5-2022

Managing Stress Tolerance on Warm-Season Putting Greens in the Transition Zone

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Citation

Walton, T. E. (2022). Managing Stress Tolerance on Warm-Season Putting Greens in the Transition Zone. *Graduate Theses and Dissertations* Retrieved from https://scholarworks.uark.edu/etd/4396

Managing Stress Tolerance on Warm-Season Putting Greens in the Transition Zone

A thesis submitted in partial fulfilment
of the requirements for the degree of
Master of Science in Horticulture

by

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University of Arkansas
Bachelor of Science in Agriculture, Food, and Life Sciences, 2017

May 2022
University of Arkansas

This thesis is approved for recommendation to the Graduate Council

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ABSTRACT

The use of warm-season putting greens in the transition zone has increased in recent years. Ultradwarf bermudagrass (*Cynodon dactylon* (L.) Pers *x C. transvaalensis* Burtt-Davy) is the most prevalent warm-season putting green selection in the transition zone, however, newly developed greens-type zoysiagrass (*Zoysia spp.*) cultivars represent another potential selection for golf courses. The two major limitations of warm-season grasses in the transition zone are a general lack of cold- and shade-tolerance. Protective covers are essential to protect ultradwarf bermudagrass putting greens in the winter months. Unfortunately, golf courses can still experience winterkill underneath protective covers. Two field trials were conducted with a goal of improving upon management strategies to improve the performance and survival of golf course putting greens under stress. Both trials were conducted on sand-based rootzones and were managed with cultural practices consistent with golf course putting greens found in the region. The first trial was conducted during the winters of 2019-20 and 2020-21 on a putting green consisting of four replicated whole plots of the three most prevalent ultradwarf bermudagrass cultivars. The goal of the trial was to improve upon cover strategies by supplementing protective covers with three air gap materials to provide additional insulation. Although materials such as straw and batting fabric provided moderate soil temperature gains compared to the cover alone, protective covers alone provided sufficient protection from winterkill during adverse weather conditions. Because of the high purchasing cost and labor requirement associated, wall to wall coverage of air gaps is not likely feasible. Where air gaps could be valuable is spot coverage of portions of putting greens that are especially vulnerable to winterkill (shade, north slopes, high traffic) and historically receive winterkill. The second trial was conducted during the growing seasons (June to October) of 2020 and 2021 on a putting green consisting of three replicated whole plots of ‘Lazer’ zoysiagrass (*Zoysia matrella* (L.) Merrill *x Z. minima* (Colenso) Zotov). Shade is a significant problem for golf course putting greens, so it is important to identify the precise amount of light is needed to maintain an acceptable putting green. Zoysiagrass is generally more shade tolerant than bermudagrass, however, ‘Lazer’ zoysiagrass has not been studied. The goal of this trial was to compare ‘Lazer’ zoysiagrass to an industry-standard putting green selection, ‘TifEagle’ bermudagrass, under varying levels of shade and management practices. Management practices included two mowing heights (2.5- and 3.2-mm) and with or without the treatment of the plant growth regulator, trinexapac-ethyl. The minimum daily light integral (DLI) was determined for both species and surface characteristics, including ball roll distance and surface firmness, were monitored. ‘Lazer’ zoysiagrass demonstrated superior shade-tolerance and had a minimum DLI requirement about 10 mol m^{-2} d^{-1} less than ‘TifEagle’. Surface firmness was greater for ‘Lazer’, while ‘TifEagle’ produced greater ball roll distance for most rating dates. However, both species consistently produced industry-standard ball roll distance. Results from this trial suggest that ‘Lazer’ zoysia can produce acceptable putting green conditions and is better adapted than ‘TifEagle’ to moderate shade conditions.

ACKNOWLEDGMENTS

I would not have been able to complete this program without the help of many individuals. I am grateful to have a mentor and advisor like Dr. Richardson to get me across the finish line. Dr. Richardson has been there every step of the way in my formal education in turfgrass science since I transferred to the University of Arkansas as an undergraduate student in 2015 and always goes above and beyond to provide me with guidance and technical assistance. I would not have started, or finished, this program if it wasn't for Dr. Richardson and I look forward to staying in touch. My graduate committee has also been invaluable. Dr. Karcher has been instrumental in my turfgrass education since 2015. From teaching me turfgrass identification and calibration as an undergraduate to providing me assistance on statistical analysis as a graduate student, Dr. Karcher has been an important mentor to me and valuable committee member. I also feel fortunate to have Dr. Brye on my committee. After taking Soil Physics and Scientific Presentations from Dr. Brye during my graduate coursework, I find Dr. Brye to be among the most detail-oriented, passionate professors that I have had which has made a significant impression on me. I also feel fortunate to have Dr. Sorochan from the University of Tennessee on my committee. His expertise, particularly on zoysiagrass putting greens, benefited this project greatly. I would also like to thank our turfgrass team for providing me with all the assistance I needed to complete my projects including John McCalla, Eric DeBoer, and Daniel O'Brien. Even though limited due to the pandemic, I would not have been able to complete my degree without our conversations and comradery. There are so many individuals within who I would like to thank including Dr. Mackay, Dr. McDonald, Michelle Wisdom, Cindy Kuhns, Jo Salazar, and Jimmy Moore, just to name a few.

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I. Introduction and Literature Review

Golf course putting greens in the transition zone

`The transition zone of the United States is a broad region of the country, with the center extending from northeastern New Mexico to Virginia (Fry and Huang, 2004). In the transition zone, turfgrass selection transitions from predominately cool-season (temperate) grasses to warm-season (tropical) grasses. The challenges growing turfgrass in the transition zone are well documented, once even being referred to as the "crabgrass belt" due to both cool-and warm-season grasses' inability to outcompete the invasion of the summer annual weed, crabgrass (*Digitaria sp.)* (Forbes and Ferguson, 1947). A constant challenge to turfgrass managers in the transition zone is the inevitability that grasses will be exposed to some form of an environmental extreme. Physiological stresses of both warm- and cool-season grasses can become so extreme that survival is challenging. Due to improvements in both genetics and management practices, golf courses in the transition zone have more options than ever before to establish high-quality putting greens (Morris, 2015).

Traditionally, creeping bentgrass (*Agrostis stolonifera* L.) and hybrid bermudagrass (*Cynodon dactylon* (L.) Pers *x C. transvaalensis* Burtt-Davy) have been planted on golf course putting greens throughout the transition zone, with the popularity of grass selection being cyclical with climatic trends. The hot, humid summers create an undesirable environment for cool-season grasses, like creeping bentgrass, and costly inputs are required for survival, while playing conditions decline. Hybrid bermudagrasses were developed in the 1950s as a superior surface to previously used, common bermudagrass (*Cynodon dactylon* (L.)). The first cultivar released for golf course putting greens was 'Tifgreen'. Putting green quality significantly improved with the develop of ‘Tifgreen’ because of ‘Tifgreen’s’ ability to tolerate lower mowing heights (6.4 mm or ¼ in) than common bermudagrass, while sustaining reasonable shoot density (Beard and Sifers, 1996). In the late 1990s, new and improved "ultradwarf” bermudagrass cultivars were developed and the cultivars ‘Champion’, ‘MiniVerde’, and ‘TifEagle’ are now considered industry standards regarding bermudagrass putting green selection in the transition zone. The term ultradwarf was first used by Dr. Phillip Busey of the University of Florida to describe the diminutive morphology of the cultivars, a characteristic that allows these grasses to tolerate very low mowing heights (Reasor et al., 2016). Under proper management, ultradwarf bermudagrasses produce superior putting surfaces compared to the older selections of bermudagrass and low-quality bentgrass (Hartwiger, 2001). Since 2005, many golf courses in the southern United States and the transition zone have converted bentgrass putting greens to ultradwarf bermudagrass (Hartwiger, 2009).

Although not traditionally thought to be a suitable putting green surface in the United States, an emerging alternative to both bentgrass and ultradwarf bermudagrass is zoysiagrass (*Zoysia sp.*). Zoysiagrass putting greens are abundantly present throughout eastern and southeast Asia, in countries like Japan and Thailand, but are rarely present in the United States. Zoysiagrass is selected in these countries out of necessity, as bermudagrass does not thrive due to cloudy conditions and a lack of solar radiation coupled with tropical temperatures being too warm for cool-season grasses (Woods, 2014). ‘Diamond’ zoysiagrass (*Zoysia matrella* (L.) Merrill) was developed at Texas A&M in 1996 as the first commercially available zoysiagrass on the market for putting green use in the United States (Engelke et al., 2002). Growth characteristics, such as very fine leaf texture and high tiller and rhizome density, allow for low, frequent mowing at putting green heights and ‘Diamond’ demonstrated excellent shade tolerance

(Qian and Engelke, 2000; Atkinson et al., 2012). Concerns that made producing industry standard putting greens a significant challenge with ‘Diamond’ included slow establishment, stiff, rigid leaf blades, and prolific seed-head production (Stiglbauer et al., 2009; McCullough et al., 2017).

The National Turfgrass Evaluation Program (NTEP) initiated a putting green trial in 2013 that included several new zoysiagrass and ultradwarf bermudagrass cultivars and experimental lines. Experimental zoysiagrass DALZ 1308 (Chandra et al., 2020) was considered one of the best zoysiagrass entries and produced turf quality that rivaled many of the ultradwarf bermudagrass varieties tested (Morris, 2015). DALZ 1308 was developed at Texas A&M and is presently known as the cultivar ‘Lazer’ (*Zoysia matrella* (L.) Merrill *x Z. minima* (Colenso) Zotov*)*. Other greens-type zoysiagrass cultivars include ‘Trinity’ (Doguet and Lehman, 2014), tested experimentally as L1F, ‘Primo’, tested as M85 (Doguet et al., 2016), and ‘Prism’, tested as M60 (Doguet et al., 2018), which are all *Z. matrella* cultivars discovered in fields under cultivated conditions near Poteet, TX. ‘Lazer’, ‘Trinity’, ‘Primo’, and ‘Prism’ zoysiagrass are all currently licensed and distributed by Bladerunner Farms (Poteet, TX). Although the development of new genetic lines is a significant advancement, additional field work will be needed to determine the environmental limits, appropriate cultural practices, and inputs required to produce highest quality putting surfaces in the transition zone. Ultimately, for zoysiagrasses to be successful in the transition zone, they must produce putting green conditions that are similar to the current industry standards, ultradwarf bermudagrass and creeping bentgrass.

C_3 and C_4 photosynthesis

Photosynthesis is the process in which plants convert light energy from the sun into carbohydrates needed for plant growth and development. Cool-season grasses are referred to as C_3 grasses for the pathway in which they fix carbon during photosynthesis, the Calvin cycle. The Calvin Cycle primarily takes place within the leaves of plants where light energy is absorbed by chloroplasts located inside the mesophyll tissue and ribulose bisphosphate (RuBP) and CO_2 react. The reaction is catalyzed by 1,5-bisphosophate carboxylase (rubisco) and the result is 3-phosphogylyceric acid (PGA) and the release of oxygen (Fry and Huang, 2004). When PGA is reduced, a three-carbon sugar is formed that ultimately produces glucose and fructose, supplying energy to the plant. A wasteful, alternative pathway also occurs in C_3 plants and is termed photorespiration. Photorespiration commonly occurs at greater temperatures, where the key enzyme, rubisco, favors oxygenase activity over carboxylation (Sage and McKown, 2006). Photorespiration is the primary reason C_3 grasses are not well-adapted to the hot summers in the transition zone. Cool-season grasses have an optimum air temperature range of 16 to 24 °C for shoot growth and 10 to 18 °C soil temperature for root growth (Fry and Huang, 2004). These temperature ranges are also the optimum temperatures for photosynthesis for C_3 plants and photorespiration is more pronounced when temperatures exceed this range.

Warm-season grasses, or C4 grasses, have the unique ability to concentrate CO_2 into the leaf where rubisco is located, increasing the ratio of CO_2 and O_2, which prevents photorespiration. The name C_4 comes from the four-carbon intermediate stage that gives warm-season plants the unique ability to efficiently photosynthesize. The optimum temperatures for C_4

grasses to photosynthesize are between 27 and 35°C (Beard, 1973), meaning warm-season grasses are more adapted for summer in the transition zone regarding temperature.

Light is another important factor that determines the photosynthetic ability of C_3 and C_4 grasses. The light compensation point, or the minimum light level required for plants to photosynthesize, is defined as the intensity of light at which the rate of CO_2 fixation and loss of CO_2 by respiration are equal (Fry and Huang, 2004). Cool-season grasses have a lower light compensation point than C_4 grasses, which gives C_3 grasses the ability to tolerate lower light levels. A similar concept is the light saturation point, which is the intensity of sunlight required to reach maximum photosynthesis (Taiz and Zeiger, 2015). Cool-season grasses have a light saturation point that translates to about 50% full sunlight, while C_4 grasses require full sunlight to reach the light saturation point (Taiz and Zeiger, 2015). The strengths and limitations of the photosynthetic pathways of C_3 and C_4 grasses further explain the types of environments each grass species will survive, ultimately leading to enhanced selection and cultural practices for producing high quality putting greens in the transition zone.

Freeze tolerance and winterkill

An ongoing challenge associated with the use of warm-season grasses in the transition zone is winterkill (Richardson et al., 2014). Winterkill is a generic term used to describe turfgrass injury that occurs over the winter months and is typically associated with either direct low-temperature stress, winter desiccation, or low-temperature diseases (Beard, 2005). One method to compare freezing tolerance of different grass species is conducting laboratory studies in controlled environments. Ahring and Irving (1969) pioneered the use of laboratory studies to estimate and compare the freeze tolerance of warm-season grasses, comparing differences in bermudagrass cultivars. Results demonstrated significant differences within species, with cultivars like ‘Afghanistan’ and ‘Yugoslavia’ being more winter hardy than ‘Coastal’, ‘common’, and ‘Midland’ (Ahring and Irving, 1969).

Anderson et al. (2002) conducted laboratory freeze-tolerance tests on the three most common cultivars of ultradwarf bermudagrass, ‘Champion’, ‘MiniVerde’, and ‘TifEagle’. The authors used a term, LT_{50}, to quantify cultivar effects and defined LT_{50} as the specific temperature at which 50% of a given cultivar fails to survive after low-temperature exposure. ‘TifEagle’ (-6.0° C) proved to be the hardiest of the new ultradwarf cultivars, followed by ‘MiniVerde’ (-5.8° C) and ‘Champion’ (-4.8° C) (Anderson, 2002). More recently, Gopinath et al. (2021) investigated the LT_{50} of ‘Champion’, ‘TifEagle’, and ‘Tahoma 31’. The mean LT_{50} values were -5.9, -6.3, and -7.8 ° C for ‘Champion’, ‘TifEagle’, and ‘Tahoma 31’, respectively (Gopinath et al., 2021). ‘Tahoma 31’ is not considered a putting green cultivar, however, the observed LT_{50} temperature represents gains in bermudagrass breeding efforts to potentially increase cold hardiness (Gopinath et al., 2021). Field trials at the University of Arkansas confirmed these laboratory findings, with TifEagle and MiniVerde having increased winter survival compared to Champion (DeBoer et al., 2019).

Similar studies have been conducted on several experimental selections and hybrids of zoysiagrass compared to ‘Meyer’ zoysiagrass (*Z. Japonica* L.*)* by Wu et al. (2017). The LT_{50} values were reported to range from –9.3° C for ‘Meyer’ to –4.8° C for DALZ 1304 zoysiagrass (Wu et al., 2017). ‘Lazer’ zoysiagrass was included under the experimental name DALZ 1308 and had an LT_{50} of -6.0° C, comparable to the freeze tolerance of ultradwarf bermudagrass (Anderson et al., 2002; Wu et al., 2017; Gopinath et al., 2021). The lethal temperatures discussed reveal differences among warm-season species and cultivars as well as the range of temperatures that yield concern for survival if sustained for extended periods.

Protective covers and air gaps

The use of protective covers during the winter season is a proven strategy to combat winterkill in both warm- and cool-season grasses. The benefits of covers on the protection of putting greens are often attributed to moisture and temperature regulation at the crown of the turfgrass plant. Covers enhanced survival of bermudagrass by retaining more moisture in the crowns compared to uncovered checks (Shashikumar and Nus, 1993). Reduction in temperature fluctuation and increases in soil temperature have been measured using protective covers on ultradwarf bermudagrass putting greens compared to uncovered checks (DeBoer et al., 2019a; Goatley et al., 2007). Historically, it was recommended that ultradwarf bermudagrass putting surfaces be covered when the predicted low temperature was going to be -4° C or lower (O'Brien and Hartwiger, 2013). Recent field trials have demonstrated that the predicted temperature for covering greens can be lowered to –9.4° C with no reduction in winter survival (DeBoer et al., 2019a). However, even when covers are used, winterkill can still be observed on putting greens in more northern locations of the transition zone. As such, additional protection for ultradwarfs may be necessary to further reduce the risk of winter injury.

The addition of an “air gap” could be a valuable tool in regulating extreme low temperatures, especially as ultradwarf putting greens are established in more northern locations. An air gap prevents the cover from coming directly in contact with the surface of the putting green, possibly providing additional insulation and warmer temperatures than covers alone. Pine tree (*Pinus spp.*) straw has been used to protect putting greens during the winter months for almost 100 years (Beckett, 1929) and straw represents a potential air gap material. Dionne et al. (1999) investigated the use of various materials under impermeable covers to create an air gap to protect annual bluegrass (*Poa annua* L.*)* putting greens during the winter in two locations that received varying snowfall in Canada. Several treatments were tested including wood shavings, straw mulch, felt material, and a 5-cm air gap under an impermeable cover. At the location that received heavy snow cover (average of 42 cm), all treatments maintained soil temperatures around 0° C, even the uncovered control. At the location under thin snow cover (average of 6 cm), soil temperature variation was reduced, and the minimum soil temperatures were warmer with the air gap treatments including the treatments with a 5-cm air gap, curled wood, and straw (Dionne et al., 1999). This study highlighted both the effectiveness of heavy snow cover to provide insulation for putting greens, but also suggests that air gaps may also help regulate temperatures in areas that receive minimal snow cover.

Jared Nemitz, a golf course superintendent in North Carolina, has recently experimented with the use of air gaps. Both a 2.5- and 5-cm layer of pine straw and 10-cm drainage pipe spaced 1.5 m apart were evaluated to create an air gap underneath protective covers during the winter months at the Peninsula Club (Jared Nemitz, personal communication). An observed advantage of the drainage pipe was that removal of the drainage pipe only took 4 hours compared to the 8 hours required to clean up pine needles. Most golf courses in the transition zone are expected to uncover putting greens during warmer periods of winter weather to open the golf course for play and the time savings of the drainage pipe over the pine straw is significant. Both air gap treatments maintained warmer soil temperatures at a 5-cm depth compared to the cover alone (O'Brien, 2017).

In a recent field study conducted at the University of Arkansas, DeBoer et al. (2019b) experimented with the inclusion of a synthetic “batting” material to create an air gap underneath covers. The batting material (Hendrix Batting, High Point, NC), made of polyester, was placed underneath permeable covers like other air gap treatments previously discussed. The results demonstrated that batting material may be an alternative to organic materials like straw, as batting material provided significantly warmer temperatures at a 2.5-cm soil depth compared to a cover alone (DeBoer et al., 2019b). However, limited research exists on the use of air gaps, in combination with covers to protect warm-season putting greens from winterkill. Therefore, the objective of the first trial was to evaluate various materials for producing an air gap and assess their effectiveness at moderating soil temperatures and enhancing winter survival and spring green-up. In addition, a detailed cost analysis of materials of various products was provided. It was hypothesized that placing an air gap under a protective cover will provide additional insulation of bermudagrass putting greens and enhance survival during a harsh winter in the transition zone.

Shade

Without proper species selection, fertility, and cultural practices, turfgrass grown in environments with reduced sunlight will eventually fail. It has been estimated that approximately 25% of turfgrass sites are affected by shade from trees, buildings, and structures, such as stadiums (Beard, 1973). When exposed to shade, warm-season grasses like bermudagrass and zoysiagrass, exhibit a reduction in lateral stem development, while increasing internode length (McBee and Holt, 1966; Dudeck and Peacock, 1981). These symptoms can appear rapidly, often in as little as 4 to 7 days, and this morphological limitation is the primary limiting factor for warm-season grasses grown in the shade (McBee, 1969; Beard, 1997). Regular mowing can damage etiolated turfgrass by removing more turfgrass than is sustainable for turf health, a phenomenon referred to as scalping (Watschke, 1978). Scalping depletes the turfgrasses' carbohydrates and removes leaves used to absorb sunlight, therefore, reducing the plant's ability to regenerate new plant tissue after loss from stresses such as pests and traffic, which ultimately leads to a reduction in density of turfgrass stands and undesirable golf course playing surfaces (Dudeck and Peacock, 1981). Not only does reduced light affect the physical turfgrass plant, but light reduction can also drastically reduce photosynthetic potential. Leaf area for light interception is decreased under shade and more functional leaf tissue is often removed due to the etiolation in response to shade. These effects are caused primarily due to a reduction in the quality and quantity of light energy needed for photosynthesis and plant survival.

Trinexapac-ethyl

Trinexapac-ethyl (TE) is a synthetic growth regulator that interferes with the synthesis of the growth-promoting plant hormone, gibberellic acid, and has been demonstrated to improve turfgrass quality when grown under shade. A structural mimic of 2-oxoglutaric acid, TE blocks the later stages of gibberellin biosynthesis and inhibits the 3B-hydroxylase from converting gibberellic acid-20 to gibberellic acid-1 (Rademacher, 2000). Plants react to TE treatment with a reduction in shoot growth, making TE effective at preventing lodging of cereal crops, reducing vegetative growth of fruit trees, and slowing turfgrass growth rate (Rademacher, 2000).

Qian et al. (1998) conducted a greenhouse experiment to assess the effects of TE on 'Diamond' zoysiagrass exposed to three shade levels (40, 75, and 88% shade). Measurable differences were observed in canopy height, tiller density, rhizome dry mass, and total non-structural carbohydrates with repeated applications of TE, which was favorable compared to the non-shaded controls. Turfgrass quality declined below commercially acceptable quality in all 88% shade treatments, however TE caused the turfgrass to decline at a slower rate. Similarly, turfgrass quality declined below acceptable levels without TE treatment at 75% shade, while plots treated with TE maintained acceptable turfgrass quality throughout the duration of the study, demonstrating the ability of TE to improve the shade tolerance of zoysiagrass (Qian et al., 1998).

Ervin et al. (2004) conducted a field trial on creeping bentgrass grown in 88% constant shade and treated with TE every 14 days. Untreated controls fell below acceptable quality two months into the trial, while TE-treated plots had 33 to 44% greater quality ratings for the duration of the two-year trial. An observation during this study was that TE-treated turfgrass exhibited consistently darker green leaf tissue than untreated controls, a characteristic linked to increased mesophyll cell density and chlorophyll concentration (Ervin et al., 2004). Although the darker green color resulting from TE application may be desirable, color improvement is not the cause of improved shade-tolerance but does have other implications on management practices. Grass clippings harvested from mowing of putting greens are collected and removed to have minimal impact on playability, which is a major loss mechanism for nitrogen. Repeated applications of TE provide consistent growth suppression and have the potential to reduce nitrogen inputs by 25 to 50% on creeping bentgrass putting greens (Kreuser and Soldat, 2012). These studies indicate that the primary reason shade-tolerance is improved with TE application is a result of restricted leaf elongation, which conserves photosynthate, and has the potential to reduce fertilizer inputs, while maintaining high-quality turfgrass.

Daily light integral (DLI)

Because turfgrasses in the golf course environment are often grown in close proximity to trees and other structures, shade can significantly impact the overall health and performance of various turfgrasses. Sunlight gives off a wide range of wavelengths ranging from 200 to 1,800 nanometers, but plants can only use light in the range of 400 to 700 nanometers for photosynthesis, and that narrow band is commonly referred to as photosynthetically active radiation or PAR. To assess the amount of light at a given site, a PAR sensor can be used to obtain an instantaneous measurement of PAR that is reported in μmol m^{-2} s^{-1}. To quantify the amount of PAR a site receives over the entire day, readings must be taken throughout the day and integrated to calculate a daily total PAR or the Daily Light Integral (DLI), expressed as mol m^{-2} day^{-1} (Richardson and Kruse, 2015). The establishment of a minimum DLI requirement for various turfgrass species or cultivars has been a popular topic in recent research, as determining the minimum DLI provides guidance on where a grass can be effectively grown depending on intensity of management.

The first minimum DLI for golf course putting greens was reported by Bunnell et al. (2005a), who established that 'TifEagle' bermudagrass mown at 3.2 mm required a minimum DLI of 32.6 mol m^{-2} d^{-1} to maintain acceptable quality. In that trial, three shade levels were applied with shade cloth (0, 41, and 92% shade) during either morning hours, afternoon hours, neither, or both, to ensure that all plots got full irradiance during the middle of the day. Afternoon shade was more problematic than morning shade to 'TifEagle' bermudagrass and plots receiving shade in the morning had reduced visual quality and total non-structural carbohydrate counts (Bunnell et al., 2005a). To examine the impact of management practices on the DLI of ‘TifEagle’, Bunnell et al. (2005b) also tested two mowing heights, application of gibberellic acid, trinexapac-ethyl, and additional nitrogen fertility as growth factor treatments to the trial. Raising mowing heights (3.2 to 4.7 mm) and the application of trinexapac-ethyl every 3 weeks at 0.0393 kg a.i. ha^{-1} resulted in a minimum DLI value of 22.1 mol m^{-2} d^{-1} to maintain acceptable quality of ‘TifEagle’ bermudagrass (Bunnell et al., 2005b). It should be noted that shade stress was only induced for an 8-week period in both studies (Bunnell et al., 2005a; Bunnell et al., 2005b), which could limit the reliability of the DLI value, especially for golf course sites that receive season-long shade stress.

Atkinson et al. (2012) conducted a 2-year shade trial to determine the light requirements of ‘Diamond’ zoysiagrass maintained at a mowing height of 3.2 mm. Shade was applied for 22 weeks for two growing seasons and treatment factors included shade level (0, 60, or 90% constant shade) and trinexapac-ethyl (0.013 kg a.i. ha^{-1} wk^{-1} or untreated). ‘Diamond’ zoysiagrass was able to maintain acceptable quality (>7) under the 60% shade treatment (DLI: 17.6 mol m^{-2} d^{-1}) over both years of the trial, excluding the final rating date in year 2. Plots treated weekly with trinexapac-ethyl maintained acceptable turfgrass quality under 60% shade for the duration of both years of the trial (Atkinson et al., 2012). The results of this trial suggest the minimum DLI of ‘Diamond’ zoysiagrass to be approximately 17.6 mol m^{-2} d^{-1} with weekly applications of trinexapac-ethyl and a higher light requirement without trinexapac ethyl, demonstrating the superior shade tolerance of zoysiagrass compared to bermudagrass mowed at 3.2-mm (Bunnell et al., 2005).

Most recently, Russell et al., (2019) found the minimum DLI to maintain an acceptable quality ‘Tyee’ creeping bentgrass in the transition zone to be approximately 30 mol m^{-2} d^{-1}. Four shade intensities were applied (0, 70, 80, or 90% shade) in either morning or afternoon hours in a two-year trial which occurred from May to October. Four chemical treatments were also tested in this trial including trinexapac ethyl at 0.028 kg a.i. ha^{-1} every 14 days, titanium oxide +zinc oxide (Turf Screen) applied every week, the combination of both products, and an untreated control. Inconsistent observations in turfgrass quality as affected by morning and afternoon shade were observed, however, afternoon shade was more detrimental to turfgrass quality in the first year of the trial. Turfgrass quality was slightly improved with the application of both chemical treatments, however, did not significantly reduce the minimum light requirements of creeping bentgrass (Russell et al., 2019)

Zoysiagrass, as a species, has consistently demonstrated excellent shade tolerance (Qian and Engelke, 2000; Atkinson et al. 2012) in comparison to more widely-used warm-season grasses such as bermudagrass. However, there have been minimal direct comparison of zoysiagrass and bermudagrass under shaded conditions, especially at putting green heights of cut. Therefore, the objectives of this field trial were to determine the minimum DLI requirement to maintain acceptable quality of ‘TifEagle’ bermudagrass and ‘Lazer’ zoysiagrass as influenced by shade intensity, mowing height, and growth regulator treatment. Another objective was to monitor the surface characteristics of each species with green speed and surface firmness measurements to determine if ‘Lazer’ zoysiagrass produces a comparable putting surface to an industry-standard ultradwarf bermudagrass like ‘TifEagle’. It was hypothesized that ‘Lazer’ zoysiagrass would have superior shade tolerance to ‘TifEagle’ bermudagrass and produce comparable putting green surfaces throughout the growing season.

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II. Alternate Cover Approaches Using Air Gaps to Protect Ultradwarf Bermudagrass Putting Greens From Winterkill

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ABSTRACT

Winterkill remains a constant concern for golf courses managing warm-season grasses in the transition zone, especially on ultradwarf bermudagrass (*Cynodon dactylon* (L.) Pers *x C. transvaalensis* Burtt-Davy) putting greens. The use of protective covers is an essential management strategy used to prevent winterkill on putting greens. Unfortunately, golf courses in the northern transition zone have still experienced detrimental winterkill under protective covers. An observation made on putting greens that experienced winterkill underneath protective covers is a rippled appearance and enhanced survival underneath the stitched seams, suggesting the presence of additional air space enhances survival. The objective of this two-year field trial was to improve upon current cover strategies with the inclusion of air gaps underneath protective covers. The trial was conducted on a United States Golf Association (USGA) specification putting green established with four replications of 'TifEagle', 'MiniVerde', and 'Champion' ultradwarf bermudagrass. Five cover treatments were applied in a strip-plot design across all cultivars. Three air gap materials, composed of straw, batting fabric, or drainage pipe, were placed underneath protective covers and compared to a cover alone and an uncovered control. Soil temperature was continuously monitored at the 2.5-cm depth throughout the trial, and spring green-up was assessed using digital image analysis and visual quality ratings. The winter of 2019-20 was mild for the region and minimal winterkill was observed, although 'Champion' and the uncovered control had delayed spring green-up compared to other treatments. In 2020-21, all uncovered controls experienced widespread winterkill, regardless of cultivar. The straw and batting air gap treatments provided significantly warmer soil temperature on multiple rating dates in both years of the trial. However, the use of air gaps did not enhance spring green-up or winter protection of ultradwarf bermudagrass during either year of the trial compared to covers alone.

Because of the high purchasing cost and labor requirement associated, wall to wall coverage of air gaps is not necessary. Where air gaps could be valuable is spot coverage on portions of putting greens that are especially vulnerable to winterkill (shade, north slopes, high traffic) and historically receive winterkill.

BACKGROUND

The use of protective covers during the winter season is a proven strategy to combat winterkill in both warm- and cool-season grasses. The benefits of covers on the protection of putting greens are often attributed to moisture and temperature regulation at the crown of the turfgrass plant. Covers enhanced survival of bermudagrass by retaining more moisture in the crowns compared to uncovered checks (Shashikumar and Nus, 1993). Reduction in temperature fluctuation and increases in soil temperature have been measured using protective covers on ultradwarf bermudagrass (*Cynodon dactylon* (L.) Pers *x C. transvaalensis* Burtt-Davy) putting greens compared to uncovered checks (Goatley et al., 2007; DeBoer et al., 2019a). Historically, it was recommended that ultradwarf bermudagrass putting surfaces be covered when the predicted low temperature was going to be -4° C or lower (O'Brien and Hartwiger, 2013). Recent field trials have demonstrated that the predicted temperature for covering greens can be lowered to –9.4° C with no reduction in winter survival (DeBoer et al., 2019a). However, even when covers are used, winterkill can still be observed on putting greens in more northern locations of the transition zone. As such, additional protection for ultradwarf putting greens may be necessary to further reduce the risk of winter injury.

The addition of an "air gap" could be a valuable tool in regulating extreme low temperatures, especially as ultradwarf putting greens are established in more northern locations. An air gap prevents the cover from coming directly in contact with the surface of the putting green, possibly providing additional insulation and warmer temperatures than covers alone. Pine tree (*Pinus spp.*) straw has been used to protect putting greens during the winter months for almost 100 years (Beckett, 1929) and straw represents a potential air gap material. Dionne et al.

(1999) investigated the use of various materials under impermeable covers to create an air gap to protect annual bluegrass (*Poa annua* L.*)* putting greens during the winter in two locations that received varying snowfall in Canada. Several treatments were tested including wood shavings, straw mulch, felt material, and a 5-cm air gap under an impermeable cover. At the location that received heavy snow cover (average of 42 cm), all treatments maintained soil temperatures around 0° C, even the uncovered control. At the location under thin snow cover (average of 6 cm), soil temperature variation was reduced, and the minimum soil temperatures were warmer with the air gap treatments including the treatments with a 5-cm air gap, curled wood, and straw air gaps (Dionne et al., 1999). This study highlighted both the effectiveness of heavy snow cover to provide insulation for putting greens, but also suggests that air gaps may also help regulate temperatures in areas that receive minimal snow cover.

Jared Nemitz, a golf course superintendent in North Carolina, has recently experimented with the use of air gaps. Both a 2.5- and 5-cm layer of pine straw and 10-cm drainage pipe spaced 1.5 m apart were evaluated to create an air gap underneath protective covers to during the winter months at the Peninsula Club (Jared Nemitz, personal communication). An observed advantage of the drainage pipe was that removal of the drainage pipe only took 4 hours compared to the 8 hours required to clean up pine needles. Most golf courses in the transition zone are expected to uncover putting greens during warmer periods of winter weather to open the golf course for play and the time savings of the drainage pipe over the pine straw is significant. At times, both treatments maintained between 1.1- and 3.3° C warmer soil temperatures at a 5-cm depth compared to the cover alone (O’Brien, 2017).

In a recent field study conducted at the University of Arkansas, DeBoer et al. (2019b) experimented with the inclusion of a synthetic "batting" material to create an air gap underneath covers. The batting material (Hendrix Batting, High Point, NC), made of polyester, was placed underneath permeable covers like other air gap treatments previously discussed. The results demonstrated that batting material may be an alternative to organic materials like straw, as batting material provided significantly warmer temperatures at a 2.5-cm soil depth compared to a cover alone (DeBoer et al., 2019b). However, limited research exists on the use of air gaps, in combination with covers to protect warm-season putting greens from winterkill. Therefore, the objective of the present study was to evaluate various materials for producing an air gap and assess their effectiveness at moderating soil temperatures and enhancing winter survival and spring green-up. In addition, a detailed cost analysis of materials and labor associated with the application of various products was provided. It was hypothesized that placing an air gap under a protective cover will provide additional insulation of bermudagrass putting greens and enhance survival during a harsh winter in the transition zone.

MATERIALS AND METHODS

A two-year field study was conducted at the Milo J. Shult Agricultural Research and Extension Center in Fayetteville, AR (36°06' N, 94°10' W) during the winters of 2019-2020 and 2020-2021 on an existing sand-based putting green built in 2013 consistent with USGA recommendations (USGA, 2004). The green consisted of four replicated plots (4.0 x 12.0 m) of 'TifEagle', 'Champion', and 'MiniVerde' ultradwarf bermudagrass (Fig. 1) and was maintained using cultural practices that are typical for ultradwarf bermudagrass putting greens in the region. Management practices included mowing six times weekly during the growing season at a bench height of cut of 3.2 mm using a Toro Triflex 3300 (The Toro Company, Bloomington, MN) and sand-topdressed every two weeks to dilute organic matter at an approximate rate of 225 $cm^3 m^{-2}$ with sand consistent with USGA recommendations. Preventative fungicide applications were made each fall to control spring dead spot (*Ophiosphaerella korrae* Walker and Smith) and monthly applications of soil surfactants were used to prevent soil hydrophobicity. Nitrogen was applied every two weeks with a complete, granular fertilizer source (Contec DG 18-9-18, The Andersons, Maumee, OH) at a rate of 12 kg N $ha^{-1}$and supplemental applications of foliar applied urea (46%N) were routinely applied. Total annual N was approximately 195 kg N ha^{-1}.

Permeable, black woven polypropylene protective covers (Xton, Inc. Florence, Al) were used for all treatments in this trial. Cover treatments consisted of an uncovered control, cover only, and three different air gap treatments that were placed under the protective cover (Table 1, Fig. 2 and 3). Protective covers and the air gap treatments were placed on the green when the predicted low temperatures were -6.7° C (Fig. 4). Predicted low air temperature data for Fayetteville, AR was obtained from the National Oceanic and Atmospheric Admiration website (www.noaa.gov). To replicate golf course conditions, covers were removed when the daytime high air temperatures were predicted to be above 7.2 ° C for consecutive days to simulate a golf facility being open for customers. The entire experimental area was covered during spring green-up if predicted low temperatures were expected to cause frost damage. Covering events were timed to estimate the labor cost associated with applying and removing the air gap treatments compared to covers alone.

Data collection and analyses

Soil temperature was continuously monitored from December through April with Onset temperature sensors (TMC50-HD, Onset Company, Bourne, MA) at a 2.5-cm depth in the center of plots. Soil temperature was recorded every 30 minutes and stored on a 4-channel data logger (HOBO U12, Onset Company, Bourne, MA). Minimum and maximum daily soil temperature was determined for each cover treatment throughout the entire season.

Turfgrass coverage was evaluated weekly from March to May using digital image analysis (Richardson et al., 2001). Pictures of each plot were taken using a digital camera (Canon PowerShot G12, Canon Inc., Melville, NY) mounted 55 cm off the turf surface in an enclosed lightbox. The bottom of the light box measured 1850 cm^2 in area and had four TCP 9W florescent light bulbs (TPC, Inc., Item#4890965, Aurora, OH) mounted inside to provide a consistent light source for each evaluation date. The Turf Analyzer software program was used to analyze turfgrass coverage in the images (Karcher et al., 2017; http://turfanlyzer.com). Within Turf Analyzer, a hue setting of 82 to 172 and saturation setting of 10 to 100 was used to select the green pixels in each image and determine the percentage of green turfgrass coverage.

Spring green-up was evaluated bi-weekly from March to May. Spring green-up ratings were evaluated consistent with the National Turfgrass Evaluation Program standards based on color, in which a rating of 1 represented a straw brown color and a rating of 9 represented complete green color throughout the turf surface (Morris and Shearmen, 1998).

The experimental design for the trial was a strip-plot design with four replications of each treatment. Strip-plot treatments included the two factors, cultivar and cover treatments. A repeated measures analysis of variance using PROC MIXED (SAS v 9.4, SAS Institute, Cary, NC) was used to evaluate the effects of cultivar and cover treatments on green turf coverage and turfgrass quality over time. Slicing was performed in PROC MIXED to identify evaluation dates when treatment effects were significant. Treatment means were separated using Fisher's protected LSD ($\alpha = 0.05$).

RESULTS

Weather and covering events

Air temperatures in the winter of 2019-20 were relatively mild and posed minimal threat of winterkill. The lowest recorded air temperature was -9.2 °C, recorded on 15 February 2020 (Fig. 5). There were eight days with a recorded air temperature less than -6.7 °C in 2019-20 (Fig. 5). There were four covering events that occurred from 10 Jan. to 14 Jan., 17 Jan. to 27 Jan., 12 Feb. to 17 Feb., and 20 Feb. to 28 Feb. 2020 for a total of 31 days (Fig. 5).

Air temperatures in the winter of 2020-2021 were more favorable for winterkill. The lowest recorded air temperature was -23.9 °C (Fig. 5). There were 12 days with a recorded air temperature less than -6.7 °C and for a 10-day period from 9 Feb. to 19 Feb., the air temperature did not exceed 0 °C (Fig. 5). There were four covering events in 2020-21 that occurred from 22 Dec. to 27 Dec. 2020, 6 Jan. to 12 Jan, 26 Jan. to 29 Jan., and 5 Feb. to 23 Feb 2021 for a total of 36 days.

Soil temperature

In the 2019-20 winter, the minimum soil temperature in the uncovered control fell below 0°C on 18 to 20 Jan., 5 to 7 Feb., 12 to 13 Feb., 20 to 21 Feb., and on 26 Feb., for a total of 11 days (Fig. 6). The lowest average minimum soil temperature recorded in the uncovered control was -2.1 °C on 20 February. The lowest average soil temperature in all covered treatments occurred on 6 Feb. and were 0.1 °C in the cover only, -0.4 °C in the cover plus straw and cover plus pipe treatments, and -0.5°C in the cover plus batting. On the three coldest days during the trial (21 Jan., 14 Feb., 21 Feb.), the minimum soil temperature in the uncovered control was significantly colder than all covered treatments (Table 4). On 21 Jan. and 14 Feb., the minimum soil temperature in cover plus straw was significantly warmer than the cover plus pipe treatment, but did not differ from other covered treatments (Table 4). On 21 Jan., the daily maximum soil temperature was significantly warmer in the cover plus pipe treatments compared to the cover plus straw, but did not differ from other covered treatments (Table 4). On 21 Feb., the cover plus pipe and uncovered control were significantly warmer than the cover plus straw and cover plus batting (Table 4). Results suggest that all cover treatments performed similarly, excluding the cover plus pipe treatment which slightly underperformed other cover treatments. The cover plus straw and cover plus batting had minor advantages to the cover plus pipe treatment, however, generally performed similarly to the cover alone.

In the 2020-21 winter, the minimum soil temperature in the uncovered control fell below 0°C on 25 Dec, 10 to 13 Jan., and 10 to 23 Feb. for a total of 19 days (Fig. 6). The lowest minimum soil temperature recorded in the uncovered control was -7.1 °C on 14 Feb., -1.2 °C on the cover plus pipe on 14 Feb., -0.7 °C on the cover alone on 15 Feb., -0.6 °C on the cover plus batting on 16 Feb., and 0.2 °C on the cover plus straw treatment on 17 Jan. (Fig. 6). On two of the three coldest days of the 2020-21 (12 Jan. and 14 Feb.), the minimum 2.5-cm soil temperature in all covered treatments was significantly warmer than in the uncovered control (Table 5). On the coldest day of the trial (14 Feb.), the maximum soil temperature in the cover pus straw treatment was significantly warmer than the cover plus pipe treatment and the uncovered control but did not differ from the cover plus batting and cover only treatments (Table 5). Results suggest that all cover treatments, excluding the cover plus pipe, perform very similarly at moderating soil temperature and were consistent with results from the first year of the trial.

Green turfgrass coverage

During spring greenup in 2020, the main effects of date and cover treatment had a significant effect on green turfgrass coverage (Table 2). However, there was also a cover × date interaction and a cultivar × date interaction, so results will be discussed based on those two, higher-order interaction (Table 2). Averaged across cultivars, on six of seven rating dates, the uncovered control had significantly less green coverage than all covered treatments (Fig. 7). On the final rating date (6 May), all plots, regardless of cover treatment, had statistically similar turfgrass coverage (Fig. 7). Averaged across all cover treatments, all cultivars had similar green turfgrass coverage during the spring of 2020 (Fig. 8).

During the spring of 2021, the main effects of date and cover had a significant effect on green turfgrass coverage (Table 2). Results discussed will be from the highest-order interaction which was cover × date interaction on turfgrass coverage (Table 2). The uncovered control had significantly less green turfgrass coverage than all covered treatments on all rating dates (Fig. 9).

All covered treatments maintained statistically similar green turfgrass coverage for the duration of the spring of 2021 except for one rating date. On 29 Mar., the cover plus straw and cover plus batting treatments had significantly more turfgrass coverage than the cover alone (Fig. 9). On the final rating date, all covered treatments were similar (Fig. 9).

Turfgrass quality

In the spring of 2020, main effects of cultivar and cover had a significant effect on turfgrass quality (Table 3). ‘Champion’ had significantly lower turfgrass quality than both ‘TifEagle’ and ‘MiniVerde’ throughout spring greenup (Fig. 10). Average turfgrass quality ratings were 5.6, 5.3, and 4.6 for ‘TifEagle’, ‘MiniVerde’, and ‘Champion’, respectively (Fig. 10). The cover plus straw and cover plus batting treatments maintained greater turfgrass quality than the cover only and uncovered control (Fig. 10). The cover plus batting treatment maintained greater turfgrass quality than the cover plus pipe (Fig. 10). The cover alone maintained greater turfgrass quality than the uncovered control throughout the spring of 2020 (Fig. 10).

In the spring of 2021, there was a significant cover × cultivar interaction on turfgrass quality. The uncovered controls, regardless of cultivar, had significantly lower turfgrass quality than all covered plots (Fig. 11). All cover treatments, including the cover alone and air gap treatments, maintained similar turfgrass quality during the spring of 2021 except for the cultivar, ‘Champion’ (Fig. 11). The cover alone treatment of ‘Champion’ had lower turfgrass quality than all air gap treatments, demonstrating moderate increases in turfgrass quality during spring green-up with the use of air gaps (Fig. 11).

DISCUSSION

The value of protective covers during the winter months in the transition zone cannot be overstated. This field trial confirms the effectiveness of black, woven polypropylene Xton turf covers to provide adequate protection from winterkill through temperature moderation (DeBoer et al., 2019b). The upfront cost of purchasing covers is substantial, requiring an investment of \$1.88 per m^{-2} (O'Brien and Hartwiger, 2013). In survey data collected from the Golf Course Superintendents Association of America (GCSAA), the median size of putting greens on a typical 18-hole golf course in the transition zone is 12,990.4 m^{-2} (GCSAA, 2015). Therefore, for typical 18-hole golf facility in the transition zone, the initial investment of covers translates to approximately \$24,422 (Table 1).

All the air gap treatments tested, excluding the batting material, have a comparable cost to purchasing covers (Table 1), so including an air gap would effectively double the cost to cover greens. The straw and batting material are also less durable and have a shorter shelf-life than the Xton covers, therefore, would likely have to be replaced on a more regular basis. Furthermore, dry storage of these bulky materials could be challenging for most golf facilities. Jared Nemitz determined the labor cost associated with applying and removing protective covers without an air gap through seven seasons of record keeping and estimated the average cost of a covering and removal event to be \$742 in labor (Jared Nemitz, personal communication). Implementing air gaps underneath protective covers will likely lead to a substantial increase in labor cost associated with covering.

Although the use of air gaps may not be practical on a large scale, this trial demonstrates some benefits in soil temperature regulation with the straw and batting air gap treatments. Both the straw and batting air gap treatments did show the potential to maintain warmer soil temperatures than the cover alone (Fig. 6). As such, the straw or batting material could be valuable on small, problematic areas such as shaded portions of putting greens and north facing slopes. A recent field trial out of Virginia Tech University demonstrated positive results in reducing temperature fluctuations with the use of two permeable covers (double layered) in comparison to a single cover or a single cover with an air gap (Booth et al., 2019). Although double layering covers does double the upfront investment, covers have a longer shelf life than both straw and batting material and covers are easier to store efficiently than straw and bathing materials. Double layering would not likely need to be implemented as frequently as single covers, however, having the two covers for every putting green could potentially extend the life span of the covers. With two covers for every putting green and most covering events only requiring a single cover, golf courses could rotate the covers used annually to prevent excessive wear on one cover through repeated use. Cover distributors could consider marketing a single, thicker cover with the same physical properties as the covers double layered and market it towards ultradwarf managers in the northern transition zone who are looking for additional protection from winterkill. However, a downside to thicker, heaver covers is that the weight of two covers (102 g m^2 to 204 g m^2) could be challenging to move and only owning a thick cover eliminates the flexibility to apply single and double covers based off forecasted temperatures.

Because of the unique weather experienced in Fayetteville in February of 2021 (Fig. 13), some similar observations to Dionne et al. (1999) relating to the insulating properties of snow cover. There are many differences in the materials and methods used in this trial and Dionne et al (1999), including differenced in species tested (cool-season vs. warm-season grasses), cover composition (impermeable vs. permeable), cover application duration (season long vs.

temperature-based), and duration of snow cover (≥80 days vs 6 days). However, the lowest observed soil temperature on the uncovered controls occurred on 14 Feb. (-7.1 °C), two days prior to the lowest observed air temperature on 17 Feb. (Fig. 13). During this two-day period, the soil temperature trended warmer while the air temperature continued to decrease (Fig. 13). A potential explanation for this phenomenon is the occurrence of snowfall, as approximately 17.8-cm of snow fell from 14 Feb. to 18 Feb. Dionne et al. (1999) concluded that 6-cm of snowfall did not provide sufficient insulation to putting green surfaces, however, 42-cm was sufficient. This trial demonstrates the potential of 17.8-cm of snowfall to provide additional insulation to putting green surfaces through creation of a "natural air gap". Dionne et al. (1999) also concluded that covers alone do not provide the insulation that air gap treatments of curled wood, straw and air space provided, however, temperatures were not cold enough or did not last for a long enough duration during this trial to confirm that covers alone do not provide enough insulation, as the covers alone were sufficient.

Although marginal, some cultivar differences in turfgrass quality were observed. Similar to observations by DeBoer et al. (2019b), 'Champion' maintained significantly lower turfgrass quality than both 'TifEagle' and 'MiniVerde' in the spring of 2020 (Fig. 10). However, in the spring of 2021, 'Champion' did not experience more winterkill than 'TifEagle' and 'MiniVerde' (Fig. 12). Laboratory freeze-tolerance tests are used to compare freeze tolerance of cultivars by exposing phytomers (root, crown, and shoot material) to increasing low temperatures and assessing regrowth. Lethal temperature 50 (LT_{50}) values for each cultivar tested are determined, which was the temperature in which 50% of the exposed grasses receive lethal winterkill. Anderson et al. 2002 conducted freeze tolerance tests on ultradwarf bermudagrass cultivars and the LT_{50} values were -4.8, -5.8, and -6.0 for 'Champion', 'MiniVerde', and 'TifEagle', respectively. This field trial confirmed that lethal values (-7.1 °C), at the 2.5-cm soil depth, were reached on 14 Feb. 2021. More recent freeze tolerance tests on ‘Tahoma 31’ bermudagrass and three experimental genotypes out of Oklahoma State have determined LT_{50} values of ‘Tahoma 31 to range from -7.8 to 9.0 °C and -7.0 to -8.1 °C for the experimental genotypes. Gopinath et al. (2021) demonstrate gains in genetic breeding of bermudagrass could lead to more freeze-tolerant ultradwarf bermudagrass varieties that are more suitable for putting green use in the northern transition zone (Gopinath et al., 2021).

CONCLUSIONS

The present trial demonstrated the importance of protective covers to protect ultradwarf bermudagrass in the transition zone. This is the first trial which investigated the use of various air gap materials to supplement protective covers. Although moderate soil-temperature benefits were observed with air gap materials, protective covers alone prevented winterkill during the adverse winter of 2020-21. Air gaps may create additional burdens to golf courses including the high up front purchasing cost, storage challenges, and it is likely that air gap materials composed of batting material and straw will have to be replaced on an annual basis. The purchase of air gaps for wall-to-wall coverage is unnecessary and financially unfeasible for many golf courses, however, air gap materials composed of straw and batting could be valuable in areas of putting greens which historically receive winterkill including portions of putting greens that are shaded, north-facing, or weakened by traffic.

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TABLES

Table 1. Description of cover treatments and air gap materials, including description, physical properties, and cost required to cover an 18-hole golf course.

Treatment Name	Description	Thickness (cm)	Weight (g m^{-2})	Cost for typical golf course
Uncovered control	None			
Cover only	Black, woven polypropylene protective covers (Xton Inc. Florence, AL)	0.4	102	$24,422
Cover + straw	Erosion control mat (A.M. Leonard Horticultural Tool and Supply Co., Piqua OH)	4	792	$27,929
Cover + batting	Polyester (polyethylene terephthalate) batting (Hendrix Batting, High Point NC)	2.5	311	$15,718
Cover + ABS	Polyethylene drainage pipe with 15-cm diameter split in half lengthways and placed 2-m apart (Advanced Drainage Systems, Hilliard, OH)	7.5	320	$32,606

*Typical 18-hole golf course putting green area was assumed to be 12,990.4 m^{-2}, adapted from survey data conducted by GCSAA (2015).

Table 2. Analysis of variance testing the main effect and their interactions on green turfgrass coverage during the spring of 2020 and 2021.

Treatment effect	2020		2021	
	F Value	P > F	F Value	P > F
Rep	2.04	0.2096	3.16	0.107
Cultivar	1.47	0.3029	0.38	0.6987
Cover	6.61	0.0047	194.84	<.0001
Cover × cultivar	0.21	0.9856	0.86	0.5588
Date	807.66	<.0001	923.92	<.0001
Cultivar × date	2.1	0.026	1.54	0.1477
Cover × date	4.81	<.0001	52.26	<.0001
Cover × cultivar × date	0.29	1	0.54	0.9804

Table 3. Analysis of variance testing the main effects and their interactions on turfgrass quality during the spring of 2020 and 2021.

Treatment effect	**2020**		**2021**	
	F Value	P > F	F Value	P > F
Rep	0.31	0.8165	1.04	0.4388
Cultivar	14.78	0.0048	5.22	0.0486
Cover	26.31	<.0001	1223.81	<.0001
Cover × cultivar	1.12	0.386	2.34	0.0385
Date	220.04	<.0001	83.21	<.0001
Cultivar × date	2.18	0.0778	2.6	0.0027
Cover × date	1.74	0.099	6.63	<.0001
Cover × cultivar × date	1.64	0.0741	0.92	0.6317

Table 4. Average daily minimum and maximum 2.5-cm soil temperature (degrees Celsius) for the three coldest days of 2019-20 and separation among treatments.

Cover treatment	1/21/2020		2/14/2020		2/21/2020	
	--------------- minimum daily soil temperature (°C) ----------------					
Uncovered	-1.9	c	-2.0	c	-2.1	b
Cover only	1.8	ab	1.6	ab	1.7	a
Cover + batting	2.5	ab	2.1	ab	2.2	a
Cover + pipe	0.8	b	0.7	b	0.8	a
Cover + straw	3.2	a	3.3	a	2.4	a
LSD P=.05	2.4		2.0		2.0	
Treatment Prob (F)	0.0077		0.0026		0.0043	
	--------------- maximum daily soil temperature (°C) --------------					
Uncovered	6.6	c	9.5		12.7	a
Cover only	9.3	ab	10.4		11.6	ab
Cover + batting	8.7	ab	9.4		10.2	b
Cover + pipe	9.3	b	11.6		12.7	a
Cover + straw	8.1	a	8.7		9.3	b
LSD P=.05	1.8		NS		2.3	
Treatment Prob (F)	0.0405		0.2424		0.0338	

*Cover treatments, within rows, labeled with the same number are not significantly different. If no letter is listed, there was no significant difference (NS) between treatments on that date.

Table 5. Average daily minimum and maximum soil temperature (degrees Celsius) for the three coldest days of 2020-21 and separation among cover treatments.

Cover treatment	12/24/2020		1/12/2021		2/14/2021	
	------------ minimum daily soil temperature (°C) ----------------					
Uncovered	0.0		-1.0	b	-7.0	b
Cover only	2.3		1.1	a	-0.6	a
Cover + batting	2.9		1.1	a	-0.3	a
Cover + pipe	1.5		0.5	a	-1.1	a
Cover + straw	3.5		1.2	a	0.6	a
LSD P=.05	NS		1.2		2.1	
Treatment Prob (F)	0.0704		0.0191		0.0004	
	------------ maximum daily soil temperature (°C) ----------------					
Uncovered	2.7	c	4.0	b	-3.2	c
Cover only	6.4	a	8.1	a	0.4	ab
Cover + batting	6.2	a	8.4	a	0.5	ab
Cover + pipe	5.2	b	8.4	a	-0.2	b
Cover + straw	5.9	ab	9.0	a	1.2	a
LSD P=.05	0.7		1.6		1.4	
Treatment Prob (F)	0.0001		0.0009		0.001	

*Cover treatments, within rows, labeled with the same number are not significantly different. If no letter is listed, there was no significant difference (NS) between treatments on that date.

FIGURES

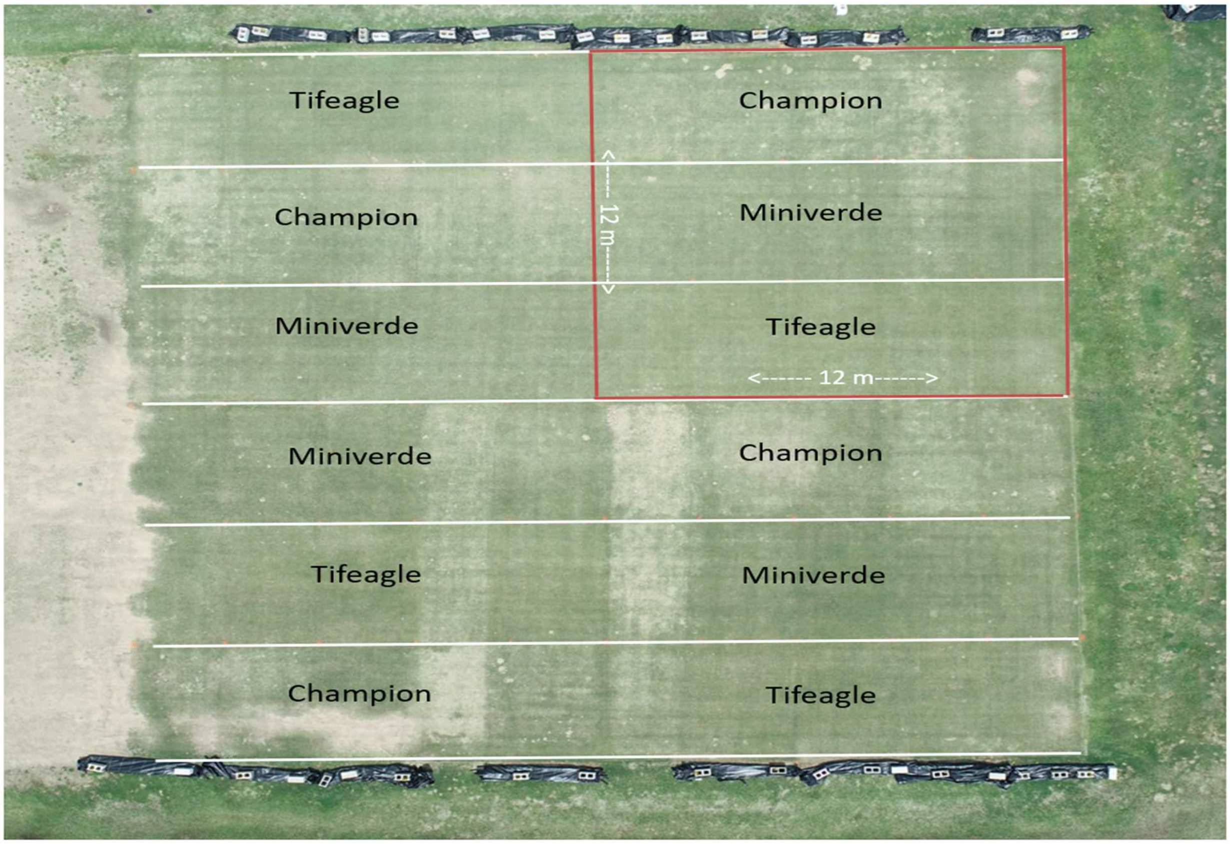

Figure 1. Aerial photograph of the experimental area showing the arrangement of cultivars on the experimental area. The red outline identifies one experimental block.

Figure 2. Random assignment of cover treatments to the experimental putting green. The four experimental blocks are identified by red lines.

Figure 3. Image of the air gap treatments; ABS (front right), straw (left), and batting (back right) prior to a covering event.

Figure 4. Photo of experimental area during a covering event on 6 Jan. 2021.

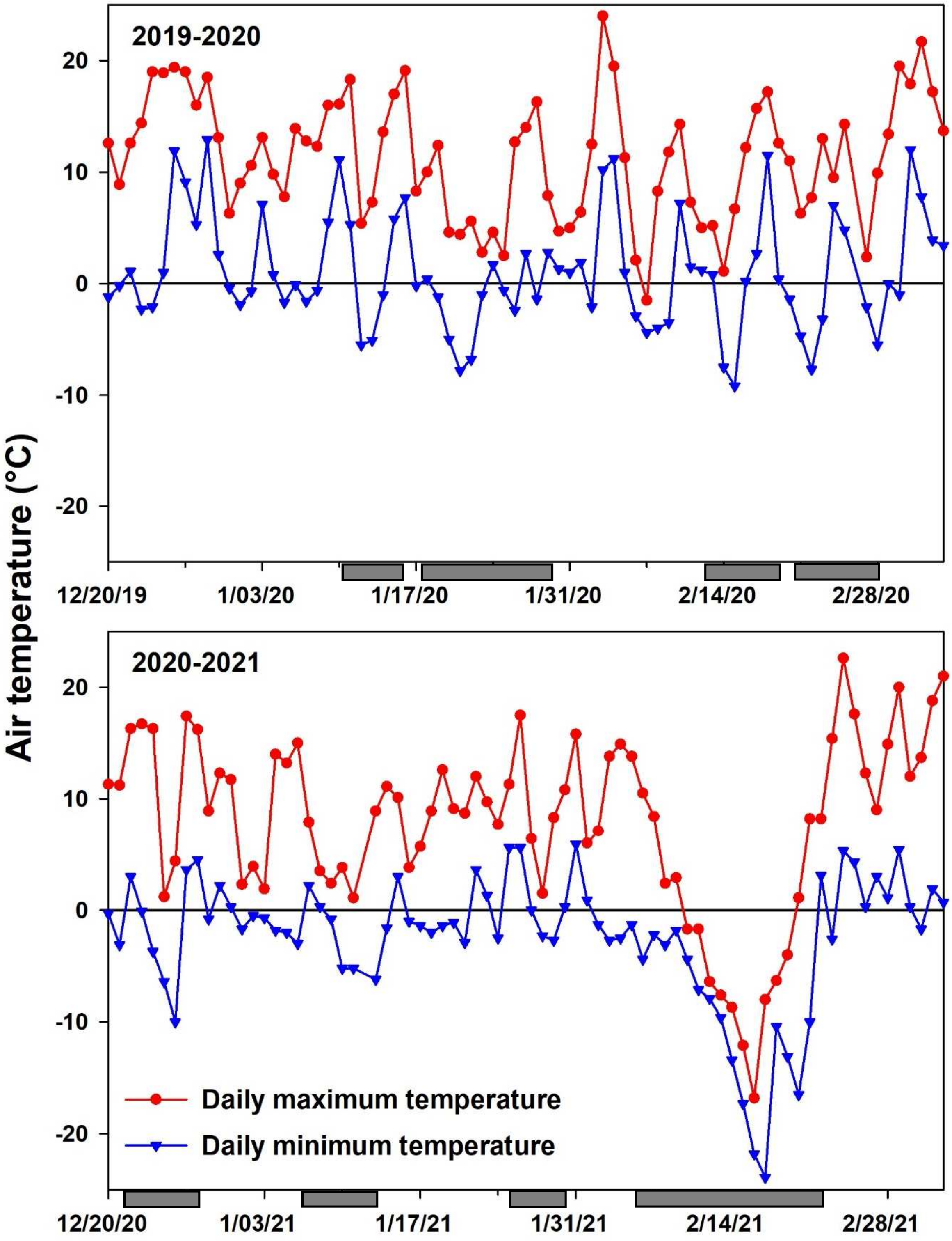

Figure 5. High and low air temperatures in Fayetteville, AR during the winters of 2019-20 and 2020-21. The grey boxes denote when the experimental area was covered.

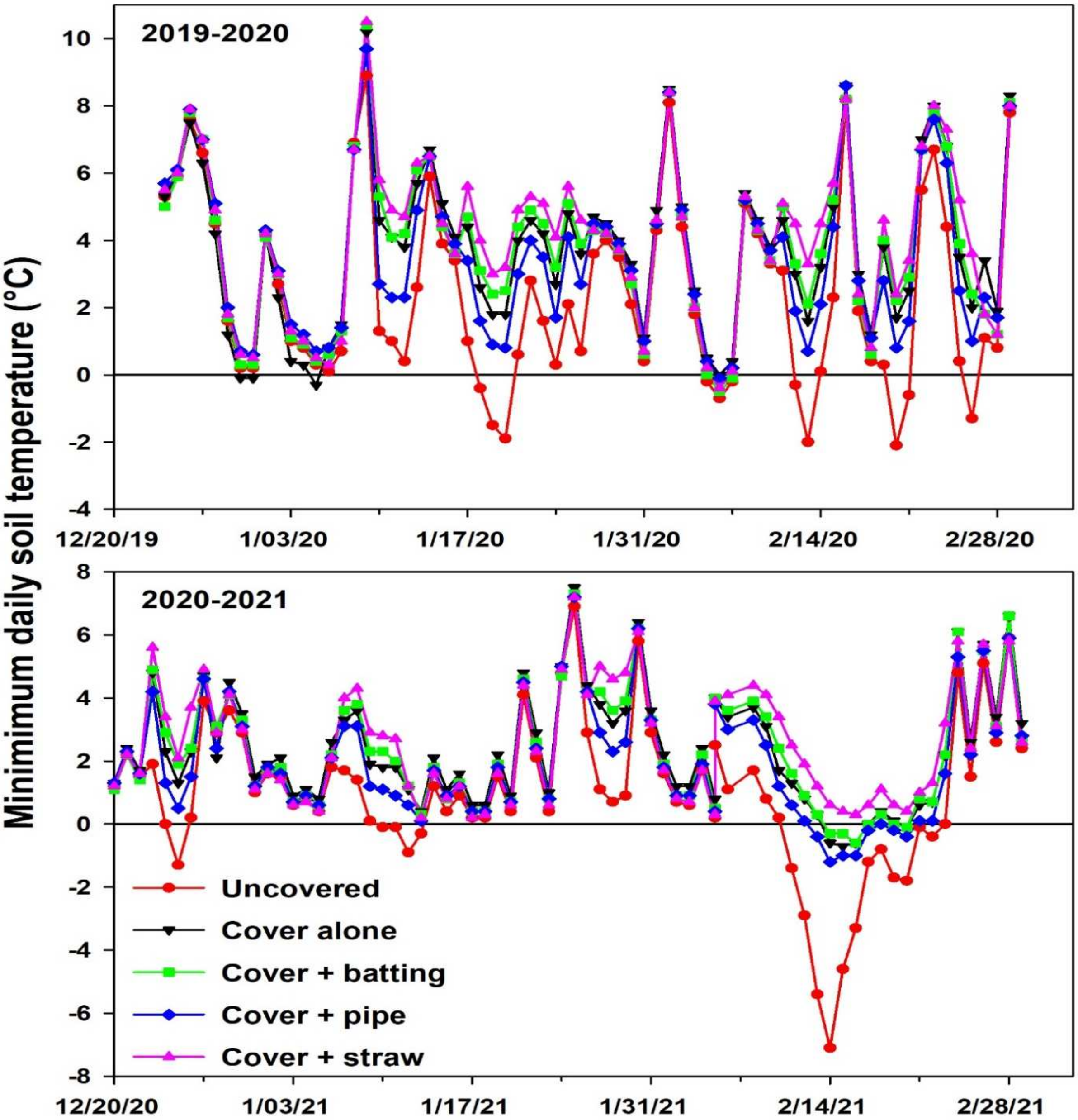

Figure 6. Minimum daily 2.5-cm soil temperature during the winter of 2019-20 and 2020-21 within each cover treatment.

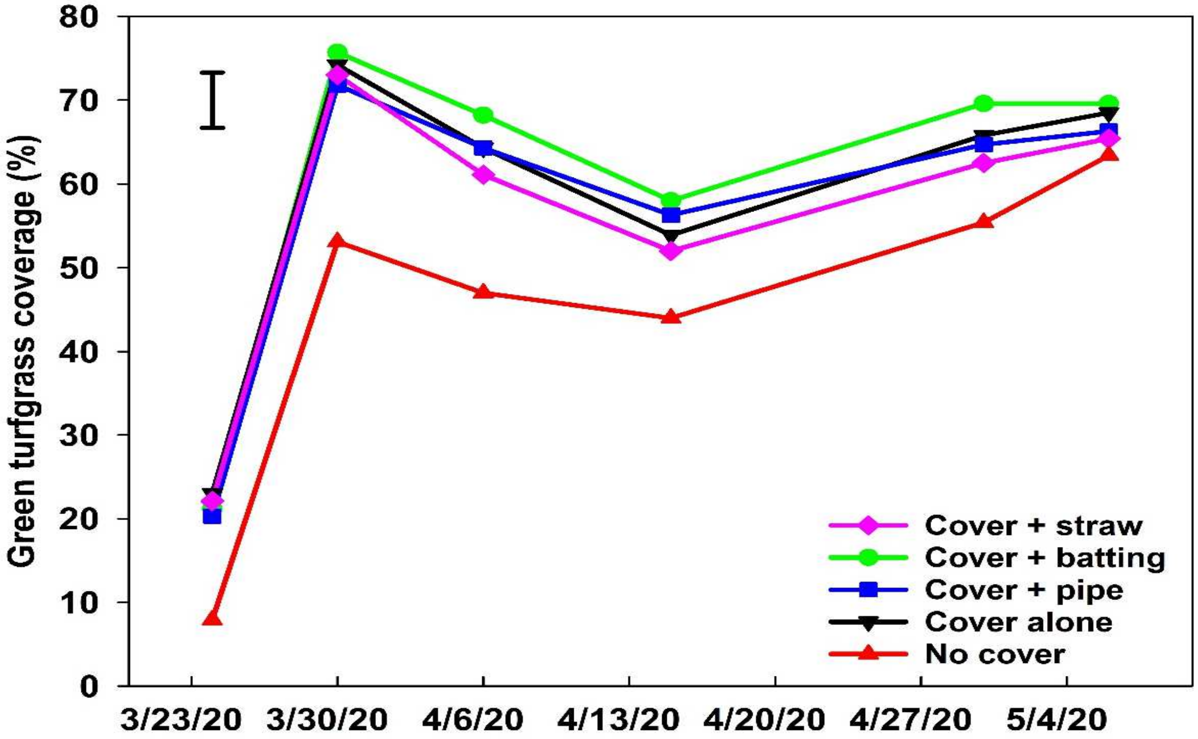

Figure 7. Percent green turfgrass coverage during the spring of 2020 among cover treatments over time. The error bars represent the least significant difference ($P \leq 0.05$) for mean comparisons.

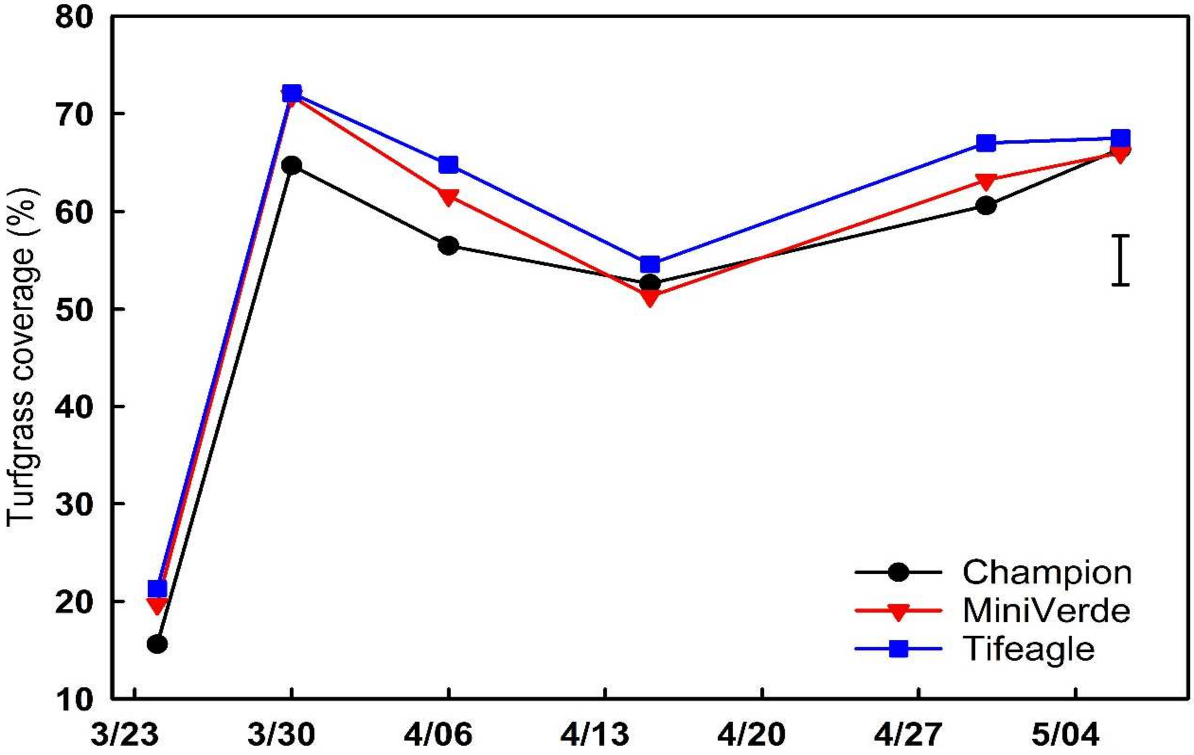

Figure 8. Percent green turfgrass coverage during the spring of 2020 among cultivars over time. The error bars represent the least significant difference ($P \leq 0.05$) for mean comparisons.

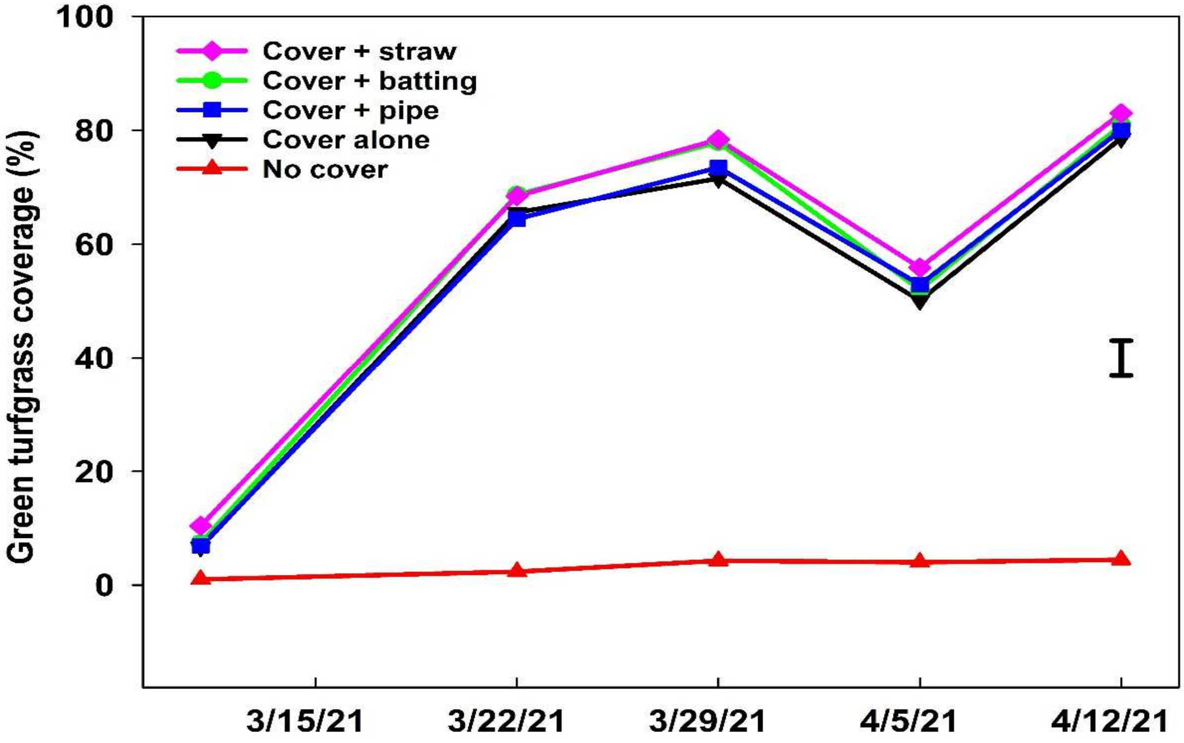

Figure 9. Percent green turfgrass coverage during the spring of 2021 among cover treatments over time. The error bars represent the least significant difference ($P \leq 0.05$) for mean comparisons.

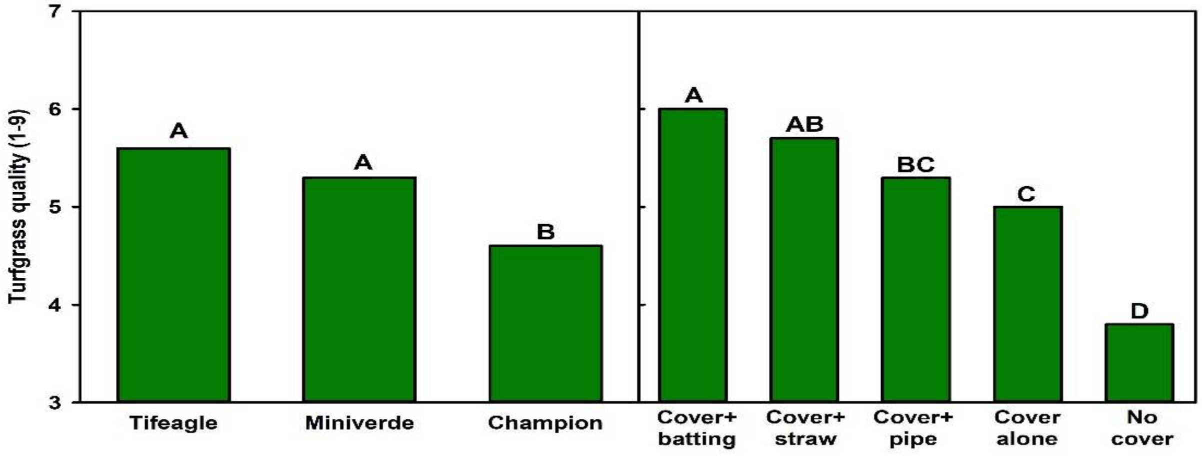

Figure 10. Turfgrass cultivar (left) and cover treatment (right) effects on turfgrass quality during the spring of 2020. Treatment means labeled with the same letter are not significantly different ($P \leq 0.05$).

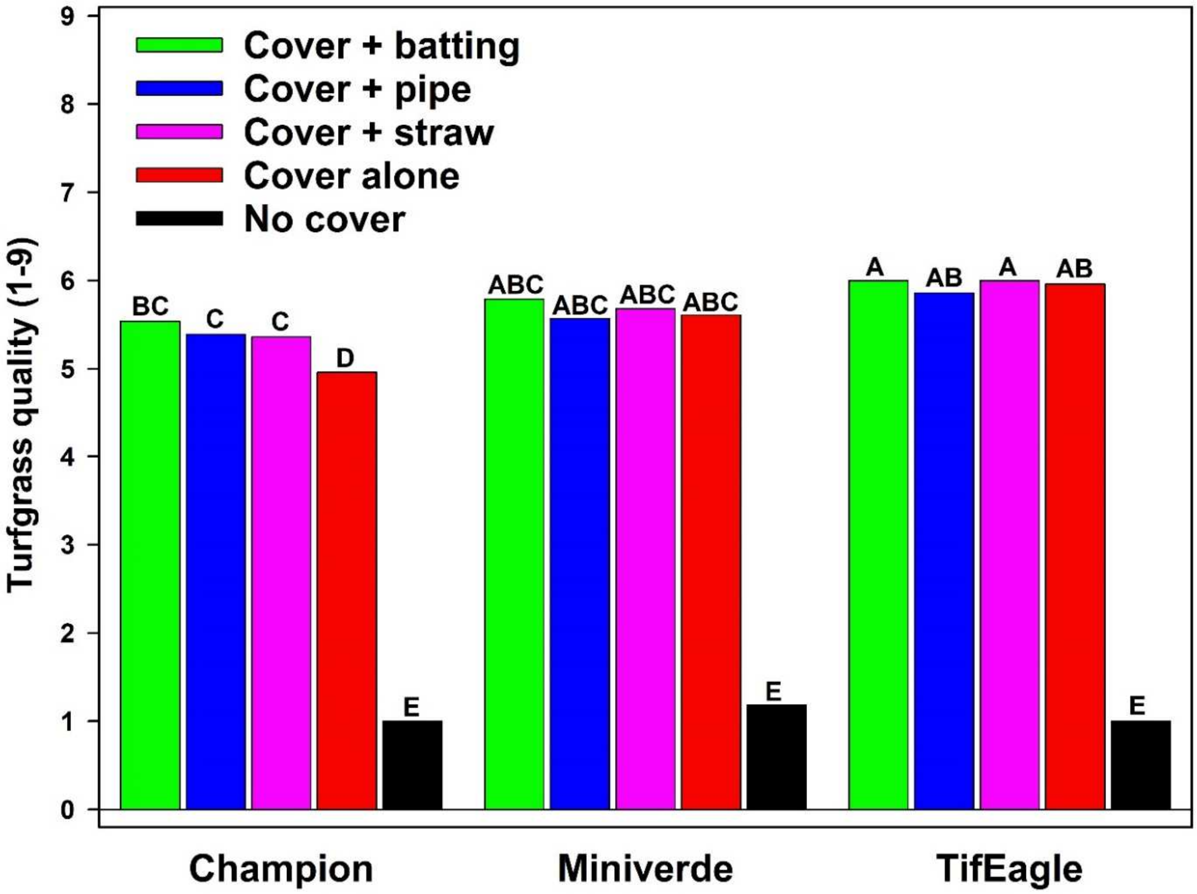

Figure 11. Cultivar x cover treatment interaction on turfgrass quality during the spring of 2021. Treatment means labeled with the same letter are not significantly different ($P \leq 0.05$).

Figure 12. Drone image of 2 replications (separated by red boxes) taken 15 April, 2021 with widespread winterkill on all the uncovered controls in Fayetteville, AR.

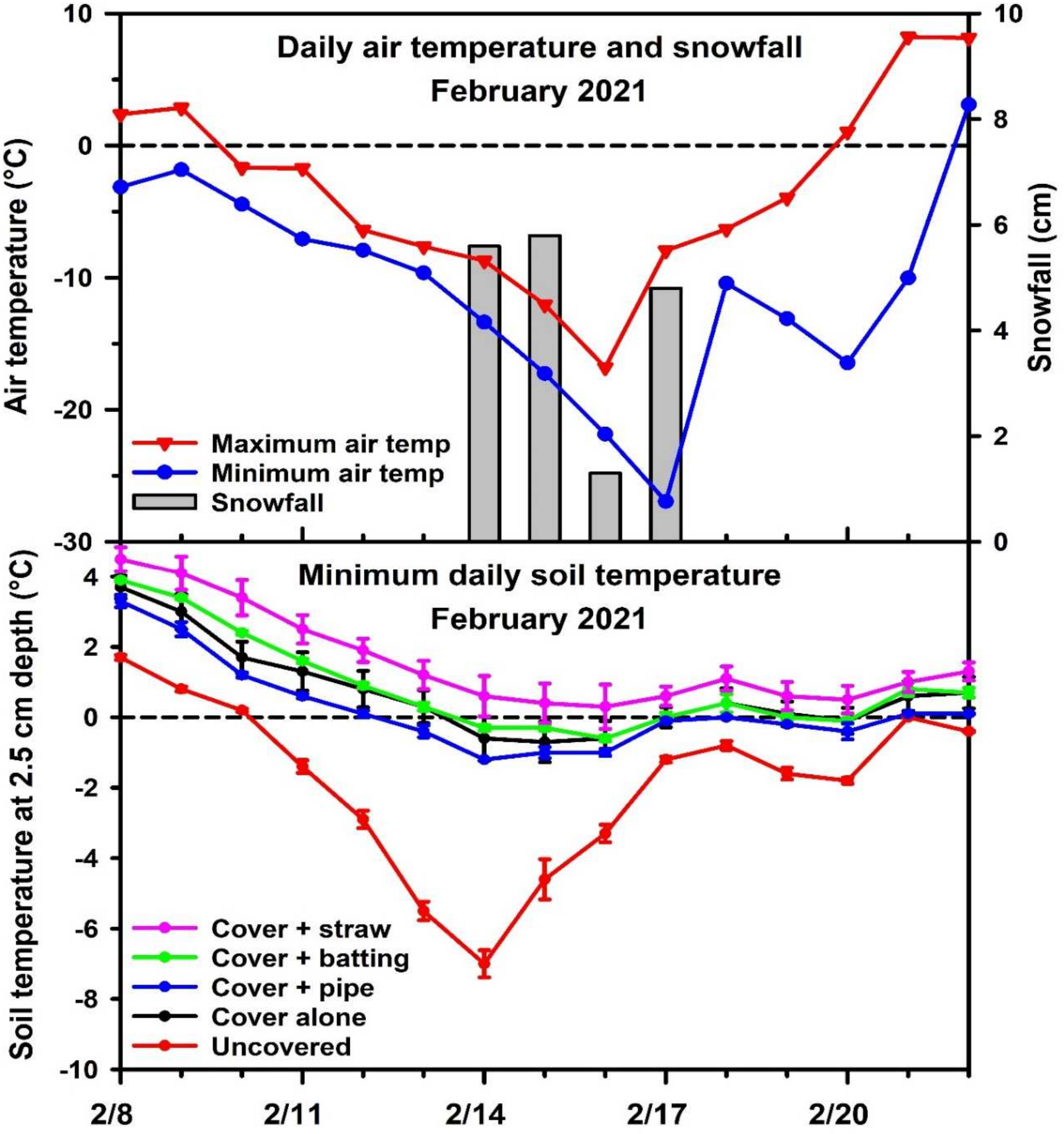

Figure 13. Minimum and maximum air temperature, snowfall, and minimum daily soil temperature during February of 2021 in Fayetteville, AR. The error bars in the bottom graph represent the standard deviation around the means

III. Establishing Daily Light Integral Requirements of Warm-Season Putting Greens

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ABSTRACT

Warm-season grasses, especially ultradwarf bermudagrass (*Cynodon dactylon* (L.) Pers *x C. transvaalensis* Burtt-Davy), continue to be used more widely on golf course putting greens in the transition zone. Ultradwarf bermudagrass (UDB) produces a high-quality putting green surface, however, has relatively poor shade-tolerance. Recently released, fine-textured zoysiagrass (*Zoysia spp.*) cultivars have emerged as another potential grass option for golf course putting greens in the transition zone. Zoysigrass is generally considered more shade- and cold-tolerant than bermudagrass, but early research on greens-type zoysiagrasses ('Diamond') concluded that zoysiagrass produced a lower-quality putting surface compared to creeping bentgrass (*Agrostis stolonifera* L.) or UDB. 'Lazer' zoysiagrass (*Zoysia matrella* (L.) Merrill *x Z. minima* (Colenso) Zotov*)*, which was developed at Texas A&M and commercially released in 2019, may have the potential to produce high-quality putting greens in the transition zone. The objective of this two-year field trial was to compare 'Lazer' zoysiagrass to 'TifEagle' UDB under varying light levels (0, 20, 40, 60 and 80% shade cloth) and management practices to determine the minimum daily light integral (DLI) requirements and assess the surface characteristics (green speed and surface firmness) for each species. Species strip plots were split with two mowing heights (2.5 and 3.2 mm), and further split with or without weekly applications of the plant growth regulator, trinexapac-ethyl. 'Lazer' demonstrated significantly greater shade tolerance and surface firmness than 'TifEagle'. The minimum DLI requirement for 'Lazer' was about 10 mol m^{-2} d^{-1} less than 'TifEagle'. Surface firmness was greater for 'Lazer', while 'TifEagle' produced higher green speed values for most evaluation dates. However, both species consistently produced ball roll distances of greater than 305 cm. Results from this trial suggest

that ‘Lazer’ zoysia can produce acceptable putting green conditions and is better adapted than ‘TifEagle’ to moderate shade conditions.

BACKGROUND

Although not traditionally thought to be a suitable putting green surface in the United States, an emerging alternative to both creeeping bentgrass (*Agrostis stolonifera* L.) and ultradwarf bermudagrass (*Cynodon dactylon* (L.) Pers *x C. transvaalensis* Burtt-Davy) is zoysiagrass (*Zoysia sp.*). Zoysiagrass putting greens are abundantly present throughout eastern and southeast Asia, in countries like Japan and Thailand, but are rarely present in the United States. Zoysiagrass is used in these countries out of necessity, as bermudagrass does not thrive due to cloudy conditions and an overall lack of solar radiation, while the tropical temperatures are too warm for cool-season grasses (Woods, 2014). 'Diamond' zoysiagrass (*Zoysia matrella* (L.) Merrill) was developed at Texas A&M in 1996 as the first commercially-available zoysiagrass for putting green use in the United States (Engelke et al., 2002). Growth characteristics, such as very fine leaf texture and high tiller and rhizome density, allowed for low, frequent mowing at putting green heights and 'Diamond' demonstrated excellent shade tolerance (Qian and Engelke, 2000; Atkinson et al., 2012). However, a number of concerns made 'Diamond' putting greens less favorable than ultradwarf bermudagrass, including slow establishment from sprigs, stiff, rigid leaf blades, and prolific seed-head production (Stiglbauer et al., 2009; Briscoe et al., 2012; McCullough et al., 2017).

Experimental zoysiagrass DALZ 1308 (Chandra et al., 2020) was developed at Texas A&M and performed well in the 2013 National Turfgrass Evaluation Program warm-season putting green trial (Morris, 2015). DALZ 1308 (*Zoysia matrella* (L.) Merrill *x Z. minima* (Colenso) Zotov*)* was commercialized by Bladerunner Farms (Poteet, TX) in 2019 as 'Lazer' zoysiagrass and is being marketed for putting green use. Although the development of new genetic lines of zoysiagrass is a significant advancement, additional field work will be needed to determine the environmental limits, appropriate cultural practices, and inputs required to produce putting surfaces that can compete with current industry standard ultradwarf bermudagrasses.

Because turfgrasses in the golf course environment are often grown in close proximity to trees and other structures such as clubhouses and hillsides, shade can significantly impact the overall health and performance of various turfgrasses. Sunlight gives off a wide range of wavelengths ranging from 200 to 1,800 nanometers, but plants can only use light in the range of 400 to 700 nanometers for photosynthesis, and that narrow band is commonly referred to as photosynthetically active radiation or PAR. To assess the amount of light at a given site, a PAR sensor can be used to obtain an instantaneous measurement of PAR that is reported in μmol m^{-2} s^{-1}. To quantify the amount of PAR a site receives over the entire day, readings must be taken throughout the day and integrated to calculate a daily total PAR or the daily light integral (DLI), expressed as mol m^{-2} day^{-1} (Richardson and Kruse, 2015). The establishment of a minimum DLI requirement for various turfgrass species or cultivars has been a popular topic in recent research, as determining the minimum DLI provides guidance on where a grass can be effectively grown depending on intensity of management.

The first minimum DLI for golf course putting greens was reported by Bunnell et al. (2005a), who established that 'TifEagle' bermudagrass mown at 3.2 mm required a minimum DLI of 32.6 mol m^{-2} d^{-1} to maintain acceptable quality. Conducted in Clemson, SC, three shade levels were applied with shade cloth (0, 41, and 92% shade) during either morning hours, afternoon hours, neither, or both, to ensure that all plots got full irradiance during the middle of the day. Afternoon shade was more problematic than morning shade to 'TifEagle' bermudagrass and plots receiving shade in the morning had reduced visual quality and total non-structural carbohydrate counts (Bunnell et al., 2005a). To examine the impact of management practices on the DLI of 'TifEagle', Bunnell et al. (2005b) also tested two mowing heights, application of gibberellic acid, trinexapac-ethyl, and additional nitrogen fertility as growth factor treatments to the trial. Raising mowing heights (3.2 to 4.7 mm) and the application of trinexapac-ethyl every 3 weeks at 0.0393 kg a.i. ha^{-1} resulted in a minimum DLI value of 22.1 mol m^{-2} d^{-1} to maintain acceptable quality of 'TifEagle' bermudagrass (Bunnell et al., 2005b). It should be noted that shade stress was only induced for an 8-week period in both studies (Bunnell et al., 2005a; Bunnell et al., 2005b), which could limit the reliability of the DLI value, especially for golf course sites that receive season-long shade stress.

Atkinson et al. (2012) conducted a 2-year shade trial to determine the light requirements of 'Diamond' zoysiagrass maintained at a mowing height of 3.2 mm in Clemson, SC. Shade was applied for 22 weeks for two growing seasons and treatment factors included shade level (0, 60, or 90% constant shade) and trinexapac-ethyl (0.013 kg a.i. ha^{-1} wk^{-1} or untreated). 'Diamond' zoysiagrass was able to maintain acceptable quality (>7) under the 60% shade treatment (DLI: 17.6 mol m^{-2} d^{-1}) over both years of the trial, excluding the final rating date in year 2. Plots treated weekly with trinexapac-ethyl maintained acceptable turfgrass quality under 60% shade for the duration of both years of the trial (Atkinson et al., 2012). The results of this trial suggest the minimum DLI of 'Diamond' zoysiagrass to be approximately 17.6 mol m^{-2} d^{-1} with weekly applications of trinexapac-ethyl and a greater light requirement without trinexapac ethyl, demonstrating the superior shade tolerance of zoysiagrass compared to bermudagrass mowed at 3.2-mm (Bunnell et al., 2005a).

Most recently, Russell et al., (2019) found the minimum DLI to maintain an acceptable quality ‘Tyee’ creeping bentgrass putting green in Fayetteville, AR to be approximately 30 mol m^{-2} d^{-1}. Four shade intensities were applied (0, 70, 80, or 90% shade) in either morning or afternoon hours in a two-year trial which occurred from May to October. Four chemical treatments were also tested in this trial including trinexapac ethyl at 0.028 kg a.i. ha^{-1} every 14 days, titanium oxide +zinc oxide (Turf Screen) applied every week, the combination of both products, and an untreated control. Inconsistent observations in turfgrass quality as affected by morning and afternoon shade were observed, however, afternoon shade was more detrimental to turfgrass quality in the first year of the trial. Turfgrass quality was slightly improved with the application of both chemical treatments, however, did not significantly reduce the minimum light requirements of creeping bentgrass (Russell et al., 2019)

Zoysiagrass, as a species, has consistently demonstrated excellent shade tolerance (Qian and Engelke, 2000; Atkinson et al. 2012) in comparison to more widely-used warm-season grasses such as bermudagrass. However, there have been minimal direct comparison of zoysiagrass and bermudagrass under shaded conditions, especially at putting green heights of cut. Therefore, the objectives of this field trial were to determine the minimum DLI requirement to maintain acceptable quality of ‘TifEagle’ bermudagrass and ‘Lazer’ zoysiagrass as influenced by shade intensity, mowing height, and growth regulator treatment. Another objective was to monitor the surface characteristics of each species with green speed and surface firmness measurements to determine if ‘Lazer’ zoysiagrass performs comparable to an industry-standard ultradwarf bermudagrass like ‘TifEagle’. It was hypothesized that ‘Lazer’ zoysiagrass would have superior shade tolerance to ‘TifEagle’ bermudagrass and produce comparable putting green surfaces throughout the growing season.

MATERIALS AND METHODS

Experimental area

A two-year field study was conducted at the Milo J. Shult Agricultural Research and Extension Center in Fayetteville, AR (36°06' N, 94°10' W) during the growing seasons of 2020 and 2021. The experimental putting green used for this study was originally constructed in 1998 with a sand-based rootzone according to United States Golf Association (USGA) specifications (USGA, 2004). The green was renovated and sprigged in June 2019 and three replicated blocks (6.1 x 9.1 m) of 'Lazer' zoysiagrass and 'TifEagle' ultradwarf bermudagrass were established. Whole plots were evenly split by species (3.0 x 9.1 m) (Fig. 1). Modeled after Russell et al. (2019), shade structures fit over whole plots to induce season-long shade stress with shade cloth at varying intensities 35-cm off of the turf surface. The shade structures were constructed out of steel pipe and mounted on six pneumatic wheels (20.3-cm diameter) which facilitated quick and efficient removal for mowing and maintenance. The shade cloth was mounted to the steel pipe with ultraviolet resistant zip-ties placed through grommets at 60 cm intervals.

The putting green was maintained with typical maintenance practices used in the transition zone. The annual nitrogen rate was 146.5 kg N ha^{-1}. Bi-weekly applications of nitrogen were applied at a rate of 12 kg N ha^{-1} with a rotation of foliar-applied urea (46% N) and a complete, granular fertilizer source (Contec DG 18-9-18, The Andersons, Maumee, OH). Preventative fungicide applications were made routinely to prevent large patch (*Rhizoctonia solani* Kűhn AG2-2 LP), spring dead spot (*Ophiosphaerella korra* Walker and Smith), and foliar diseases such as leaf spot. Soil hydrophobicity was prevented with biweekly applications of a wetting agent (Immerse GT, AmegaA Sciences, Lakeland, FL) and sufficient irrigation was applied to prevent symptoms of drought stress. Mowing was conducted six times a week with a walk-behind greens mower (Flex 2120, The Toro Company, Bloomington, MN). Light weight rolling was performed three times weekly using a commercial light weight greens roller (R52-11TC, Tru-Turf Pty. Ltd., Australia). Sand topdressing was applied bi-weekly to prevent excessive organic matter production and promote surface smoothness at an approximate rate of 225 cm^3 m^{-2} with sand consistent with USGA recommendations.

Treatments

Shade structures were divided into five shade treatment levels (1.8 x 6.1 m) and randomly stripped across the two grass species (Fig. 1). Shade was applied with shade cloth (Bulk Shade Cloth, International Greenhous Co., Danville, IL) that reduced light intensity by 20, 40, 60, and 80% of full-sun conditions and were compared to a full-sun control (Fig. 2). Species plots were further split in half to include a low (2.5 mm) and high (3.2 mm) height-of-cut (HOC) with a plot size of 1.5 x 9.0 m (Fig. 1). The HOC treatments were further split to compare an untreated control to weekly applications of the plant growth regulator trinexapac-ethyl (PGR) (Primo Maxx,Syngenta Crop Protection LLC, Greensboro, NC). The PGR was applied at 0.028 kg active ingredient (a.i.) ha^{-1} week (w^{-1}) to ‘TifEagle’ bermudagrass and 0.014 kg a.i. ha^{-1} w^{-1} to ‘Lazer’ zoysiagrass with a plot size of 0.8 x 9.0 m (Fig. 1). The rate difference between species was due to phytotoxic symptomology observed in ‘Lazer’ zoysiagrass early in 2020. After the initial three weekly applications of PGR at 0.028 kg a.i. ha^{-1} w^{-1} to both species in 2020, ‘Lazer’ experienced substantial phytotoxicity and the rate was reduced to 0.14 kg a.i ha^{-1} w^{-1} on 30 July 2020 for the remainder of the trial. The PGR treatments were applied with a carbon dioxide (CO_2) pressurized boom sprayer calibrated to deliver a 406.9 L ha^{-1} spray volume with flat fan nozzles (8003VS; Teejet, Springfield, IL).

Evaluations

Shade was induced for 11 weeks in 2020 (29 June to 14 Sep. 2020) and 16 weeks in 2021 (21 June to 11 Oct. 2021). Lightscout quantum light sensors (Spectrum Technologies, Aurora, IL) were installed 10 cm below each shade treatment on two of three replications to quantify the total photosynthetically active radiation (PAR) for each shade level. Readings of PAR were recorded every 30 minutes on a 4-channel data logger (Watchdog 1000 Series Micro Station, Spectrum Technologies, Aurora, IL) and were used to calculate the daily light integral (DLI) for each individual shade treatment.

Surface evaluations were assessed on 0.8 x 1.8 m plots to determine the effect of species, shade intensity, HOC, and PGR treatments on visual quality, turfgrass coverage, ball roll distance, and surface firmness. Visual turfgrass quality ratings, based off uniformity, density, coverage, and color of the turfgrass, were recorded weekly consistent with recommendations from the National Turfgrass Evaluation Program, in which a 9 represented ideal turfgrass and 1 represented dead turfgrass (Morris and Shearmen, 1998).

Turfgrass coverage was measured weekly using digital image analysis. Pictures of each plot were taken using a digital camera (Canon PowerShot G12, Canon Inc., Melville, NY) mounted 55 cm off the turf surface in an enclosed light box. The bottom of the light box measured 1850 cm^2 in area and had four TCP 9W florescent light bulbs (TPC, Inc., Item#4890965, Aurora, OH) mounted inside to provide a consistent light source for each evaluation date. Turf Analyzer software program was used to analyze images (Karcher et al., 2017; http://turfanlyzer.com). Within Turf Analyzer, a hue setting of 70 to 170 and saturation setting of 20 to 100 was used to select the green pixels in each image and determine the percentage of green turfgrass coverage.

Ball roll distance and surface firmness were assessed every two weeks. A Stimpmeter (USGA, Far Hills, NJ) was used to measure ball roll distance. The procedure used was consistent with the methods defined by the USGA (USGA, 2012), in which a golf ball is placed on the designated 2x ball release notch located 38 cm from the beveled end while the stimpmeter is flat on the green. The stimpmeter is raised approximately 20° until the golf ball begins to roll down the stimpmeter and eventually comes to rest. The resting point of the center of the golf ball is marked and the distance from where the rolling was initiated is measured. Three golf balls were tested in opposite directions to account for any slope on the surface and the average of the six rolls doubled (2x), to obtain the average ball roll distance for each treatment.

A Clegg meter (Turf-Tec International, Tallahassee, FL) was used to evaluate surface firmness. Equipped with a 2.25-kg hammer, the hammer was raised through a guide tube to a designated 45 cm height and subsequently dropped on the surface of the putting green. The Clegg meter's accelerometer then measured the deceleration force, in gravities, on impact with the ground, with the greater readings indicating harder or firmer surfaces. Surface firmness was recorded as the average of three sperate hammer drops per evaluation plot.

Statistical design and analysis

A randomized complete block design was used for this study in a 2 x 5 x 2 x 2 strip-split-split plot design. Species ('Lazer' zoysiagrass or 'TifEagle' bermudagrass) plots were stripped with five shade-intensity levels. Species strip plots were split with two height of cut (HOC) treatments and HOC plots were further split with or without the weekly treatment of trinexapac-ethyl (PGR). Data were analyzed using a repeated measures analysis of variance, using PROC MIXED (SAS version 9.3; SAS Institute Inc., Cary, NC). Treatment means were separated using Fisher's protected LSD ($\alpha = 0.05$).

Visual quality ratings were used to determine the minimum DLI requirement to maintain an acceptable putting green. Mean turfgrass quality ratings for each treatment combination were plotted against the associated seasonal DLIs produced by the varying shade intensities. Three parameter, sigmoidal models were fit to the data using the nonlinear regression, Dynamic Fitting tool in SigmaPlot 14.5 (Systat Software, 2018). The equation that provided the best fit for the models was as follows:

$$y = \frac{a}{1 + \exp\left(-\frac{x - x0}{b}\right)}$$

A minimum visual quality rating of 7.0 was used as the critical threshold for an acceptable putting green. The non-linear regression equations that were generated were used to obtain a critical DLI value at a minimum turfgrass quality rating of 7.0.

RESULTS AND DISCUSSION

Turfgrass quality

In both 2020 and 2021, species, shade, HOC, and PGR impacted turfgrass quality throughout the year (Table 1). The highest-order interactions from 2020 included a significant four-way interaction between species × shade × PGR × date and a significant four-way interaction between species × shade × HOC × date (Table 1). ‘Lazer’ had lower turfgrass quality than ‘TifEagle’ on the first rating date in 2020 because of slower establishment from initial planting (Fig. 3). ‘TifEagle’ and ‘Lazer’ were sprigged on the same date in June of 2019 and ‘Lazer’ was much slower to reach full establishment than ‘TifEagle’. The slow establishment of greens-type zoysiagrass compared to ultradwarf bermudagrass is consistent with observations made by Briscoe et al. (2012), in which ‘MiniVerde’ ultradwarf bermudagrass was faster to establish than ‘Diamond’ zoysiagrass via sprigging.

‘Lazer’ and ‘TifEagle’ had similar turfgrass quality in the 0%, 20%, and 80% shade treatments throughout 2020, with the most notable differences in quality among species and PGR treatments occurring in the 40% and 60% shade treatments (Fig. 3). On all rating dates after 27 Jul., ‘Lazer’ without PGR had greater turfgrass quality than ‘Lazer’ with PGR and ‘TifEagle’ with and without PGR (Fig. 3). On the final rating date (7 Sep.), ‘Lazer’ without PGR had greater turfgrass quality than all other treatments when grown in 40% shade, and ‘TifEagle’ without PGR had lower turfgrass quality than all other treatments (Fig. 3). In 40% shade, ‘TifEagle’ treated with PGR had greater turfgrass quality than the no PGR treatment on all rating dates after 6 Jul. (Fig. 3). In 40% shade, ‘Lazer’ without PGR had greater turfgrass quality than ‘Lazer’ treated with PGR on all rating dates after 6 Jul. (Fig. 3).

In 2020, turfgrass quality was also influenced by a significant species × shade × HOC × date interaction (Table 1, Fig. 4). In general, the HOC treatment had less of an impact on overall turfgrass quality than the PGR treatment (Fig. 3 and Fig. 4). In the 0% and 20% shade treatments, turfgrass quality was not impacted for either species by HOC. In the 40% shade treatment, ‘TifEagle’ at a HOC of 3.2-mm had greater turfgrass quality than ‘TifEagle’ at a HOC of 2.5-mm on the final two rating dates (31 Aug. and 7. Sep.).

In 2021, turfgrass quality was impacted by a significant four-way interaction between species × shade × PGR × date (Table 1, Fig. 5). Turfgrass quality was similar for ‘TifEagle’ and ‘Lazer’ in the 0, 20, and 80% shade treatments for most of the year, with or without PGR treatment (Fig. 5). ‘Lazer’ had higher turfgrass quality than ‘TifEagle’ on most rating dates throughout 2021 in the 40 and 60% shade treatments, regardless of PGR treatment (Fig. 5). In the 40 and 60% shade treatments, turfgrass quality of ‘Lazer’ was reduced by the PGR treatment on multiple rating dates, while ‘TifEagle’ had improved turfgrass quality with the PGR treatment

(Fig. 5). In 2021, turfgrass quality was also impacted by a three-way interaction between shade × HOC × date (Table 1, Fig. 6). In the 0, 20, and 80% shade treatments, turfgrass quality was similar among HOC treatments (Fig. 6). The most striking quality differences occurred in the 60% shade treatment, in which turfgrass quality was significantly greater for the 3.2-mm HOC treatment than the 2.5-mm HOC treatment on all rating dates after 19 Jul. (Fig. 6).

Zoysiagrass has consistently demonstrated superior shade tolerance to bermudagrass (Bunnell et al., 2005c; Trappe et al., 2011; Zhang et al., 2017; Chen et al., 2021). Bunnell et al. (2005c) determined ‘Meyer’ zoysiagrass (*Z. japonica* L.) had greater turfgrass quality than three hybrid bermudagrass cultivars when grown under varying shade levels. Trappe et al. (2011) compared the shade- and traffic-tolerance of multiple bermudagrass and zoysiagrass cultivars and determined that both *Z. matrella* and *Z. japonica* cultivars had greater turfgrass quality when compared to the hybrid bermudagrass cultivars tested when grown under 49% shade. In a greenhouse study, Zhang et al. (2017) compared the shade tolerance of twelve warm-season turfgrasses. The four bermudagrass cultivars tested had the lowest turfgrass quality in a 61-81% light reduction, while the four of the five zoysiagrass cultivars tested had the highest turfgrass quality in the 61-81% light reduction (Zhang et al., 2017). Chen et al. (2021) compared the shade tolerance of nine cultivars of bermudagrass and zoysiagrass and all five zoysiagrass cultivars tested had greater turfgrass quality in reduced light conditions. The observations from the present trial are consistent with previous shade trials in which zoysiagrass has superior shade tolerance to bermudagrass, as ‘Lazer’ zoysiagrass consistently had greater turfgrass quality than ‘TifEagle’ bermudagrass when grown in equal shade, especially in the range of 40-60% light reduction.

Repeat applications of the PGR, trinexapac-ethyl, have been shown to increase the turfgrass quality of both bermudagrass and zoysiagrass in shaded conditions (Qian and Engelke, 1999; Bunnell et al., 2005b; Atkinson et al., 2012; Chen et al., 2021). Consistent with observations by Bunnell et al. (2005b), turfgrass quality of 'TifEagle' bermudagrass in the present trial was improved with repeat trinexapac-ethyl applications when grown in shade intensity of 40% light reduction and greater (Fig. 3 and Fig. 4). Qian and Engelke (1999) applied trinexapac-ethyl to 'Diamond' zoysiagrass either on a monthly, bi-monthly, or tri-monthly schedule. Increases in turfgrass quality were observed in shaded plots that received trinexapac-ethyl on a monthly or bi-monthly schedule (Qian and Engelke, 1999). Atkinson et al. (2012) applied trinexapac-ethyl weekly to a 'Diamond' zoysiagrass putting green when grown in 60% and 90% shade and observed greater turfgrass quality in trinexapac-ethyl treated plots compared to the untreated controls. Chen et al. (2021) tested monthly applications of trinexapac-ethyl multiple zoysiagrass and bermudagrass cultivars mowed at a fairway mowing height (19-mm). The turfgrass quality of three of the five zoysiagrass cultivars was greater when treated with trinexapac ethyl monthly while the turfgrass quality of four of the four bermudagrass cultivars was similar with or without trinexapac-ethyl (Chen et al., 2021).

Given the results of previous studies, the decrease in turfgrass quality of 'Lazer' zoysiagrass treated with trinexapac-ethyl and grown in the shade was unexpected (Fig. 3 and 4). The initial four applications in 2020 were applied at 0.028 kg a.i. ha^{-1} wk^{-1} and caused significant phytotoxicity and discoloration. Turfgrass quality in the PGR treated zoysia was decreased through most of the 2020 trial because of the injury sustained from the initial applications. Discoloration has been reported when applying trinexapac-ethyl to 'TifEagle' bermudagrass and is generally associated with reapplication intervals being too close together during periods when temperatures are not suitable for growth (McCullough et al., 2007).

In addition to the previous trials discussed with positive results with application intervals of monthly (Chen et al., 2021), or bimonthly applications (Qian and Engelke, 1999), Steinke and Stier (2003) investigated longer reapplication intervals (28- and 56-day) trinexapac-ethyl application regimes on three different cool-season turfgrass types grown in 80% shade. Turfgrass quality of the plots on the 28-day reapplication interval of trinexpac-ethyl had greater turfgrass quality than plots that were reapplied 56-day interval and the untreated controls (Steinke and Stier, 2003). Conclusions on reapplication intervals of trinexapc-ethyl to improve turfgrass quality in the shade by Qian and Engelke (1999), Steinke and Steir (2003), and Chen et al. (2021) suggest that a longer reapplication interval could be a potential strategy to improve the turfgrass quality of 'Lazer' favorably compared to weekly applications. It should also be noted that 'Lazer' zoysiagrass is the first zoysiagrass cultivar with parental lines from the species, *Z. minima* (Chandra et al., 2020); currently, there is no information available about the tolerance of'Lazer' (or other *Z. minima* selections) to any type of chemical treatment.

Daily light integral (DLI)

Light intensity among shade treatments and full sun conditions was consistent during the growing seasons of 2020 and 2021. Full sunlight conditions (0% shade treatment) produced seasonal DLI values of 45.2 mol m^{-2} d^{-1} in 2020 and 47.3 mol m^{-2} d^{-1} in 2021 (Table 2). The most variability between years occurred in the 40% shade treatment, which produced a seasonal DLI value of 24.9 mol m^{-2} d^{-1} in 2020 and 22.5 mol m^{-2} d^{-1} in 2021 (Table 2). The seasonal DLI values observed in the present trial are consistent with DLI values recorded in historical solar radiation data for Fayetteville, AR (Faust and Logan, 2018), and seasonal DLI values produced on a trial conducted in Fayetteville, AR in 2016 and 2017 (Russell et al., 2019).

Minimum DLI requirements were generated for both species treatments as influenced by the PGR treatment using turfgrass quality data and PAR data from each shade intensity level for years of the trial (Fig. 7 and 8). In 2020, the minimum DLI requirement for 'TifEagle' bermudagrass was approximately 32 mol m^{-2} d^{-1} without PGR and approximately 27 mol m^{-2} d^{-1} with PGR (Fig. 7). The minimum DLI requirement for 'Lazer' zoysiagrass was approximately 17 mol m^{-2} d^{-1} without PGR and turfgrass quality was unacceptable (≤ 7) for the duration of 2020 because of the phytotoxicity experienced in July of 2020 (Fig. 7). In 2021, the minimum DLI requirement for 'TifEagle' was approximately 29 mol m^{-2} d^{-1} without PGR and approximately 22 mol m^{-2} d^{-1} with PGR (Fig. 8). The minimum DLI requirement for 'Lazer' zoysiagrass was 15 mol m^{-2} d^{-1} without PGR and 17 mol m^{-2} d^{-1} with PGR (Fig. 8). The minimum DLI for both species decreased from 2020 to 2021. The experimental area was relatively immature during 2020 and was healthier to start the 2021 season. It is hypothesized that the increase in maturity of the putting green from 2020 to 2021 is the explanation for the significantly lower DLI light requirements in 2021 after two consecutive seasons of shade stress.

The minimum DLI requirement of 'TifEagle' bermudagrass determined during this trial of 31 mol m^{-2} d^{-1} PAR is consistent with observations by Bunnell et al. (2005a) who determined the minimum DLI for 'TifEagle' in Clemson, SC to be 32.6 mol m^{-2} d^{-1} at a mowing height of 3.2-mm. Bunnell et al. (2005a) only maintained shade for 8-weeks during both years of the trial while 11- and 16-weeks of shade was maintained during the present trial. Hodges et al., determined the minimum DLI requirement for multiple ultradwarf bermudagrass cultivars, including 'TifEagle' to establish 80% turfgrass coverage. Although the methodology differs from the present trial, the minimum DLI requirement to establish 'TifEagle' was 30.1 mol m^{-2} d^{-1}, consistent with results from the present trial (Hodges et al., 2016).

Minimum DLI requirements of ‘Lazer’ and ‘TifEagle’ were also determined as influenced by the HOC treatments (Fig. 9 and 10). In 2020, the minimum DLI requirement for ‘TifEagle’ bermudagrass was approximately 31 mol m^{-2} d^{-1} with the 2.5-mm HOC and 26 mol m^{-2} d^{-1} with the 3.2-mm HOC (Fig. 9). The minimum DLI requirement for ‘Lazer’ zoysiagrass was approximately 21 mol m^{-2} d^{-1} with the 2.5-mm HOC and 19 mol m^{-2} d^{-1} with the 3.2-mm HOC. In 2021, the minimum DLI requirement for ‘TifEagle’ bermudagrass was approximately 31 mol m^{-2} d^{-1} with the 2.5-mm HOC and 20 mol m^{-2} d^{-1} with the 3.2-mm HOC. The minimum DLI requirement for ‘Lazer’ zoysiagrass was 17 mol m^{-2} d^{-1} and was not influenced by HOC in 2021.

The significant reduction of the minimum DLI requirements of ‘TifEagle’ bermudagrass when applying trinexapac-ethyl and increasing the HOC from 2.5- to 3.2-mm is notable. The minimum DLI requirement of ‘TifEagle’ was reduced with PGR by 5 mol m^{-2} d^{-1} in 2020 and 7 mol m^{-2} d^{-1} in 2021. In addition, the minimum DLI requirement of ‘TifEagle’ was reduced by 5 mol m^{-2} d^{-1} in 2020 and 11 mol m^{-2} d^{-1} by raising the HOC from 2.5- to 3.2-mm. Bunnell et al (2005b) reduced the minimum DLI requirements of ‘TifEagle’ by 10 mol m^{-2} d^{-1} with the combination of trinexapac-ethyl every 3-weeks and raising the HOC from 3.2- to 4.7-mm. Russell et al. (2019) determined the minimum DLI requirement to maintain an acceptable ‘Tyee’ creeping bentgrass putting green was about 30 mol m^{-2} d^{-1} when mowed at 3.2-mm. However, repeat applications of trinexapac-ethyl did not reduce the light requirements and only provided temporary benefits in visual quality (Russell et al., 2019). Monthly applications of trinexapac-ethyl decreased the DLI requirements of the zoysiagrass cultivars ‘Zorro’, ‘Palisades’ and ‘JaMur’ by 4.7, 4.0, and 5.7 mol m^{-2} d^{-1}, respectively, at a mowing height of 19-mm (Chen et al., 2021).

Minimum DLI requirements have been determined on varying bermudagrass and zoysiagrass cultivars maintained at higher mowing heights than the present study (Zhang et al., 2017; Russell et al., 2020; Chen et al., 2021. Zhang et al. (2017) determined the minimum DLI requirements of multiple warm-season grasses in a greenhouse study. At a mowing height of 38-mm, the minimum summer DLI requirement of the bermudagrass cultivars tested ranged from 20.2 to 21.4 mol m^{-2} d^{-1} and the zoysiagrass cultivars tested ranged from 9.9 to 11 mol m^{-2} d^{-1}, both less of a light requirement than 'Lazer' and 'TifEagle' established during the present trial (Zhang et al., 2017). Russell et al. 2020 investigated the minimum DLI requirements of multiple zoysiagarss and bermudagrass cultivars in a recent field trial. At a mowing height of 12.7-mm, the minimum DLI requirements of the bermudagrass cultivars ranged from 19.5 to 24.6 mol m^{-2} d^{-1} and the zoysiagrass cultivars ranged from 15.9 to 29.5 mol m^{-2} d^{-1} (Russell et al., 2020). 'Meyer' zoysiagrass is a *Z. japonica* cultivar and had the highest light requirement (29.5 mol m^{-2} d^{-1}), demonstrating that in general, *Z. japonica* cultivars are less shade-tolerant than *Z. matrella* cultivars (Russell et al., 2020). Chen et al. (2021) determined the minimum DLI requirements of multiple bermudagrass and zoysiagrass cultivars in a field trial at a mowing height of 19-mm which ranged from 20.9 to 26.9 mol m^{-2} d^{-1} for the bermudagrass cultivars and from 13.3 to 21.3 mol m^{-2} d^{-1} for the zoysiagrass cultivars, lower than the light requirements of 'Lazer' and 'TifEagle' in the present trial at lower mowing heights (Chen et al., 2021). Differing from Russell et al. (2020), the most shade tolerant cultivar of zoysiagrass was 'Jamur' zoysiagrass, a *Z. japonica* cultivar, which has outperformed *Z. matrella* cultivars in multiple shade trials (Zhang et al., 2017; Chen et al., 2021). This variability in shade-tolerance among zoysiagrass cultivars and species demonstrates the need for further field trials as new zoysiagrass cultivars, such as 'Lazer', are released to the public.

The minimum DLI light requirements of ultradwarf bermudagrass and creeping bentgrass putting greens appear to be similar, while fine-textured zoysiagrasses appears to be significantly more shade-tolerant. Creeping bentgrass is a cool-season grass, which are generally more shade-tolerant than warm-season grasses like bermudagrass and zoysiagrass. However, the low mowing heights of golf course putting greens have a significant impact on overall shade tolerance, especially in a stressful transition zone summer enviroment. Results from the present study and many other trials (Qian and Engelke, 1999; Bunnell et al., 2005b; Atkinson et al., 2012; Zhang et al., 2017; Russell et al., 2020; Chen et al., 2021) suggest repeat applications of trinexpac-ethyl and raising HOC are two best management practices to reduce light requirements of warm-season putting greens grown in shaded environments.

Turfgrass coverage

Turfgrass coverage was impacted by species, shade, HOC, and PGR treatments during 2020 and 2021 (Table 3). The highest-order interactions on turfgrass coverage in 2020 include a significant three-way interaction between species × PGR × date, another three-way interaction between species × shade × date, and a significant two-way interaction between HOC × date (Table 3). 'Lazer' had lower turfgrass coverage than 'TifEagle' early for the first two rating dates in 2020 (2 July and 9 July) because of slower establishment from initial planting (Fig. 11). Greens-type zoysiagrass having less turfgrass coverage during establishment is an observation consistent with a previous trial conducted by Hodges et al. (2016) in which 'Diamond' zoysiagrass had less turfgrass coverage than four ultradwarf bermudagrass cultivars throughout establishment.

'Lazer' consistently had less turfgrasss coverage with the PGR treatment and, on the final two rating dates (28 Aug. and 4 Sep.) in 2020, 'Lazer' treated with PGR had significantly lower turfgrass coverage than ‘Lazer’ with no PGR (Fig. 11). ‘TifEagle’ consistently had greater turfgrass coverage with the PGR treatment and had significantly greater turfgrass coverage with PGR treatment than no PGR on 30 Jul. and 14 Aug. (Fig. 11). Excluding the first two rating dates (2 July and 9 July) in 2020, ‘Lazer’ maintained greater turfgrass coverage than ‘TifEagle’ in the 40, 60, and 80% shade treatments and similar turfgrass coverage in the 0 and 20% shade treatments (Fig. 12). In the 40% shade treatment, ‘Lazer’ had greater turfgrass coverage than ‘TifEagle’ from 24 Jul to 4 Sep. (Fig. 12). In the 60 and 80% shade treatments, ‘Lazer’ had greater turfgrass coverage than ‘TifEagle’ on all rating dates after 24 Jul. (Fig. 12). On four of eight rating dates in 2020, the 3.2-mm HOC treatment had greater turfgrass coverage than the 2.5-mm HOC treatment (Fig. 13).

In 2021, turfgrass coverage was affected by a significant three-way interaction of species × shade × PGR treatments and a significant two-way interaction of shade × HOC treatments (Table 3). ‘Lazer’ consistently had greater turfgrass coverage than ‘TifEagle’ throughout 2021 (Fig. 14). In the 60% shade treatment, ‘TifEagle’ had significantly greater turfgrass coverage when treated with PGR compared to the untreated from 19 Aug. to 8 Sep. (Fig. 14). Turfgrass coverage of ‘Lazer’ was not impacted by PGR treatment for a majority of 2021 (Fig. 14). Turfgrass coverage was greater with both HOC treatments in the 0, 20, and 40% shade treatments than in the 60 and 80% shade treatments (Fig. 15). The 3.2-mm HOC treatments had greater turfgrass coverage than the 2.5-mm HOC treatment in both the 60 and 80% shade treatments (Fig. 15).

Results of the present trial are consistent with observations in other previous shade experiments; as shade intensity increases, turfgrass coverage decreases (Trappe et al., 2011; Richardson et al., 2019; Russell et al., 2019). Trappe et al. (2012) reported that hybrid bermudagrass had reduced turfgrass coverage compared to both *Z. japonica* and *Z. matrella* when grown in 49% shade, which also demonstrates superior shade tolerance of zoysiagrass over bermudagrass. Richardson et al. (2019) established minimum DLI requirements for 'Riviera' bermudagrass under four shade-levels (0, 30, 90, and 90% shade) based off turfgrass coverage rather than turfgrass quality ratings. Turfgrass coverage of 'Riviera' bermudagrass began to substantially decrease in shade treatments that represented DLI values between 15 and 26 mol m^{-2} d^{-1}, which corresponds to the decline in turfgrass coverage of 'TifEagle' bermudagrass in the present study, especially in the 40 and 60% shade treatments (Fig. 12) (Richardson et al., 2019). Russell et al. (2019) investigated the impact varying shade intensities and timing had on turfgrass coverage of a creeping bentgrass putting green. Turfgrass coverage in the full-sun plots was statistically greater than any shaded plot for the duration of the two-year trial, and the lowest turfgrass coverage occurred in the highest shade intensity treatment (90% afternoon shade) at a DLI of 24.8 mol m^{-2} d^{-1} (Russell et al., 2019). Turfgrass coverage of course putting greens comprised of ultradwarf bermudagrass and creeping bentgrass appear to decrease as the minimum DLI approaches 25 mol m^{-2} d^{-1}, while turfgrass coverage of 'Lazer' zoysiagrass appears to decrease as the minimum DLI approaches 15 mol m^{-2} d^{-1}.

Surface firmness

Surface firmness was primarily influenced by the main treatment factor of species during both 2020 and 2021, as well as several higher-order interactions (Table 4). Results were consistent in 2020 and 2021, and the higher-order interactions which will be further discussed include a two-way interaction between species × date and a two-way interaction between shade × date (Table 4). In both 2020 and 2021, 'Lazer' had greater surface firmness than 'TifEagle' on all rating dates (Fig. 16). Across both years of the trials, surface firmness of 'Lazer' was, on average, 21% greater than ‘TifEagle’ in 2020 and 11% in 2021 (Data not shown). In 2020, the shade treatments all maintained similar firmness (Fig. 17). However, in 2021, the 80% shade treatment was significantly firmer than the 0, 20, and 40% shade treatments on the final three of seven rating dates. On the final rating date (23 Sep.), the 60 and 80% shade treatments were significantly firmer than the 0%, 20%, and 40% shade treatments (Fig. 17).

There is limited research which differentiates surface firmness of golf course putting greens among species, shade intensity, or PGR treatments. Trinexapac-ethyl did not significantly impact surface firmness of either ‘Lazer’ zoysiagrass or ‘TifEagle’ bermudagrass during the present trial, consistent with results from firmness data taken on a previous field trial conducted on a ‘Diamond’ zoysiagrass putting green (Menchyk et al., 2014). The surface firmness of ‘Lazer’ zoysiagrass warrants further discussion. The slow establishment of the ‘Lazer’ zoysiagrass was evident in early 2020, with reduced turfgrass quality and coverage compared to ‘TifEagle’ bermudagrass (Fig. 3 and Fig. 4). Because of this slow growth rate, the ‘Lazer’ zoysiagrass was potentially accumulating less organic matter than the ‘TifEagle’ bermudagrass, which could explain the large differences in firmness during 2020. The putting green was routinely sand-topdressed to dilute organic matter at the surface and the ‘TifEagle’ bermudagrass was significantly firmer and more closely related to ‘Lazer’ zoysiagrass in 2021 than in 2020 (Fig. 16).

According to guidelines set by Stowell et al. (2009), an ideal range of firmness for putting greens is 70 to 125 gravities (GMAX). As such, both ‘TifEagle’ and ‘Lazer’ produced acceptable surface firmness within the recommended guidelines for the duration of both years of the trial (Fig. 16 and 17). However, casual observations by scientists and visitors over the two years of the trial suggest that the surface firmness of ‘Lazer’ zoysiagrass may be excessive and could negatively impact the shot-holding ability of a green. This would certainly be an interesting area for future study.

Ball roll distance

Ball roll distance data was consistent in 2020 and 2021 and a significant two-way interaction occurred between species × date (Table 5). In 2020, 'TifEagle' bermudagrass had greater ball roll distance than 'Lazer' zoysiagrass on three of five rating dates (Fig. 18). In 2021, 'TifEagle' bermudagrass had greater ball roll distance than 'Lazer' zoysiagrass on six of seven rating dates (Fig. 18). Ball roll distance increased throughout the growing season on both species and, on the final rating date of both years, both species had similar ball roll distances.

There are no published studies comparing the ball-roll distance of greens-type zoysiagrass and ultradwarf bermudagrass under the same management conditions, however, ball roll distance data of both grass types is available. Published green speeds on 'Diamond' zoysiagrass have ranged from 185- to 260-cm when mowed at 3.2- and 2.5-mm (Stiglbauer et al., 2009) from 210- to 272-cm when mowed at 3.2-mm (Menchyk et al., 2014), considerably slower than ball roll distance produced by 'Lazer' zoysiagrass in the present trial which ranged from 240- to 320-cm at the same mowing heights. Therefore, 'Lazer' zoysiagrass appears to represent a new greens-type zoysiagrass with the ability to produce faster ball roll distances than the old cultivar, 'Diamond' zoysiagrass.

CONCLUSIONS

The present experiment represented an initial comparison of an industry-standard ultradwarf bermudagrass cultivar (‘TifEagle’) to a newly released greens-type zoysiagrass cultivar (‘Lazer’). Based on previous field trials that have established minimum DLI requirements for putting greens (Bunnell et al., 2005; Russell et al., 2019), the shade-tolerance of ‘Lazer’ zoysiagrass appears to be significantly greater than both ultradwarf bermudagrass and creeping bentgrass. The minimum DLI requirements generated in the present trial will provide golf courses a baseline for identifying problematic greens sites that do not have adequate light to grow an acceptable putting green. This objective measurement of light provided by portable PAR sensors can provide golf course superintendents with justification for solutions to increase playing conditions. Best management practices when managing golf course putting greens in the shade include raising the mowing height and applying trinexapac-ethyl, tree trimming and removal, and potentially re-surfacing to a more shade-tolerant grass selection.

‘Lazer’ zoysiagrass also appears to produce more desirable surface characteristics than older greens-type zoysiagrass varieties such as ‘Diamond’ zoysiagrass, particularly as it relates to ball roll distance. However, ‘TifEagle’ bermudagrass consistently produced greater ball roll distance when managed under the same conditions. Further field work identifying best management practices to increase ball roll distance of ‘Lazer’ zoysiagrass will likely include improvement in mower setup (brushes and or groomers), implementation of routine vertical mowing, and more frequent light-weight rolling to determine how to optimize the playing conditions of ‘Lazer’.

Major areas of focus going forward with research on greens-type zoysiagrass should include increasing establishment efficiency. Greens-type zoysiagrasses are slower to establish than ultradwarf bermudagrass from sprigging. Sodding, which would significantly increase the upfront establishment cost, may still be the most cost-effective way for golf courses looking to reduce the lost revenue while the putting greens are being established. The winter hardiness of greens-type zoysiagrass is also a concern. Field observations from previously developed fine-textured *Zoysia matrella* cultivars such as ‘Diamond’ (Parent of ‘Lazer) have shown susceptibility to winterkill. Implementation of protective covers will likely be necessary for greens-type zoysiagrass and further work investigating temperature thresholds will be warranted going forward. Because of the uncertainties about management strategies to create surface characteristics similar to industry-standard ultradwarf bermudagrass, slow establishment rate, and other unanswered questions, more field work is needed before recommending greens-type zoysiagrass over ultradwarf bermudagrass. The most likely scenario where greens-type zoysiagrass will find its niche is at golf courses with wide-spread shade stress on putting greens complexes and there is resistance to eliminating the shade.

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TABLES

Table 1. Analysis of variance of main effects and their interactions on turfgrass quality during 2020 and 2021.

Treatment effect	2020		2021	
	F Value	P > F	F Value	P > F
Block	3.06	0.246	1.7	0.3706
Species	93.88	0.0105	4.03	0.1826
Shade	247.02	<.0001	289.78	<.0001
Species × shade	123.34	<.0001	22.38	<.0001
Height of cut (HOC)	12.58	0.0239	31.61	0.0049
Species × HOC	0.11	0.7542	0.55	0.4995
Shade × HOC	2.64	0.0434	26.84	<.0001
Species × shade × HOC	0.95	0.4415	4.82	0.0021
Plant growth regulator (PGR)	7.1	0.0286	1.21	0.3031
Species × PGR	107.33	<.0001	52.9	<.0001
Shade × PGR	1.2	0.3209	3.24	0.0185
Species × shade × PGR	4	0.0063	12.53	<.00017
HOC × PGR	0.75	0.4123	0.33	0.5816
Species × HOC × PGR	0.87	0.377	0.15	0.7118
Shade × HOC × PGR	0.39	0.8179	1.25	0.2992
Species × shade × HOC × PGR	1.26	0.2964	1.63	0.179
Date	167.24	<.0001	189.93	<.0001
Species × date	67.77	<.0001	34.99	<.0001
Shade × date	92.87	<.0001	122.16	<.0001
Species × shade × date	20.96	<.0001	16.88	<.0001
HOC × date	0.94	0.4683	3.22	<.0001
Species × HOC × date	0.68	0.6672	1.26	0.2333
Shade × HOC × date	1.23	0.2069	1.75	0.001
Species × shade × HOC × date	1.87	0.0077	0.78	0.8745
PGR × date	0.72	0.6371	7.72	<.0001
Species × PGR × date	12.58	<.0001	4.58	<.0001
Shade × PGR × date	0.97	0.5092	1.32	0.0674
Species × shade × PGR × date	1.89	0.0072	3.34	<.0001
HOC × PGR × date	0.61	0.7239	0.23	0.9979
Species × HOC × PGR × date	0.65	0.6942	0.77	0.6952
Shade × HOC × PGR × date	0.32	0.9993	0.44	0.9998
Species × shade × HOC × PGR × date	0.53	0.97	0.51	0.9987

Table 2: Average daily light integral recorded under the five shade intensity treatments during 2020 and 2021.

	Daily light integral	
Shade cloth treatment[†]	2020	2021
% light reduction	mol m^{-2} d^{-1}	
0	45.2	47.3
20	38.3	38.1
40	24.9	22.5
60	15.7	14.5
80	8.3	8.1

[†] **-** Shade was applied using Bulk Shade Cloth (International Greenhouse Co., Danville, IL)

Table 3. Analysis of variance of main effects and their interactions on green turfgrass cover during 2020 and 2021.

Treatment effect	2020		2021	
	F Value	P > F	F Value	P > F
Block	0.64	0.6105	4.14	0.1945
Species	0.01	0.9154	137.63	0.0072
Shade	4.19	0.0403	74.11	<.0001
Species × shade	18.48	<.0001	39.69	<.0001
Height of cut (HOC)	5.33	0.0821	9.6	0.0363
Species × HOC	9.89	0.0347	3.06	0.1552
Shade × HOC	1.31	0.2772	9.17	<.0001
Species × shade × HOC	0.45	0.7746	1.35	0.263
Plant growth regulator (PGR)	2.05	0.1897	0.05	0.8362
Species × PGR	37.38	0.0003	12.16	0.0082
Shade × PGR	2.96	0.0275	6.58	0.0002
Species × shade × PGR	3.19	0.0198	13.14	<.0001
HOC × PGR	0.09	0.7675	0.25	0.633
Species × HOC × PGR	0.76	0.4084	0	0.9864
Shade × HOC × PGR	0.34	0.8527	1.36	0.261
Species × shade × HOC × PGR	0.24	0.9138	1.44	0.2332
Date	93.5	<.0001	193.47	<.0001
Species × date	137.89	<.0001	85.17	<.0001
Shade × date	14.02	<.0001	30.98	<.0001
Species × shade × date	16.09	<.0001	15.77	<.0001
HOC × date	3.65	0.0007	1.31	0.1965
Species × HOC × date	0.86	0.541	1.41	0.1412
Shade × HOC × date	0.89	0.6324	0.4	1
Species × shade × HOC × date	0.74	0.835	0.68	0.9636
PGR × date	11.29	<.0001	8.21	<.0001
Species × PGR × date	3.94	0.0003	3.03	0.0001
Shade × PGR × date	1.32	0.1289	1.51	0.0097
Species × shade × PGR × date	1.4	0.0848	1.67	0.0017
HOC × PGR × date	0.39	0.9064	1.08	0.3687
Species × HOC × PGR × date	0.4	0.9037	0.42	0.9674
Shade × HOC × PGR × date	0.21	1	0.27	1
Species × shade × HOC × PGR × date	0.24	1	0.44	0.9999

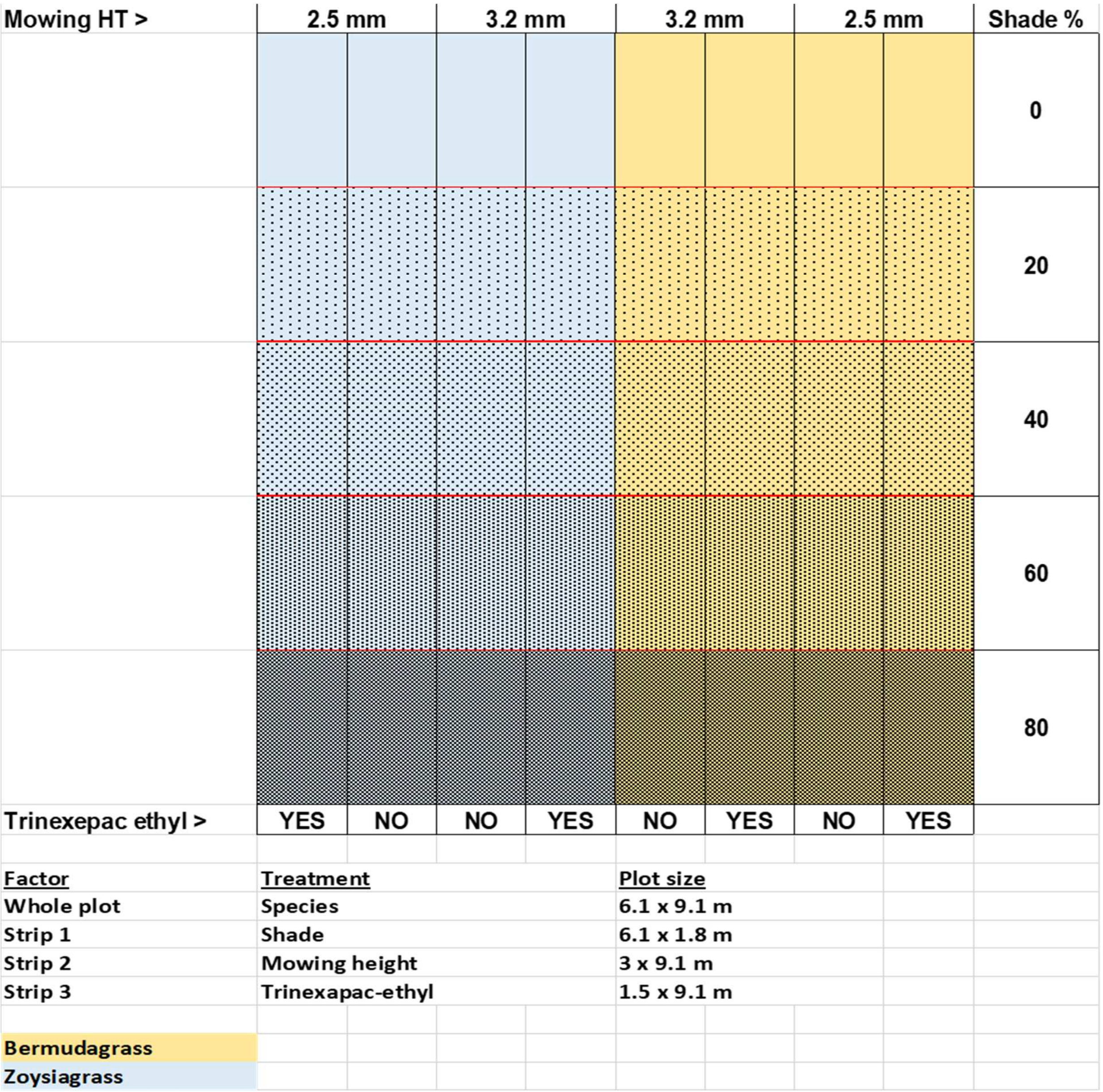
Table 4. Analysis of variance of main effects and their interactions on surface firmness during 2020 and 2021.

Treatment effect	2020		2021	
	F Value	P > F	F Value	P > F
Block	5.26	0.1596	0.14	0.8798
Species	220.17	0.0045	79.25	0.0124
Shade	1.37	0.3251	3.48	0.0627
Species × shade	0.76	0.5567	2.34	0.0662
Height of cut (HOC)	0.06	0.8235	2.25	0.208
Species × HOC	0.02	0.8913	0.02	0.9019
Shade × HOC	0.72	0.5787	0.23	0.9207
Species × shade × HOC	0.28	0.8923	0.25	0.9104
Plant growth regulator (PGR)	1.42	0.268	0.45	0.5194
Species × PGR	1.06	0.3338	4.17	0.0754
Shade × PGR	0.2	0.9389	0.17	0.9541
Species × shade × PGR	0.93	0.4544	0.17	0.9521
HOC × PGR	0.05	0.8317	0.02	0.8799
Species × HOC × PGR	2.17	0.1791	1.54	0.2497
Shade × HOC × PGR	0.63	0.6445	0.24	0.9169
Species × shade × HOC × PGR	0.42	0.7935	0.26	0.9021
Date	228.71	<.0001	61.68	<.0001
Species × date	14.85	<.0001	12.59	<.0001
Shade × date	1.98	0.0138	4.77	<.0001
Species × shade × date	2.1	0.0084	0.91	0.5829
HOC × date	0.05	0.996	1.91	0.0775
Species × HOC × date	0.71	0.5876	0.21	0.974
Shade × HOC × date	0.21	0.9996	1.11	0.3241
Species × shade × HOC × date	0.52	0.936	1.02	0.4426
PGR × date	0.96	0.4286	0.34	0.9146
Species × PGR × date	0.59	0.6683	2.26	0.0371
Shade × PGR × date	0.49	0.951	0.36	0.9983
Species × shade × PGR × date	0.3	0.9964	1.17	0.2612
HOC × PGR × date	0.37	0.8311	1.44	0.1977
Species × HOC × PGR × date	0.77	0.5477	0.4	0.8773
Shade × HOC × PGR × date	0.41	0.9791	0.42	0.994
Species × shade × HOC × PGR × date	0.46	0.9657	0.68	0.8766

Table 5. Analysis of variance of main effects and their interactions on ball roll distance during 2020 and 2021.

Treatment effect	2020		2021	
	F Value	P > F	F Value	P > F
Block	0.24	0.8081	2.97	0.2519
Species	49.88	0.0195	56.5	0.0172
Shade	2.47	0.1286	27.07	0.0001
Species × shade	2.91	0.0294	22.72	<.0001
Height of cut (HOC)	64.81	0.0013	89.09	0.0007
Species × HOC	3.16	0.1499	0	0.9938
Shade × HOC	3.02	0.0252	7.73	<.0001
Species × shade × HOC	4.95	0.0017	0.82	0.5156
Plant growth regulator (PGR)	68.55	<.0001	40.16	0.0002
Species × PGR	3.5	0.0981	7	0.0295
Shade × PGR	0.41	0.7977	0.25	0.908
Species × shade × PGR	0.46	0.7674	0.54	0.7078
HOC × PGR	3.21	0.1108	5.72	0.0437
Species × HOC × PGR	0.03	0.857	0.23	0.6457
Shade × HOC × PGR	0.73	0.5759	0.49	0.74
Species × shade × HOC × PGR	0.18	0.9466	0.79	0.5352
Date	173.03	<.0001	419.16	<.0001
Species × date	11.1	<.0001	8.25	<.0001
Shade × date	4.78	<.0001	9.28	<.0001
Species × shade × date	1.31	0.2206	0.93	0.5511
HOC × date	13.98	<.0001	6.37	<.0001
Species × HOC × date	2.03	0.0908	0.93	0.4744
Shade × HOC × date	1.13	0.3348	0.95	0.5228
Species × shade × HOC × date	1.02	0.4321	0.7	0.8308
PGR × date	1.38	0.2423	2.6	0.0173
Species × PGR × date	1.36	0.2482	0.56	0.759
Shade × PGR × date	0.29	0.9951	1.07	0.3777
Species × shade × PGR × date	0.56	0.8621	0.34	0.9974
HOC × PGR × date	1.61	0.1718	0.21	0.9722
Species × HOC × PGR × date	0.38	0.824	0.65	0.6937
Shade × HOC × PGR × date	0.22	0.9987	0.37	0.9956
Species × shade × HOC × PGR × date	0.59	0.8379	0.39	0.9939

FIGURES



Mowing HT >	2.5 mm		3.2 mm		3.2 mm		2.5 mm		Shade %
									0
									20
									40
									60
									80
Trinexepac ethyl >	YES	NO	NO	YES	NO	YES	NO	YES	

Factor	Treatment	Plot size
Whole plot	Species	6.1 x 9.1 m
Strip 1	Shade	6.1 x 1.8 m
Strip 2	Mowing height	3 x 9.1 m
Strip 3	Trinexapac-ethyl	1.5 x 9.1 m

Bermudagrass
Zoysiagrass

Figure 1. An example replicate of the experimental design, including all treatment factors of species, shade level, mowing height, and plant growth regulator (trinexapac-ethyl).

Figure 2. Transportable shade structures used to apply shade at different intensity levels.

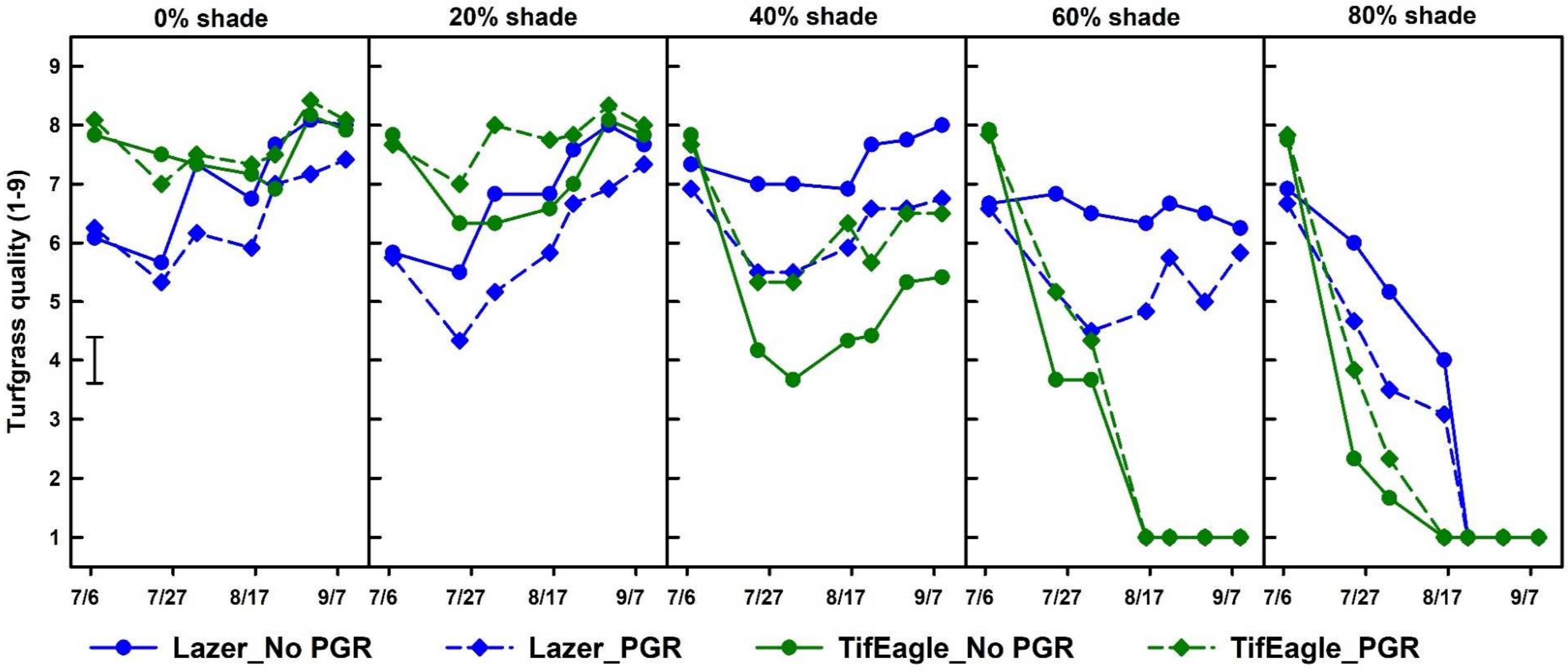


Figure 3. Effect of species × shade × plant growth regulator (PGR) × date on turfgrass quality in 2020. The error bar represents the least significant difference ($P \leq 0.05$) for mean comparisons.

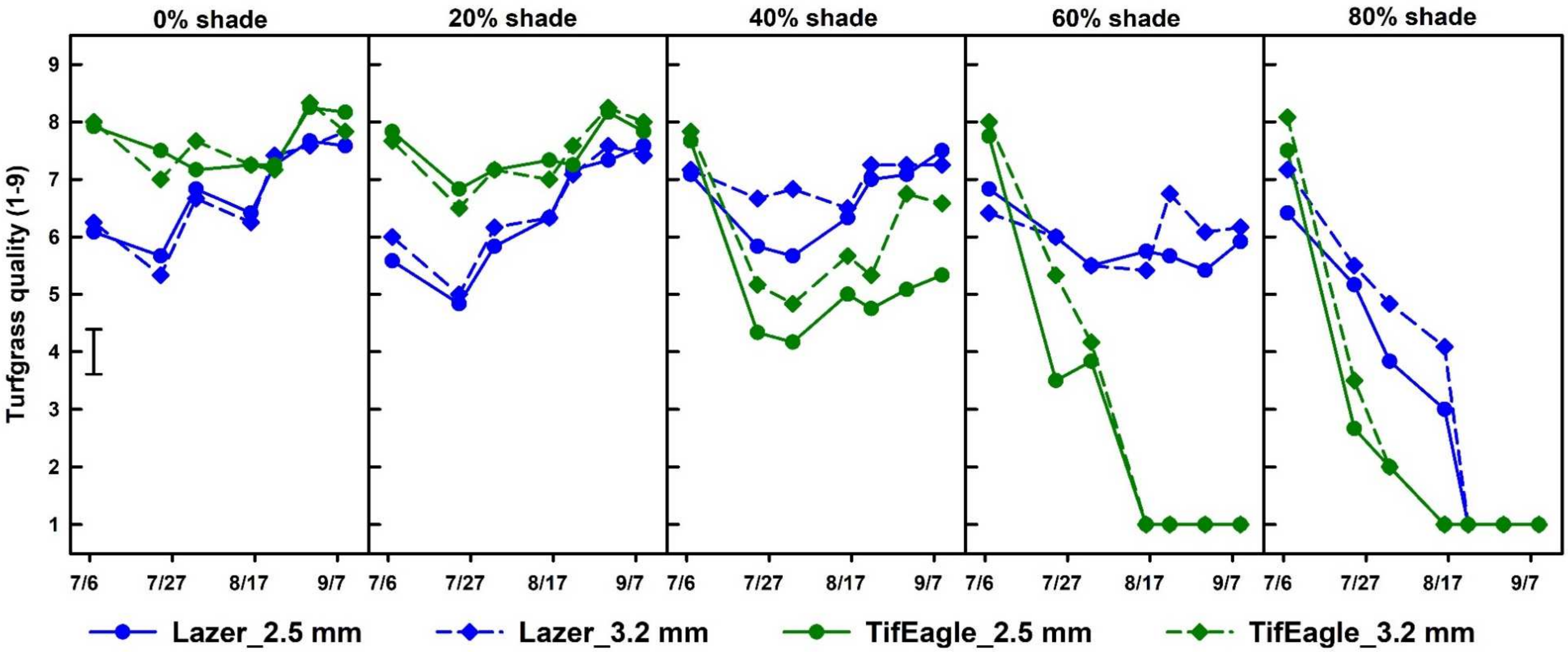


Figure 4. Effect of species × shade × height of cut (mm) × date on turfgrass quality in 2020. The error bar represents the least significant difference (P ≤ 0.05) for mean comparisons.

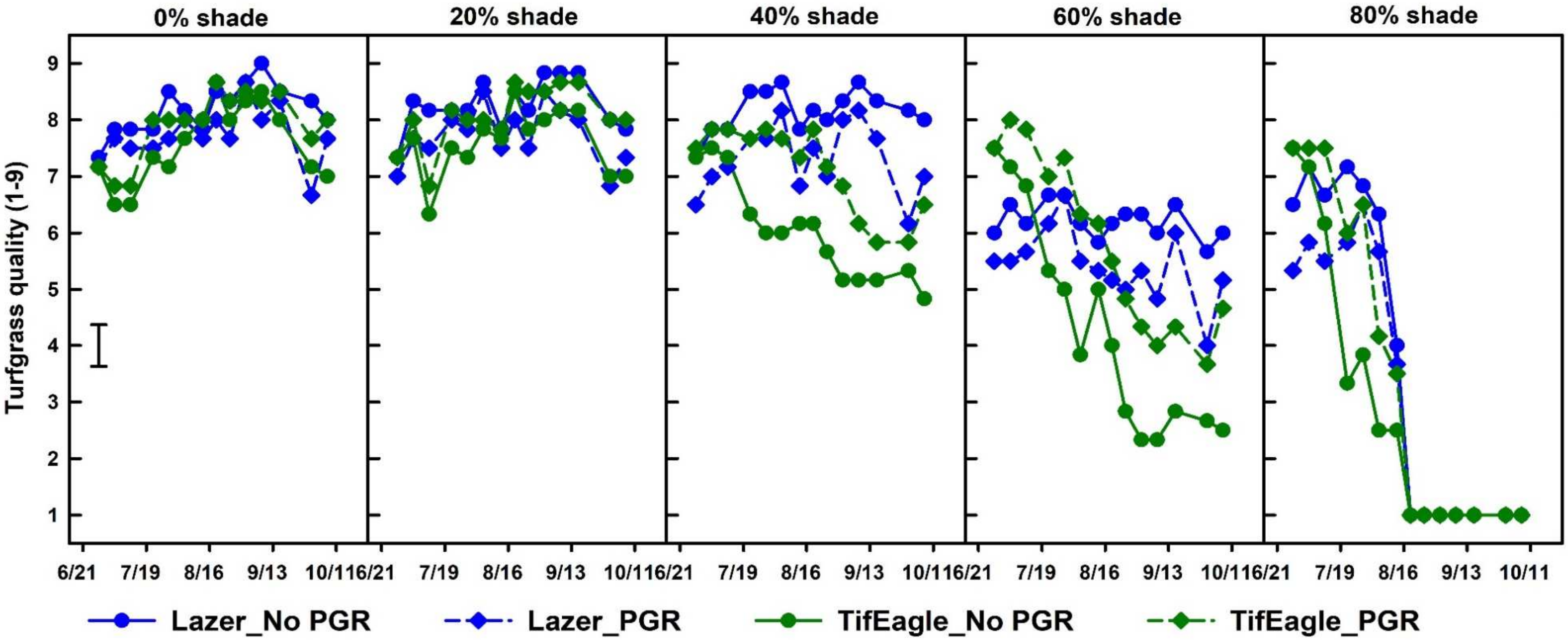


Figure 5. Effect of species × shade × plant growth regulator (PGR) × date on turfgrass quality in 2021. The error bar represents the least significant difference ($P \leq 0.05$) for mean comparisons.

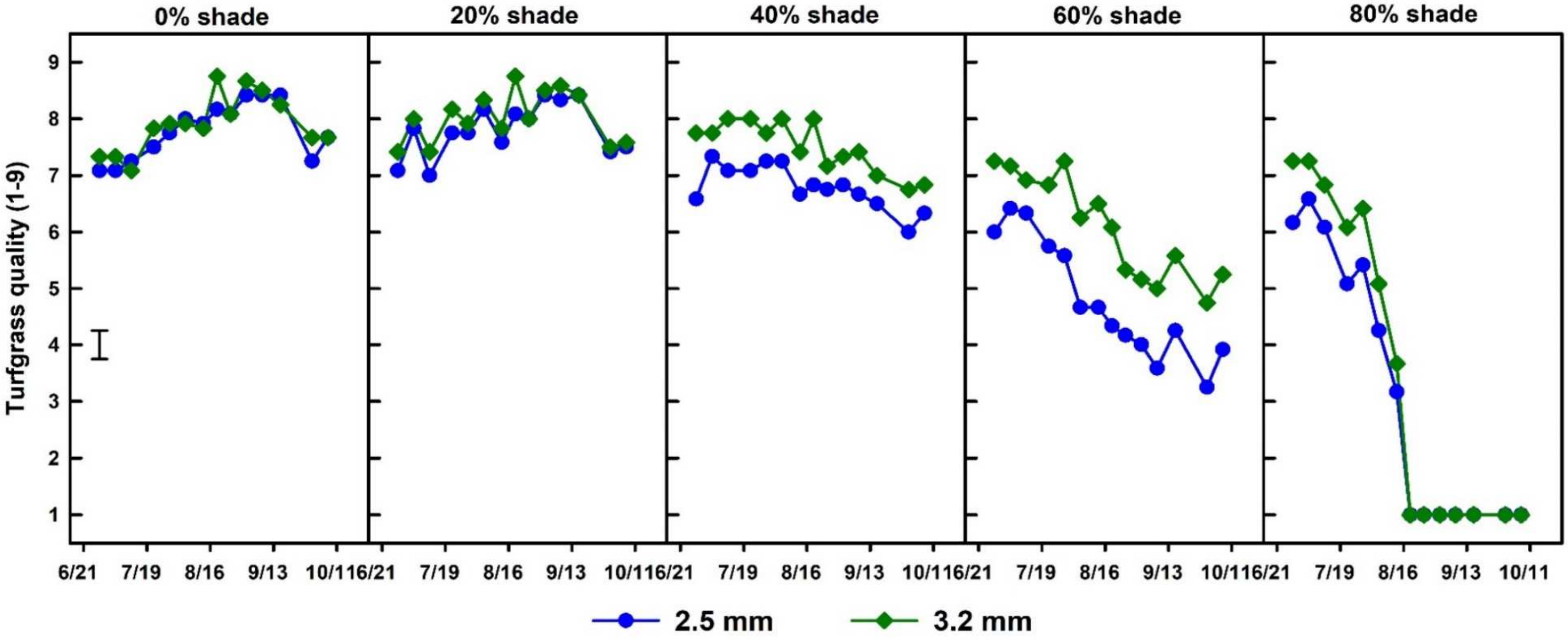


Figure 6. Effect of shade × height of cut (mm) × date on turfgrass quality in 2021. The error bar represents the least significant difference (P ≤ 0.05) for mean comparisons.

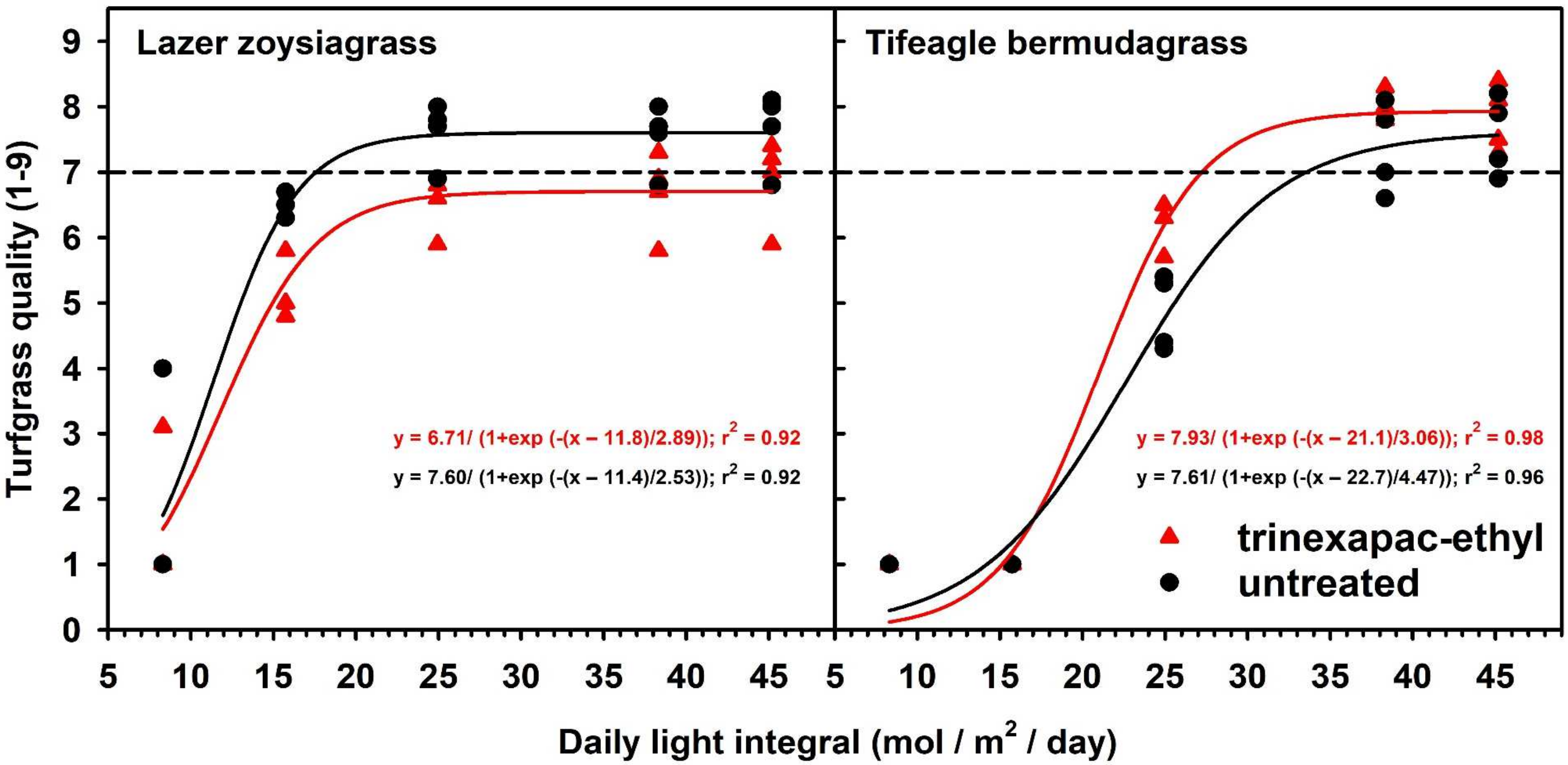


Figure 7. Non-linear regression analysis of mean turfgrass quality of 'Lazer' zoysiagrass and 'TifEagle' bermudagrass plotted against the daily light integral (DLI) (mol m^{-2} d^{-1}) produced by five shade intensity treatments as influenced by trinexapac-ethyl during 2020. The dashed line at a turfgrass quality rating of 7 represents minimally acceptable turfgrass quality of a golf course putting green and was used to predict the minimum DLI requirements of both species with and without trinexapac-ethyl.

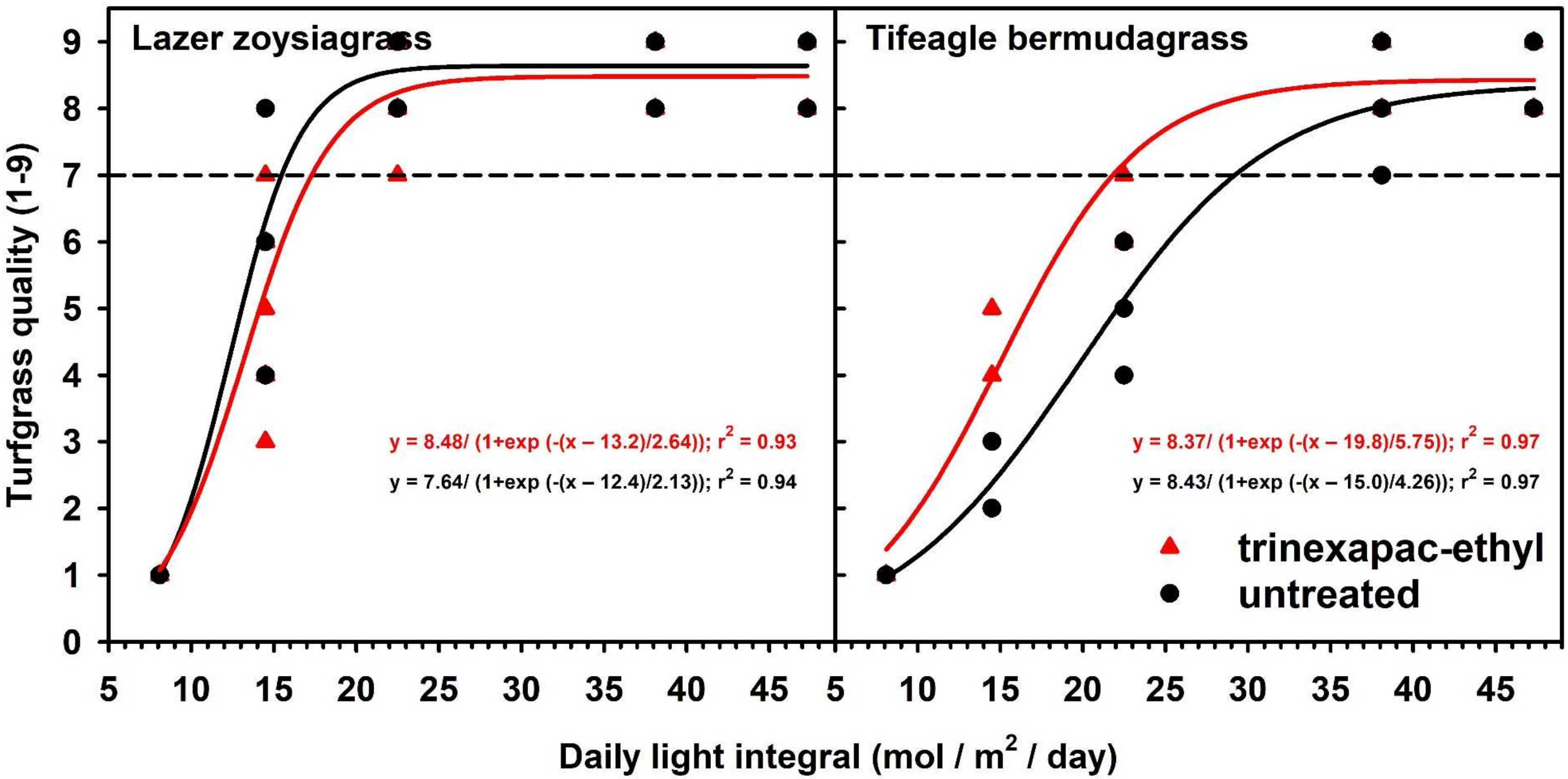


Figure 8. Non-linear regression analysis of mean turfgrass quality of 'Lazer' zoysiagrass and 'TifEagle' bermudagrass plotted against the daily light integral (DLI) (mol m^{-2} d^{-1}) produced by five shade intensity treatments as influenced by trinexapac-ethyl during 2021. The dashed line at a turfgrass quality rating of 7 represents minimally acceptable turfgrass quality of a golf course putting green and was used to predict the minimum DLI requirements of both species with and without trinexapac-ethyl.

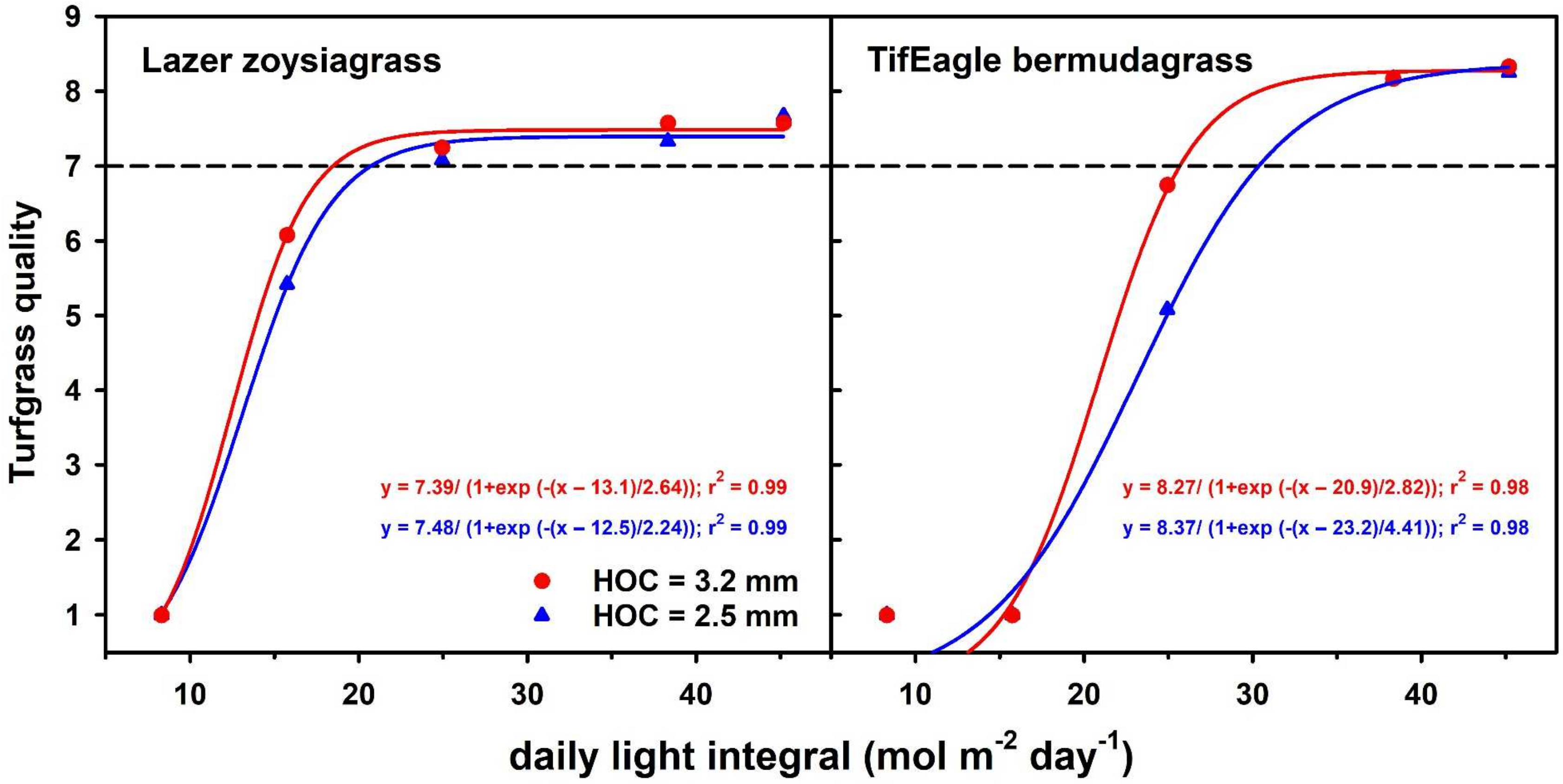


Figure 9. Non-linear regression analysis of mean turfgrass quality of 'Lazer' zoysiagrass and 'TifEagle' bermudagrass plotted against the daily light integral (DLI) (mol m^{-2} d^{-1}) produced by five shade intensity treatments as influenced by height of cut (HOC) during 2020. The dashed line at a turfgrass quality rating of 7 represents minimally acceptable turfgrass quality of a golf course putting green and was used to predict the minimum DLI requirements of both species at both HOC treatments.

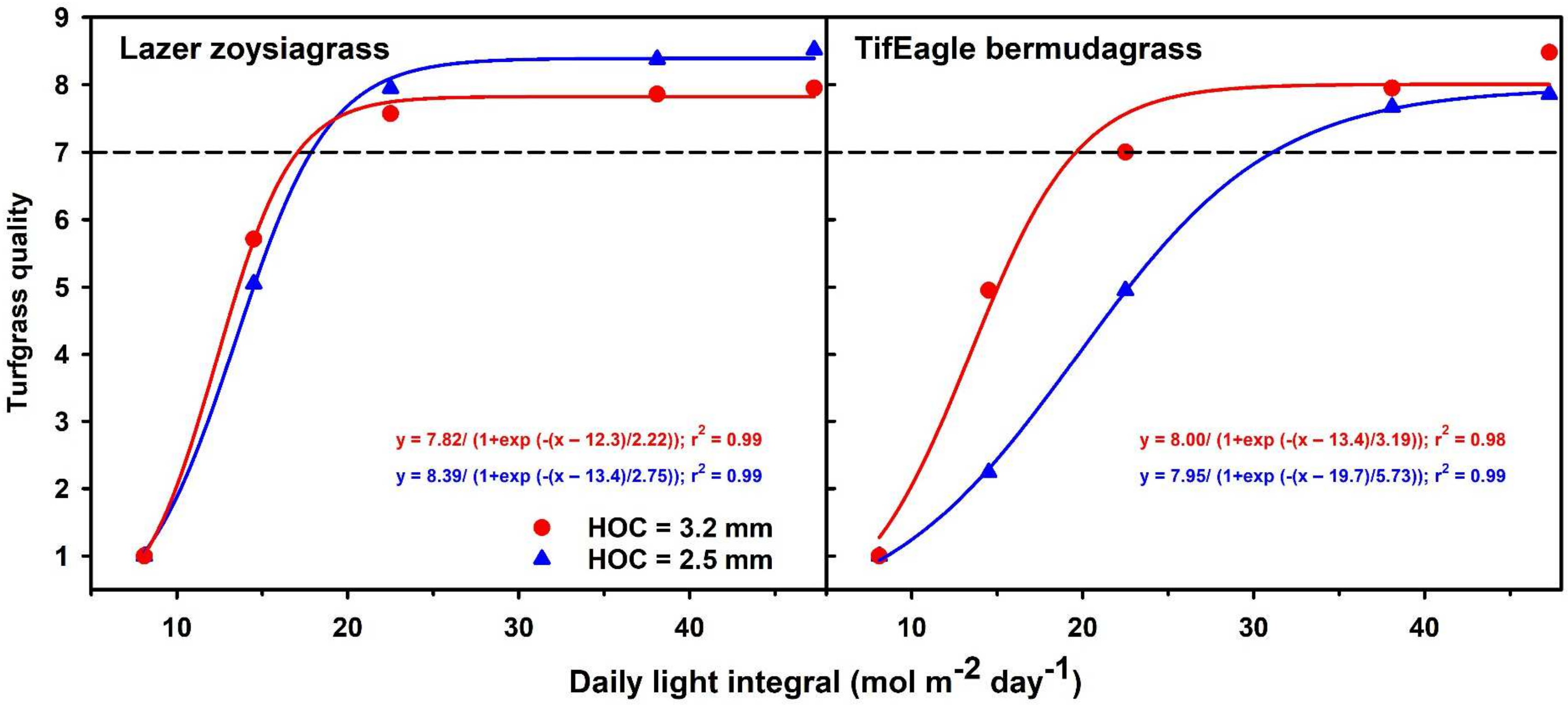


Figure 10. Non-linear regression analysis of mean turfgrass quality of ‘Lazer’ zoysiagrass and ‘TifEagle’ bermudagrass plotted against the daily light integral (DLI) (mol m^{-2} d^{-1}) produced by five shade intensity treatments as influenced by height of cut (HOC) during 2021. The dashed line at a turfgrass quality rating of 7 represents minimally acceptable turfgrass quality of a golf course putting green and was used to predict the minimum DLI requirements of both species at both HOC treatments.

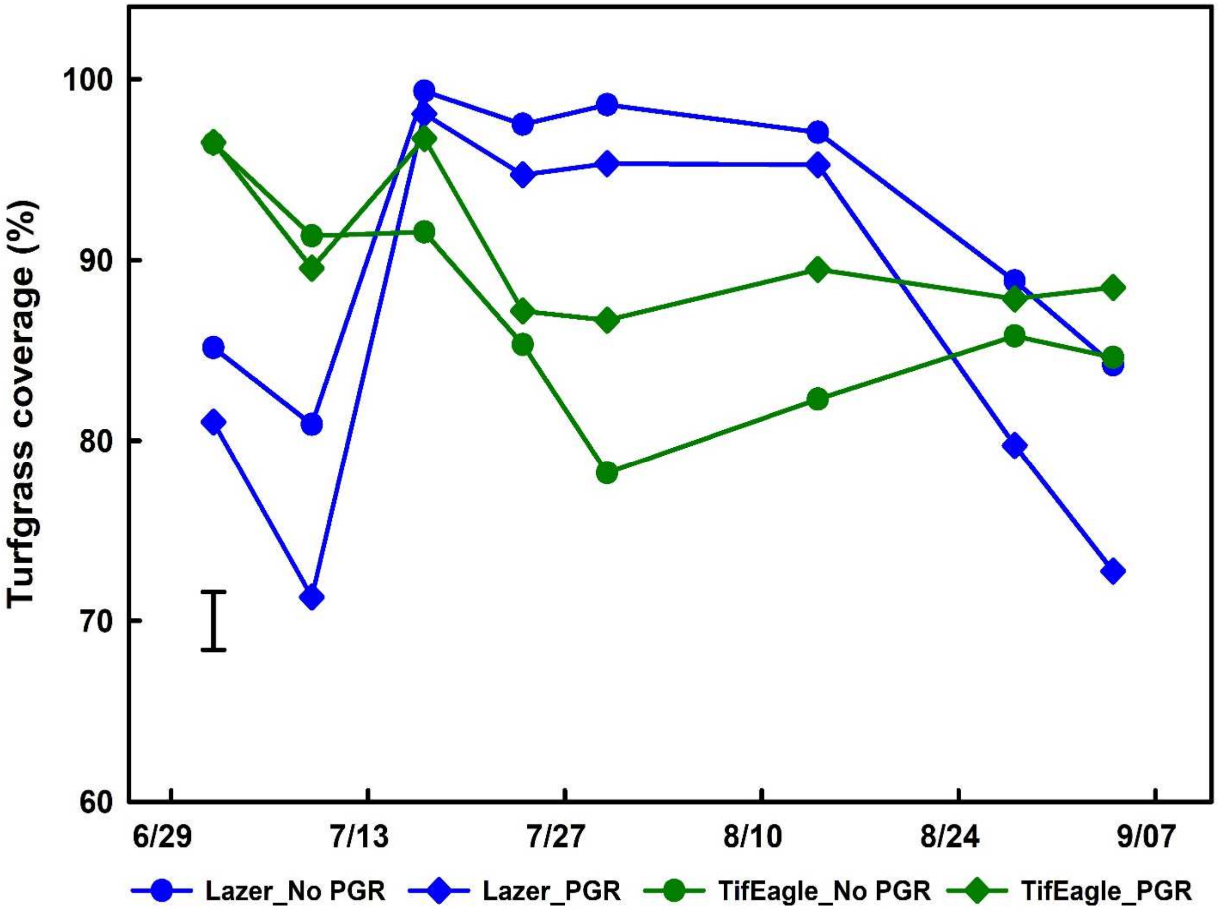


Figure 11. Effect of species × plant growth regulator (PGR) × date on turfgrass coverage in 2020. The error bar represents the least significant difference ($P \leq 0.05$) for mean comparisons.

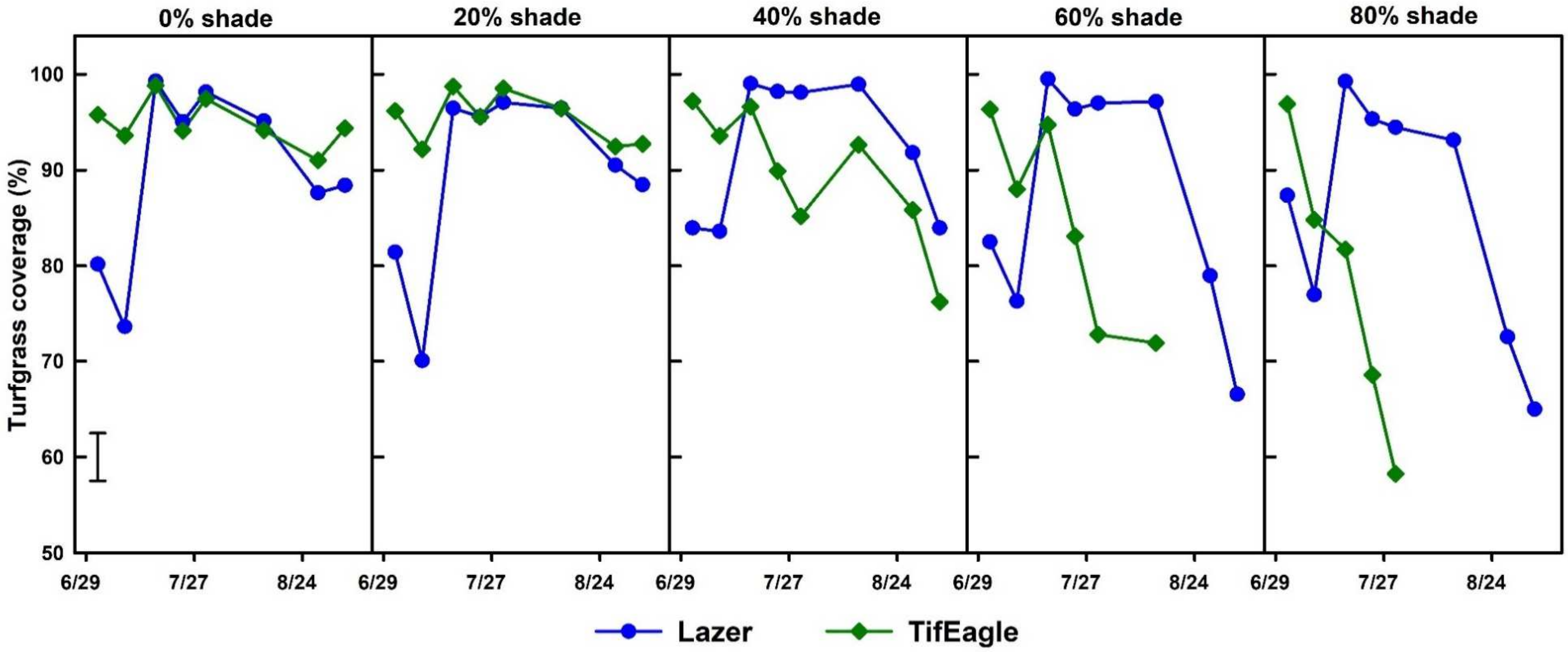


Figure 12. Effect of species × shade × date on turfgrass coverage in 2020. The error bar represents the least significant difference ($P \leq 0.05$) for mean comparisons.

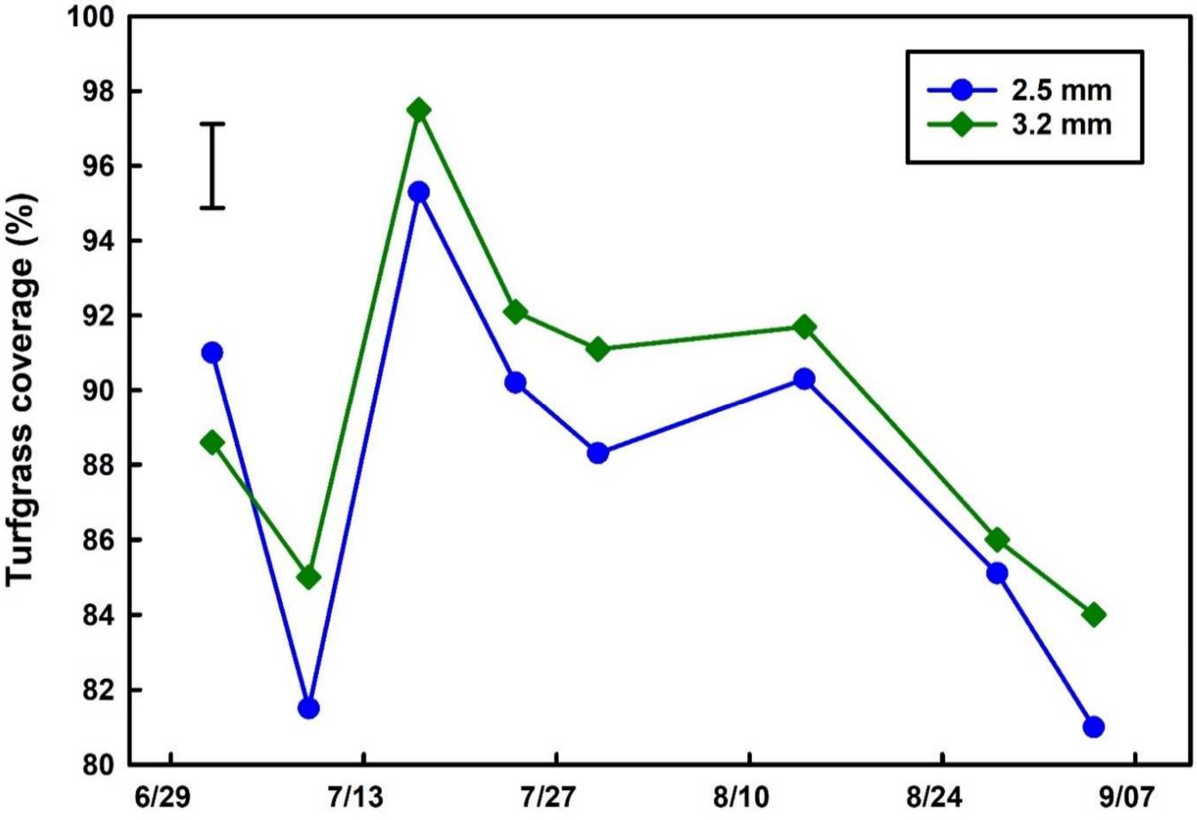


Figure 13. Effect of height of cut (mm) × date on turfgrass coverage during 2020. The error bar represents the least significant difference ($P \leq 0.05$) for mean comparisons.

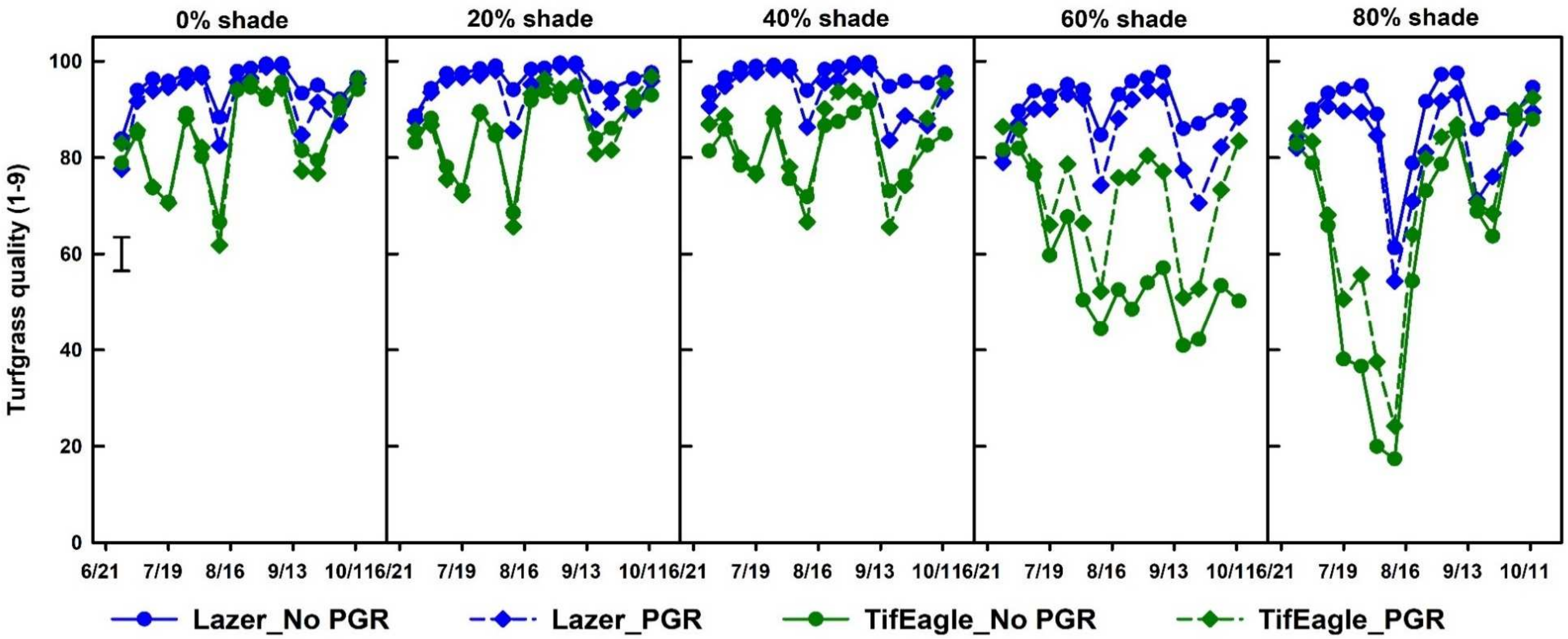


Figure 14. Effect of species × shade × plant growth regulator (PGR) on turfgrass coverage in 2020. The error bar represents the least significant difference ($P \leq 0.05$) for mean comparisons.

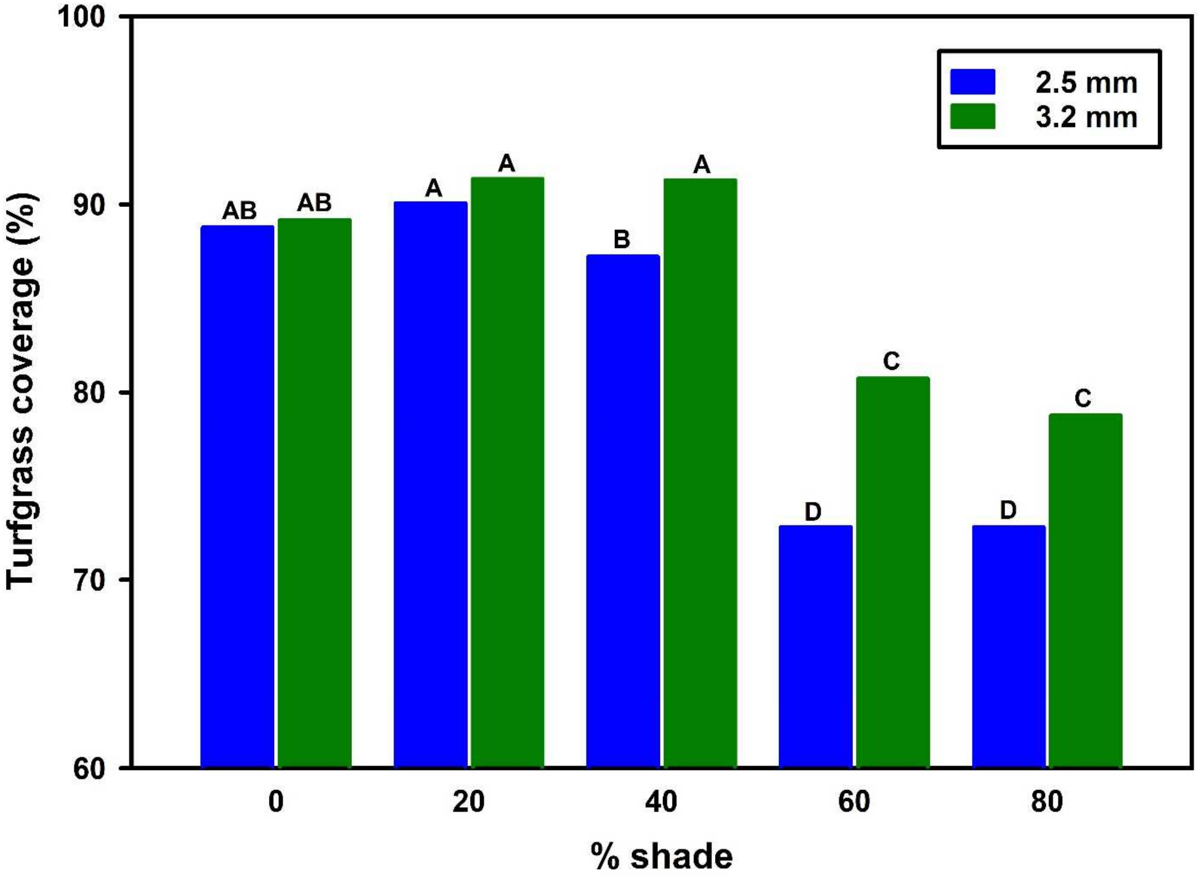


Figure 15. Effect of shade × height of cut (mm) on turfgrass coverage in 2021. The error bar represents the least significant difference ($P \leq 0.05$) for mean comparisons.

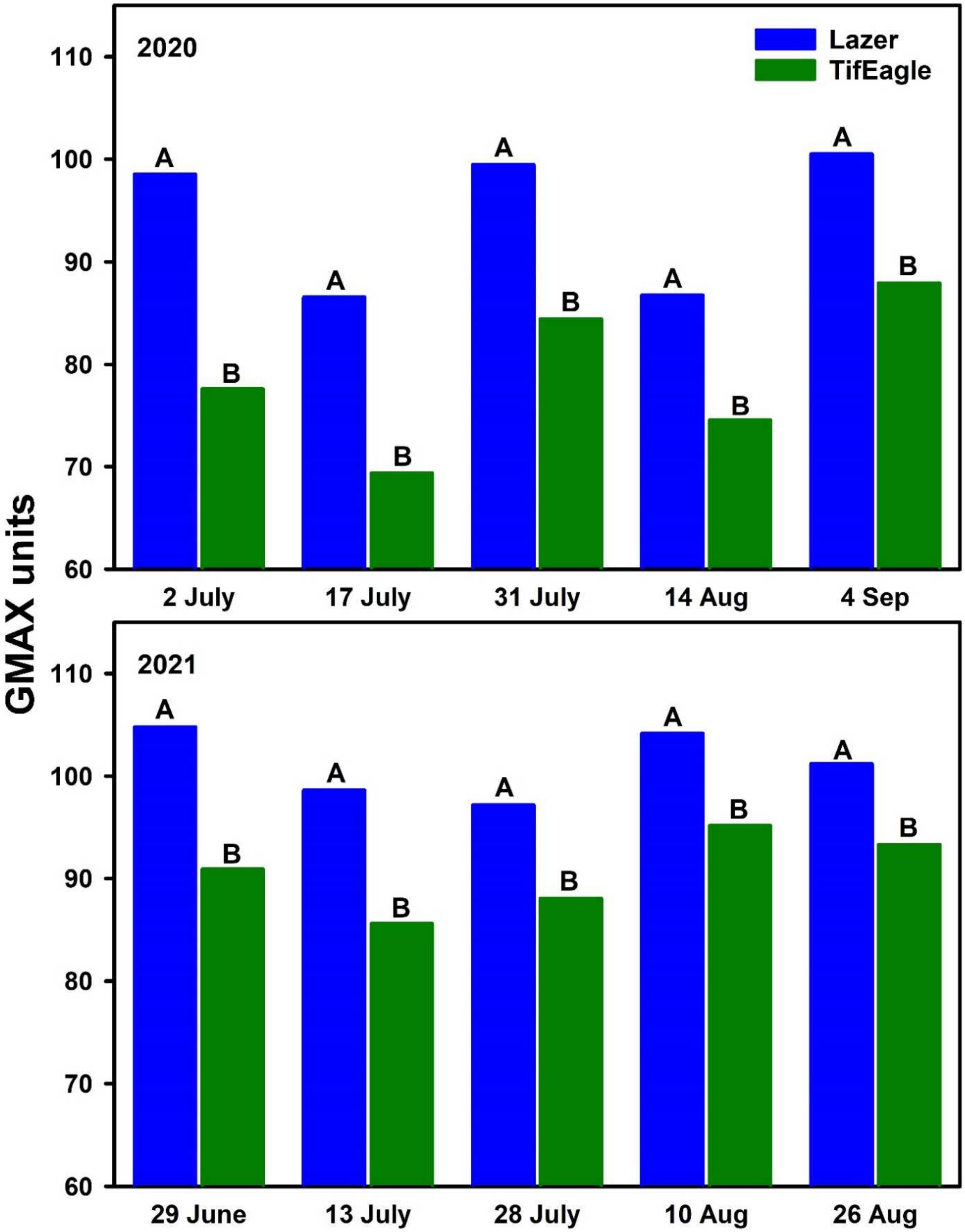


Figure 16. Effect of species × date on surface firmness in 2020 and 2021. For each rating date, bars with different letters are significantly different (P ≤ 0.05).

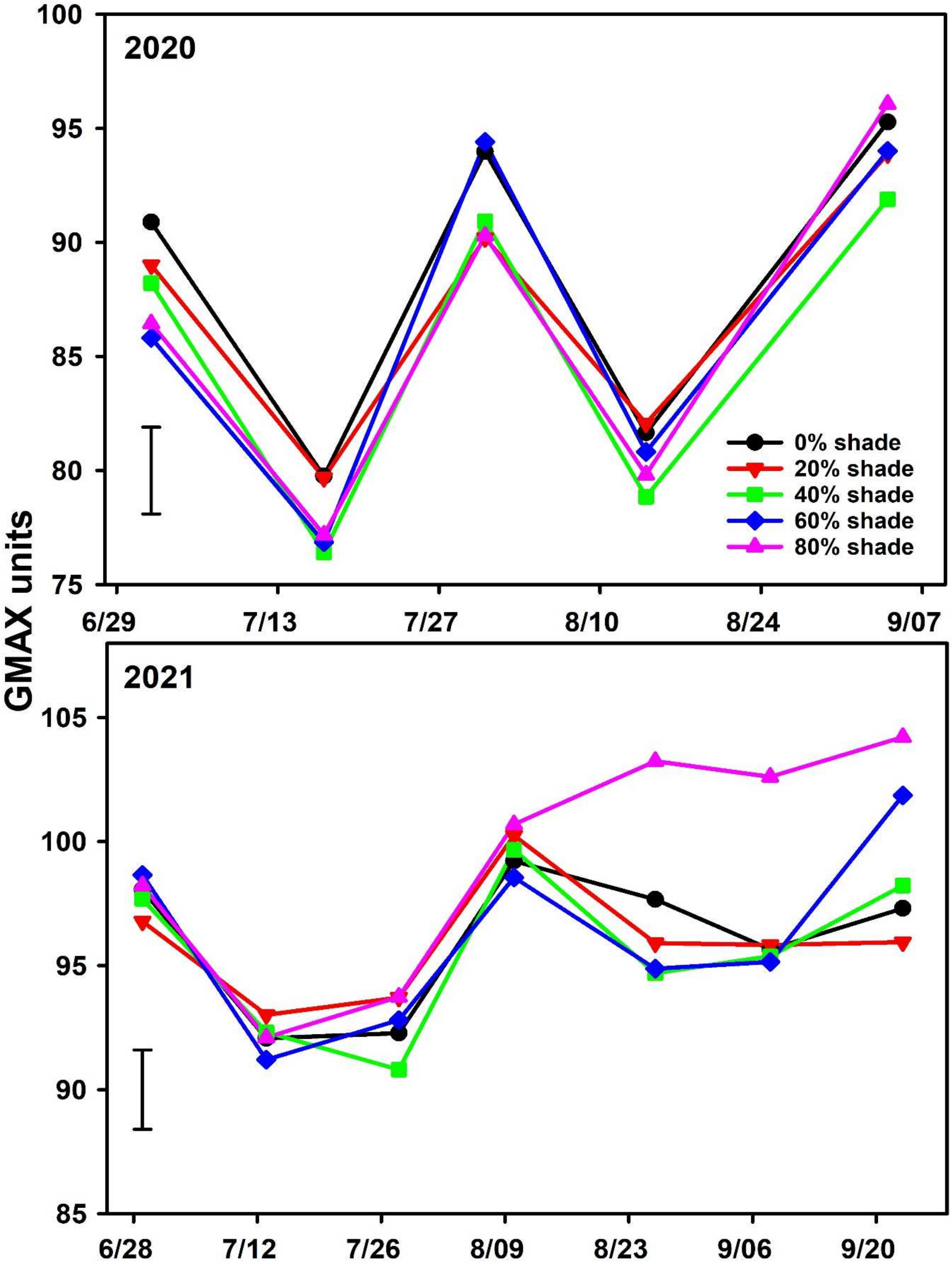


Figure 17. Effect of shade × date on surface firmness in 2020 and 2021. The error bar represents the least significant difference ($P \leq 0.05$) for mean comparisons.

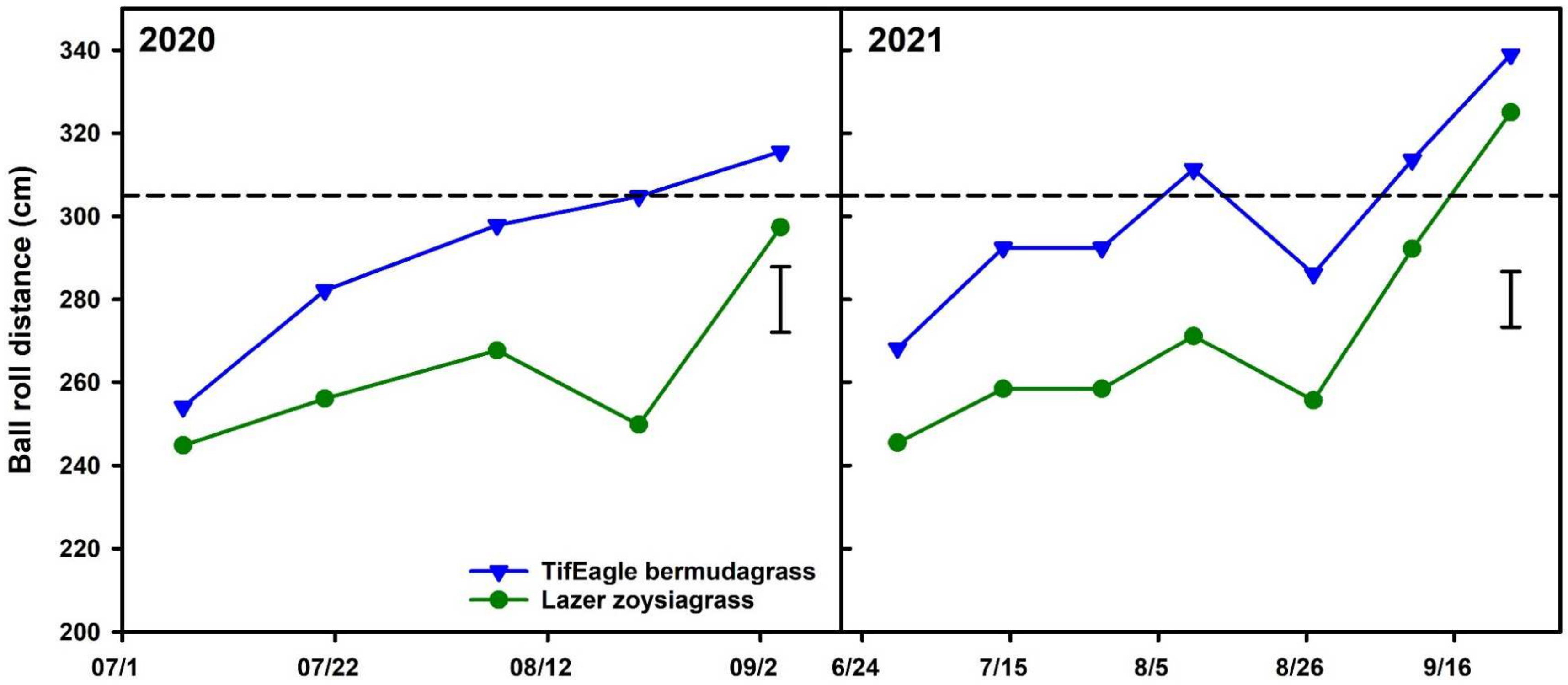


Figure 18. Effect of species × date on ball roll distance (cm) in 2020 and 2021. The error bar represents the least significant difference ($P \leq 0.05$) for mean comparisons. The dashed line at approximately 305-cm (10 feet) represents a ball roll distance that is considered an industry standard for a golf course putting green.

IV. Conclusions

Chapter II demonstrated the importance of protective covers to protect ultradwarf bermudagrass in the transition zone. This is the first trial which investigated the use of various air gap materials to supplement protective covers. Although moderate soil-temperature benefits were observed with air gap materials, protective covers alone prevented winterkill during the adverse winter of 2020-21. Air gaps may create additional burdens to golf courses including the high up front purchasing cost, storage challenges, and it is likely that air gap materials composed of batting material and straw will have to be replaced on an annual basis. The purchase of air gaps for wall-to-wall coverage is unnecessary and financially unfeasible for many golf courses, however, air gap materials composed of straw and batting could be valuable in areas of putting greens which historically receive winterkill including portions of putting greens that are shaded, north-facing, or weakened by traffic.

Chapter III represented an initial comparison of an industry-standard ultradwarf bermudagrass cultivar (‘TifEagle’) to a newly released greens-type zoysiagrass cultivar (‘Lazer’). Based on previous field trials that have established minimum DLI requirements for putting greens (Bunnell et al., 2005; Russell et al., 2019), the shade-tolerance of ‘Lazer’ zoysiagrass appears to be significantly greater than both ultradwarf bermudagrass and creeping bentgrass. The minimum DLI requirements generated in the present trial will provide golf courses a baseline for identifying problematic greens sites that do not have adequate light to grow an acceptable putting green. This objective measurement of light provided by portable PAR sensors can provide golf course superintendents with justification for solutions to increase playing conditions. Best management practices when managing golf course putting greens in the shade include raising the mowing height and applying trinexapac-ethyl, tree trimming and removal, and potentially re-surfacing to a more shade-tolerant grass selection.

‘Lazer’ zoysiagrass also appears to produce more desirable surface characteristics than older greens-type zoysiagrass varieties such as ‘Diamond’ zoysiagrass, particularly as it relates to ball roll distance. However, ‘TifEagle’ bermudagrass consistently produced greater ball roll distance when managed under the same conditions. Further field work identifying best management practices to increase ball roll distance of ‘Lazer’ zoysiagrass will likely include improvement in mower setup (brushes and or groomers), implementation of routine vertical mowing, and more frequent light-weight rolling to determine how to optimize the playing conditions of ‘Lazer’.

Major areas of focus going forward with research on greens-type zoysiagrass should include increasing establishment efficiency. Greens-type zoysiagrasses are slower to establish than ultradwarf bermudagrass from sprigging. Sodding, which would significantly increase the upfront establishment cost, may still be the most cost-effective way for golf courses looking to reduce the lost revenue while the putting greens are being established. The winter hardiness of greens-type zoysiagrass is also a concern. Field observations from previously developed fine-textured *Zoysia matrella* cultivars such as ‘Diamond’ (Parent of ‘Lazer) have shown susceptibility to winterkill. Implementation of protective covers will likely be necessary for greens-type zoysiagrass and further work investigating temperature thresholds will be warranted going forward. Because of the uncertainties about management strategies to create surface characteristics similar to industry-standard ultradwarf bermudagrass, slow establishment rate, and other unanswered questions, more field work is needed before recommending greens-type zoysiagrass over ultradwarf bermudagrass. The most likely scenario where greens-type zoysiagrass will find its niche is at golf courses with wide-spread shade stress on putting greens complexes and there is resistance to eliminating the shade.