly with increased rolling frequencies (Hartwiger et al., 2001; Richards, 2010). In these cases, continuous rolling multiple times per day may have minimized the effects of surface interacting with the golf ball as previously discussed.

These results indicate that decreasing mowing heights and increasing rolling frequencies will increase ball roll distances, but only when putting green turf is maintained at full turfgrass coverage. The implications of these data for golf course managers demonstrate the diminishing returns of maintaining extremely low mowing heights on putting green speeds. In 2010 and 2011, treatments mowed at 3.2 mm maintained ball roll distances that golfers would not be able to distinguish from treatments maintained at 2.5 mm, with the only exception being 18 Jun 2010, when residual ball roll was evaluated on treatments rolled three days per week. Similar to previous data, putting greens can be mowed at higher mowing heights and rolled daily to maintain faster and consistent green speeds. Although few physiological differences were observed at the higher mowing heights, turf quality and coverage were greater with increased mowing heights (Young, 2013). Many other mechanical, environmental, and chemical components can also affect ball roll distances as noted by Nikolai (2005).

Comprehensive studies have been conducted in New Jersey to determine the effects of common putting green management practices on annual bluegrass (*Poa annua* L.) susceptibility to anthracnose (*Colletotrichum cereale* Manns sensu lato Crouch, Clarke & Hillman) (Inguagiato et al., 2009; Roberts et al., 2012), a disease known to be most problematic on stressed turfgrass. Both studies recommended that managing putting greens at mowing heights greater than 3.2 mm would decrease anthracnose severity. Increasing rolling frequencies or mowing frequency (double cutting) at these higher mowing heights had no effect on anthracnose severity (Inguagiato et al., 2009; Roberts et al., 2012), which indicates that these practices can be performed without increasing stress levels compared to lower mowing heights. Although the current project did not evaluate increased mowing frequencies, these practices could possibly be implemented to maintain higher ball roll distances without significantly affecting physiological stress. Future studies should be conducted to determine if this is an accurate statement.

Table 7. ANOVA table of ball roll distance data from 2010 and 2011.

	P-value for all interactions and main factors evaluated	
Effect	2010	2011
Rep	0.3429	0.3410
Cultivar	0.5364	0.0825
Mow	0.0002	<0.0001
Cultivar*Mow	0.5557	0.3491
Roll	0.0014	0.1073
Cultivar*Roll	0.2525	0.2986
Mow*Roll	0.2749	0.8111
Cultivar*Mow*Roll	0.6667	0.2371
Date	<0.0001	<0.0001
Cultivar*Date	<0.0001	0.0578
Date*Mow	0.0041	0.0895
Cultivar*Date*Mow	0.9627	0.7980
Date*Roll	0.0038	<0.0001
Cultivar*Date Roll	0.4497	0.2837
Date*Mow*Roll	0.7361	0.9345
Cult*Date*Mow*Roll	0.7239	0.7799

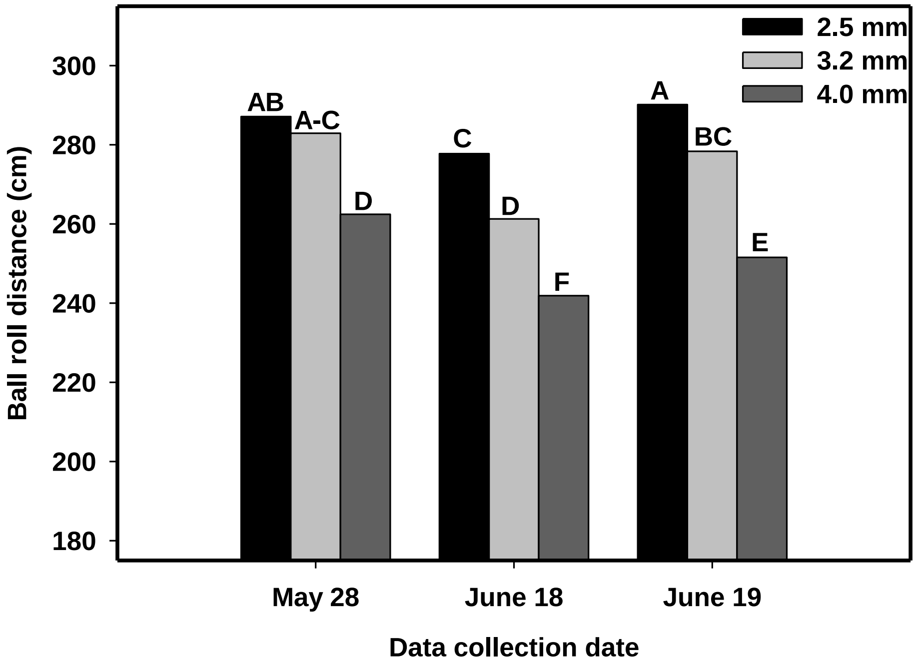

Figure 24. Date by mowing height interaction for ball roll distance in 2010. All rolling treatments were applied on 28 May and 19 Jun, but only daily rolling was applied on 18 Jun to determine residual rolling effect. These data were averaged over cultivars and rolling frequencies. Bars sharing the same letter are statistically similar at $\alpha = 0.05$.

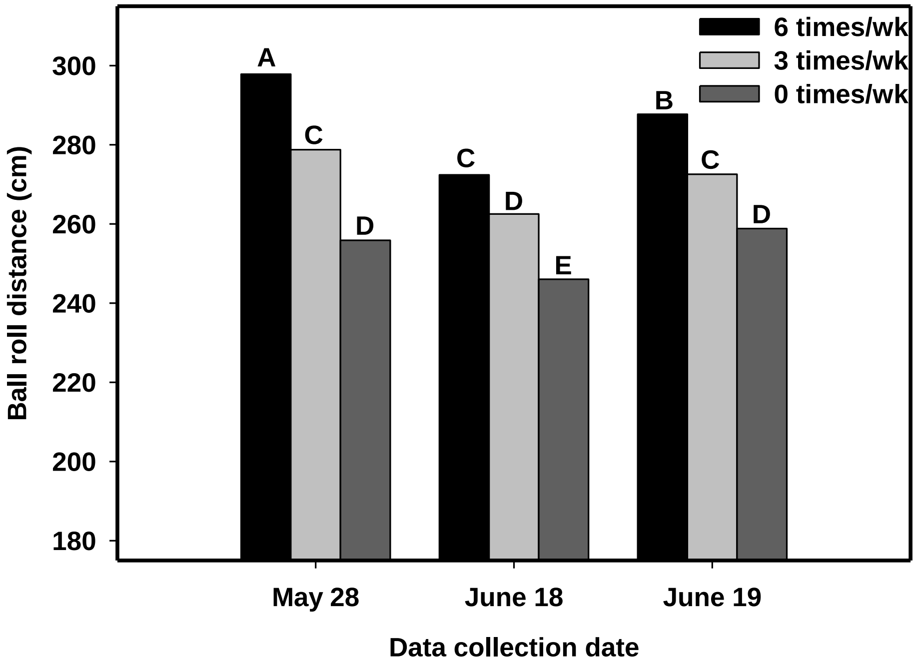

Figure 25. Date by rolling frequency interaction for ball roll distance in 2010. All rolling treatments were applied on 28 May and 19 Jun, but only daily rolling was applied on 18 Jun to determine residual rolling effect. These data were averaged over cultivars and mowing heights. Bars sharing the same letter are statistically similar at α = 0.05.

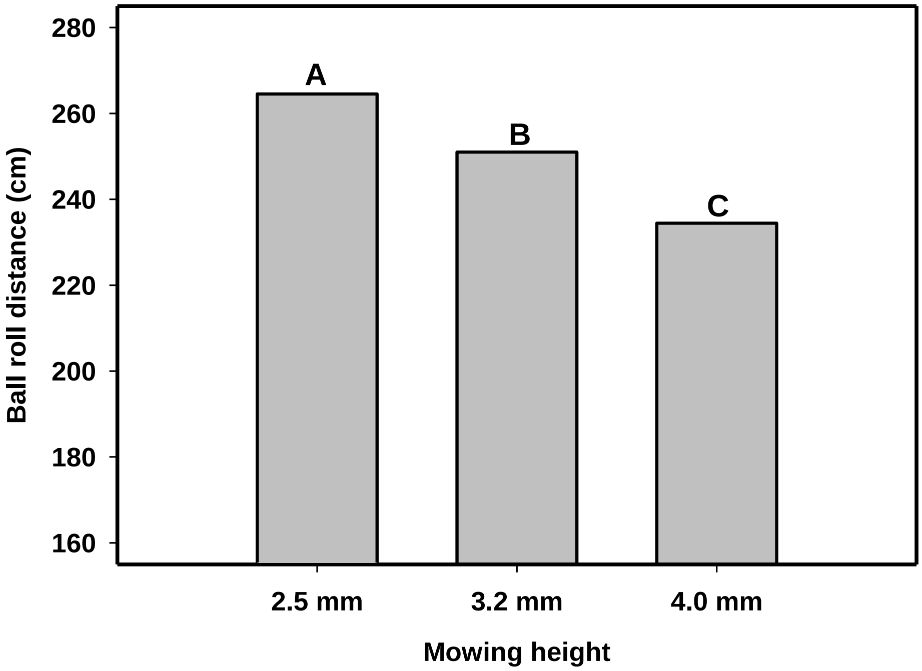

Figure 26. The effect of mowing height on ball roll distance in 2011. These data were averaged over cultivars, dates, and rolling frequencies. Bars sharing the same letter are statistically similar at α = 0.05.

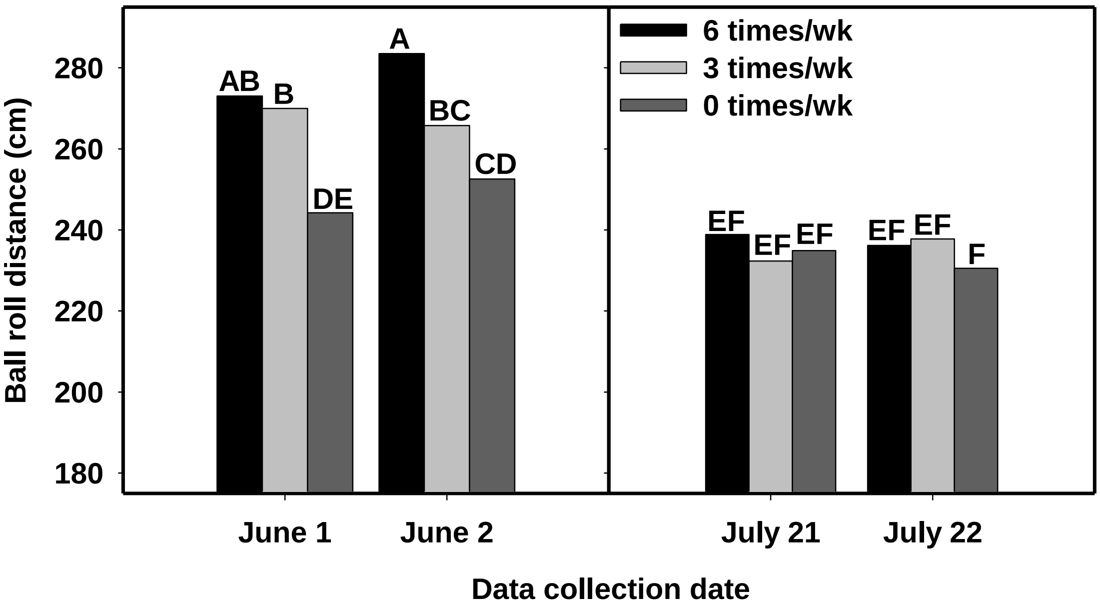

Figure 27. Date by rolling frequency interaction for ball roll distance in 2011. All rolling treatments were applied on 1 Jun and 22 Jul, but only daily rolling was applied on 2 Jun and 21 Jul to determine residual rolling effect. These data were averaged over cultivars and mowing heights. Bars sharing the same letter are statistically similar at $\alpha = 0.05$.

Rooting parameters

Significant differences in rooting parameters were observed during the initial sampling dates in May of 2010 to 2012 prior to foot traffic application (Table 8). Mowing height was the main treatment factor that appeared to affect rooting parameters in early summer. A significant year by cultivar interaction also occurred with respect to cumulative root length, root surface area, root diameter, and dry root mass. SR 1020 exhibited significant differences in cumulative root length and surface area each year, but results were variable. SR 1020 mowed at 2.5 mm had significantly less cumulative root length in 2010, but treatments maintained at 3.2 mm had the greatest cumulative root length in 2011 (Fig. 28). The inherent variability of root data was verified with treatments maintained at 4.0 mm having significantly lower cumulative root length in 2012 (Fig. 28). Root surface area data followed a similar trend with the lowest mowing height resulting in the lowest surface area in 2010; however, SR 1020 maintained at 3.2 mm had the greatest surface area in 2011 and 2012 (Fig. 29). Similarly, root dry mass was significantly reduced in 2010 at the 2.5 mm mowing height, but the 3.2 mm mowing height resulted in the greatest dry mass in 2012 (Fig. 30). The only significant difference observed for Penn G2 occurred in 2010 with cumulative root length at 3.2 mm being significantly greater than treatments mowed at 4.0 mm (Fig. 28). This initial root sampling was conducted fairly early each summer to determine the relative values for each of these rooting parameters prior to severe heat stress. Therefore, significant differences in treatments were not expected since mowing and rolling treatments had only been applied for three to six weeks once root samples were obtained.

Both SR 1020 and Penn G2 had significant reductions in all rooting parameters in 2011 compared to 2010 and 2012 (Table 9). The winter of 2011 was extreme resulting in record breaking snow fall and low temperatures for this area. These extreme winter conditions combined with a quick burst of above average temperatures early in the summer may have resulted in the decreased root production observed in May 2011 (Fig. 4).

The combination of extreme environmental stress and treatment application throughout summer months resulted in significant reductions in all rooting parameters. When data were averaged over years and cultivars, cumulative root length, root surface area, average root diameter, and dry root mass were reduced by 63%, 71%, 23%, and 77%, respectively, when comparing the initial root sampling data in May to those determined in August each year. Foot traffic significantly affected rooting parameters evaluated in this study from the August root sampling, while mowing heights and rolling frequencies interacted with other factors to affect all rooting characteristics except root dry mass (Table 10).

SR 1020 mowed at 2.5 mm had significantly less cumulative root length and root surface area compared to plots maintained at 4.0 mm in August 2010 (Figs. 31 and 32). The trends observed in August 2010 for cumulative root length and root surface area were expected because of decreased rooting at lower mowing heights. No other significant differences were observed for SR 1020 in 2011 or 2012 (Figs. 31 and 32). Cumulative root length (Fig. 31) and root surface area (Fig. 32) were never significantly different for mowing heights of Penn G2 on any sampling dates. However, there was a significant reduction in root diameter for Penn G2 mowed at 2.5 mm compared to plots mowed at 3.2 mm (Fig. 33). Although this was statistically significant, the biological significance of this minute reduction in average root diameter is unknown.

It is well established that decreasing mowing heights decreases rooting of turfgrasses (Beard, 1973; Bell, 2011; Fry and Huang, 2004; Turgeon, 2005). These root reductions at low mowing heights are compounded by a compromised root system of cool-season grasses with increasing air and soil temperatures later in the summer (Huang et al., 1998b; Huang and Gao, 2000). Dry root mass is often cited as a means of demonstrating changes in root production due to various treatments or seasonal changes. Liu and Huang (2002) incorporated minirhizotron technology in their research to determine more intricate details of root morphology and mortality. Creeping bentgrass cultivars exhibited reduced total root length and maximum rooting depth under lower mowing heights (3 mm vs. 4 mm) during summer heat stress (Liu and Huang, 2002). This evaluation method allowed these researchers to prove that root loss exceeds new root production during summer stress, and that root death increases with lower mowing heights. Similar processes likely occurred in the current study, resulting in the reductions previously discussed for all rooting parameters.

The negative effects of low mowing heights and increased temperatures on creeping bentgrass roots are well established, but the combination of these mechanical and environmental stresses with light-weight rolling have not been evaluated extensively. Incorporating light-weight rolling three or six times per week had a significant effect on surface area of Penn G2 roots in 2011 and 2012 (Fig. 34). In 2011, daily rolled treatments had significantly less root surface area than treatments rolled three times per week; however, Penn G2 rolled three times per week exhibited significantly less root surface area than non-rolled and daily rolled treatments in 2012. Similar to this study, Hartwiger et al. (2001) did not observe a significant difference in dry root mass with increased rolling frequency. Utilizing the WinRhizo software allowed us to look at more intricate details to determine potential morphological changes to the root system that would have gone unnoticed if only dry root mass was evaluated.

Cumulative root length, root surface area, and root dry mass were significantly reduced with foot traffic treatments throughout summer months in 2010 and 2012 (Table 11). Root diameter was reduced significantly with foot traffic in 2012 (Table 11); however, the biological importance of this reduction on the physiological health of the turf is unknown. The variation in weather conditions from year to year may help explain the treatment separation observed, and the lack of differences in 2011. The research facility received greater precipitation and maintained higher humidity levels in 2010 compared to 2011 and 2012 (Figs 3-5). The increased humidity levels, even at slightly lower temperatures, would decrease the plants' ability to transpire water and naturally cool themselves. These environmental conditions would increase physiological stress that may have led to the significant reductions in rooting in 2010. Weather conditions in 2011 and 2012 were similar with continuous hot, dry conditions throughout summer months. These conditions were much more conducive for maintaining the physiological health of the turf, even under severe heat stress because evaporative cooling would continue to be high maintaining a more moderate surface temperature. The separation in foot traffic treatments observed in 2012 was likely due to increasing the frequency of foot traffic application. Rather than applying foot traffic every two weeks, foot traffic was applied weekly. The reduction in recovery time between foot traffic applications may have contributed to these significant reductions.

The combination of wear treatments significantly affected root diameter when averaged over the cultivars, mowing heights, and three years of August samples (Fig. 35). Treatments that received no rolling or foot traffic had significantly thicker roots than those that received either rolling or foot traffic. These data suggest that any consistent form of wear will decrease root diameter. The range of root diameters was between 0.1508 and 0.1564 mm. As previously mentioned, a statistical difference was identified with P-value 0.0569, resulting in a least significance difference level of 0.0024 mm. The methods used to evaluate root morphology in this study were more detailed than many previous studies, so these results indicate some of the minor changes that occur in root morphology under intensive management practices during environmental stress. One must also keep the perspective that some of these statistical differences may be too minor to create a significant benefit to the physiological health of the creeping bentgrass putting green.

Regardless of the treatments applied, roots of creeping bentgrass were reduced from May to August. Mowing heights did not consistently reduce rooting parameters from year to year as hypothesized for this study. Weather conditions combined with all these management practices appeared to affect these rooting parameters more than the individual practices. These data demonstrate that general putting green management practices do not have a consistent negative effect on rooting of creeping bentgrass putting greens. Extreme environmental conditions are going to compromise root production regardless of management practices. This shallower root system later in summer will alter water management practices of creeping bentgrass putting greens. More frequent, light irrigation may need to be applied to keep moisture levels adequate in this minimal root zone. Increasing the use of handwatering will allow for more precise water application to problem areas, while higher moisture areas would not be irrigated. Also, transitioning from granular fertilizer applications to foliar fertilization will help maintain healthier turf during stress periods.

The ability to have consistent moisture conditions throughout the root zone will likely have a significant effect on these rooting parameters. These plots were sprayed with wetting agents monthly that are capable of maintaining more consistent moisture conditions in the upper layer of the root zone (Karnok and Tucker, 2001). The entire area was also core aerified in the spring and fall, which helps minimize the thatch layer and improves root production when conditions are favorable for root growth (Huang et al., 1998b; Kurtz and Kneebone, 1980). Cultivation practices are critical for maintaining a healthy root system before environmental stresses become prevalent. Foregoing these cultivation practices may lead to reduced regrowth of roots in fall and spring and increased stress during supraoptimal temperature conditions. Under these circumstances, reduced mowing heights combined with high traffic may have a greater affect on rooting parameters.

Rooting parameters are difficult to evaluate and generally require destructive sampling practices to obtain samples. Soil and organic matter must be removed from all material, and depending on soil type; this can be a challenging process. Most studies that evaluated roots have cited changes in dry mass when demonstrating root loss. Root dry mass reductions would be highly correlated with minimized rooting parameters, but it would remain unknown where those reductions actually took place. Cumulative root length and surface area measurements would likely be the most important parameters with regards to creeping bentgrass during summer months. The WinRhizo software can easily be used to evaluate these parameters, especially for evaluations being performed on sand-based rootzones.

Table 8. ANOVA table of rooting parameters evaluated at the May sampling date from 2010 to 2012.

	P-value for all interaction and main factors evaluated			
Effect	Root Length	Root Surface Area	Root Diameter	Dry Root Mass
Rep	0.2338	0.1925	0.5090	0.3954
Cultivar	0.2981	0.5392	0.3658	0.5981
Mow	0.0492	0.0234	0.4635	0.0375
Cultivar*Mow	0.8624	0.5872	0.2330	0.3386
Roll	0.2903	0.3576	0.5794	0.4191
Cultivar*Roll	0.5791	0.6240	0.4858	0.3287
Mow*Roll	0.1899	0.2338	0.4834	0.6342
Cultivar*Mow*Roll	0.9887	0.9413	0.5902	0.8301
Year	<0.0001	<0.0001	<0.0001	<0.0001
Cultivar*Year	0.0582	0.0272	0.0009	0.0905
Year*Mow	0.5487	0.5470	0.9446	0.3316
Cultivar*Year*Mow	0.0389	0.0385	0.4982	0.0913
Year*Roll	0.5547	0.8658	0.3517	0.9242
Cultivar*Year*Roll	0.8619	0.6127	0.6616	0.8501
Year*Mow*Roll	0.2228	0.1143	0.9304	0.4322
Cultivar*Year*Mow*Roll	0.5565	0.2998	0.8301	0.1765

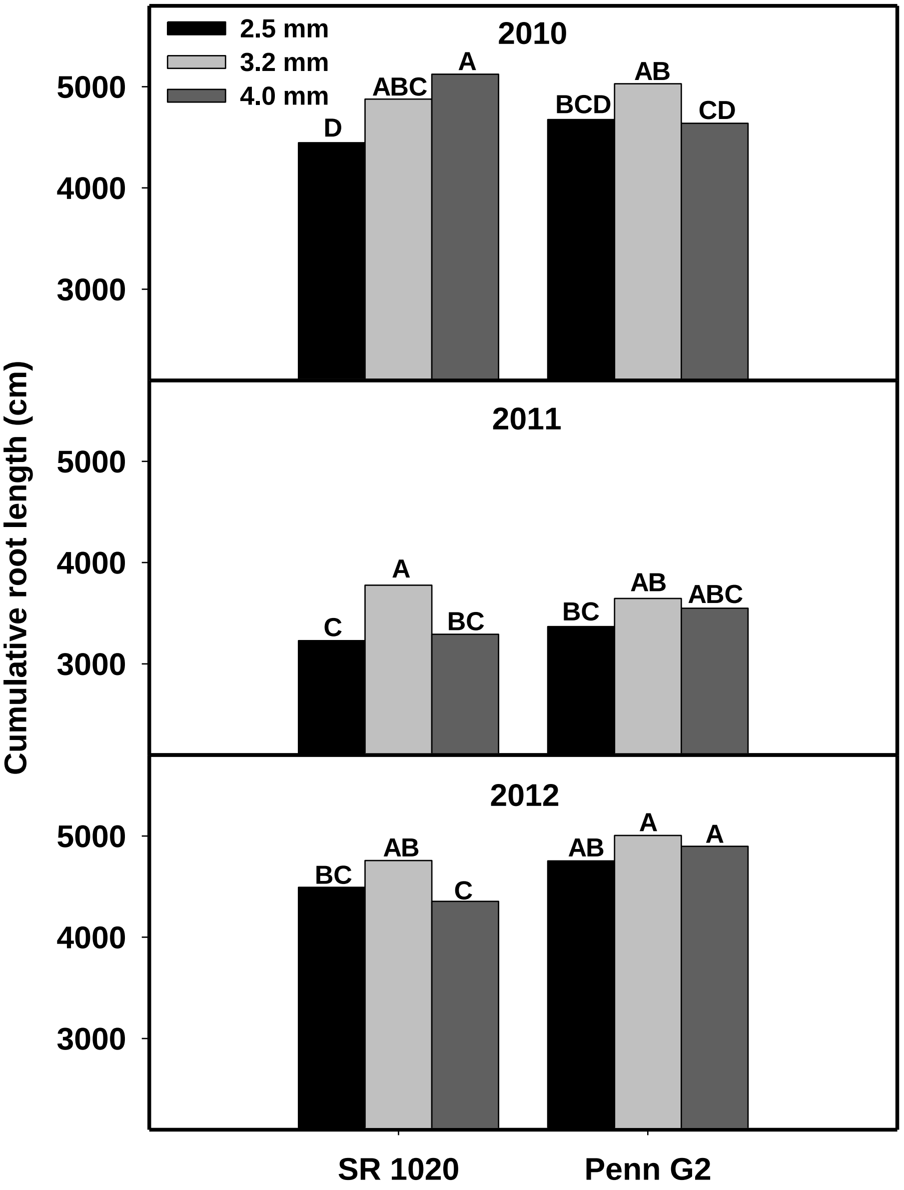

Figure 28. Cultivar by year by mowing height interaction for cumulative root length following the May root sample collection. Values are averaged over rolling treatments. Bars sharing the same letter within years are statistically similar at α = 0.1.

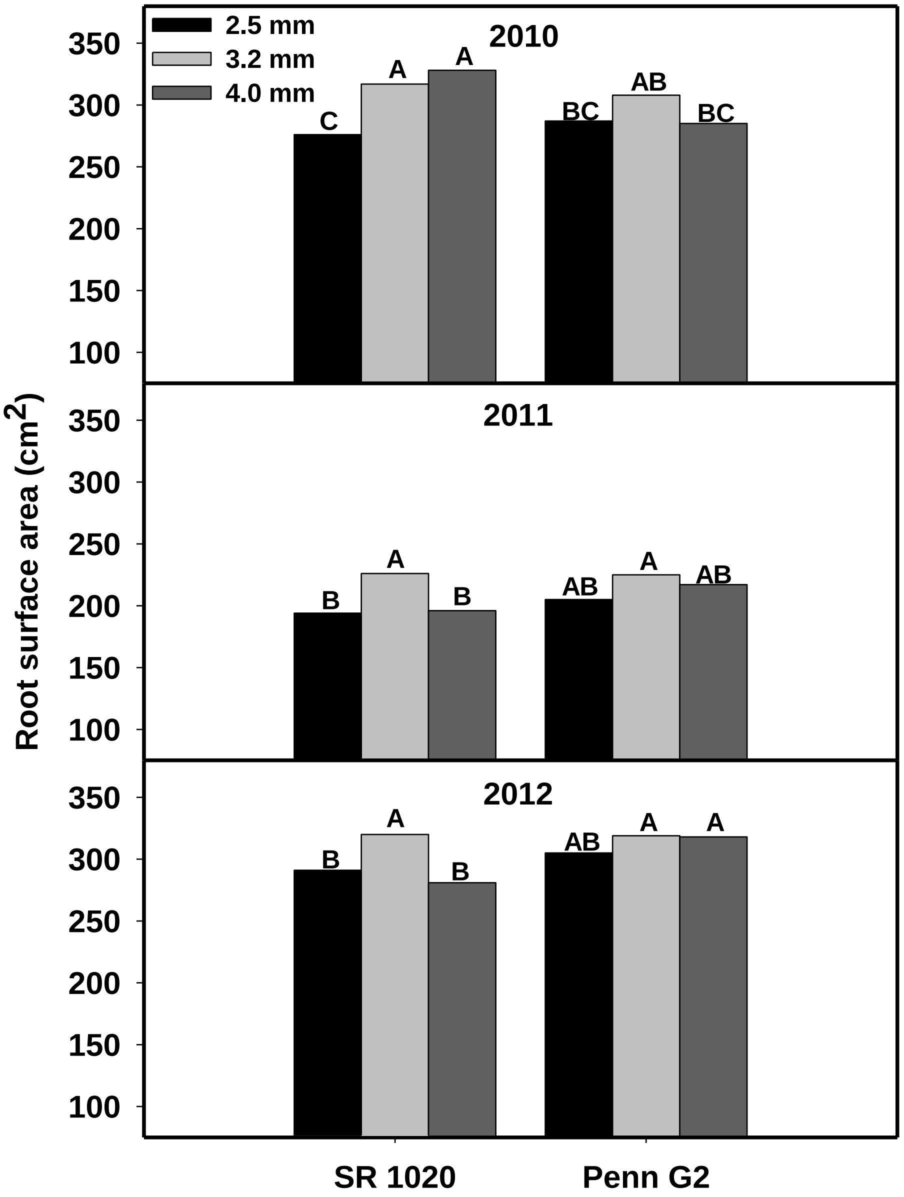

Figure 29. Cultivar by year by mowing height interaction for root surface area following the May root sample collection. Values are averaged over rolling treatments. Bars sharing the same letter within years are statistically similar at α = 0.1.

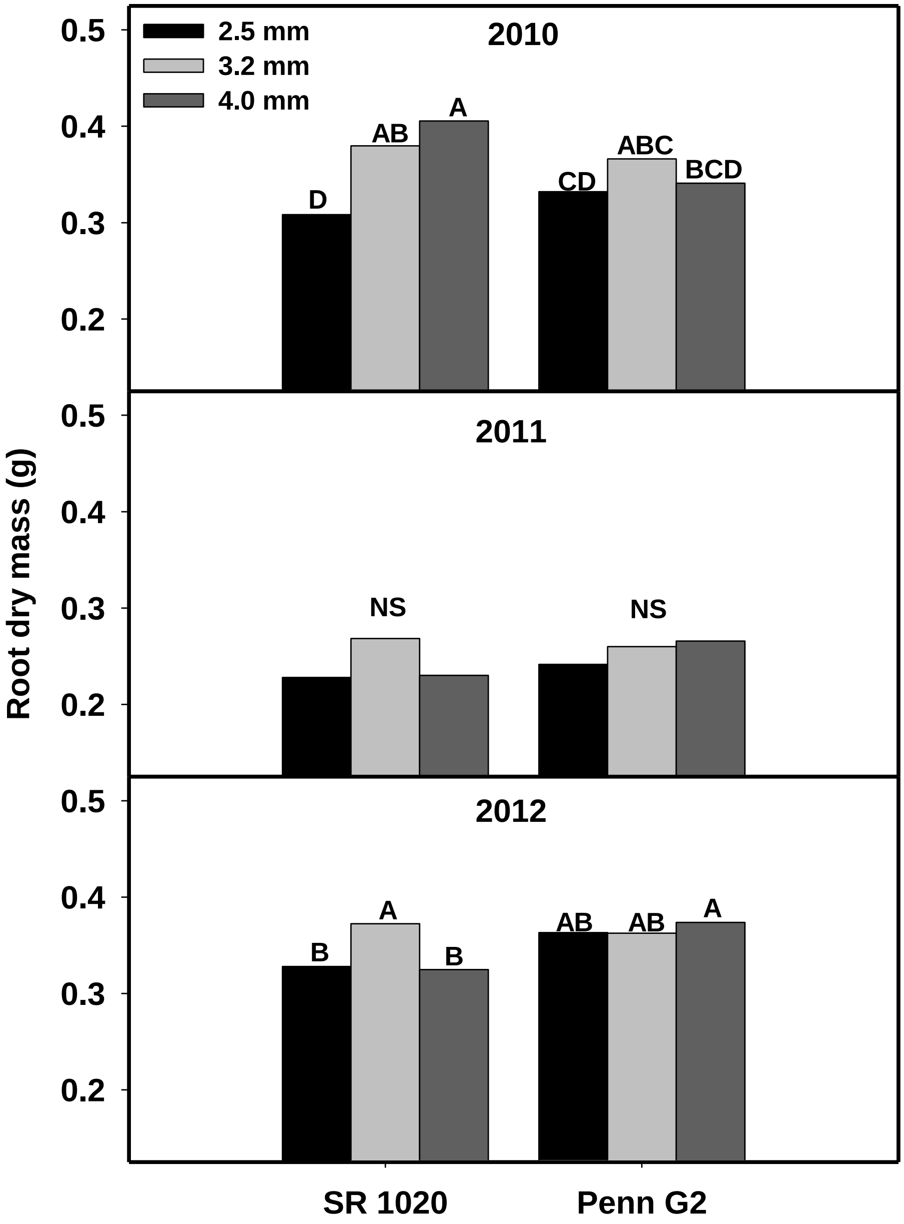

Figure 30. Cultivar by year by mowing height interaction for root dry mass following the May root sample collection. Values are averaged over rolling treatments. Bars sharing the same letter within years are statistically similar at $\alpha = 0.1$. (NS = Not significant)

Table 9. Cultivar by year interactions for all rooting parameters at the May sampling date of each year.

Cultivar	Year	Root Length	Root Surface Area	Average Root Diameter	Root Dry Mass
		-----cm---------	-----cm^2------	-----mm-----	----g----
SR 1020	2010	4816a[z]	307.0a	0.2037a	0.3646a
	2011	3433c	205.2c	0.1895c	0.2422b
	2012	4535b	297.6b	0.2080a	0.3417a
Penn G2	2010	4782a	293.7b	0.1958b	0.3464a
	2011	3521c	215.4c	0.1945b	0.2558b
	2012	4886a	314.4a	0.2043a	0.3665a

[z] Values sharing the same letter within cultivar and year are similar at $\alpha = 0.05$.

Table 10. ANOVA table of rooting parameters evaluated following the August sampling date from 2010 to 2012.

	P-value for all main factors and interactions evaluated			
Effect	Root Length	Root Surface Area	Root Diameter	Dry Root Mass
Rep	0.1239	0.1305	0.8335	0.2284
Cultivar	0.3365	0.5030	0.1561	0.6724
Mow	0.6430	0.6790	0.8419	0.9713
Cultivar*Mow	0.8646	0.8273	0.7873	0.4538
Roll	0.2001	0.1823	0.3170	0.2373
Cultivar*Roll	0.6360	0.6982	0.9219	0.2717
Mow*Roll	0.8973	0.8020	0.5944	0.2828
Cultivar*Mow*Roll	0.1698	0.2542	0.8593	0.2829
Foot	0.0012	0.0007	0.0014	0.0018
Cultivar*Foot	0.0079	0.0105	0.2828	0.3030
Mow*Foot	0.2351	0.2936	0.7210	0.1473
Cultivar*Mow*Foot	0.8735	0.8819	0.2739	0.5767
Roll*Foot	0.8168	0.4919	0.0569	0.2727
Cultivar*Roll*Foot	0.3488	0.3546	0.8249	0.9825
Mow*Roll*Foot	0.4706	0.5078	0.4923	0.8186
Cultivar*Mow*Roll*Foot	0.8393	0.7940	0.5550	0.7104
Year	<0.0001	<0.0001	<0.0001	<0.0001
Cultivar*Year	0.1194	0.3670	0.0236	0.9854
Year*Mow	0.0223	0.0253	0.0086	0.8497
Cultivar*Year*Mow	0.0828	0.0662	0.0211	0.3964
Year*Roll	0.2720	0.1549	0.1917	0.3842
Cultivar*Year*Roll	0.1068	0.0999	0.6080	0.4314
Year*Mow*Roll	0.1822	0.2427	0.7840	0.6798
Cultivar*Year*Mow*Roll	0.8794	0.7965	0.6366	0.7072
Year*Foot	0.0001	<0.0001	0.0352	0.0342
Cultivar*Year*Foot	0.5737	0.7032	0.6406	0.6635
Year*Mow*Foot	0.6416	0.6760	0.3038	0.4728
Cultivar*Year*Mow*Foot	0.6773	0.8429	0.7559	0.8681
Year*Roll*Foot	0.7393	0.6667	0.3621	0.9766
Cultivar*Year*Roll*Foot	0.3461	0.4941	0.7687	0.4045
Year*Mow*Roll*Foot	0.5323	0.6491	0.8489	0.6143
Cultivar*Year*Mow*Roll*Foot	0.2984	0.2816	0.1039	0.6984

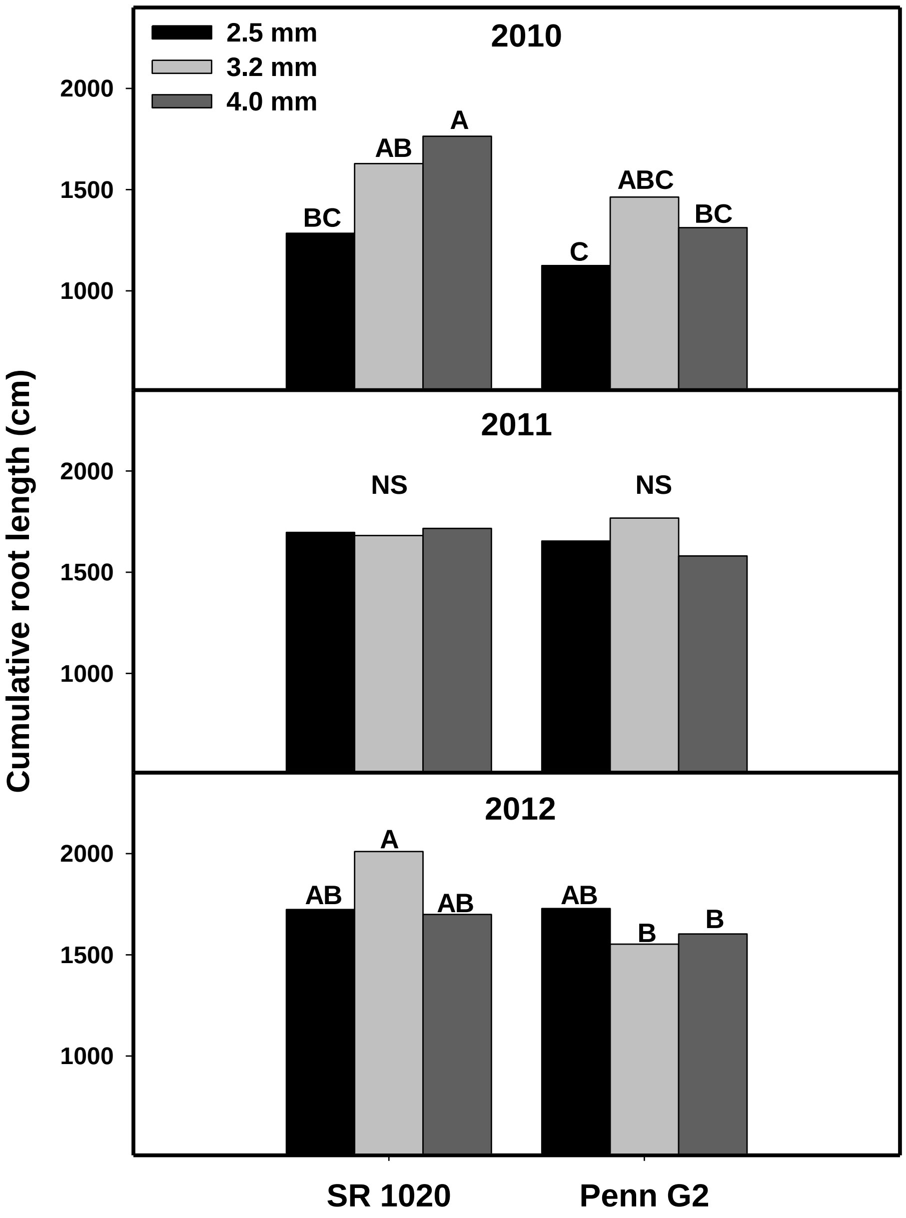

Figure 31. Cultivar by year by mowing height interaction for cumulative root length following the August root sample collection. Values are averaged over rolling and foot traffic treatments. Bars sharing the same letter within years are statistically similar at α = 0.1. (NS = not significant)

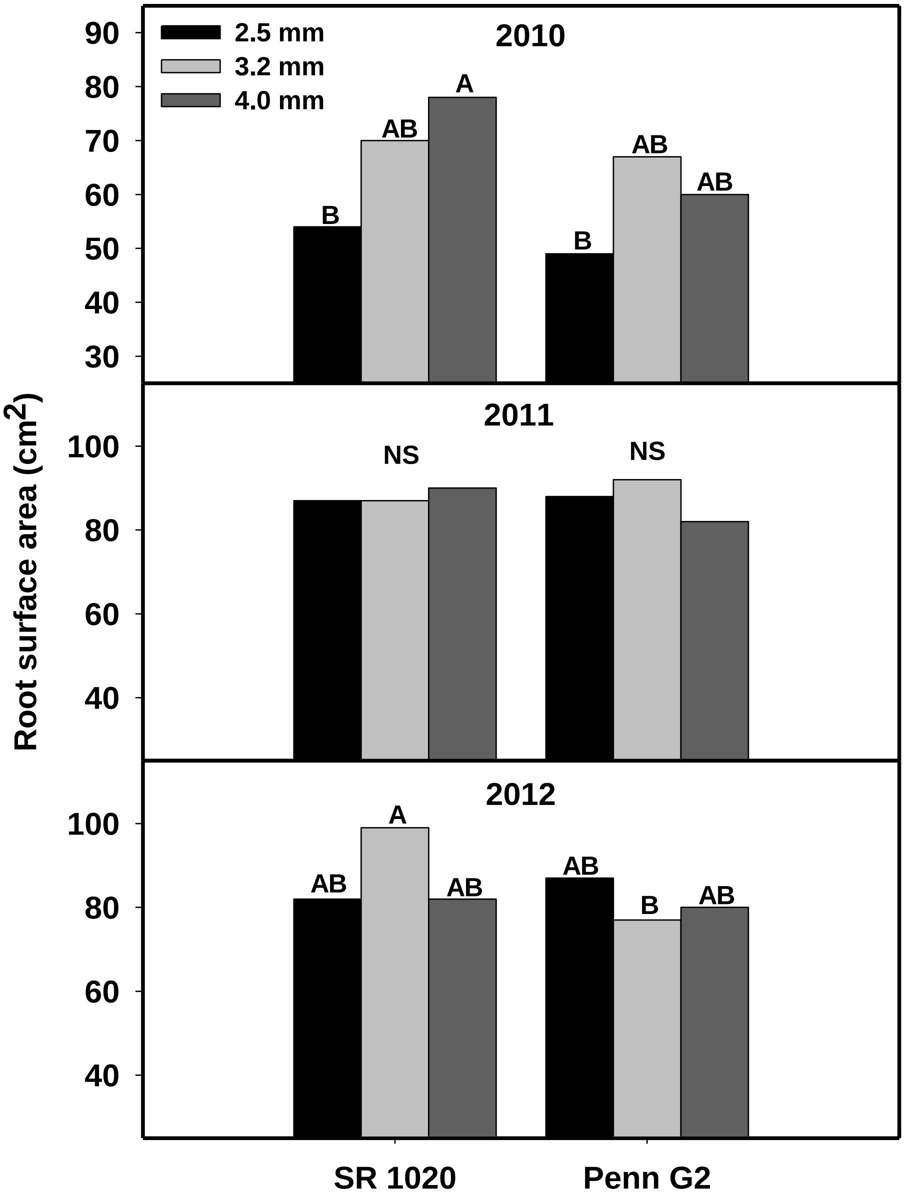

Figure 32. Cultivar by year by mowing height interaction for root surface area following the August root sample collection. Values are averaged over rolling and foot traffic treatments. Bars sharing the same letter within years are statistically similar at α = 0.1. (NS = not significant)

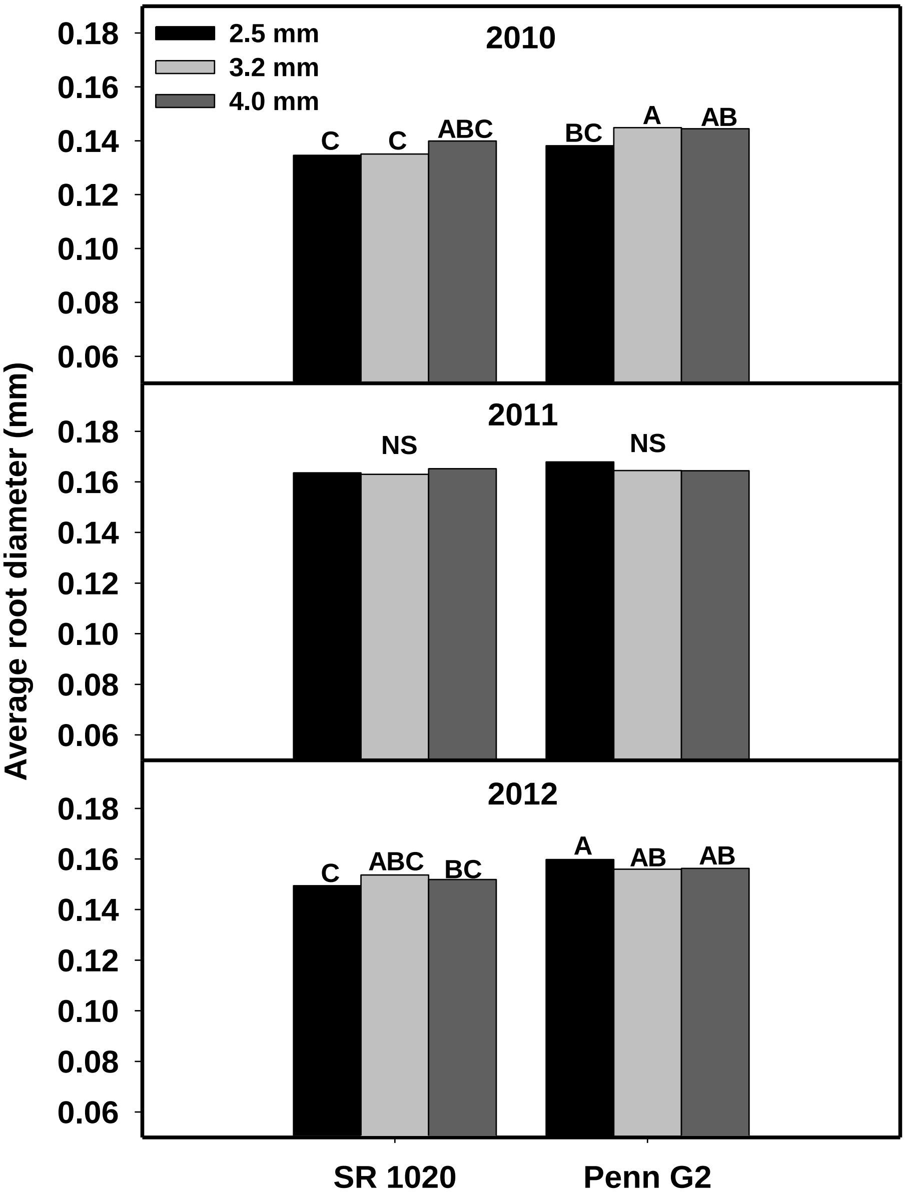

Figure 33. Cultivar by year by mowing height interaction for average root diameter following the August root sample collection. Values are averaged over rolling and foot traffic treatments. Bars sharing the same letter within years are statistically similar at α = 0.1. (NS = not significant)

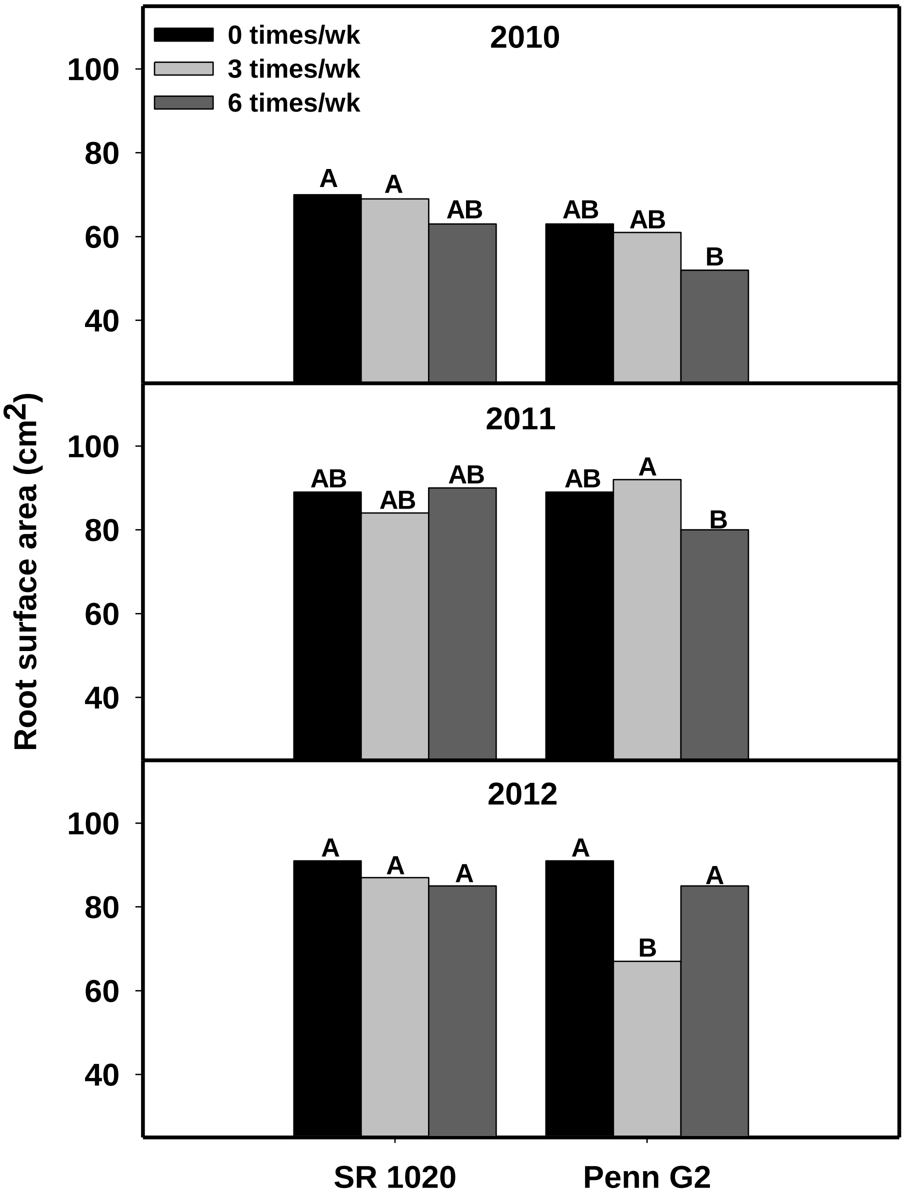

Figure 34. Cultivar by year by rolling frequency interaction for root surface area following the August root sample collection. Values are averaged over mowing and foot traffic treatments. Bars sharing the same letter within years are statistically similar at $\alpha = 0.1$.

Table 11. Sampling date by foot traffic interactions for cumulative root length, root surface area, average root diameter, and dry root mass following August sampling dates from 2010 to 2012.

Response Variable	Treatment	August 2010[w]	August 2011[x]	August 2012[y]
Cumulative Root Length (cm)	No Foot Traffic	1520a[z]	1639a	1918a
	Foot Traffic	1338b	1725a	1521b
Root Surface Area (cm^2)	No Foot Traffic	67.13a	85.49a	95.82a
	Foot Traffic	58.70b	89.59a	73.03b
Average Root Diameter (mm)	No Foot Traffic	0.140a	0.166a	0.157a
	Foot Traffic	0.139a	0.164a	0.152b
Dry Root Mass (g)	No Foot Traffic	0.074a	0.087a	0.082a
	Foot Traffic	0.057b	0.088a	0.059b

[w] Foot traffic was applied on 22 Jun, 7 Jul, 21 Jul, 11 Aug 2010 prior to collecting root samples.

[x] Foot traffic was applied on 9 Jun, 22, Jun, 7 Jul, 21 Jul, and 10 Aug 2011 prior to collecting root samples.

[y] Foot traffic was applied on 2 Jul, 9 Jul, 16 Jul, 23 Jul, 30 Jul, and 10 Aug 2012 prior to collecting root samples.

[z] Values sharing the same letter were statistically similar at $\alpha = 0.1$.

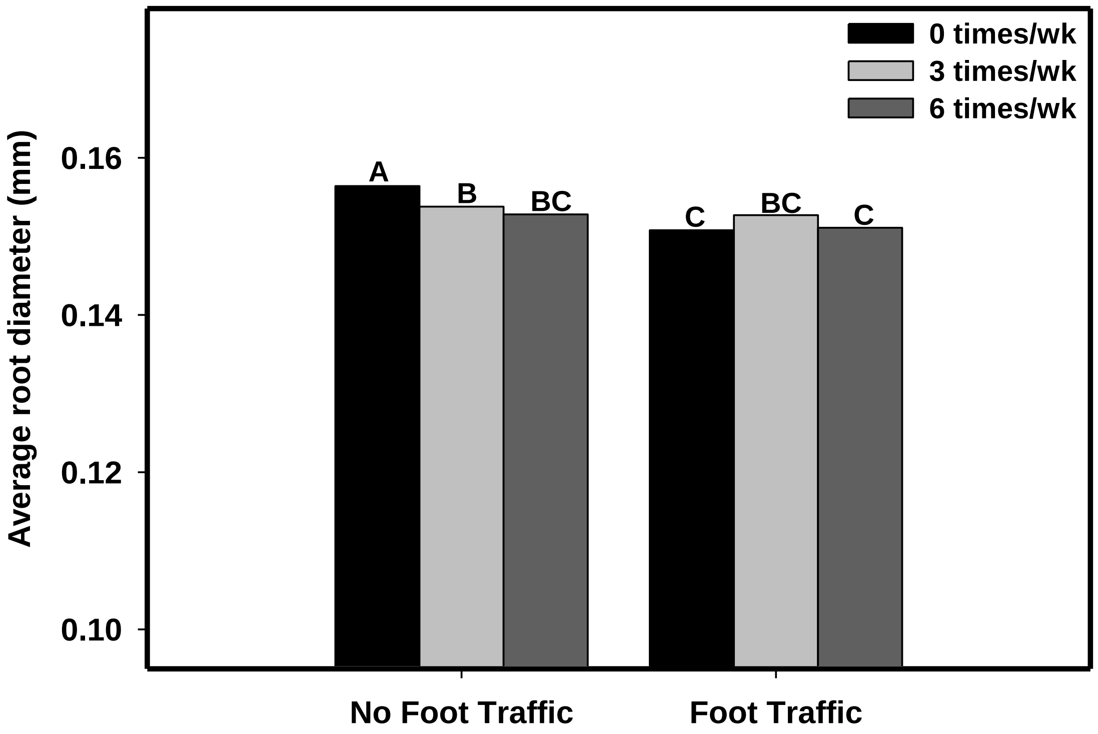

Figure 35. Rolling frequency by foot traffic interaction for average root diameter following the August root sample collection. Values are averaged over cultivars, mowing heights, and August sampling dates. Bars sharing the same letter are statistically similar at α = 0.1.

Photosynthetic measurements

Net photosynthetic rates progressed similarly for both cultivars throughout 2011 and 2012, regardless of management treatments. The only difference identified for SR 1020 in 2011 was for collection dates (Table 12). All the main factors interacted for Penn G2 in 2011 and both cultivars in 2012 to significantly affect net photosynthetic rates (Table 12). Although F-tests indicated significant differences under these conditions, few consistent trends were established.

Net photosynthetic rate decreased as temperatures increased throughout the summer in 2011 when pooling treatment combinations for SR 1020 and Penn G2 (Table 13). Both SR 1020 and Penn G2 reached the lowest net photosynthetic rates on 26 August 2011. SR 1020 treatments did not differ statistically on 17 Jun and 19 Jul, but a significant decrease in net photosynthetic rate was observed on Penn G2 between 17 Jun and 19 Jul 2011 (Table 13). In addition to the significant differences among dates for Penn G2, there was a significant interaction among mowing height, rolling frequency, and foot traffic when combining data for each date (Table 12). Overall, combining these data demonstrate the similarity of net photosynthetic rates at all mowing heights and rolling frequencies with or without foot traffic (Fig. 36). Few consistent trends could be derived from this data, but there were some significant differences. Penn G2 mowed at 3.2 mm exhibited a positive response to increased rolling frequencies when excluding foot traffic treatments. Each increase in rolling frequency increased net photosynthetic rate with non-rolled and daily rolled treatments being significantly different (Fig. 36). The lack of consistency and high variability was verified by the significant increase in net photosynthesis of non-rolled Penn G2 at 3.2 mm with foot traffic treatments (Fig. 36). Lastly, when applying foot traffic without rolling, treatments maintained at 3.2 mm exhibited significantly greater net photosynthetic rates than those mowed at 2.5 mm. These data demonstrate the possible benefits of managing the higher density creeping bentgrass cultivars, like Penn G2, at moderate mowing heights (3.2 mm) during summer heat stress to maximize photosynthetic rates.

Similar to 2011, photosynthetic rates of both cultivars were reduced later in the summer of 2012 once heat stress was prominent (Table 13). Mowing, rolling, and foot traffic treatments interacted on 25 Jul to significantly affect net photosynthesis rates of SR 1020 (Table 12). Net photosynthetic rates increased slightly as mowing heights increased for treatments receiving foot traffic, but none of the treatment combinations differed statistically (Fig. 37). In contrast to Penn G2 in 2011, both rolling treatments on SR 1020 mowed at 3.2 mm with no foot traffic caused significant reductions in net photosynthetic rate. Net photosynthetic rate was also reduced significantly in treatments maintained at 4.0 mm and rolled three days per week without foot traffic. When rolling treatments were applied three days per week without foot traffic, there was an inverse relationship among mowing heights and net photosynthesis with significant differences between the lowest and highest mowing heights (Fig. 37).

When combining data from 30 Jun and 26 July 2012, Penn G2 net photosynthetic rates exhibited a significant interaction among mowing height, rolling frequency, and foot traffic treatments (Table 12). Similar to SR 1020, net photosynthetic rates of treatments receiving foot traffic and rolling appeared to increase as mowing heights were increased (Fig. 38). When rolling treatments were applied either three or six days per week combined with foot traffic, treatments mowed at 4.0 mm had significantly greater net photosynthetic rates than those mowed at 2.5 mm. However, non-rolled treatments maintained similar net photosynthetic rates at all mowing heights when foot traffic was applied (Fig. 38). Non-trafficked treatments that were rolled three or six times per week maintained similar net photosynthetic rates at all three mowing heights. However, each increase in mowing height without rolling or foot traffic resulted in a significant increase in net photosynthetic rate (Fig. 38). Lastly, foot traffic treatments significantly reduced net photosynthetic rate when Penn G2 was mowed at 2.5 mm and rolled three days per week (Fig. 38).

Few consistent differences were observed through these net photosynthetic measurements, but significant reductions in net photosynthetic rate were observed as heat stress became more prominent later in the summer. These data follow trends that have been established with reduced photosynthetic rates of cool-season grasses experiencing heat stress (Huang et al., 1998a; Huang and Gao, 2000; Liu and Huang, 2001; Xu and Huang, 2000). Previous studies have also established reduced net photosynthetic rates as mowing heights are lowered (Krans and Beard, 1985; Liu and Huang, 2003), but the current data did not consistently establish significant differences among the mowing heights evaluated in this study. Previous studies suggested that the reduction in leaf area caused photosynthetic rates to decrease. However, the 1.5 mm increase in mowing height from the lowest to highest mowing height rarely caused a significant increase in net photosynthesis with the exception being Penn G2 plots in 2012 (Fig. 38). The heat stress that was prominent later in the summers of 2011 and 2012 appeared to affect these two cultivars similarly, regardless of the mowing height. Both of the cultivars evaluated in the current study were improved type cultivars, which may have facilitated the similar responses at all mowing heights. Previous studies that included older creeping bentgrass cultivars, such as Penncross or Crenshaw, were capable of distinguishing differences among cultivars when grown in controlled environments or under field conditions (Huang et al., 1998a; Liu and Huang, 2001). Although few significant differences in net photosynthetic rate were observed with increased mowing heights in 2011, rates for both SR 1020 and Penn G2 appeared to increase as mowing heights increased in 2012, especially on treatments receiving foot traffic.

Turf managers often increase mowing heights during environmental stresses to increase leaf area, photosynthesis, and overall turf health during the stress. Liu and Huang (2003) documented increased net photosynthetic rates at higher mowing heights and suggested this was a result of maintaining higher density at the higher mowing height. Although turf coverage decreased significantly in July 2011 and August 2012 when mowing heights were lowered and rolling frequencies increased (Young, 2013), net photosynthetic rates were not increased at higher mowing heights. The cultivars utilized in the two studies differed, which could explain the contrasting results. During the initial measurements in June, turf density and coverage remained high for all mowing heights and treatment combinations. The higher mowing heights did not have higher photosynthetic rates at that point, which may have been a result of shading older leaves. Although more leaf area should be present at the higher mowing height, similar amounts of leaves may be receiving light and photosynthesizing. Previous studies have removed leaf material from a known area and determined leaf area index using a leaf area meter; however, the minimal amount of leaf material and high density of putting green turf makes this measurement nearly impossible. Leaf area measurements would be highly beneficial to correlate with photosynthetic rates if methods could be developed to more easily measure leaf area index of putting green turf. As temperatures continued to increase and the effects of traffic became more prominent, the higher mown turf was able to maintain numerically higher photosynthetic rates, but the differences were rarely statistically significant. Similarly, Liu and Huang (2001) mention turfgrass color as an important attribute to photosynthetic rate. Statistically significant differences in turfgrass color were observed in the current study in 2011 and 2012 (Young, 2013), but these differences in color did not translate to significant differences in photosynthetic rate. Leaf area and color do play critical roles in determining photosynthetic rates of plants, but under the conditions these plots were maintained, neither were capable of distinguishing treatments on a consistent basis.

The majority of photosynthetic data for creeping bentgrass cultivars have been obtained from controlled environment studies (Huang et al., 1998a; Huang and Gao, 2000; Xu and Huang, 2000), but a few others have collected data from the field (Fu and Dernoeden, 2009a; Liu and Huang, 2001; Liu and Huang, 2003). To date, this is the first study to evaluate photosynthetic rates of creeping bentgrass putting greens in field conditions experiencing light-weight rolling and foot traffic. Few consistent differences were observed with rolling treatments, but combining lower mowing heights and light-weight rolling caused a significant reduction in net photosynthetic rate of Penn G2 in 2012. Although many factors evaluated in this study demonstrated negative effects of increased rolling frequencies, many previous rolling studies have not observed any negative effects of rolling three or six times per week (Hartwiger et al., 2001; Nikolai, 2005; Richards, 2010). These photosynthesis data appear to follow a similar trend with little effects observed with increased rolling, which indicates that statistically significant decreases in wear tolerance, turf quality, coverage, and color did not significantly alter photosynthetic rates. Similarly, foot traffic rarely reduced net photosynthetic rate significantly. However, foot traffic treatments were never applied in close proximity to collecting photosynthetic data. The extended period of time that passed likely allowed foot traffic plots to overcome wear injury and minimize the separation of treatments.

Lewis (2010) constructed a custom photosynthetic chamber similar to the one used in the current study. Initial evaluations were conducted with the custom chamber on a mix of tall fescue (*Festuca arundinacea* Schreb.) and perennial ryegrass (*Lolium perenne* L.) and data were compared to an eddy covariance tower to determine the accuracy of the custom chamber. Between 1145 and 1245 hours, there was a significant increase in carbon dioxide flux that peaked at 1215 hours (Lewis, 2010). These data indicate the inherent variation that is possible when collecting data, even when measurements were recorded between 1100 and 1400 hours when photosynthetic rates should not be in an exponential growth or lag stage. Measurements in the current study required approximately 45 min to complete data collection on a single replication. The lack of significant differences among the treatment combinations may have been a result of this inherent variability of conducting these measurements over even a short period of time.

Based on the data obtained from this research, golf course managers may realize a slight increase in photosynthetic rates by increasing mowing heights. However, the increases in photosynthetic rate were rarely significant among the mowing heights tested in this study.

Table 12. ANOVA table of net photosynthesis rates for each cultivar from 2011 and 2012.

	P-values for all main factors and interactions evaluated			
	SR 1020		Penn G2	
Effect	2011	2012	2011	2012
Rep	0.3020	0.5573	0.9131	0.9727
Mow	0.4662	0.8098	0.8730	0.4385
Roll	0.5746	0.5888	0.6345	0.4711
Mow*Roll	0.3507	0.4862	0.1738	0.3504
Foot	0.8290	0.5149	0.0971	0.0957
Mow*Foot	0.8468	0.4077	0.7175	0.6407
Roll*Foot	0.6851	0.9403	0.1471	0.1243
Mow*Roll*Foot	0.6225	0.1324	0.0358	0.0318
Date	<0.0001[w]	0.0004[x]	<0.0001[y]	<0.0001[z]
Date*Mow	0.5316	0.8811	0.8963	0.5352
Date*Roll	0.2095	0.2836	0.9775	0.0630
Date*Mow*Roll	0.9725	0.1602	0.3398	0.1495
Date*Foot	0.5189	0.8981	0.1151	0.0712
Date*Mow*Foot	0.5772	0.7162	0.6491	0.0596
Date*Roll*Foot	0.7152	0.3493	0.6830	0.3836
Date*Mow*Roll*Foot	0.0885	0.0474	0.1068	0.3880

[w] Data collected on 17 Jun, 19 Jul, and 26 Aug 2011

[x] Data collected on 30 Jun and 25 Jul 2012

[y] Data collected on 1 Jul, 19 Jul, and 26 Aug 2011

[z] Data collected on 30 Jun and 26 Jul 2012

Table 13. Significant differences in net photosynthetic rates of SR 1020 and Penn G2 plots for collection dates in 2011 and 2012.

Cultivar	Year	Date[x]	Net photosynthetic rate[y]
			----- µmol m^{-2} s^{-1}--------
SR 1020	2011	17 June	15.55a[z]
		19 July	15.29a
		26 August	7.99b
	2012	30 June	16.29a
		25 July	12.83b
Penn G2	2011	1 July	16.75a
		19 July	15.79a
		26 August	7.05b
	2012	30 June	19.10a
		26 July	12.33b

[x] Date photosynthetic measurements were obtained for all plots of this cultivar

[y] Net photosynthesis = carbon dioxide flux from full sun lit chamber minus completely dark chamber (canopy and soil respiration)

[z] Values sharing the same letter within both cultivar and year are statistically similar at $\alpha = 0.05$.

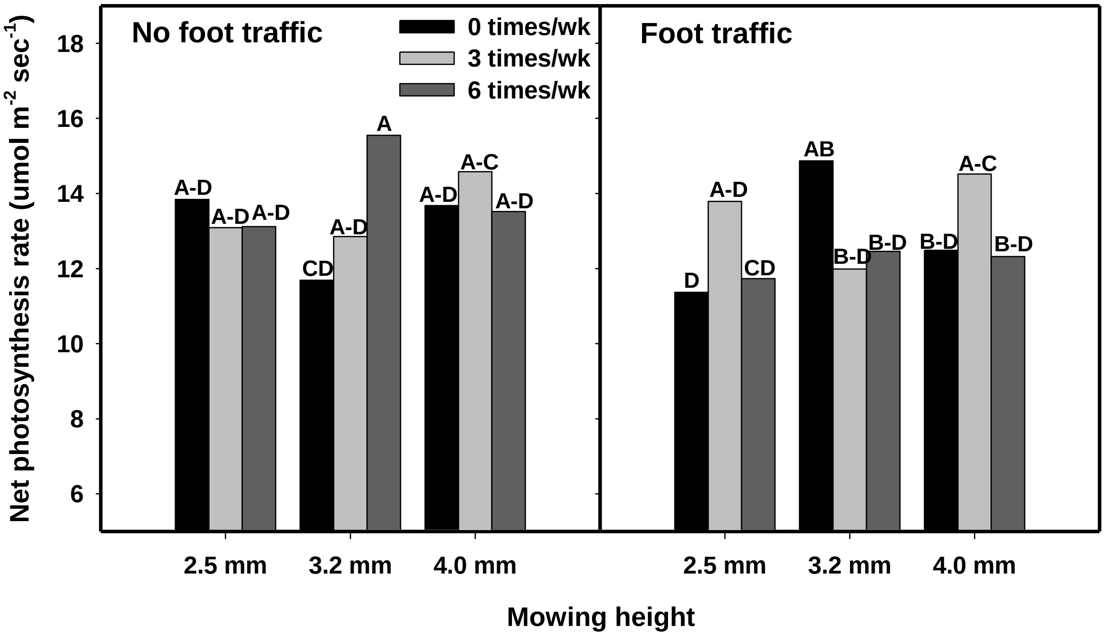

Figure 36. Mowing height by rolling frequency by foot traffic interaction for net photosynthetic rate of Penn G2 in 2011. Photosynthetic measurements from the three collection dates were combined. Bars sharing the same letter within either graph are statistically similar at α = 0.05.

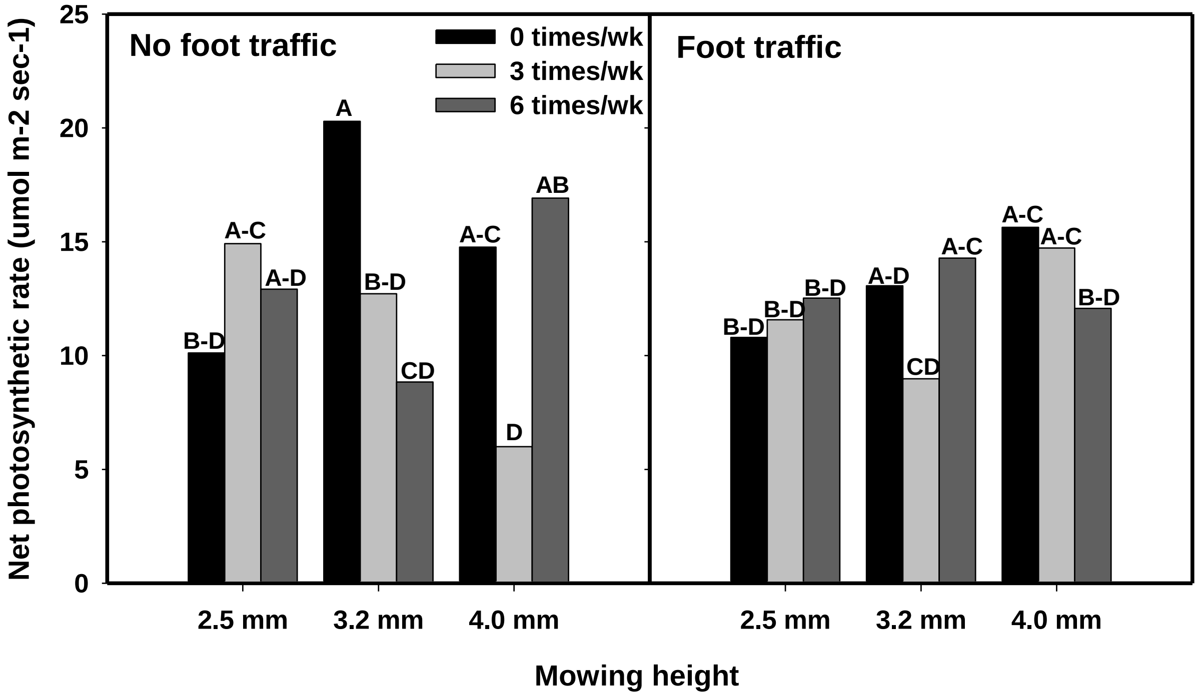

Figure 37. Mowing height by rolling frequency by foot traffic interaction for SR 1020 plots on 25 Jul 2012. Bars sharing the same letter within either graph are statistically similar at α = 0.05.

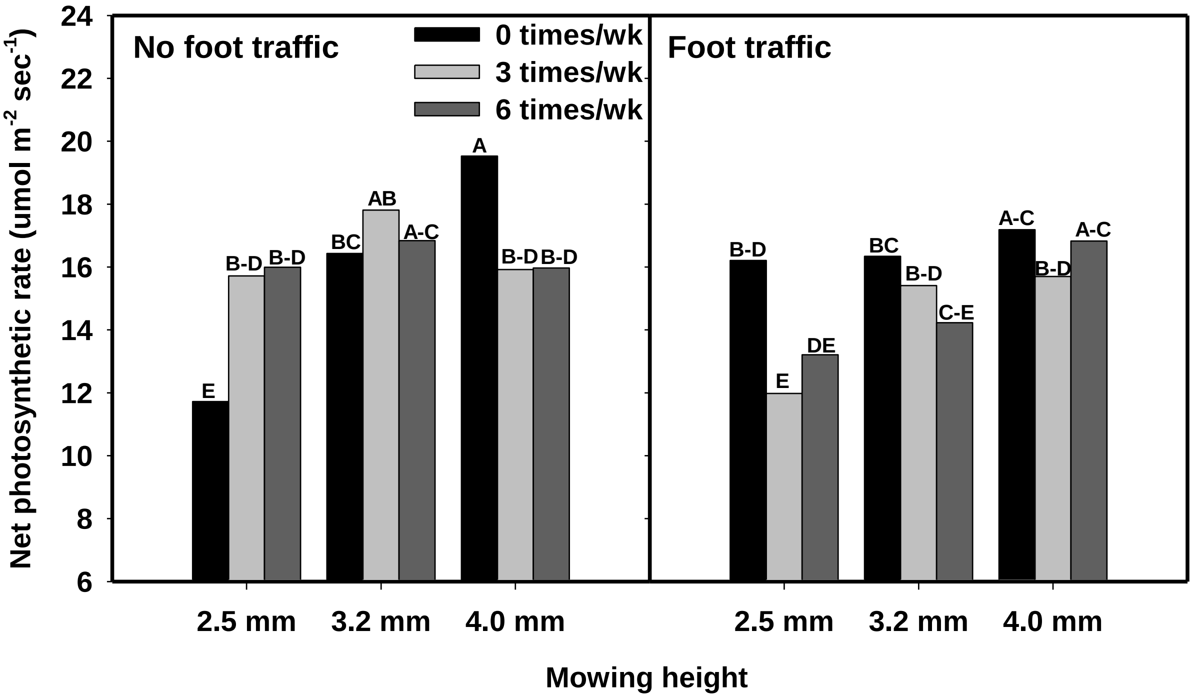

Figure 38. Mowing height by rolling frequency by foot traffic interactions for Penn G2 plots in 2012. Photosynthetic measurements from the two collection dates were combined. Bars sharing the same letter within either graph are statistically similar at α = 0.05.

Carbohydrate analysis

The main factor treatments applied did not result in significant differences with respect to total ethanol soluble sugars in 2011 or 2012. As expected, total ethanol soluble sugar levels were significantly different for cultivars, tissues, and sampling dates in both years (Table 14). On the initial sampling date in June 2011, SR 1020 foliage and crown material had significantly greater total ethanol soluble sugars than root material, but no differences were observed for Penn G2 (Fig. 39). Crown material of SR 1020 and Penn G2 exhibited significant reductions in total ethanol soluble sugars from June to August. In contrast, SR 1020 roots had a significant increase in total ethanol soluble sugars, while Penn G2 roots decreased from June to August (Fig. 39). Total ethanol soluble sugars remained similar from June to August in foliage of both cultivars. Foliage from SR 1020 and Penn G2 maintained significantly higher ethanol soluble sugar levels than crowns and roots at the August sampling in 2011 (Fig. 39). All tissues demonstrated significant increases in total ethanol soluble sugars from August to October for both cultivars. Foliage, crowns, and roots of Penn G2 had significantly different ethanol soluble sugar levels; whereas, SR 1020 crown and root material were similar with foliage having significantly greater sugar levels (Fig. 39).

Significant differences in cultivars, tissues, and sampling dates were also observed in 2012, but only lower order interactions were statistically significant (Table 14). There was a significant interaction between cultivars and tissues when sampling dates, mowing heights, and rolling frequencies were pooled (Table 15). SR 1020 foliage and crown material maintained increased total ethanol soluble sugars compared to roots similar to 2011. All tissues were significantly different for Penn G2 with the greatest amount of total ethanol soluble sugars in foliage and least in root material. A second significant interaction was detected for tissue and sampling date when averaging cultivars, mowing heights, and rolling frequencies (Table 14). Root material contained the lowest total ethanol soluble sugars and maintained similar concentrations on every sampling date (Table 16). Foliage material possessed the greatest sugar levels on the initial sampling date. Total ethanol soluble sugars in foliage were reduced significantly from June to July; whereas, crown material retained statistically similar sugar levels. Once environmental stresses were reduced in September, foliage regained a greater amount of total ethanol soluble sugars than crown material (Table 16).

Significant differences in glucose concentrations were observed for an interaction involving cultivars, sampling dates, and mowing heights in 2011 (Table 14). Glucose concentrations at all mowing heights remained similar from June to August for SR 1020 and Penn G2, but glucose concentrations increased significantly for both cultivars maintained at all mowing heights in October (Fig. 40). The October sampling date for SR 1020 was the only date where significant differences among mowing heights were identified. The lowest mowing height resulted in significantly greater glucose than the higher mowing heights; whereas, SR 1020 mowed at 3.2 mm had the lowest glucose concentration (Fig. 40). Penn G2 at all mowing heights had similar glucose levels on each sampling date.

In 2011 and 2012, glucose concentrations resulted in a significant interaction among cultivars, tissues, and sampling dates (Table 14). Glucose in crowns of SR 1020 and Penn G2 was extremely low in 2011, but glucose steadily increased the remainder of the year. All tissues for both cultivars had similar glucose concentrations in August, but glucose content in foliage increased much higher than other tissue types in October (Fig. 41). Significant differences in glucose concentration were observed on all sampling dates in 2012 with the exception of Penn G2 in July (Fig. 42). SR 1020 foliage, crown, and root material were significantly different on each sampling date. Similar to total ethanol soluble sugars, foliage contained highest glucose levels initially, but crown material was highest during heat stress of July (Fig. 42). Interestingly, SR 1020 root material retained similar glucose concentrations on every sampling date, never experiencing the rebound generally observed in the fall. Penn G2 glucose concentration followed similar patterns with a significant reduction in foliage from June to July before recovering to significantly highest levels in September. Both crown and root material experienced significant changes throughout the season, but these changes were not as pronounced as seen in foliage material (Fig. 42).

Similar to previous sugar data discussed, there was a significant interaction among cultivar, tissue, and sampling date for sucrose in 2011 (Table 14). Crown material had the greatest sucrose concentration in June for both cultivars (Fig. 43). SR 1020 crown material lost a significant amount of sucrose from June to August, whereas, foliage material exhibited a significant increase in sucrose. These results suggest possible translocation of sucrose from crown material to foliage and roots during higher stress time periods. Sucrose levels of all three tissues increased significantly in October. Foliage samples maintained significantly greater sucrose in October compared to crown and root material of SR 1020 (Fig. 43). Foliage, roots, and crown material of Penn G2 were all reduced to similar sucrose concentrations in August. Penn G2 foliage and crown material gained significant sucrose levels following more conducive weather. All three tissues were significantly different with foliage regaining the largest quantity of sucrose and root material the least (Fig. 43).

Both mowing and rolling treatments interacted with other factors to affect sucrose concentrations in 2011 (Table 14). There was a significant interaction with cultivar, sampling date, and mowing height. Penn G2 never displayed significant differences on individual sampling dates for any mowing height, but there was a significant reduction at the most stressful portion of the summer followed by a subsequent rebound in October to similar sucrose concentrations observed in June (Fig. 44). In contrast, SR 1020 maintained similar sucrose levels from June to August 2011 at all mowing heights. SR 1020 mowed at 4.0 mm had a significantly lower sucrose concentration than treatments mowed at 2.5 mm in June, but all mowing heights were statistically similar at the August sampling date. Sucrose concentrations at the two higher mowing heights increased significantly from August to October, while treatments maintained at 2.5 mm remained similar (Fig. 44).

There was also a significant interaction among cultivars, tissues, and rolling frequencies for sucrose concentrations in 2011 (Table 14). This was the only sugar that exhibited any significant variation with rolling treatments either year. Rolling frequencies only significantly affected sucrose concentrations in foliage of SR 1020 and Penn G2 (Fig. 45). SR 1020 rolled daily demonstrated a significant reduction when averaged over all three sampling dates and mowing heights, but Penn G2 rolled three times per week had significantly less sucrose than non-rolled or daily rolled treatments (Fig. 45). These differences in foliage sucrose concentration seem logical because the roller was in direct contact with foliage while crown and root material would be protected by the thatch layer and soil.

There was a significant higher order interaction among cultivars, sampling dates, tissues, and mowing heights when evaluating sucrose concentration in 2012 (Table 14). Similar to 2011 results, roots of SR 1020 and Penn G2 maintained minimal sucrose levels throughout 2012 (Fig. 46). The progression of sucrose concentrations of SR 1020 crowns from June to September were in contrast to 2011 results, but the reduction in sucrose levels from July to September may have been caused by the drought and heat stress previously discussed for turf quality and coverage data (Young, 2013). Sucrose concentrations of crown material from SR 1020 mowed at 2.5 mm was reduced significantly while higher mown treatments were not reduced to this magnitude (Fig. 46). Penn G2 was not affected as significantly by drought and heat stress and was able to maintain a similar trend to 2011. Sucrose concentrations of Penn G2 crowns did not increase significantly from July to September, but obtaining samples earlier in the fall may have caused this reduction in recovery. The fact that Penn G2 maintained at the two lower mowing heights demonstrated significantly increased sucrose concentrations compared to treatments mowed at 4.0 mm was not expected. Foliage of both cultivars followed a similar pattern as observed in 2011 (Fig. 46). SR 1020 foliage from treatments mowed at 3.2 had the highest sucrose level compared to the other two mowing heights in June. Sucrose concentrations in foliage of SR 1020 at all mowing heights were reduced significantly at the July sampling date, but all mowing heights recovered significantly in September. In comparison, Penn G2 foliage from 4.0 mm treatments had the greatest sucrose concentration at the June sampling date, but sucrose was depleted in July to a level significantly less than the 2.5 mm mowing height (Fig. 46). All mowing heights regained significant sucrose concentrations in September and were all statistically similar.

The variation in sucrose concentrations between foliage and crown material from July to September in SR 1020 may have occurred due to sampling methodology. The two random samples obtained for crown material only encompassed 23 cm^2 of the sub-sub plot; whereas, foliage samples were collected from the entire sub-sub plot. Because the crown and root samples were randomly collected using a numbered grid, some of the samples collected in September were completely necrotic from drought and heat stress.

Similar to the ethanol soluble sugars, there was a significant interaction among cultivars, sampling dates, and tissues for fructans in 2011 (Table 17). SR 1020 exhibited significant differences in fructan concentrations among tissues on each sampling date (Fig. 47). On the initial sampling date in June, fructan levels were significantly different for each tissue type with crowns having the greatest concentration and roots least. Foliage and root material maintained similar fructan concentrations from June to August, while fructans from crowns declined significantly in August (Fig. 47). Even at these low levels, SR 1020 crown and foliage tissue were able to maintain significantly greater fructans than root material. Fructans increased significantly for all tissues at the October sampling date, but fructan concentrations in foliage increased to the greatest level, while roots still maintained the lowest concentration. Penn G2 followed similar trends as SR 1020 throughout 2011. Crown material had significantly greater fructan levels than foliage and root material in June (Fig. 47). In contrast to SR 1020, Penn G2 foliage exhibited a significant increase in fructans at the August sampling date to a level significantly greater than crown and root material. Each tissue had significantly increased fructan levels in October, separating tissues in the same order observed for SR 1020 (Fig. 47).

There was also a significant interaction for tissue, sampling date, and mowing height with respect to fructan concentrations in 2011 when combining cultivars and rolling treatments (Table 17). There were no differences among mowing heights when evaluating fructan concentrations from foliage on any sampling date. However, fructans were increased significantly in foliage from August to October (Fig. 48). The foliage maintained significantly higher fructans at all mowing heights compared to other tissues on the final sampling date. Fructans from crown material exhibited a significant reduction from June to August followed by a significant increase into the fall sampling date. Crown material from treatments maintained at 2.5 mm had the greatest fructan level compared to the higher mowing heights on the initial sampling date (Fig. 48). All mowing heights were similar after the reductions in August, but treatments maintained at 4.0 mm had significantly greater fructans than those mowed at 2.5 mm in October. There were no significant differences in fructan levels for root material observed on any sampling date at the mowing heights evaluated (Fig. 48). Fructan concentrations remained similar from June to August, but were increased significantly in October. Although fructan levels were increased from August to October, fructans were still lowest in root material compared to other tissues.

Fructan concentrations exhibited a significant higher order interaction in 2012 for cultivars, tissues, sampling dates, and mowing heights when averaging these factors over rolling frequencies (Table 17). The trends observed in 2012 were in opposition to those discussed for 2011. Fructans in foliage and crown material of both cultivars at all mowing heights were reduced significantly in July, but crown material did not increase in September following more favorable environmental conditions (Fig. 49). Foliage from SR 1020 at 3.2 mm had significantly more fructans than treatments mowed at 4.0 mm in June. Following more conducive environmental conditions, the higher mowing heights exhibited greater fructans than SR 1020 at 2.5 mm (Fig. 49). Penn G2 foliage from the 4.0 mm mowing height had significantly higher fructans than the two lower mowing heights in June, but the different mowing heights never effected fructan concentrations on other sampling dates (Fig. 49). Crown material from SR 1020 mowed at 4.0 mm contained significantly greater fructans than lower mowing heights; however, Penn G2 at the two lower mowing heights had significantly more fructans than the 4.0 mm mowing height in June (Fig. 49). No other significant differences were observed in either cultivar for crown material at all mowing heights. Root material of both cultivars maintained numerically lower fructan levels than other tissues on each sampling date in 2012. There were no significant differences observed for fructan levels of roots at any mowing height throughout 2012; however, roots of Penn G2 mowed at 3.2 mm had a significant reduction in fructan level from June to July (Fig. 49).

In both 2011 and 2012, there was a significant interaction among cultivars, tissues, and sampling dates for average degree of polymerization (DP) fraction when pooling data for mowing heights and rolling frequencies (Table 17). Significant differences were observed for each tissue on each rating date for SR 1020 with regards to average DP fraction. In June and August 2011, crowns maintained the highest average DP fraction, while foliage had the lowest average DP fraction. Once environmental stresses eased, SR 1020 foliage had significantly higher average DP fractions than crown and root material (Fig. 50). Average DP fraction of crown material from Penn G2 was significantly greater than foliage and root material in June and remained numerically higher than foliage and root material throughout 2011 (Fig. 50). Crown material maintained significantly higher average DP fraction than foliage in August and roots in October. Average DP fraction for Penn G2 foliage and roots followed an inverse relationship when examining levels over sampling dates in 2011, but never differed significantly (Fig. 50). In June 2012, significant differences in average DP fraction for each tissue were observed for both cultivars (Fig. 51), but average DP fractions progressed differently for the remainder of the summer. Crown material maintained significantly higher average DP fraction in July for SR 1020, but a significant decline in September reached levels similar to root material. Average DP fractions for SR 1020 foliage and root material changed inversely throughout the remainder of the summer with foliage having the lowest average DP fraction in September (Fig. 51). The progression of Penn G2 crown and root material was similar throughout 2012, but crowns maintained significantly higher average DP fraction than roots on all sampling dates (Fig. 51).

Average DP fraction of foliage increased significantly to a level similar to crown material in July; then declined significantly in September to levels statistically similar to the initial sampling date (Fig. 51).

The overall results from this study demonstrate the high variation in performing carbohydrate analysis similar to previous evaluations (Howieson and Christians, 2008; Narra et al., 2004; Sweeney et al., 2001). Although variation within samples was present, there was high consistency when comparing carbohydrate levels for the two cultivars on the same rating date. These consistencies allow for determining trends associated with carbohydrate levels in different tissues under intensive putting green management practices. All the carbohydrates evaluated followed trends previously described with the lowest concentrations being observed in July or August when creeping bentgrass was experiencing higher environmental stress (Fu and Dernoeden, 2009a; Fu and Dernoeden, 2008; Huang and Gao, 2000; Narra et al., 2004; Xu and Huang, 2000; Xu and Huang, 2003). As temperatures increase above 30°C in the summer, respiration rates in the plant exceed photosynthetic rates diminishing carbohydrates within creeping bentgrass (Fry and Huang, 2004). The majority of carbohydrates increased significantly once temperatures became more favorable for growth, regardless of the treatments applied.

In addition to the environmental stresses magnifying these carbohydrate reductions, golf course putting greens also undergo mechanical stress from mowing and rolling practices. A comprehensive study was performed in a controlled environment to determine the effect of these management practices on individual carbohydrates (Howieson and Christians, 2008). Glucose and fructan concentrations were decreased with mowing, but rolling never significantly affected either carbohydrate. Sucrose and fructose levels were never altered with any of the treatments applied. The combination of these mechanical and environmental stresses in this field trial likely increased the overall physiological stress that created significant differences in glucose, sucrose, and fructans under these intensive management practices. Significant differences in all three of these sugars were observed at different mowing heights, but the results did not consistently follow the hypothesis of the study. Although differences were observed for mowing heights on individual sampling dates, few consistent differences were observed to clearly indicate that carbohydrate reserves are depleted more at extremely low mowing heights for either cultivar.

This is the first study to demonstrate a reduction in carbohydrates with light-weight rolling. Sucrose concentrations in foliage of SR 1020 and Penn G2 were the only response variable that was significantly affected by rolling treatments. SR 1020 exhibited significantly less sucrose with daily rolling in 2011, which may be indicative of increased wear stress with daily rolling that inhibited sucrose production in foliage. However, Penn G2 sucrose levels were significantly reduced in 2011 when rolling was applied three times per week. It is unclear why this minimal rolling frequency would result in decreased sucrose levels, but this may be compromised by the variation observed with the carbohydrate analysis.

Most of the carbohydrate data previously reported have described variation in total nonstructural carbohydrates (TNC) (Pollock and Jones, 1979; Rong et al., 1996; Xu and Huang, 2003) or water soluble/storage carbohydrates (Fu and Dernoeden, 2009a; Fu and Dernoeden, 2008). These evaluations are capable of demonstrating the general trends and changes in carbohydrate levels under environmental and mechanical stresses, but the individual carbohydrates each play pivotal roles in the physiological health of the plant. The concentration of these carbohydrates regulates the production of polysaccharides or degradation of storage sugars into monosaccharides (Hull, 1992; Ritsema and Smeekens, 2003; Fry and Huang, 2004).

In addition to the regulation process, the carbohydrate concentrations present in different portions of the plant could indicate translocation of sugars from sources to sinks and determine the strength of the sinks during summer stress and recovery periods.

Root material generally contained the lowest levels of each sugar throughout the year, but foliage and crown material differed in concentrations throughout the summer. The fact that root material maintained low concentrations of each carbohydrate contrasts previous work that demonstrated significant increases in carbohydrates from roots with different aerification timings (Fu and Dernoeden, 2009a). In 2011, crown material of both cultivars had significantly higher sucrose and fructans than foliage or root material in June, but increased temperatures raised respiration rates proportionately causing the degradation of larger sugars to sustain plant health. Once conditions became favorable for growth again, all the sugars were increased with foliage comprising the largest quantity of each in October. Data from 2012 followed a similar trend, but the replenishment of carbohydrates in crown material was not observed. Due to time constraints, the final sampling date occurred in early September, so foliage material exhibited the sharp increase similar to 2011, but carbohydrate production rate may not have reached the point where sugars would be transported to sinks for storage in preparation for fall. Youngner et al. (1978) suggested that cooler temperatures were required to enable the plant to begin building up storage carbohydrates, which could provide reasoning for the lack of carbohydrate levels in crowns in 2012.

Similarly, average DP fraction demonstrates the relative physiological health or stress experienced by creeping bentgrass. As photosynthetic rates rise and remain above respiration rates, creeping bentgrass is capable of forming longer chained fructans. Results from this study determined that the largest DP fractions were located in the crowns of creeping bentgrass. These larger DP fructans are used when the energy budget of the plant falls below production level to maintain plant health. Smaller DP fructans could be used for the same purpose, but these would sustain the plant for a shorter time period under stress conditions. The reduction in average DP fraction for both cultivars in this study indicates that increased temperature stress results in the degradation of large DP fructans. In addition, increased respiration rates limit the plants ability to add fructose molecules to these polysaccharides forming larger average DP fractions.

Based on the data collected at this site, the intensive management practices evaluated in this study did not have a significant effect on carbohydrate concentrations of SR 1020 or Penn G2 creeping bentgrass. The variation in mowing heights had the greatest affect on carbohydrate levels, but few consistent differences were observed on sampling dates to suggest mowing heights had a significant effect on carbohydrate concentrations. Increased rolling frequency had little effect on carbohydrate concentrations as well, similar to previous research in a controlled environment (Howieson and Christians, 2008). Many studies have demonstrated reductions in carbohydrates with continual defoliation (Howieson and Christians, 2008; Yamamoto and Mino, 1982), which is performed consistently on putting green turf to maintain a high quality putting surface. All plots were mowed 6 days per week, regardless of mowing height, which should create similar reductions at each cutting for all mowing heights. It is also well established that increased temperatures will decrease carbohydrate levels (Huang and Gao, 2000; Xu and Huang, 2000). Based on this data, these reductions from high temperature were consistent at all mowing heights, which were not expected when the study was initiated. Golf course superintendents cannot control these environmental conditions, so turf managers need to maximize the carbohydrate levels as high as possible during the spring when conditions are favorable for creeping bentgrass growth prior to summer heat stress.

Although few significant differences in carbohydrates were observed throughout this study, turf quality and coverage were reduced at the lowest mowing height with daily rolling. Golf course superintendents should remain cognizant of annual carbohydrate cycles when determining best management practices for putting greens, but visual quality and performance are the only parameters that concern golfers. The mowing and rolling treatments incorporated in this study are important aspects of putting green management, but these practices are not the only management decisions that will affect carbohydrate levels. Maintaining adequate nutrient supply (Westhafer et al., 1982), cultivation practices (Fu and Dernoeden, 2009a), and irrigation management (Fu and Dernoeden, 2008) can have a significant effect on carbohydrate levels of creeping bentgrass putting greens. All of these factors were applied evenly over the entire study area in the current study to ensure these management practices did not affect carbohydrate concentrations.

The two cultivars used in this evaluation were chosen because they were available and located in close proximity to one another at our research facility when initiating the study. Penn G2 was beneficial because it is a higher density cultivar that is more adapted to lower mowing heights (Fraser, 1998). In contrast, SR 1020 was released in the late 1980's from the University of Arizona and was considered a standard, improved cultivar (Samples and Sorochan, 2007). Previous studies have demonstrated differences between these two cultivars when comparing shoot density, turf quality, longest root length, and root dry mass under hot, humid conditions as well as conducive environmental conditions (Sifers et al., 2001). Sweeney et al. (2001) observed very few significant differences when evaluating total nonstructural carbohydrate levels of high density creeping bentgrass cultivars and standard cultivars, but we felt that Penn G2 would be more capable of withstanding lower mowing heights leading to increased carbohydrate production. Unfortunately, the treatments were not able to be separated with either of the cultivars used in this study. If an older cultivar, like Penncross, with reduced heat tolerance had been exposed to these intensive management practices, we may have been able to demonstrate negative effects on carbohydrate concentrations from the treatments. However, many golf courses throughout the transition zone or southeast have one of the higher density bentgrasses that would perform similar to Penn G2.

This study was conducted on a putting green in an open space with no inhibition of air movement, effects of shade, and maintained adequate soil moisture. Each year carbohydrate analysis was performed; environmental conditions consisted of hot, dry weather patterns (Figs. 4 and 5). Creeping bentgrass seems to experience greater stress under humid conditions because transpiration rates are decreased, minimizing the plants ability to cool itself (Bell, 2011). The treatment factors evaluated in the current study may have been separated to a greater extent if the hot, dry weather pattern was not persistent in 2011 or 2012. Golf course putting greens also receive high levels of foot traffic from golfers. Carbohydrate analysis was not performed on the foot traffic treatments in this study due to time constraints to complete sampling and carbohydrate analysis of various tissues. Sangwook et al. (2004) demonstrated significant reductions of TNC under high frequency, simulated traffic on creeping bentgrass maintained as a golf course fairway. The authors stated that increased traffic resulted in greater compaction of the native soil that possibly caused reductions in TNC (Sangwook et al., 2004). If this was solely a compaction effect, traffic may not have significantly affected carbohydrate levels, but this is a major source of stress on putting greens that should be evaluated in future research.

Table 14. ANOVA table of carbohydrate analysis for total ethanol soluble sugars, glucose, and sucrose in 2011 and 2012.

	P-value for all main factors and interactions evaluated					
	Total Ethanol Sugars		Glucose		Sucrose	
Effect	2011	2012	2011	2012	2011	2012
Rep	0.5882	0.7067	0.7926	0.8372	0.7063	0.9482
Cultivar	0.3629	0.0584	0.5325	0.1697	0.5640	0.7852
Tissue	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Cultivar*Tissue	0.0114	0.0006	0.2986	<0.0001	<0.0001	0.7407
Mow	0.9543	0.2771	0.3106	0.2393	0.3916	0.9438
Cultivar*Mow	0.7482	0.3847	0.1133	0.5368	0.4851	0.6247
Tissue*Mow	0.3605	0.3893	0.2251	0.5294	0.2282	0.9905
Cultivar*Tissue*Mow	0.1924	0.0812	0.1993	0.6342	0.2978	<0.0001
Roll	0.6245	0.7473	0.3853	0.9117	0.6736	0.2339
Cultivar*Roll	0.4534	0.4313	0.7533	0.4953	0.6313	0.9861
Tissue*Roll	0.6961	0.9116	0.2993	0.9799	0.9700	0.7679
Cultivar*Tissue*Roll	0.6377	0.8665	0.4251	0.3428	0.0319	0.9755
Mow*Roll	0.9979	0.9650	0.7635	0.9727	0.2925	0.6075
Cultivar*Mow*Roll	0.7274	0.3725	0.4078	0.4331	0.6794	0.9173
Tissue*Mow*Roll	0.4798	0.9383	0.3692	0.7959	0.2690	0.8732
Culti*Tissue*Mow*Roll	0.7159	0.6014	0.6675	0.5746	0.9258	0.9792
Date	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Cultivar*Date	0.7513	0.0946	0.3745	<0.0001	0.0002	0.2830
Tissue*Date	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Cultivar*Tissue*Date	<0.0001	0.5934	0.0098	0.0026	<0.0001	0.0003
Date*Mow	0.4240	0.0716	0.3815	0.9321	0.1085	0.2005
Cultivar*Date*Mow	0.4731	0.4405	0.0493	0.1908	0.0310	0.0496
Tissue*Date*Mow	0.2673	0.6304	0.5509	0.9348	0.9686	0.3046
Culti*Tissue*Date*Mow	0.9228	0.3543	0.1730	0.4381	0.0521	0.0104
Date*Roll	0.9679	0.6034	0.8781	0.6644	0.3009	0.2619
Cultivar*Date*Roll	0.9183	0.6517	0.9297	0.9168	0.7999	0.9121
Tissue*Date*Roll	0.9484	0.3383	0.4084	0.3683	0.6007	0.2127
Culti*Tissue*Date*Roll	0.5639	0.5058	0.6788	0.8708	0.8659	0.9160
Date*Mow*Roll	0.9856	0.3968	0.9974	0.2932	0.7293	0.8632
Culti*Date*Mow*Roll	0.8283	0.4574	0.9197	0.8081	0.1314	0.6658
Tissue*Date*Mow*Roll	0.9839	0.5634	0.9969	0.6670	0.9885	0.9642
Cult*Tis*Date*Mow*Roll	0.9393	0.4421	0.9416	0.5178	0.8973	0.7158

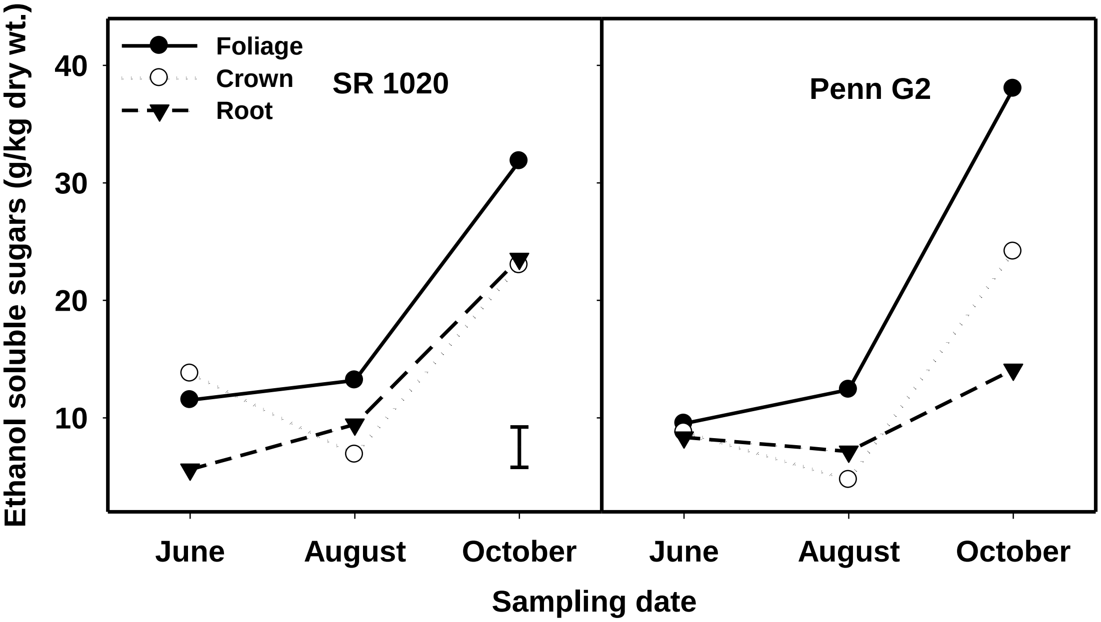

Figure 39. Cultivar by tissue by sampling date interaction for total ethanol soluble sugars in 2011. Values were averaged over mowing heights and rolling frequencies. Error bar represents LSD (α = 0.05) for the cultivar by tissue by sampling date interaction for all data points.

Table 15. Cultivar by tissue interaction for total ethanol soluble sugar concentrations averaged over sampling dates, mowing heights, and rolling frequencies in 2012.

Cultivar	Tissue	Ethanol soluble sugar concentration[y]
		---g/kg dry weight---
SR 1020	Foliage	30.9a[z]
	Crown	28.5a
	Root	7.7c
Penn G2	Foliage	28.7a
	Crown	21.9b
	Root	7.8c

[y] Ethanol soluble sugars include: glucose, fructose, sucrose, and low degree of polymerization fructans

[z] Values sharing the same letter are similar at $\alpha = 0.05$.

Table 16. Sampling date by tissue interaction for total ethanol soluble sugar concentrations averaged over cultivars, mowing heights, and rolling frequencies in 2012.

Sampling date	Tissue	Ethanol soluble sugar concentration[y]
		---g/kg dry weight---
June	Foliage	31.0b[z]
	Crown	23.8c
	Root	7.2e
July	Foliage	14.4d
	Crown	20.8c
	Root	7.6e
September	Foliage	44.1a
	Crown	31.1b
	Root	8.5e

[y] Ethanol soluble sugars include: glucose, fructose, sucrose, and low degree of polymerization fructans

[z] Values sharing the same letter are similar at α = 0.05.

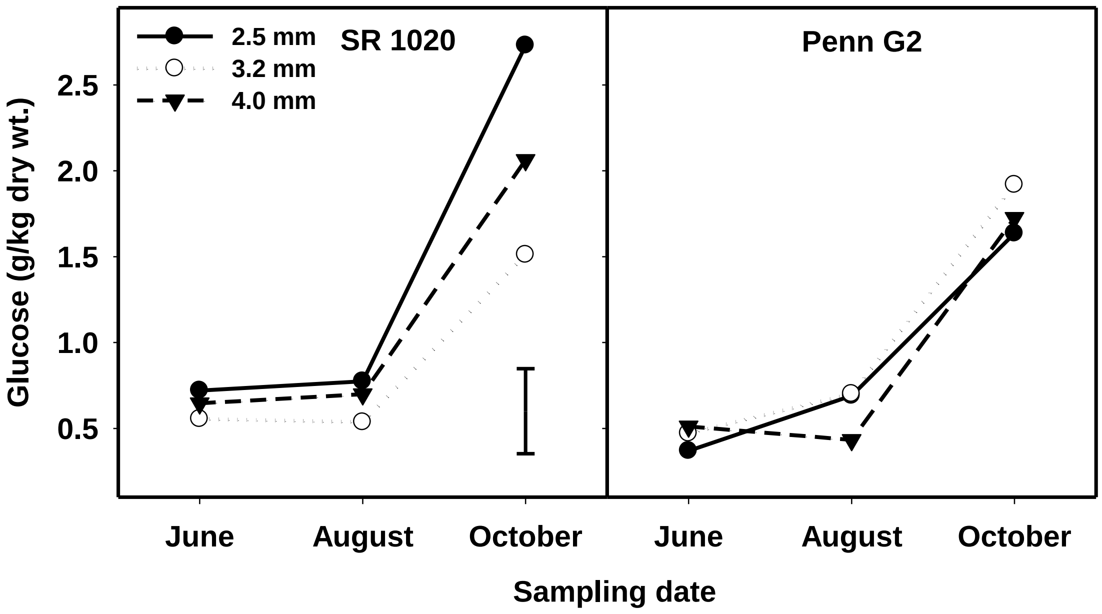

Figure 40. Cultivar by sampling date by mowing height interaction for glucose in 2011. Values are averaged over tissues and rolling frequencies. Error bar represents LSD (α = 0.05) for the cultivar by sampling date by mowing height interaction for all data points.

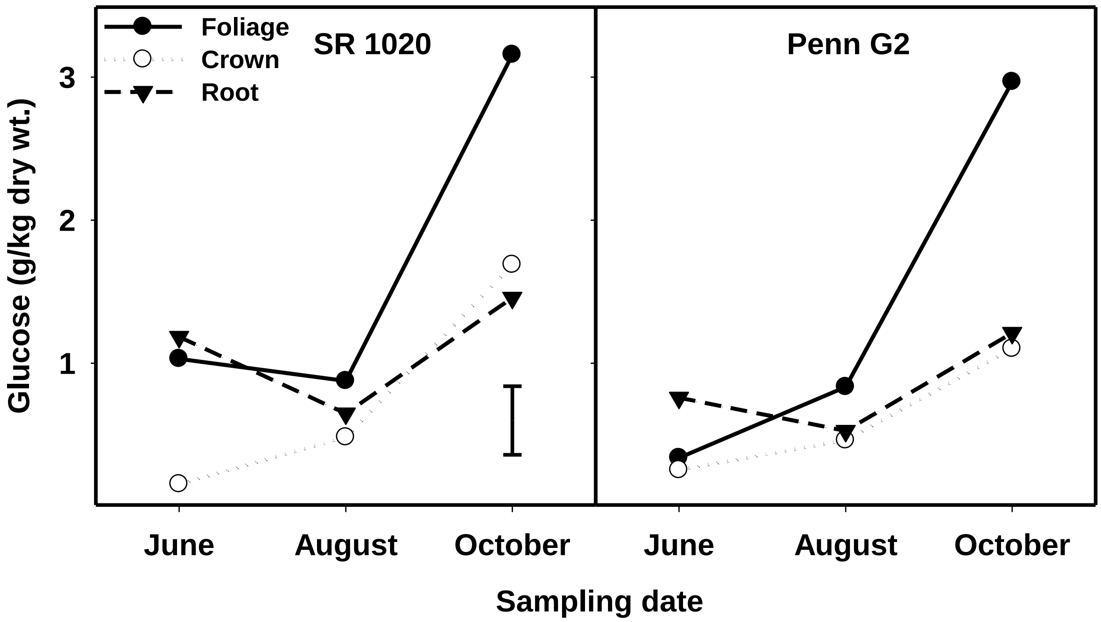

Figure 41. Cultivar by tissue by sampling date interaction for glucose in 2011. Values are averaged over mowing heights and rolling frequencies. Error bar represents LSD (α = 0.05) for the cultivar by tissue by sampling date interaction for all data points.

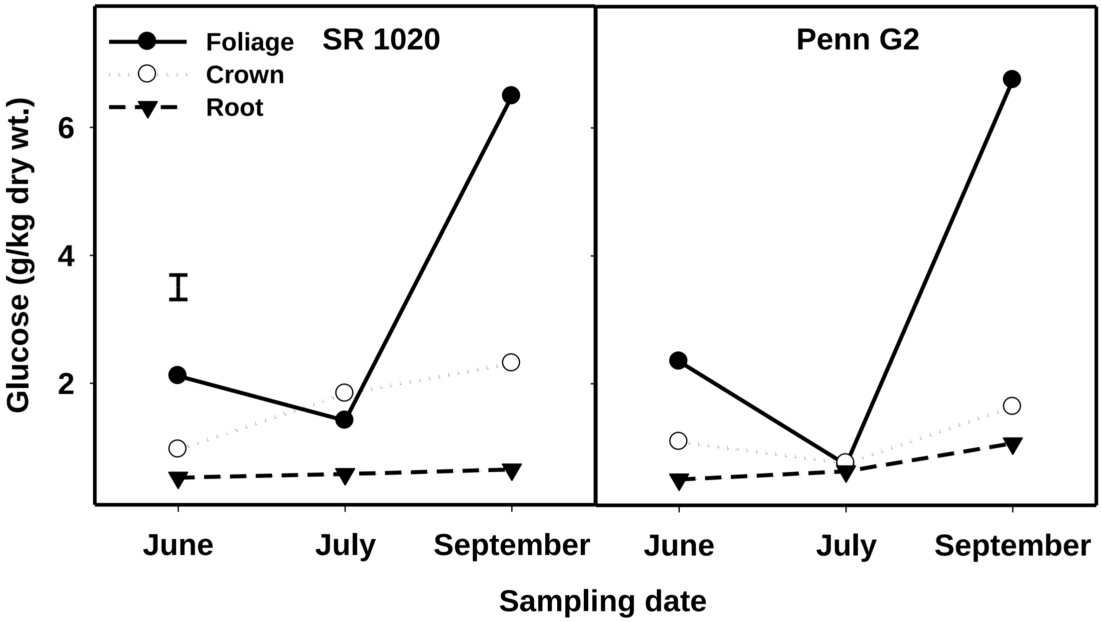

Figure 42. Cultivar by tissue by sampling date interaction for glucose in 2012. Values are averaged over mowing heights and rolling frequencies. Error bar represents LSD (α = 0.05) for the cultivar by tissue by sampling date interaction for all data points.

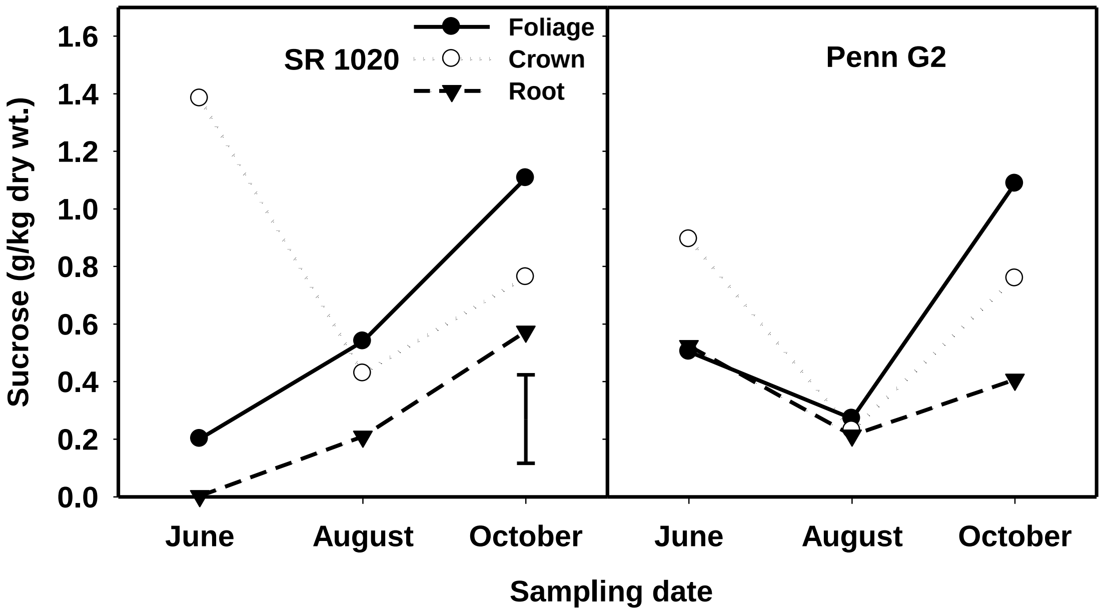

Figure 43. Cultivar by tissue by sampling date interaction for sucrose in 2011. Values are averaged over mowing heights and rolling frequencies. Error bar represents LSD (α = 0.05) for the cultivar by tissue by sampling date interaction for all data points.

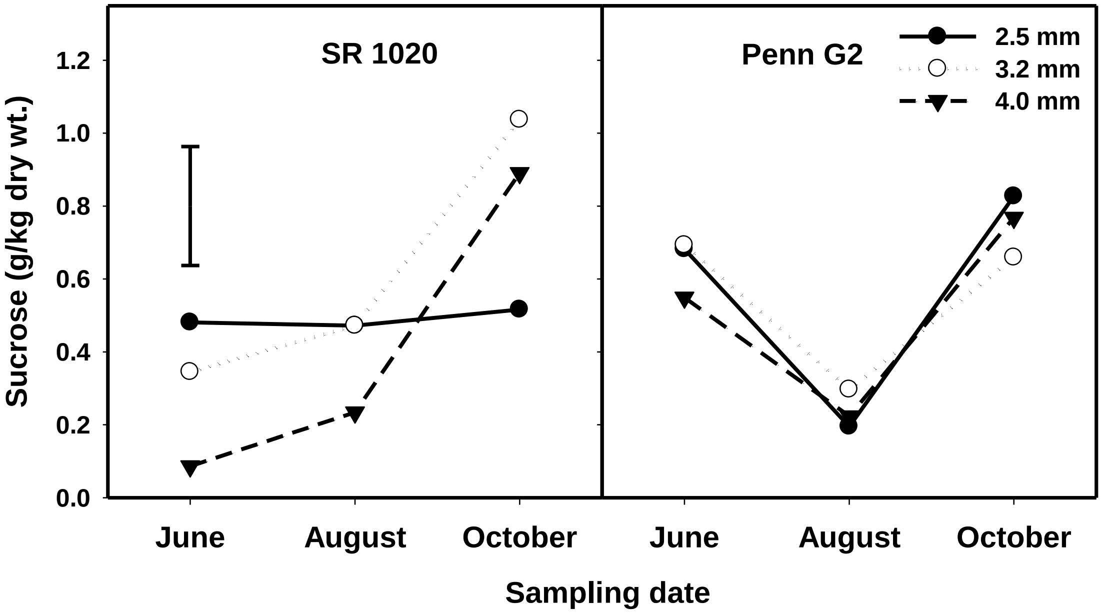

Figure 44. Cultivar by sampling date by mowing height interaction for sucrose in 2011. Values are averaged over tissues and rolling frequencies. Error bar represents LSD (α = 0.05) for the cultivar by sampling date by mowing height interaction for all data points.

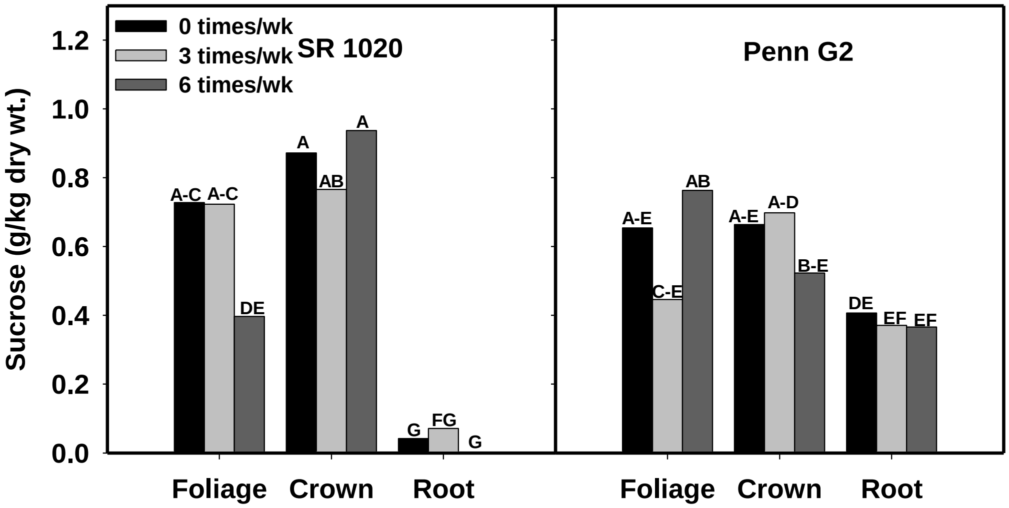

Figure 45. Cultivar by tissue by rolling frequency interaction for sucrose in 2011. Values are averaged over sampling dates and mowing heights. Bars sharing the same letter for either cultivar are statistically similar at α = 0.05.

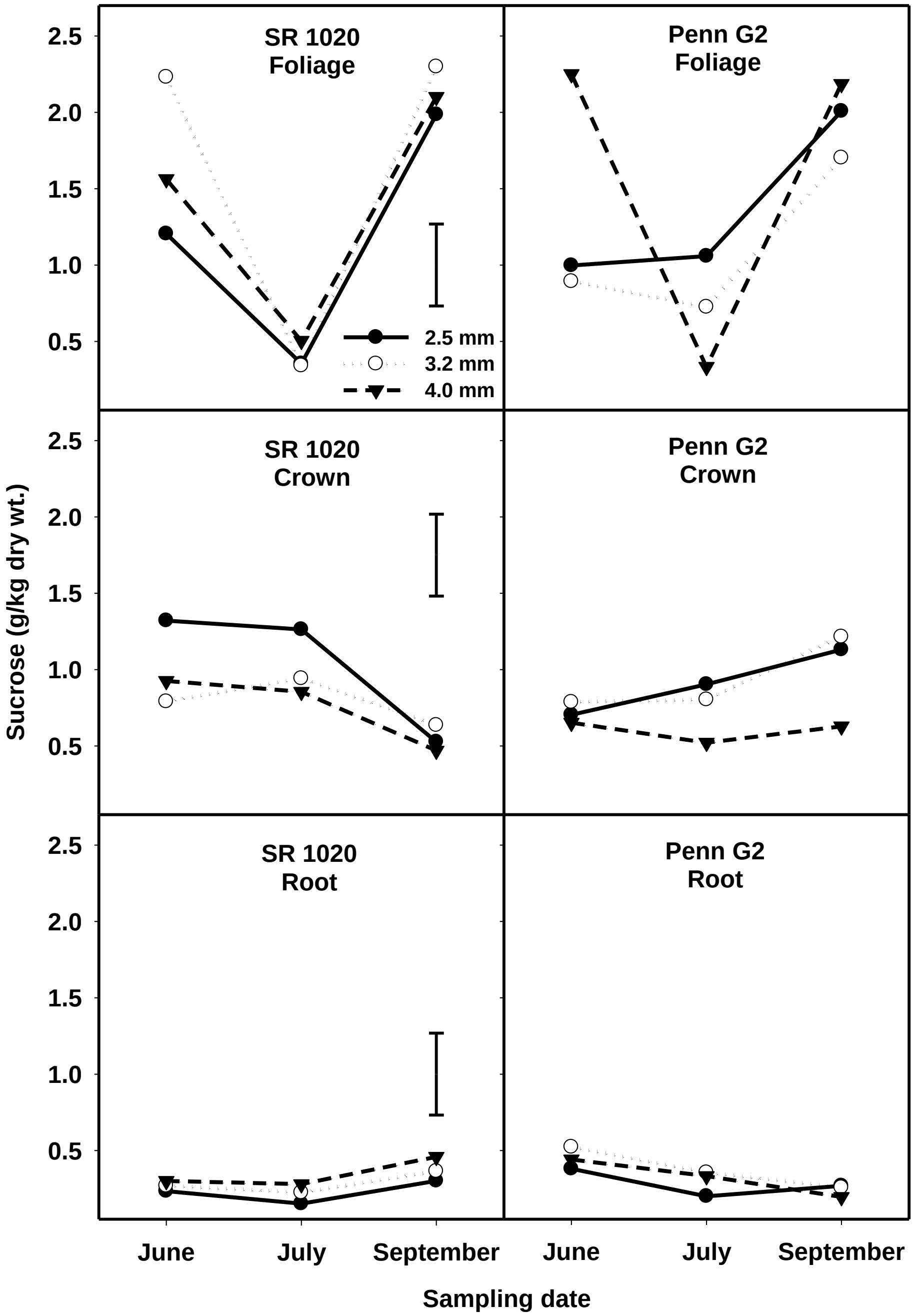

Figure 46. Cultivar by tissue by sampling date by mowing height interaction for sucrose in 2012. Values are averaged over rolling frequencies. Error bars represent LSD (α = 0.05) for the cultivar by tissue by sampling date by mowing height interaction for all data points.

Table 17. ANOVA table of carbohydrate analysis for fructans and average degree of polymerization (DP) fraction in 2011 and 2012.

	P-value for all main factors and interactions evaluated			
	Fructans		Average DP Fraction	
Effect	2011	2012	2011	2012
Rep	0.4804	0.4322	0.6471	0.6357
Cultivar	0.2161	0.0523	0.3210	0.1069
Tissue	<0.0001	<0.0001	<0.0001	<0.0001
Cultivar*Tissue	0.2168	0.0002	0.6536	0.0006
Mow	0.8492	0.5813	0.8520	0.6489
Cultivar*Mow	0.5118	0.7140	0.8872	0.6194
Tissue*Mow	0.6785	0.8418	0.7461	0.3265
Cultivar*Tissue*Mow	0.1870	0.0299	0.6341	0.6775
Roll	0.6713	0.1775	0.2223	0.3260
Cultivar*Roll	0.7171	0.8816	0.6731	0.5031
Tissue*Roll	0.9539	0.4266	0.2181	0.9416
Cultivar*Tissue*Roll	0.9977	0.6922	0.6501	0.6419
Mow*Roll	0.9929	0.3903	0.9969	0.8839
Cultivar*Mow*Roll	0.4696	0.2267	0.9562	0.5494
Tissue*Mow*Roll	0.9956	0.8004	0.9796	0.6424
Culti*Tissue*Mow*Roll	0.2913	0.1497	0.5947	0.8978
Date	<0.0001	<0.0001	<0.0001	<0.0001
Cultivar*Date	0.4909	0.0030	0.3630	<0.0001
Tissue*Date	<0.0001	<0.0001	<0.0001	<0.0001
Cultivar*Tissue*Date	<0.0001	0.0079	<0.0001	0.0279
Date*Mow	0.1858	0.9425	0.4421	0.7809
Cultivar*Date*Mow	0.7978	0.7182	0.3176	0.0991
Tissue*Date*Mow	0.0097	0.5506	0.7971	0.3979
Culti*Tissue*Date*Mow	0.9344	0.0003	0.1238	0.7562
Date*Roll	0.3705	0.1869	0.2636	0.4985
Cultivar*Date*Roll	0.5721	0.6656	0.4872	0.2047
Tissue*Date*Roll	0.7018	0.4901	0.9461	0.9752
Culti*Tissue*Date*Roll	0.6796	0.8665	0.5723	0.6223
Date*Mow*Roll	0.9996	0.7431	0.9489	0.4048
Culti*Date*Mow*Roll	0.4823	0.1201	0.9937	0.4361
Tissue*Date*Mow*Roll	0.9937	0.4247	0.9244	0.4100
Cult*Tis*Date*Mow*Roll	0.0723	0.4721	0.9508	0.6557

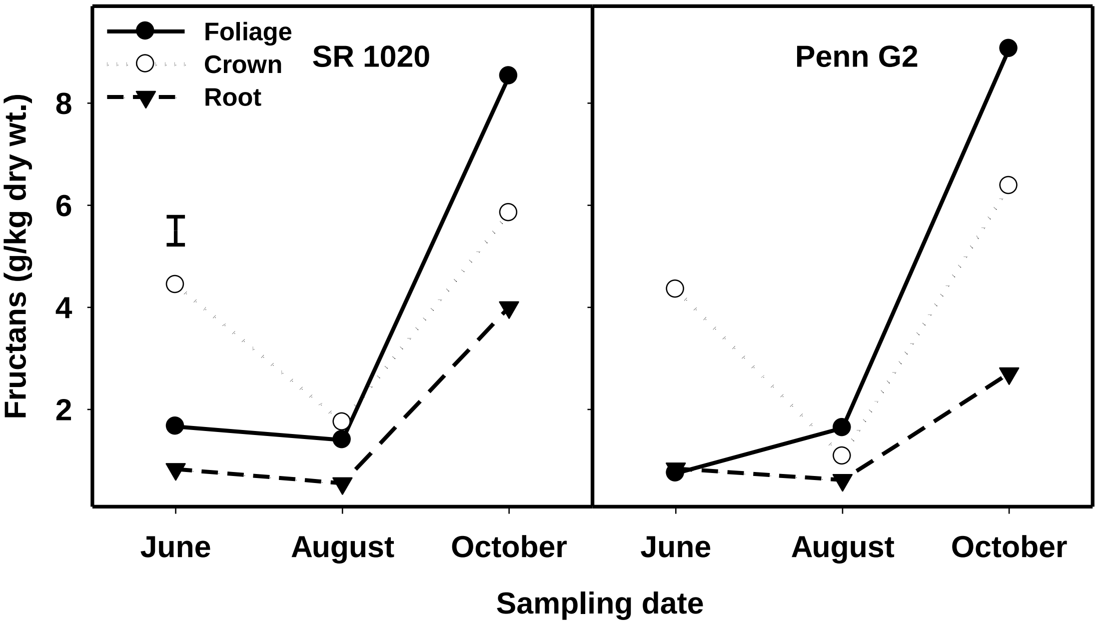

Figure 47. Cultivar by tissue by sampling date interaction for fructans in 2011. Values are averaged over mowing heights and rolling frequencies. Error bar represents LSD (α = 0.05) for the cultivar by tissue by sampling date interaction for all data points.

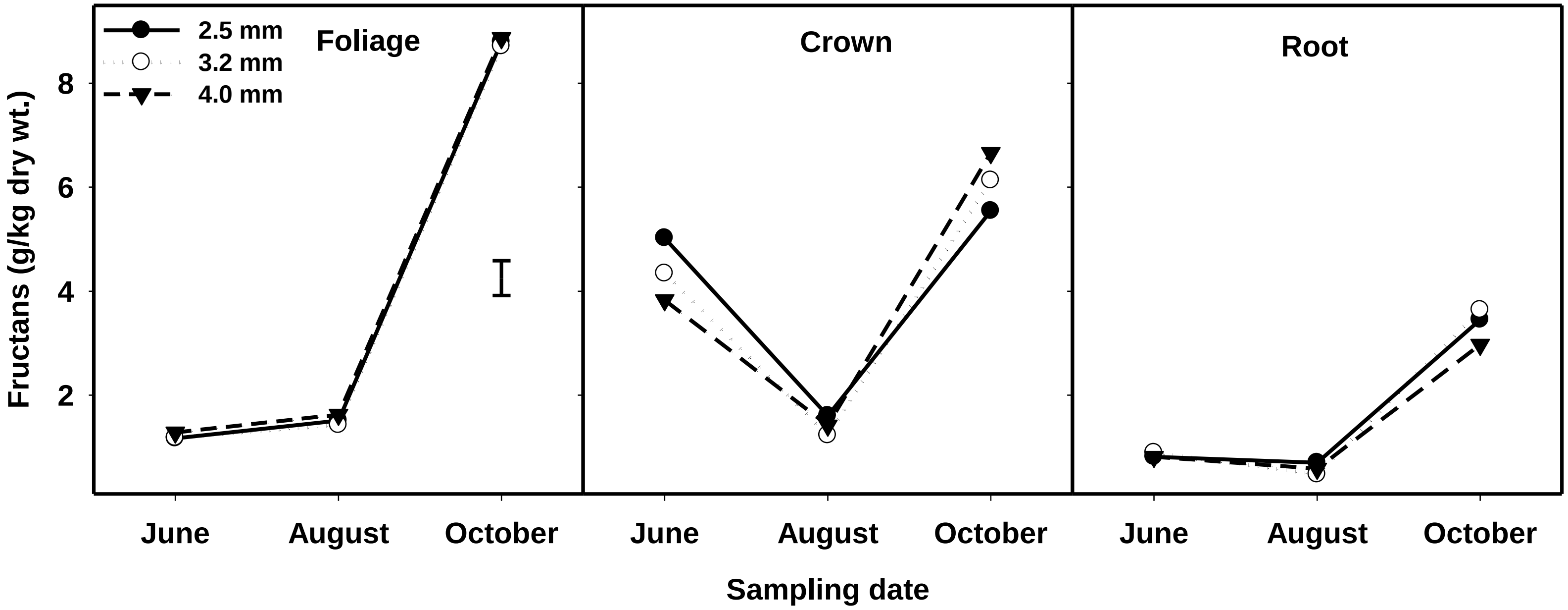

Figure 48. Tissue by sampling date by mowing height interaction for fructans in 2011. Values are averaged over cultivars and rolling frequencies. Error bar represents LSD (α = 0.05) for the tissue by sampling date by mowing height interaction for all data points.

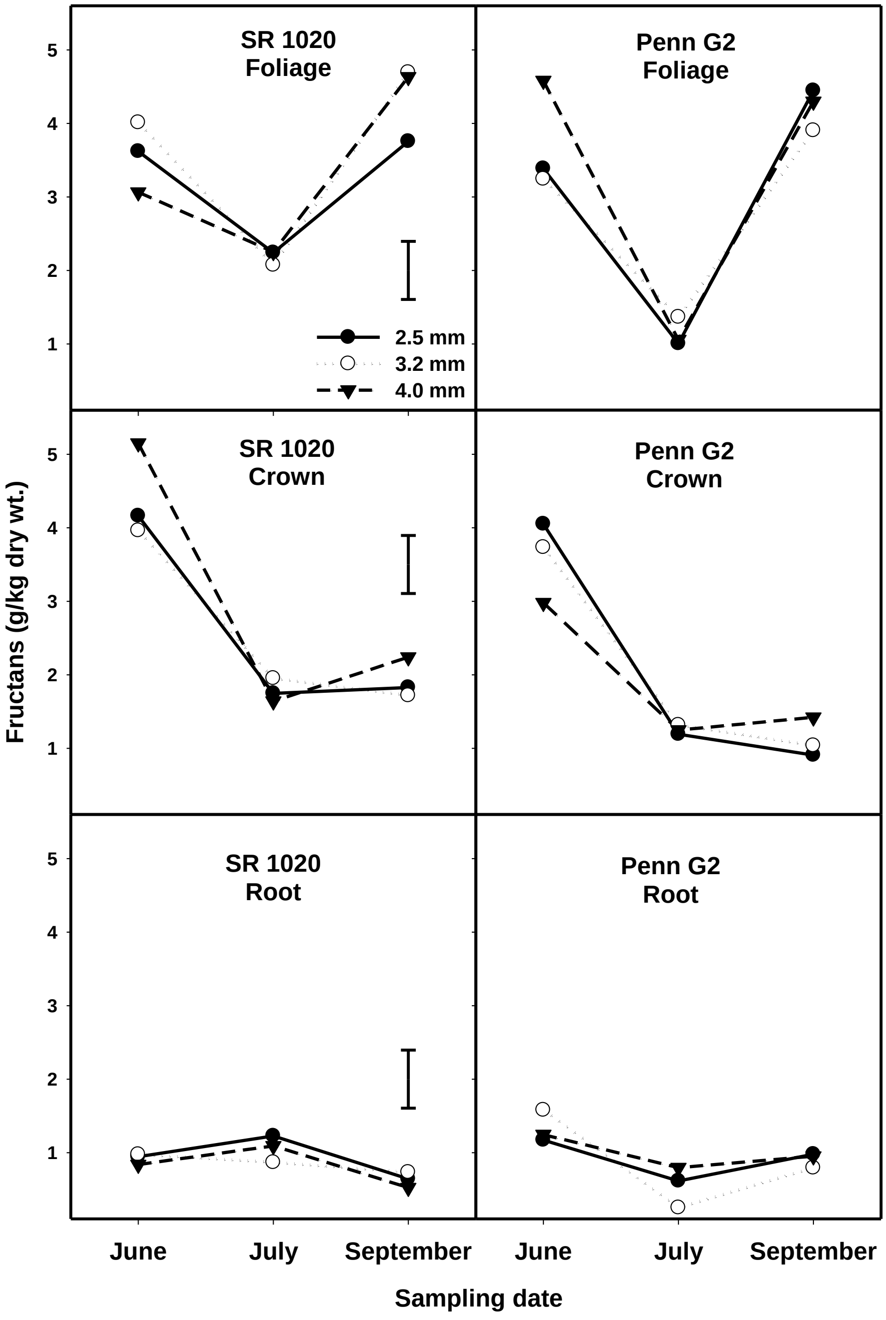

Figure 49. Cultivar by tissue by sampling date by mowing height interaction for fructans in 2012. Values are averaged over rolling frequencies. Error bars represent LSD (α = 0.05) for the cultivar by tissue by sampling date by mowing height interaction for all data points.

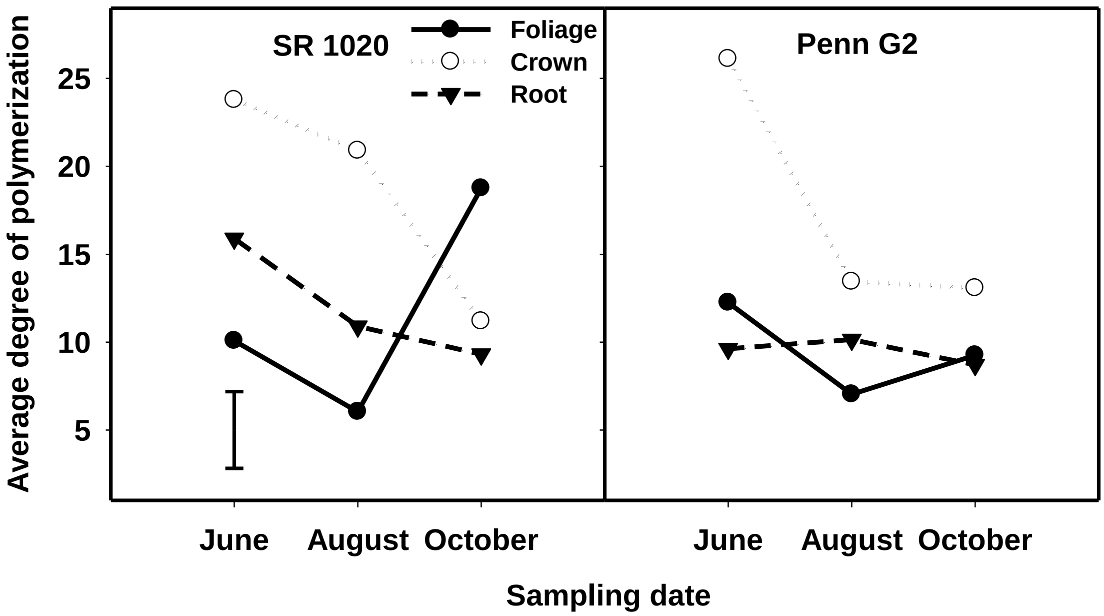

Figure 50. Cultivar by tissue by sampling date interaction for average degree of polymerization (DP) fraction in 2011. Values are averaged over mowing heights and rolling frequencies. Error bar represents LSD (α = 0.05) for the cultivar by tissue by sampling date interaction for all data points.

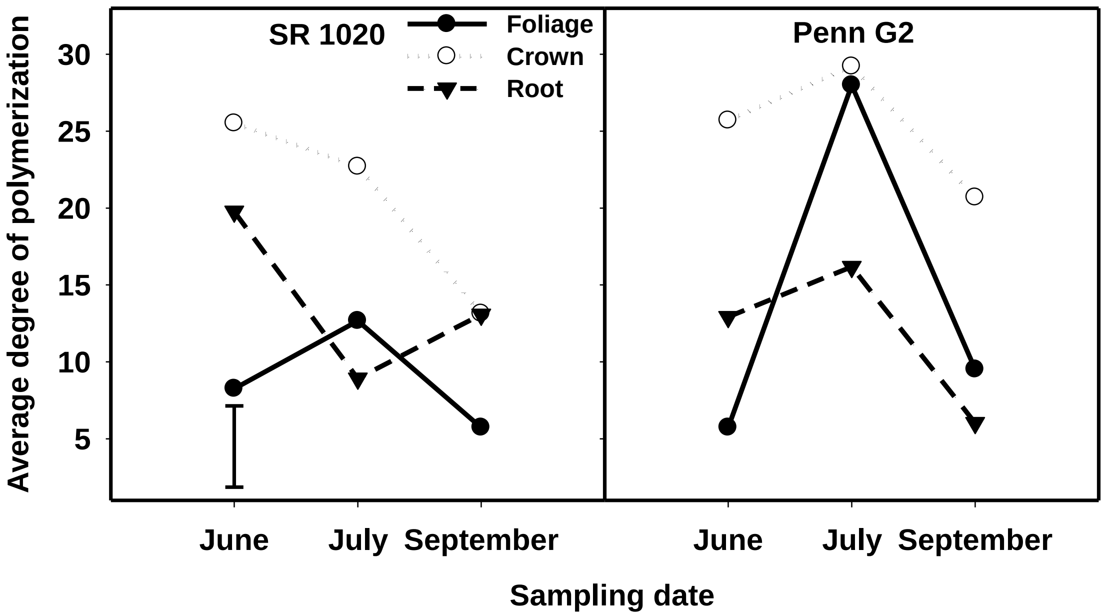

Figure 51. Cultivar by tissue by sampling date interaction for average degree of polymerization (DP) fraction in 2012. Values are averaged over mowing heights and rolling frequencies. Error bar represents LSD (α = 0.05) for the cultivar by tissue by sampling date interaction for all data points.

Ball mark severity and recovery

None of the treatments resulted in significant differences in ball mark severity (depth of ball mark) in 2010, but there was a significant cultivar by rolling frequency by foot traffic interaction in 2011 (Table 18). The only significant differences within this interaction occurred on SR 1020 without foot traffic (Fig. 52). As rolling frequencies were increased, ball mark severity increased. Even though ball marks were enlarged with each increase in rolling frequency, the only statistically significant difference was indentified between daily and non-rolled plots. Although there were few significant differences observed for main treatment factors alone or their interactions, volumetric water content was moderately correlated with ball mark severity (Fig. 53). As volumetric water content increased, ball mark severity increased in both 2010 (p-value < 0.0001) and 2011 (p-value < 0.0001).

Similar to ball mark severity data, there were few individual treatments or interactions among treatments that significantly affected the recovery of ball marks over time in 2010 or 2011 (Table 19). Rolling frequency significantly affected maximum ball mark injury area in 2010 (Table 19). Maximum ball mark injury area increased numerically with each increase in rolling frequency, but daily rolled treatments had significantly larger ball mark injury area than other rolling frequencies (Table 20). No treatments resulted in significant differences in maximum ball mark injury area in 2011.

Although there was a difference in maximum ball mark injury area with increased rolling frequency in 2010, the rate of recovery (slope of curve) was not significantly different for any of the treatments in 2010. There was a cultivar by foot traffic interaction for recovery rate when pooling mowing height and rolling frequency data (Table 19). The only significant difference observed based on the 95% confidence intervals calculated was between SR 1020 and Penn G2 receiving foot traffic, but these differences cannot be confirmed because cultivars were not replicated in the study (Table 21). The lower rate of recovery (slope) signifies a shallower, more elongated recovery from ball mark injury.

The final parameter evaluated with regards to ball mark recovery was days to 50% recovery. There were two different significant interactions containing foot traffic treatments that significantly altered days to 50% recovery in 2010 and 2011 (Table 19). In 2010, treatments mowed at 2.5 mm receiving foot traffic were slower to reach 50% recovery than all other treatment combinations (Table 22). Based on data of means, these treatments required two and a half days longer to reach 50% recovery compared to other treatment combinations. Although significant differences were observed with mean separation techniques, high variability in recovery data caused overlapping of 95% confidence intervals, and resulted in lack of significant differences in ball mark recovery. There was a significant difference in days to 50% recovery when evaluating rolling frequency and foot traffic treatments in 2011 (Table 19). Based on 95% confidence intervals constructed from days to 50% recovery data, the ball marks in daily rolling and foot traffic plots recovered more slowly than daily rolled treatments with no foot traffic and non-rolled treatments with foot traffic (Table 23).

Few researchers have evaluated the effects of putting green management practices on ball mark severity and recovery. The majority of ball mark studies that have been conducted have evaluated differences in recovery with various ball mark repair tools and techniques to non-repaired ball marks (Fry et al., 2005; Munshaw et al., 2007; Nemitz et al., 2008). The current study effectively used digital image analysis techniques to evaluate ball mark severity and recovery to obtain quantitative data to help establish differences with these intensive putting green management strategies (Young et al., 2012a).

A previous study demonstrated increased ball mark severity and longer recovery time under softer conditions (Nemitz et al., 2008). There was high variation within these data, but general trends indicate that maximum ball mark injury was decreased with greater ball mark severity under increased soil moisture levels. Incorporating the theoretical maximum ball mark injury area into these scatter plots reduced the correlation and significance previously discussed when including actual maximum ball mark injury area observed through digital image analysis (Young et al., 2012b; Young et al., 2010). The drier conditions in 2010 illustrated this point more so than when the putting green moisture was higher in 2011 (Fig. 54). The slope of the regression line and y-intercept value depicts this increase in maximum ball mark injury area under drier conditions (Fig. 54), which differs from previous studies evaluating ball mark recovery (Young et al., 2012b; Young et al., 2010). The previous study by Nemitz et al. (2008) was performed in mid-June in Indiana on ‘Penncross’ creeping bentgrass mowed at 3.6 mm, so variations in cultivars maintained under intensive management practices and high environmental stress may have led to increased ball mark size under drier conditions.

One of the first projects that evaluated ball mark severity and recovery was conducted in New Jersey to determine if ball marks differed for creeping bentgrass cultivars or compaction and wear treatments (Murphy et al., 2003). The author stated that ball mark severity among cultivars resulted in greater separation the initial year of the study, but as the cultivars matured and began forming structure through a thatch mat layer; the separation in cultivars was reduced. Wear and compaction treatments reduced recovery rates in the study, but compaction alone had no significant effect on the recovery of ball marks. The results from the present study follow this trend. Based on these data, rolling frequency had a significant effect on maximum ball mark injury in 2010 with daily rolled plots having significantly larger ball mark injury area that would take longer to recover. Although rolling frequencies did not significantly affect maximum injury in 2011, increased wear from light-weight rolling and foot traffic lengthened the time ball marks required to reach 50% recovery.

The methods used to evaluate ball mark severity and recovery in this study were unique and effective at differentiating ball mark severity and recovery under these intensive management practices. These data were collected in a more objective manner compared to many of the previous studies that visually estimated ball mark severity or recovery. In addition, the methods used to determine ball mark injury area were accomplished efficiently and effectively compared to measuring perpendicular diameters of a large number of ball marks (Nemitz et al., 2008).

Although there was variation in these data from year to year, there were some conclusions that can assist golf course superintendents managing putting greens that are subjected to widespread ball mark injury. First and foremost, it is important to inform golfers on the importance of fixing ball marks and teach golfers the correct method to repair ball marks. It has been well established that ball marks repaired appropriately will heal much quicker than non-repaired or improperly repaired ball marks (Fry et al., 2005; Munshaw et al., 2007; Nemitz et al., 2008). Putting green management practices significantly affected ball mark recovery in this study, even when repaired properly. The increase in wear damage from higher rolling frequencies increased maximum ball mark injury. Increasing rolling frequencies result in a firmer surface that in this research resulted in increased ball mark injury area, even when ball marks were shallower as expected under drier, firmer conditions. These data further demonstrate the potential benefit of implementing target rolling techniques to reduce the frequency of rolling the entire putting greens surface. Target rolling consists of rolling the areas in close proximity to the hole location, but not the entire putting greens surface (Gilhuly, 2006). This practice would help disperse wear traffic from rolling to different portions of the putting surface without reducing green speed and performance in close proximity to the hole location. This research indicates that reducing rolling frequency would reduce maximum ball mark injury area and allow ball marks to recover more quickly, assuming ball marks are repaired appropriately.

Ball marks took longer to reach 50% recovery when high rolling frequencies were combined with foot traffic in 2011. Although the difference observed was just over a single day, these results indicate that additional stress on the putting green under concentrated traffic stress increases maximum ball mark injury area and lengthens recovery time. In addition, as mowing heights were decreased and foot traffic applied, ball mark recovery was slowed. The results from this study differ from previous studies where few differences were observed for ball mark recovery, but the combination of these intense management practices and increased environmental stress likely helped separate these treatments. Under more optimum conditions, these factors may not significantly affect recovery from ball mark injury.

Table 18. ANOVA table of statistical analysis performed for ball mark severity determined by digital image analysis in 2010 and 2011.

	P-values for all main factors and interactions analyzed	
Effect	2010	2011
Rep	0.5620	0.9964
Cultivar	0.3008	0.3002
Mow	0.8055	0.8418
Cultivar*Mow	0.5245	0.8986
Roll	0.2041	0.3826
Cultivar*Roll	0.4620	0.9181
Mow*Roll	0.3191	0.8907
Cultivar*Mow*Roll	0.7946	0.9722
Foot	0.7086	0.6204
Cultivar*Foot	0.0740	0.2888
Mow*Foot	0.0676	0.9789
Cultivar*Mow*Foot	0.3923	0.1114
Roll*Foot	0.5704	0.5203
Cultivar*Roll*Foot	0.0786	0.0240
Mow*Roll*Foot	0.2123	0.4960
Cultivar*Mow*Roll*Foot	0.2290	0.0949

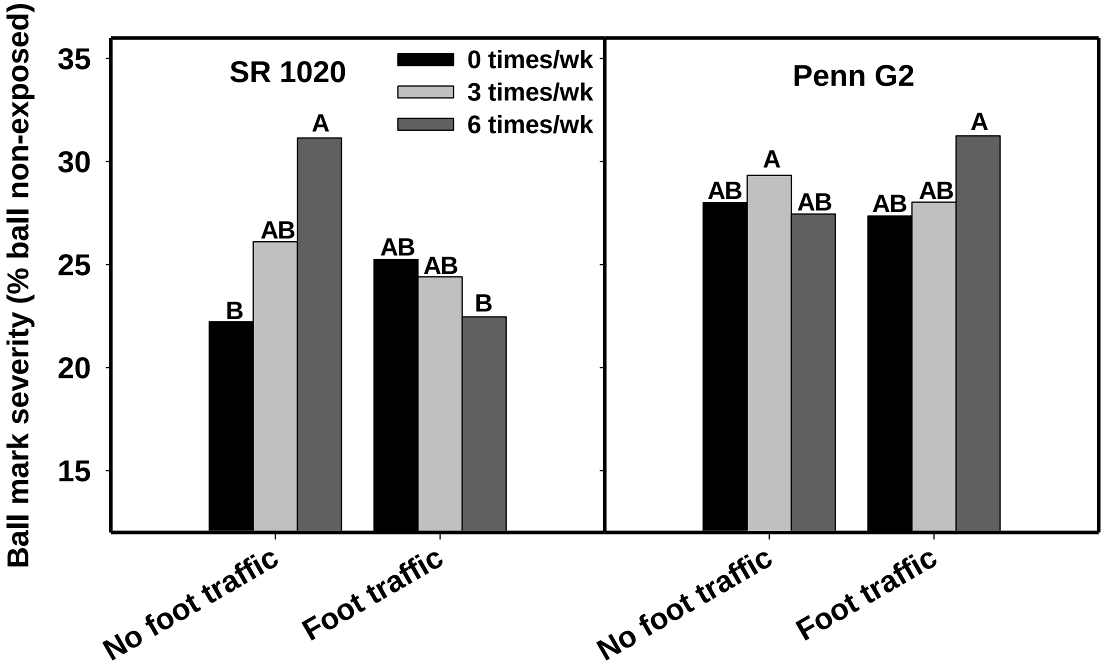

Figure 52. Cultivar by rolling frequency by foot traffic interaction for ball mark severity in 2011. Data were averaged over mowing heights. Bars sharing the same letter within these graphs are statistically similar at α = 0.05.

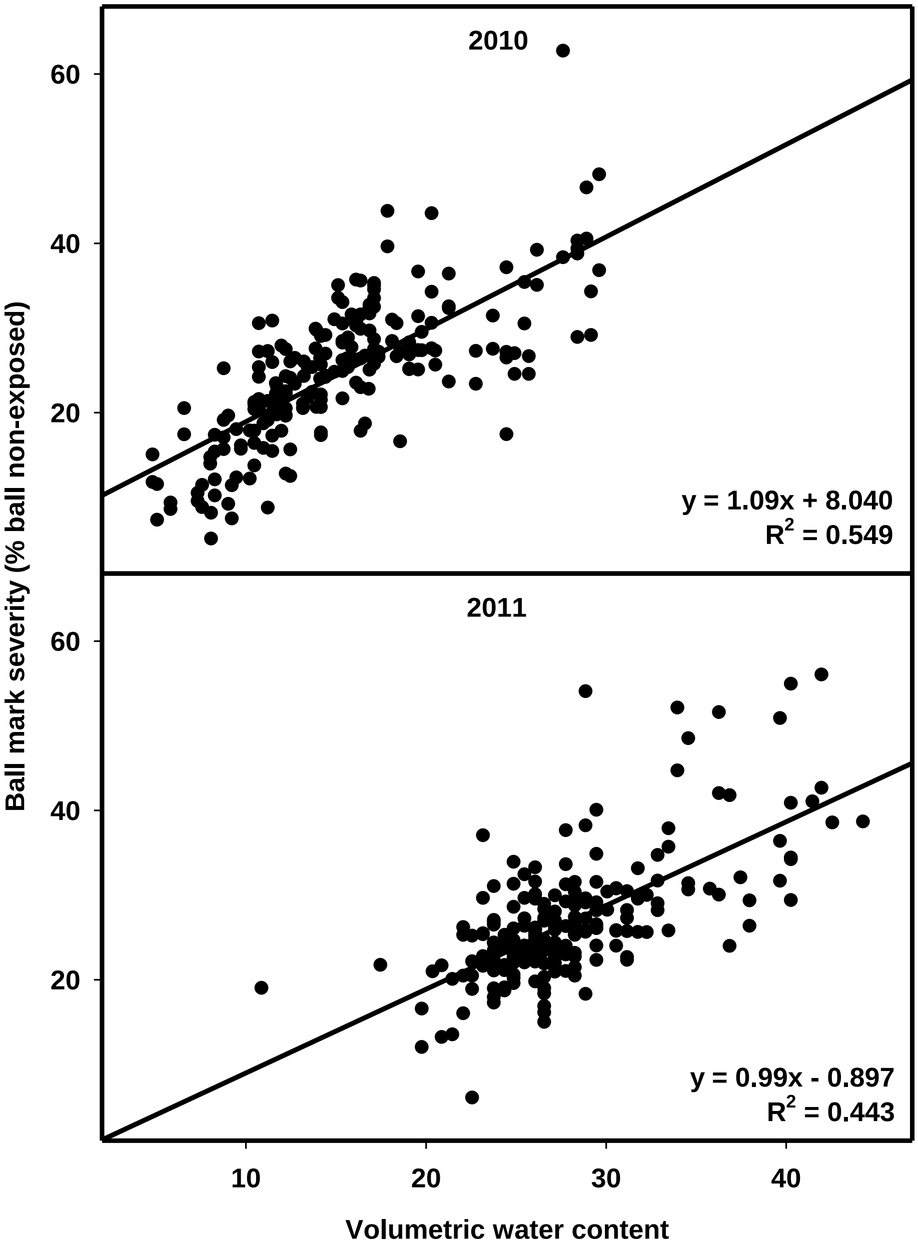

Figure 53. Scatter plot and regression line illustrating the positive relationship between volumetric water content and ball mark severity in 2010 and 2011 (p-values < 0.0001). Data points represent all ball marks for both cultivars within the year. Volumetric water content was determined by time domain reflectometry with 3.8 cm rods.

Table 19. ANOVA table of statistical analysis performed for parameters in the exponential decay equation for ball mark recovery in 2010 and 2011.

	P-values for all main factors and interactions analyzed					
	Maximum injury area		Rate of recovery		Days to 50% recovery	
Effect	2010	2011	2010	2011	2010	2011
Rep	0.4670	0.9512	0.5707	0.9632	0.5532	0.6047
Cultivar	0.3544	0.4372	0.1348	0.2055	0.2014	0.1214
Mow	0.5162	0.0781	0.1762	0.7331	0.0554	0.4805
Cultivar*Mow	0.5791	0.4190	0.9158	0.7844	0.9708	0.3235
Roll	0.0209	0.4929	0.3041	0.3294	0.2092	0.5066
Cultivar*Roll	0.8786	0.2676	0.9197	0.6470	0.6441	0.3777
Mow*Roll	0.7888	0.4930	0.2071	0.3647	0.0902	0.4098
Cultivar*Mow*Roll	0.2766	0.7345	0.5835	0.1944	0.3588	0.7022
Foot	0.9997	0.2427	0.6308	0.3130	0.1146	0.3735
Cultivar*Foot	0.0539	0.3427	0.9567	0.0350	0.8099	0.1471
Mow*Foot	0.8920	0.9768	0.0720	0.8541	0.0248	0.6645
Cultivar*Mow*Foot	0.4159	0.6355	0.1797	0.1181	0.4155	0.1901
Roll*Foot	0.1528	0.3179	0.6025	0.0785	0.1579	0.0218
Cultivar*Roll*Foot	0.3810	0.1673	0.8214	0.1761	0.9089	0.0644
Mow*Roll*Foot	0.4217	0.5667	0.4876	0.4860	0.4654	0.6202
Cultivar*Mow*Roll*Foot	0.5034	0.7672	0.6136	0.0926	0.3461	0.9518

Table 20. Maximum ball mark injury area and 95% confidence intervals for rolling frequencies in 2010.

Rolling frequency	Maximum ball mark injury[y]	95% Confidence intervals[z]
	-----------------mm^2------------------	
0 times/wk	1099	1008 – 1190
3 times/wk	1253	1162 – 1345
6 times/wk	1476	1367 – 1585

[y] Maximum ball mark injury calculated from one phase exponential decay equation.

[z] Confidence intervals that do not overlap are significantly different at $\alpha = 0.05$.

Table 21. Rate of recovery (slope) and 95% confidence intervals for cultivar by foot traffic interaction on ball mark recovery in 2011.

Cultivar	Foot traffic	Rate of recovery[y]	95% Confidence intervals[z]
SR 1020	No foot traffic	0.1251	0.1121 – 0.1381
	Foot traffic	0.1051	0.0905 – 0.1152
Penn G2	No foot traffic	0.1371	0.1208 – 0.1534
	Foot traffic	0.1446	0.1284 – 0.1607

[y] Rate of recovery (slope) calculated from one phase exponential decay equation.

[z] Confidence intervals that do not overlap are significantly different at $\alpha = 0.05$.

Table 22. Days to 50% recovery and 95% confidence intervals for mowing height by foot traffic interaction on ball mark recovery in 2010.

Mowing height (mm)	Foot traffic	Days to 50% recovery[y]	95% Confidence intervals[z]
		--------------days--------------	
2.5	No foot traffic	11.36	9.709 – 13.68
	Foot traffic	13.96	11.87 – 16.96
3.2	No foot traffic	10.12	7.915 – 14.03
	Foot traffic	11.35	9.253 – 14.67
4.0	No foot traffic	11.03	9.686 – 12.82
	Foot traffic	10.01	8.816 – 11.57

[y] Days to 50% recovery calculated from one phase exponential decay equation.

[z] Confidence intervals that do not overlap are significantly different at α = 0.05.

Table 23. Days to 50% recovery and 95% confidence intervals for rolling frequency by foot traffic interaction on ball mark recovery in 2011.

Rolling frequency	Foot traffic	Days to 50% recovery[y]	95% Confidence intervals[z]
		--------------days--------------	
0 times/wk	No foot traffic	5.757	5.016 – 6.756
	Foot traffic	4.883	4.326 – 5.605
3 times/wk	No foot traffic	5.146	4.483 – 6.041
	Foot traffic	5.599	4.968 – 6.413
6 times/wk	No foot traffic	5.024	4.523 – 5.650
	Foot traffic	6.741	5.891 – 7.876

[y] Days to 50% recovery calculated from one phase exponential decay equation.

[z] Confidence intervals that do not overlap are significantly different at α = 0.05.

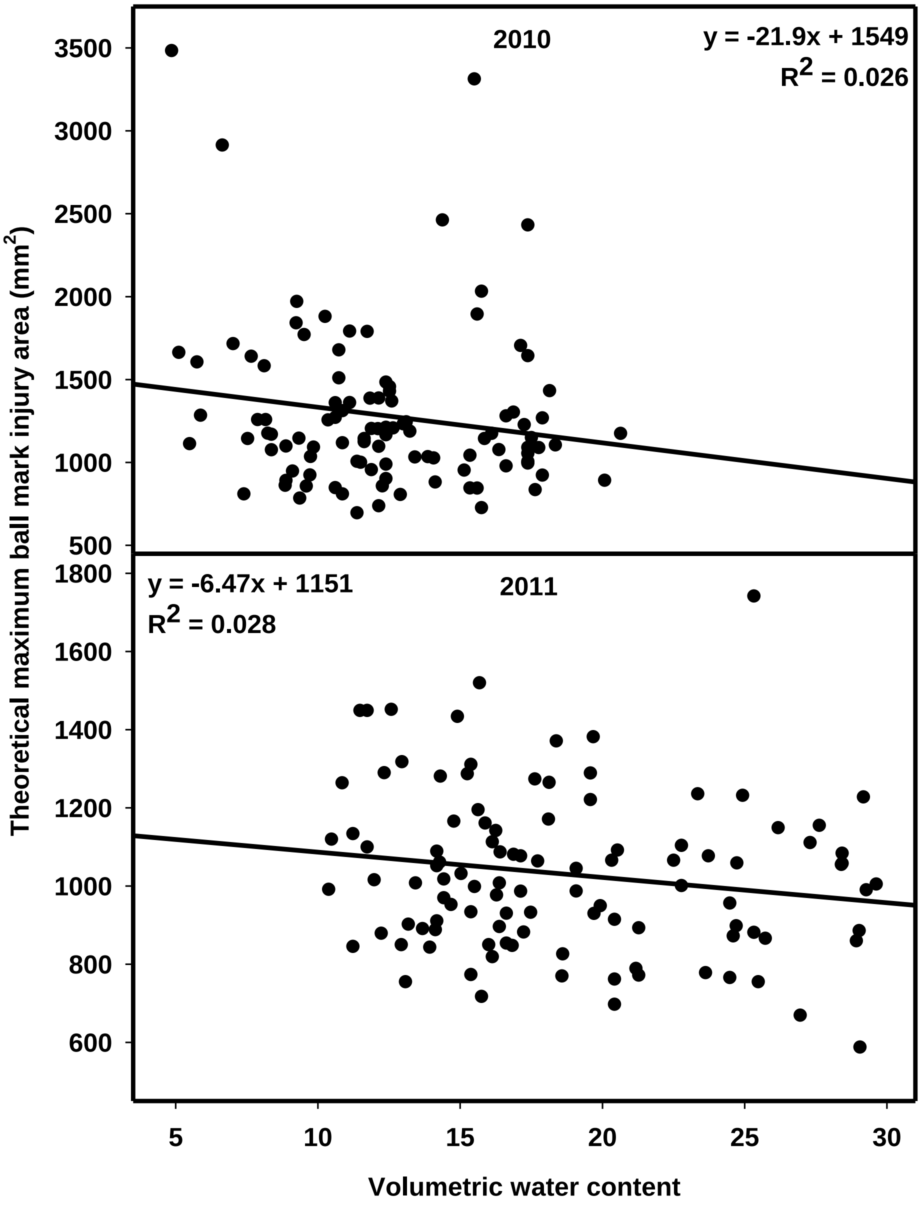

Figure 54. Scatter plot and regression line illustrating the negative relationship between volumetric water content and theoretical maximum ball mark injury area in 2010 and 2011. Data points represent all ball marks for both cultivars within the year. Volumetric water content was determined by time domain reflectometry with 3.8 cm rods.

SUMMARY

Overall, there was less separation among mowing heights, rolling frequencies, and foot traffic treatments than hypothesized, but all the parameters evaluated reached lowest values in July or August each year following extended periods of heat stress. Although environmental stresses affected these parameters, most of the parameters returned to levels observed earlier in the summer following more favorable weather conditions. These results indicate the significant effect of environmental stress on creeping bentgrass putting greens in the transition zone during summer months, regardless of mechanical stresses from the treatments applied.

Following the hypothesis of the study, lowering mowing heights appeared to be associated with more significant differences than rolling and foot traffic treatments. Turfgrass quality, coverage, and color of SR 1020 maintained acceptable levels and were highest when mowed at 4.0 mm. In contrast, the higher density cultivar, Penn G2, was able to maintain improved visual turf quality at 3.2 mm. Penn G2 exhibited greater coverage and darker green color when mowed at 3.2 or 4.0 mm compared to the lowest mowing height. Net photosynthesis rates and carbohydrates were rarely significantly increased at the highest mowing heights, but the data suggest that these parameters can be increased slightly as mowing heights are increased.

Rolling treatments were not expected to have a great effect on these parameters, but wear tolerance was significantly reduced as rolling frequencies were increased. Increased rolling frequencies also significantly affected ball mark recovery. Maximum ball mark injury increased significantly under daily rolling in 2010, and increased rolling frequencies slowed recovery time in 2011. The negative effect of increased rolling frequencies and foot traffic in combination also affected the parameters evaluated in this study. Turfgrass quality, coverage, and color were reduced as rolling frequencies increased and foot traffic was applied. Although foot traffic generally reduced many of the parameters that were evaluated, rooting characteristics were affected to a greater degree than many of the other parameters. Cumulative root length, root surface area, root diameter, and root dry mass were all significantly reduced by foot traffic treatments in 2010 and 2012.

The overwhelming conclusion from this research that impacts golf course superintendents is the significant reduction in all parameters associated with environmental stress, regardless of treatment combinations applied. Unfortunately, the environment is one of the factors that the turf manager does not control; however, these data demonstrate the importance of maintaining the healthiest putting green turf possible in the spring prior to summer heat stress. Applying adequate nutrient levels, maintaining appropriate moisture levels, and incorporating cultivation practices during the spring will help produce a putting green surface that maximizes performance and physiological characteristics. Optimizing these practices when cool-season grass is in one of its peak growth cycles will better prepare creeping bentgrass for environmental stresses in the summer. Once temperatures increase above optimum in summer months and the number of golf rounds played remain high, increasing mowing heights and implementing target rolling should maintain a healthier and more consistent putting surface.

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