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Determining the Light Requirements of Various Turfgrass Systems and Investigating Techniques to Quantify Photosynthetically Active Radiation

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Determining the Light Requirements of Various Turfgrass Systems and Investigating Techniques to Quantify Photosynthetically Active Radiation

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ABSTRACT

Light is one of the primary growth-limiting factors of turfgrass. Without sufficient quantities of photosynthetically active radiation (PAR; 400-700 nm wavelength), turfgrass quality will decline and could ultimately result in plant death. PAR light can be expressed in a daily quantity known as the daily light integral (DLI) and has been utilized to determine minimum light requirements for turfgrass as well as other plants. With an estimated 25% of all turfgrass being maintained under some level of shaded conditions, it is imperative to define minimum DLI requirements of various turfgrass systems to ensure acceptable turf quality. In addition, it is necessary to evaluate novel methods of quantifying and assessing light conditions so that turfgrass managers can direct appropriate agronomic decisions. This research aims to determine a minimum DLI requirement of a creeping bentgrass putting green, evaluate an efficient quantification method of DLI requirements for multiple warm season turfgrasses in an established landscape, and to estimate PAR reduction with total visible light measuring devices under various tree species. After evaluation of creeping bentgrass putting green turfgrass quality and coverage under 0, 70, 80, and 90% shade for two years, a minimum DLI requirement was estimated to be 30 mol m^{-2} d^{-1}. In a controlled research setting over two years, minimum DLI requirements of four warm season turf types, 'Astro-DLM' bermudagrass, common bermudagrass, 'Cavalier' zoysiagrass, and 'Meyer' zoysiagrass, were determined to be 20.4, 25.9, 15.0, and 21.1 mol m^{-2} d^{-1}, respectively. However, an efficient method to determine DLI requirements in an established golf course landscape was able to accurately estimate DLI requirements for just two of the four warm season turf types and further evaluation is needed. PAR reduction beneath tree shade canopies varied among tree species, but was not able to be estimated from visible light measurements with sufficient precision. This results of this research

establishes minimum DLI requirements of popular turfgrass selections for turfgrass managers to utilize as a baseline when making agronomic decisions in shaded conditions. Additionally, alternate methodology is evaluated to efficiently and accurately estimate minimum DLI requirements.

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DEDICATION

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TABLE OF CONTENTS

Chapter I:
Introduction and Literature Review

Chapter II:
Determining the Minimum Daily Light Integral Requirement of a Creeping Bentgrass Putting Green as Affected by Shade Timing and Intensity, Plant Growth Regulator, and Plant Foliar Colorant

Chapter III:
Investigating an Efficient Method to Determine Daily Light Integral Requirements of Various Warm-season Turfgrasses in an Established Landscape

Chapter IV:
Estimating Photosynthetically Active Radiation Reduction under Various Tree Shade Canopies with Photometric Light Measuring Devices

Chapter V:
Conclusions

LIST OF TABLES

Table **Page**

Chapter II

Chapter III

Chapter IV

LIST OF FIGURES

Figure **Page**

Chapter II

Chapter III

Chapter IV

Chapter I: Introduction and Literature Review

INTRODUCTION

With an estimated 20-25% of all managed turfgrass grown under some level of shaded conditions (Beard, 1973), there is a high likelihood that most turf managers will be responsible for maintaining turfgrass to an acceptable level in a reduced light environment. However, most turfgrass species are best adapted to full sun and will not grow optimally in reduced light environments. If careful attention is not given to turfgrass selection and maintenance practices in reduced light environments, shade stress will result in a decline in overall turfgrass quality that could ultimately lead to plant death.

The job performance of a turfgrass manager is primarily evaluated by the visual quality and condition of the turfgrass. Turfgrass managers are often tasked to maintain healthy and aesthetically pleasing turfgrass in sites that are not conducive to successful plant growth such as reduced light environments. Tree canopies, sports stadium infrastructure, buildings, and many other objects in the landscape can result in shaded conditions that could become a growth limiting factor in turfgrass systems (Glenn et al., 2012). Implementing agronomic practices such as lowering nitrogen fertility (Baldwin et al., 2009), raising mowing height (Glenn et al., 2013), and applying plant growth regulators (Qian and Engelke, 1999) reduce the negative effects on turfgrass quality caused by shaded conditions. However, these cultural practices may not fully eliminate the decline in quality of turfgrasses grown in shaded conditions and increasing light availability to the turfgrass may be the only solution. Therefore, determining precise light requirements of various turfgrass systems to avoid decline in turfgrass quality as a result of shade stress warrants further investigating.

C_3 and C_4 Photosynthesis

Photosynthesis is a critical chemical reaction in plant growth that is used to supply energy in the form of carbohydrates to be used by the turfgrass plant for growth and development. Through this process, plants absorb and utilize solar energy to drive the chemical reaction of converting carbon dioxide from the atmosphere and water from the soil into carbohydrates essential for plant growth. Photosynthesis also releases oxygen back into the atmosphere. All photosynthetic plants utilize the chemical reactions in the Calvin cycle to convert CO_2 to carbohydrates needed for plant growth, but the photosynthetic pathway that CO_2 is initially assimilated inside the chloroplasts is what distinguishes cool-season turfgrasses from warm-season turfgrasses (Fry and Huang, 2004).

Cool-season turfgrasses only fix carbon through the Calvin cycle by way of the C_3 photosynthetic pathway. The first step in C_3 photosynthesis is the reaction of CO_2 with the plant acceptor molecule ribulose 1,5-biphosphate (RuBP) to form two molecules of 3-phosphoclyceric acid (3-PGA). 3-PGA is a three carbon compound that is responsible for the name of the C_3 photosynthetic pathway used in cool-season turfgrasses. Reduction of 3-PGA then takes place to produce a three carbon sugar generated by photochemically derived adenosine triphosphate (ATP) and reductant equivalent nicotinamide adenine dinucleotide phosphate (NADPH). The resulting carbohydrate is then available for plant growth and development. The enzyme 1,5-biphosphate carboxylase (rubisco) that catalyzes carboxylation of RuBP to form 3-PGA can also act as a catalyst for the oxegenation of RuBP which results in CO_2 being released and not being converted to carbohydrates resulting in solar energy being wasted. This process is termed photorespiration and becomes problematic in C_3 photosynthesis when temperatures exceed 30°C where concentrations of CO_2 are lower and O_2 is higher in the current atmospheric conditions.

Warm-season grasses contain bundle sheath cells that are tightly arranged around mesophyll cells. This special leaf anatomical feature is unique to plants using the C_4 photosynthetic pathway and provides the plant with a more efficient process of fixing CO_2. In the mesophyll cells, phosphoenolpyruvate carboxylase will aid in fixing CO_2 that reacts to form oxaloacetate. Oxaloacetate is then converted to malate, a four carbon acid. Malate is transported by plasmodesmata from the mesophyll cells to the bundle sheath cells, releasing CO_2 when malate is decarboxylated. CO_2 is then fixed again by the Calvin cycle to produce carbohydrates. Photorespiration is minimal in C_4 plants due to rubisco being saturated with CO_2, deterring oxygenase activity (Fry and Huang, 2004). The difference in photosynthetic pathways between warm-season and cool-season grasses are in part responsible for differences in shade adaptability. The photosynthetic pathway directly effects the rate of photosynthetic efficiency for turfgrasses under shaded conditions.

Warm-Season Turfgrass versus Cool-Season Turfgrass

Even though warm-season turfgrasses are more efficient at utilizing CO_2 in the Calvin cycle compared to cool-season turfgrasses, higher amounts of light are needed to maintain photosynthetic rates in the C4 pathway (Taiz and Zieger, 2015). Photosynthesis requires the presence of sufficient light to convert solar energy into chemical energy in the form of ATP and NADPH to drive the chemical reaction. An increase in available light quantity does not often inhibit turf photosynthesis, but a decline in the rate of photosynthesis can occur when light quantity is reduced in shaded environments (Fry and Huang, 2004). The maximum quantity of available light that turfgrasses can use for photosynthesis is termed the light saturation point (McCarty, 2005). Cool-season turfgrasses have a light saturation point near 50% of full sunlight while warm-season turfgrasses require full sunlight to reach the light saturation point (McCarty

2005). The minimum quantity of light necessary for the rate of photosynthesis to equal the rate of respiration in turfgrass plants is termed the light compensation point (Fry and Huang 2004). The light compensation point of cool-season grasses is considerably lower than the light compensation point of warm-season grasses due to higher photosynthetic rates and lower respiration rates in low light levels (Fry and Huang, 2004; Taiz and Zeiger, 2015). Some cool-season turfgrass species have been reported to survive in conditions where only 5% of sunlight is available, but most cool-season turfgrasses require 25-35% of full sun to sustain normal growth depending on species and management (Beard, 1965; McBee and Holt; 1966). The difference in light compensation and saturation points indicate that cool-season and warm-season grass likely have different precise light requirements to maintain acceptable quality, but those thresholds have yet to be established for most turf types.

Shade Physiology

In both cool-season and warm-season turfgrasses, photosynthetic rates are significantly reduced when shaded conditions are increased (Stier and Gardner, 2008). Respiration rates are also reduced in shaded conditions to conserve carbohydrates. Therefore, the photosynthesis-respiration balance is an important factor in shade adaptation. Low ratios of photosynthesis to respiration can result in reduced total nonstructural carbohydrate content. (Burton et al., 1959; Qian and Engelke, 1999; Schmidt and Blaser, 1967). Continued reduction of nonstructural carbohydrates in the plant due to lowered photosynthesis rates in shaded conditions can result in a weakened turf stand. A decline in plant vigor, recuperative potential, and turfgrass quality could potentially result if the turfgrass cannot acclimate to the physiological growth changes that occur in a reduced light environment.

Shade Morphology

Adequate levels of solar radiation promotes root development, thicker leaves, and increased stem diameter in turfgrass plants (Dudeck and Peacock, 1992). However, if solar radiation quantities are not adequate, morphological responses in plant growth can be detrimental in recovery of turfgrass from physical wear stresses such as mowing events or foot traffic (Trenholm and Carrow, 2000; Cattani and Struik, 2001). The most noticeable morphological change in turfgrass that is grown in a reduced light environment is the elongation of the stem (Holmes and Smith, 1977). Increased internode length and leaf length result in taller plant height and an upright growth habit that is not desired in turfgrass systems (Dudeck and Peacock, 1992; McBee and Holt 1966; Wilkinson et al., 1975). Normal mowing practices could scalp turfgrasses that exhibit stem and shoot elongation in shade. Turfgrass becomes weakened further by allocating energy to recover from mower scalping. In addition, there are numerous other morphological changes that occur in turfgrass exposed to reduced light intensities such as decreases in leaf thickness, stem diameter, shoot density, and rhizome/stolon growth (Peacock and Dudeck, 1981; McBee and Holt, 1966; Wilkinson, et al., 1975). These morphological changes can occur in turfgrasses 4-7 days after being exposed to a reduced light environment (McBee, 1969). These morphological and physiological responses of turfgrasses to shaded conditions will often result in weaker turf and possible turfgrass loss that indicate the need of precise light requirements to ensure acceptable turf quality.

Solar Radiation and Photosynthetically Active Radiation

Plants utilize a band of light within the electromagnetic spectrum that only accounts for 37% of the energy that is delivered to the earth’s surface from the sun. Only 1 to 5% of that light is being utilized to produce chemical energy through the process of photosynthesis while 10% is reflected and 10% is transmitted through the leaf (Fry and Huang 2004; Turgeon, 2005). This band of light contains wavelengths of 400-700 nm and is termed photosynthetically active radiation (PAR) (Pearcy, 1989). Plant pigments such as chlorophyll absorb PAR at specific wavelengths within the 400-700 nm band. Chlorophyll *a* selectively absorbs light at 410, 430, and 660 nm and absorption by chlorophyll *b* occurs at 430, 455, and 640 nm. Light with wavelengths of 700-800 nm is not absorbed by chlorophyll, but may influence photomorphogensis and shade avoidance in turfgrasses (Wherley, et al., 2005). The ratio of red light (R; 600-700 nm) to far-red light (FR; 700-800 nm) is important in turfgrass shade adaptation (Holmes and Smith, 1977). The leaves of tree canopies can alter R:FR ratios due to reflection and absorption from the daily average of 1.15 in unobstructed light to as low as 0.36 once light reaches the turfgrass surface (Wherley et al., 2005). The altered R:FR ratios under tree shade induces metabolic and physiological changes in the turfgrass plant that can result in undesired visual plant responses and determine turfgrass shade tolerance (Wherley et al., 2005). Tree canopy architecture such as leaf color, shape, quantity, etc. could impact light quality and quantity available to turfgrass growing in the shaded areas created by tree canopies. Research is needed to evaluate the possible variation in PAR and total visible light quantities available under different tree species canopies.

Daily Light Integral Measurement

PAR light is measured in quantum radiometric units of μmol m^{-2} s^{-1} and is an instantaneous measurement of light energy at a specific location. The daily light integral (DLI; expressed as mol m^{-2} d^{-1}) is a quanta measurement of PAR light at a specific site over a 24-hour period (Korczynski et al., 2002). DLI measurement has been utilized as an important research tool to evaluate flowering periods, chlorophyll content, and other plant growth processes in many horticulture crops (Armitage and Carlson, 1981; Faust and Heins, 1994; Pearcy, 1989). In addition, DLI measurement has been demonstrated to be an effective method in quantifying turfgrass light requirements. Most notably, DLI requirements have been established for various ultradwarf bermudagrass (*Cynodon dactylon* (L.) Pers. x *C. transvaalensis* Burtt-Davy) cultivars for putting greens (Bunnell et al., 2005; Hodges et al., 2016; Miller et al, 2005) and other warm-season (C_4) turfgrass species (Zhang et al., 2017). Bunnell (2005) found that 32.6 mol m^{-2} d^{-1} is the necessary DLI during the months of July and August to maintain acceptable 'TifEagle' ultradwarf bermudagrass putting green quality in South Carolina. 'FloraDwarf' and 'TifDwarf', two ultradwarf bermudagrass cultivars used on putting greens in the southeastern United States, required a DLI of 38.6 mol m^{-2} d^{-1} to maintain acceptable turfgrass coverage (Miller et al., 2005). However, very little research has focused on DLI requirements of cool-season turfgrasses (C_3) such as creeping bentgrass (*Agrostis stolinifera* L.), a popular turfgrass selection for putting greens. A change in mowing height has been observed to affect the daily light integral needed to maintain acceptable turfgrass quality (Bunnell et al., 2005b; Glenn, 2013). With each mowing height increase of 1 mm, DLI requirement of 'Champion' and 'TifEagle' ultradwarf bermudagrass decreased by 2.0 m^{-2} d^{-1} (Glenn, 2013). Other cultural practices in shaded environments such as application of a plant growth regulator are known to increase shade tolerance (Goss et al., 2002; Qian and Engleke, 1999), but effect of these practices on the DLI requirement have not been quantified. In addition, all studies regarding DLI requirements of turfgrass have been conducted in a controlled field or greenhouse trial. Further research is needed to investigate a method to efficiently determine DLI requirements of various turf types in an established landscape.

Based on the limited literature on precise light requirements of various turfgrass types, the following objectives are proposed:

1) Determine the minimum DLI requirement of a creeping bentgrass putting green as affected by shade timing and intensity, plant growth regulator, and plant foliar colorant.
2) Develop an efficient method to determine DLI requirements of various warm-season turfgrasses in an established landscape.
3) Estimate photosynthetically active radiation reduction under various tree species` shade canopies with total visible light measuring devices.

A series of studies were conducted to evaluate the effect of shade on precise light requirements for turfgrass systems. The DLI requirements established in these studies should serve turfgrass managers as a benchmark for evaluating light needs for turfgrass at their own facilities. Furthermore, the results of this study aim to guide agronomic practices for turfgrass maintenance in shaded environments.

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Chapter II:

Determining the Minimum Daily Light Integral Requirement of a Creeping Bentgrass Putting Green as Affected by Shade Timing and Intensity, Plant Growth Regulator, and Plant Foliar Colorant

ABSTRACT

Turfgrass quality can be limited by the availability of photosynthetically active radiation delivered to the turf surface. The cumulative photosynthetically active radiation for one day at a given site is termed the daily light integral (DLI) and has been demonstrated as an effective measurement for quantifying light requirements in various turfgrass systems. However, the minimum DLI necessary to maintain acceptable quality on a creeping bentgrass (*Agrostis stolonifera* L.) putting green has yet to be determined. In addition, the impact of shade timing and intensity in combination with the effects of growth regulator Primo Maxx (trinexapac-ethyl) and Turf Screen plant colorant on DLI requirements need further investigating. The objective of this research was to determine the DLI requirement of a creeping bentgrass putting green by evaluating the effects of shade intensity and timing as well as the influence of Primo Maxx and Turf Screen on turfgrass quality in reduced light environments. Four shade intensity treatments (0%, 70%, 80% and 90% reduction of full irradiance) were applied to the turf during morning hours (sunrise to solar noon) or afternoon hours (solar noon to sunset) to observe differences in turf quality from May through October 2016 and 2017. Evaluations of visual turf quality ratings, turf coverage, and clipping yield were performed every two weeks during the trial. After two years of data collection, the minimum DLI requirement to maintain acceptable turfgrass quality for a 'Tyee' creeping bentgrass green was estimated to be 30 mol m^{-2} d^{-1}. While effective in improving turf quality on late summer rating dates, Primo Maxx and Turf Screen did not significantly reduce the minimum DLI requirement of creeping bentgrass.

INTRODUCTION

Creeping Bentgrass

Creeping bentgrass (*Agrostis stolonifera* L.) can produce an exceptional putting green surface under the proper growing conditions. The ability to withstand low mowing heights, very fine leaf texture, and dense turfgrass canopy make creeping bentgrass a popular turfgrass selection for putting greens (Fry and Huang, 2004). As a cool-season grass, creeping bentgrass has optimal shoot growth at ambient temperature between 16 and 24 °C and root growth between 10 and 18 °C (Fry and Huang, 2004). Temperate and sub-arctic climate zones throughout the United States typically sustain these optimal growing conditions for extended periods of time in the spring and fall months and result in creeping bentgrass being a popular turfgrass selection for putting green use (Christians and Engelke, 1994). Despite being marginally adapted to the climate conditions, creeping bentgrass is still a popular turfgrass selection for putting greens in the transition zone and southern United States where persistent above-optimal temperatures for growth during the summer months can result in heat stress. The perceived superior putting surface quality of creeping bentgrass is often the deciding factor of putting green turfgrass selection in these regions compared to bermudagrass that is more adapted to the climate (Christians and Engelke 1994; McCarty, 2005).

Creeping Bentgrass Shade Tolerance

Extensive work has investigated the various physiological and morphological effects of cool-season turfgrasses grown in shade, but there is limited research on overall shade limitations and precise light requirements to maintain acceptable quality of creeping bentgrass putting greens in reduced light environments. Creeping bentgrass grows best in full sunlight but can also acclimate well when grown in partial shade environments (Beard, 1973). Cool-season grasses such as creeping bentgrass reach light saturation, the light level where net photosynthesis is zero or where the photosynthesis rate equals the respiration rate (Danneberger, 1993), at nearly half of full sunlight (McCarty, 2005). Positive net photosynthesis is required to ensure plant survival (Wilkinson et al., 1975). Tree canopies and other structures in the landscape that surround putting greens often result in reduced light environments where reaching the light compensation point can prove to be difficult.

Bell and Danneberger (1999) found that creeping bentgrass produced unacceptable turfgrass quality when grown under 80% - 100% persistent shade levels and mowed at putting green height. However, if the same shade levels were cast upon the turf for 6 or fewer hours, creeping bentgrass maintained the same overall quality as if grown under full sun. There were no differences in turf quality if shade was applied to the turf during morning or afternoon hours (Bell and Danneberger, 1999). It is worth noting that the trial conducted by Bell and Danneberger (1999) took place in Columbus, Ohio (39.96° N, 82.99°W; USDA Plant Hardiness Zone 6a) where growing conditions tend to be less stressful on creeping bentgrass compared to the higher summer temperatures of Fayetteville, Arkansas (36°06' N, 94°10' W; USDA Plant Hardiness Zone 7a) in the transition zone where the following studies were conducted. Anecdotal evidence reported from golf course superintendents and other turfgrass managers has consistently indicated that morning sun is more essential for turfgrass growth compared to afternoon sun (Bell and Danneberger, 1999). These reports seem valid due to morning temperatures being better optimized for efficient photosynthesis compared to afternoon (Bell and Danneberger, 1999). However, there is little research to substantiate these claims and additional studies are needed to confirm the effects of shade timing on creeping bentgrass putting greens. In addition, there is no published work quantifying the amount of light necessary to maintain acceptable turf quality on creeping bentgrass putting greens.

Daily Light Integral

As previously presented, most studies regarding light requirements of creeping bentgrass focus on quantifying the percent reduction of full sun or duration of shade that results in unacceptable turf quality (Bell and Danneberger, 1999; Goss et al., 2002). In a golf course setting, shade is rarely constant, instead fluctuating throughout the day, and can be difficult for turfgrass managers to quantify. Instead of quantifying shade, the DLI is a measurement that quantifies the total amount of photosynthetically active radiation delivered to the surface over an entire day (Korczynski et al., 2002). The DLI has been utilized by researchers to develop minimum DLI requirements for various turfgrasses to maintain acceptable quality. Most notably, DLI requirements have been established for various ultradwarf bermudagrass (*Cynodon dactylon* (L.) Pers. x *C. transvaalensis* Burtt-Davy) cultivars for putting greens (Bunnell et al., 2005; Hodges et al., 2016; Miller et al, 2005). Bunnell (2005) reported that 32.6 mol m^{-2} d^{-1} was the DLI necessary during the months of July and August to maintain acceptable quality of a 'TifEagle' ultradwarf bermudagrass putting green in South Carolina. 'FloraDwarf' and 'TifDwarf', two ultradwarf bermudagrass cultivars used on putting greens in the southeastern United States, require a DLI of 38.6 mol m^{-2} d^{-1} to maintain acceptable turfgrass coverage (Miller et al., 2005). However, very little research has focused on DLI requirements of cool-season turfgrass species such as creeping bentgrass. To fill this gap in the scientific literature, this study aims to determine a minimum daily light integral requirement needed for creeping bentgrass putting greens through evaluating turfgrass under various shade intensity and timing regimes.

Trinexapac-ethyl

Undesirable shade avoidance mechanism of turfgrasses in reduced light environments are increased shoot growth and elongation requiring frequent mowing that could result in a lowered stand density and overall visual quality (Qian and Engelke, 1999). Increased turfgrass shoot elongation and leaf succulence grown in shade is due to an increase in the gibberellic acid (GA) biosynthesis of GA_1 to GA_{20} (Tan and Qian, 2003; Adams et al., 1992). The plant growth regulator trinexapac-ethyl (Primo Maxx) effectively suppresses unwanted shoot elongation by inhibiting GA biosynthesis of GA_1 to GA_{20} in turfgrasses (Adams et al., 1992). As a result, trinexapac-ethyl enhances turfgrass quality and shade tolerance by decreasing shoot elongation (Baldwin et al., 2009). Monthly or bi-monthly applications of Primo Maxx when conditions favor turfgrass growth have significantly increased turfgrass quality in reduced light environments (Qian and Engelke, 1999; Steinke and Stier, 2003). In addition to suppressing shoot elongation, trinexapac-ethyl also can improve turfgrass density, color, and quantity of stored carbohydrates (Goss et al., 2002; Steinke and Stier, 2003; Qian and Engelke, 1999). Trinexapac-ethyl applied to creeping bentgrass grown under 80% shade increased turfgrass cover up to 33% and tiller production up to 52% (Goss et al., 2002). Total carbohydrate levels, especially fructose concentration, were increased up to 20% in the shoots of creeping bentgrass treated with Primo Maxx. Higher concentrations of carbohydrates in the shoots indicate conservation/reallocation of carbohydrates to areas of more favorable growth under reduced light conditions (Goss et al., 2002). The direct cause of darker green color in turfgrass treated with trinexapac-ethyl is not confirmed in the literature, but previous research has resulted in possible explanations. Turfgrass treated with trinexapac-ethyl increased quantity and density of chlorophyll in leaf tissue and allowed for higher light harvesting in the photosynthesis process that could have resulted in improved turfgrass color (Heckman et al., 2001). Trinexapac-ethyl also could have maintained or enhanced turfgrass color by minimizing removal of plant tissue nitrogen during mowing events, the most limiting nutrient of turfgrass color (Christians et al., 1979; Kreuser and Soldat, 2012). The primary means of improving cool-season turfgrass shade tolerance is reducing leaf elongation through proper application of trinexapac-ethyl that can improve turfgrass density, color, and carbohydrate storage in shaded environments (Ervin et al., 2004). There is a need to quantify how the effects of trinexapac-ethyl applied to turfgrass in shaded environments may affect the critical DLI requirement of creeping bentgrass putting greens.

Turf Screen

Applying foliar colorants to putting green turfgrass is becoming an increasingly popular practice among golf course superintendents (Liu et al., 2007). Colorants enhance green color and visual quality of turfgrass by minimizing or masking turf stress symptoms (Ervin et al., 2004; Kreuser and Rossi, 2014). Colorant applications are being implemented by turfgrass managers to provide a viable alternative to overseeding warm-season turfgrasses, masking turfgrass shoot imperfections, spray pattern indicators, and enhancing spring green-up (McCarty et al., 2013; Liu et al., 2007). Product manufacturers have suggested that colorants such as Turf Screen (zinc oxide + titanium oxide + green dye) can reduce summer heat stress, increase photosynthetic efficiency, and decrease canopy temperature for cool-season turfgrasses during summer months by blocking turfgrass absorption of UVB (280-320 nm) radiation. Previous research has confirmed that colorants possess the capability to block UVB radiation that can cause oxidative stress and turfgrass injury (Ervin et al., 2004), but will also reduce the quantity of available PAR light (McCarty et al., 2013). McCarty et al. (2013) and Kreuser (unpublished data, 2016) demonstrated that colorants increase surface temperature, do not increase photosynthetic efficiency, and provide no reduction in summer heat stress of cool-season turfgrasses. Obear et al. (2017) reported improved turfgrass color when applied with Turf Screen and attributed the increase to green dye in product formulation instead of improvement of turf quality. Colorants applied to creeping bentgrass under 70% shade had significantly reduced year-end rooting depth compared to turfgrass exposed to full sun conditions, suggesting that colorants could enhance shade stress problems (Kreuser, unpublished data, 2016). There is a need to quantify how a colorant applied to turfgrass in shaded conditions may affect the critical DLI requirement for creeping bentgrass putting greens.

Objectives

To advance the current understanding of precise light requirements and shade tolerance of creeping bentgrass putting greens the following research objectives of this study were established: 1) determine a daily light integral requirement of a creeping bentgrass putting green, 2) evaluate turf quality differences between morning and afternoon shade with varying levels of shade intensity, and 3) evaluate the effects that plant growth regulators and plant colorants may have on creeping bentgrass shade tolerance.

MATERIALS AND METHODS

Experimental Area

This study was conducted during the growing seasons of 2016 and 2017 on a 'Tyee' creeping bentgrass (*Agrostis stolonifera* L.) putting green at the University of Arkansas Agricultural Research and Extension Center in Fayetteville, AR (36°06' N, 94°10' W). The Year 1 study was conducted from 1 May to 31 October 2016 and Year 2 from 3 May to 31 October 2017. The 18.3 m x 18.3 m experimental area was established from seed in the fall of 2013 and originally constructed with a soil profile and soil physical properties consistent with United States Golf Association recommendations (USGA, 1993). Mowing was performed 6 days per week at a 3.1 mm height of cut. Experimental area was fertilized every two weeks during the trial period at a rate of 12.2 kg N ha^{-1} with rotating applications of urea (46-0-0 N-P-K) and water soluble complete fertilizer (28-5-18 N-P-K). Overhead irrigation was applied as necessary to prevent drought symptoms.

Plots with significant turf loss after Year 1 were renovated to mimic a golf course management scenario and to capture the cumulative effect of shade over multiple growing seasons. To prepare a seedbed on the existing putting surface, renovated plots received solid tine aerification in one direction and vertical mowing at a 0.64 cm depth below putting surface in three directions on 24 February 2017. Plot were then seeded with 'Tyee' creeping bentgrass at a rate 97.7 kg ha^{-1} using a drop spreader (24" Variable Rate Drop Spreader, Gandy Company, Owatonna, MN) on 24 February and 30 March 2017. Seeds were topdressed with sand consistent to USGA specifications (USGA, 1993) and lightly raked to provide adequate seed to soil contact. Plots were fertilized immediately after seeding at a rate of 24.4 kg N ha^{-1} with an organic-based fertilizer (6-4-0 N-P-K). Translucent germination blankets (International Greenhouse Company, model #GR-DTB, Danville, IL) were installed after seeding and fertilization practices and removed once germination was complete. Overhead irrigation was scheduled to ensure sufficient moisture for germination and seedling development.

Three individual shade structures were modeled after a shade application system previously implemented at the University of Arkansas Agricultural Research and Extension Center (Trappe et al., 2011). The structures were constructed using 6.4 cm diameter steel pipe and measured 7.3 x 4.8 m, acting as shade timing whole plots (Fig.2.1). Each individual shade structure was divided into 1.8 x 4.8 m strips containing the four shade treatments that represented strip plots within the shade timing whole plots. The shade cloth was custom ordered to fit inside each section on the structures and the reinforced edges of the cloth had grommets installed every 60 cm. The shade cloths were tightly affixed to the structure using ultraviolet-resistant cable zip ties and wire cabling was installed under the cloth to prevent sagging of the cloth. The shade structures were supported 35 cm above the turf canopy by 6 wheels spaced evenly on the exterior steel pipes of the structure to allow for transportation. Quantum light sensors (LightScout Quantum Light Sensor, Spectrum Technologies, Aurora, IL) that measured photosynthetically active radiation (400-700 nm) were attached in a fixed placement under each shade cloth on two of the three shade structures.

Treatments

Four shade intensities, 0%, 70%, 80% and 90% reduction of full sun irradiance, were applied during either the morning or afternoon hours daily. Morning hours were deemed to be sunrise to solar noon and afternoon hours from solar noon to sunset. Shade structures were manually transported to apply shade treatments to turf within one hour of sunrise and solar noon.

The four shade intensities were applied with neutral density, polyfiber black shade cloth (International Greenhouse Company, model # SC-BL70, SC-BL80, SC-BL90, Danville, IL).

Four spray application treatment strips measuring 7.3 x 1.8 m were applied to the turfgrass canopy across each shade intensity strip within shade timing treatments. The four spray application treatments included: Primo Maxx (trinexapac-ethyl) at 0.028 kg ha^{-1} applied every 14 days, Turf Screen (titanium oxide + zinc oxide, green dye) at 3.2 kg ha^{-1} applied every 7 days, a combined application of Primo Maxx at 0.028 kg ha^{-1} applied every 14 days + Turf Screen at 3.2 kg ha^{-1} applied every 7 days, and a non-treated control. Spray applications were made with a CO_2 pressurized boom sprayer calibrated to a spray volume of 57.5 L ha^{-1}.

Evaluations

Daily and 30-year average ambient temperature data was collected from the National Weather Service (hhttp://weather.gov) station at Drake Field Airport in Fayetteville, AR during the trial period.

Daily light integrals (mol m^{-2} d^{-1}) were calculated by summing PAR measurements recorded in a 4-channel datalogger (WatchDog 1000 Series Micro Station, Spectrum Technologies, Aurora, IL) connected with quantum light sensors. Quantum light sensors were programmed to record the quantity of PAR photons (μmol m^{-2} s^{-1}) present under each shade intensity level at fifteen minute intervals. Removal of shade structures to allow for plot maintenance was treated as full sun conditions as was accounted for in DLI calculations. Daily light integrals were calculated for each shade treatment and timing as monthly and seasonal averages.

Visual turfgrass quality ratings were taken every two weeks during the study. Visual turfgrass quality ratings were based on evaluation of turfgrass coverage, color, density, and uniformity using a 1 to 9 scale with 1 representing dead turf and 9 representing dark green, healthy turf according to National Turfgrass Evaluation Program evaluation guidelines (Morris and Shearman, 1998). Any turfgrass quality rating below 7 was deemed unacceptable.

Digital images of each plot were recorded every two weeks to evaluate turfgrass coverage. Images (1200 x 1600 pixel resolution) were taken using a Canon Powershot G1X 14 Megapixel digital camera (Canon USA Inc., Melville, NY) placed inside of a portable, enclosed light box that provided a consistent artificial light source to improve objectivity in image data (Karcher and Richardson, 2013). Digital image analysis was used to evaluate percent turfgrass coverage in each captured image using the Turf Analyzer software program (Turf Analyzer, http://turfanalyzer.com) (Karcher et al, 2017). Healthy turfgrass was identified by selecting pixels with a hue of 45 to 140 and a saturation of 10 to 100. Selected pixels were divided by the number of total pixels of each image to determine turfgrass coverage expressed as a percent. Turfgrass coverage below 90% was deemed unacceptable.

Clipping yields for each treatment were collected every 14 days using a walk-behind greens mower (Eclipse 2 122F, Jacobsen, Charlotte, NC) set to a mowing height of 3.1 mm. Clipping yield collection occurred after daily mowing was suspended for a minimum of 3 days to allow sufficient turfgrass growth for accurate collection. Collected clippings were dried at 70° C for 72 hours and then weighed to determine dry weight.

Statistical Design and Analysis

This study was designed as a randomized complete block design with treatments in a 2 x 4 x 2 x 2 split-strip plot design with three replications. Shade timing (morning or afternoon shade) whole plots were stripped by four shade intensity factors of 0, 70, 80, and 90% shade, and stripped by spray application factors of Primo Maxx (trinexapac-ethyl) growth regulator or none and Turf Screen plant colorant or none. Data were analyzed using the PROC MIXED procedure of SAS (version 9.3; SAS Institute Inc., Cary, NC). Treatment means for significant main effects and interactions were separated using Fisher's protected Least Significant Difference (LSD) test. An alpha value of 0.05 was used to determine statistical significance.

Minimum DLI requirements for each treatment were determined using nonlinear regression analysis in Graph Pad Prism software program (GraphPad Software Inc., La Jolla, CA). For regression analysis, a 3-parameter sigmoidal curve was fitted to the data collected from each treatment to obtain a critical DLI value at which a turf quality rating of 7 or 90% turf coverage would be expected for a creeping bentgrass putting green. The following 3-parameter sigmoidal function was used:

$$y = C + \frac{D - C}{1 + e^{[(I_{50} - x) * b]}}$$

where C is the lower limit, D is the upper limit, b equals the slope, and I_{50} equals the DLI that elicits a 50% response in turf quality. A sum of squares reduction test was used to determine if a single model with shared parameter estimates should be used for all treatments to estimate a critical DLI value or if separate models with treatment specific parameter estimates were necessary.

RESULTS AND DISCUSSION

Weather Data

The average monthly air temperature varied between both years of this trial and potentially influenced the effects of shade on turfgrass quality, coverage, and clipping yield. In 2016, five of the six months during the trial resulted in average monthly temperatures greater than the 30-year average (Fig 2.2). Comparatively, only three months had above average air temperatures in 2017 (Fig 2.2). August, usually the warmest month of the year and most stressful on creeping bentgrass during the summer, resulted in an average monthly temperature 1.9 °C lower than the 30-year average in 2017 (Fig 2.2). The consecutive trend of above-average temperatures in 2016 as opposed to the fluctuating air temperature patterns in 2017 are possible confounding factors of turfgrass decline under shaded conditions observed in this trial.

Daily Light Integrals

Average DLI for non-shaded conditions from May through October during the 2016 and 2017 trials were 45.0 and 46.0 mol m^{-2} d^{-1}, respectively (Table 2.1). Morning shade had an increase of 0.7, 2.8, and 1.8 mol m^{-2} d^{-1} to reach the turfgrass surface under shade intensities of 70, 80, and 90% shade, respectively, in 2017 compared to 2016. Afternoon shade had an increase of 0.9, 1.2, and 0.3 mol m^{-2} d^{-1} under shade intensities of 70, 80, and 90% shade, respectively, to reach the turfgrass from 2016 to 2017. DLI quantities were higher in plots receiving morning shade compared to afternoon shade intensities of 70, 80, and 90% shade levels by 1.8, 1.6, 1.7 mol m^{-2} d^{-1} in 2016 and 2.7, 3.2, and 3.2 mol m^{-2} d^{-1} in 2017.

Turfgrass Quality

Visual turfgrass quality of creeping bentgrass was affected by shade intensity and timing, as well as chemical spray applications of Primo Maxx and Turf Screen throughout the trial

(Table 2.2). Although several significant effects were present ($P \leq 0.05$), only the highest order interaction containing each treatment effect will be discussed. In 2016, a significant ($P \leq 0.05$) three-way interaction of shade intensity and shade timing main effects by evaluation date was observed (Table 2.2). In addition, there were significant two-way interactions of separate main effects of Primo Maxx and Turf Screen by evaluation date in 2016.

For each evaluation date in 2016, there were significant differences among shade intensity x shade timing treatments ($P \leq 0.05$). During the month of May, the full sun treatment was significantly lower in turfgrass quality compared to all treatments (Fig. 2.3). This result can be attributed to the black neutral density shade cloth absorbing solar radiation and creating a warmer microclimate under the shade treatments. The warmer microclimate encouraged more turfgrass growth under shade treatments compared to full sun conditions that were suboptimal temperatures for turf growth at this early period of the growing season. However, once ambient temperatures became stressful on turfgrass growth later during the trial period, the reduction in solar radiation under shade cloths resulted in a cooling effect compared to the full sun treatment. Beginning in June, full sun turfgrass quality remained above minimal acceptability (rating score $\geq$7) and maintained significantly greater turfgrass quality compared to all other shade treatments by at least 0.6 rating units throughout the remainder of the 2016 trial period (Fig. 2.3). Regardless of shade timing, turfgrass quality under shade intensities of 70, 80, and 90% shade had dropped below acceptable quality by 9 August. Both timings at 70% shade intensity resulted in acceptable quality on 14 and 30 September rating dates, but only the 80% morning shade treatment rose above the threshold for minimum acceptability. On July 7, turfgrass quality under 90% afternoon shade was significantly lower compared to 90% morning shade and this trend continued for the duration of the trial. Morning 80% shade maintained significantly higher turfgrass quality above afternoon shade through the duration of the trial beginning on 9 August evaluation date. In addition, 70% morning shade resulted in significantly increased turfgrass quality compared to 70% afternoon shade during the stressful environmental conditions on 9 and 18 August evaluation dates.

Significant interactions of Primo Maxx by evaluation date and Turf Screen by evaluation date were observed in 2016 on turfgrass quality (Table 2.2). Across all shade timing and shade intensity treatments, the effects of Turf Screen and Primo Maxx applications each increased turfgrass quality compared to the untreated control on select rating dates during 2016 (Fig. 2.4). Turfgrass treated with Turf Screen had increased turfgrass quality compared to the untreated control on 7 July. Both Primo Maxx and Turf Screen increased turfgrass quality compared to the untreated control on 14 and 30 September. Furthermore, turfgrass quality was increased to above minimal acceptable levels for turf treated with Primo Maxx and Turf Screen on those evaluation dates.

In 2017, no treatment interactions were observed and only the main treatment effects of shade intensity, Primo Maxx, and Turf Screen were significant ($P \leq 0.05$) (Table 2.2). Shade intensity treatment resulted in a significant main effect in 2017 (Fig. 2.4). Compared to full sun treatments, turfgrass quality of 70 and 80% shade intensity treatments tended to have slightly lowered turfgrass quality, but were not statistically different (Fig. 2.5). However, 90% shade resulted in significantly lower quality compared to all other shade intensity treatments by at least 1 rating unit (Fig. 2.5). The effect of 90% shade also dropped turfgrass quality below minimum acceptability while all other shade intensity treatments remained above the minimum acceptability threshold (Fig. 2.5).

The separate treatment main effects of Primo Maxx and Turf Screen applications on turfgrass quality were significant in 2017 (Table 2.2). It is important to note that all treatments resulted in acceptable quality scores (Fig. 2.6). Across all shade timings, shade intensities and evaluation dates, applications of Primo Maxx and Turf Screen improved turfgrass quality compared to the untreated control (Fig. 2.6). This slight significant increase in turfgrass quality demonstrates the ability of Primo Maxx or Turf Screen to increase visual turfgrass quality during the summer months on creeping bentgrass putting greens.

Similar to other findings on creeping bentgrass shade tolerance, turfgrass quality continued to decline under increasing levels of shade intensity in this study (Bell and Danneberger 1999; Goss et al. 2002). However, afternoon shade resulted in lower turfgrass quality compared to morning shade, a result that had not been observed previously on creeping bentgrass. While Bell and Danneberger did not observe differences between morning and afternoon shade on creeping bentgrass, Bunnell et al. (2005) reported that afternoon shade was more detrimental to turfgrass quality on a ‘TifEagle’ bermudagrass putting green. The amplified effect of afternoon shade on turf quality decline was attributed to a 2 mol m^{-2} d^{-1} reduction in DLI during afternoon hours compared to morning hours. (Bunnell et al., 2005). This reduction in DLI in the afternoon was also observed in the present study and is presumed to be why creeping bentgrass turf quality decline was greater in afternoon shade.

Primo Maxx was observed to improve turfgrass quality under various shade intensity and timing regimes. This observation is concurrent with other studies evaluating the use of Primo Maxx to increase turfgrass quality and shade tolerance (Baldwin et al., 2009; Qian and Engelke, 1999; Steinke and Stier, 2003). However, this is the first study to observe Turf Screen improving turfgrass quality during environmentally stressful growing conditions in summer months. This was an unexpected finding due to previous research demonstrating the use of colorants such as Turf Screen to be detrimental to turfgrass photosynthetic processes (McCarty et al., 2013). It is important to note that Obear et al. (2017) reported that the green dye in the product formulation of Turf Screen increased visual turfgrass color ratings and masked turfgrass stress symptoms. That conclusion could be an explanation as to why visual quality was increased compared to the untreated control in this study. These observations indicate that applications of Primo Maxx or Turf Screen are capable of significantly improving visual turfgrass quality during stressful growing conditions of late summer months.

Average turfgrass quality was plotted against average DLI for each shade timing and intensity treatment to estimate a DLI requirement to maintain acceptable turfgrass quality. Nonlinear regression analysis indicated that model parameters were significantly different ($P \leq 0.05$) among chemical spray treatments, therefore separate models were developed for the untreated control, Primo Maxx, Turf Screen, and Primo Maxx + Turf Screen treatments. According to the models for 2016, estimated minimum DLI requirement of 30.5 mol m^{-2} d^{-1} was determined for a creeping bentgrass putting green with no Primo Maxx or Turf Screen chemical spray treatment (Fig. 2.7). Estimated minimum DLI requirements when chemical spray treatments of Primo Maxx, Turf Screen, and Primo Maxx + Turf Screen were applied to creeping bentgrass were 30.4, 29.4, and 29.2mol m^{-2} d^{-1}, respectively (Fig. 2.7). During 2017, minimum DLI requirements of creeping bentgrass were estimated to be 29.1, 28.2, 29.2, and 28.1 mol m^{-2} d^{-1} for the untreated control, chemical spray treatments of Primo Maxx, Turf Screen, and Primo Maxx + Turf Screen, respectively (Fig. 2.8).

While Primo Maxx and Turf Screen applications were able to increase turfgrass quality during specific time periods throughout the study, those applications were not able to significantly lower the creeping bentgrass minimum DLI requirement (Fig. 2.7 and 2.8). Results from this study estimate a minimum of 30.5 and 29.1 mol m^{-2} d^{-1} were required to maintain acceptable turfgrass quality of a creeping bentgrass putting green in 2016 and 2017, respectively. It is important to note that even though the intensity of turfgrass quality decline varied between years, the estimated DLI requirements remained very similar. The minimum DLI requirement of 30 mol m^{-2} d^{-1} determined over a two-year period in this study is lower than the 32.6 mol m^{-2} d^{-1} DLI requirement that Bunnell et al. (2005) established to maintain acceptable turfgrass quality of a 'TifEagle' ultradwarf bermudagrass green. The difference in the two DLI requirements can be attributed to the relatively increased shade tolerance that creeping bentgrass has over bermudagrass (Fry and Huang, 2004). The variation in shade tolerance can be linked to the light saturation point of cool-season turfgrass being near 50% of full sun, while warm-season turfgrasses require close to full sun conditions (McCarty, 2005). Therefore, as is the case in this comparison, a cool-season turfgrass like creeping bentgrass would be expected to have a lower minimum DLI requirement than that of warm-season turfgrass like ultra-dwarf bermudagrass if managed similarly.

Turfgrass Coverage

Turfgrass coverage of creeping bentgrass was affected by shade intensity, shade timing, and chemical spray treatments of Primo Maxx and Turf Screen (Table 2.2). In 2016 and 2017, there was a significant three-way treatment interaction of shade intensity, shade timing, and evaluation date. Additionally in 2016, there was a significant four-way interaction of Primo Maxx, Turf Screen, shade timing, and evaluation date.

A significant three-way interaction of shade intensity and shade timing by evaluation date was observed on turfgrass coverage of creeping bentgrass in both years (Table 2.2). During 2016 and 2017, creeping bentgrass under 0% shade (full sun) had the highest turfgrass coverage among all shade treatment combinations for each evaluation date (Fig. 2.9 and 2.10). In 2016, 70 and 80% shade treatments applied in morning or afternoon were not significantly different from each other except for one evaluation date in October (Fig. 2.9). Both shade timings of 90% shade produced significantly lower turfgrass quality compared to 0, 70, and 80% shade on 9 September and continued throughout the remainder of the trial (Fig. 2.9). Under 90% shade, morning shade treatments resulted in significantly greater turfgrass coverage compared to afternoon shade from 8 September through the remainder of the trial (Fig. 2.9). Similarly, morning shade resulted in greater turfgrass coverage compared to afternoon shade under 80% shade intensity on 20 October 2016. There were no significant differences in turfgrass coverage between morning and afternoon timings of 70% shade (Fig. 2.9).

In 2017, there were no significant differences in creeping bentgrass turfgrass coverage between full sun treatments and both shade timings of 70% and 80% shade on any evaluation date (Fig. 2.10). Morning and afternoon shade timing treatments of 90% shade were significantly lower than all other shade treatments on the first rating date of 2017 (Fig. 2.10). Turf coverage under 90% shade was lower than other shade treatments on the first rating date due to not being completely filled in from reestablishment practices after turfgrass loss in the first year of the trial. After the initial rating date, afternoon timing of 90% shade was the only treatment with significantly lower turfgrass coverage compared to the full sun treatment and this trend remained for the duration of the trial (Fig. 2.10). After turfgrass loss in the first year of the trial and subsequent reestablishment practices, the young turfgrass stand was not able to achieve acceptable turf coverage under the low light conditions associated with 90% afternoon shade.

Previous research has demonstrated similar decreases in turfgrass coverage under increasing shade intensities (Goss et al., 2002; Qian and Engelke, 1999). In agreement, this study observed that creeping bentgrass coverage decreased when increasing intensities of 70, 80, and 90% shade were applied in 2016. A decrease in DLI quantities delivered to the turfgrass under increasing shade can explain the observed turfgrass decline under various shade intensities. However, in 2017, this trend was only observed under increasing shade intensity from 80 to 90% shade on select evaluation dates. The disparity in turf quality between 80 and 90% shade can be attributed to incomplete reestablishment of turfgrass under 90% shade during the second year of the trial more so than a matter of differences in DLI. The increase in DLI under each shade treatment in 2017 over 2016 could have led to lack of turf coverage separation between shade intensity treatments. This study is the first report of afternoon shade timing resulting in lower turfgrass coverage compared to morning sun. This observation was most pronounced under 90% shade intensity for a majority of the trial, but did occur under 70 and 80% shade on select evaluation dates. The decrease in turfgrass coverage between shade timings can be attributed to the differences in DLI reduction under afternoon shade compared to morning shade.

During both years of this study, analysis of variance indicated a significant ($P \leq 0.05$) four-way treatment interaction of shade timing, Primo Maxx application, and Turf Screen application by evaluation date (Table 2.2). In 2016, turfgrass coverage under morning shade was relatively similar among all spray treatment combinations until 10 October 2016 evaluation date (Fig. 2.11). Under morning shade, the combination spray treatment of Primo Maxx + Turf Screen had greater turfgrass coverage by at least 6.4% compared to the untreated control on two late season evaluation dates in October (Fig. 2.11). There was greater discrepancy among treatment applications of Primo Maxx, Turf Screen, and the untreated control on turfgrass coverage when turfgrass was shaded in the afternoon compared to the morning. Under afternoon shade, all chemical spray treatments of Primo Maxx or Turf Screen resulted in significantly greater turfgrass coverage compared to the untreated control on 18 August, 22 and 30 September, and 10 October 2016 evaluations dates (Fig. 2.11). Applications of Primo Maxx to creeping bentgrass maintained significantly greater turfgrass coverage by at least 7.1% compared to all other spray treatments and the untreated control on the final two evaluation dates (Fig. 2.11).

During 2017, a significant interaction of shade timing, Primo Maxx, and Turf Screen was observed on the 28 August evaluation date. No significant differences existed between chemical spray treatments of Primo Maxx and Turf Screen compared to the untreated control under morning shade. Under afternoon shade, however, chemical application treatments of Primo Maxx, Turf Screen, and Primo Maxx + Turf Screen significantly improved turfgrass coverage compared to the untreated control (Fig. 2.12).

Turfgrass coverage was improved under shaded conditions on evaluation dates throughout the trial when treated with regular spray applications of Primo Maxx. Previous research (Baldwin et al., 2009; Goss et al., 2002; Qian and Engelke, 1999) also reported increased coverage when Primo Maxx was applied to shaded turfgrass. No previous research has investigated the effects of Turf Screen turfgrass colorant on turfgrass coverage. This study revealed no significant benefit of applying Turf Screen to improve turfgrass coverage in shaded conditions instead of Primo Maxx. While there were no differences under morning shade, this is the first report of Primo Maxx or Turf Screen applications improving turfgrass coverage under afternoon shade.

Average turfgrass coverage was plotted against average DLI for each shade timing and intensity treatment to quantify a DLI requirement to maintain minimal acceptable turfgrass coverage quantity of 90%. Nonlinear regression analysis indicated that model parameters were significantly different ($P \leq 0.05$) among chemical spray treatments, therefore separate models were developed for the untreated control, Primo Maxx, Turf Screen, and Primo Maxx + Turf Screen treatments. According to the model for 2016, estimated minimum DLI requirement of 27.9 mol m^{-2} d^{-1} was determined for a creeping bentgrass putting green with no Primo Maxx or Turf Screen chemical spray treatment (Fig. 2.13). Estimated minimum DLI requirements of creeping bentgrass applied with chemical spray treatments of Primo Maxx, Turf Screen, and Primo Maxx + Turf Screen were 28.0, 27.8, and 27.4 mol m^{-2} d^{-1}, respectively (Fig. 2.13). During 2017, minimum DLI requirements of creeping bentgrass was estimated to be 27.9 mol m^{-2} d^{-1} when no Primo Maxx or Turf Screen treatments were applied. Minimum DLI requirements of Turf Screen and Primo Maxx + Turf Screen were estimated to be 28.4, and 28.9 mol m^{-2} d^{-1}, respectively (Fig. 2.14). No minimum DLI requirement was estimated for the spray application of Primo Maxx due to the average turfgrass coverage of all shade treatments and Primo Maxx combinations never dropping below 90%. Therefore, it can be assumed that a DLI greater than 25.1 mol m^{-2} d^{-1} would result in acceptable turfgrass coverage if treated with Primo Maxx in 2017.

Estimated DLI requirements of creeping bentgrass for acceptable turfgrass coverage were slightly lower than the DLI requirements determined from turfgrass quality. Turf coverage DLI requirements ranged 0.8 to 2.6 mol m^{-2} d^{-1} lower than turfgrass quality DLI requirements. This difference in minimum DLI is due to turfgrass coverage evaluations measuring strictly percent turfgrass coverage while turf quality ratings were evaluated based on coverage, color, density, and coverage. The inclusion of additional parameters under evaluation (i.e. color and uniformity) for turf quality ratings could have led to a higher DLI requirement than evaluation on turf coverage alone.

Clipping Yield

Clipping yields were affected by shade timing, shade intensity, and applications of Primo Maxx and Turf Screen during 2016 and 2017 (Table 2.2). In both years, there was a significant three-way interaction of shade intensity, shade timing, and evaluation date (Table 2.2).

A significant three-way interaction of shade intensity and shade timing by evaluation date was observed on clipping yield in 2016 and 2017 (Table 2.2). The first three evaluation dates of 2016 resulted in no differences in clipping yield between shade intensity and timing treatments compared to full sun (Fig. 2.15). All shade treatments resulted in lower clipping yield on three of the final four evaluation dates in 2016 compared to full sun treatment (Fig. 2.15). Clipping yields of both 90% shade timings were significantly lower than 70 and 80% shade treatments on one evaluation date in early September (Fig. 2.15). Morning shade treatments resulted in 51, 72, and 80% greater clipping yields compared to afternoon treatments of 70, 80 and 90% shade, respectively, on 8 August 2016 evaluation date (Fig. 2.15).

On 6 June 2017, turfgrass under afternoon shade had increased clipping yield compared to turfgrass under morning shade for all shade intensity treatments (Fig. 2.16). Clipping yields in full sun were significantly greater than other shade treatments on 21 August (Fig. 2.16).

Turfgrass under shaded conditions has been observed to have increased clipping yields compared to turfgrass in full sun (Baldwin et al., 2009) due to increased gibberellic acid synthesis and subsequent shoot elongation (Tan and Qian, 2003). However, turfgrass density and percent cover will decline over time as turfgrass is continuously exposed to shaded conditions

(Goss et al., 2002; Stienke and Stier 2003). These previous findings are similar to the observations in the present study of higher clipping yields of turfgrass under shade on early season evaluation dates compared to full sun. However as turf coverage and density declines under shaded conditions on subsequent evaluation dates, clipping yield of turfgrass under shade becomes lower than turf in full sun.

In 2016, analysis of variance indicated a significant two-way interaction of Primo Maxx spray application and evaluation date (Table 2.2). On the first two evaluation dates of 2016, Primo Maxx lowered clipping yield compared to the untreated control by 14 and 6%, respectively, across all shade intensity and timing treatments (Fig. 2.17). For all subsequent evaluation dates, Primo Maxx did not significantly lower clipping yield compared to the untreated control (Fig. 2.17).

In 2017, a significant four-way interaction of shade timing, Primo Maxx application, Turf Screen application, and evaluation date was observed (Table 2.2). Under both shade timings, there were no statistical differences in clipping yield between Turf Screen and untreated control treatments (Fig. 2.18). Similarly, there were no significant differences observed between applications of Primo Maxx and Primo Maxx + Turf Screen on clipping yield (Fig. 2.18). However, Primo Maxx and Primo Maxx + Turf Screen reduced clipping yield compared to Turf Screen and the untreated control on 2 and 3 evaluation dates under morning and afternoon shade treatments, respectively (Fig. 2.18).

This is the first report on the effect of Turf Screen turfgrass colorant on creeping bentgrass clipping yield response. No physiological differences were observed between Turf Screen and the untreated control in terms of turfgrass clipping collection throughout the study. As was the case in this study, Primo Maxx has been previously demonstrated to reduce clipping yield compared to the untreated control under shaded conditions (Baldwin et al., 2009; Bunnell et al., 2005b). A combination of Primo Maxx and Turf Screen produced similar results compared to the Primo Maxx application alone. This finding suggests that a tank mix of the two products could both limit shoot growth via the growth regulator and maintain color via the green dye contained in Turf Screen plant colorant.

CONCLUSIONS

This is the first study to estimate a minimum DLI requirement for a creeping bentgrass putting green. ‘Tyee’ creeping bentgrass managed as a putting green required a minimum DLI quantity of 30 mol m^{-2} d^{-1} to maintain acceptable turfgrass quality throughout this study. Furthermore, this is the first report to evaluate the role of Primo Maxx plant growth regulator and Turf Screen turfgrass colorant in determining a minimum DLI requirement. Although Primo Maxx and Turf Screen were able to slightly improve turfgrass quality on certain evaluation dates during the trial, regular applications of the growth regulator and turfgrass colorant were not able to lower the minimum DLI requirement. This research provides a baseline for quantifying minimum DLI requirements of cool-season putting green turfgrass species. Further investigation is needed to determine minimum DLI requirements of other creeping bentgrass putting green varieties. Additional research on the effects of different putting green cultural practices, such as reduced nitrogen fertilization and alternative mowing heights, would be beneficial.

Daily light integral quantities delivered to the turfgrass surface were observed to be higher during the morning hours compared to the afternoon. As a result, afternoon shade caused a greater decline in turfgrass quality of creeping compared to morning shade. This is the first report of afternoon shade being more detrimental to creeping bentgrass health, but a similar finding was observed by Bunnell et al. (2005) on a ‘TifEagle’ bermudagrass putting green. This study did not seek to explain the diurnal differences between morning and afternoon DLI quantities and is a topic for further research.

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Table 2.1. Average daily light integrals of four shade intensities (0, 70, 80, and 90% shade) during morning (sunrise to solar noon) and afternoon (solar noon to sunset) shade timings from May-October in Fayetteville, AR during 2016 and 2017. Average daily light integrals are followed by ± to indicate standard errors for each shade treatment.

Shade treatment	Daily light integral	
	2016	2017
	($mol\ m^{-2}\ d^{-1}$)	
None	45.0 ± 1.1	46.0 ± 1.2
70% Morning	29.9 ± 0.8	31.6 ± 0.9
70% Afternoon	28.1 ± 0.7	28.9 ± 0.8
80% Morning	28.0 ± 0.7	30.8 ± 0.9
80% Afternoon	26.4 ± 0.7	27.6 ± 0.8
90% Morning	26.5 ±0.7	28.3 ± 0.8
90% Afternoon	24.8 ± 0.7	25.1 ± 0.8

Table 2.2. Analysis of variance (ANOVA) table of turf quality rating, turf coverage, and clipping yield evaluation main effects and interactions on a 'Tyee' creeping bentgrass putting green in 2016 and 2017. P-values in bold are highest order significant ($P \leq 0.05$) treatments interactions that warrant further discussion.

	Turfgrass quality		Turfgrass coverage		Clipping yield	
Effect	2016	2017	2016	2017	2016	2017
			(P-value)			
Block	0.353	0.821	0.602	0.61	0.321	0.452
Shade	0.001	**0.001**	0.001	0.006	0.001	0.130
Timing	0.285	0.649	0.246	0.205	0.927	0.160
Shade x Timing	0.048	0.665	0.165	0.063	0.054	0.282
Primo Maxx	0.039	**0.017**	0.003	0.634	0.630	0.001
Shade x Primo Maxx	0.010	0.227	0.001	0.940	0.271	0.112
Timing x Primo Maxx	1.000	0.642	0.311	0.836	0.690	0.148
Shade x Timing x Primo Maxx	0.366	0.999	0.049	0.994	0.687	0.001
Turf Screen	0.008	**0.048**	0.028	0.812	0.779	0.181
Shade x Turf Screen	0.248	0.520	0.0012	0.200	0.953	0.188
Timing x Turf Screen	0.594	0.396	0.348	0.319	0.778	0.718
Shade x Timing x Turf Screen	0.762	0.338	0.300	0.234	0.221	0.694
Primo Maxx x Turf Screen	0.659	0.728	0.323	0.749	0.207	0.741
Shade x Primo Maxx x Turf Screen	0.293	0.236	0.693	0.988	0.653	0.703
Timing x Primo Maxx x Turf Screen	0.316	0.841	0.180	0.623	0.565	0.293
Shade x Timing x Primo Maxx x Turf Screen	0.083	0.983	0.003	0.932	0.198	0.171
Date	0.001	0.001	0.001	0.001	0.001	0.001
Shade x Date	0.001	0.090	0.00	0.001	0.001	0.001
Timing x Date	0.001	0.431	0.001	0.075	0.001	0.001
Shade x Timing x Date	**0.001**	0.618	**0.001**	**0.050**	**0.001**	**0.001**
Primo Maxx x Date	**0.042**	0.522	0.001	0.001	**0.001**	0.001
Shade x Primo Maxx x Date	0.993	0.775	0.001	0.022	0.864	0.138
Timing x Primo Maxx x Date	0.881	0.733	0.161	0.097	0.473	0.001
Shade x Timing x Primo Maxx x Date	0.999	0.739	0.576	0.999	0.394	0.757
Turf Screen x Date	**0.001**	0.349	0.001	0.001	0.562	0.002
Shade x Turf Screen x Date	0.391	0.714	0.026	0.101	0.932	0.839
Timing x Turf Screen x Date	0.175	0.462	0.438	0.172	0.807	0.433
Shade x Timing x Turf Screen x Date	0.998	0.878	0.998	0.790	0.074	0.811
Primo Maxx x Turf Screen x Date	0.786	0.794	0.673	0.011	0.807	0.503
Shade x Primo Maxx x Turf Screen x Date	0.999	0.798	1.000	0.979	0.979	0.887
Timing x Primo Maxx x Turf Screen x Date	0.625	0.646	**0.007**	**0.001**	0.630	**0.038**
Shade x Timing x Primo Maxx x Turf Screen x Date	0.999	0.713	0.490	0.119	0.783	0.630

Figure 2.1. Transportable shade structure system utilized to apply various shade intensities and shade timings.

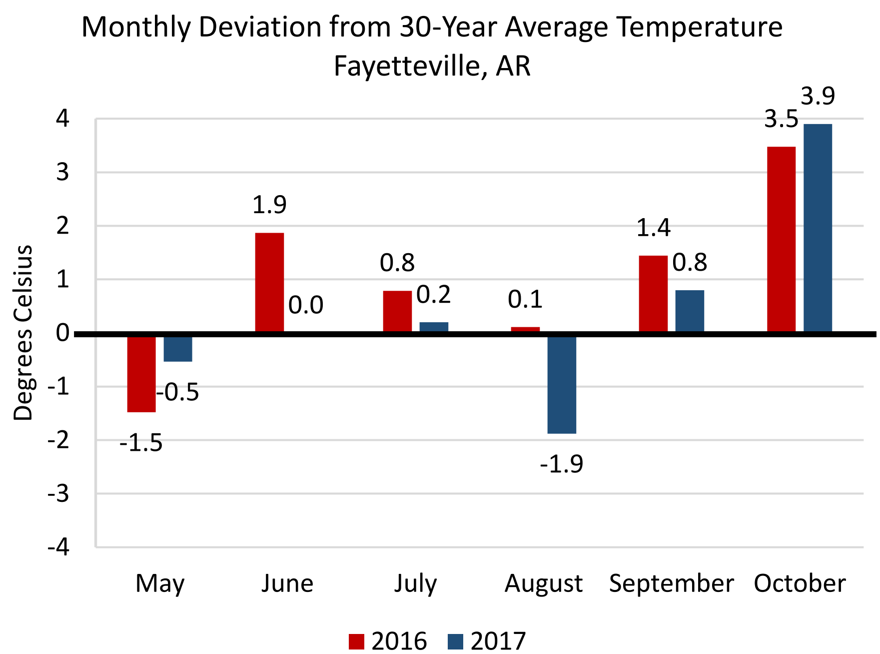

Figure 2.2. Average air temperature (°C) deviation from the 30-year average air temperature for each month of the study in 2016 and 2017.

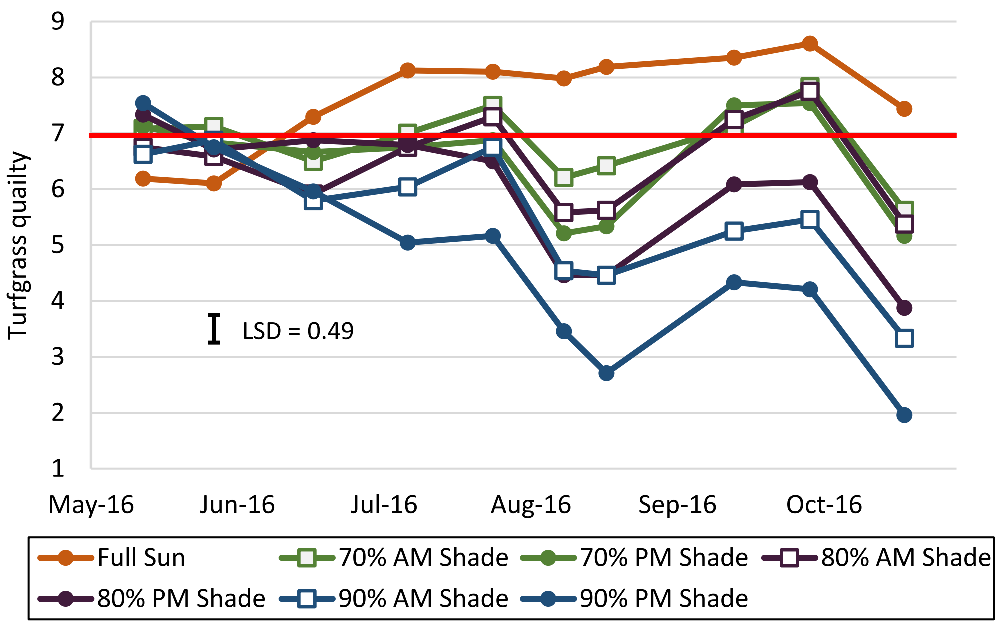

Figure 2.3. Visual turfgrass quality ratings (1-9 scale, 7 = minimum acceptability) of creeping bentgrass as affected by shade intensity and shade timing by evaluation date in 2016. Red line at turfgrass quality rating of 7 indicates a visual reference of minimum acceptability. LSD bar indicates least significant difference value to make treatment comparisons within evaluation dates.

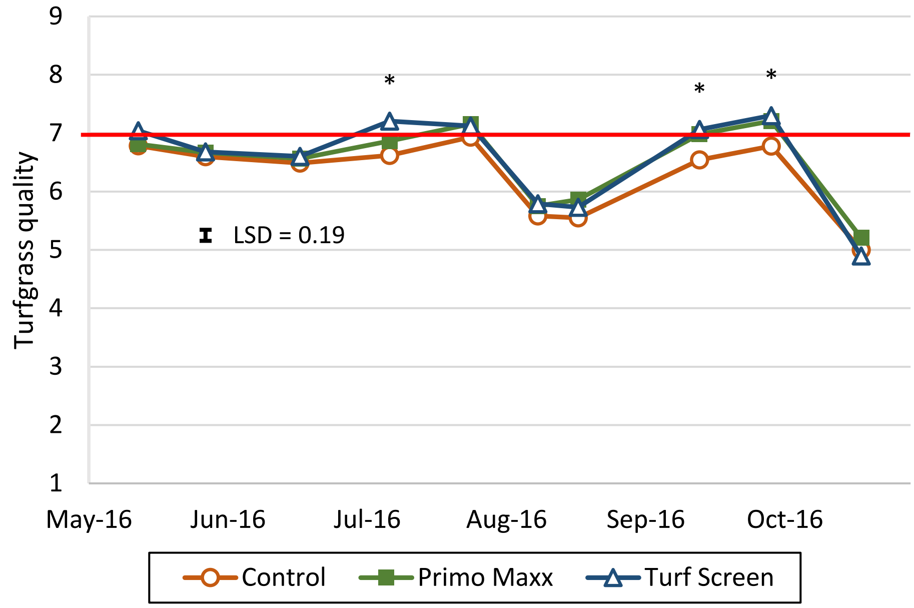

Figure 2.4. Visual turfgrass quality ratings (1-9 scale, 7 = minimum acceptability) of creeping bentgrass as affected by chemical spray treatments of Primo Maxx and Turf Screen by evaluation date in 2016. Red line at turfgrass quality rating of 7 indicates a visual reference of minimum acceptability. LSD bar indicates least significant difference value to make treatment comparisons within evaluation dates. (* = date when applications of Primo Maxx or Turf Screen significantly increased turfgrass quality over the untreated control)

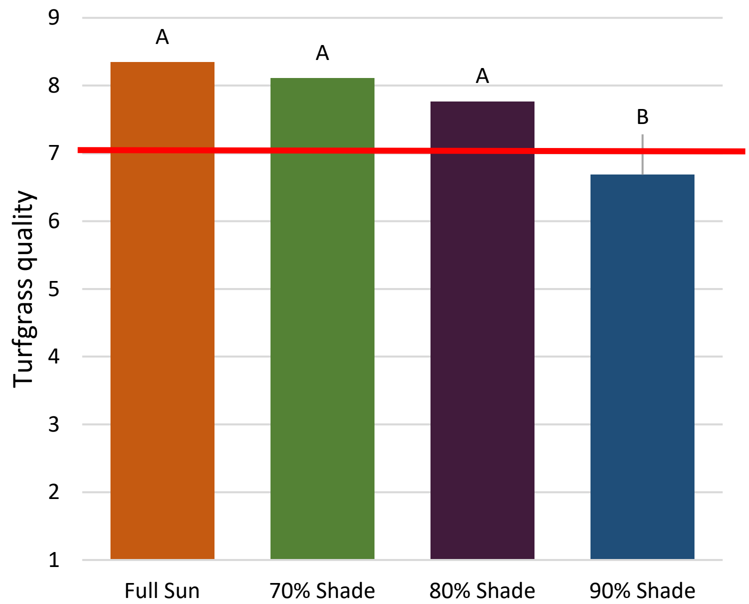

Figure 2.5. Visual turfgrass quality ratings (1-9 scale, 7 = minimum acceptability) of creeping bentgrass as affected by the significant main effects of the four shade intensity levels (0, 70, 80, 90% shade) averaged across all shade timings and evaluation dates during 2017. Red line at turfgrass quality rating of 7 indicates a visual reference of minimum acceptability. Bars that share a letter are not significantly different using Fisher's protected LSD at α = 0.05.

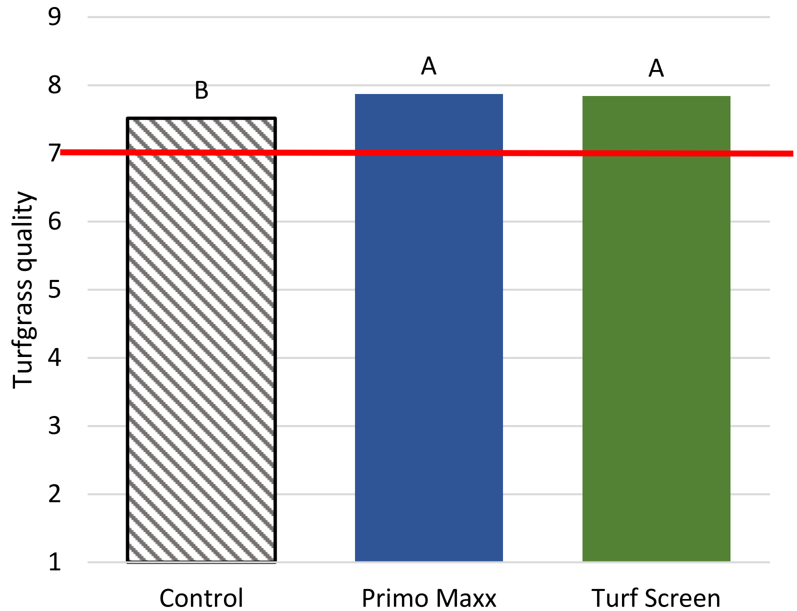

Figure 2.6. Visual turfgrass quality ratings (1-9 scale, 7 = minimum acceptability) of creeping bentgrass as affected by the significant main effects of Primo Maxx and Turf Screen chemical treatments averaged across all shade timings, shade treatments, and evaluation dates during 2017. Red line at turfgrass quality rating of 7 indicates a visual reference of minimum acceptability. Bars that share a letter are not significantly different using Fisher's protected LSD at $\alpha = 0.05$.

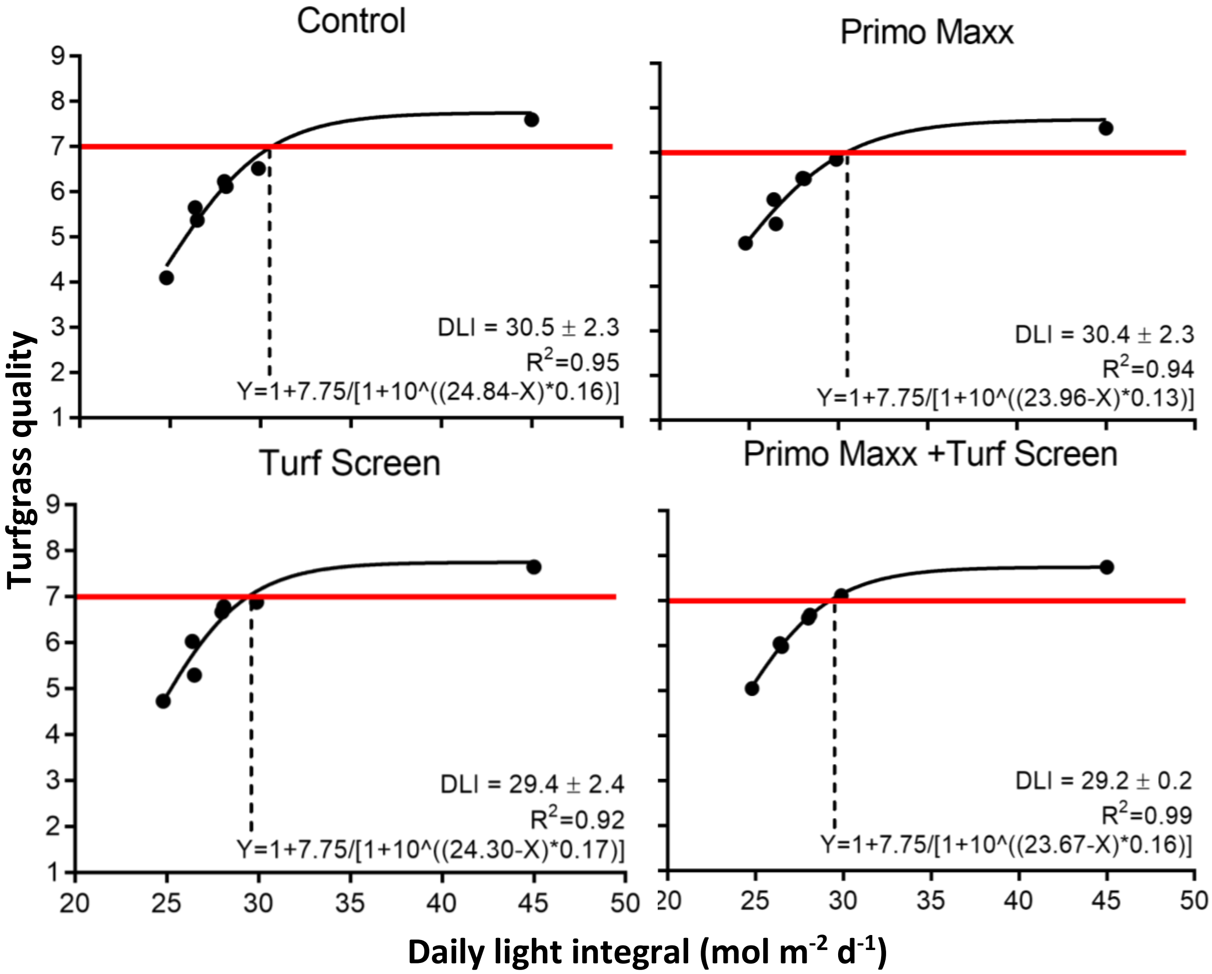

Figure 2.7. Nonlinear regression analysis of turfgrass quality response of creeping bentgrass to daily light integrals for each shade intensity and shade treatment by chemical spray treatment during 2016. Red line indicates minimal acceptable quality rating of 7. Dashed line represents estimated DLI requirement to achieve acceptable quality rating. ± represents 95% confidence intervals of estimated DLI requirement.

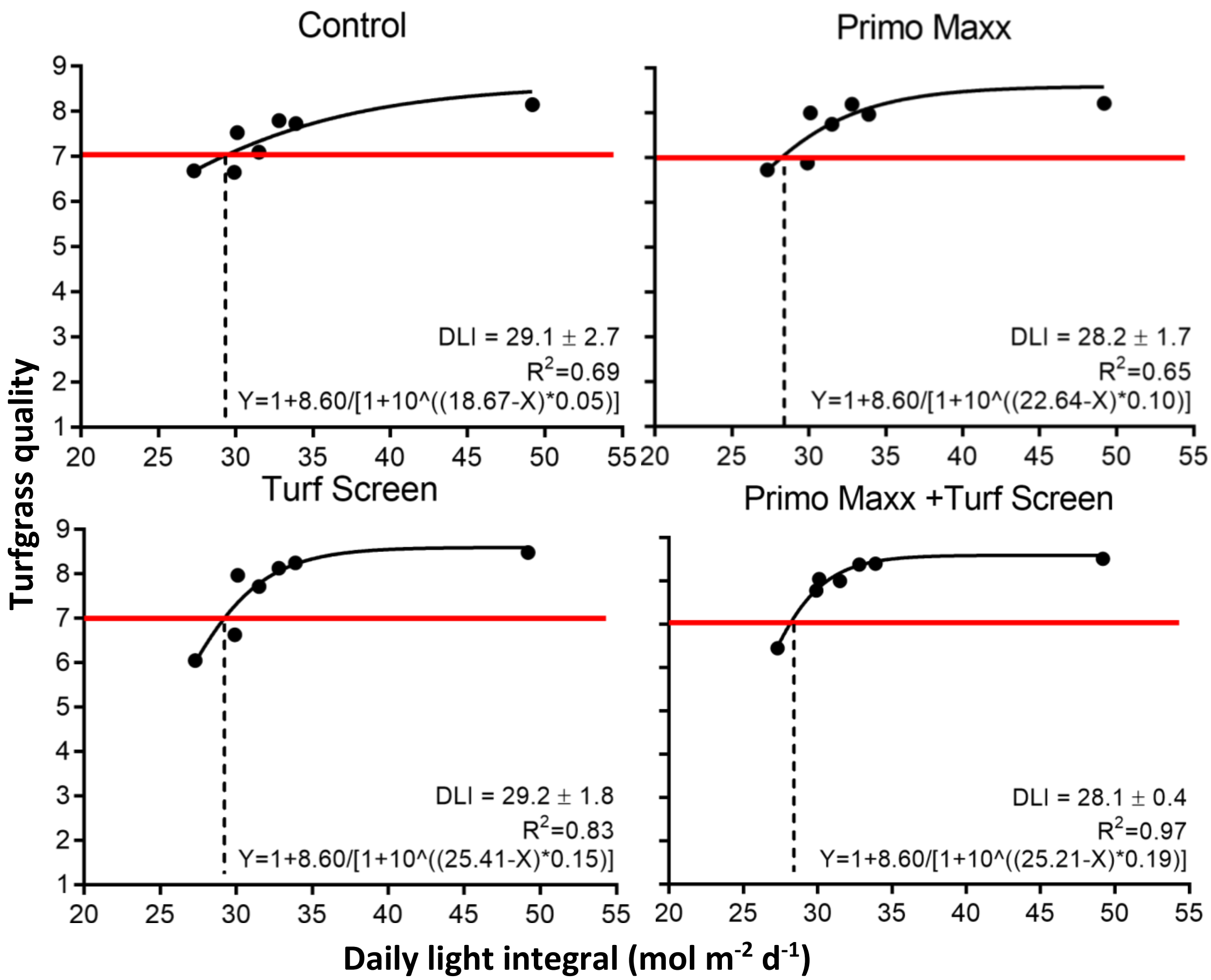

Figure 2.8. Nonlinear regression analysis of turfgrass quality response of creeping bentgrass to daily light integrals for each shade intensity and shade treatment by chemical spray treatment during 2017. Red line indicates minimal acceptable quality rating of 7. Dashed line represents estimated DLI requirement to achieve acceptable quality rating. ± represents 95% confidence intervals of estimated DLI requirement.

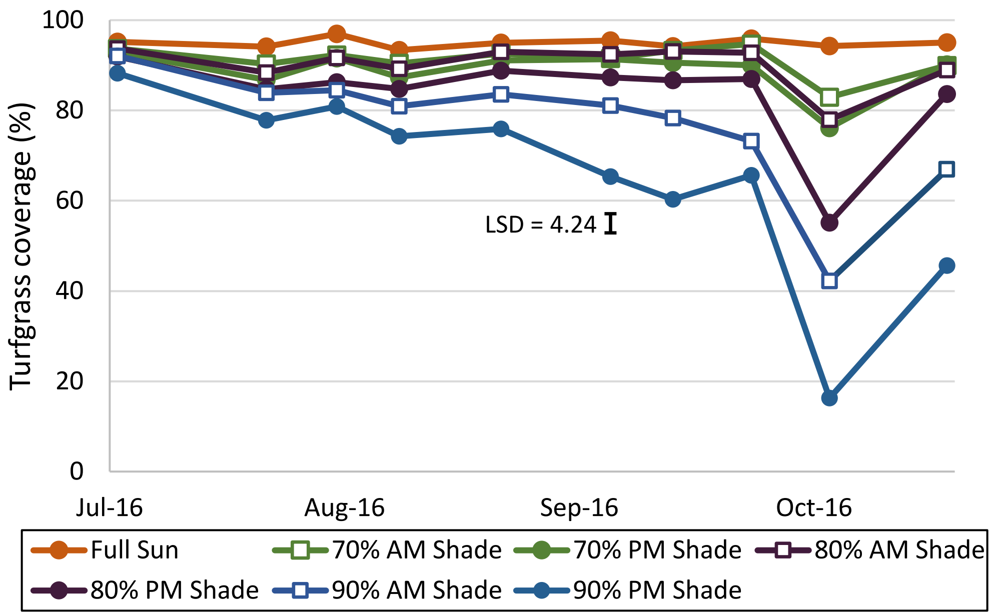

Figure 2.9. Turfgrass coverage of creeping bentgrass, expressed as a percent of turfgrass coverage in area under evaluation, as affected by shade timing and shade intensity treatments by evaluation date in 2016. LSD bar indicates least significant difference value to make treatment comparisons within evaluation dates.

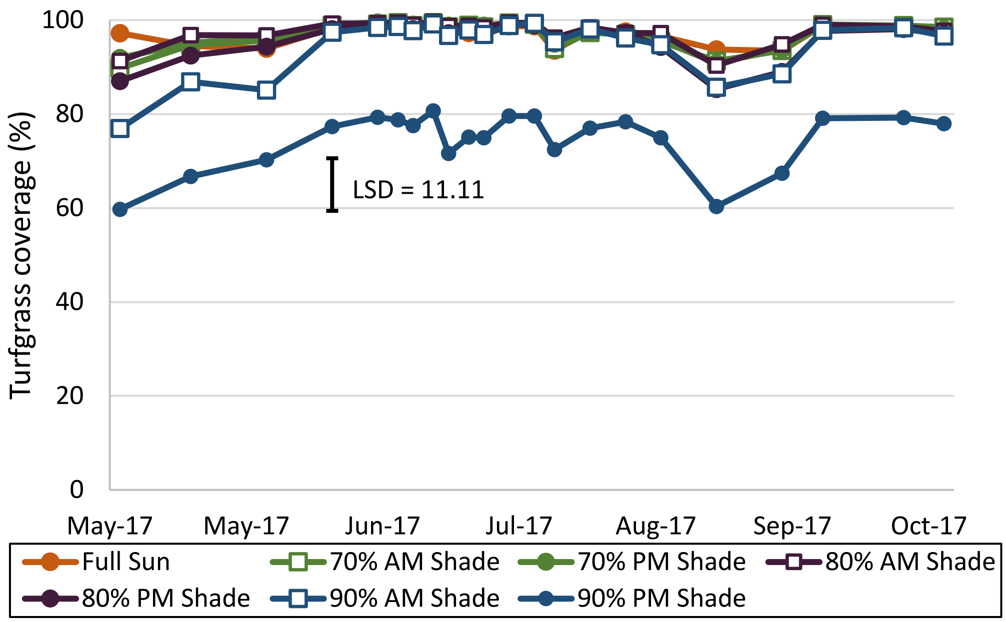

Figure 2.10. Turfgrass coverage of creeping bentgrass, expressed as a percent of turfgrass coverage in area under evaluation, as affected by shade timing and shade intensity treatments by evaluation date in 2017. LSD bar indicates least significant difference value to make treatment comparisons within evaluation dates.

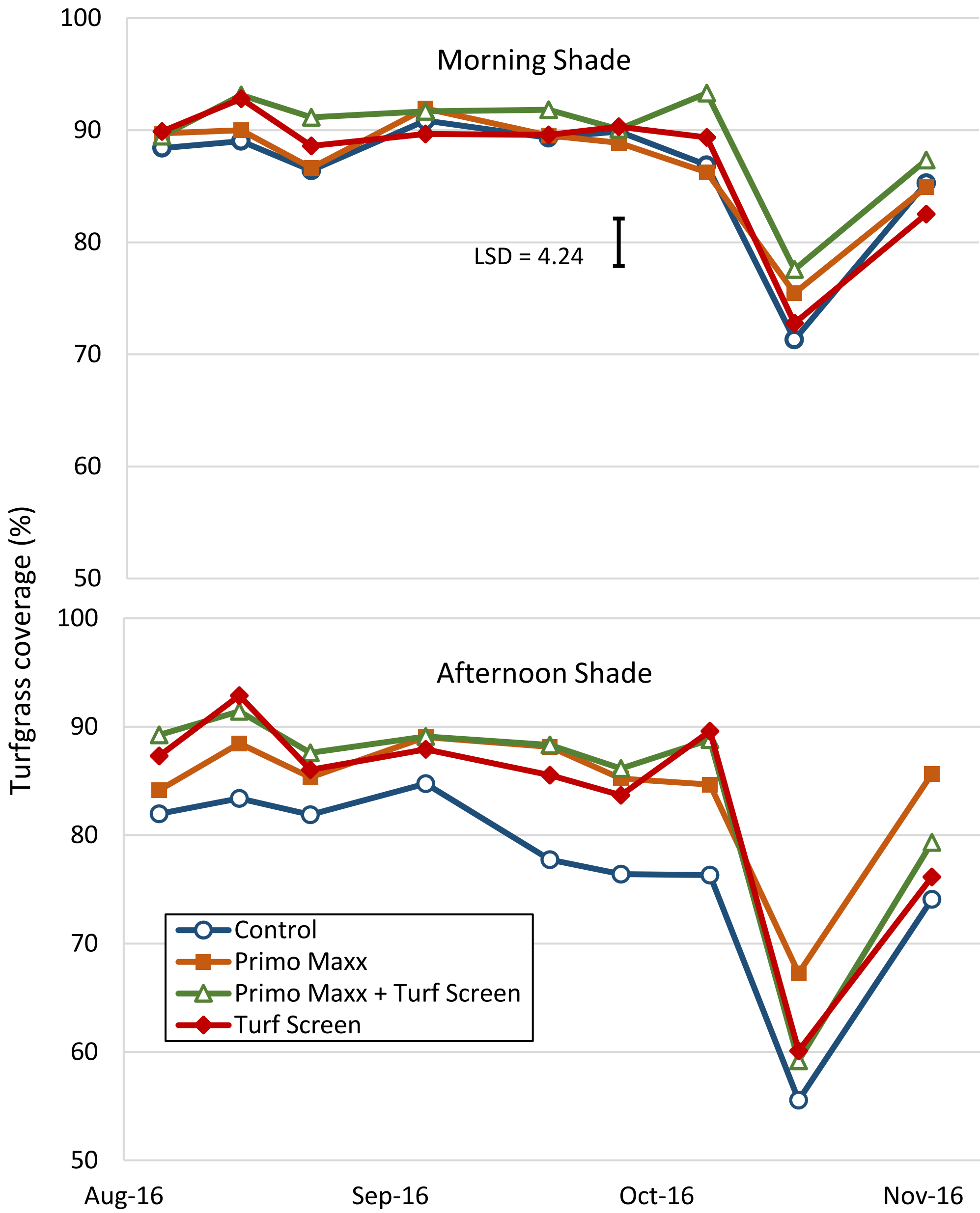

Figure 2.11. Turfgrass coverage, expressed as a percent, of creeping bentgrass as affected by morning and afternoon shade and chemical spray treatment of Primo Maxx and Turf Screen by evaluation date in 2016. LSD bar indicates least significant difference value to make treatment comparisons within evaluation dates.

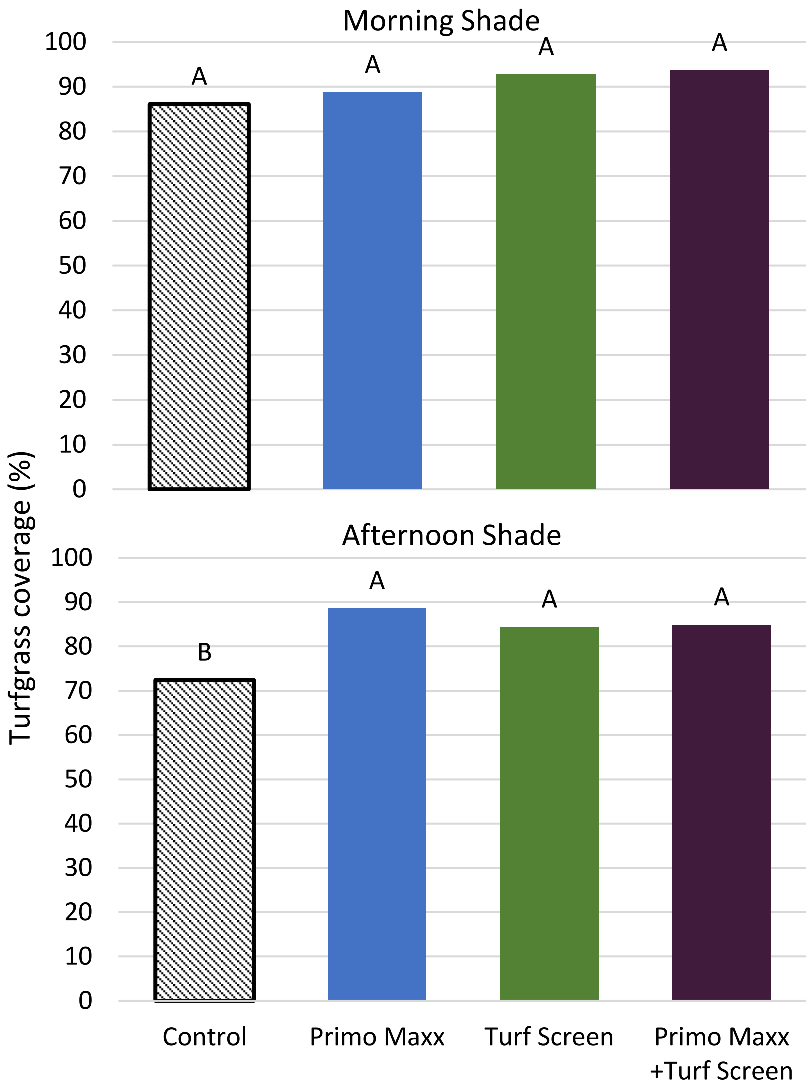

Figure 2.12. Turfgrass coverage of creeping bentgrass expressed as a percent of turfgrass under area of evaluation as affected by shade timing and chemical spray treatment on 28 August 2017. Means followed by the same letter are not significantly different using Fisher's protected LSD at $\alpha = 0.05$.

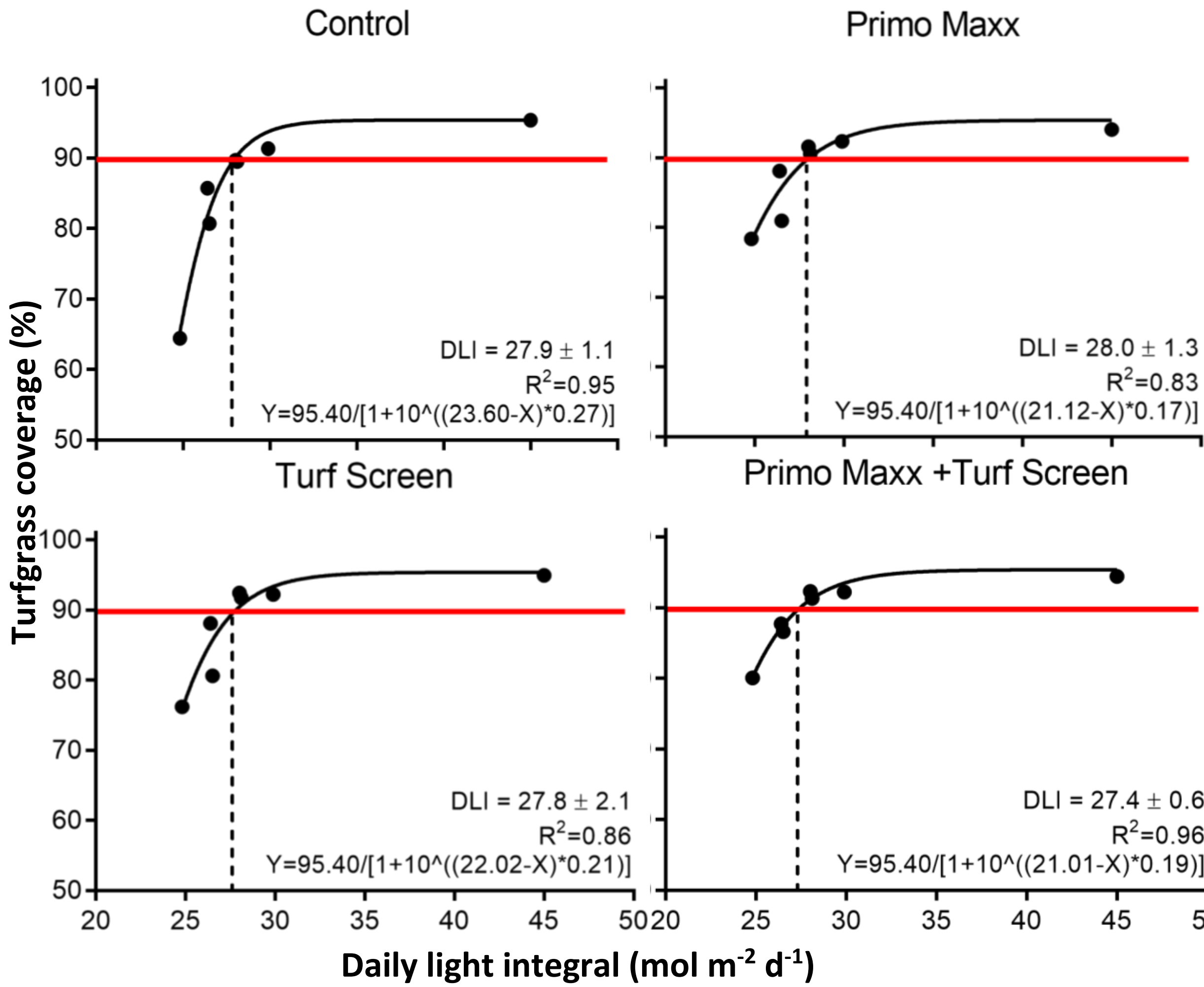

Figure 2.13. Nonlinear regression analysis of creeping bentgrass turfgrass coverage response to daily light integrals for each shade intensity and shade treatment by chemical spray treatment during 2016. Red line indicates minimal acceptable turf coverage of 90%. Dashed line represents estimated DLI requirement to achieve acceptable coverage. ± represents 95% confidence intervals of estimated DLI requirement.

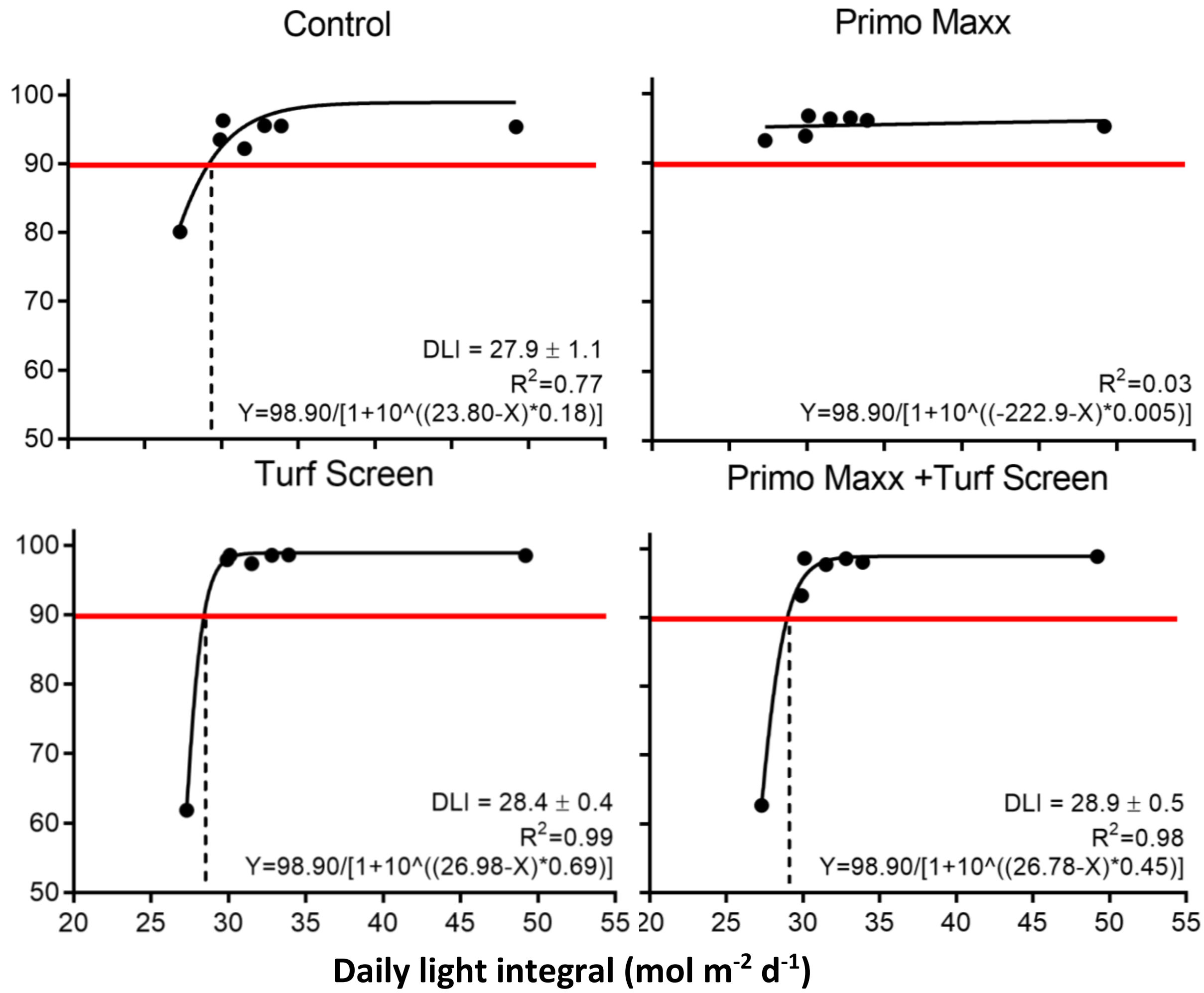

Figure 2.14. Nonlinear regression analysis of creeping bentgrass turfgrass coverage response to daily light integrals for each shade intensity and shade treatment by chemical spray treatment during 2017. Red line indicates minimal acceptable turf coverage of 90%. Dashed line represents estimated DLI requirement to achieve acceptable coverage. ± represents 95% confidence intervals of estimated DLI requirement.

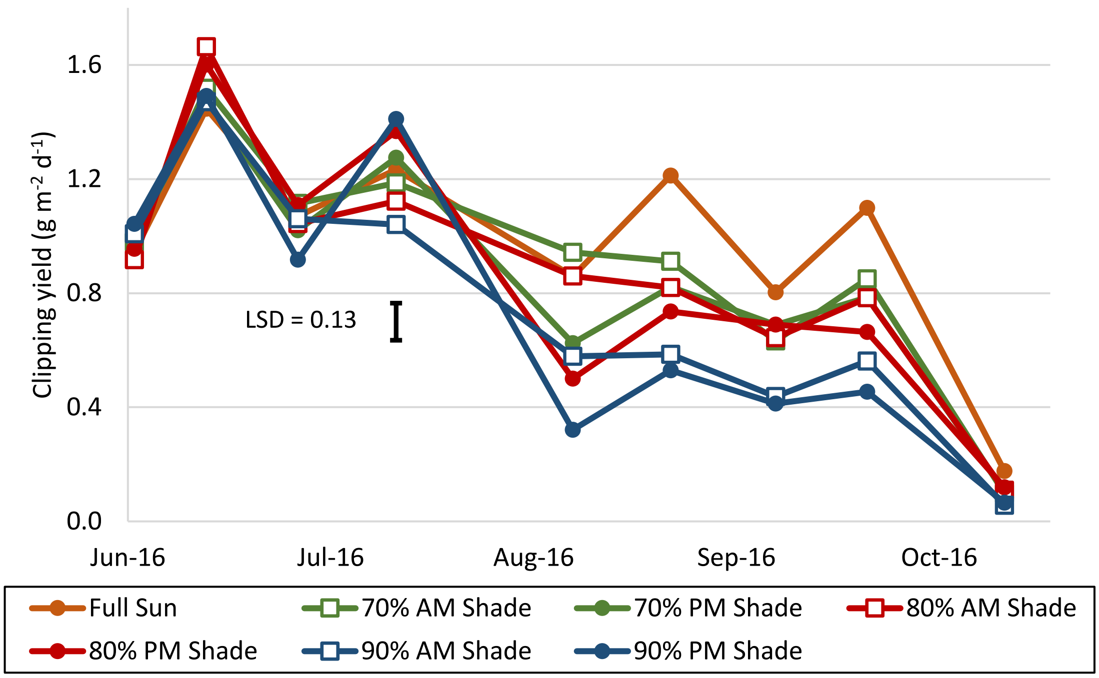

Figure 2.15. Turfgrass clipping yield of creeping bentgrass as affected by shade intensity and shade timing by evaluation date in 2016. LSD bar indicates least significant difference value to make treatment comparisons within evaluation dates.

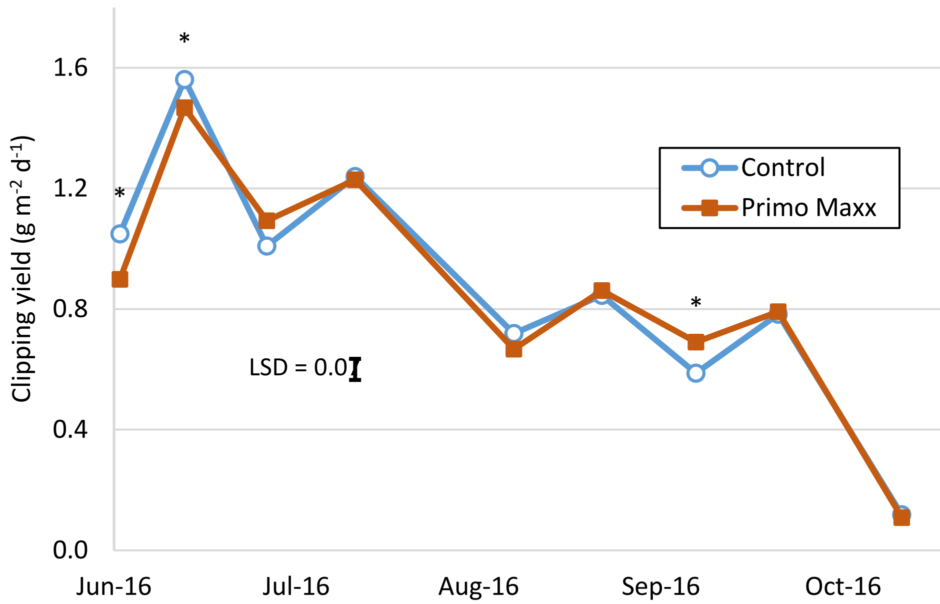

Figure 2.16. Clipping yield response of creeping bentgrass as affected by spray applications of Primo Maxx by evaluation date in 2016. LSD bar indicates least significant difference value to make treatment comparisons within evaluation dates. * = date when applications of Primo Maxx and the untreated control resulted in a significant difference in clipping yield.

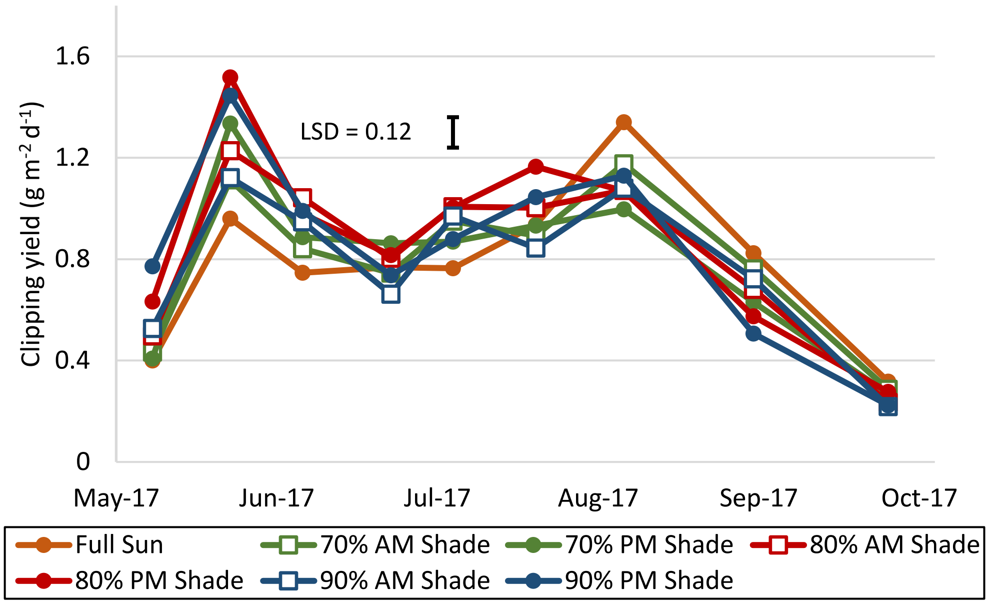

Figure 2. 17. Turfgrass clipping yield of creeping bentgrass as affected by shade intensity and shade timing by evaluation date in 2017. LSD bar indicates least significant difference value to make treatment comparisons within evaluation dates.

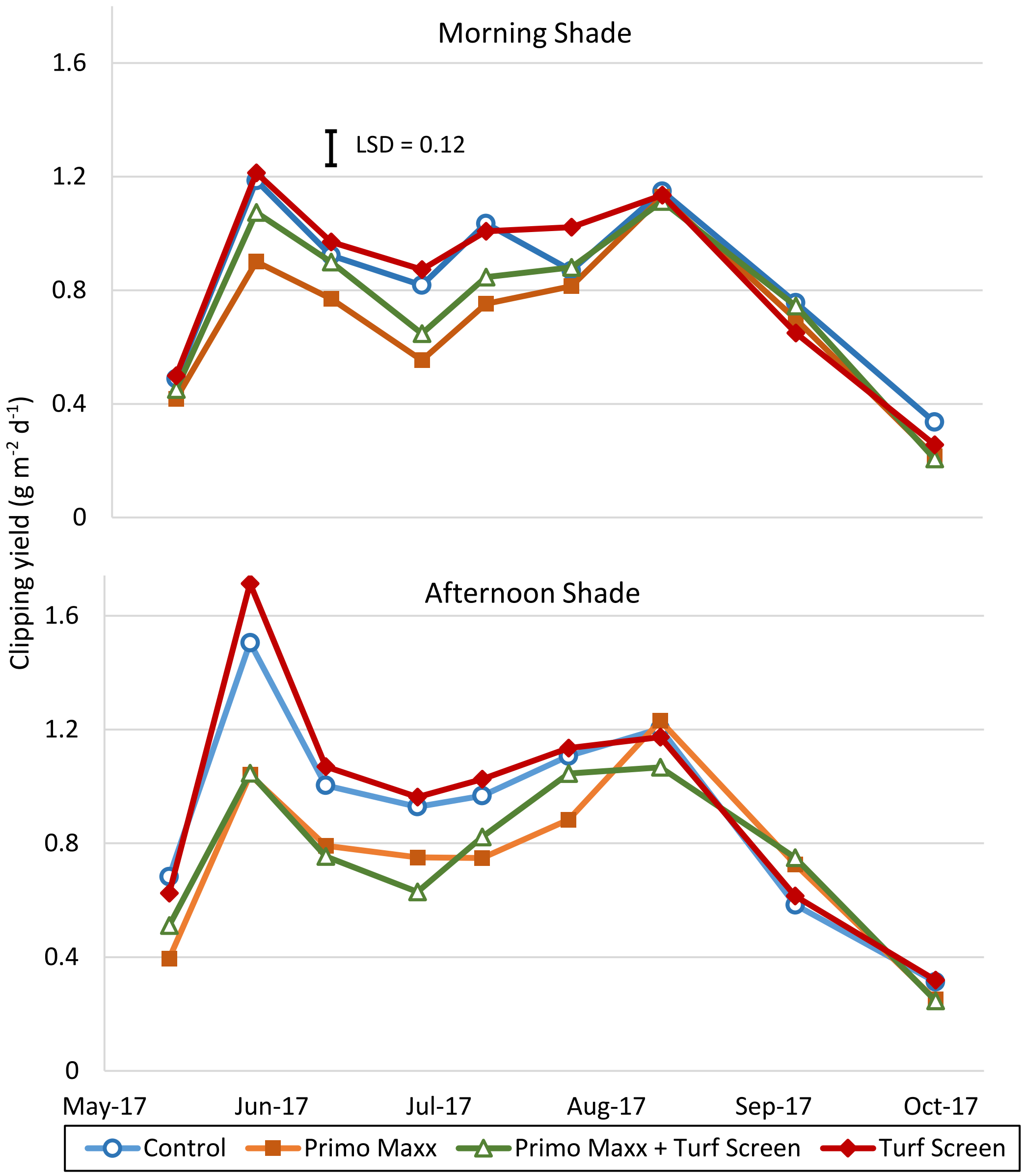

Figure 2. 18. Turfgrass clipping yield of creeping bentgrass as affected by morning and afternoon shade treatments and chemical spray treatment combinations of Primo Maxx and Turf Screen by evaluation date in 2017. LSD bar indicates least significant difference value to make treatment comparisons within evaluation dates.

Chapter III:

Investigating an Efficient Method to Determine Daily Light Integral Requirements of Various Warm-season Turfgrasses in an Established Landscape

ABSTRACT

Determining daily light integral (DLI) requirements for various turfgrass systems has been an effective method for quantifying the daily amount of photosynthetically active radiation (PAR) necessary to maintain acceptable quality turfgrass in a controlled research setting. However, shaded areas in the existing landscape often vary in quantity and duration of PAR available to turfgrasses. The objective of this research was to evaluate an efficient method to determine DLI requirements in an existing landscape. Two zoysiagrasses, 'Cavalier' (*Z. japonica* Steud.) and 'Meyer' (*Z. matrella* [L.] Merr.), and two bermudagrasses, common bermudagrass (*Cynodon dactylon* [L.] Pers.) and 'Astro-DLM' hybrid bermudagrass (*C. dactylon* [L.] Pers. x *C. transvaalensis* Burtt-Davy), were selected for evaluation in this study. In areas where shade was limiting turfgrass growth at local golf courses, quantum sensors measuring PAR were installed along a line transect at the following positions: 1) full turfgrass coverage, 2) slight turfgrass decline, 3) extensive turfgrass decline, and 4) complete turfgrass failure to calculate the DLI at each position for 6 days in 2017. Each turfgrass type was also established under 22, 40, 60 , and 90% shade in a controlled research setting for two seasons from August to October 2016 and May to October 2017. Turfgrass quality and coverage evaluations were made in both settings. Estimated minimum DLI requirements for 'Astro-DLM' bermudagrass, common bermudagrass, 'Cavalier' zoysiagrass, and 'Meyer' zoysiagrass were 20.4, 25.9, 15.0, and 21.1 mol m^{-2} d^{-1} in the controlled research setting. The methodology utilized in the golf course setting was able to accurately estimate the minimum DLI of 'Astro-DLM' bermudagrass and 'Meyer' zoysiagrass compared to thresholds established in the controlled research setting, but not the other two turf types. A misrepresentation of the actual DLI at each site during the six day

evaluation period as well as differing shaded microclimate characteristics could explain the differences in the minimum DLI requirements for the other three turfgrass types.

INTRODUCTION

Trees are an integral component of many golf courses due to the aesthetic benefits provided in the landscape as well as the design and playability of the course. Most reduced light environments on golf courses are a direct result of tree shade, but can also be present in the form of shade from topography, landscape plants, buildings, and other structures. Reduced light environments can limit turfgrass growth and health due to lack of available photosynthetically active radiation (Bell and Danneberger, 2000).

Warm-season turfgrasses (C4) are the main selection for use on golf course fairway and tee area settings in the transition zone and throughout the southeast United States. These turfgrasses are generally better adapted to higher temperatures and other plant stresses associated with the summer months in the transition zone (Turgeon, 2005). One drawback of implementing warm-season turfgrasses on golf course tees and fairways is their relatively lower shade adaptability compared to that of cool-season turfgrasses. Warm-season turfgrasses do not perform optimally in shaded conditions and can develop physiological and morphological changes that lead to a weakened turfgrass stand (Dudeck and Peacock, 1992; Taiz and Zieger, 2015). The light compensation point of cool-season grasses is nearly half that of warm-season grasses due to higher photosynthetic and lower respiration rates of cool-season turfgrasses in reduced light environments and often results in better relative shade adaptation (Fry and Huang, 2004; Taiz and Zeiger, 2015). While cool-season and warm-season grasses have similar physiological and morphological responses to shade, these responses have been reported to be more severe in warm-season turfgrasses compared to cool-season turfgrasses grown under the same shaded conditions (Kephart et al., 1992).

Three of the most common warm-season turfgrasses used on golf course fairways and tee areas in warm climates are various cultivars of bermudagrass (*Cynodon spp.*), hybrid bermudagrass ([*Cynodon dactylon* (L.)Pers. X *C. transvaalensis* Burtt-Davy), and zoysiagrass (*Zoysia spp.*). Some hybrid bermudagrasses are more shade tolerant than common bermudagrasses, but shade tolerance is cultivar specific and based on genetic diversity (Baldwin et al., 2009). The shade tolerance of zoysiagrass is also species and cultivar specific. Cultivars within *Zoyisa matrella* and *Zoysia japonica* vary in shade adaptability (Sladek et al., 2009; Trappe et al., 2011; Wherley et al., 2011). In addition to heat and drought tolerance, many bermudagrass and zoysiagrass cultivars can tolerate low mowing heights and produce a consistent leaf blade canopy desired of golf courses in the transition zone and southern United States. Very few studies have compared the shade tolerance differences between bermudagrass and zoysiagrass cultivars. Bunnell (2005b) found that *Zoysia japonica* cultivar 'Meyer' maintained higher visual quality and total nonstructural carbohydrates under continual shade compared to 'Tifsport' and 'Tifway' hybrid bermudagrass cultivars. In a study comparing multiple cultivars of each species, Trappe et al. (2011) found that, as a species, hybrid bermudagrass had lower percentage of turfgrass coverage under 49% continual shade compared to common bermudagrass and zoysiagrass. Additional research is needed to evaluate the shade tolerance of bermudagrass and zoysiagrass cultivars in a research setting to improve site specific turfgrass selection.

Precise light requirements of various warm season turfgrass cultivars have been effectively evaluated by estimating minimum daily light integral (DLI) requirements to maintain acceptable turf quality (Bunnell et al., 2005b; Miller et al., 2005; Zhang et al., 2017). The DLI measurement is defined as the cumulative sum of photosynthetically active radiation received over an entire day (Korczynski et al., 2002). A common bermudagrass cultivar know for shade tolerance, ‘Celebration’, was reported to have a DLI requirement of 20.2 mol m^{-2} d^{-1} (Zhang et al., 2017). In a greenhouse study, hybrid bermudagrass cultivars ‘Tifway’ and ‘TifGrand’ required DLI quantities of 21.4 and 20.9 mol m^{-2} d^{-1} (Zhang et al. 2017), while cultivars ‘TifEagle’, ‘TiDwarf’, and ‘FloraDwarf’ needed 32.6, 38.6, and 38.6 mol m^{-2} d^{-1} , respectively, to maintain acceptable quality in a putting green field study (Bunnell et al, 2005; Miller et al., 2005). ‘Palisades’ *Zoysia japonica* and ‘Taccoa Green’ *Zoysia matrella* had established DLI requirements of 10.9 and 10.5 mol m^{-2} d^{-}1 during summer months in a greenhouse trial (Zhang et al., 2017). While DLI requirements have been established for some warm-season turfgrasses in a controlled research setting, there is no established methodology to determine a minimum DLI requirement of turfgrasses in an existing landscape on a golf course.

Research Objectives

To determine light requirements of additional turf types and evaluate DLI measurement in existing landscapes, the following research objectives were established: 1) estimate the minimum DLI requirements of four warm season turfgrasses in a controlled research setting, 2) evaluate methodology to estimate minimum DLI requirements of turfgrasses in an established golf course landscapes, 3) and compare DLI requirements estimated from the two previous objectives to determine accuracy of each methodology.

MATERIALS AND METHODS

Controlled Research Setting

Experimental Area

This study was conducted during the summer of 2016 and 2017 on four warm-season turfgrass types: common bermudagrass (*Cynodon dactylon* (L.) Pers.), ‘Astro-DLM’ hybrid bermudagrass (*Cynodon dactylon* (L.)Pers. X *C. transvaalensis* Burtt-Davy), ‘Meyer’ zoysiagrass (*Zoysia japonica* Steud.), and ‘Cavalier’ zoysiagrass (*Zoysia matrella* (L.) Merr.). The study was conducted at the University of Arkansas Agricultural Research and Extension Center in Fayetteville, AR (36°06' N, 94°10' W). The Year 1 study was conducted from 30 July to 31 October 2016 and Year 2 from 3 May to 31 October 2017. Turfgrass cultivars were established from cup cutter plugs (Lever Action Hole Cutter, Par Aide, Lino Lakes, MN) extracted from golf courses in the Northwest Arkansas region and planted in June 2016 into a 21.3 m x 21.3 m bare ground experimental area. Whole plots measuring 6.4 m x 2.2 m of each turf type were divided into subplots of 1.6 x 2.2 m. Each subplot contained two plugs of the individual turf type and was established for four weeks under full sun in a Captina silt loam soil (*Typic Fragiudalt*). Mowing was performed three times weekly at 12.7 mm height of cut. All plots were fertilized with urea (46-0-0 N-P-K) at 24 kg N ha^{-1} twice per season. Irrigation was applied only when visible symptoms of drought stress occurred.

Four shade intensities, 22, 40, 60, and 90% reduction of full irradiance, were applied above the turfgrass canopy on 30 July 2016 with structures modeled after a previous shade application system used at the University of Arkansas Agricultural Research and Extension Center (Trappe et al., 2011). The dimensions of each shade structure were 6.4 x 8.6 m and were constructed using 6.4 cm diameter steel pipe. Each structure was divided into 1.6 m x 8.6 m strip plots across the four turf cultivars containing the four shade treatments (Fig. 3.1). The various shade cloths (Bulk Shade Cloth, International Greenhouse Co., Danville IL) were custom ordered to fit inside each section on the structures and the reinforced edges of the cloth had grommets installed every 60 cm. The shade cloths were tightly affixed to the structure using ultraviolet-resistant cable zip ties and wire cabling was installed every 2 m under the cloth to prevent sagging of the cloth. The shade structures were supported 35 cm above the ground by six wheels that allowed transportation for plot maintenance and data collection.

Evaluations

Quantum light sensors (Light Scout Quantum Light Sensor, Spectrum Technologies, Aurora, IL) measuring photosynthetically active radiation (PAR) were mounted under each of the shade cloth treatments and connected to a 4-channel datalogger (Watchdog 1000 Series Micro Station, Spectrum Technologies, Aurora, IL) on two of three shade structures. The quantum light sensors recorded PAR on 15 minute intervals for the duration of the study. The PAR light measurements were summed to calculate the DLI under each shade treatment for monthly and seasonal averages.

Visual turfgrass quality ratings were based on evaluation of turfgrass coverage, color, density, and uniformity using a 1 to 9 scale with 1 representing dead turf and 9 representing dark green, healthy turf according to National Turfgrass Evaluation Program evaluation guidelines (Morris and Shearman, 1998). Any turfgrass quality rating below 6 was deemed unacceptable. Visual turfgrass quality ratings were taken every two weeks during the study.

Digital images of each plug were recorded every two weeks to evaluate turfgrass coverage. Images (1200 x 1600 pixel resolution) were taken using a Canon Powershot G1X 14

Megapixel digital camera (Canon USA Inc., Melville, NY) placed inside of a portable, enclosed light box that provided a consistent artificial light source to improve objectivity in image data (Karcher and Richardson, 2013). Digital image analysis was used to evaluate percent turfgrass coverage in each captured image using the Turf Analyzer software program (Turf Analyzer, http://turfanalyzer.com) (Karcher et al, 2017). Due to complications with color threshold settings, pixels representing healthy turfgrass were selected by manually tracing the outline of each turfgrass plug and filling in with a solid color that Turf Analyzer was set to select. Selected pixels were divided by the number of total pixels of each image to determine turfgrass coverage expressed as a percent.

Statistical Design and Analysis

This designed study was a randomized complete block design with treatments factors in a 4 x 4 split-strip plot design with three replications. This design evaluated four turfgrass types under four levels of shade intensity. Data were analyzed using the PROC MIXED procedure of SAS (version 9.3; SAS Institute Inc., Cary, NC). Treatment means for significant main effects and interactions were separated using Fisher's protected Least Significant Difference (LSD) test. An alpha value of 0.05 were used to determine statistical significance.

Minimum DLI requirements for each turf type were determined using linear regression analysis in the Graph Pad Prism software program (GraphPad Software Inc., La Jolla, CA). For regression analysis, a 3-parameter sigmoidal curve was fitted to the data collected from each treatment to obtain a critical DLI value at which a turf quality rating of 6 or 80% turf coverage would be expected for each turfgrass type.

The following 3-parameter sigmoidal function was used:

$$y = C + \frac{D - C}{1 + e^{[(I_{50} - x) * b]}}$$

where *C* is the lower limit, *D* is the upper limit, *b* equals the slope, and I_{50} equals the DLI that elicits a 50% response in turf quality. A sum of squares reduction test was used to determine if a single model with shared parameter estimates should be used for all turf types to estimate a critical DLI value or if separate models specific parameter estimates was necessary for each turfgrass type.

Golf Course Setting

Experimental Area

This study was conducted during the summer of 2017 on four warm-season turfgrass types mowed at a fairway height of cut at three golf courses located in the Northwest Arkansas Region (Table 3.1). Two individual sites for each turf type that displayed visual decline in turfgrass quality where a lack of available light was presumed to be the limiting factor in turfgrass growth and quality were selected for evaluation at each golf course. At four points on a line transect established perpendicular to the line of shade stress/damage, quantum light sensors (LightScout Quantum Light Sensor, Spectrum Technologies, Aurora, IL) were installed to measure PAR. An individual sensor was placed in the following positions along the line transect: 1) area of full turfgrass coverage, 2) slight turfgrass decline, 3), extensive turfgrass decline, and 4) complete turfgrass failure (Fig. 3.2). Quantum light sensors connected to a 4-channel datalogger (WatchDog 1000 Series Micro Station, Spectrum Technologies, Aurora, IL) measured and recorded PAR (µmol m^{-2} s^{-1}) on 15 minute intervals.

Evaluations

DLI at each quantum sensor positioning along the line transect were calculated by summing the PAR measurements for each day during a 6 day period in July-August 2017. Turfgrass visual quality ratings and coverage evaluations were recorded as previously described.

Statistical Design and Analysis

Estimated season-long DLI values at each location was calculated by multiplying the percent reduction of full irradiance at each sensor location over the 6 day evaluation period by the full sun DLI recorded for each day during May-October of 2016 and 2017 at the University of Arkansas Agricultural Research and Extension Center in Fayetteville, AR. Minimum DLI requirements for turfgrass types at each evaluation site were determined using nonlinear regression analysis as previously described.

RESULTS AND DISCUSSION

Daily Light Integral

The two year combined DLI average that was delivered to the turfgrass under 22, 40, 60, and 90% shade was 33.4, 24.1, 15.3, and 2.6 mol m^{-2} d^{-1}, respectively (Table 3.2). Average DLI under shade treatments varied between 2016 and 2017 trials from 0.9 to 4.6 mol m^{-2} d^{-1} depending on shade intensity (Table 3.2). It is important to note that a possible source of the variance in DLI between years is due to the duration of each trial (August-October 2016 and May-October 2017) in addition to implied variability in full sun environmental conditions from one year to the next. Interestingly, the August-October time period during the 2017 trial was almost identical to what was observed in 2016, with an average increase of 0.5 mol m^{-2} d^{-1} across all shade treatments in 2017 (data not shown). Although there was no turfgrass subjected to a non-shaded treatment in this study, full sun DLI was recorded for the duration of the trial and reported for reference.

Turfgrass Quality

The visual quality of the evaluated turf types was affected by shade intensity treatments in 2016 and 2017 (Table 3.3). During both years of this study, analysis of variance indicated a significant ($P \leq 0.05$) three-way interaction between turfgrass type, shade intensity treatment, and evaluation date (Table 3.3).

Each turfgrass type varied in turfgrass quality response to continuous 22, 40, 60, or 90% shade during 2016 and 2017. Both of the bermudagrass turf types, 'Astro-DLM' bermudagrass and common bermudagrass, maintained acceptable quality (rating score > 6) under 22% shade for the entirety of the trial (Fig. 3.3). Under 40% shade, 'Astro-DLM' bermudagrass and common bermudagrass resulted in unacceptable turf quality on five and twelve evaluation dates during the two-year study, respectively (Fig. 3.3). Both bermudagrass turf types produced unacceptable turfgrass quality under 60% shade for all evaluation dates except for one where 'Astro-DLM' resulted in acceptable turf quality in June 2017 (Fig. 3.3). Turf quality of both bermudagrasses was unacceptable under 90% shade for the entire trial period (Fig. 3.3). Under 60% shade, 'Astro-DLM' bermudagrass turf quality was significantly greater than under 90% shade for the entire trial, but only on select evaluation dates for common bermudagrass (Fig. 3.3).

Similar to the bermudagrass turf types, both zoysiagrasses, 'Cavalier' and 'Meyer', maintained acceptable turfgrass quality for the entirety of the trial under 22% shade (Fig. 3.4). 'Cavalier' zoysiagrass had acceptable quality under 40% shade throughout both years of the trial, but 'Meyer' zoysiagrass had unacceptable quality throughout 2017 (Fig. 3.4). Under 60% shade, 'Cavalier' zoysiagrass turf quality never declined below acceptable quality in 2016 (Fig. 3.4). However in 2017, 'Cavalier' zoysiagrass had unacceptable turfgrass quality for all but three evaluation dates (Fig. 3.4). 'Meyer' zoysiagrass declined to unacceptable quality under 60% shade on 7 September 2016 and only recovered to minimum acceptable quality on one subsequent evaluation date for the remainder of the trial (Fig. 3.4). Under 90% shade, both zoysiagrasses resulted in unacceptable turf quality on the second evaluation date and declined rapidly until plant death (Fig. 3.4).

All four warm-season turfgrasses remained above acceptable turfgrass quality under 22% shade (Fig. 3.5). There were no significant differences in turf quality among 'Cavalier' zoysiagrass, 'Meyer' zoysiagrass, and 'Astro-DLM' bermudagrass except on three evaluation dates where 'Meyer' zoysiagrass had significantly lower turf quality (Fig. 3.5). Common bermudagrass resulted in significantly lower turfgrass quality compared to other turf types on six of 20 evaluation dates under 22% shade (Fig. 3.5). Under 40% shade, common bermudagrass had lower quality than all turf types for a majority of evaluation dates in 2016, but recovered in 2017 (Fig. 3.5). This recovery could be explained by an increase in photosynthetic processes of common bermudagrass as a result of the greater average DLI quantities delivered to the turfgrass in 2017. 'Meyer' zoysiagrass dropped below acceptable quality under 40% shade and resulted in significantly lower quality than all other turf types on five of ten evaluation dates in 2017 (Fig. 3.5). Under 60% shade, both zoysiagrasses had significantly better quality than the two bermudagrasses for all but the final two evaluation dates during 2016 (Fig. 3.5). In 2017, only 'Cavalier' zoysiagrass had acceptable turfgrass quality under 60% shade (Fig. 3.5). In addition, 'Cavalier' zoysiagrass had significantly better turfgrass quality than the other three turfgrasses beginning on 26 June 2017 evaluation date through the remainder of the trial (Fig. 3.5). Under 90% shade, the quality of all four turfgrasses declined below an acceptable level on the second evaluation date and continued to decline for the remainder of the trial (Fig. 3.5).

The results of this study support the necessity of multi-year trials when screening for shade tolerance. During the second year of the trial, turfgrass quality continued to decline among turf types under various intensities of continuous shade. Turf quality of 'Cavalier' zoysiagrass even improved under shade during year two of this study. The study indicates that there exists a cumulative effect of shade on turfgrass quality and shade tolerance should be quantified by observing the cumulative effect of shade on turf quality over multiple years of evaluation.

This study is the first evaluation on the shade tolerance of 'Astro-DLM' bermudagrass compared to common bermudagrass. The improved shade tolerance of other hybrid bermudagrasses such as 'Astro-DLM' over other common bermudagrass cultivars has been observed, but is variable based on genetic diversity (Baldwin et al., 2009). Bermudagrass shade tolerance has been demonstrated to be cultivar specific more so than by species. In a screening of 42 common and hybrid bermudagrass cultivars, Baldwin et al. (2009) reported that 'Celebration' common bermudagrass had the greatest shade tolerance while 'Arizona Common' common bermudagrass was the most shade intolerant.

Similar to other studies on zoysiagrass shade tolerance, a *Zoysia matrella* turf type ('Cavalier') was observed to maintain higher turfgrass quality under dense shade (> 40%) compared to a *Zoysia japonica* turfgrass ('Meyer') (Sladek et al.,2009; Wherley et al., 2011). However, shade tolerance of zoysiagrasses are not exclusively species dependent, but also vary by cultivar. Trappe et al. (2011) reported that 'El Toro' and 'Palisades' cultivars of *Zoysia japonica* had shade tolerance equivalent to 'Cavalier' *Zoysia matrella*. The increased shade tolerance of 'Cavalier' zoysiagrass over 'Meyer' are in agreement with the direct comparison of the two turf types in a three-year study under 89% tree shade (Wherley et al., 2011).

Average turfgrass quality under each shade intensity level was plotted against two year average DLI under each shade intensity to quantify a DLI requirement to maintain acceptable turfgrass quality for each evaluated turfgrass. A turfgrass quality rating score of 9 was assumed for turfgrass in non-shaded conditions and was included in the analysis. Nonlinear regression analysis indicated that model parameters were significantly different ($P \leq 0.05$) among turf types, therefore separate models were developed for 'Astro-DLM' bermudagrass, common bermudagrass, 'Cavalier' zoysiagrass, and 'Meyer' zoysiagrass. Individual prediction models for the two bermudagrasses estimated a minimum DLI requirement of 20.1 mol m^{-2} d^{-1} for 'Astro-DLM' bermudagrass and 25.9 mol m^{-2} d^{-1} for common bermudagrass (Fig. 3.6). For the zoysiagrasses, minimum DLI requirements were estimated to be 15.0 mol m^{-2} d^{-1} for 'Cavalier' zoysiagrass and 21.1 mol m^{-2} d^{-1} for 'Meyer' zoysiagrass (Fig. 3.6).

The DLI of 21.1 mol m^{-2} d^{-1} determined in this study for 'Meyer' zoysiagrass is higher than the previous estimation of 12.7 mol m^{-2} d^{-1} when mowed at 16 mm (Bunnell et al., 2005b). The continued decline of 'Meyer' zoysiagrass during the second year of this trial contributed to an increased DLI requirement compared to previous reports. Additionally, the increased DLI requirement observed in this study could be attributed to trial duration. Bunnell et al. (2005b) evaluated 'Meyer' zoysiagrass quality after applying shade for two months during the summer. The cumulative effect of shade on turfgrass quality after extended duration of shade in this study (August-October 2016 and May-October 2017) could have resulted in an increased DLI requirement of 'Meyer'. This is the first report of DLI requirements for 'Cavalier' zoysiagrass, 'Astro-DLM' bermudagrass, and a common bermudagrass. The increased turfgrass quality in heavy shade (40 and 60% shade) of 'Cavalier' zoysiagrass resulted in a lower DLI requirement of 15.0 mol m^{-2} d^{-1} compared to 'Meyer' at 21.1 mol m^{-2} d^{-1}. Similarly, the improved shade tolerance of 'Astro-DLM' bermudagrass led to a lower DLI requirement of 20.1 mol m^{-2} d^{-1} over common bermudagrass at 25.9 mol m^{-2} d^{-1}. These DLI requirements support the notion from previous reports that zoysiagrasses are not always more shade tolerant than bermudagrasses, but that shade tolerance of turfgrass types is dependent on cultivar (Baldwin et al., 2009; Trappe et al., 2011). The range of DLI requirements for bermudagrasses evaluated in this study are similar to those observed in a greenhouse study where two hybrid bermudagrasses ('Tifway' and 'TifGrand') and one common bermudagrass ('Celebration') required a DLI of 21.4, 20.9, and 20.2 mol m^{-2} d^{-1}, respectively (Zhang et al., 2017).

Turfgrass Coverage

Turfgrass coverage of the four turfgrass types were affected by shade intensity treatments in 2016 and 2017 (Table 3.3). During both years of this study, analysis of variance indicated a significant ($P \leq 0.05$) three-way interaction between turfgrass type, shade intensity treatment, and evaluation date (Table 3.3).

Results from turfgrass coverage evaluation were similar to those observed for turf quality. Each evaluated turfgrass varied in turfgrass coverage response to continuous 22, 40, 60, 90% shade during 2016 and 2017. For 'Astro-DLM' bermudagrass, there were no significant differences between 22 and 40% shade (Fig. 3.7). Significant turfgrass quality differences between 22 and 40% shade treatments for common bermudagrass were observed beginning on 30 September 2016 (Fig. 3.7). This significant separation in turfgrass quality was observed for the remaining evaluation dates during the trial. After the first five evaluation dates, both bermudagrasses possessed significantly lower turfgrass coverage under 60% shade than turfgrass under 22 and 40% shade (Fig. 3.7). Similarly, after two evaluation dates, turfgrass coverage of both bermudagrasses under 90% shade was significantly lower than turfgrass under 60% shade and were dead by the end of 2016 (Fig. 3.7).

A significant separation in turfgrass coverage as a result of shade intensity did not occur until September 2016 for both zoysiagrasses (Fig. 3.8). Under 22% shade, 'Cavalier' zoysiagrass had significantly greater turfgrass coverage than all other shade intensity treatments beginning on 30 September 2016 through 13 July 2017 when the turfgrass under 40% shade approached 100% cover (Fig. 3.8). 'Meyer' zoysiagrass under 22% shade maintained significantly greater turfgrass coverage over all other shade intensity treatment from 30 September 2016 through the remainder of the trial (Fig. 3.8). There were no statistical differences between zoysiagrass under 40 and 60% shade until 13 July and 31 July 2017 for 'Cavalier' and 'Meyer' zoysiagrass, respectively (Fig. 3.8). Turfgrass quality under 90% shade was significantly lower than under 60% shade on

30 September and 7 October 2016 for ‘Cavalier’ and ‘Meyer’ zoysiagrass, respectively, after which they approached 0% coverage (Fig. 3.8).

Lateral growth rate of each evaluated turfgrass varied in term of turf coverage under each shade intensity level. It is important to note that due to the difference in spreading habits between zoysiagrass and bermudagrass turf types, turf coverage in this trial should be viewed more as a growth rate evaluation over time than an overall turf health evaluation. In general, the bermudagrasses spread rapidly during establishment whereas lateral growth of the zoysiagrasses were slower before shade was applied (Fig. 3.9). Under 22% shade, both bermudagrasses reached 90% turfgrass coverage in less than two months after shade was applied (Fig. 3.9). Both zoysiagrasses did not reach 90% coverage until late summer of 2017 (Fig. 3.9). Under 22% shade, there were no significant differences in turfgrass coverage between turf types of bermudagrass. Zoysiagrass turf types were statistically different only on one evaluation date under 22% shade (Fig. 3.9). No significant difference between bermudagrasses occurred under 40% shade until after two months into the trial (Fig. 3.9). At that time, common bermudagrass coverage declined significantly compared to ‘Astro-DLM’ bermudagrass and continued until 14 June 2017 when common bermudagrass began to regain coverage similar to ‘Astro-DLM’ bermudagrass. The initial rapid growth of both bermudagrasses under 40% shade in 2016 and then subsequent decline of common bermudagrass in 2017 indicate the importance of prolonged shade trials over multiple years. Significant differences between zoysiagrasses under 40% shade did not occur until the first evaluation date in 2017 (Fig. 3.9). Beginning in 2017, ‘Cavalier’ zoysiagrass spread more quickly than ‘Meyer’ under 40% shade. ‘Cavalier’ was able to achieve above 90% coverage by the end of the trial while ‘Meyer’ never reached above 60% turf coverage under 40% shade. Under 60% shade, turfgrass coverage of both bermudagrasses declined throughout the trial period. ‘Astro-DLM’ bermudagrass maintained greater turf coverage under 60% shade compared to common bermudagrass for all but two evaluation dates during the trial (Fig. 3.9). Both zoysiagrasses continued to grow laterally under 60% shade, but not as quickly compared to the 40% shade treatment. Beginning on 13 July 2017 and continuing through the remainder of the trial, ‘Cavalier’ zoysiagrass had greater turf coverage over all other turfgrasses (Fig. 3.9). Under 90% shade, all turfgrasses died. There were no differences in decline among zoysiagrasses, but common bermudagrass declined faster than ‘Astro-DLM’ bermudagrass under 90% shade (Fig. 3.9).

Final turfgrass coverage percentage under each shade intensity level was plotted against two year average DLI under each shade intensity to quantify a DLI requirement to maintain acceptable turfgrass coverage (> 80%) for each evaluated turfgrass. A turfgrass coverage of 100% was assumed for turfgrass in non-shaded conditions and was included in the analysis. Nonlinear regression analysis indicated that model parameters were significantly different ($P \leq 0.05$) among turf types, therefore separate models were developed for ‘Astro-DLM’ bermudagrass, common bermudagrass, ‘Cavalier’ zoysiagrass, and ‘Meyer’ zoysiagrass. A turf coverage of 100% was assumed for turfgrass not under shaded conditions and was included in the analysis. Individual prediction models for the two bermudagrasses estimated a minimum DLI requirement of 19.4 mol m^{-2} d^{-1} for ‘Astro-DLM’ bermudagrass and 24.6 mol m^{-2} d^{-1} for common bermudagrass (Fig. 3.10). For the zoysiagrasses, minimum DLI requirements were estimated to be 15.8 mol m^{-2} d^{-1} for ‘Cavalier’ zoysiagrass and 29.5 mol m^{-2} d^{-1} for ‘Meyer’ zoysiagrass (Fig. 3.10).

Turfgrass coverage has previously been used to determine DLI requirements of warm-season putting green species and cultivar establishment from sprigs (Hodges et al., 2016). This is the first study to determine a minimum DLI requirement based off of turfgrass coverage from a circular 15.2 cm diameter plug. Evaluation of turfgrass coverage for DLI requirement estimation provides objective data to confirm the DLI estimations determined from visual turfgrass quality ratings. The DLI requirements from turfgrass coverage varied slightly in range of 0.9 to 8.4 mol m^{-2} d^{-1} compared to those obtained via turfgrass quality. This discrepancy was expected due to the turfgrass quality rating system evaluating not only turfgrass cover, but also turfgrass color, uniformity, and density.

DLI values recorded at multiple golf courses where shade was a limiting factor of turfgrass growth varied among courses and individual sites at each course (Table 3.4). The reduction of PAR light at each individual site was variable due to differences in tree shade density and shade duration based off of tree positioning in relation to the evaluated turfgrass. Percent reduction of full sun DLI at each position during the 6 day evaluation period in 2017 (Table 3.4) was utilized to estimate average seasonal DLI from August-October 2016 and May-October 2017 at each golf course site (Table 3.5).

Estimated average DLI at each of the four positions was plotted against turfgrass quality at the individual sites to predict the minimum DLI requirement to maintain acceptable quality (rating score > 6) of the four evaluated turfgrasses. Nonlinear regression analysis indicated that model parameters were significantly different ($P \leq 0.05$) among turf types and individual sites, therefore separate models were developed each turf type and evaluation site. A turfgrass quality rating score of 9 was assumed for turfgrass in non-shaded conditions and was included in the analysis. The estimated minimum DLI requirement for 'Astro-DLM' bermudagrass at the two individual sites were 20.6 and 19.3 mol m^{-2} d^{-1} (Fig. 3.11). The DLI requirement of common bermudagrass was estimated to be 7.4 and 8.2 mol m^{-2} d^{-1} at each respective site (Fig. 3.12).

‘Cavalier’ zoysiagrass was estimated to require a DLI of 18.6 and 26.3 mol m^{-2} d^{-1} to maintain acceptable quality at the two individual sites (Fig. 3.13). Only one golf course site of ‘Meyer’ zoysiagrass was included in this analysis due to shade not being the limiting factor of turfgrass decline in one of the evaluation sites. The minimum DLI for ‘Meyer’ zoysiagrass was estimated to be 22.5 mol m^{-2} d^{-1} based off of the one site included in this data set (Fig. 3.14).

Minimum DLI requirements established in the research setting varied among turf types to accurately represent minimum DLI requirements in the established landscape. Relatively small differences existed from the DLI estimated in the standardized research stetting to the estimated DLI at the golf course for ‘Astro-DLM’ bermudagrass and ‘Meyer’ zoysiagrass (Table 3.6). However, relatively large differences were observed for common bermudagrass and ‘Cavalier’ zoysiagrass between the estimated DLI from the research setting and the golf course setting (Table 3.6).

Minimum DLI requirements for each evaluated turfgrass were also estimated based off of turfgrass coverage. Turfgrass coverage was plotted against estimated average DLI at each of the four sensors positions at the individual sites for each turfgrass to estimate the minimum DLI necessary to maintain acceptable turfgrass coverage (> 80 %). Turfgrass coverage of 100% was assumed for turfgrass in non-shaded conditions and was included in the analysis. Independent models were determined to be necessary for each respective site through nonlinear regression analysis. The minimum DLI requirement of ‘Astro-DLM’ bermudagrass at the two individual sites were estimated to be 20.8 mol m^{-2} d^{-1} (Fig. 3.15) Common bermudagrass was estimated to require a minimum DLI of 7.5 and 8.3 to maintain acceptable turfgrass coverage (Fig. 3.16). The DLI necessary for ‘Cavalier’ zoysiagrass to produce acceptable turf coverage was estimated at 17.6 and 23.6 mol m^{-2} d^{-1} at the two respective sites (Fig. 3.17). Based off the turfgrass coverage at one site, the estimated DLI requirement for ‘Meyer’ zoysiagrass was estimated to be 26.3 mol m^{-2} d^{-1} (Fig. 3.18).

The comparison of the DLI requirement determined in the research setting to accurately represent the golf course setting DLI requirement in an established landscape based off turfgrass coverage was similar to the previous comparison utilizing turfgrass quality ratings. ‘Astro-DLM’ bermudagrass and ‘Meyer’ zoysiagrass differed slightly in comparison of the research setting minimum DLI and golf course setting minimum DLI by 1.3 and 3.2 mol m^{-2} d^{-1}, respectively (Table 3.7). However, the accuracy comparison for common bermudagrass and ‘Cavalier’ zoysiagrass varied by 17.1 and 7.8 mol m^{-2} d^{-1}, respectively (Table 3.7).

This is the first study to evaluate a method to estimate the minimum DLI requirement of a turfgrass in the established landscape. The four evaluated warm-season turfgrasses varied in turfgrass quality and coverage response under continual 22, 40, 60, or 90% shade during 2016 and 2017 in a research setting. Minimum DLI requirements of ‘Astro-DLM’ bermudagrass, common bermudagrass, ‘Cavalier’ zoysiagrass, and ‘Meyer’ zoysiagrass to maintain acceptable turfgrass quality in a research setting were determined to be 20.4, 25.9, 15.0, and 21.1 mol m^{-2} d^{-1}, respectively. These DLI requirements were an accurate representation of the minimum DLI requirement observed in an existing golf course landscape for ‘Astro-DLM’ bermudagrass and ‘Meyer’ zoysiagrass. However, the DLI requirement determined in the research setting was not able to accurately represent what the minimum DLI requirement was observed to be in an existing landscape for common bermudagrass and ‘Cavalier’ zoysiagrass. This misrepresentation could be explained due to the narrow time span that DLI measurements were collected in the golf course setting. The shaded conditions at the individual sites during the six days may not have been an accurate depiction of shade over the two year period. Furthermore, the effects on turf quality and coverage of long time shade present in the golf course setting may not able to be captured during the two year time span of this trial. Unique properties of shaded microclimates at individual evaluation sites such as restricted air movement, increased relative humidity, and extended dew periods (Dudeck and Peacock, 1992) could have resulted in further turf quality and coverage decline that was not observed in the standardized research setting. In addition, individual site characteristics (cultural practices, tree root competition, water/soil interaction, etc.) at each golf course could have impacted turf quality and resulted in DLI requirement differences compared to the standardized research setting. However in the standardized research setting, shade was the only known limiting factor on turfgrass quality. Therefore, the DLI requirement estimated in the standardized research setting is the more reliable baseline when evaluating light requirements in an existing landscape.

CONCLUSIONS

The minimum DLI requirements established in a research setting should serve as a baseline for turfgrass managers when evaluating DLI needs for turfgrass at their facilities. While the methods presented in this research were able to accurately estimate the minimum DLI requirement of 'Astro-DLM' bermudagrass and 'Meyer' zoysiagrass in an established landscape, further evaluation and validation of this methodology is necessary to efficiently estimate DLI requirements *in situ* for all turfgrass types. In addition, determination of DLI requirements of other turfgrass types and the effect that cultural practices (fertilization, irrigation, plant growth regulators, etc.) can impact those requirements would prove beneficial. It is imperative that future DLI requirement research be conducted over multiple years in a controlled setting to capture the cumulative effect of shade on turf health and establish reliable estimates.

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Table 3.1. Location sites of four turfgrass types under evaluation when estimating a minimum DLI requirement in an existing landscape.

Turfgrass	Scientific Name	Golf Course	Location
'Astro-DLM' bermudagrass	*Cynodon dactylon* (L.)Pers. X *C. transvaalensis* Burtt-Davy	Shadow Valley Golf Club	Rogers, AR
Common bermudagrass	*Cynodon dactylon* (L.) Pers.	Bella Vista Golf Club	Bella Vista, AR
'Cavalier' zoysiagrass	*Zoysia matrella* (L.) Merr.	Blessings Golf Club	Johnson, AR
'Meyer' zoysiagrass	*Zoysia japonica* Steud.	Shadow Valley Golf Club	Rogers, AR

Table 3.2. Average daily light integrals (mol m^{-2} d^{-1}) under four shade intensities (22, 40, 60, and 90% shade) from August-October 2016 and May-October 2017 in Fayetteville, AR.

	Daily Light Integral		
Shade Intensity	2016	2017	2-Year Average
	(mol m^{-2} d^{-1})		
Full Sun*	41.4	46.0	44.4
22% Shade	31.6	34.4	33.4
40% Shade	21.5	25.4	24.1
60% Shade	13.8	16.1	15.3
90% Shade	2.0	2.9	2.6

Table 3.3. Analysis of variance (ANOVA) table of turfgrass quality rating and turfgrass coverage evaluations of four warm-season turfgrasses under four shade intensity regimes at the Arkansas Agricultural Research and Extension Center in Fayetteville, AR in 2016 and 2017. P-values in bold are highest order significant ($P \leq 0.05$) treatment interactions that warrant further discussion.

	Turfgrass quality		Turfgrass coverage	
Effect	2016	2017	2016	2017
	(P-value)			
Block	0.056	0.500	0.533	0.536
Shade	0.001	0.001	0.001	0.001
Turf Type	0.001	0.001	0.001	0.001
Shade x Turf Type	0.001	0.001	0.001	0.003
Date	0.001	0.001	0.001	0.001
Shade x Date	0.001	0.001	0.001	0.001
Turf Type x Date	0.005	0.001	0.001	0.001
Shade x Turf Type x Date	**0.001**	**0.029**	**0.001**	**0.001**

Table 3.4. Average daily light integrals (DLI) for 6 consecutive days in June-August 2017 in a golf course site at four different positions along a line transect where shade was assumed to be limiting quality and growth of the evaluated turfgrass. Positions along the line transect were as followed: 1) full turfgrass coverage, 2) slight turfgrass decline 3) extensive turfgrass decline, and 4) complete turfgrass failure. Percent reduction of full sun is included in parentheses. * Full Sun DLI was recorded at the Arkansas Agricultural Research and Extension Center, Fayetteville, AR.

Turfgrass	Daily Light Integral					
	Site No.	Full Sun*	Position 1	Position 2	Position 3	Position 4
		($mol\ m^{-2}\ d^{-1}$)				
‘Astro-DLM’ bermudagrass	1	51.7	24.6 (52%)	24.4 (53%)	23.7 (54%)	20.2 (61%)
	2	43.3	23.8 (45%)	21.9 (49%)	17.2 (60%)	7.2 (83%)
Common bermudagrass	1	58.8	24.0 (59%)	20.2 (66%)	9.7 (84%)	7.6 (87%)
	2	58.8	31.8 (45%)	11.2 (81%)	10.6 (82%)	6.0 (90%)
‘Cavalier’ zoysiagrass	1	57.1	26.6 (53%)	24.6 (57%)	22.1 (61%)	20.2 (65%)
	2	57.1	38.7 (32%)	35.4 (38%)	33.8 (41%)	9.9 (83%)
‘Meyer’ zoysiagrass	1	51.7	27.0 (48%)	24.4 (53%)	23.6 (54%)	7.7 (85%)
	2	43.3	28.0 (35%)	26.1 (40%)	23.1 (47%)	23.7 (45%)

Table 3.5. Estimated average daily light integrals (DLI) for August-October 2016 and May-October 2017 in a golf course site at four different positions along a line transect where shade was assumed to be limiting quality and growth of the evaluated turfgrass. Positions along the line transect were as followed: 1) full turfgrass coverage, 2) slight turfgrass decline 3) extensive turfgrass decline, and 4) complete turfgrass failure. * Full Sun DLI was recorded at the Arkansas Agricultural Research and Extension Center, Fayetteville, AR

		Estimated Average Daily Light Integral				
Turfgrass	Site No.	Full Sun*	Position 1	Position 2	Position 3	Position 4
		(mol m^{-2} d^{-1})				
‘Astro-DLM’ bermudagrass	1	44.4	21.1	21.0	20.4	17.3
	2	44.4	24.4	22.5	17.6	7.4
Common bermudagrass	1	44.4	18.1	15.3	7.3	5.7
	2	44.4	24.0	8.5	8.0	4.5
‘Cavalier’ zoysiagrass	1	44.4	20.7	19.1	17.2	15.7
	2	44.4	30.1	27.5	26.3	7.7
‘Meyer’ zoysiagrass	1	44.4	23.2	21.0	20.3	6.6
	2	44.4	28.7	26.8	23.7	24.3

Table 3.6. Estimated minimum daily light integral required to maintain acceptable turfgrass quality (rating score > 6) quality of four warm-season turfgrass cultivars in a standardized research setting evaluated under various shade intensities as well as in an established turfgrass setting at two individual locations on a golf course.

Turfgrass	Estimated Minimum Daily Light Integral		
	Research Setting	Golf Course Site 1	Golf Course Site 2
	(mol m^{-2} d^{-1})		
‘Astro-DLM’ bermudagrass	20.4 ± 0.8	20.6 ± 0.1	19.3 ± 3.9
Common bermudagrass	25.9 ± 2.1	7.4 ± 1.2	8.2 ± 0.4
‘Cavalier’ zoysiagrass	15.0 ± 3.3	18.6 ± 1.7	26.3 ± 0.6
‘Meyer’ zoysiagrass	21.1 ± 5.2	----	22.5 ± 4.0

Table 3.7. Estimated minimum daily light integral required to maintain acceptable turfgrass coverage (> 80%) quality of four warm-season turfgrass cultivars in a standardized research setting evaluated under various shade intensities as well as in an established turfgrass setting at two individual locations on a golf course.

Turfgrass	Estimated Minimum Daily Light Integral		
	Research Setting	Golf Course Site 1	Golf Course Site 2
	(mol m^{-2} d^{-1})		
‘Astro-DLM’ bermudagrass	19.5 ± 1.1	20.8 ± 0.4	20.8 ± 6.2
Common bermudagrass	24.6 ± 0.2	7.5 ± 0.8	8.3 ± 1.0
‘Cavalier’ zoysiagrass	15.9 ± 1.4	17.6 ± 0.1	23.7 ± 5.11
‘Meyer’ zoysiagrass	29.5 ± 7.5	----	26.3 ± 5.5

Figure 3.1. Shade structure system utilized to apply various shade intensities to four turfgrass types.

Figure 3.2. Quantum light sensors placed along a line transect perpendicular to shade damage in the following positions: 1) area of full turfgrass coverage, 2) slight turfgrass decline, 3), extensive turfgrass decline, and 4) complete turfgrass failure.

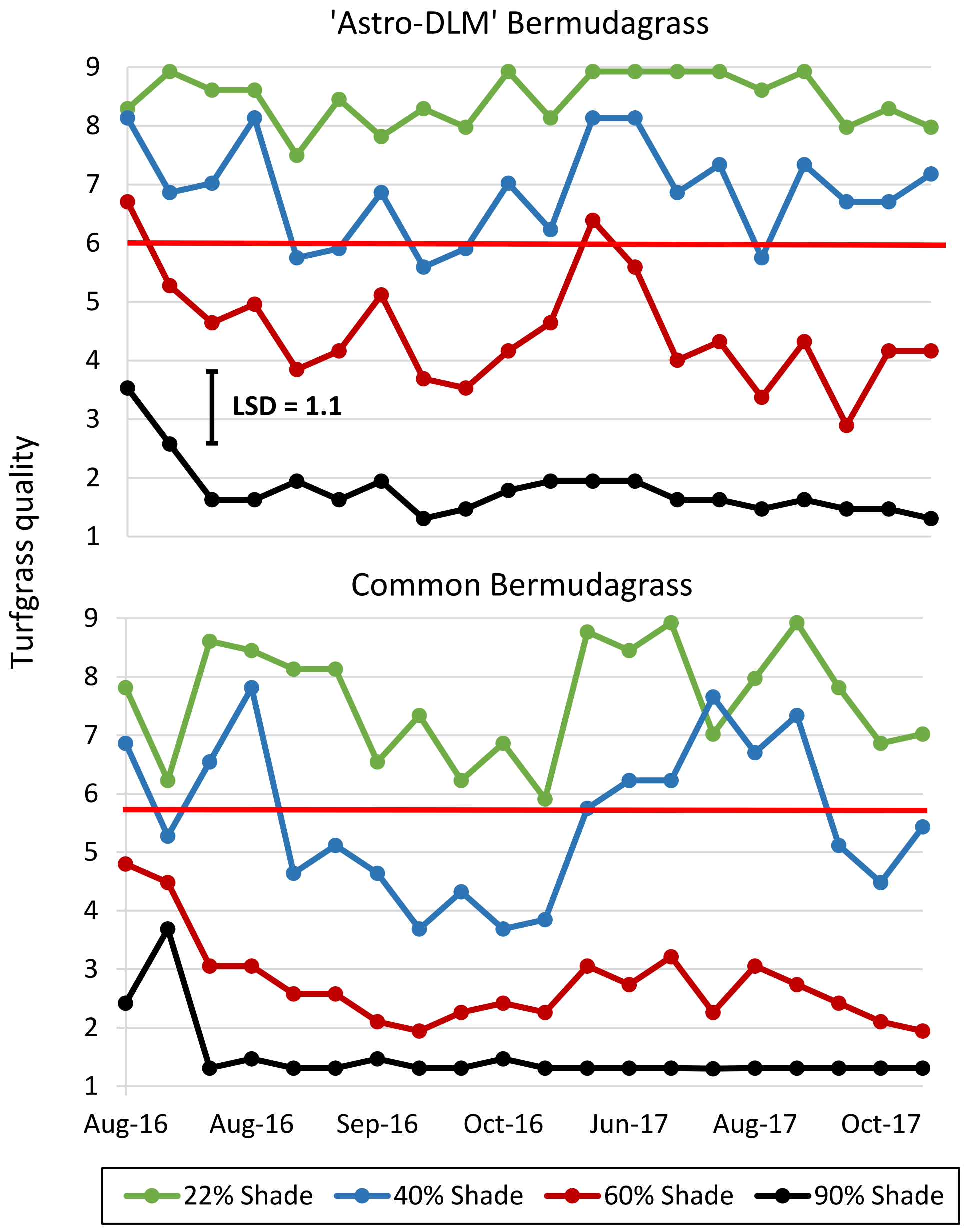


Figure 3.3. Visual turfgrass quality ratings (1-9 scale, 6 = minimum acceptability) of 'Astro-DLM' bermudagrass (top) and common bermudagrass (bottom) as affected by shade intensity from August-October 2016 and May-August 2017. LSD bar indicates least significant difference value to make treatment comparisons within evaluation dates.

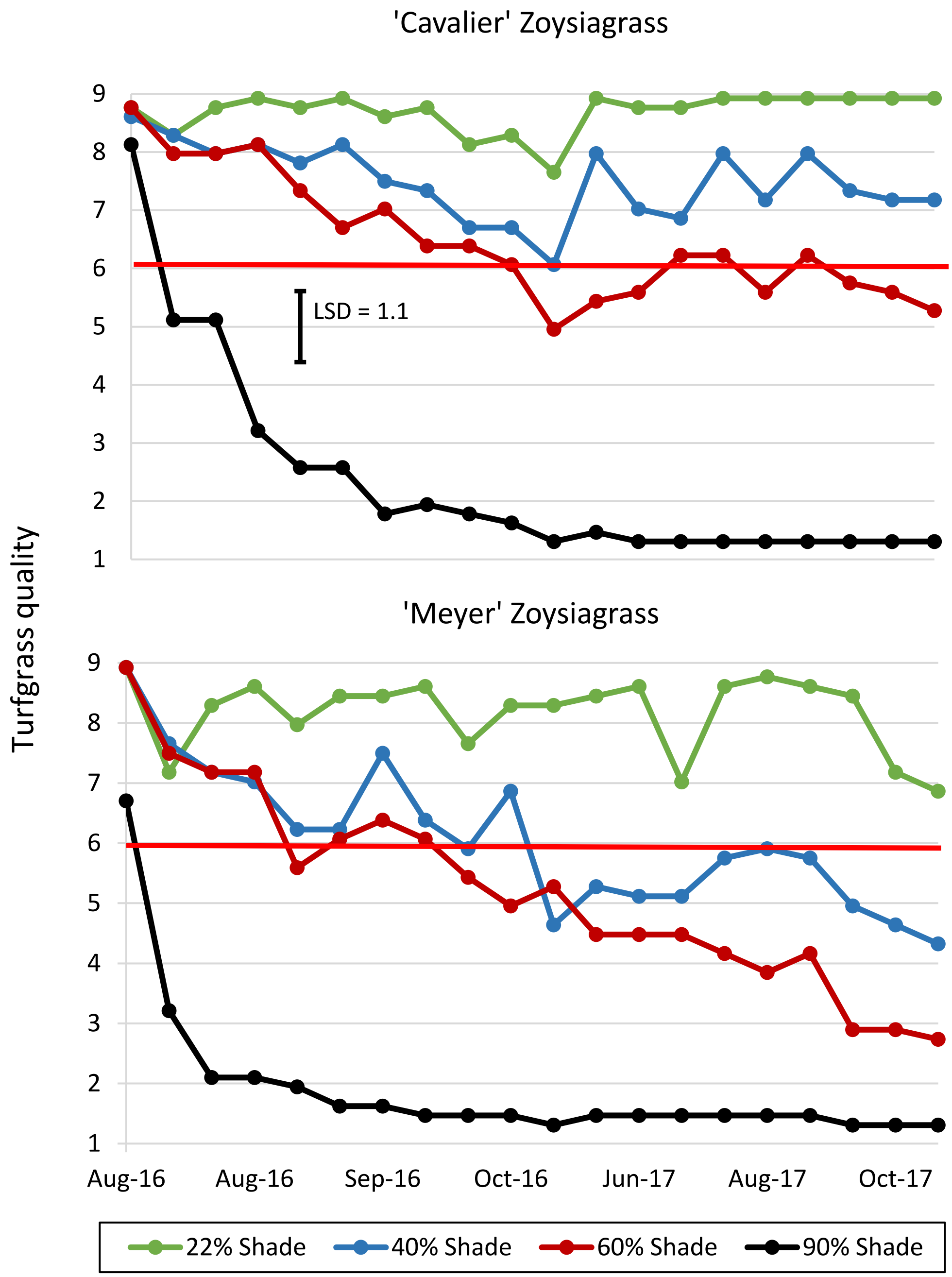


Figure 3.4. Visual turfgrass quality ratings (1-9 scale, 6 = minimum acceptability) of ‘Cavalier’ zoysiagrass (top) and ‘Meyer’ zoysiagrass (bottom) as affected by shade intensity from August-October 2016 and May-August 2017. LSD bar indicates least significant difference value to make treatment comparisons within evaluation dates.

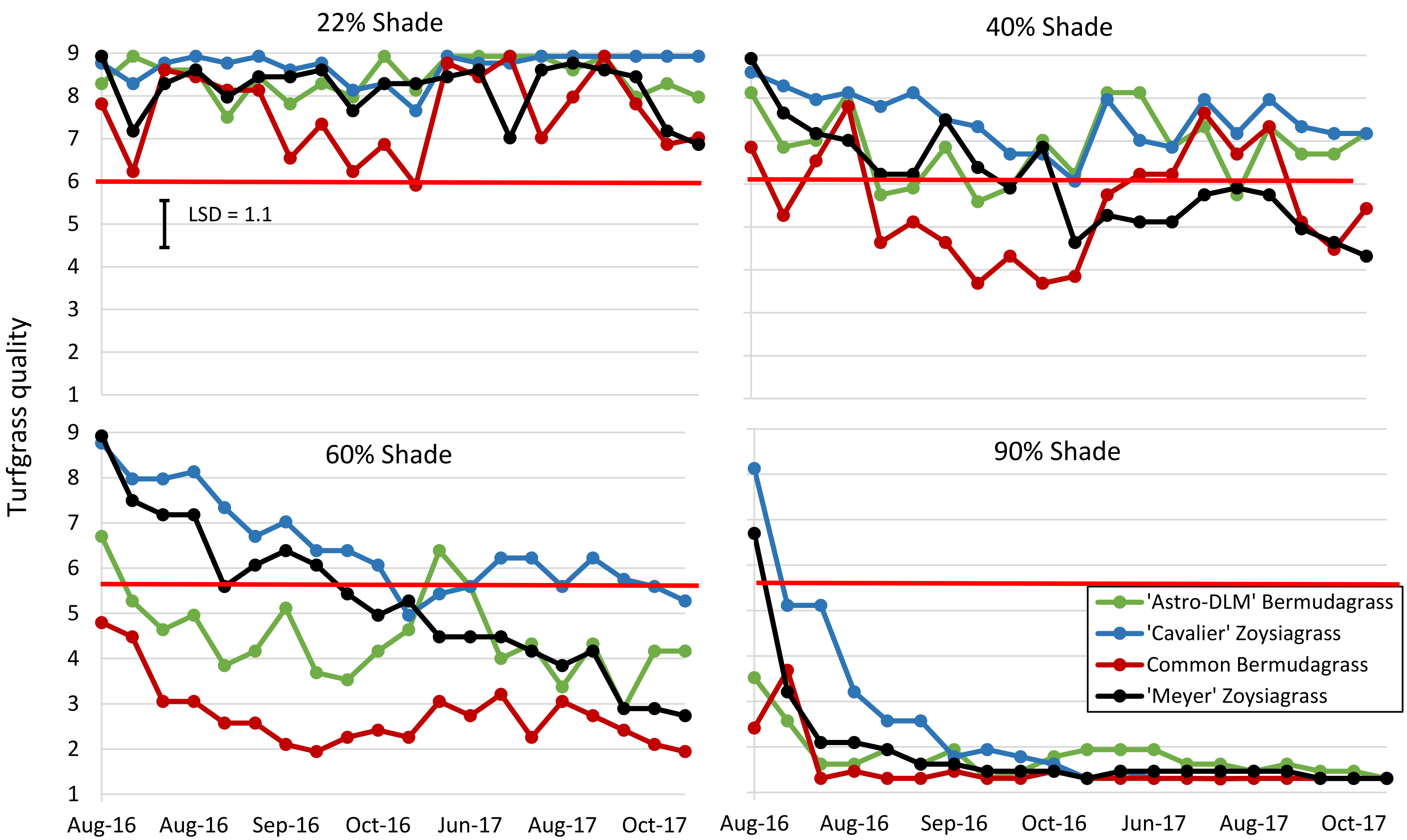


Figure. 3.5. Turfgrass quality of four warm-season turfgrasses under shade intensities of 22% (top left), 40% (top right), 60% (bottom left), and 90% (bottom right) shade in August-October 2016 and May-October 2017. LSD bar indicates least significant difference value to make treatment comparisons within evaluation dates.

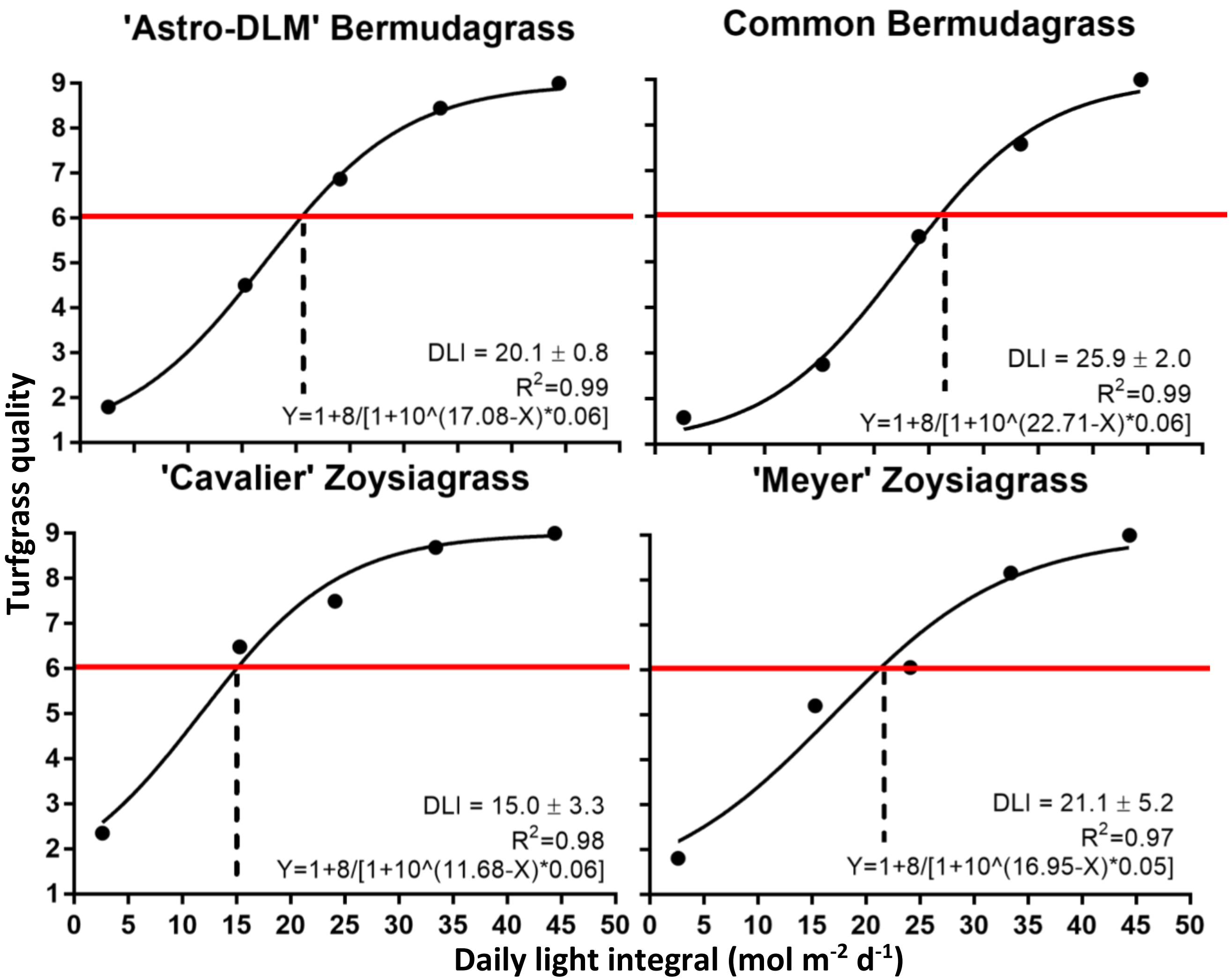


Figure 3.6. Nonlinear regression analysis of average turfgrass quality response of four warm-season turfgrass cultivars to average daily light integrals observed under 22, 40, 60, and 90% shade treatments in 2016 and 2017. Red line indicates minimal acceptability rating of 6. Dashed line represents estimated DLI requirement to achieve acceptable quality rating. ± represents 95% confidence intervals of estimated DLI requirement.

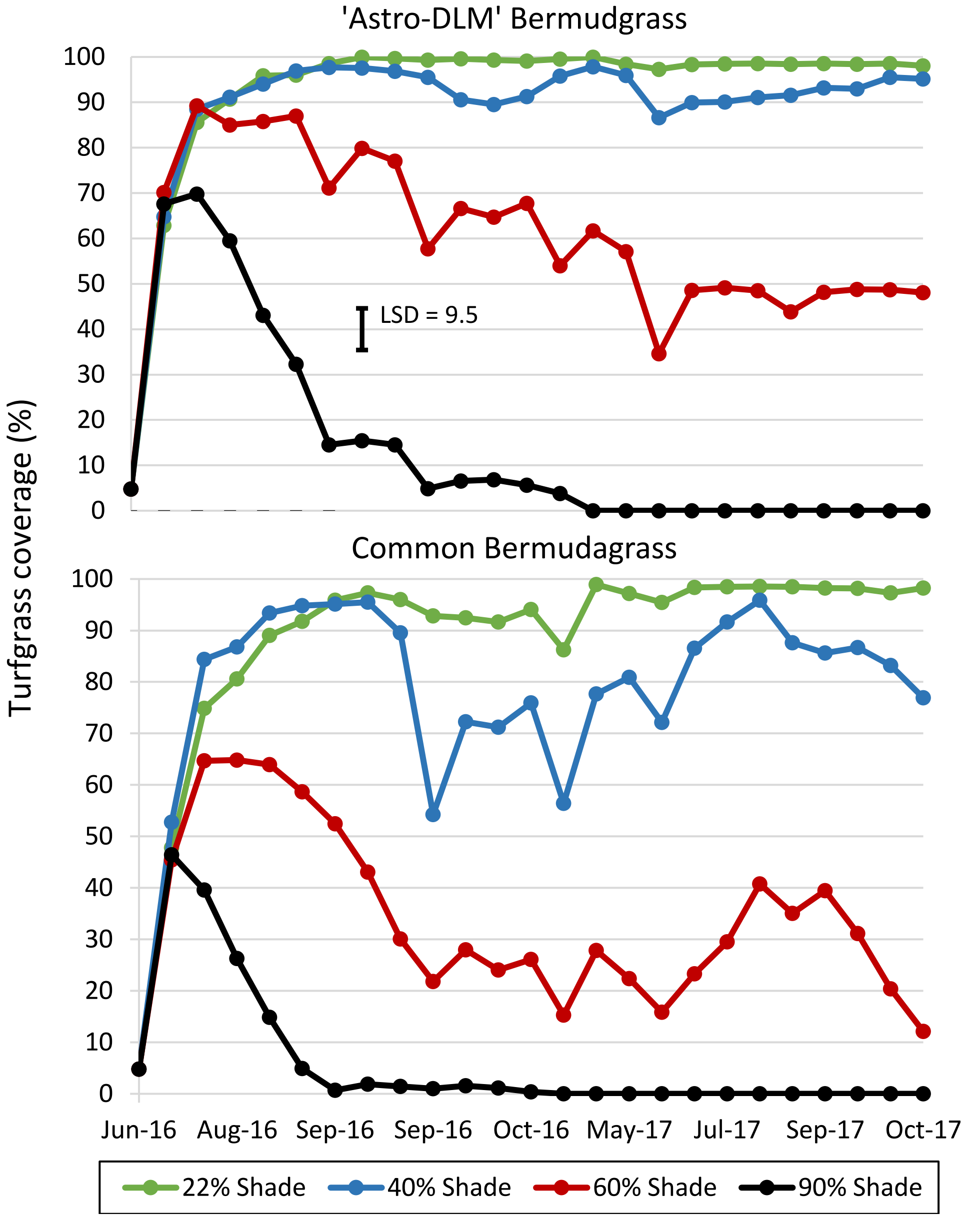


Figure 3.7. Turfgrass coverage, expressed as a percent, of 'Astro-DLM' bermudagrass (top) and common bermudagrass (bottom) as affected by shade intensity treatments during 30 June - October 2016 and May-October 2017. LSD bar indicates least significant difference value to make treatment comparisons within evaluation dates.

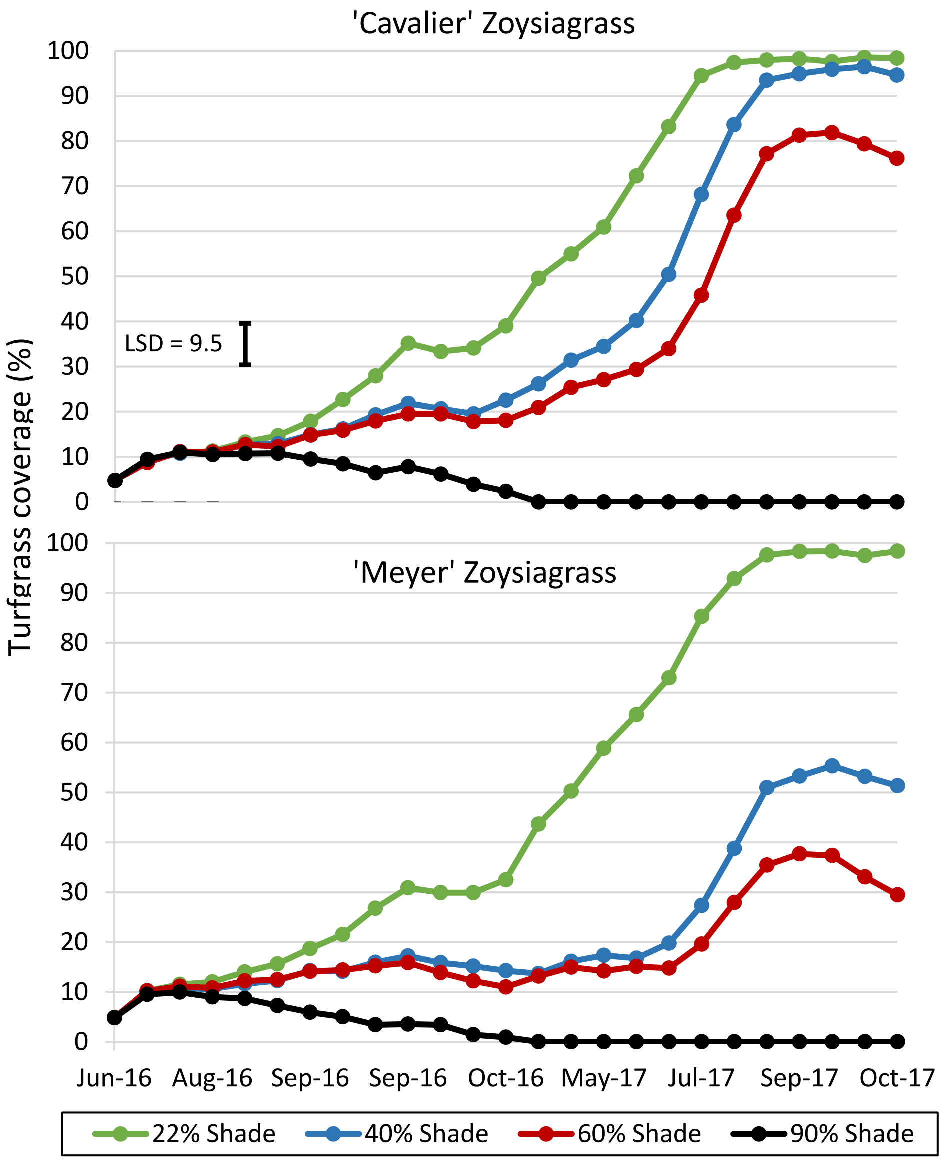


Figure 3.8. Turfgrass coverage, expressed as a percent, of 'Astro-DLM' bermudagrass (top) and common bermudagrass (bottom) as affected by shade intensity treatments during 30 June - October 2016 and May-October 2017. LSD bar indicates least significant difference value to make treatment comparisons within evaluation dates.

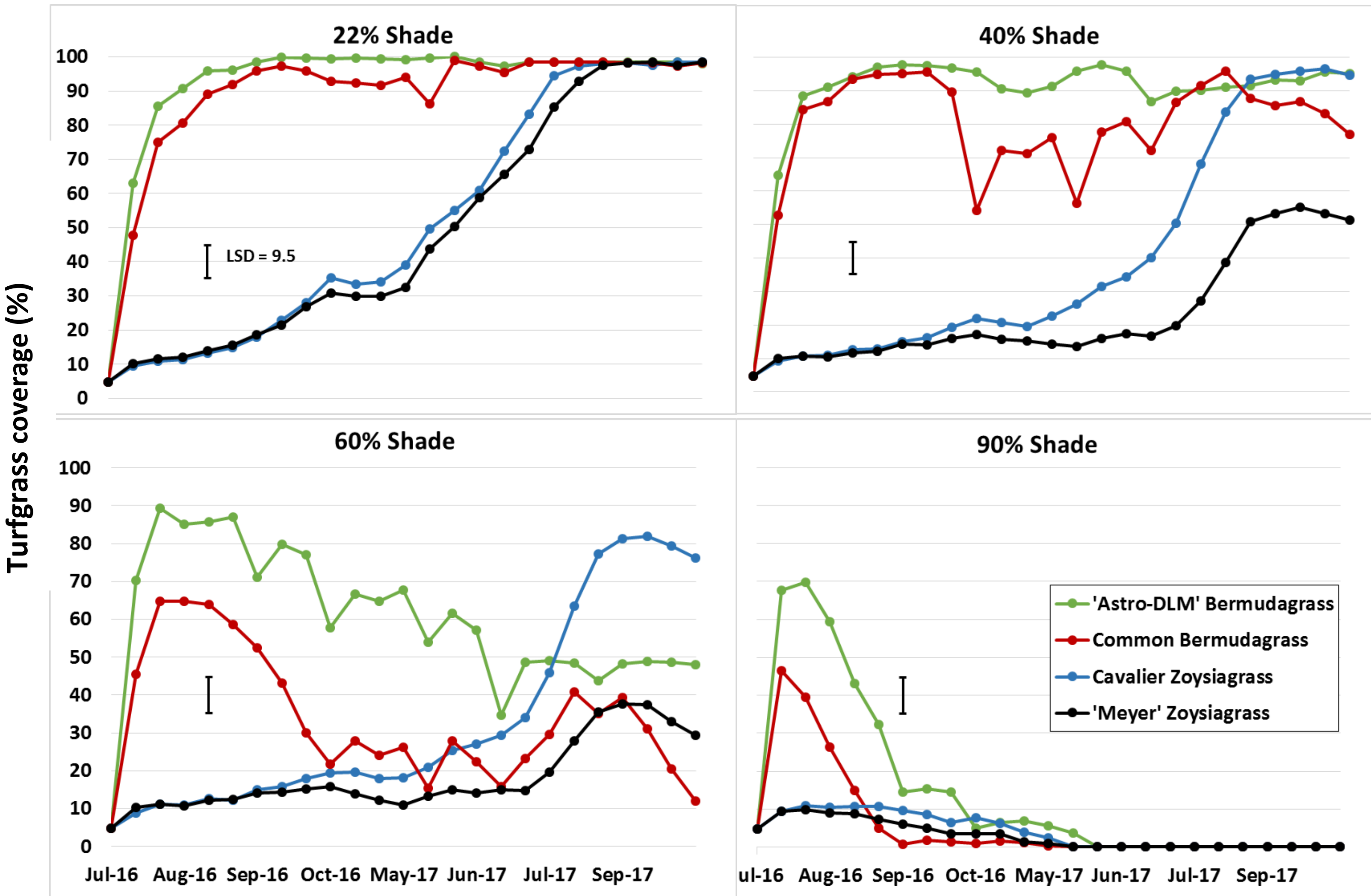


Figure. 3.9. Visual turfgrass quality ratings (1-9 scale, 6 = minimum acceptability) of four warm-season turfgrasses under shade intensities of 22% (top left), 40% (top right), 60% (bottom left), and 90% (bottom right) shade in 30 June-October 2016 and May-October 2017. LSD bar indicates least significant difference value to make treatment comparisons within evaluation dates.

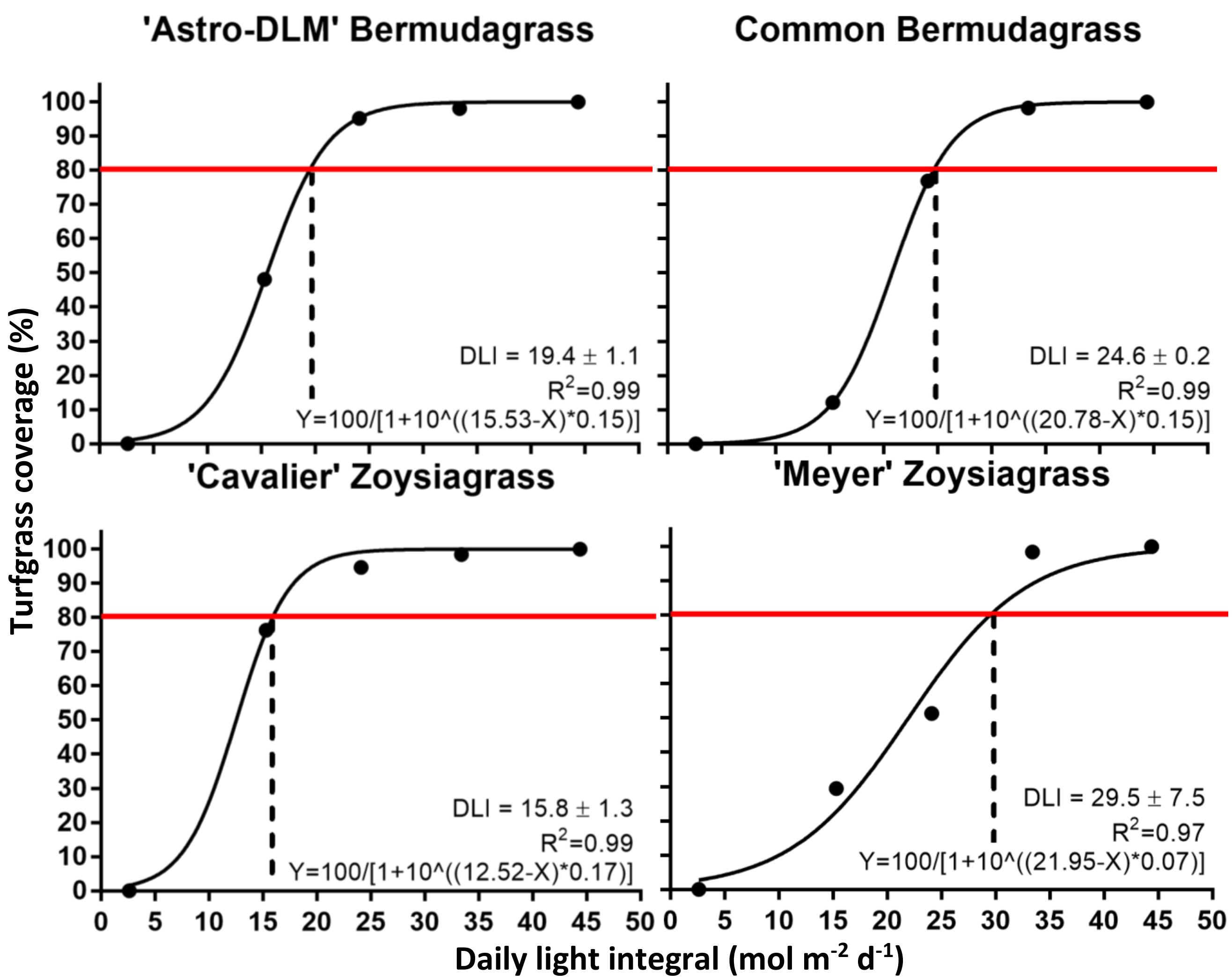


Figure 3.10. Nonlinear regression analysis of final turfgrass cover response of four warm-season turfgrass cultivars to average daily light integrals observed under 22, 40, 60, and 90% shade intensity treatment in 2016 and 2017. Red line indicates minimal acceptable turfgrass coverage of 80%. Dashed line represents estimated DLI requirement to achieve acceptable coverage. ± represents 95% confidence intervals of estimated DLI requirement.

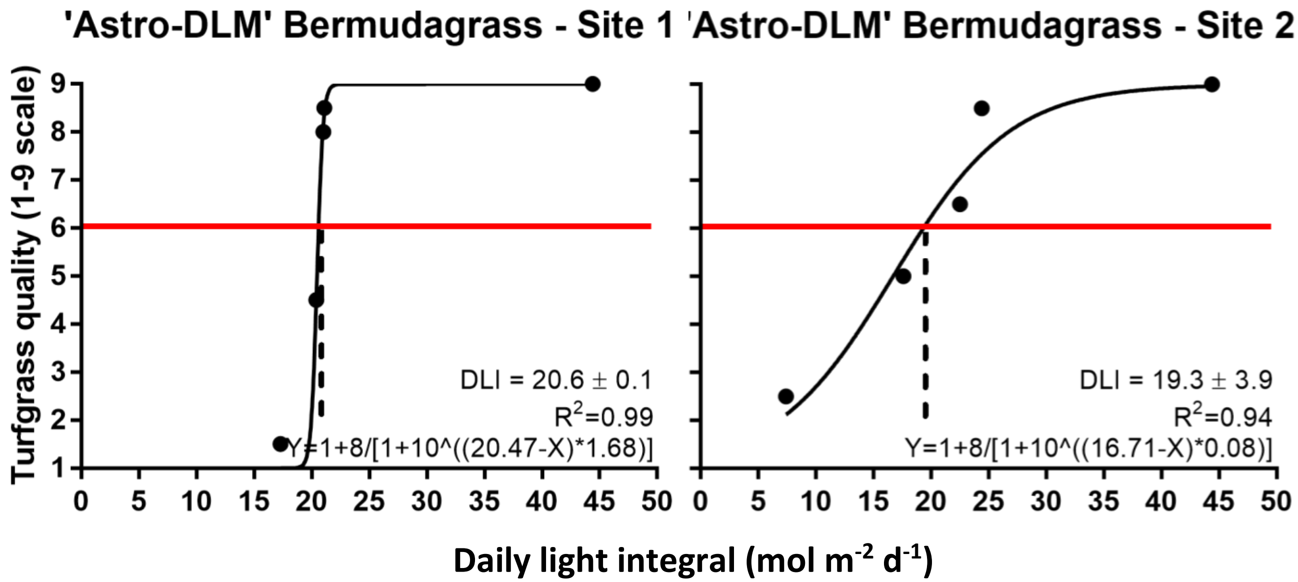


Figure 3.11. Nonlinear regression analysis of turfgrass quality response to estimated season long daily light integrals of ‘Astro-DLM’ bermudagrass from August-October 2016 and May-August 2017 at two individual sites at Shadow Valley Golf Club in Rogers, AR. Red line indicates minimal acceptable turfgrass quality rating of 6. Dashed line represents estimated DLI requirement to achieve acceptable quality rating. ± represents 95% confidence intervals of estimated DLI requirement.

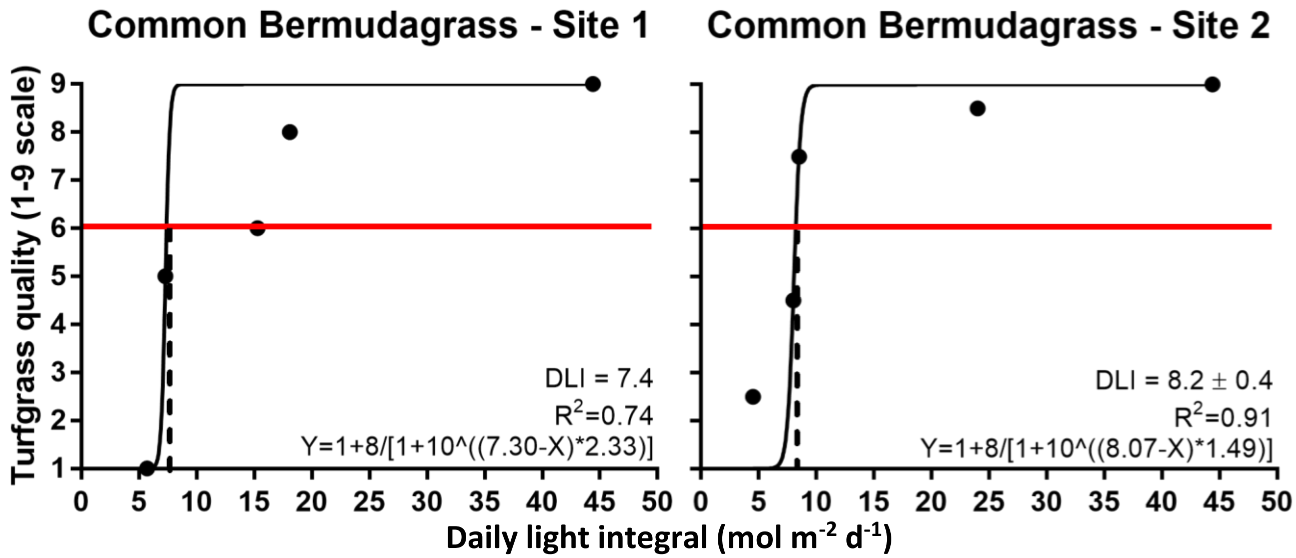


Figure 3.12. Nonlinear regression analysis of turfgrass quality response to estimated season long daily light integrals of common bermudagrass from August-October 2016 and May-August 2017 at two individual sites at Bella Vista Golf Club in Bella Vista, AR. Red line indicates minimal acceptable turfgrass quality rating of 6. Dashed line represents estimated DLI requirement to achieve acceptable quality rating. ± represents 95% confidence intervals of estimated DLI requirement.

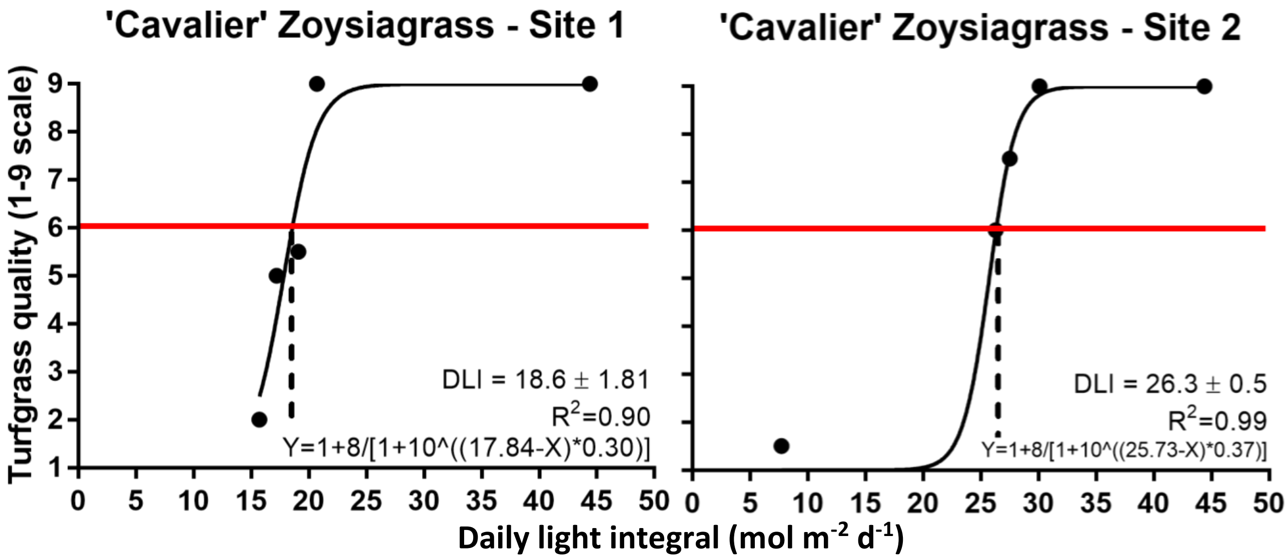


Figure 3.13. Nonlinear regression analysis of turfgrass quality response to estimated season long daily light integrals of 'Cavalier' zoysiagrass from August-October 2016 and May-August 2017 at two individual sites at Blessings Golf Club in Johnson, AR. Red line indicates minimal acceptable turfgrass quality rating of 6. Dashed line represents estimated DLI requirement to achieve acceptable quality rating. ± represents 95% confidence intervals of estimated DLI requirement.

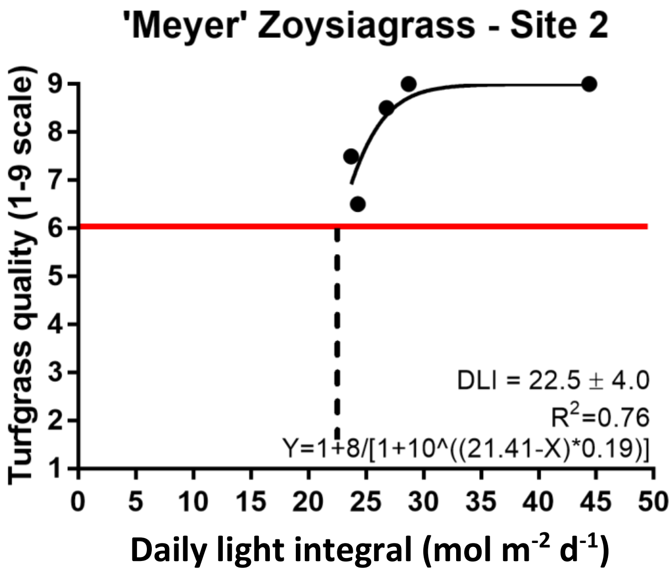
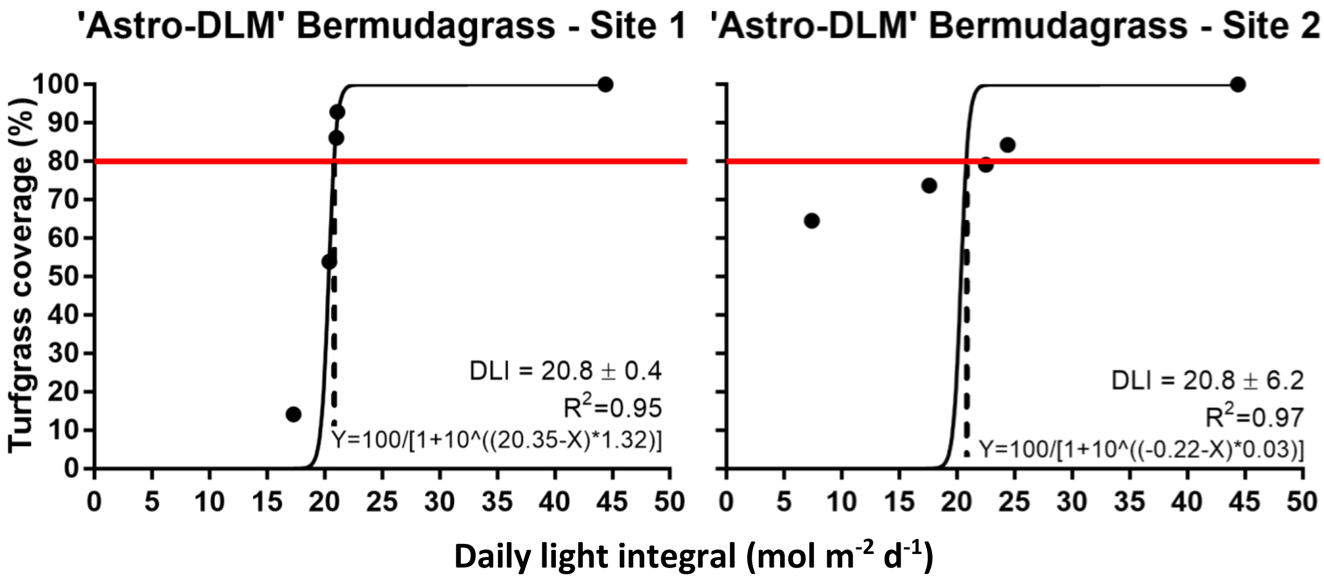


Figure 3.14. Nonlinear regression analysis of turfgrass quality response to estimated season long daily light integrals of 'Meyer' zoysiagrass from August-October 2016 and May-August 2017 at an individual site at Shadow Valley Golf Club in Rogers, AR. Red line indicates minimal acceptable turfgrass quality rating of 6. Dashed line represents estimated DLI requirement to achieve acceptable quality rating. ± represents 95% confidence intervals of estimated DLI requirement.



110

Figure 3.15. Nonlinear regression analysis of turfgrass coverage response to estimated season long daily light integrals of ‘Astro-DLM’ bermudagrass from August-October 2016 and May-August 2017 at two individual sites at Shadow Valley Golf Club in Rogers, AR. Red line indicates minimal acceptable turf coverage of 80%. Dashed line represents estimated DLI requirement to achieve acceptable coverage. ± represents 95% confidence intervals of estimated DLI requirement.

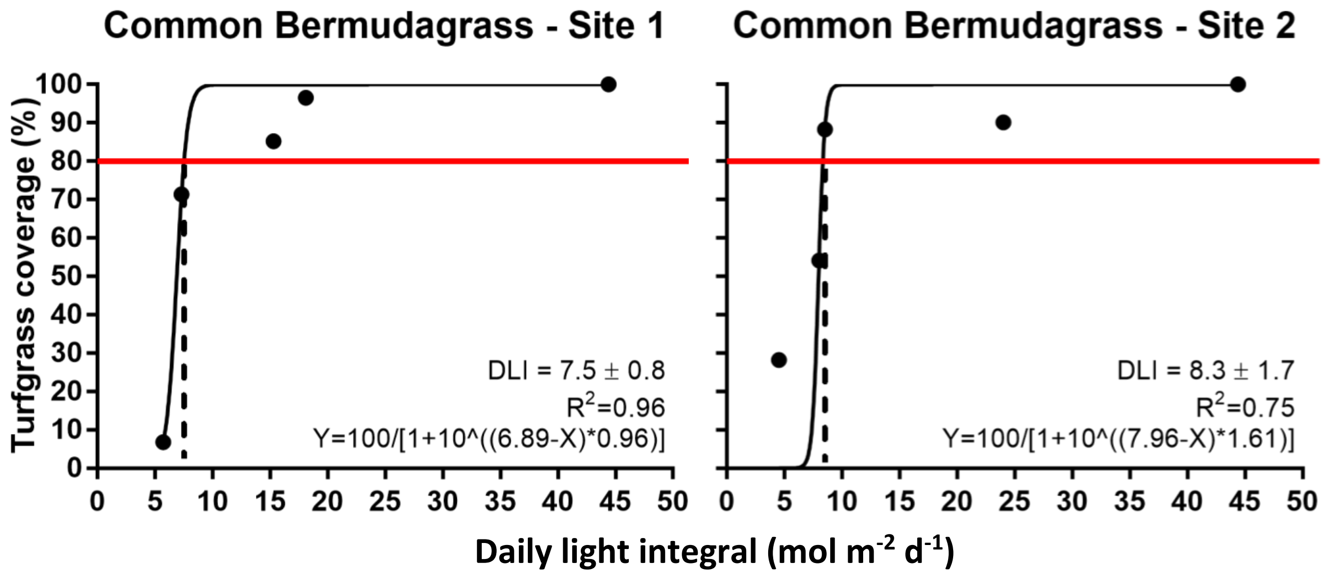


Figure 3.16. Nonlinear regression analysis of turfgrass coverage response to estimated season long daily light integrals of common bermudagrass from August-October 2016 and May-August 2017 at two individual sites at Bella Vista Golf Club in Bella Vista, AR. Red line indicates minimal acceptable turf coverage of 80%. Dashed line represents estimated DLI requirement to achieve acceptable coverage. ± represents 95% confidence intervals of estimated DLI requirement.

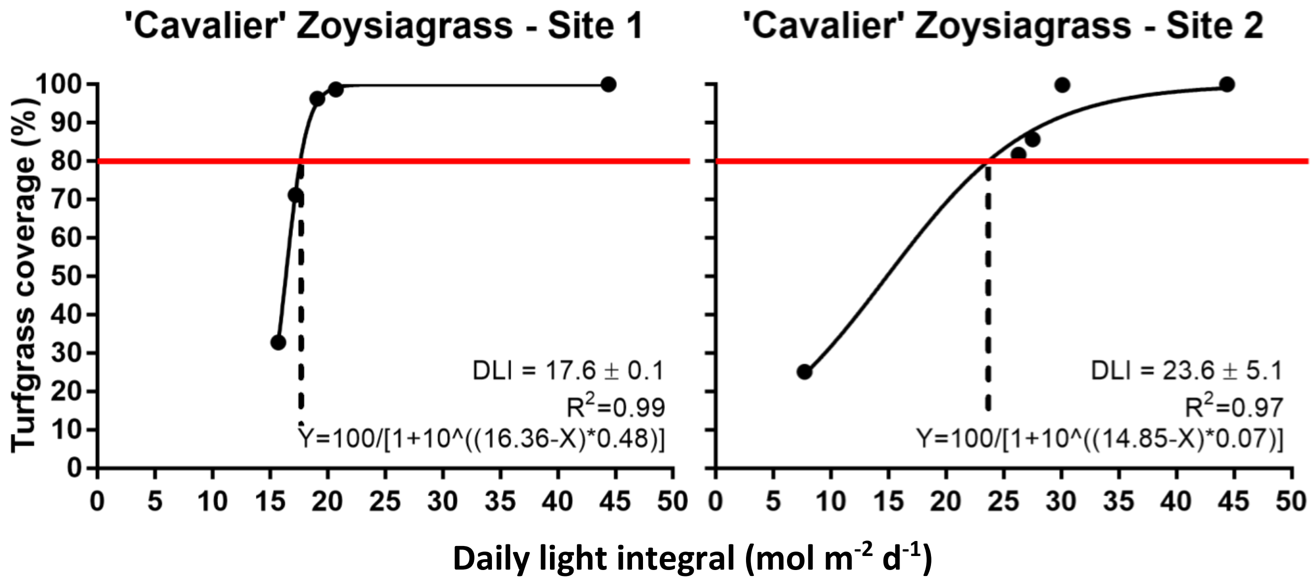


Figure 3.17. Nonlinear regression analysis of turfgrass coverage response to estimated season long daily light integrals of ‘Cavalier’ zoysiagrass from August-October 2016 and May-August 2017 at two individual sites at Blessings Golf Club in Johnson, AR. Red line indicates minimal acceptable turf coverage of 80%. Dashed line represents estimated DLI requirement to achieve acceptable coverage. ± represents 95% confidence intervals of estimated DLI requirement.

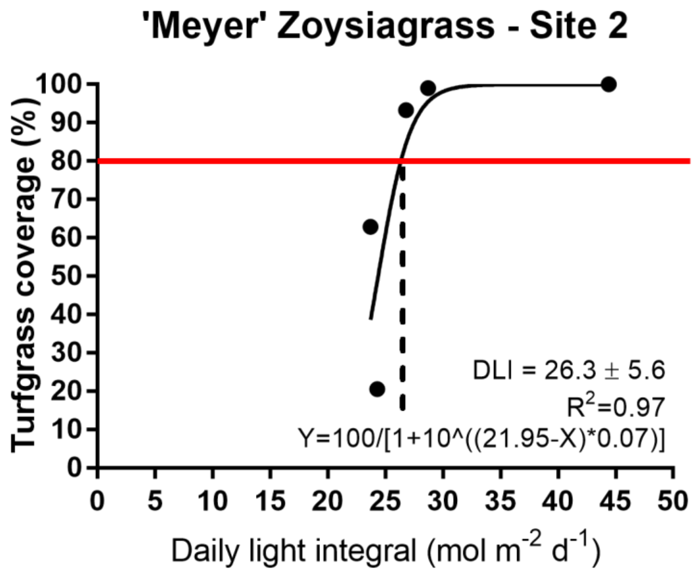


Figure 3.18. Nonlinear regression analysis of turfgrass coverage response to estimated season long daily light integrals of ‘Meyer’ zoysiagrass from August-October 2016 and May-August 2017 at an individual sites at Shadow Valley Golf Club in Rogers, AR. Red line indicates minimal acceptable turf coverage of 80%. Dashed line represents estimated DLI requirement to achieve acceptable coverage. ± represents 95% confidence intervals of estimated DLI requirement.

Chapter IV:

Estimating Photosynthetically Active Radiation Reduction under Various Tree Shade Canopies with Photometric Light Measuring Devices

ABSTRACT

Photosynthetically active radiation (PAR), the 400-700 nm band of light in electromagnetic spectrum that turfgrasses use for photosynthesis, is reduced under tree canopies. The quantity of PAR that is allowed through the canopy to the turfgrass surface can vary by tree species due to leaf and branch architecture. If not enough PAR is received, turfgrass can begin to show signs of shade stress such as stem elongation and thinning of the turf that could result in plant death. Turfgrass managers who wish to evaluate PAR light availability at their property have been advised to utilize quantum light meters to accurately measure PAR. These meters may be out of the range of affordability for some turfgrass practitioners. Devices that measure visible light in photometric units of footcandles or lux are still in use for some turfgrass managers and could be a viable alternative to diagnosing PAR light needs. This objective of this study was to evaluate the effectiveness of photometric light meters to estimate PAR reduction under shade of six tree species. The six tree species were American sycamore (*Platanus occidentalis* L.), bald cypress (*Taxodium distichum* [L.] Rich.), lacebark elm (*Ulmnus parvifolia* Jacq.), littleleaf linden (*Tilia cordata* Mill.), shortleaf pine (*Pinus echinata* Mill.), and water oak (*Quercus nigra* L.). Light measurements were taken under each tree species in 0.61 m increments from the base of tree to edge of shade canopy with a PAR quantum light meter, a general purpose footcandle/lux meter, and a light meter phone application utilizing the camera on an iPhone 5. Results indicate that average PAR reduction ranged from 76 to 90% of full sun PAR depending on tree species. Individual models were necessary for each total light measuring device to estimate PAR for each tree species. The explained variation in the models ranged widely from 2 to 99%. Accuracy of estimating PAR using total light meters is device and species specific. Quantum light meters still provide the best option to accurately assess light needs for turfgrass managers.

INTRODUCTION

Due to the fundamental role of light energy in plant systems, accurate light measurement is of critical importance. Light is frequently quantified by the amount of visible radiation delivered during a sunny day. Among commercial plant growers, visible radiation is often measured in photometric units such as lumens and footcandles that quantify light based on a scale of brightness similar to that perceived by the human eye (Korczynski et al, 2012; Shibbles, 1976). Lumens and footcandles are quantities of visible light measurement that are closely related. A lumen delivered to a square foot area is termed a lux and a footcandle is equivalent to 10.76 lux (Meyer-Arendt, 1968).

Early plant science studies utilized these photometric measurements and their use has continued to persist in current plant science despite evidence proving its inadequacy compared to newer measurement methods (McCree, 1972). Photometric units measure total visible light without the consideration of the specialized wavelengths of light absorbed by plants for photosynthesis (McCree, 1972). Plants utilize radiation within the 400-700 nm bandwidth of the electromagnetic spectrum for photosynthesis and is termed photosynthetically active radiation (PAR). Therefore, academic plant studies now report PAR as a quantum radiometric unit delivered to the plant (Tibbitts et al., 2000). Quantum radiometric units describe the number of photons within the 400-700 nm bandwidth delivered to the plant surface per second and reported as µmol m^{-2} s^{-1}. Quantum sensors that measure PAR have been developed to aid researchers and growers to accurately quantify light as it pertains to photosynthesis.

For turfgrass managers, specifically, the quantum light sensor has become an important instrument in evaluating light availability to turfgrass in shaded environments beneath tree canopies and other impediments in the landscape. Tree leaves can absorb or reflect a significant amount of PAR that would otherwise be available to the turfgrass plant and possibly produce a less dense and weaker turfgrass stand (Wherley et al., 2005). The change in spectral light quality of red: far red wavelength ratios under tree shade has been well documented (Bell and Danneberger, 2000; Grant, 1997; Wherley et al. 2005), but limited information exists documenting the variation in PAR reduction among tree species and more research is warranted. Bell and Danneberger (2000) found that no differences existed in PAR reduction among deciduous and conifer trees, but only two deciduous tree and one conifer tree were evaluated. There is information available discussing quality effects of specific turfgrass species grown under an individual tree species (Bell et al., 2011; Okeyo et al., 2009; Peterson et al., 2012; Wherley et al., 2011), but no work exists evaluating turf performance under multiple tree species. Additionally, quantum light sensors may be outside the range of affordability or photometric light quantification is still the preferred method for some turfgrass managers. There is a need to evaluate alternative methods of PAR measurement in turfgrass landscapes such as photometric light meters that measure total visible light (footcandles and lux) as well as total light measurement apps on smart phones or other mobile devices.

Research Objectives

The research objectives of this study are to 1) evaluate the reduction in PAR and total visible light under various tree species shade canopies, 2) determine a method to predict PAR values from photometric measurements, and 3) to develop equations for predicting PAR values using photometric light meters based on tree species.

MATERIALS AND METHODS

Experimental Area

This study was conducted in the summers of 2016 and 2017 on six deciduous and evergreen trees species on the University of Arkansas Campus, Fayetteville, AR and the University of Arkansas Agricultural Research and Extension Center in Fayetteville, AR (36°06' N, 94°10' W). Six tree species were selected for evaluation in this study: American sycamore (*Platanus occidentalis* L.), bald cypress (*Taxodium distichum* [L.] Rich.), lacebark elm (*Ulmnus parvifolia* Jacq.), littleleaf linden (*Tilia cordata* Mill.), shortleaf pine (*Pinus echinata* Mill.), and water oak (*Quercus nigra* L.).

Evaluations

Five devices were used to measure solar radiation quantities in various units of light under the canopy of each tree species (Table 4.1). Units of light measurement recorded were either PAR photons, footcandles, or lux. These devices included: a quantum light sensor (LightScout Quantum Light Meter, Spectrum Technologies, Aurora, IL), a 1-meter line quantum sensor (Model: LI-191R, LI-COR Biosciences, Lincoln, NE) a footcandle light sensor (LightScout Foot-candle Light Meter, Spectrum Technologies, Aurora, IL), a general purpose light meter (Model: Extech 401025, FLIR Commercial Systems Inc., Nahua, NH), and the "Light Meter" application (Developer: Elena Polyanskaya) available in the Apple App Store on iPhone 5s that uses the front facing camera to measure solar radiation.

PAR photons (μmol) were measured with the quantum light sensor and the line quantum sensor. Footcandles were measured with the footcandle light sensor, the general purpose light meter, and the "Light Meter" application. Lux were measured using the general purpose light meter and the "Light Meter" application (Table 4.1).

Three replicates of each tree species were evaluated for solar radiation measurements. Individual trees of each species were mature specimens and similar in height, trunk diameter, and canopy density. Solar radiation measurement under tree canopies was evaluated with each device in 0.61 m increments from the base of the tree to the edge of the shade canopy. One additional measurement was taken 0.61 m past the edge of each shade canopy to evaluate percent reduction at each tree for subsequent light reduction calculations. Measurements were made uniformly, taken on the north side of each specimen perpendicularly to the trunk to standardize shade casting. Measurements were made at the ground surface underneath each tree replicate. All evaluations were made within 1 month of the summer solstice (20 June) during both years of the study and within 2 hours of solar noon.

The Spectrum LightScout Quantum Light meter is a popular choice among turfgrass managers to quantify PAR light at their properties. To evaluate the effectiveness of other light measuring devices to accurately predict PAR light, it is imperative to ensure the accuracy of the Spectrum meter in quantifying PAR light. Data were obtained using the LI-COR 1-m line quantum sensor, factory calibrated and assumed to accurately quantify PAR, and compared to data collected from the Spectrum meter to determine accuracy.

Statistical Design and Analysis

Data were analyzed using PROC ANOVA of SAS (version 9.3; SAS Institute Inc., Cary, NC) to determine tree species effect on PAR reduction. Treatment means were separated using Fisher's protected Least Significant Difference (LSD) test. An alpha value of 0.05 was used to determine statistical significance. To assess the PAR measurement accuracy of the Spectrum quantum light meter, regression analysis was performed utilizing PROC REG to define the linear relationship with measurements obtained with the calibrated LI-COR line quantum light meter.

Correlation of measurements from each device to the Spectrum PAR light meter were determined with PROC CORR to develop Pearson correlation coefficients for each tree species. Analysis of covariance using PROC GLM was used to test if tree species was a significant effect in the model to warrant separate models for each device and tree species to predict PAR. Separate models for each device and tree species were developed from linear regression analysis with PROC REG.

RESULTS AND DISCUSSION

PAR Reduction in Shade

Average reduction in PAR significantly varied ($P \leq 0.05$) among the six evaluated tree species. Bald cypress, little leaf, linden, and American sycamore had the greatest PAR reduction, near 90% (Fig. 4.1). Lacebark elm and shortleaf pine had significantly lower PAR reductions of 76 and 77%, respectively (Fig. 4.1). Water oak did not have significant differences in PAR reduction compared to the other evaluated tree species. These differences in PAR reduction can be attributed to the differences in leaf texture and density allowing variable amounts of PAR light to reach the ground beneath the canopy. The lone evergreen species in this trial, shortleaf pine, differed in average PAR reduction compared to three of the five evaluated deciduous trees. This report is contrary to previous observations reporting no differences in PAR reduction between deciduous and conifer tree species (Bell and Danneberger, 2000). Bell and Danneberger (2000) observed PAR reduction over an entire 24-hour period while this study was a single measurement at one time point. In addition, the previous study evaluated only three tree species in comparison to the six species evaluated in this trial. The larger sample size provided additional species comparison that possibly resulted in greater disparity in PAR reduction among tree species.

Spectrum PAR Meter Accuracy

Comparison of measurements from the Spectrum Quantum LightScout meter and the LI-COR 1-meter quantum light meter indicated significant ($P < 0.05$) correlation between the two meters. A Pearson correlation coefficient of 0.84 across all evaluated tree shade species represents a significant linear relationship between the Spectrum and LI-COR meters. To assess accuracy of the Spectrum meter, a model to predict PAR light from the Spectrum meter from measurements using a calibrated LI-COR meter was developed through linear regression analysis. According to the model, the intercept of 25.15 and slope of 0.51 indicate that measurements from the LI-COR meter would result in lower measurements if using the Spectrum meter (Fig. 4.2). The model was able to explain 72% of the variation in measurements between the two meters (Fig. 4.2). It is important to note that the model includes observations from all evaluated tree species. The differences in leaf density and texture could be an unexplained source of variation within the model. Additionally, measurements with each device were not taken at the exact same time, and shifting tree limbs could cause shade levels to change. Further, the LI-COR meter averaged readings across four sensors placed along the 1-m length of the meter and could have varied in light detection due to the Spectrum meter obtaining a single reading from one sensor. In addition, variation between the two meters becomes greater when PAR light totals exceed greater than 500 µmol (Fig. 4.2). These observations greater than 500 µmol are representative of measurements taken near the edge of the shade canopy and in non-shaded conditions. Despite the variation within the model, the following data were obtained under the assumption that the Spectrum meter was accurately measuring PAR light under various tree species shade canopies.

Correlation of Light Meters to PAR

Across all tree species, the Spectrum meter measuring footcandles had the greatest Pearson correlation value to PAR light measurements from the Spectrum meter and the "Light Meter" phone application measuring lux had the lowest (Table 4.2). This high correlation of the Spectrum meter measuring footcandles was expected due to the footcandle and PAR light sensors being present on the same device. By using the same device, measurements of PAR and footcandles were obtained in identical time and space. Correlation of readings from each light measuring device to PAR light measurements also varied by tree species (Table 4.2). All devices resulted in significant Pearson correlation coefficients for each tree species, except shortleaf pine. The “Light Meter” phone application correlation coefficients of 0.14 for footcandles and 0.12 for lux on shortleaf pine indicate that measurements using the application were not able to significantly correlate with PAR light measurements (Table 3.2). The irregular shade patterns of shortleaf pine and flecking of radiation through the canopy between evaluations could have resulted in this discrepancy.

Estimating PAR with Light Meters

Analysis of covariance indicated that separate models to predict PAR light were necessary (P <0.05) for each light measuring device and tree species. Explained variation in the individual PAR prediction models ranged widely from 2 to 99% (Fig. 4.3-7). The wide range of explained variation resulted in inconsistent degrees of accuracy based off of 95% prediction limits for each tree species and light measuring device (Fig. 4.3-7). For example, the Spectrum footcandle meter was able to predict PAR light within ~10 µmol for littleleaf linden, but could only predict PAR for lacebark elm within ~450 µmol (Fig. 4.5). These results indicate that accuracy of PAR light estimation from total visible light measuring devices is limited to certain tree species that have developed models with sufficient degrees of explained variation as defined by the end user.

CONCLUSIONS

Based on the complexity and inconsistency of predictive models for each tree species, using a photometric meter quantifying visible light to estimate PAR results in a tedious process based on the methodology utilized in this study. Continual measurement of light quantities over time instead of single measurements in time that was used in this study has the potential improve model accuracy. Additional testing on other tree species and light meters would also be recommended to improve accuracy. The results of this study indicate that if turfgrass managers wish to perform onsite PAR evaluations, investment in a PAR quantum light meter is worthwhile.

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Table 4.1. Light measuring devices utilized to quantify PAR and total visible light reduction under tree shade canopies.

Meter	Model	Units Measured
Quantum light meter	LightScout Quantum and Footcandle Light Meter	PAR, footcandles
1-m line quantum line sensor	LI-COR Line Quantum Meter	PAR
General purpose light meter	Extech Footcandle/Lux Light Meter	Footcandles, lux
Light meter phone application	"Light Meter" Phone Application	Footcandles, lux

Table 4.2. Pearson correlations coefficients of PAR light measurements from a Spectrum LightScout quantum light meter under six tree species to three total light measuring devices: Spectrum Light Scout footcandle meter (footcandles), general purpose light meter (footcandles and lux), and “Light Meter” phone application (footcandles and lux). * indicates correlation significance ($P \leq 0.05$) with the Spectrum LightScout quantum light meter.

	Pearson Correlation Coefficients – PAR Light				
	Light Meter (footcandles)	Phone App. (footcandles)	Spectrum (footcandles)	Light Meter (lux)	Phone App. (lux)
All species	0.76*	0.71*	0.94*	0.79*	0.63*
American sycamore	0.84*	0.50*	0.99*	0.94*	0.58*
Bald cypress	0.61*	0.75*	0.89*	0.89*	0.60*
Lacebark elm	0.80*	0.62*	0.65*	0.87*	0.46*
Littleleaf linden	0.47*	0.66*	0.99*	0.74*	0.76*
Shortleaf pine	0.69*	0.14	0.98*	0.66*	0.12
Water oak	0.75*	0.70*	0.97*	0.89*	0.60*

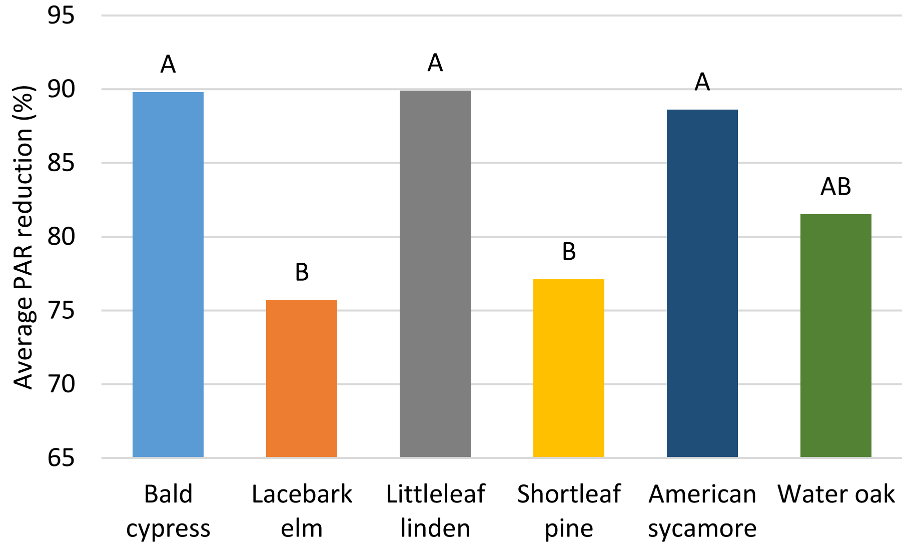

Figure 4.1. Average PAR reduction under canopies of six tree species for one date in 2016 and 2017 within one month of the summer equinox. Bars that share a letter are not significantly different using Fisher's protected LSD at $\alpha = 0.05$.

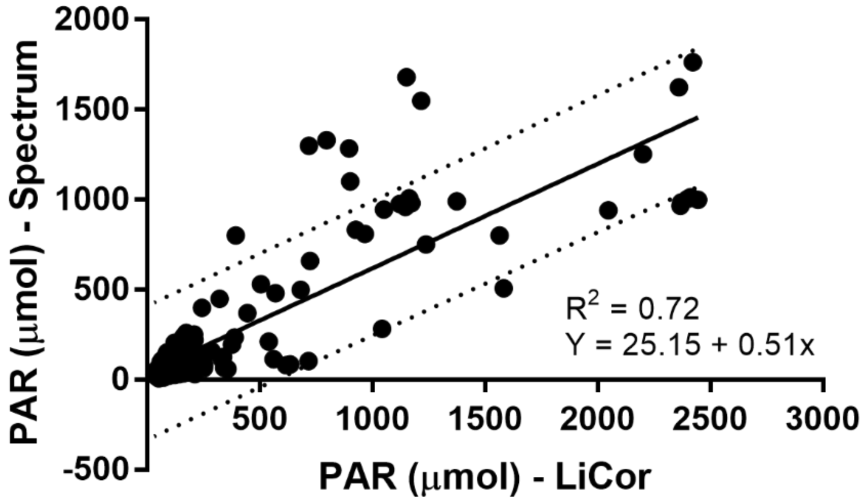

Figure 4.2. Linear regression model to evaluate accuracy of a Spectrum LightScout quantum light meter to measure PAR light compared to measurements obtained from LI-COR 1-m line quantum light meter under shade canopies of six tree species. Dashed lines represent 95% prediction intervals.

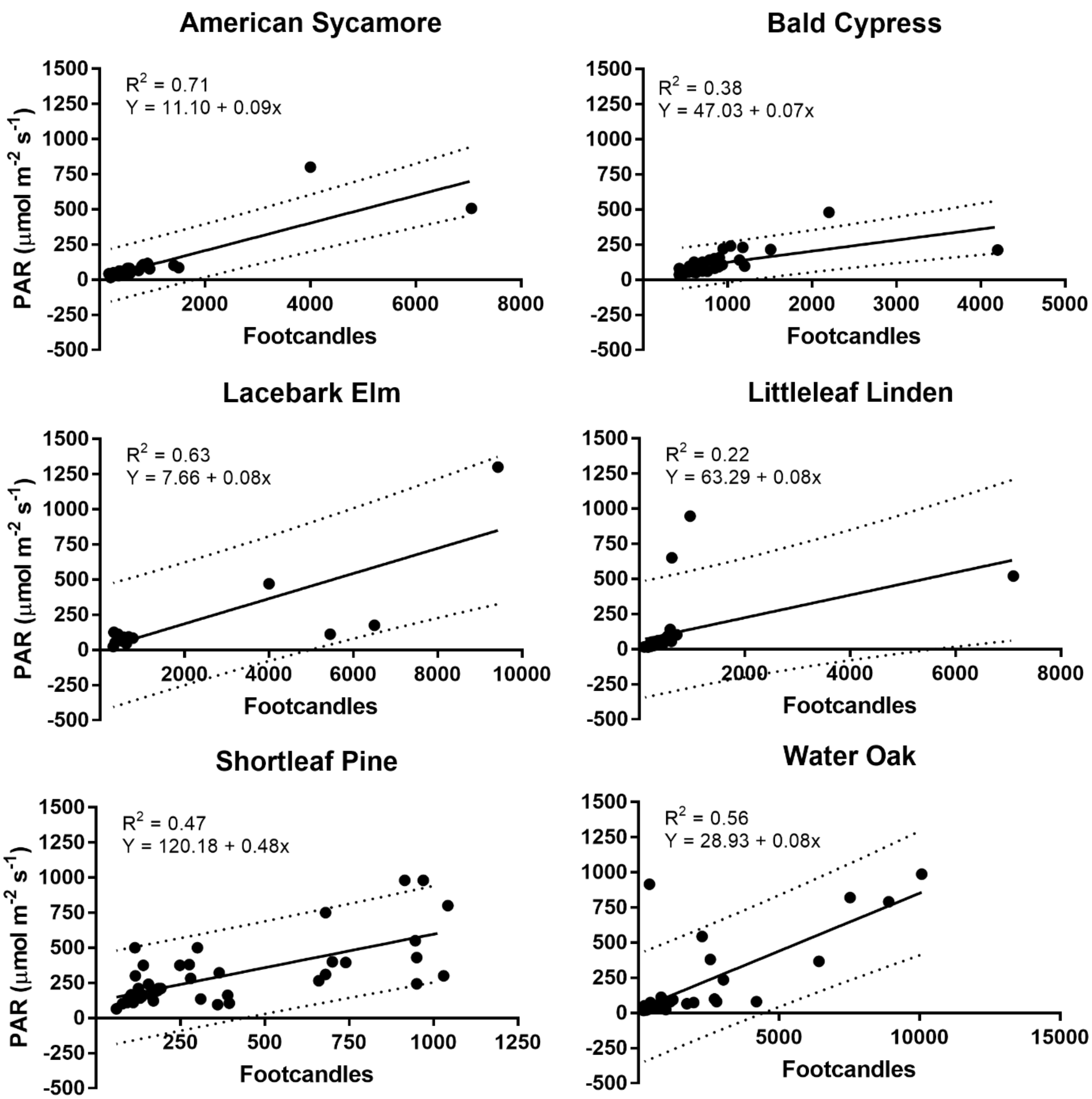

Figure 4.3. Linear regression models for a general purpose light meter measuring visible light footcandles to predict PAR light measurements from a Spectrum LightScout quantum light meter for six tree species. Dashed lines represent 95% prediction intervals.

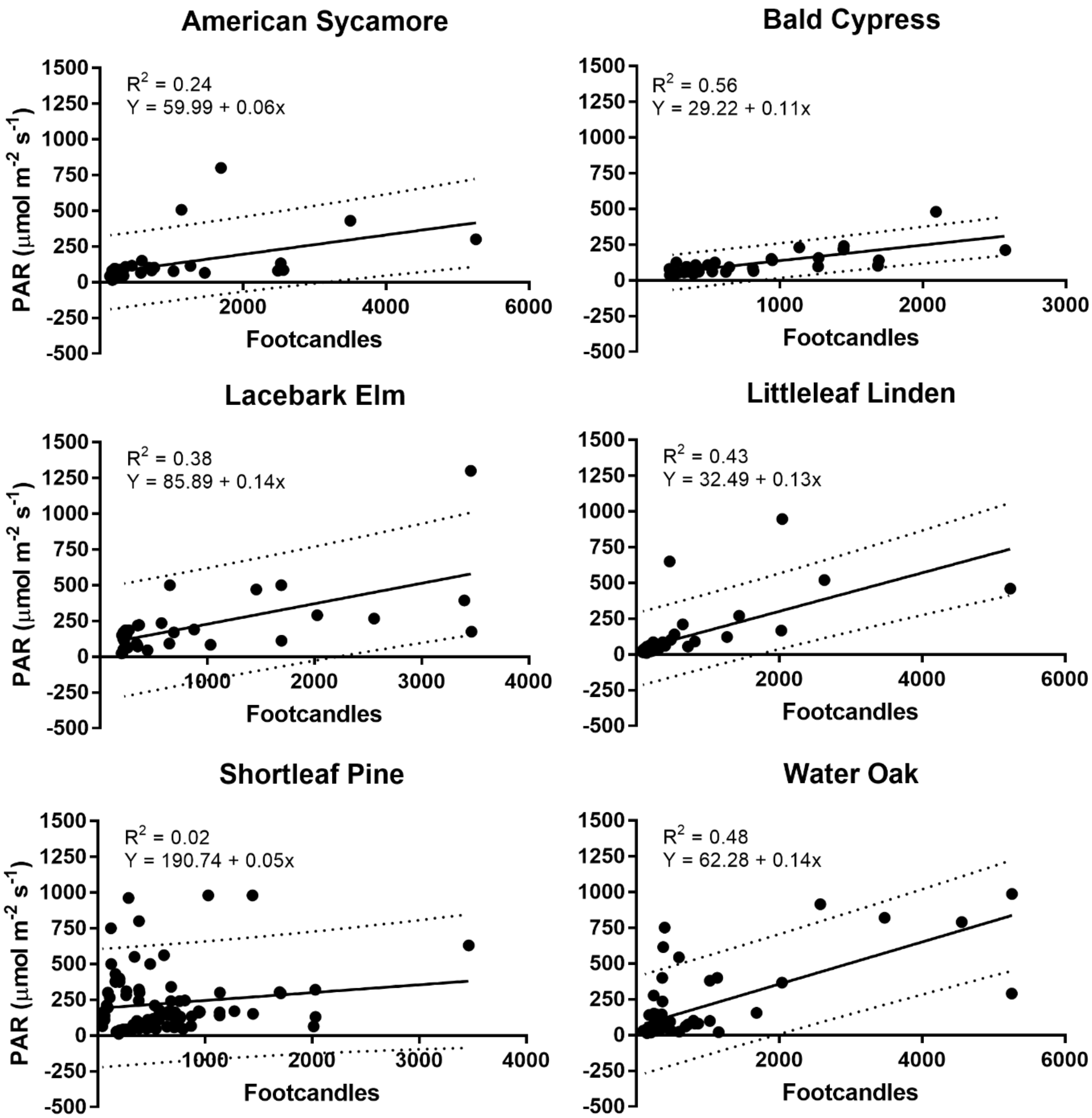

Figure 4.4. Linear regression models for the "Light Meter" phone application measuring visible light in footcandles to predict PAR light measurements from a Spectrum LightScout quantum light meter for six tree species. Dashed lines represent 95% prediction intervals.

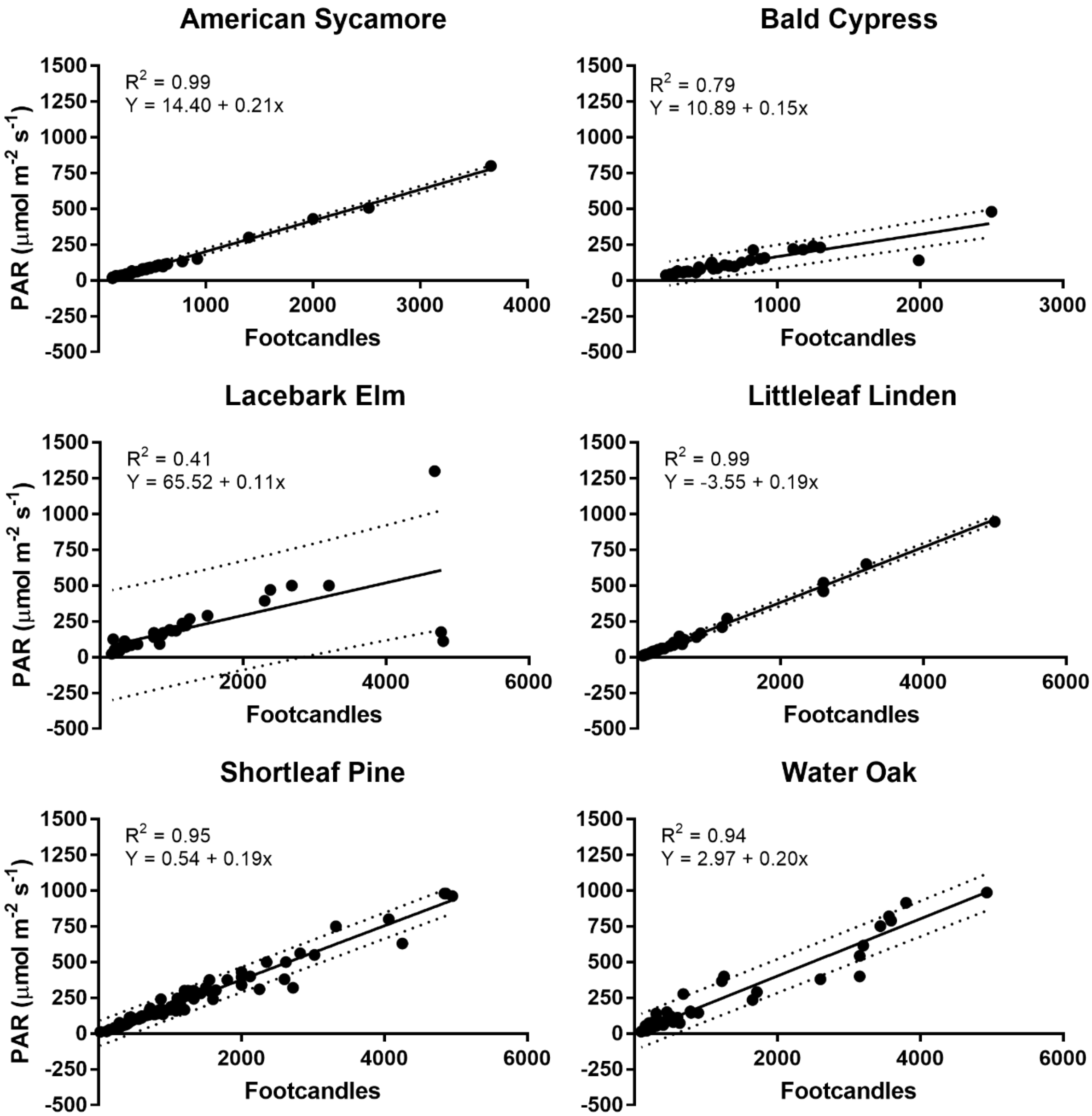

Figure 4.5. Linear regression models for the Spectrum Light Scout measuring visible light in footcandles to predict PAR light measurements from a Spectrum LightScout quantum light meter for six tree species. Dashed lines represent 95% prediction intervals.

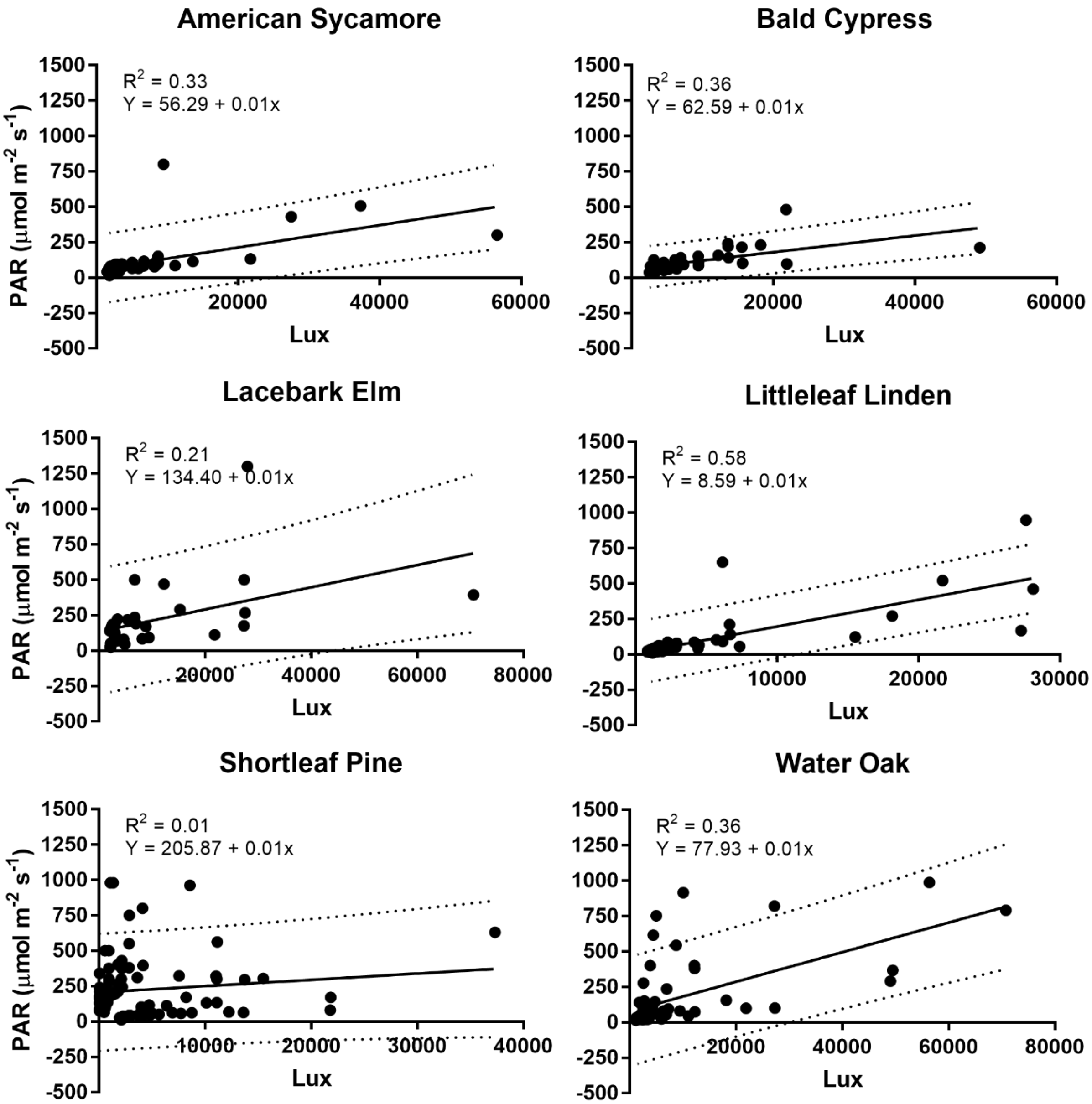

Figure 4.6. Linear regression models for the "Light Meter" phone application measuring visible light in lux to predict PAR light measurements from a Spectrum LightScout quantum light meter for six tree species. Dashed lines represent 95% prediction intervals.

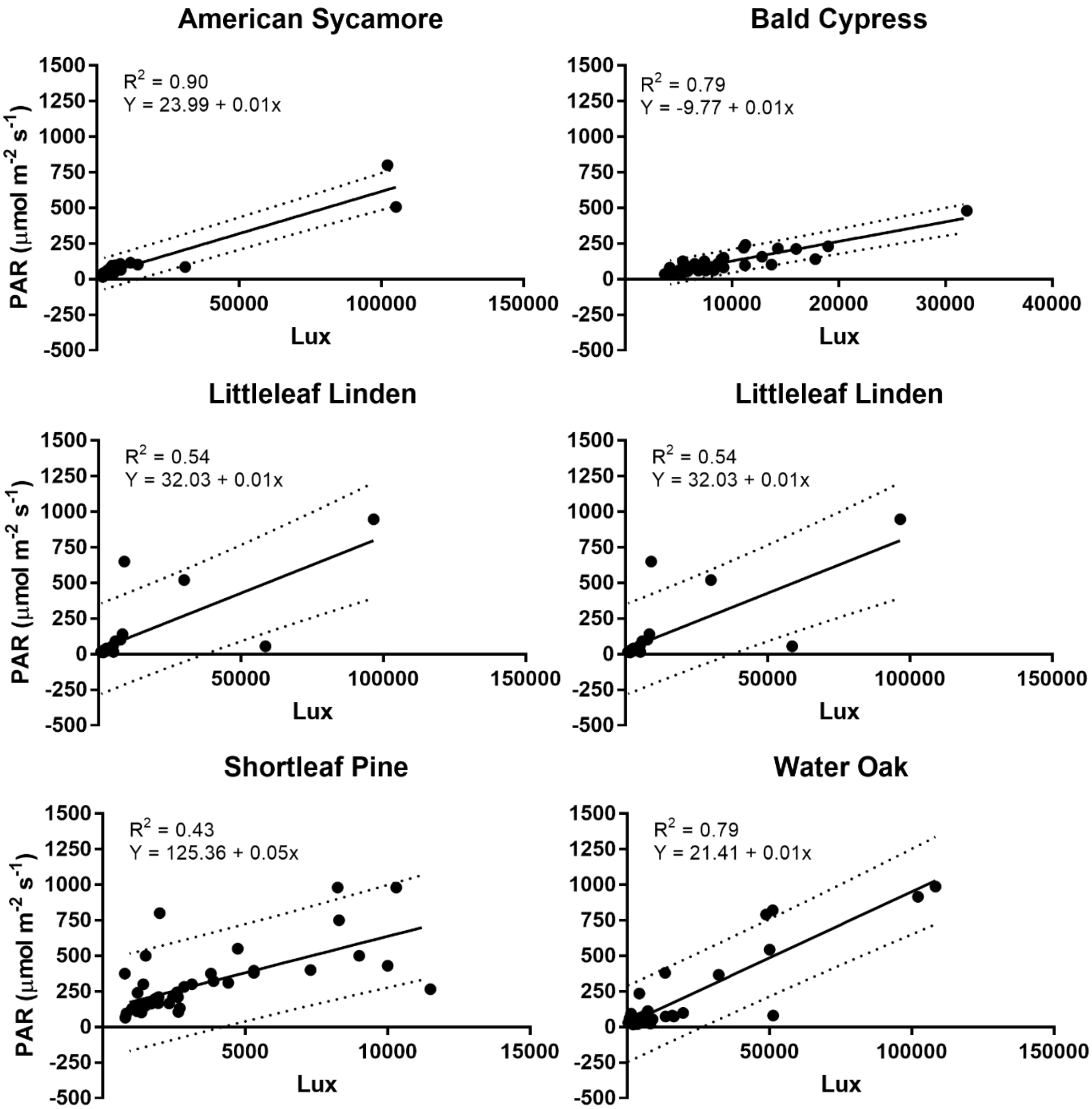

Figure 4.7. Linear regression models for a general purpose light meter measuring visible light in lux to predict PAR light measurements from a Spectrum LightScout quantum light meter for six tree species. Dashed lines represent 95% prediction intervals.

CONCLUSIONS

Maintaining acceptable quality and coverage of turfgrasses grown in shaded environments remains an important component of the responsibilities of turfgrass practitioners. These studies aim to lend a more thorough understanding to the effect of shade on turfgrass systems and necessary light quantities to sustain growth. In order to guide agronomic decisions for shaded turfgrass, studies were designed to determine precise light requirements of common turfgrasses found on golf courses in the transition zone. A two year field study was established to determine the minimum daily light integral to maintain acceptable creeping bentgrass putting greens by evaluating the effect of various shade intensities, shade timings, and chemical applications on turf quality. Turfgrass managers who manage creeping bentgrass putting greens can utilize the daily light integral requirement developed in this study as a baseline for assessing light conditions at their respective facilities and altering cultural practices to ensure optimal growth conditions for turf under shade.

Contributing to the growing scientific literature on precise light needs of warm-season turfgrass types, a second two-year field study determined the minimum DLI requirements of four warm-season turfgrasses. In addition to establishing these minimum DLI requirements, a method for efficient determination of minimum DLI thresholds in an established landscape was investigated. The method was successful at accurately estimating the critical DLI requirement of two of the four turf types based on DLI requirements obtained in a controlled research setting. Modification of this method to improve accuracy will be beneficial to turfgrass managers who wish to perform site specific analysis of light needs.

To further encourage the adoption of daily light integral measurements among turfgrass managers, affordable total light meters were evaluated for their effectiveness to estimate photosynthetically active radiation (PAR) beneath various tree canopies. After evaluation, the PAR quantum light meter remains the standard for assessing PAR available to turfgrass under tree canopies.

Collectively, these studies have provided important scientific information regarding the effect of shade on turfgrass systems and quantifying precise light requirements to maintain acceptable quality. These studies have brought forth additional research questions worth investigating regarding turfgrass shade tolerance. Improving upon these studies among turfgrass researchers is encouraged to more effectively and accurately determine light requirements of turfgrass.