METHODS FOR ANALYZING SHADE TOLERANCE IN WARM SEASON TURFGRASSES

by

JONATHON FOX

(Under the Direction of Brian M. Schwartz)

ABSTRACT

Improving shade tolerance is of great importance in the development of new bermudagrass cultivars. Current methods for studying shade tolerance in the field can be very time consuming. The objectives of this study aim to compare shade tolerance of new genotypes to commercially available cultivars using a traditional field study method, and to use this knowledge to verify a potentially new and more efficient method of quantifying shade tolerance in turfgrass. The first method compared the turf performance of experimental genotypes and cultivars for bermudagrass, St. Augustinegrass, and zoysiagrass grown under 73% shade from 2014 through 2017. The second method examined light compensation points, among other traits, of the shade tolerant experimental genotype 11-T-56 and non-tolerant Tifway bermudagrass. Results indicated genetic improvement for maintaining turfgrass cover in the shade has been made with the experimental bermudagrass and St. Augustinegrasses, and that light compensation points predicted shade tolerance during spring dates.

INDEX WORDS: Shade, warm-season turfgrass, *Cynodon*, bermudagrass, St.Augustinegrass, *Stenotaphrum*, *Zoysia*, zoysiagrass, light response curve, light compensation point, dark respiration, chlorophyll fluorescence, chlorophyll content, dark green color index (DGCI)

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DEDICATION

I would like to dedicate this work to my loving fiancée Paige. Thank you for all of your support and kindness.

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CHAPTER 1

ANALYZING GROWTH HABITS OF WARM SEASON TURFGRASSES UNDER SHADE STRUCTURES

LITERATURE REVIEW

Shade cast by trees or structures can negatively influence turf growth and development in bermudagrass (*Cynodon* spp.), St. Augustinegrass (*Stenotaphrum secundatum*), and zoysiagrass (*Zoysia* spp.) An estimated 20 to 25% of the turf managed in the United States is grown in shaded conditions (Beard, 1973). Shade problems are enhanced in older residential areas as trees grow and mature, creating a closed canopy. Construction of large buildings and stadiums can cause greater stress if sunlight is completely blocked for long periods during the day (Beard, 1997).

Reduced light intensity can cause a number of deleterious morphological and physiological responses. These include increased leaf length, decreased specific leaf weight, thinner leaf blades, decreased photosynthesis, decreased carbohydrate production, reduced lateral stem growth, and reduced turf quality and cover (Burton et al., 1959; Trappe et al., 2011; Winstead and Ward, 1974; Zhang et al., 2017). Shaded microenvironments with longer dew periods and higher humidity can also enhance the risk of disease occurrence (Beard, 1965).

Bermudagrass is a very popular turfgrass choice for utilization in the southern United States, especially for full sun applications. It is known for its fast establishment rates, heat and drought resistance, wear tolerance, and recuperative potential (Beard, 1973). However, most bermudagrass cultivars are more sensitive to shade than other warm-season species such as

zoysiagrass (Baldwin et al., 2009; Zhang et al., 2017). McBee and Holt (1966) found that increasing shade pressure caused bermudagrass canopies to become etiolated. They also found genotypic differences within turfgrass species in terms of stem elongation and reduced turf density within shaded environments, and deemed it necessary to study them individually. Bunnell et al. (2005a) found that both morning and afternoon shade differentially affected the turfgrass quality (TQ) of 'TifEagle' bermudagrass, with afternoon shade potentially being more detrimental than morning shade. Most studies have concluded that bermudagrasses have a low tolerance of shaded environments, but Hanna et al. (2010) demonstrated that with directed breeding efforts and new screening techniques, shade tolerance can be improved in new bermudagrass cultivars. They identified 'TifGrand' as a shade tolerant bermudagrass cultivar after over 10 years of shade tolerance research. This new cultivar maintained acceptable turfgrass quality ratings (7 and 8) in up to 70% shade during 2003 and 2004.

St. Augustinegrass can be found in tropical areas near coastlines because it has salt tolerance, excellent heat tolerance, and is documented to be one of the most shade tolerant warm-season turfgrass species (Beard, 1973). When evaluating St. Augustinegrass at shade levels exceeding 60%, Trenholm and Nagata (2005) and Zhang et al. (2017) noted acceptable turfgrass visual quality ratings. Cai et al. (2011) found that a newer cultivar, 'Captiva', maintained acceptable turf quality scores when subjected to 50% shade in their greenhouse study during 2009 and 2010. An experimental genotype (PI 600734) had a higher TQ rating (7.2) than the reported shade tolerant cultivar, Captiva (6.3) at 32% photosynthetic photon flux (PPF) and an equal TQ at 15%PPF (Wherley et al., 2013).

Zoysiagrass is popular throughout many parts of the United States because of its wide adaptability. Zoysiagrass can have a dense leaf canopy, heat and drought tolerance, winter

hardiness, and higher tolerance of shade than most other warm-season turfgrass species (Baldwin et al., 2009; Beard, 1973; Patton, 2009; Zhang et al., 2017). Well established 'Diamond' zoysiagrass subjected to various shade treatments (0, 47%, 73%, and 87%) maintained acceptable turf quality at up to 73% shade (Qian and Engelke, 2000). Breeding for improved shade tolerance in zoysiagrass remains a priority even though it is more adapted to low-light environments than many other species. Qian and Engelke (1997) demonstrated that the experimental grasses TAES4373 and TAES4377 have improved shade tolerance when compared to commercial cultivars ('Palisades', Diamond, and 'Jamur'). In a 12 week evaluation of zoysiagrass grown under 0%, 50%, and 90% shade, Sladek et al. (2009) classified the newer cultivar 'ShadowTurf' as having improved shade tolerance after discovering its ability to maintain acceptable turf quality in up to 50% shade. They did however, state that performance of all zoysiagrass genotypes in the study declined to an unacceptable quality when subjected to the 90% shade treatment. Zhang et al. (2016) performed a field study that evaluated six cultivars (ShadowTurf, Diamond, 'Emerald', JaMur, 'Empire', and 'Zorro') and two experimental genotypes (BA-305, later renamed as 'Taccoa Green', and BA-189) to 0% and 63% shade over one year and did not find a significant difference in green cover from the different treatments.

Currently, there are several methods used to mitigate the stress caused by shaded environments. With regards to the turfgrass, renovation of an area by planting new cultivars with improved shade tolerance is the most effective (Hanna et al., 2010) although it can be costly. As demonstrated by Bunnell et al. (2005a), raising the mowing height of bermudagrass in combination with application of trinexypac-ethyl can increase overall turf quality under shaded conditions. A common misconception is that increasing nitrogen fertilization will stimulate bermudagrass growth in the shade. Burton et al. (1959) found that 'Coastal' bermudagrass performed best under

shaded conditions with lower rates of nitrogen. High rates of nitrogen increased the protein content and reduced the total available carbohydrates from 12.4% to 7.4%. This reduction in carbohydrate reserves caused a decrease in plant density and leaf area. Another method commonly used to reduce shade stress is to selectively remove trees or tree limbs to allow more sunlight to reach the turfgrass canopy. By pruning tree limbs 3 m and below, wind movement can be increased to help reduce the incidence of fungal diseases that thrive in the cool and moist microenvironment typically found under dense tree shade (Beard, 1973). Traffic reduction can play a large role in keeping turf healthy under shaded conditions as well (Trappe et al., 2011).

OBJECTIVES

i. Compare the turf coverage, canopy height, and dark green color index (DGCI) of experimental genotypes against commercially available cultivars of bermudagrass, St. Augustinegrass, and zoysiagrass under 73% shade cloth.
ii. Determine if these traits are indicators of turfgrass persistence in the shade
iii. Assess whether genetic improvements for each of these traits has been made through breeding

MATERIALS AND METHODS

Plant Materials

Bermudagrasses studied were ‘Celebration’, ‘Latitude 36’, ‘Tahoma 31’, TifGrand, ‘TifTuf’, ‘Tifway’, and two experimental grasses from the University of Georgia. The St. Augustinegrasses were ‘Floratam’, ‘Palmetto’, ‘Raleigh’, five experimental grasses from Texas A&M, and four experimental grasses from North Carolina State University. The zoysiagrasses included Empire, Palisades, ‘Zeon’, four experimental grasses from Texas A&M, five experimental grasses from the University of Florida, and two experimental grasses from the University of Georgia (Table 1.1).

Experimental Design

This test took place at the University of Georgia Tifton Campus on Tifton loamy sand. The grasses were planted in the field during 2014 from single 26 cm^2 plugs that were vegetatively propagated in the greenhouse. The grasses were planted on 0.9 m centers with five replications of every genotype for each species. The experiment was designed as a randomized complete block and each plot was grown into a 0.9 m by 0.9 m plot. After planting the experiment, the grasses were promptly covered with mobile shade structures. The square metal frames of the structures are mobile with wheels that allow the structures to be moved as needed for routine turf maintenance. The frames are 9 m by 6.1 m in size and stand 0.3 m off of the ground in order to exclude the most amount of sunlight as possible while still allowing ample air movement (Trappe et al., 2011). A black shade cloth that produced 73% shade was spread over the frames. This was verified using a WatchDog 1000 series micro station paired with a LightScout 6 sensor quantum bar (Spectrum Technologies Inc., Aurora, IL) after the shade cloth was installed. The shade cloth was fastened to the structures with a Wiggle Wire® fastening

system (Poly-Tex, Castle Rock, MN). This system incorporates a bendable, stainless steel spring wire that seats into an aluminum U-channel base. This technique allowed the shade cloth to drape over the sides of the frames so that it shaded the plots properly. The plots were mowed every two weeks starting in May and continuing through November (the growing season for turfgrass in Tifton, GA). The bermudagrass and zoysiagrass were mowed at 5.1 cm and the St. Augustinegrass was mowed at 8.9 cm. During the summer months (May- August), all turfgrass species exhibited substantial vertical growth that led to scalping. To compensate for this, mowing heights were raised 1.3 cm for all grasses resulting in a height of 6.4 cm for bermudagrasses and zoysiagrasses, and 10.2 cm for St. Augustinegrasses. The plots were fertilized three times per year at 2.44 g N m^{-2} with 16-4-8 (Rainbow Plant Food, Loveland, CO). Plots were kept separate by spraying a 0.3 m border around each plot with glyphosate and mechanically removing rhizomes and stolons once per month. The shade cloths were removed on the day before the first freezing temperatures of the year (mid- November to December in Tifton, GA) to allow the grasses to undergo a normal dormancy stage.

Response Variables

Data was collected for turf coverage (%), leaf canopy height (cm), and DGCI. Turf coverage was quantified using digital image analysis (Richardson et al., 2001; Trappe et al., 2011). Images were taken once per month prior to mowing with a Canon PowerShot G5 (Canon, Tokyo, Japan) digital camera mounted to an enclosed photo box (0.31 m^2) with four 9-W compact fluorescent lamps (TCP; Lighthouse Supply, Bristol, VA). Each image was analyzed using SigmaScan Pro 5 (Systat Software Inc., Richmond, CA) under the macro "Turf Analysis" for turf coverage (0% to 100%) (Karcher and Richardson, 2005) using a hue range from 60-120 for bermudagrass and 55 to 120 for zoysiagrass and St. Augustinegass, and saturation range from

10 to 100 for all species. Leaf canopy height was recorded once per month prior to mowing by placing a meter stick in the center of the plot and recording the average height of the leaf canopy. As discussed by McBee and Holt (1966), turfgrass tends to have a more upright growth habit, (which is undesirable to turf managers) when exposed to shade. By measuring leaf canopy height, we were able to identify a more desirable, prostrate growth habit that is less susceptible to mower scalping. DGCI was calculated based on the hue (H), saturation (S), and brightness (B) output from the SigmaScan Pro analysis with the following equation:

DGCI value = $[(H - 60)/60 + (1 - S) + (1 - B)]/3$ (Karcher and Richardson, 2003).

Statistical Analysis

Before analysis, means for three seasons, Spring (March through May), Summer (June through August), and Fall (September through November) were calculated for every trait within each species separately and used for the analysis for all dependent variables. The distribution of data for turf cover, canopy height and DGCI were assessed with a histogram and normal probability plots. Square root transformations were used on datasets where conditions of normality were not met, including turf cover and canopy height for bermudagrass and zoysiagrass. No data transformations were used for St. Augustinegrass.

An analysis of variance was performed on each of the measured traits for each species independently. The General Linear Models (GLM) procedure in SAS 9.4 (SAS Institute, Cary, NC) using the appropriate error terms and assuming a mixed model with “years” and “genotypes” as fixed variables and “seasons” and “replications” as random variables was used for the analysis. Significant main effects were separated using the Waller-Duncan k-ratio LSD. Pearson correlation between all variables for each species was performed using Proc CORR in SAS.

RESULTS AND DISCUSSION

Turf Cover

Bermudagrass. Analysis of variance for turf cover of the eight bermudagrass genotypes (Table 1.1) over the three-year study yielded a significant genotype × year interaction (Table 1.2). Turf coverage was also analyzed separately for each year (ANOVA not shown). Careful inspection of genotypes over years revealed no considerable rank changes among genotypes, only slight differences in turf cover of Latitude 36 and Tifway during 2015 and 2016. Even though the interaction was significant, each of these genotypes remained in the same statistical ranking. Therefore, the combined analysis will be presented (Table 1.3).

The experimental genotype 11-T-56 was the top performing bermudagrass genotype for turf cover (39.6%) for the duration of the experiment. It maintained significantly higher turf coverage under the shade cloth than both TifTuf and Celebration at 31.0 and 30.7%, respectively. Tahoma 31 had slightly less turf cover (25.3%) but was higher than TifGrand (19.5%). Latitude 36 and Tifway performed similarly with turf coverages of 13.5 and 11.8%, respectively but greater than the experimental genotype UGB-118, which had the lowest turf cover of 3.7%.

Warm-season turfgrasses respond differently when subjected to shaded conditions (Beard, 1973; Winstead and Ward, 1974; Zhang et al., 2017). Bermudagrass has consistently shown poor shade tolerance when compared to other warm-season turfgrass species (Baldwin et al., 2009; Bunnell et al., 2005b; J. Trappe et al., 2008). There has been improvement of shade tolerance in recent years due to new cultivar development. Hanna et al. (2010) reported that ST-5, later released as TifGrand, exhibited higher TQ in 2003 and 2004 than both Tifway (4.1 to 5.5) and ‘TifSport’ (3.8 to 5.5), by maintaining acceptable ratings ranging from 6.1 to 8.4 under 70% continuous shade through the months of June to October. Bunnell (2005b) found that

Celebration had the highest turf quality (7.2) when compared to other bermudagrass genotypes such as Tifway (5.9) grown under 71% shade, which corresponds to the turf coverage rankings in this study for these cultivars (Table 1.3). All cultivars maintained significantly lower turf coverage than the new experimental genotype 11-T-56, therefore genetic improvement of bermudagrass turf cover in the shade has been achieved.

St. Augustinegrass. A significant genotype × year interaction ($P \leq 0.01$) was detected from an analysis of variance for turf cover of all St. Augustinegrass genotypes included in this study (Table 1.2). Turf coverage was analyzed separately for each year (ANOVA not shown). After careful investigation, the interaction was likely only caused by slight rank changes among eight genotypes in the different seasons. Therefore, the analysis of turf cover over years and seasons is presented in Table 1.3.

NCS-150 from NC State had the numerically highest turf coverage (71.1%) of all other genotypes included in this study, but was statistically similar with NCS-156 (68.0%) and NCS-153 (66.5%) (Table 1.3). Experimental genotypes Dalsa-1404 (63.4%), NCS-155 (62.3%), Dalsa-1318 (61.9%) and Dalsa-1405 (61.7%) all performed within the same statistical group as NCS-156 and NCS-153. Dalsa-1316 and Dalsa-1401 had similar turf coverages (52.1% and 43.3% respectively) to Palmetto (45.8%) throughout the entire study. Raleigh and Floratam had the lowest turf coverage (27.5% and 23.3% respectively) of all other St. Augustinegrass genotypes evaluated in 2015, 2016, and 2017.

Previous reports have classified St. Augustinegrass as one of the most shade tolerant warm-season turfgrass species (Beard, 1973), though some zoysiagrass genotypes have been reported to be comparable (Zhang et al., 2017). Trenholm and Nagata (2005) evaluated five St. Augustinegrass cultivars at 0, 30, 50, and 70% shade levels in a glasshouse in two sequential

trials. Using a predictive regression analysis, they determined that Palmetto maintained acceptable turf quality at 68% shade in the first trial but was unacceptable at shade levels greater than 30% in the second trial. Floratam only expressed acceptable turf quality in the first year of their study, in conditions of 56% shade or less, indicating that Palmetto is more shade tolerant than Floratam. These results agree with our findings that Palmetto maintained higher turf cover (45.8%) than Floratam (23.3%) over three years under 73% shade. In our research, Palmetto maintained greater turf cover than Raleigh (27.5%), in contrast to the findings of Wherley et al. (2013) who reported that Raleigh maintained higher turf coverage (61.1%) than Palmetto (52.6%) under 68% shade. All three of these commercially available cultivars sustained turf coverages in lower statistical categories when compared to newly bred experimental genotypes (Table 1.3), indicating genetic improvement of St. Augustinegrass for persistence in shaded conditions has been made.

Zoysiagrass. All main and interaction effects were found significant according to the overall analysis of variance for turf cover in the zoysiagrass genotypes (Table 1.2). Further assessment of turf coverages in each year revealed that changes among the genotypes as the experiment progressed were not consistent. Seasonal difference among the zoysiagrasses was generally not as important or telling (ANOVA not shown); therefore, genotypic means from individual years but combined over seasons are presented (Table 1.4).

Turf cover for all genotypes was numerically lower while they were establishing in 2015 than in any other year of the experiment (Table 1.4). The experimental genotype Dalz-1409 from Texas A&M University had the numerically highest turf coverage (29.5%) and was statistically similar to UFZ-1306 (29.3%), Dalz-1310 (25.7%), Dalz-1311 (25.6%), Dalz-1410 (24.6%), and Palisades (24.4%). 09-TZ-53-20, UFZ-1305, and 09-TZ-54-9 each had similar turf coverage

(23.0%, 22.7%, and 21.6%, respectively) to Palisades and Empire (20.1%) in 2015. UFZ-1252 (17.7%) had similar turf coverage to Empire and Zeon (14.7%) during the beginning of this study where UFZ-1307 (13.6%) had the lowest turf cover, performing similarly to Zeon.

The range of percentage increase in turf coverage for all zoysiagrass genotypes during 2016 was 40 to 207% (Table 1.4). Experimental genotypes 09-TZ-53-20 and 09-TZ-54-9 from the University of Georgia had the most turf coverage (56.1% and 54.1%, respectively), increasing 144% and 150%, respectively, from the previous year. In addition to these two genotypes, UFZ-1305, UFZ-1201, UFZ-1252, and Zeon displayed turf cover increases of over 100% (110%, 128%, 144%, and 186%, respectively). Although UFZ-1307 displayed the highest percentage increase (207%), it was still among the lowest with a coverage (41.7%), similar to the zoysiagrass cultivar Empire (37.9%) in 2016.

By the conclusion of the study in 2017, changes in turf cover for all genotypes had stabilized compared to previous years. UFZ-1201, an experimental genotype from the University of Florida, displayed the highest turf coverage (57.7%) with one of the largest increases in turf coverage (24%) from the previous year. Experimental genotypes 09-TZ-54-9, UFZ-1305, 09-TZ-53-20, Dalz-1310, UFZ-1252, and Dalz-1409 all had turf coverages (56.4%, 53.9%, 53.4%, 52.3%, 50.8%, and 49.7%, respectively) within the top statistical ranking, which were similar to both Palisades (56.3%) and Zeon (50.8%). All zoysiagrass genotypes displayed slight increases in turf cover from the previous year, ranging from 4% to 29%, except 09-TZ-53-20 (-5%), UFZ-1306 (-22%), and UFZ-1307 (0%). The 22% decrease observed for UFZ-1306 also resulted in the lowest turf cover (32.1%) of all other genotypes at the conclusion of the trial.

This research trial was planted in the early fall of 2014, which in-part explains lower observed turf coverages during 2015 since zoysiagrass typically has a slow establishment rate

(Beard, 1973; Busey and Myers, 1979). Patton et al. (2007) reported on the establishment rates of thirty-five zoysiagrass cultivars and genotypes at 59 DAP, and 91 DAP in the field under full sun during 2004 and 2005. Although not in the shade, they found that Palisades had the fastest establishment rate, similarly to what we observed in our research during 2015. However, their findings suggested that Zeon established slightly faster than Empire, contrasting with our 2015 results, possibly indicating that Empire is more shade-tolerant than Zeon in the Tifton, GA environment. Wherley et al. (2011) found that Palisades was able to effectively maintain higher turf quality (3.8, 2.3, and 2.8) over a three year evaluation compared to Zeon (3.4, 2.2, and 2.4) when grown under 89% shade. They also included newer cultivars such as ShadowTurf (2008) that outperformed both Palisades and Zeon, although Zhang et al. (2017) found that ShadowTurf and Empire maintained similar turf cover (67.4% and 66.4%, respectively) in research conducted in the Southeastern United States.

Canopy Height

Bermudagrass. The overall analysis for canopy height of all bermudagrass genotypes detected a significant ($P \leq 0.05$) genotype × season interaction (Table 1.2). This warranted further analysis of each season separately (ANOVA not shown), revealing that genotypes performed statistically similar during the fall and summer. Minor rank changes in TifGrand, Tahoma 31, and Celebration during the spring season likely caused the significant interaction, but it was determined that these were not biologically important differences. Therefore, a combined analysis that included both season and year (Table 1.3) was utilized to determine differences in canopy height.

11-T-56, the experimental genotype from the University of Georgia, was the most compact genotype of all the bermudagrasses established under the shaded environment,

maintaining an average canopy height of 5.4 cm over the duration of the experiment. UGB-118 was also low-growing (6.7 cm), performing similarly to the cultivars Tahoma 31 (7.1 cm), TifGrand (7.1 cm), and Celebration (7.2). Latitude 36 had a mean height of 7.6 cm which was statistically similar to Tifway at 7.7 cm. TifTuf was the tallest cultivar in the study with a canopy height of 9.0 cm.

Researchers have documented that turfgrasses have a more upright growth habit with less turf density when they are exposed to shade (McBee and Holt, 1966; Wherley et al., 2013; Winstead and Ward, 1974). A more prostrate growth habit allows the plant to capture more light and incur less scalping of actively growing leaves (Tegg et al., 2004), although this was generally not the case for our study. Pearson correlation coefficients indicated a weak (0.179) but significant relationship ($P \leq 0.01$) between turf cover and canopy height (Table 1.5) even though the lowest growing bermudagrass 11-T-56 also displayed the highest turf cover. Baldwin et al., (2009) published an eight-week study on turfgrass reactions to different color shade cloths that all produced ~65% shade. They found that Tifway produced 50, 32, and 44% greater clipping yields at 2, 4, and 6 weeks respectively, than Celebration, indicating that Tifway became etiolated during the study. These two cultivars performed similarly in our test with Tifway (7.7 cm) maintaining a statistically equal canopy height to Celebration (7.2 cm) but taller growth habit than TifGrand (7.1), which is in agreement with Aldahir (2015) and Zhang et al. (2017).

St. Augustinegrass. An analysis of variance was conducted over years and seasons for the 11 selected St. Augustinegrass genotypes. Significant genotype × season ($P < 0.0001$) as well as genotype × year ($P \leq 0.01$) interactions were identified (Table 1.2). No significant genotype × year interactions were found when seasons were analyzed individually (ANOVA not shown). Further review of the individual analysis for the spring, summer, and fall revealed that most of

the genotypes performed very similarly throughout the seasons, except for Palmetto, Dalsa-1316, and NCS-155. Each of these genotypes had slightly different canopy heights throughout the year, which likely caused the significant genotype × season interaction in the combined analysis. These small changes were not biologically important enough to warrant the split analysis by seasons, so means over years and seasons are presented (Table 1.3).

The experimental genotype Dalsa-1401 from Texas A&M University, maintained the shortest canopy height (8.6 cm) during the study under 73% shade. Experimental genotypes NCS-150 (10.0 cm), NCS-153 (10.3 cm), NCS-155 (10.4 cm), Dalsa-1316 (10.5 cm), Dalsa-1405 (10.7 cm) and NCS-156 (10.9 cm) all performed similarly to Raleigh (10.2 cm) and Palmetto (10.6 cm). The canopy height of Dalsa-1404 grew similarly to Floratam with means of 11.4 cm and 11.9 cm, respectively. Dalsa-1318 had the tallest canopy height at 14.0 cm.

Canopy heights for Palmetto and Raleigh were similar (10.6 cm and 10.2 cm, respectively) in this study, each remaining shorter than some other experimental genotypes and Floratam (11.9 cm). Wherley et al. (2013) also found the leaf elongation rates of Palmetto and Raleigh to be very similar (5.6 $mm \cdot d^{-1}$ and 5.1 $mm \cdot d^{-1}$, respectively) but longer than those of newer experimental genotypes. Zhang et al. (2017) reported that Floratam had a numerically higher shoot biomass for spring, summer, and fall (2.5, 3.2, and 1.4g, respectively) compared to the newer cultivar Captiva (2.4, 2.4, and 1.0 g respectively), indicating that Floratam likely grows taller than other St. Augustinegrass genotypes. There has been limited research on the comparison of St. Augustinegrass canopy heights, with or without shade stress.

Zoysiagrass. Analysis of variance for canopy height of zoysiagrass yielded a significant genotype × year interaction ($P \leq 0.05$) as well as a significant genotype × season interaction ($P < 0.0001$) (Table 1.2). Canopy height was analyzed separately for each season (ANOVA not

shown). After examining genotypic canopy heights over the individual seasons, there were only slight changes in rank among the genotypes. Consequently, means for canopy heights over years and seasons will be discussed (Table 1.3).

The experimental genotype 09-TZ-53-20 maintained the lowest canopy height (4.9 cm) throughout the duration of the study. 09-TZ-54-9 was slightly taller (5.4 cm) but statistically shorter than the other zoysiagrasses. UFZ-1306 and UFZ-1201 had similar canopy heights (6.0 cm and 6.1 cm, respectively) to Zeon (6.3 cm). Empire was among the tallest grasses (8.6 cm), but Palisades had the highest (9.3 cm) canopy height of the three cultivars included in this research. The experimental genotype Dalz-1311 was the tallest experimental zoysiagrass included in the study (9.6 cm), performing similarly to Palisades.

Other research that included the evaluation of canopy height in the three zoysiagrass cultivars in our test under shade stress agrees with our results. Engelke and Qian (1997) found that Palisades had a taller growth habit (6.7 cm) than Zeon (2.4 cm) when exposed to 75% shade. In an evaluation of zoysiagrass genotypes under 89% shade, Wherley et al. (2011) was able to measure the vertical canopy extension of Palisades and Zeon. Their findings were similar to our study in that Palisades was consistently taller (20.0 cm and 22.3 cm) than Zeon (15.0 and 14.3) throughout the test in 2007 and 2008. Zhang et al. (2016) also came to similar conclusions by measuring clipping dry weights of zoysiagrass genotypes under 61% shade. They discovered Palisades to have a numerically higher clipping weight (5.9 g) than Empire (5.8 g) and Zeon (5.0 g). Our study demonstrates that newer genotypes can maintain lower canopy heights when grown in the shade.

DGCI

Bermudagrass. A significant genotype × season interaction was detected in the analysis of variance for DGCI (Table 1.2). When analyzed separately by season to identify the cause of the significant interaction (ANOVA not shown), it was determined that slight rank changes within the median statistical group likely caused the interaction. These seasonal trends were determined unimportant, so the data was analyzed as a combined set of years and seasons (Table 1.3).

Celebration and 11-T-56 were the darkest green genotypes of all the bermudagrasses in this trial with mean DGCI of 0.7933 and 0.7869, respectively, closely followed by UGB-118 (0.7760). Tahoma 31 performed similarly to TifTuf in terms of color with DGCIs of 0.7173 and 0.7100, respectively. Tifway and Latitude 36 were categorized in the same statistical group as the lightest green (0.7018 and 0.7011, respectively) of all of the genotypes evaluated in this study.

Dark green colored leaves are generally considered preferable to light green or yellow in all turfgrass species (Morris, 2012). This study uses DGCI to quantitatively define dark green color where most turfgrass shade studies use a visual rating of 1 to 9. Winstead and Ward (1974) published evidence that darker green turfgrass leaves could be correlated with increased shade tolerance in their studying of chlorophyll content in 'Tiflawn' bermudagrass and a St. Augustinegrass genotype. Both Tiflawn and the St. Augustinegrass genotype exhibited numerically higher chlorophyll contents in the shade (1.58 and 0.86 mg g^{-1}, respectively) compared to the plots grown in the sun (1.4 and 0.65 mg g^{-1}, respectively) indicating that both species were darker in color. Both our research and Hanna et al. (2010) determined that TifGrand has significantly darker green color than Tifway, potentially explaining its increased shade

tolerance. Alternatively, TifTuf is among the lightest green cultivars in our study (0.7100), yet it was the second highest-ranking genotype for turf coverage (31.0%). Research to determine the relationship between turfgrass color and DGCI is lacking in shade studies. A significant ($P <$ .0001) correlation between DGCI and turf cover was found in our study; although it was low (0.340), indicating the need for further evaluation of the importance of dark green color and chlorophyll content for turfgrass persistence in the shade (Table 1.5).

St. Augustinegrass. In the analysis over years and seasons for DGCI among the selected St. Augustinegrass genotypes, significant genotype × season ($P \leq 0.01$) and genotype × year ($P \leq 0.05$) interactions were found (Table 1.2). In the analysis split by seasons (ANOVA not shown), slight rank changes in DGCI were identified throughout all years with most genotypes, though each consistently ranked within the same statistical groupings. It was determined that presenting separately would not add to the discussion, so data are presented as means over years and seasons (Table 1.3).

Experimental genotypes from NC State, NCS-155 and NCS-156, along with the cultivar Floratam, had the darkest green canopies (0.6950, 0.6926, and 0.6908, respectively) of the study. NCS-150 was numerically the darkest green experimental genotype (0.6667) of a grouping of five that were statistically similar to both Raleigh (0.6761) and Palmetto (0.6627). Dalsa-1316 was considered the lightest green (0.6361) genotype among this set of St. Augustinegrasses.

Captiva, which exhibited acceptable turf quality ratings when exposed to shaded conditions up to 50 and 60% (Wherley et al., 2013; Zhang et al., 2017), also received acceptable turf color ratings (6.1) in up to 70% shade (Cai et al., 2011). Zhang et al. (2017) found that Captiva and Floratam performed similarly for turf quality when exposed to 33, 61, and 92% shade, indicating that Floratam had acceptable turf color as well. Trenholm et al. (2011)

classified Floratam as “dark green”, Raleigh as “medium green”, and Palmetto as “lighter green”, exactly as digital image analysis ranked these cultivars in our study. The Pearson correlation coefficients for St. Augustinegrass detected a significant negative relationship ($P < 0.0001$) between canopy height and dark green color (-0.265), indicating that the newer, taller leaves were typically lighter green than the more mature canopy underneath.

Zoysiagrass. An analysis of variance for all genotypes of zoysiagrass detected a significant ($P \leq 0.01$) genotype × season interaction (Table 1.2). Further analysis of each season separately (ANOVA not shown) revealed that most genotypes performed within the same statistical ranking throughout each season. The significant interaction was likely caused by Zeon and UFZ-1305 exhibiting a darker green color in the spring and Dalz-1310 and Dalz-1410 being darker green in summer and fall than in the spring. These few inconsistences were not enough to warrant the use of an analysis split by seasons, so overall means will be presented (Table 1.3).

The University of Florida experimental genotype, UFZ-1201, maintained the darkest green color (0.7402) throughout the three-year study and was similar to Empire (0.7321). Dalz-1310 (0.7289), 09-TZ-53-20 (0.7275), and 09-TZ-54-9 (0.7220) all had significantly similar color but were darker than Palisades (0.7129) and Zeon (0.7114). Experimental genotypes Dalz-1311 (0.7175), UFZ-1305 (0.7132), Dalz-1409 (0.7125), and UFZ-1306 (0.7080) generally had lighter green color than the experimental genotypes mentioned above but were similar to both Palisades and Zeon. UFZ-1307 had the lightest color (0.6919) throughout the duration of the study.

Engelke and Qian (1997) visually rated the turf color of many zoysiagrasses in their study grown under 75% shade and found that Zeon (8.4) was darker green than Palisades (8.0). Wherley et al. (2011) noted a wide range of genetic variability for leaf color throughout a three-

year study from 2007 to 2009. After subjecting ten zoysiagrass cultivars to 89% shade, they stated, “Each cultivar fluctuated from year to year with no one particular cultivar consistently outperforming the others.” Although, in 2007 and 2009, they found Palisades to be darker green (7.0 and 7.7, respectively) than Zeon (6.3 and 7.0, respectively) but equal in color (5.7) during 2008. Comprehensive research including the direct comparison of turfgrass color in a wide range of *Zoysia* spp. is not complete, with some studies contradicting each other.

CONCLUSIONS

Turf cover. Maintaining canopy cover is the primary goal for effectively growing turfgrass in the shade. This three-year study found general differences between specific phenotypic variation within each species for turfgrass cover when exposed to 73% shade. St. Augustinegrass and zoysiagrass both had several genotypes that we are able to maintain over 50% turfgrass cover at the conclusion of the trial, where the most established bermudagrass was under 40%. There were newly bred experimental genotypes in both bermudagrass and St. Augustinegrass that exhibited genetic improvement when compared to commercially available cultivars. 11-T-56 had significantly higher turfgrass coverage than all other bermudagrasses included in the study, as did NCS-150, NCS-156, and NCS-153 St. Augustinegrasses. Performance of the experimental zoysiagrass genotypes from several turfgrass breeding programs through 2017 does not indicate that there has been a significant improvement in the shade persistence within *Zoysia*. There does seem to be genetic differences in the speed at which newer zoysiagrasses with different phenotypes can initially spread by rhizomes and stolons when grown under 73% shade. Further research should be conducted to determine if juvenile growth is an indicator of real-world shade tolerance under shade cast by trees or structures.

Canopy Height. A low-growing turfgrass is generally considered preferable to one that is taller. Pearson correlation coefficients found significant relationships between canopy height and turf cover for bermudagrass (0.179), St. Augustinegrass (0.428), and zoysiagrass (0.541) (Table 1.5). Interestingly, the experimental bermudagrass genotype 11-T-56 and zoysiagrass genotype 09-TZ-54-9 maintained the shortest canopy height compared to all other grasses, which could have been a contributing factor in the high-observed turf cover for both of these genotypes if each had a lower tendency to scalp when mowed. This was not true for the St. Augustinegrasses as the experimental genotype Dalsa-1401 did display a significantly lower canopy height, but also had poor turf coverage. These results indicate that canopy heights can not be used to predict shade tolerance, but can be a good trait to monitor in order to identify a more desirable turfgrass.

DGCI. Dark green leaf color is often considered aesthetically pleasing in an ideal turfgrass. There were no experimental genotypes that maintained statistically darker green color than the cultivars each was compared to. Pearson correlation coefficients showed significant ($P < 0.0001$) relationships between DGCI and turf cover for bermudagrass and zoysiagrass, though they were low (0.340 and 0.349, respectively). These relationships were likely derived from genotypes such as Celebration for bermudagrass and UFZ-1201 for zoysiagrass, which had the top statistical DGCI in their respective species and also displayed a high turf cover. In contrast, the experimental bermudagrass UGB-118 and zoysiagrass Empire were able to maintain dark color, but showed very poor turfgrass cover. Most of the St. Augustinegrass genotypes were statistically similar in color, resulting in the lack of correlation between DGCI and turf cover. There was also a negative relationship between DGCI and canopy height in St. Augustinegrass, indicating that the tallest of these species were lighter green and vice versa. This could possibly be because pictures were taken prior to mowing each month (two week growing period),

therefore the tallest of leaves were probably the new growth and displayed a lighter green color than mature leaves that were lower. Environmental conditions, including soil type and fertility can influence turfgrass color; therefore, analysis over many different environments would be helpful to correctly estimate this trait. Results from this study indicate that DGCI is not a direct indicator for shade tolerance but it can be used in comparison to turf cover and canopy height in order to identify a more desirable turfgrass.

Screening new germplasm under shade structures in the field can allow the detection of shade persistent genotypes, although these methods can require three or four years. In addition to time, the associated supply and labor costs of conducting this type of research under limited space where multiple replications are needed for accurate designation of plants likely would exclude plant breeders from using shade structures during early generation tests. Further, turfgrasses that persist under consistently reduced levels of solar radiation, but not shorted periods of light, may not necessarily be adapted to shade cast by trees or structures. If improving shade tolerance is a primary goal of a turfgrass breeding program, a faster screen that better predicts real-world shade persistence would enhance the identification of superior genotypes that can be prioritized for real-world validation in shaded lawns, stadiums, and golf courses.

CHAPTER 2

SCREENING FOR SHADE TOLERANCE IN BERMUDAGRASS USING PHOTOSYNTHETIC LIGHT RESPONSE CURVES

LITERATURE REVIEW

Screening for the shade tolerance of new turfgrasses can take many years due to the perennial nature of the crop, accumulated effects of reduced photosynthesis, reoccurring disease pressures and other factors that do not stress turfgrasses grown in the full sun. Barrios et al. (1986) studied zoysiagrass ('Emerald'), St. Augustinegrass ('Floratam' and 'Floratine') and centipedegrass (*Eremochloa ophiuroides*) ('Oklawn') and reported significant leaf canopy reduction in subsequent years under 63% shade for all grasses. Although Beard (1973) previously reported St. Augustinegrass to be the most shade tolerant warm season grass species, neither 'Floratam' nor 'Floratine' persisted at the conclusion of the three year study. A separate eight-week greenhouse study with 42 bermudagrass genotypes subjected to 64% continuous shade also resulted in unacceptable TQ scores (<6) for all genotypes by the end of the experiment (Baldwin et al., 2008). Other problems can occur when plants are grown in the shade for long periods. For example, the microenvironment caused by shade (high humidity, lessened air movement, and reduced light intensity) often creates a higher risk for disease incidence that can reduce the vigor of plants that would otherwise be shade tolerant (Beard, 1965; Beard, 1973). Turfgrasses growing near or under trees can also experience root competition for soil moisture and nutrients, and

allelopathic interactions are sometimes found between species in these environments (Whitcomb, 1972).

The exact amount of light required to balance photosynthetic CO_2 uptake with CO_2 release from respiration is defined as the light compensation point (LCP) (Taiz and Zeiger, 2010). It is determined by plotting the net CO_2 exchange of the crop canopy on the y-axis versus light intensity on the x-axis. The light intensity at the x-intercept of the light response curve is the LCP, and all parts of the curve above this point result in a net positive CO_2 uptake by the crop. The point at which this photosynthetic response reaches a maximum is the light saturation point (LSP). By definition, light intensities beyond this point will have no effect on the photosynthetic response, indicating that light is no longer the limiting factor for plant growth and development (Taiz and Zeiger, 2010). Shade adapted plants tend to have lower LCPs and LSPs (Meng et al., 2014) when compared to species adapted to higher light intensity environments.

Commercially available instruments to measure photosynthetic gas exchange typically have an integrated chamber that performs a single leaf analysis. It is difficult to measure CO_2 assimilation rates on bermudagrass cultivars with these single leaf chambers because the leaves are too narrow. Further, net photosynthesis can be difficult to accurately measure in any plant due to differences in leaf age (Poni et al., 1994), chlorophyll content (Candolfi-Vasconcelos and Koblet, 1991), angle of incident radiation (Flore and Lakso, 1989), leaf shading (Flore, 1994), and respiration of vegetative or reproductive tissues (Corelli-Grappadelli and Magnanini, 1993). There are many types of gas exchange systems that measure photosynthesis (Mitchell, 1992). These systems can be closed (Chen et al., 2013), semi-closed (Zahoor et al., 2017), open (Augustine et al., 1976; Sams & Flore, 1982), and semi-open (Chun and Mitchell, 1997). Each chamber has advantages and shortcomings, but all are capable of producing an estimate of net photosynthetic

rate. Twenty-five to thirty years ago, most researchers had to construct custom gas exchange systems and chambers to conduct their studies (Long & Bernacchi, 2003; Long et al., 1996). The need for this is now reduced with the availability of *"*off-the-shelf*"* photosynthetic systems such as the LI-6400 (Li-Cor Inc., Lincoln, Nebraska, USA), CIRAS-II (PP Systems, Hitchin, UK), and LCA4 (ADC-Biosciences, Hoddesdon, UK). During the study of chilling treatments on centipedegrass in a controlled growth chamber, Chen et al. (2013) were able to create light response curves that revealed three genotypes had lower LCPs and LSPs when exposed to low light levels, indicating that this species is capable of adapting to environments with lower light intensities. Gaussoin et al. (2005) were able to derive the LCPs from Kentucky bluegrass (46 μmol m^{-2} s^{-1}), creeping bentgrass (84 μmol m^{-2} s^{-1}), and annual bluegrass (74 μmol m^{-2} s^{-1}) by using an open gas analysis system. This system allowed for the control of light intensity by changing the distance of the chamber to the light source. Using light compensation points, Miller et al. (2005) were able to determine that 'Tifdwarf' and 'Floradwarf' need more than 38.6 mols m^{-2} day^{-1} of light in order to maintain acceptable turfgrass quality.

Photosynthetic research of turfgrasses has been conducted with natural sunlight (Baldwin et al., 2009; Jiang et al., 2004) as well as by using artificial incandescent and fluorescent light sources (Gaussoin et al., 2005; Miller et al., 2005; Chen et al., 2013). There are many advantages to using light emitting diodes (LEDs) compared to other supplemental light sources. LEDs operate more efficiently in terms of electrical input, have a longer lifespan, are rugged and small, and do not radiate heat within the light beam (Bourget, 2008). LEDs with specific wavelengths can be used alone or in combination with additional LEDs at different wavelengths to study targeted responses (Massa et al., 2008). Apostol et al. (2015) reported that LEDs produced higher growth rates, gas exchange rates, and chlorophyll contents than high-pressure sodium (HPS) lamps in

Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and Engelmann spruce (*Picea engelmannii* Parry ex Engelm.). Specifically, there were significant differences in dark respiration (R_d), quantum yield (ϕCO_2) and maximum rate of photosynthesis at saturating irradiance attributed to the two different light sources, although there were no effects on LSP or LCP across species and seed sources.

OBJECTIVES

i. Build a custom chamber that can be coupled with an open infrared gas analysis system in which photosynthetic characteristics can be reproducibly estimated at different light intensities on a single day.

ii. Develop light response curves for different genotypes grown in full sun, as well as in plots that have been established under 73% shade to determine whether the derived light compensation points are indicative of known shade tolerance.

MATERIALS AND METHODS

Experiment 1

CO_2 assimilation rates were measured on two bermudagrass genotypes (Tifway and 11-T-56) in the full sun during 2016 and 2017. The experimental genotype 11-T-56 persisted under 73% shade cloth with higher turf cover than Tifway in a separate study (Chapter 1: 39.6% and 11.8%, respectively). Tifway has been reported as having poor shade tolerance (Baldwin et al., 2009; Zhang et al., 2017); therefore, this method is only valid if it determines that 11-T-56 is more shade tolerant than Tifway. This experiment was established using 26 cm^2 plugs that were vegetatively propagated in the greenhouse and planted in the field and established into 10.7 m × 4.6 m plots in Tifton, GA during 2014. The experimental design was a randomized complete block with each day within a month being defined as a replication due to the daylong

measurement duration needed to build the light response curves. On each rating day, the first CO_2 assimilation rates were taken pre-dawn in order to produce a true dark respiration rate at 0 μmol m^{-2} s^{-1} photosynthetically active radiation (PAR). The light level was then incrementally increased throughout the day while recording CO_2 assimilation rates at seven other light intervals to create the light response curve.

Experiment 2

After performing preliminary analysis on data from 2016 and 2017, very high CVs were observed for each cultivar and replication within date was a significant source of variation for all parameters except for F_v/F_m (Table 2.1). Therefore, beginning in 2018 the experimental design was changed to measure four replications of each genotype in a single day in an attempt to reduce variability attributed to replication, thereby increasing the repeatability of our comparisons. Similar methods to those described for Experiment 1 were used during 2018 to build light response curves for Tifway and experimental genotype 11-T-56 bermudagrasses. Measurements were conducted on sequential days on each genotype because there were only four chambers. This experiment was conducted in full sun on plots that were planted on May 2, 2017 as 5.1 cm plugs on 1.8 m centers with four replications of each genotype. The experimental design was a randomized complete block with four replications of each genotype per day.

Experiment 3

The shade plots were planted on August 11, 2016 as 5.1 cm plugs on 0.9 m centers and established under 73% shade cloth. Though these plots were not planted at the same time as Experiment 2, it takes longer for turfgrasses to mature when grown under shade and we wanted to measure plants at the same maturity stage. Due to limitations in total area under the shade structures, only three replications of experimental genotype 11-T-56 and Tifway were planted in

the block. This experiment was a randomized complete block design with three replications of a single genotype per day. The same methods as listed above in Experiment 2 were used to record measurements taken from plots that were established in the shade. Light response curves and the corresponding light compensation points were measured once per month for each cultivar, with all cultivars in the shade plots being measured during the same week as those in Experiment 2 when weather permitted.

Chamber Construction

The sensor head of the LI-6400 was modified by attaching a 10.2 cm rubber polyvinyl chloride (PVC) cap on it so that it would fasten to a customized chamber. The open system used a 10.2 cm, thin wall, PVC T-coupling as the chamber. The top of the PVC chamber was sealed with clear Lexan glass that is held in place with Lexal sealing glue. The light source was fixed above this glass in order to cast the light directly on the turf surface. For Experiment 1 the controlled light source was a 70W 'warm white' (2700-3500k) LED High Power Chip (EPILEDS; Tainan, Taiwan) that was capable of reaching up to 1100 μmol m^{-2} s^{-1}. For Experiment 2 and 3 we decided to use a 100W LED that produced well over 2000 μmol m^{-2} s^{-1} in order to reach a "full sun" irradiance. The color 'warm white' (2700-3500k) was chosen based on the research of Zhen and Van Iersel, (2017) where they found the LED had a primary peak at 578 nm and a secondary peak at 444 nm with 98.5% of its total photon flux falling between 400-700 nm. The LED was mounted to a 12V, 100W (92 mm×30 mm) cooling fan with an aluminum heatsink to dissipate heat from the light. The cooling fan was powered individually by a 12V Deep Cycle Marine battery (O'Reilly Auto Parts; Springfield, MO) using a separate electrical circuit (Figure 1). A parallel electrical circuit was created to give individual control of the LEDs for each of the chambers during the experiment (Figure 2). The LED light was powered by a 0-

60V/0-10A switch mode bench power supply (CircuitSpecialists; Tempe, AZ), which was plugged in to a 110V receptacle to allow the user to reduce the input voltage and maintain a specific output voltage. In Experiment 1 the voltage was set to 45.1V and with the larger light in Experiment 2 the voltage could be set to 46.1V. This system was controlled by using a 6V-90V, 15A, pulse width modulator (PWM) which allowed the DC motor speed to be controlled using a pulse-width-modulated DC voltage with a duty cycle fully adjustable from 0-100%. Using both the PWM and the switch-mode bench power supply together gives the ability to easily change the light intensity of the LEDs by controlling the amperage sent to the LED. Corresponding voltage and current were recorded with a multimeter (Southwire, Digital 600-Volt Manual Ranging Multimeter; Carrolton, GA) through a short designed in the electrical series that used two Dual Banana Plug Gold Plated Screw Type Audio Speaker Wire Cable Connectors. For Experiment 1 the light level increments were 0A, 0.05A, 0.1A, 0.2A, 0.3A, 0.5A, 0.7A, and 1.0A. Care was made not to increase higher than this because these LEDs can only operate at a maximum of 70W (W = V x A) before the diode blows out. Also, the diodes should last longer if used at lower wattages. Experiments 2 and 3 light level increments were 0A, 0.02A, 0.04A, 0.1A, 0.2A, 0.5A, 0.8A, and 1.2A. Higher light levels were reached using lower wattages because these LEDs were brighter. The chamber was connected to the PWM via 91.4 m of 18-gauge cable power wire to allow the use on distant plots in the field during the experiment.

On each sample date, a separate length of 10.2 cm PVC pipe was first hammered into the ground and removed to pre-cut the edge of the measurement area and make insertion of the actual chamber easier. Then the chambers were inserted 25 mm down into the turfgrass canopy for stability and to form a seal on the bottom of the chamber. A consistent distance between the turfgrass canopy and each chamber's light source was maintained for the different genotypes on

each measurement date by lining the top of the turf canopy with a precisely measured line inside of the chamber. Each chamber was covered with a small shade structure that measured 60.96 cm × 60.96 cm × 30.48 cm in area. The structures were assembled with 1.27 cm PVC pipe with Black Faux Stretch Leather Fabric (Hobby Lobby Stores, Inc.; Oklahoma City, Oklahoma) which prevented the penetration of any ambient light and allowed for complete control of light intensity at each step.

Response Variables

CO_2 assimilation rates were measured using an infrared gas analyzer (LI-6400, LI-COR Biosciences; Lincoln, NE) attached to the custom chamber mentioned above. The flow rate was set to 700 μmol s^{-1}, the CO_2 reference mixer was set to 400 μmol, and the area was set to 81 cm^2 (the turf surface area covered by each chamber). Light intensities inside of the chambers were measured at each increment in PAR using a light meter (Extech, LT45 Color LED Light Meter; Wilmington, NC) in which the sensor was fixed to a 10.2 cm PVC cap that fit onto the chamber and would read light at equal distances from the LED. After each light intensity increase, the turfgrass was allowed a 15 to 20 minute acclimation period before CO_2 assimilation rates were measured and recorded as net photosynthesis. Due to chamber size, an additional five minutes was also required for sample CO_2 exchange rates to reach a steady state. The photosynthetic rates were graphed with the corresponding light level to create a light response curve. The initial slope of this curve was recorded as maximum quantum yield of CO_2 assimilation (ϕCO_2). Assimilation rates were recorded at 0 μmol m^{-2} s^{-1} to obtain the R_d rate. Soil temperature (ST) was recorded at 11.43 cm once on each day that assimilation rates were recorded (General Digital Stem Thermometer with 4.5 Probe; Secaucus, NJ). Visual plot ratings (TQ) were taken on a scale of 1 to 9 by a single researcher; 1 being poorest possible quality, 6 or above considered acceptable,

and 9 being best possible quality (Morris, 2012). Turf coverage (TC) and DGCI were calculated using digital image analysis to provide the total turf cover and plot color (Richardson et al., 2001). These images were taken and analyzed as described in chapter one. Variability was observed for TC between replications, therefore photosynthetic rate per unit effective leaf area was calculated by dividing LCP by the turf cover for that replication (LCP TC^{-1}). Chlorophyll content (CC) was measured using a chlorophyll content meter (OPTI- SCIENCES CCM-300; Hudson, NH) with a signal gain of four, taking three leaf samples from the total sample area and calculating the average (Jones et al., 2017). Maximum quantum yield of photosystem II (F_v/F_m) measured on Experiment 1 and 2 by taking five samples from the total sample area with a portable chlorophyll fluorometer (OPTI-SCIENCES Multimode Chlorophyll Fluorometer; Hudson, NH) and averaging five values (Yasuor et al., 2011). Measurements consisted of placing the fluorometer prove in direct contact with the turf surface, exposing the sample to a low intensity modulation light to determine F_0 then exposing the surface to a saturating flash of light for ~0.8s to determine F_m. F_v/F_m was calculated as $[(F_m - F_0)/ F_m]$ (Maxwell and Johnson, 2000)

Statistical Analysis

Photosynthetic rates were recorded from the LI-COR at each light level for both genotypes and the rates and corresponding light intensities were plotted onto a graph to develop a light response curve (Figure 3 and 4) (SigmaPlot 14.0, Systat Software Inc., San Jose, CA). An analysis of variance was performed on each of the measured traits for each species independently. The General Linear Models (GLM) procedure in SAS 9.4 (SAS Institute, Cary, NC) using the appropriate error terms and assuming a mixed model with “dates” and “genotypes” as fixed variables and “seasons” and “replications” as random variables was used for the analysis (Table 2.1). Linear regression of the initial phase of the curve was used to

determine the LCP for each genotype. Data was analyzed by date to determine relationships over time. Square root transformations were used on datasets where conditions of normality were not met, including LCP, LCP turf cover $^{-1}$ (LCP TC^{-1}), ϕCO_2, and R_d for all experiments. No transformations were used for CC and F_v/F_m. Significant main effects were separated using a Fisher's LSD. Pearson correlation coefficients (PCC) between LCP, LCP TC^{-1}, ϕCO_2, R_d, TC, DGCI, TQ, CC, F_v/F_m, and ST were determined at ($P \leq 0.05$) for Experiment 1 and 2 (Table 2.2) and Experiment 3 (Table 2.3).

RESULTS AND DISCUSSION

Light Compensation Point

Dates, genotypes and the interaction between the two were not significant sources of variation in the analysis of variance of LCP for Experiment 1. However, Pearson correlation coefficients (PCC) did show a significant relationship between LCP and DGCI (0.34) (Table 2.2). ANOVA for this trait found date to be a significant effect in Experiment 2 (Table 2.1). On May 2, 2018 LCPs were significantly lower (69.4) than measurements taken on July 23 (231.7) and August 8 (270.2) (Table 2.4). Also in this experiment LCP was found to be significantly negatively correlated with TC (-0.70), DGCI (-0.72), TQ (-0.49), and CC (-0.54), and very highly related to ST (0.95) (Table 2.2). In Experiment 3, the analysis of variance for LCP determined that date and the genotype × date interaction were significant (Table 2.1). There were genotypic differences in LCP for 11-T-56 (2.6) and Tifway (57.6) for measurements taken on May 4 but not for July 27 and August 14 (Table 2.4). Significant correlations of LCP with TQ (-0.51), F_v/F_m (-0.94), and ST (0.47) were found in the shade during Experiment 3 (Table 2.3).

Previous attempts to determine LCPs of turfgrass that is grown in full sun (Jiang et al., 2004; Yoshiko et al., 2010) using clear chambers with ambient light were largely unsuccessful due to intermittent daily and seasonal cloud cover and the amount of time needed for CO_2 assimilation rates to stabilize. Our chamber and design allowed the accurate production of light response curves using a controlled light source, which is highly important because of the unpredictable cloud cover observed in the Southeast. Miller et al. (2005) studied LCPs of the bermudagrass cultivars 'FloraDwarf' and Tifdwarf using a growth chamber method. They found genotypic differences between bermudagrasses when the plants were exposed to 12h 1540 μmol m^{-2} s^{-1}, comparable to the full sun exposure in our study, but no differences were observed in the

plants that were exposed to the shade treatments. In our research, genotypic differences in LCP were only found on the grasses that were grown in the shade. Interestingly, the only trait correlated to LCP that was not derived from the gas exchange measurements in Experiment 1 was DGCI. As discussed in chapter one, other studies have found that darker green color in the full sun is related to improved shade tolerance (Hanna et al., 2010). Experiment 2 however, shows a negative correlation of LCP with DGCI and CC, and also a very high correlation with ST, which can strongly influence photosynthesis (Taiz and Zeiger, 2010). A greater number of higher and significant correlations between traits previously reported to be related in Experiment 2 indicates that measuring all replications for one genotype on the same day may have more accurately estimated measured the photosynthetic parameters than Experiment 1. Other studies have found that plants exposed to shade will have lower LCPs (Bernardino Dias-Filho, 2002; Chen et al., 2013), but research comparing genotypic differences for LCPs in sun-acclimated or shade-acclimated plants is far less complete.

LCP TC^{-1}

When LCP was transformed by dividing it by the percent turf cover in the plot during Experiment 1, the ANOVA detected no significant differences (Table 2.1). The PCCs for Experiment 1 indicated that LCP TC^{-1} was significantly correlated with DGCI (0.43), and TQ (-0.31) (Table 2.2). Experiment 2's ANOVA found a significant ($P \leq 0.01$) genotype × date interaction (Table 2.1). There were only genotypic differences in the transformed LCPs between 11-T-56 and Tifway for measurements performed on May 2 (68.5 and 96.5 respectively) and July 23 (256.4 and 399.5, respectively), but no differences were observed on August 14 (398.5 and 397.4, respectively) (Table 2.4). In Experiment 2 significant correlations of LCP TC^{-1} to TC (-0.82), DGCI (-0.80), CC (-0.54), and ST (0.93) were detected (Table 2.2). The ANOVA for

LCP TC^{-1} in Experiment 3 detected both date as well as a genotype to be significant (Table 2.1). The lowest LCPs were found on May 2018 (32.9), and they progressively increased on July 2018 (65.6) and August 2018 (251.2) (Table 2.5). Experimental genotype 11-T-56 had a lower transformed LCP than Tifway over the entire experiment (35.0 and 192.4, respectively) (Table 2.5). The PCCs for Experiment 3 suggest that LCP TC^{-1} was very strongly related to TC (-0.89), and F_v/F_m (-0.94) in the shade (Table 2.3).

Our study was similar to Jiang et al., (2004) in that turf cover and quality varied between genotypes and throughout the seasons. In order to resolve the issue we divided the LCP by percent turf cover and were then able detect genotypic difference in Experiment 2 where there were no differences using LCP independently of cover. Differences in transformed LCP occurred during the months of May and July (Table 2.4) where we also noticed the lowest LCPs in experiments two (Table 2.4) and three (Table 2.5). This suggests that screening for shade tolerance could be more accurate in the spring and early summer in this region, possibly due to other factors such as increased soil respiration (Frank et al., 2002) and drought conditions observed later in the season. Jiang et al., (2004) did not find genotypic differences in the bermudagrasses included in their study, possibly because their research was performed in summer months and they did not transform LCP divided by turf cover to standardize the data. Using this transformation also greatly strengthened most of the correlations for experiments two and three. There is limited research to support our method; therefore, it should be studied further to test for repeatability in other environments.

Quantum Yield (ϕCO_2)

In Experiment 1, the analysis of variance for quantum yield found a significant ($P \leq 0.01$) genotype × date interaction (Table 2.1). Analysis was performed by dates and no genotypic

differences were found, only a significant amount of unexplained Rep variability on April 2017. There were no differences found for ϕCO_2 in Experiment 2 or 3. Pearson correlation coefficients for all experiments did not find ϕCO_2 to be significantly related with any of the measured parameters (Table 2.2 and Table 2.3).

According to Taiz and Zeiger (2010), there should not be much difference in the quantum yields of plants with similar photosynthetic pathways. Even though there was a significant interaction in Experiment 1, there was still no evidence of genotypic differences. Several other studies also support our finding a lack of differences in quantum yield between genotypes within C_4 species (Avalos and Mulkey, 1999; Bernardino Dias-Filho, 2002). Although quantum yield is a critical component of calculating overall light response curves, it does not appear to be predictive of shade tolerance.

Dark Respiration Rate (R_d)

The analysis of variance for dark respiration in Experiment 1 found Date to be a significant ($P \leq 0.01$) source of variation (Table 2.1). April 2017 and September 2017 had similar LSD values (0.6 and 0.7, respectively) and were numerically the lowest of all other dates (Table 2.6). May 2017, June 2017, and October 2016 performed similarly to each other (1.1, 1.1, and 1.3, respectively), while being statistically lower than August 2016 (1.7). The PCC for this experiment found R_d significantly correlated with DGCI (0.29) but no other parameters (Table 2.2). Experiment 2 ANOVA also found the source of variation Date to be significant ($P < 0.0001$) (Table 2.1). The dark respiration rate on May 2 (0.8) was significantly lower than July 23 (2.4) and August 14 (2.7) (Table 2.4). Experiment 2 PCC detected significant correlations with TC (-0.59), DGCI (-0.63), TQ (-0.43), CC (-0.43) and ST (0.95) (Table 2.2). In Experiment

3 there were no differences detected by the ANOVA and no significant correlations found by the PCC.

Previous studies have found that plants grown under shade will have lower dark respiration rates when compared to a plant grown in full sun (Boardman, 1977; Bernardino Dias-Filho, 2002). Wilkinson and Beard (1975) reported that dark respiration rates for 'Pennlawn' red fescue grown in full sun declined when grown in the shade where 'Merion' Kentucky bluegrass did not, potentially indicating that red fescue was more shade tolerant. The experimental design of our study did not allow for the direct comparison of the full sun and shade trials, but they were grown in close proximity. Generally, the R_d rates were lower on the grasses that were grown in shade (Table 2.5). Research of whether dark respiration rates measured on plants grown in the full sun can be used to indicate shade tolerance is limited. This trait may not be associated with the ability of 11-T-56 to maintain higher turfgrass qualities under the shade than Tifway.

Chlorophyll Content

In Experiment 1, the analysis of variance for chlorophyll content detected that 11-T-56 and Tifway were significantly ($P \leq 0.05$) different (Table 2.1). Throughout all seasons Tifway maintained a higher chlorophyll content (467.7) than experimental genotype 11-T-56 (438.0) (Table 2.6). The significant ($P \leq 0.01$) genotype × date interaction for chlorophyll content that was found in Experiment 2 (Table 2.1) was due to the genotypic differences on May 2 where experimental genotype 11-T-56 had significantly higher chlorophyll content than Tifway (553.5 and 383.5, respectively) when they were equal on the other two rating dates (Table 2.4). In Experiment 3 there were no differences detected by the ANOVA (Table 2.1).

Some studies of turfgrass and other plant species have found that chlorophyll contents will increase when a plant is exposed to shade in order to maximize the light-harvesting capacity

in low-light conditions (Dai et al., 2009; Winstead and Ward, 1974) . Jiang et al. (2004) studied shade responses of eight seashore paspalum genotypes and two bermudagrass cultivars by comparing full sun treatments to light conditions reduced by 70 and 90%. They discovered that 'TifSport' bermudagrass displayed the highest chlorophyll content in the full sun treatment, but had lower levels when grown in both shade treatments. TifSport did not adapt after exposure to the shade, implying that chlorophyll content in the full sun may not be a direct indicator of true shade tolerance in bermudagrass. Chlorophyll content should be more thoroughly researched in the future so that direct comparison between shade and sun grown plants can be accomplished.

Maximum quantum yield (F_v/F_m)

The ANOVA for maximum quantum yield in Experiment 1 did not identify any significance. However, the ANOVA for Experiment 2 found a significant genotype × date interaction (Table 2.1) caused by significantly higher F_v/F_m for 11-T-56 (0.7436) when compared to Tifway (0.5490) on May 2 (Table 2.4). Measurements performed on July 23 and August 14 yielded no genotypic differences.

The value of F_v/F_m has been studied in the past to understand the effects of shade on different plant species (Dąbrowski et al., 2015; Pollastrini et al., 2011). Jiang et al. (2005) tested this trait when comparing Sea Isle 1 seashore paspalum to TifSport bermudagrass under high light conditions (500-900 μmol m^{-2} s^{-1}) and low light conditions (60-100 μmol m^{-2} s^{-1}). They discovered slight variation but stated that F_v/F_m in these grasses were generally not affected by shade, although, these measurements were done in the greenhouse during the fall. Maximum quantum yield could be an accurate indicator of shade tolerance when performed in the field on spring days, but this hypothesis should be further analyzed.

CONCLUSIONS

Leaves that are shaded by other leaves tend to have lower photosynthetic rates than the ones above them (Taiz and Zeiger, 2010). This chamber gave us the ability to study the turf canopy at natural leaf angles for light interception rather than only a single leaf, theoretically producing a more accurate average for the whole plant. The variable light chamber constructed for this research to estimate light compensation points in turfgrass seems to be very precise based on the high R^2 of the light response curves that were produced. Though these curves fit the data very well, the inconsistent ranking of the LCPs between two genotypes with high (11-T-56) and low (Tifway) shade tolerance when measurements were taken more than a few days apart led us to conclude that shade tolerance could not be predicted using the methodology of Experiment 1. In an attempt to increase the LCP prediction accuracy, we modified the experimental design in Experiment 2 so that all replications were measured in a single day for each genotype. The ANOVAs from Experiment 2 for all traits measured with the photosynthesis chamber had lower CVs than observed in Experiment 1, indicating that there was lower variation between replications for these parameters. Because this is a field study, other factors such as soil respiration and turf cover could have greatly affected the results. To eliminate turf cover as a factor we transformed the LCP by dividing it by TC, and after doing so found genotypic differences between the known shade tolerant genotype 11-T-56 and non-tolerant Tifway. This transformed value was generally more highly correlated to most of the parameters estimated in this research. In the spring dates we observed that for both genotypes the LCPs and the R_d rates were numerically lower and were accurate in showing that 11-T-56 is more shade tolerant than Tifway (Table 2.4 and Table 2.5). The R^2 of the light response curves were also slightly better in the spring months compared to the late summer months (Figure 3). Soil respiration studies

(Frank et al., 2002) have found that soil respiration is lower in the spring when the soil temperatures are cooler, so by performing this study in Spring we believe that we were able minimize that factor as well. Future studies using the methods from Experiments 2 and 3 need to be conducted, with a high priority given to spring dates due to the findings in our research.

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Table 1.1. Species and cultivars evaluated in 2015, 2016, and 2017 under 73% shade in Tifton, GA.

Species	Genotype	Breeder or Supplier
Bermudagrass		
	Celebration	Sod Solutions Inc., Mt. Pleasant, SC (2000)
	Tahoma 31	Oklahoma St. Univ., Stillwater, OK (2018)
	Latitude 36	Oklahoma St. Univ., Stillwater, OK (2014)
	TifGrand	Univ. of Georgia, Tifton, GA (2009)
	TifTuf	Univ. of Georgia, Tifton, GA (2014)
	Tifway	Univ. of Georgia, Tifton, GA (1960)
	UGB-118	Univ. of Georgia, Tifton, GA
	11-T-56	Univ. of Georgia, Tifton, GA
St. Augustinegrass		
	Floratam	Univ. of Florida, Gainesville, FL Texas A&M Univ., Dallas, TX (1973)
	Palmetto	Sod Solutions Inc., Mt. Pleasant, SC (1995)
	Raleigh	North Carolina State Univ., Raleigh, NC (1980)
	NCS-150	North Carolina State Univ., Raleigh, NC
	NCS-153	North Carolina State Univ., Raleigh, NC
	NCS-155	North Carolina State Univ., Raleigh, NC
	NCS-156	North Carolina State Univ., Raleigh, NC
	Dalsa-1316	Texas A&M Univ., Dallas, TX
	Dalsa-1318	Texas A&M Univ., Dallas, TX
	Dalsa-1401	Texas A&M Univ., Dallas, TX
	Dalsa-1404	Texas A&M Univ., Dallas, TX
	Dalsa-1405	Texas A&M Univ., Dallas, TX
Zoysiagrass		
	Empire	Sod Solutions Inc., Mt. Pleasant, SC (1999)
	Palisades	Texas A&M Univ., Dallas, TX (1996)
	Zeon	Bladerunner Farms Inc., Poteet, TX (1996)
	Dalz-1310	Texas A&M Univ., Dallas, TX
	Dalz-1311	Texas A&M Univ., Dallas, TX
	Dalz-1409	Texas A&M Univ., Dallas, TX
	Dalz-1410	Texas A&M Univ., Dallas, TX
	UFZ-1201	Univ. of Florida, Gainesville, FL
	UFZ-1252	Univ. of Florida, Gainesville, FL
	UFZ-1305	Univ. of Florida, Gainesville, FL
	UFZ-1306	Univ. of Florida, Gainesville, FL
	UFZ-1307	Univ. of Florida, Gainesville, FL
	09-TZ-53-20	Univ. of Georgia, Tifton, GA
	09-TZ-54-9	Univ. of Georgia, Tifton, GA

Table 1.2. Analysis of variance for turf cover, canopy height, and DGCI of all bermudagrass, St. Augustinegrass, and zoysiagrass genotypes evaluated under 73% shade in 2015, 2016, and 2017 in Tifton, GA.

Source	df	Mean Squares		
		Turf Cover	Canopy Height	DGCI
Bermudagrass (n = 8)				
Year (Y)	2	155.3*	1.2	0.0116
Season (S)	2	57.2***	10.4***	0.0631***
Y × S	4	10.6**	0.2	0.0048
Error A, Rep(Y × S)	36	1.6	0.1	0.0022
Genotype (G)	7	91.2***	1.6***	0.0691***
G × Y	14	3.5**	0.1	0.0012
G × S	14	1.6	0.1*	0.0019**
G × Y × S	28	0.8	0.1	0.0001
Error B, MSE	252	1.1	7.1	9.2
% CV		23.7%	10.0%	4.1%
St. Augustinegrass (n = 12)				
Year (Y)	2	25.2	292.5	0.0718
Season (S)	2	150.7***	807.0***	0.0238**
Y × S	4	55.4***	207.0***	0.0181***
Error A, Rep(Y × S)	36	5.1	5.0	0.0021
Genotype (G)	11	112.5***	74.0**	0.0136**
G × Y	22	3.8**	6.4**	0.0025*
G × S	22	4.3	11.4***	0.0023**
G × Y × S	44	1.3	2.5	0.0012
Error B, MSE	396	3.2	373.3	11.4
%CV		33.2%	17.9%	5.1%
Zoysiagrass (n = 14)				
Year (Y)	2	342.1*	3.9*	0.0392
Season (S)	2	475.3***	35.8***	0.1103***
Y × S	4	47.5***	0.4*	0.0501***
Error A, Rep(Y × S)	36	1.0	0.1	0.0018
Genotype (G)	13	4.3**	3.6***	0.0073**
G × Y	26	2.8**	0.1*	0.0008
G × S	26	1.3**	0.2***	0.0018***
G × Y × S	52	0.9**	0.1*	0.0010**
Error B, MSE	468	0.5	3.4	5.3
%CV		12.0%	7.0%	3.2%

*,**,*** Significant at the 0.05, 0.01, and <0.0001 levels of probability, respectively

Table 1.3. Means for turf coverage, canopy height, and DGCI for 8 bermudagrasses, 12 St. Augustinegrasses and 14 zoysiagrass genotypes evaluated under 73% shade in 2015, 2016, 2017 in Tifton, GA

	Means		
Genotype	Turf Cover	Canopy Height	DGCI
Bermudagrass	(%)	(cm)	(Index)
11-T-56	39.6a	5.4e	0.7896ab
TifTuf	31.0b	9.0a	0.7100de
Celebration	30.7b	7.2bcd	0.7933a
Tahoma 31	25.3c	7.1cd	0.7173d
TifGrand	19.5d	7.1cd	0.7356c
Latitude 36	13.5e	7.6bc	0.7011e
Tifway	11.8e	7.7b	0.7018e
UGB-118	3.7f	6.7d	0.7760b
St. Augustinegrass			
NCS-150	71.1a	10.0e	0.6667bc
NCS-156	68.0ab	10.9cd	0.6926a
NCS-153	66.5ab	10.3de	0.6601c
Dalsa-1404	63.4b	11.4bc	0.6596c
NCS-155	62.3b	10.4de	0.6950a
Dalsa-1318	61.9b	14.0a	0.6615c
Dalsa-1405	61.7b	10.7cd	0.6582c
Dalsa-1316	52.1c	10.5de	0.6361d
Palmetto	45.8cd	10.6de	0.6627c
Dalsa-1401	43.3d	8.6f	0.6590c
Raleigh	27.5e	10.2de	0.6761b
Floratam	23.3e	11.9b	0.6908a
Zoysiagrass			
Dalz-1311	*See table 1.4	9.6a	0.7175def
Palisades	–	9.3ab	0.7129efg
Dalz-1310	–	9.1b	0.7289bc
Empire	–	8.6c	0.7321ab
Dalz-1410	–	7.2d	0.7215cde
UFZ-1252	–	7.1de	0.7008h
UFZ-1307	–	6.8ef	0.6919i
UFZ-1305	–	6.7f	0.7132efg
Zeon	–	6.3g	0.7114fg
UFZ-1201	–	6.1g	0.7402a
UFZ-1306	–	6.0gh	0.7080gh
Dalz-1409	–	5.8h	0.7125fg
09-TZ-54-9	–	5.4i	0.7220cd
09-TZ-53-20	–	4.9j	0.7275bc

Means within a column followed by the same letter are not significantly different according to Waller-Duncan LSD

Table 1.4. Means and percent change for turf coverage over each year of 14 zoysiagrass genotypes evaluated under 73% shade in Tifton, GA

	Means of Turf Cover				
Genotype	2015	2016	Change†	2017	Change‡
	----------%----------				
UFZ-1201	20.5cd	46.6cd	+128	57.7a	+24
09-TZ-54-9	21.6bcd	54.1ab	+150	56.4ab	+4
Palisades	24.4abc	44.1cde	+79	56.3ab	+28
UFZ-1305	22.7bc	47.7bc	+110	53.9abc	+13
09-TZ-53-20	23.0bc	56.1a	+144	53.4abc	-5
Dalz-1310	25.7ab	47.6bc	+86	52.3abc	+10
UFZ-1252	17.7de	43.2c-f	+144	50.8abc	+18
Zeon	14.7ef	42.0c-f	+186	50.8abc	+21
Dalz-1409	29.5a	45.9cde	+56	49.7abc	+8
Dalz-1311	25.6ab	46.9cd	+83	49.4bc	+5
Empire	20.1cd	37.9f	+88	49.0bcd	+29
Dalz-1410	24.6abc	40.1ef	+63	47.4cd	+18
UFZ-1307	13.6f	41.7c-f	+207	41.7d	0
UFZ-1306	29.3a	40.9def	+40	32.1e	-22

Means within a column followed by the same letter are not significantly different according to Waller-Duncan LSD

† Percent change from year 2015 to 2016

‡ Percent change from year 2016 to 2017

+ increase in turf cover percentage

-decrease in turf cover percentage

Table 1.5. Pearson correlation coefficients for the relationship of turf cover, canopy height, and DGCI for all turfgrass species during the three year study.

	Turf Cover	Canopy Height	DGCI
Bermudagrass			
Turf Cover	–	0.179**	0.340***
Canopy Height	–	–	0.038^{NS}
DGCI	–	–	–
St. Augustinegrass			
Turf Cover	–	0.428***	-0.017^{NS}
Canopy Height	–	–	-0.265***
DGCI	–	–	–
Zoysiagrass			
Turf Cover	–	0.541***	0.349***
Canopy Height	–	–	0.252***
DGCI	–	–	–

*,**,*** Significant at the 0.05, 0.01, and <0.0001 levels of probability, respectively
^{NS} Nonsignificant

Table 2.1. Analysis of variance for light compensation point (LCP), LCP turf cover^{-1} (LCP TC^{-1}), maximum quantum yield (ϕCO_2), dark respiration (R_d), chlorophyll content (CC), and chlorophyll fluorescence (F_v/F_m) of experimental genotype 11-T-56 and Tifway in Experiment 1 (full sun, 2016-2017), Experiment 2 (full sun, 2018) and Experiment 3 (73% shade, 2018) performed in Tifton, GA.

Source	df	Mean Squares					
		LCP	LCP TC^{-1}	ϕCO_2	R_d	CC	F_v/F_m
Experiment 1		---------- μmol m^{-2} s^{-1}----------				mg m^{-2}	
Date (D)	5	57.7	59.3	0.3057	1.23*	8877.3	0.0076
Error A, Rep(D)	18	23.9**	48.3**	0.1154***	0.39**	3824.5*	0.0043
Genotype (G)	1	16.0	11.2	0.0268	0.35	10314.3*	0.0003
(D) × (G)	5	6.0	21.8	0.0209*	0.07	1256.4	0.0030
Error B, MSE	18	5.1	9.4	0.0060	0.07	1274.2	0.0018
%CV		19.7%	22.4%	41.9%	23.8%	7.9%	5.7%
Experiment 2							
Date (D)	2	135.7***	233.9***	8.56 x 10^{-5}	1.30***	18951.1**	0.0300**
Error A, Rep(D)	9	1.3	2.4	6.36 x 10^{-5}	0.01	1558.1	0.0016
Genotype (G)	1	1.2	12.7	1.34 x 10^{-5}	0.01	16590.0	0.0171
(D) × (G)	2	0.8	7.8**	3.37 x 10^{-5}	0.04	20683.8**	0.0242**
Error B, MSE	7	0.5	0.7	6.99 x 10^{-5}	0.02	1568.0	0.0013
%CV		5.6%	5.6%	8.3%	10.9%	9.6%	5.4%
Experiment 3							
Date (D)	2	18.3**	168.0**	9.86 x 10^{-5}	0.01	431.7	–
Error A, Rep(D)	6	0.9	4.4	4.65 x 10^{-5}*	0.02	812.1	–
Genotype (G)	1	49.8	284.8*	1.58 x 10^{-5}	0.09	162.0	–
(D) × (G)	2	13.6**	13.5	4.29 x 10^{-6}	0.01	862.2	–
Error B, MSE	6	0.9	2.7	6.58 x 10^{-6}	0.02	1037.9	–
%CV		14.8%	16.8%	14.6%	18.1%	8.0%	–

*,**,*** Significant at the 0.05, 0.01, and <0.0001 levels of probability, respectively

Table 2.2. Pearson correlation coefficients for light compensation point (LCP), LCP turf cover^{-1} (LCP TC^{-1}), quantum yield (ΦCO_2), turf cover (TC), dark green color index (DGCI), turf quality (TQ), chlorophyll content (CC), chlorophyll fluorescence (F_v/F_m), and soil temperature (ST) for bermudagrass in Experiment 1 (above diagonal) and Experiment 2 (below diagonal) performed from August 2016 through August 2018 in Tifton, GA.

	LCP	LCP TC^{-1}	ΦCO_2	R_d	TC	DGCI	TQ	CC	F_v/F_m	ST
	(μmol m^{-2}s^{-1})	(μmol m^{-2}s^{-1})	(μmol m^{-2}s^{-1})	(μmol m^{-2}s^{-1})	%	index	visual rating	mg m^{-2}		C°
LCP		0.774***	-0.004	0.902***	0.069	0.335*	-0.040	-0.182	0.318	0.26413
LCP TC^{-1}	0.973***		0.029	0.595***	-0.376**	0.433**	-0.314*	-0.242	0.329	-0.029
ΦCO_2	0.177	0.122		-0.305*	-0.125	-0.065	-0.218	0.207	-0.073	-0.152
R_d	0.947***	0.898***	0.391		0.218	0.289*	0.173	-0.134	0.316	0.409**
TC	-0.698**	-0.817***	0.011	-0.589**		-0.456**	0.609***	0.139	-0.028	0.440**
DGCI	-0.722**	-0.803***	-0.230	-0.629**	0.658**		-0.329*	-0.122	0.189	-0.171
TQ	-0.487*	-0.402	-0.091	-0.433*	0.338	-0.001		0.425**	-0.132	0.246
CC	-0.538**	-0.541**	-0.009	-0.427*	0.612**	0.366	0.533**		-0.30	-0.056
F_v/F_m	0.115	0.137	0.25	0.239	0.016	0.059	0.206	0.412		0.251
ST	0.949***	0.928***	0.331	0.948***	-0.694**	-0.620**	-0.510*	-0.479*	0.268	

*,**,***Significant at the 0.05, 0.01, and <0.0001 probability levels respectively

Table 2.3. Pearson correlation coefficients for light compensation point (LCP), LCP turf cover^{-1} (LCP TC^{-1}), quantum yield (ΦCO_2), turf cover (TC), dark green color index (DGCI), turf quality (TQ), chlorophyll content (CC) and soil temperature (ST) of experimental genotype 11-T-56 and Tifway in Experiment 3 grown under 73% shade in during 2018 in Tifton, GA

	LCP	LCP TC^{-1}	ΦCO_2	R_d	TC	DGCI	TQ	CC	ST
	(μmol m^{-2}s^{-1})	(μmol m^{-2}s^{-1})	(μmol m^{-2}s^{-1})	(μmol m^{-2}s^{-1})	%	index	visual rating	mg m^{-2}	C°
LCP		0.520*	-0.184	-0.200	-0.310	-0.347	-0.510*	-0.150	0.474*
LCP TC^{-1}			-0.464	-0.098	-0.892***	-0.308	-0.583*	0.120	0.474
ΦCO_2				0.270	0.433	-0.076	0.258	-0.080	0.057
R_d					0.083	0.136	0.417	0.203	0.045
TC						0.264	0.628**	-0.246	-0.251
DGCI							0.267	0.111	-0.814
TQ								-0.118	-0.066
CC									-0.182
ST									

*,**,***Significant at the 0.05, 0.01, and <0.0001 probability levels respectively

Table 2.4. Main effects and interactions for light compensation point (LCP), LCP turf cover^{-1} (LCP TC^{-1}), maximum quantum yield (ϕCO_2), dark respiration (R_d), chlorophyll content (CC), and chlorophyll fluorescence (F_v/F_m) for bermudagrass genotypes 11-T-56 and Tifway in Experiment 2 grown in the full sun during 2018 in Tifton, GA

Date	LCP	ϕCO_2	R_d
	----------	μmol m^{-2} s^{-1}	----------
May 2018	69.4c	0.0096a	0.8b
July 2018	231.7b	0.0095a	2.4a
August 2018	270.2a	0.0118a	2.7a
Genotype	LCP	ϕCO_2	R_d
	----------	μmol m^{-2} s^{-1}	----------
11-T-56	240.1a	0.0100a	2.4a
Tifway	214.6a	0.0105a	2.1a
Genotype	May 2018	July 2018	August 2018
LCP TC^{-1} (μmol m^{-2} s^{-1})			
11-T-56	68.5b	256.4b	398.5a
Tifway	96.5a	399.5a	397.4a
CC (mg m^{-2})			
11-T-56	553.5a	390.0a	374.8a
Tifway	383.5b	397.5a	379.5a
F_v/F_m			
11-T-56	0.7436a	0.7301a	0.6358a
Tifway	0.5490b	0.7625a	0.6290a

Means within a column followed by the same letter are not significantly different according to Fisher's LSD test.

Table 2.5. Main effects and interactions for light compensation point turf cover^{-1} (LCP TC^{-1}), maximum quantum yield (ϕCO_2), dark respiration (R_d), and chlorophyll content (CC) reported on bermudagrass evaluated on 2018.05.04, 2018.07.27 and 2018.08.16 in Experiment 3 when grown under 73% shade in Tifton, GA

Date	LCP TC^{-1}	ϕCO_2	R_d	CC
	---------- μmol m^{-2} s^{-1}----------			mg m^{-2}
May 2018	32.9c	0.0184a	0.5a	405.5a
July 2018	65.6b	0.0217a	0.5a	391.3a
August 2018	251.2a	0.0136a	0.6a	405.8a
Genotype	LCP TC^{-1}	ϕCO_2	R_d	CC
	---------- μmol m^{-2} s^{-1}----------			mg m^{-2}
11-T-56	35.0b	0.0185a	0.6a	404.1a
Tifway	192.4a	0.0167a	0.4a	396.6a
Genotype	May 2018	July 2018		August 2018
LCP	---------- μmol m^{-2} s^{-1}----------			
11-T-56	2.6b	20.8a		64.8a
Tifway	57.6a	72.2a		65.8a

Means within a column followed by the same letter are not significantly different according to Fisher's LSD test

Table 2.6. Main effects for light compensation point (LCP), LCP turf cover^{-1} (LCP TC^{-1}), maximum quantum yield (ϕCO_2), dark respiration (R_d), chlorophyll content (CC), and chlorophyll fluorescence (F_v/F_m) reported on bermudagrass genotypes 11-T-56 and Tifway in Experiment 1 evaluated in August 2016, October 2016, April 2017, May 2017, June 2017 and September 2017 grown in the full sun in Tifton, GA

Date	LCP	LCP TC^{-1}	ϕCO_2	R_d	CC	F_v/F_m
	---------- μmol m^{-2} s^{-1}----------				mg m^{-2}	
August 2016	248.6a	303.2a	0.0114a	1.7a	407.9a	0.7885a
October 2016	211.4a	309.1a	0.0094a	1.3b	469.4a	0.7613a
April 2017	141.2a	208.5a	0.6299a	0.6c	421.3a	0.7513a
May 2017	110.1a	120.1a	0.0120a	1.1b	505.0a	0.6993a
June 2017	114.7a	130.3a	0.0147a	1.1b	447.9a	0.7310a
September 2017	72.7a	235.8a	0.0093a	0.7c	449.9a	0.7082a
Genotype	LCP	LCP TC^{-1}	ϕCO_2	R_d	CC	F_v/F_m
	---------- μmol m^{-2} s^{-1}----------				mg m^{-2}	
11-T-56	138.7a	212.9a	0.0711a	1.3a	467.7a	0.7510a
Tifway	160.8a	222.8a	0.1578a	1.7a	438.0b	0.7370a

Means within a column followed by the same letter are not significantly different according to Fisher's LSD test

Cooling Fan Circuit

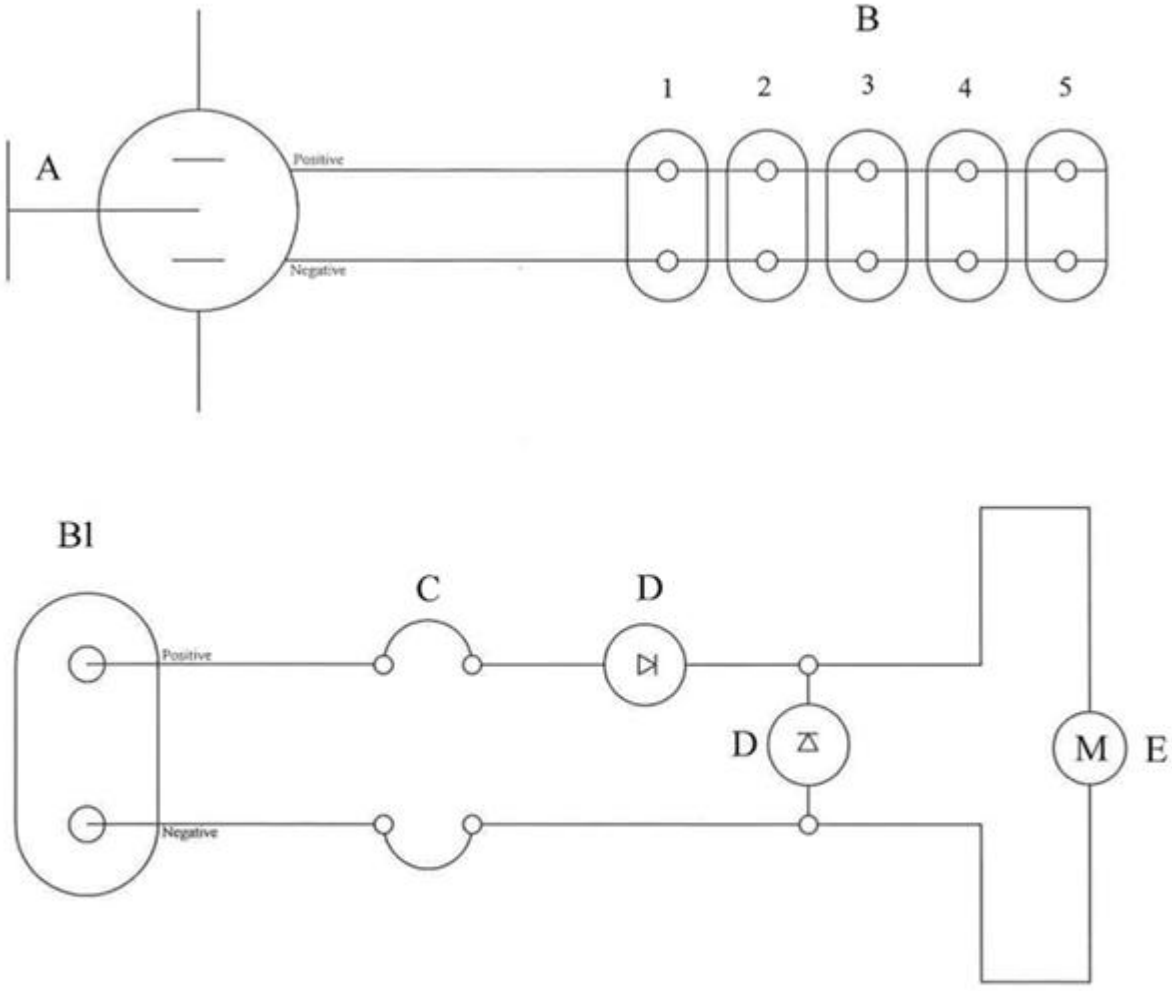

Figure 1. Wiring schematic for the cooling fan circuit:
A – 12V deep cycle marine battery
B – Electrical series (B_1, Series 1; B_2, Series 2; etc…)
C – 300' 18 gauge red/ black zip wire
D – 3A/ 400V zener diode
E – 100W LED cooling fan aluminum heatsink

LED Light Circuit

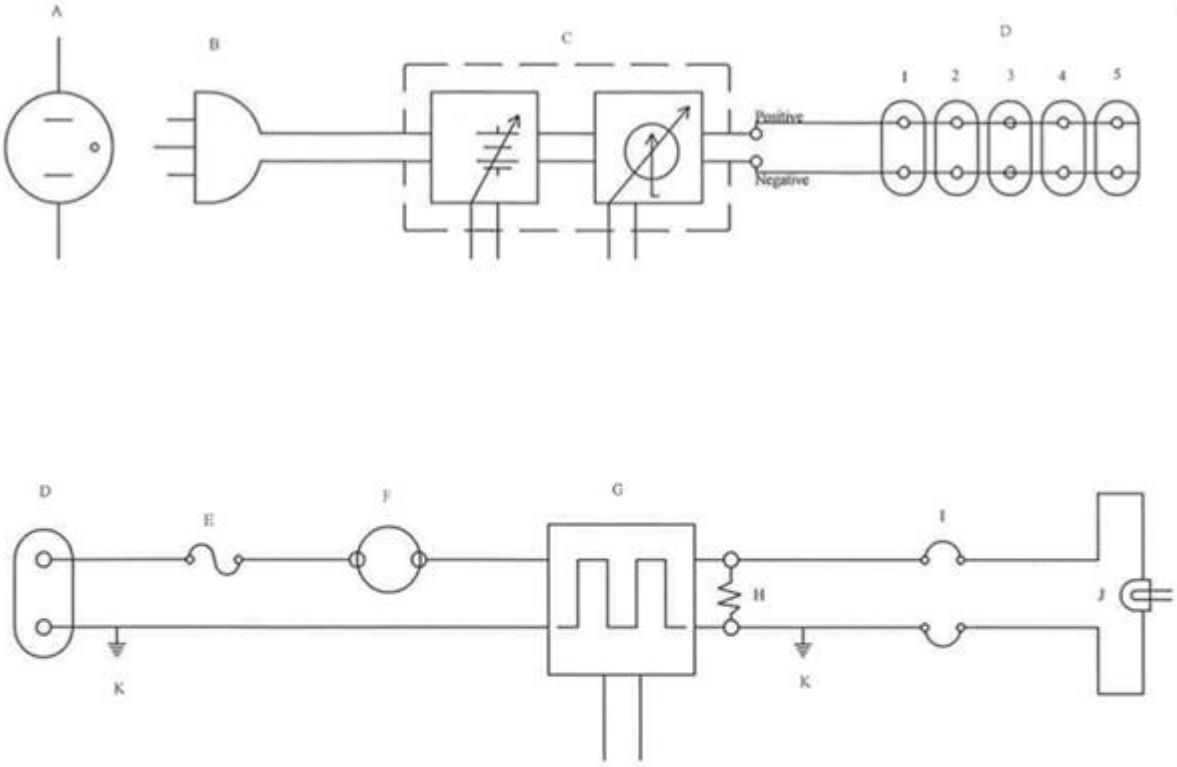

Figure 2. Wiring schematic for the LED light circuit:
A – 120V electrical outlet
B – 100' 125V/ 15A 10 gauge extension cord
C – 0-60V/ 0-10A switch mode bench power supply
D – Terminal blocks 1-5
E – Fast acting 5A/ 250V fuse
F – 2x dual banana plug used as an inline short (used for amperage reading with multimeter)
G – 6-90V/ 15A pulse width modulator
H – 350 Ohm 5W wire wound cement sand block resistor
I – 300' 18 gauge red/ black zip wire
J – 100W warm white LED high power chip
K – Ground

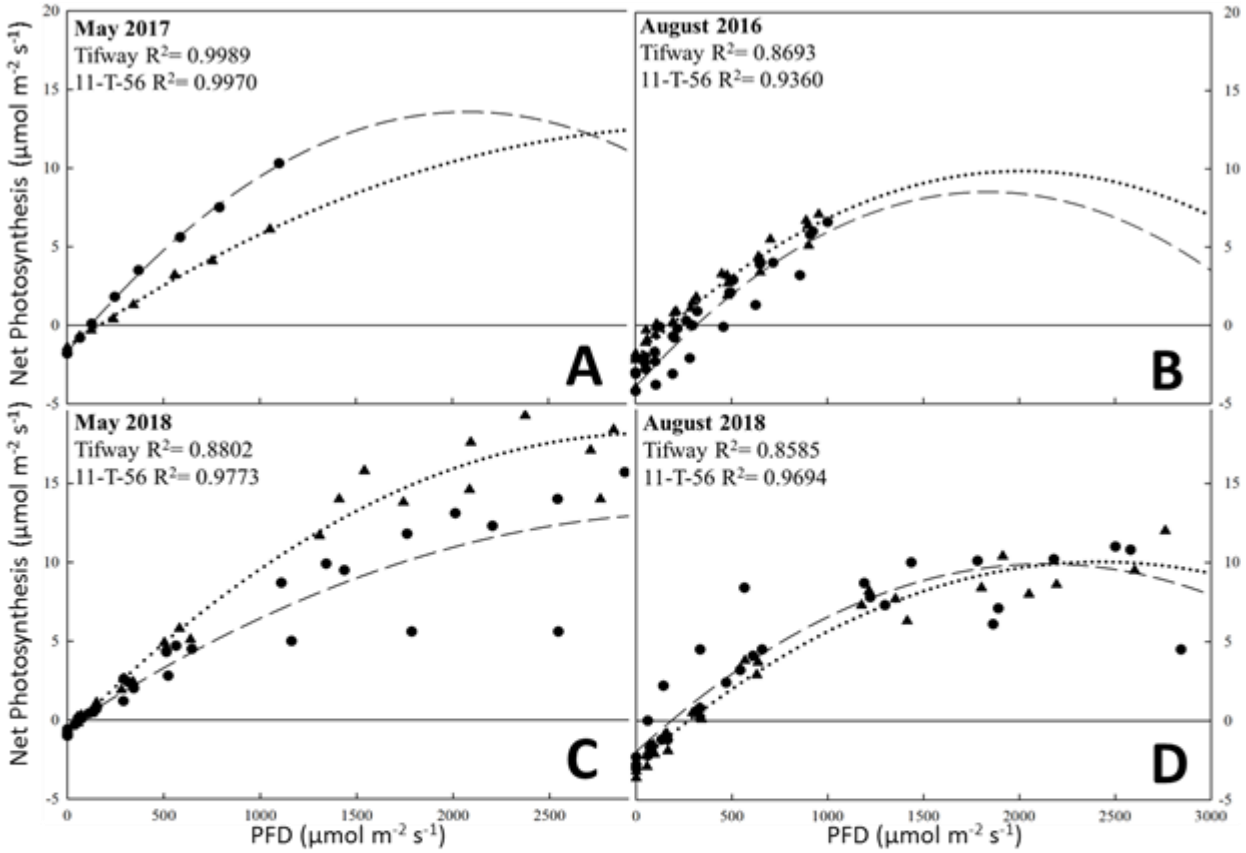

Figure 3. Comparison of light response curves for experimental genotype 11-T-56 (▲, ·····) and Tifway (●, − −) from experiment one (**A** and **B**) and experiment 2 (**C** and **D**) with the R^2 of the polynomial presented. May 2017 displays methods of experiment one performed on a single day and August 2017 shows a monthly average using the same method. May 2018 shows an example using methods from experiment two using a single day for each genotype, this is the same for August 2018.

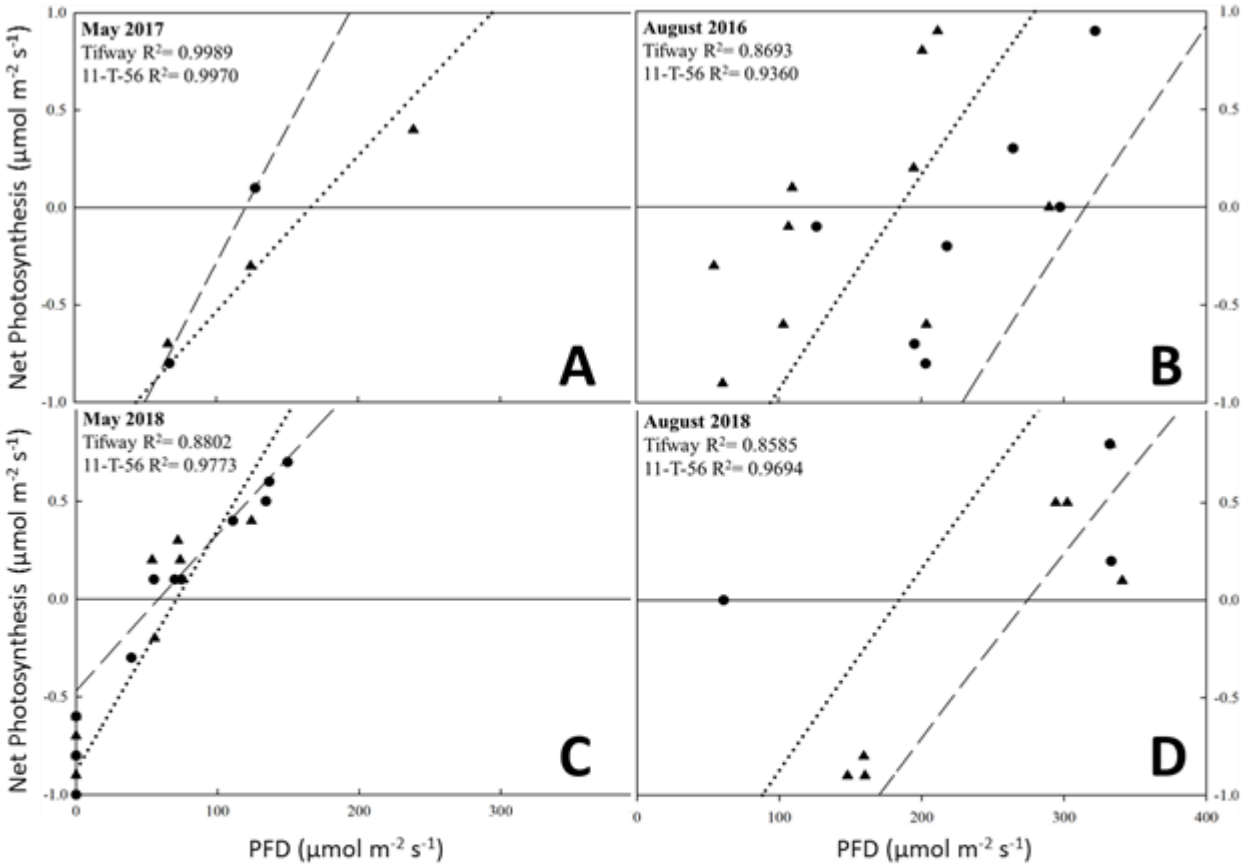

Figure 4. A magnified comparison of light response curves for experimental genotype 11-T-56 (▲, ·····) and Tifway (●, − −) that help to see the LCPs from experiment one (**A** and **B**) and experiment 2 (**C** and **D**) with the R^2 of the polynomial presented. May 2017 displays methods of experiment one performed on a single day and August 2017 shows a monthly average using the same method. May 2018 shows an example using methods from experiment two using a single day for each genotype, this is the same for August 2018.