EFFECTS OF SHADE IN COMBINATION WITH DROUGHT STRESS ON BERMUDAGRASS (*CYNODON* SPP.)

By

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Abstract: Bermudagrass (*Cynodon* spp.) is the predominant warm-season turfgrass in the U.S., largely due to its excellent adaptation and stress tolerance. However, bermudagrasses are not adapted to shaded environments. A three-year field study was conducted from 2014 through 2016 to test the shade tolerance of bermudagrass including two Oklahoma State University experimental genotypes (OKS 2011-1 and OKS 2011-4) and eight commercial cultivars of bermudagrass (‘Latitude 36’, ‘Northbridge’, ‘Riviera’, ‘Yukon’, ‘Patriot’, ‘Celebration’, ‘TifGrand’, and ‘Princess 77’). Bermudagrasses were evaluated under a combined neutral and vegetative shade environment: severe shade (75 % shade), moderate shade (49 % shade), and open sun (0 % shade). In terms of cumulative turf performance, Northbridge and Celebration were the top two performers in moderate shade and severe shade, respectively. Patriot was the worst performing cultivar under severe shade. Under severe shade, each cultivar demonstrated turf quality below the ‘minimally acceptable’ threshold.

Shade and drought stress commonly co-exist in managed turfgrass systems. Two greenhouse experiments tested the hypothesis that shade would reduce the severity of drought stress on common bermudagrass [*C. dactylon* (L.) Pers.] and interspecific hybrid bermudagrasses (*C. dactylon* x *C. transvaalensis*) as compared to a non-shaded environment. The cultivars Celebration, Latitude 36, and Patriot were established from washed plugs in 10 cm diameter x 45cm long pots filled with a 1:1 top soil: sand root-zone. ‘Non-shade’ and ‘Shade’ (58% shade) treatments were applied using a black shade fabric. Irrigation was applied manually with treatments being either well-watered (100% ET) or drought-stressed (50% ET). Data collected included TQ, NDVI, leaf relative water content, leaf electrolyte leakage, and evapotranspiration rate. Patriot had the poorest performance in drought stress alone, shade alone or combined shade and drought stress treatments. Whereas, Celebration and Latitude 36 performed similarly under each treatment. Shade delayed visible bermudagrass drought stress symptoms by one week in the first experiment, but no delay in drought stress was detected in the second experiment.

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LITERATURE REVIEW

Introduction

Bermudagrass (*Cynodon* spp. L.C. Rich) is the most widely used warm-season turfgrass in the southern United States (Emmons, 1995). It is adapted to a wide range of soil pH, soil texture, and soil fertility (Hanna et al., 2013). Bermudagrass can establish rapidly and recuperates well because it propagates quickly through stolons and rhizomes (Turgeon, 2002). Turf bermudagrass is suitable for almost all turf conditions in golf courses, athletic fields, home lawns, industrial parks and for soil stabilization as well. Turf bermudagrass is common in warm, humid tropical and sub-tropical climates because it performs relatively well in dry and saline soil and shows resistance to most disease and insect pests (Christians, 2011). However, the most serious limitation of bermudagrass within its adapted region is poor shade tolerance (Emmons, 1995).

It has been estimated that 20 to 25% of existing turfs are managed under some degree of shade from trees, shrubs or buildings (Beard, 1973). For instance, trees are inevitable components of a golf course system, but the shade from trees on turfgrass community creates a challenge for turfgrass managers.

Likewise, shade spots in home lawns and landscape gardens either from trees and shrubs or from physical structures bring challenges in managing turf under shade. In recent years, modern architectural design of sports stadium has increased shade stress in athletic fields as well (Gardner and Gross, 2013).

Turfgrasses evolved under full sun environments and thus are often not well-adapted to grow under shade (Gardner and Goss, 2013). In shaded environments, reduction in light intensity is usually combined with several other important environmental factors, such as alteration of light quality, air flow restriction, tree-root competition, and increased relative humidity (Beard, 1973). Shade, a major physiological stress can rapidly alter morphological and physiological characteristics of a turfgrass community (McBee, 1969; Stanford et al., 2005). While a primary consequence of shade stress on cool-season turfgrasses is increased disease pressure, warm-season turfgrass growth and development can be dramatically altered (Beard, 1997). Cool-season grasses contain the C_3 photosynthetic system while warm-season grasses contain the C_4 photosynthetic system. It is known that C_3 grasses have a lower light compensation point and have greater photosynthetic efficiency at lower light conditions compared to C_4 grasses. Cool-season turfgrasses, therefore, perform better in moderate shade than warm-season turfgrasses. Several physiological and morphological changes such as reduced photosynthesis, increased disease pressure, reduced carbohydrate production, increased tree-root competition, and reduced lateral stem growth have been reported to affect warm-season turfgrasses under shade (Baldwin et al., 2008).

Light intensity, light quality and light duration are the three aspects of light that are influenced by shade-inducing structures (Baldwin et al., 2008; Bell et al., 1999; Bunnell et al., 2005a). These factors, along with the other microclimatic factors interact within shaded turfgrass ecology to cause changes in physiology, morphology, and anatomy (Beard, 1973). Shade stress can be alleviated to some extent by following cultural practices such as increasing mowing heights, reducing nitrogen rates, and applying plant growth regulators (Gardner and Goss, 2013). Alternatively, proper selection of species or cultivars can improve turf performance in shade. Efforts to improve shade tolerance in bermudagrass turf may lead to reduced inputs needed to maintain good turf quality in shaded environments.

Bermudagrass (*Cynodon* spp. L. C. Rich)

Taxonomically, all grasses including turfgrasses belong to a single family of a plant kingdom called Gramineae or Poaceae. Within this family, there are 12 subfamilies including a total of 51 tribes, 80 subtribes, 771 genera, and 12074 species (Soreng et al., 2015). Among them, only a few dozens of species are tolerant of frequent relatively low mowing and traffic and, therefore, are adapted as turfgrasses. All turfgrasses are broadly categorized into three sub-families: Festucoideae, Panicoideae, and Eragrostoideae or Chloridoideae. Festucoid turfgrasses grow best at temperatures between 60^0 F to 75^0 F growing actively in cooler portion of the year, therefore, usually referred as cool-season turfgrasses. While turfgrasses under Panicoideae and Eragrostoidea subfamilies have optimum growing temperature between 80^0 F and 95^0 F. These grasses grow actively in warmer portion of the year and, therefore, called warm-season turfgrasses (Turgeon, 2002). Not only do these two broad categories of turfgrasses vary in optimum growing temperature but also, they vary in photosynthetic pathway. Cool-season grasses use the Calvin cycle (or C_3 cycle) to fix carbon-dioxide for photosynthesis; hence, they are also referred to as C_3 grasses. Warm-season turfgrasses fix carbon through the Hatch and Slack pathway (or C_4 cycle); hence, they are also referred to as C_4 grasses (Taiz and Zeiger, 2010). In C_3 plants, photosynthesis process yields the first stable metabolite 3-phosphoglyeric acid a three-carbon product whereas in C_4 plants, oxaloacetate- a four-carbon product is produced (Hull, 1992).

Bermudagrass belongs to the sub-family Chloridoideae and tribe Cynodonteae (Hanna et al., 2013). Taliaferro et al. (2004) noted that *Cynodon* species are distributed world-wide and are particularly abundant in Africa extending to South-east Asia. Early records suggest that bermudagrass thrived in southern Colonial America and began its spread through the southern colonies (Taliaferro et al., 2004). Within the genus *Cynodon*, common bermudagrass [*C. dactylon* (L.) Pers. var. *dactylon*] and interspecific hybrid of common bermudagrass and African bermudagrass (*C. transvaalensis* Burtt Davy), commonly known as hybrid bermudagrass are the most successful turf bermudagrasses. These bermudagrasses are genetically diverse which show significant differences within cultivars in color, texture, density, vigor, and environmental adaptation (Taliaferro, 2003). Bermudagrasses are widely adapted to warm humid, tropical and sub-tropical regions of the world (Beard, 1973). In the United States turfgrass adaptation zone, bermudagrasses extend from southern warmer zone to southern and central parts of transition zone, but they cannot overcome winters in northern transition zone (Christians, 2011). Several cultivars of common bermudagrass and hybrid bermudagrass have been developed so far and have been extensively used as fine turfs for use in golf course tees, roughs, fairways, putting greens, home lawns and athletic fields as well.

A major factor limiting use of bermudagrass within its zones of adaptation is poor shade tolerance, but prior studies suggest variation in shade tolerance exists within the species. In a study of effects of low light treatments in hybrid bermudagrass, significant differences have been reported among hybrid bermudagrass cultivars in turf quality, color, density, canopy photosynthetic rate, canopy chlorophyll index, canopy spectral reflectance, and leaf dry weight when subjected to 70% and 90% low light treatments (Jiang et al., 2004). Similarly, variation in response among 32 bermudagrass cultivars under 90% perpetual shade have been reported (Gaussoin et al., 1988). Because of the apparent genetic variability among bermudagrasses, it is reasonable to hypothesize that improvement in the shade tolerance trait is possible.

Light intensity and quality

Light intensity

Light is essential for plant life. Plant growth and development are dependent on the amount of solar energy which is converted into chemical energy by photoautotrophic plants via photosynthesis (Stier and Gardner, 2007). Only 1 to 2% of the total incident light energy is absorbed and converted into chemical energy by higher plants while the major portion of the incident light is either transmitted, reflected or re-radiated at longer wavelengths (Beard, 1973).

The light energy that reaches a defined area is known as irradiance. It can be measured in terms of energy (watts per square meter) also called solar irradiance. Alternatively, it can be measured in number of photons. Quantum measurement of incident light in moles per square meter per second (mol/ m^2/ s) is also defined as photon flux or quantum flux. For biological processes, the quantum flux of light with a distinct wavelength is more relevant than the irradiance (Taiz and Zeigler, 2010). Solar energy varies at different wavelengths of light. Solar radiation in 400 nm to 700 nm (visible band) is commonly referred to as photosynthetically active radiation (PAR). This PAR designates the spectral range of light where photosynthetic apparatus can capture light energy for photochemical processes (Wherley et al., 2005). Plants predominantly use sunlight in two distinct regions within the PAR wavelengths. Chlorophyll *a* absorbs light at 410 nm, 430 nm and 660 nm whereas Chlorophyll *b* absorbs light at 430 nm, 455 nm, and 640 nm (Taiz and Zeiger, 2010). The amount of PAR available to the plant is described as photosynthetic flux density (PPFD) which is conventionally measured in μmol m^{-2} s^{-1} (Bell et al., 2000). For instance, in the Midwestern United States, a clear day in June will produce a peak PPFD of approximately 1900 μmol m^{-2} s^{-1} (Gardner and Goss, 2013).

For purposes of carbon balance estimates, PPFD is often summed for a given day which gives the daily light integral (DLI, mol m^{-2} d^{-1}). The average monthly DLI for the United States ranges from 55 to 60 mol m^{-2} d^{-1} in the south during summer months to 5 to 10 mol m^{-2} d^{-1} in the north during winter months (Korczynski et al., 2002). Because of the frequent changes in micro-climate, DLI values fluctuate constantly over a short period of time (Korczynski et al., 2002). These variations may be due to location, diurnal cycle, season, atmospheric conditions, cloud cover, plant organ, and plant competition (Gardner and Goss, 2013). Therefore, light conditions need to be monitored in a site-specific basis to determine the exact level of incident irradiance.

In the recent years, the minimum DLI requirements needed to maintain acceptable turf quality (TQ) in a few warm-season turfgrasses have been determined. Bunnell et al. (2005c) determined that the DLI requirements for ‘TifEagle’ bermudagrass to maintain acceptable TQ is 32.6 mol m^{-2} d^{-1}. Similarly, Bunnell et al. (2005a) reported a DLI requirement for hybrid bermudagrasses (‘Tifway’ and ‘TifSport’) to be 16.7 mol m^{-2} d^{-1} during August through October and ‘Celebration’ bermudagrass to be 11.9 and 18.4 mol m^{-2} d^{-1} for acceptable TQ during fall and summer months, respectively. In a similar study done by Miller et al. (2005), ‘Floradwarf’ and ‘Tifdwarf’ bermudagrass required 45.6 mol m^{-2} d^{-1} to maintain acceptable turf cover.

Light intensity in shaded environment

Chlorophyll-containing green plant tissue fixes atmospheric carbon-dioxide to form carbohydrates through photosynthesis utilizing energy from sunlight. These carbohydrate reserves are utilized by plants in respiration. Plant survival requires net photosynthesis to exceed respiration (Wilkinson et al., 1975). However, under reduced light intensities, carbohydrate consumption by respiration may exceed the production by photosynthesis resulting in deterioration of overall turfgrass health (Wilkinson et al., 1975). If the rate of photosynthesis equals the respiration rate, a compensation point is reached. The light intensity at which the photosynthesis rate equals the respiration rate is defined as the light compensation point (Danneberger, 1993). Below this point, a deficit in the carbohydrate balance occurs. Increasing the light on a single leaf will increase CO_2 assimilation rates up to a certain level. However, at one level of light intensity, a saturation effect occurs where additional light will not affect photosynthesis and any additional incident light will be lost through radiation-less transfer (Gardner and Goss, 2013).

In a comparative study of light saturation curves of apparent photosynthesis, natural sun plants showed higher compensation point and higher saturation point than natural shade plants (Burnside and Bohning, 1957). It is also reported that more shade tolerant species will have lower light compensation points (Gardner and Goss, 2013). In general, cool-season turfgrasses that are more shade tolerant reach saturation point at 50 % of full sunlight, while warm-season turfgrasses that are relatively less shade tolerant require full sunlight to saturate (Kephart et al., 1992).

According to Beard (1969), light intensity under shade varies among tree species. Generally, evergreen trees block more light than deciduous trees. Also, due to differences in leaf density and design, maples (*Acer* spp.) and oaks (*Quercus* spp.) provide more shade than ash (*Fraxinus* spp.) or locust (*Robinia* spp.). However, shade related research is usually carried out under neutral shade cloth either in field or greenhouse environments. These shade cloths are specifically designed to reduce light intensity without altering light quality.

In a study to investigate the response of isolated leaf tissue to varying light intensity as compared to total leafage of plant community, Alexander and McCloud (1962) found that in bermudagrass community, the diurnal range effects of light intensities will be the product of inter-leaf interference as well as orientation of the incoming radiation on the individual swards of plant.

Alexander and McCloud (1962) estimated light intensities between 511 to 613 μmol m^{-2} s^{-1} are required for saturation of individual bermudagrass leaves. However, in bermudagrass swards, light saturation points for different cutting heights were different. In a plant community, the partial shading, angle of the leaf, and reflected light on the underside of the leaves will increase the light saturation point.

Light quality

The relative number of photons of each wavelength within a light spectrum is referred to as light quality. The light spectrum is generally separated into three segments of infra-red (greater than 700 nm), visible light (400 nm for blue to 700 nm for red) and ultra-violet (below 400 nm). Turfgrass response to light quality is like other plant species. Plant pigments including chlorophyll and carotenoids have peak spectral absorption at specific wavelengths of light (French, 1963). According to Hendricks (1958), several plant responses, such as flowering, stem elongation, seed germination, leaf enlargement, and rhizome development are influenced by 630 nm to 780 nm region. In general, blue light of about 435 nm influences compact growth, mesocotyl elongation, and has more effects on chlorophyll a than that of red light. Red light enhances shoot elongation, rhizome development and seed germination whereas, infra-red light inhibits seed germination. It was found that turfgrass quality was better when grown under the blue and green wavelengths than the red (McBee, 1969).

The ratio of red to far-red (R:FR) wavelengths of light is also considered important in plant development as it regulates phytochrome activity (Gardner and Goss, 2013). Light quality is also reported to vary with the season and time of a day (Beard, 1973). For instance, at dawn and dusk, the shorter wavelengths are filtered because of lesser angle of incident light. Turfgrass grown in full sun are not affected by the seasonal and diurnal variations in light quality; however, in shade environment where selective reflection, absorption, and transmission occur turfgrass growth and development is affected.

Shade reduces light intensity and alters the light quality which affects the photosynthesis and photo-morphogenensis in turfgrass (Dudeck and Peacock, 1992). McKee (1963) studied characteristics of spectral quality in various types of shade with a color temperature meter. It was found that red wavelengths were filtered in deciduous shade and shade from buildings, while blue light was depleted in dense herbaceous shade. In a similar study with saran shade cloth, Gaskin (1965) found that when shade reduced light intensity by less than 75%, the quality of light (in terms of proportion of red and blue light) did not change compared to tree shade. However, when light intensity was more than 75% in saran shade cloth, the light spectrum changed due to the increased absorption of blue light by tree leaves and quality of light was not comparable between tree shade and cloth shade. Bell et al. (2000) assessed the light spectrum in four different environments: deciduous tree shade, coniferous shade, building shade, and full sun. Changes in spectral quality in morning and afternoon periods in full sun without affecting the total PAR were reported. Results indicated that both shade sources and shade density influence plant pigment content. Light quality differed in shade from tree canopies and buildings compared to those in full sun, with shade from tree canopy preferentially reducing red and blue quanta compared to shade from buildings.

In another study by Baldwin et al. (2009), three warm-season turfgrass species were subjected to variable light spectral qualities in a greenhouse. Turfgrasses selected were ‘Diamond’ zoysiagrass [*Zoysia matrella* (L.) Merr.], ‘Sea Isle 2000’ seashore paspalum (*Paspalum vaginatum* Swartz.) and ‘Tifway’ and ‘Celebration’ bermudagrass [*Cynodon dactylon* (L.) Pers. × *C. transvaalensis* Burtt-Davy]. To create the varying light spectra, four differently-colored shade cloths were used to filter specific wavelengths of visible light. Measurements found that black shade was most detrimental to turfgrass health followed by blue shade, yellow shade, and red shade.

Across shade treatments, Tifway declined the most in turf quality (TQ), while Diamond was the least affected, and Sea Isle 2000 and Celebration responded intermediately. Results indicated that different types of shade have significant impact on TQ of warm-season turfgrasses.

Shade avoidance versus shade tolerance

Shade tolerance can be described as various leaf-level traits interacting together to maximize carbon fixation under reduced solar irradiance (Henry and Aarssen, 1997). Valladares and Niinemets (2008) pointed out shade tolerance as a vital trait in plant community dynamics as all plants are exposed to some degree of shade during their lifetime. Although, general agreement is made on the group of traits that control shade tolerance, the research is still insufficient in understanding the relative importance of traits in influencing the plant growth and development for shade versus full sun environment. According to Grime (1966), shade avoidance can be commonly described as architectural traits causing strong vertical growth under reduced light environment. Mowing turfgrass under shade causes rapid shoot growth. Each time the turf is mowed, shoot growth has to start again resulting loss of energy reserves in clippings. The term shade avoidance is used in conjunction with shade tolerance to explain different mechanisms that can occur simultaneously or exclusively within a plant under shade stress.

Henry and Aarssen (2001) have studied the differences between shade avoidance and shade tolerance in temperate deciduous trees. Generally, shade tolerance is the outcome of physiological changes, while shade avoidance is the result of morphological changes. In a study of relationship between shade avoidance and shade tolerance in woody plants, Henry and Aarssen (1997) described three traits related to shade tolerance mechanism: efficient blue light capture, efficient low irradiance light capture, and efficient harvesting of sunflecks. Sunflecks are brief increases in solar irradiance due to change of sun angle. In understory forest plants, sunflecks contribute significant amount of photon flux density (PFD) available for photosynthesis (Leakey et al., 2004).

Morphological traits relating to shade avoidance are varied, but many of them are observed visually. Generally, mechanisms of shade avoidance are similar to those of strong apical dominance (Smith, 1986). Plants exhibiting apical dominance when grown under low light maximize light interception in the future by growing vertically (Franklin, 2008). Other architectural traits observed are rapid stems and leaves elongation (Morgan and Smith, 1979), upward shift of leaf orientation (Whitelam and Jhonson, 1982), and reduction in leaf chlorophyll content (Smith and Whitelam, 1997).

One of the most serious effects of shade in grasses is the decline in basal axillary meristem activity and ultimately reduced tillering (Bahmani et al., 2000). Reduction in R:FR ratio in shaded environment triggers apical dominance at the expense of tiller development (Brutnell, 2007). According to Devlin et al. (1999), shade avoidance can reduce leaf area and shoot biomass due to shifting of resources in seed setting and flowering if R:FR reduction persists. Smith and Whitelam (1997) have referred these responses collectively as shade avoidance syndrome. Morphological and physiological responses influenced by the reduced light intensity and altered spectral quality is commonly defined as the shade avoidance syndrome (Brutnell, 2007).

Responses to shade

Physiological responses to shade

All turfgrass species grow best in full sun. Shade can cause numerous morphological and physiological changes (Dudeck and Peacock, 1992). Some of these changes in the turfgrass physiology include decrease in respiration rate, light compensation point, carbohydrate reserve, C/N ratio, transpiration rate, and osmotic pressure; as well as an increase in chlorophyll content and tissue moisture (Beard, 1973).

Chlorophyll content

Photosynthesis of a turfgrass plant depends on amount of light pigments in leaf tissue (Gardner and Goss, 2013), and the amount of light absorbing pigment will vary in different light intensities and light qualities. According to Beard (1973), chlorophyll content is reduced when leaves are exposed to high light intensity due to pigment degradation, while chlorophyll content is maximum at relatively lower light intensity. Wilkinson and Beard (1975) found that ‘Merion’ Kentucky bluegrass (*Poa pratensis* L.) exposed to shade produced more chloroplasts and had higher concentrations of chlorophyll in relation to leaf area, yet lower chlorophyll concentrations in relation to leaf weight.

More recent research indicates chlorophyll concentration of plants in shaded environments varies with species and cultivar. Jiang et al. (2005) reported exposure to low light treatments caused reduction in chlorophyll a and chlorophyll b by 34 to 36 % in ‘Sea Isle 1’ seashore paspalum and by 51 to 63 % in ‘TifSport’ hybrid bermudagrass relative to their high light treatments. Low light treatment (60 to 100 μmol m^{-2} s^{-1}) showed no effect in chlorophyll a/b ratio in ‘Sea Isle 1’ but increased the ratio in ‘TifSport’ hybrid bermudagrass compared to high light treatment (500 to 900 μmol m^{-2} s^{-1}). When grasses were transferred from low light to high light environment, both chlorophyll a and chlorophyll b increased but with a greater rate in Sea Isle 1. However, photochemical efficiency did not change under shade in either species. Baldwin et al. (2008) also found variability in shoot chlorophyll concentration tested among 42 bermudagrass cultivars at four and eight weeks after 64% continuous shade initiation. Up to 42% chlorophyll concentration was found to have increased in few genotypes after eight weeks in shade environment, however, the increment was reported to be transient. A few cultivars decreased by nearly 66% in chlorophyll concentration under shade when compared with full sunlight. Bell and Danneberger (1999) found that creeping bentgrass grown in perpetual shade or 100 % morning shade had a lower chlorophyll content than did bentgrass grown in full sun, 100 % afternoon shade, or 80 % morning or afternoon shade. Plant pigments (chlorophyll a, chlorophyll b, neoxanthin, violaxanthin, and lutein) varied significantly in creeping bentgrass among each treatment, but the chlorophyll a/b ratio was unaffected. Results indicated that ratio of chlorophyll a to chlorophyll b was not a reliable indicator of turfgrass shade stress. The concentration of violaxanthin was least in perpetual shade followed by temporal shade and full sun treatments. The authors suggested that violaxanthin content can be better used as a direct indicator of light stress or an inverse indicator of shade stress.

Management practices can influence the turfgrass physiological response and performance in shaded environments. In a study assessing the impacts of growth factor (gibberellic acid, trinexapac-ethyl, nitrogen) and mowing heights on ‘TifEagle’ bermudagrass performance, Bunnell et al. (2005b) found that each treatment combination of growth factors and mowing heights (3.2 mm and 4.7 mm) influenced total shoot chlorophyll concentration in reduced light at four weeks of shade initiation. Specifically, each of the growth factors increased the total shoot chlorophyll concentration. At four weeks after shade initiation, trinexapac-ethyl increased the chlorophyll content by 19-42 % compared with other factors. In the same study, the higher mowing height increased the chlorophyll content by 24% and 45% at four weeks and eight weeks after shade initiation, respectively. Results indicated that greater mowing heights in ‘TifEagle’ bermudagrass increases total leaf area and net photosynthesis and ultimately increasing the chlorophyll content.

Morphological and anatomical responses to shade

Shade induces numerous changes in the morphology and anatomy of the turfgrass leaf blade, leaf sheath, rhizome, stolon and root (Gardner and Goss, 2013). Increases in leaf area, specific leaf area, leaf length, plant height but decrease in root/shoot ratio are some of the morphological changes demonstrated by shaded turfgrass (Dudeck and Peacock, 1992). The common visible changes in the shaded turfgrasses are elongated stems, narrower leaf blades, reduced tillering, and decreased lateral stem growth (Beard 1973; Gardner and Goss, 2013). At the root and rhizome level, shade reduces both the biomass and total lengths. Genotypes capable of maintaining higher root biomass and root length are reported to able to tolerate shade in a better way. In 64% neutral shade study for 60 days, 'Celebration' bermudagrass outperformed 41 other cultivars in shade tolerance (as defined by turf quality) due to its capacity to maintain root biomass and root length (Baldwin et al., 2008). Wilkinson and Beard (1975) noted shade tolerant 'Pennlawn' red fescue (*Festuca rubra* L.) modified leaf angle remaining horizontal to enhance light interception and to avoid green tissue loss, whereas leaf angle in shade intolerant Kentucky bluegrass increased. Jiang et al. (2004) reported differences in plant heights of non-mowed turfs under 70% and 90% shade whereas, no differences in plant heights were observed in full sunlight among seashore paspalum and bermudagrass cultivars. Increased vertical growth for turf managed under shade is a common visible attributes of shade avoidance.

Anatomical characteristics of turfgrass leaves associated with photosynthesis, such as stomatal density and mesophyll cell density are determined earlier in ontogeny than the physiological and biochemical characteristics. Consequently, they result in decreased net CO_2 exchange rate in shaded turfgrass leaves either by anatomical or physiological characteristics or both when compared to full sun grown leaves (Allard et al., 1991). In studying the effects of shade on anatomy of tall fescue leaves, Allard et al. (1991) found that leaf blades under dense shade environment were longer, thinner and had more leaf area but less specific leaf weight than those grown in partial shade or full sun environment. It was reported that leaves in low irradiance showed lower total stomatal density but greater air space than those in high irradiance. Fescues grown at 30% sun showed a reduction in dry matter production associated with a shift towards a higher shoot/root ratio and higher leaf area ratio than those grown in full sun. Results indicated that shaded plants effectively partitioned carbohydrates to produce leaf area; however, those leaves had fewer mesophyll cells, more air space per unit area, and lower stomatal density.

Effects of management in shaded turfgrass

Fertilization, irrigation, and mowing are the three primary cultural practices in turfgrass management. Because the turfgrass growing under shade will undergo numerous physiological and morphological changes, it creates a unique maintenance challenge. Therefore, management practices should be modified accordingly to increase the turfgrass adaptation and performance under shade.

Mowing

Mowing height is a critical management practice for a successful turfgrass stand grown in shade. A higher height of cut provides greater leaf area which presumably increases carbon uptake capacity (Dudeck and Peacock, 1992). However, this increased leaf area may potentially cause higher respiration rates, increased shading from surrounding blades, decreased leaf evaporation, and reduced traffic tolerance that can negatively affect turfgrass quality (Gardner and Goss, 2013).

Few studies have been done on evaluating the shade tolerance of turfgrasses based on mowing height. A shaded 'TifEagle' bermudagrass green when mowed at 4.7 mm improved turf quality and chlorophyll content compared to bermudagrass green maintained at 2.5 mm height (Bunnell et al., 2005b). However, total nonstructural carbohydrates in roots were reduced by increasing mowing heights after eight weeks of shade initiation. In a similar study, Miller and Edenfield (2002) reported that increasing mowing height from 3 mm to 4 mm in ‘Champion’, ‘Floradwarf’, ‘TifEagle’, ‘Tifdwarf’, and ‘Reesegrass’ bermudagrass had little effects on root biomass. However, net photosynthetic rates were increased by 13% for full sun treatment versus increased by 10% for 30% shade treatment at greater mowing heights. In a recent study, Dunne et al. (2017) found that increasing mowing height from 19 mm to 51 mm improved percent turfgrass cover, percent divot recovery and NDVI in bermudagrass cultivars treated under 63% shade.

Fertilization

Nitrogen is the essential nutrient in turfgrass management that provides color, density, recuperative ability and improves overall plant health when used at proper rates. It is commonly accepted that in low light environment, reduction of nitrogen will benefit overall turfgrass health. In 'Coastal' bermudagrass, Burton et al. (1959) reported high nitrogen fertilization increased plant density and total leaf area in full sunlight whereas, in 64% shade, plant density and total leaf area were decreased with addition of nitrogen. Lower nitrogen by alternate monthly application (98 kg N ha^{-1}) comparted to higher nitrogen (195 kg N ha^{-1}) was reported to improve NDVI, turfgrass cover, lateral spread, and recovery in bermudagrass cultivars grown under 63% shade (Dunne et al., 2017).

Plant growth regulators

Turfgrass performs poorly in shade due to the excessive elongation of shoot and reduction of tillering capacity. Plant growth regulator, such as trinexapac-ethyl (TE) effectively reduces gibberellic acid bio-synthesis and subsequent shoot cell elongation (Ervin et al., 2002). Application of TE to 'Meyer' zoysiagrass under shade (77% and 89% shade) reduced shoot growth and improved turf quality compared to control (Ervin et al., 2002).

Qian and Engelke (1999) assessed the effects of TE on 'Diamond' zoysiagrass under shade. Plants receiving monthly (0.048 kg a.i. ha^{-1}) and bimonthly treatments (0.096 kg a.i. ha^{-1}) maintained acceptable turf quality throughout the treatment period, while control treatment declined in turf quality after shading. Results illustrated TE when applied once or twice a month decreased 76% to 73% vertical shoot growth and 77% to 75% clipping yield, while increased 40% to 38% total nonstructural carbohydrates, 60% to 50% root mass, 51% to 46% root viability and 48% to 42% photosynthesis rate (Qian and Engleke, 1999).

Effects of gibberellic acid inhibiting plant growth regulators, TE and its combination with other growth regulators and bio-stimulants in shaded creeping bentgrass were also studied (Ervin et al., 2004). It was reported that twice monthly application of TE improved leaf color and turf quality relative to control. Also, the creeping bentgrass under 88% shade responded better to propiconazole treatment in terms of leaf color, density and overall turf quality than the control. The combinations of other stimulants with TE did not influenced better than TE alone. The effects of TE alone or combined with lower mowing height were reported to improve turfgrass cover in bermudagrass cultivars under 63% shade (Dunne et al., 2017). The above studies support the use of plant growth regulators as an effective tool in management of shade stress.

Relative shade tolerance of bermudagrass cultivars

Among the warm-season turfgrasses, bermudagrass is considered relatively shade intolerant turfgrass. The relative shade tolerance of bermudagrass is considered better than bahiagrass (*Paspalum notatum* Fluegge), and buffalograss [*Buchloe dactyloides* (Nutt.) Engelm.] but worse than St. Augustine (*Stenotaphrum secundatum* Walt.), zoysiagrass, centipedegrass [*Eremochloa ophiuroides* (Munro) Hack.], and seashore paspalum (Gardner and Goss, 2013).

Among the turf-type bermudagrasses, there have been reports of considerable variation in shade adaptation (Gaussoin et al., 1988; Baldwin et al., 2008). Gaussoin et al. (1988) evaluated the performance of 32 bermudagrass clones in shade where ‘Boise’, ‘No Mow’, ‘R9-P1’, ‘NM2-13’, and ‘NM3’ were reported to be relatively shade tolerant, whereas ‘NM 47-3’, ‘Santa Ana’, and ‘AZ Common’ were highly shade intolerant. Rankings were based on percent dry matter yield reduction from high to low light treatment and non-significant treatment differences for measured attributes (Gaussoin et al., 1988). Baldwin et al. (2008) in a recent evaluation of 42 bermudagrass cultivars under shade classified them into separate groups based on their relative shade tolerance. Cultivars with the best performance under shade were ‘Celebration’, ‘Tift No.4’ (later named TifGrand), ‘Tift No.1’, and ‘Transcontinental’. Cultivars ‘SWI-1014’, ‘Arizona Common’, ‘Sundevil’, ‘SR 9554’, ‘GN-1’, and ‘Patriot’ were most shade sensitive. And cultivars with intermediate shade tolerance included ‘Aussie Green’, ‘MS-Choice’, ‘Princess 77’, ‘SWI-1045’, ‘SWI-1041’, and ‘SWI-1012’.

Currently, the National Turfgrass Evaluation Program (NTEP) 2013 bermudagrass trial has set out eight standard entries namely ‘Tifway’, ‘Latitude 36’, ‘Patriot’, ‘Celebration’, ‘NuMex-Sahara’, ‘Princess 77’, ‘Riviera’, and ‘Yukon’(ntep.org). Parameters used to access selected turfgrass in the NTEP typically include turfgrass quality, color, leaf texture, density, spring green up, seedling vigor, living ground cover, drought tolerance, winter kill, disease/insect damage (Morris and Shearman, 2000).

Interaction of shade and drought

Evapotranspiration and drought resistance

Evapotranspiration (ET) is the total water loss through evaporation from soil and vegetation and plant water loss through transpiration. Evapotranspiration is affected by wind velocity, relative humidity, air temperature, soil temperature, turfgrass species and cultivar, and soil characteristics (Kim and Beard, 1988). Water requirements of turfgrass depend on the species, the function of the turf, and the climate in which it is grown (Kopp and Jiang, 2013). Turfgrass water requirements can generally be described in terms of their relationship to ET. It is a common practice to measure ET using hydrological approaches such as lysimeter, which provide a direct measurement of ET. However, higher variability in ET rates either between the species or within the species of turfgrasses have been reported. Highly variable results are due to climatic conditions, turfgrass species and cultivars, mowing height and fertilization (Romero and Dukes, 2016).

When soil moisture is insufficient to meet the water demand of a turfgrass, plants become exposed to drought stress. Drought stress is an extensive area of research in turfgrass because of limitations of urban water use and a societal need for water conservation. Although bermudagrass is considered a drought resistant species, adequate soil moisture is needed to maintain high quality turf (Taliaferro, 2003). In the context of perennial turfgrass species, plants can exhibit two mechanisms of drought resistance: tolerance and / or avoidance. Drought avoidance mechanism allows plant to avoid tissue dehydration either by developing deep root system to reach soil moisture in deeper soil profile and/or by closing stomata to slow down transpiration (Fry and Huang, 2004). Drought tolerance mechanism allows plant to maintain cell turgor at low water potential through osmotic adjustments and to delay wilting (Fry and Huang, 2004).

Numerous studies have been conducted in improving the drought resistance in bermudagrass. On evaluating the drought resistance of seven commonly used turfgrasses, Carrow (1996) reported ‘Tifway’ bermudagrass and common bermudagrass were the best performers. Baldwin et al. (2006) conducted a greenhouse study to evaluate the drought resistance of six bermudagrass cultivars. Although, no cultivars showed acceptable turf quality after four weeks of 5 d irrigation interval, observed differences at week two suggested ‘Celebration’ and ‘Aussie Green’ were better than others tested. In another study of evaluating the turf quality after 60 d of dry-down, Steinke et al. (2011) found that among eight cultivars of bermudagrass, cultivars ‘Celebration’ and ‘Texturf’ showed greater drought resistance than others tested.

Several studies have suggested different physiological techniques for screening drought resistance including leaf water potential (Sojka et al., 1981), relative water content (Fu et al., 2004;

Jiang et al., 2009), canopy temperature (Jiang et al., 2009), and electrolyte leakage (Jiang and Huang 2001; Su et al., 2007).

Combined effects of shade and drought

Shade stress is often confounded with soil water stress due to tree root competition. Although there have been numerous studies on individual effect of either shade stress or drought stress on turf quality, there is no attempt made until now to study the combined effects of shade and drought interactions. However, studies on combined impacts of shade and drought on woody seedlings are common. In studying the interaction, the basic question is to know whether a drought stress has facilitation role or trade-off role in tolerance.

Sack and Grubb (2002) synthesized five hypotheses to explain the relationship between shade and drought stress in a plant community. First, the *influential trade-off* hypothesis predicts that drought has a stronger negative effect on shade-weakened plants. This could be more important for plants having lower root: shoot ratio, resulting in greater sensitivity to drought stress a high specific leaf area and leaf area ratio for efficient irradiance capture at the expense of their root allocation as indicated by Smith and Huston (1989). Second, the *above-ground facilitation* hypothesis predicts that shade-induced temperature moderation reduces the effect of drought stress by alleviating the evaporative demand at the leaf. Third, the primary limitation hypothesis predicts that the impact of drought will be less in dense shade because water will have less role in growth due to limitation of light. Shade reduces the effect of drought stress in a linear relationship with the severity of shade. The fourth is the *interplay* hypothesis, which predicts that moderate shade reduces the effect of drought stress while dense shade can worsen it. Finally, a *null* hypothesis predicts that effects of shade and drought are orthogonal. These hypotheses have not been tested for managed turfgrasses and how the two stresses shade and drought interact to influence turfgrass quality warrants study.

Research goal and objectives

The long-term goal of this research is to develop best management practices for shaded landscapes in regards to grass selection and water management.

The objectives of this research are:

1. To compare the relative shade tolerance of eight commercially-available and two experimental bermudagrass cultivars in a transition zone climate.
2. To measure the effect of drought stress on shaded and non-shaded bermudagrass turf quality and water use rate.
3. To determine if the response to shade, drought, or combined shade and drought differ among bermudagrass cultivars.

Testable hypothesis

1. The two experimental bermudagrass lines (OKS 2011-1 and OKS 2011-4) will demonstrate better or equal turf quality to commercially available cultivars when grown under moderate to heavy shade in Oklahoma.
2. Shade will reduce the severity of drought stress in bermudagrass cultivars.
3. Relative performance of bermudagrass cultivars will differ in shade alone, drought alone, or combine shade and drought environments.

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CHAPTER II

EVALUATION OF BERMUDAGRASS CULTIVARS IN DIFFERENT SHADE DENSITIES IN OKLAHOMA

Introduction

Nearly 25% of turfgrasses are estimated to be growing under shade (Beard, 1973). The unfavorable microclimatic conditions created by shade can include reduced solar irradiance, altered light quality, restricted air-flow, and increased tree-root competition (Baldwin et al., 2009; Gardner and Goss, 2013; Koh et al., 2003). Turfgrass areas encounter shade caused by adjacent physical structures or trees and shrubs, often resulting in reduced turfgrass quality. Bermudagrass (*Cynodon* spp.) is a popular turfgrass species in the southern United States and commonly used in home lawns and golf course roughs. The reason for bermudagrass' widespread usage is its many desirable traits including drought resistance, traffic tolerance, disease resistance, weed resistance and excellent recuperative potential (Beard, 1973). However, bermudagrasses are sensitive to low irradiance. In the transition zone, this often requires managers to establish multiple turfgrass species within a single landscape which decreases the uniformity of the turf and increases the complexity of managing two turfgrass species. Development of a more shade-tolerant bermudagrass would remove the necessity for multi-species lawns.

Screening of germplasm, poly-crossing, and testing the performance of potential cultivars for better shade tolerance are standard approaches to identifying and improving plant stress tolerance. There has been a continuing effort from turfgrass scientists to improve the shade tolerance trait in bermudagrass but this has been met with minimal success. However, considerable variation in the adaptation of bermudagrass cultivars to shade has been reported. Under 90% perpetual shade, Gaussoin et al. (1998) found variations in shade tolerance among 32 bermudagrass clones. Similarly, under 64% perpetual shade, 42 bermudagrass cultivars were categorized into three distinct shade tolerance groups based on their relative performance in shade (Baldwin et al., 2006). Five bermudagrass cultivars exhibited variable shade tolerance evaluated in summer and autumn seasons (Trappe et al., 2011). Under 70% shade, the interspecific hybrid bermudagrass [*Cynodon dactylon* (L.) Pers. x *C. transvaalensis* Burtt-Davy] 'TifGrand' exhibited a two-fold increase in turf cover compared to other dwarf bermudagrass cultivars (Hanna et al., 2010). Several studies have reported better shade tolerance in common bermudagrass [*C. dactylon* (L.) Pers.] 'Celebration' (Baldwin et al., 2008; Bunnell et al., 2005; Dunne et al., 2015). However, the improved shade tolerance of Celebration and TifGrand remains inadequate in maintaining acceptable quality for moderate and severe shade conditions. Further, these two cultivars were developed in sub-tropical climates and are not likely to be well-adapted to the transition zone of the United States. Improving cold and shade tolerance traits in bermudagrass will eventually broaden the species use and function while reducing management inputs for golf and lawn sites. Therefore, there is a critical need to evaluate and improve the shade tolerance of bermudagrasses for use in the transition zone.

The objective of this research was to compare the relative shade tolerance of eight commercially-available and two experimental bermudagrass cultivars in a transition zone climate. The hypothesis for this experiment was that two experimental lines of bermudagrass tested in the project will perform better in shade than the commercially available cultivars.

Materials and methods

Experimental area

A field study was conducted at the Oklahoma Agriculture Experiment Station, Turfgrass Research Center in Stillwater, OK (lat. 36^0 7’ N, long. 97^0 6’ W). The research site was composed of three light blocks which subjected turfgrasses to either ‘open sun’, ‘moderate shade’ (average 52% shade), or ‘severe shade’ (average 75% shade). The severe shade block was bordered by evergreen trees on the west, eastern redbud (*Cercis canadensis* L.) on the east and sugar maple (*Acer saccharum* Marsh.) on the south. The effect of this natural vegetation in the borders reduced the daily photosynthetically active radiation (PAR) by an average of 25% compared to the open sun in 2016. Two 3m- wide strips of black shade fabric (high density polyethylene knitted cloth) rated to reduce incoming radiation by 75% were laid across a hoop structure 4.5m above the site to reduce mid-day radiation. The moderate shade treatment was implemented by suspending a 3m strip of shade cloth across a metal structure approximately 2.7m tall and centered on the plots. Nearby deciduous trees on the east and west sides of the block applied shade only in the early morning and late evening. The open sun block had no artificial obstruction to light, although deciduous trees to the east applied shade for 2 hours each morning.

Cultivars

Ten bermudagrass cultivars were planted within 0.9m x 1.5m plots in summer 2013 and allowed to establish under ambient conditions for one year. Two of the cultivars, OKS 2011-1 and OKS 2011-4, were experimental cultivars whose parental lines had previously demonstrated improved shade tolerance (Bell and Wu, 2014). These two synthetic cultivars were obtained by poly-crossing the 10 best-performing clones from a 3-year shade selection process. The other eight entries were commercially-available seeded and clonal cultivars: ‘Celebration’, ‘Latitude 36’, ‘Northbridge’, ‘TifGrand’, ‘Patriot’, ‘Princess 77’, ‘Riviera’, and ‘Yukon’ (Table 1). Clonal cultivars were established from plugs, while seeded cultivars were established from seeds.

Research design and data analysis

The study was arranged in a randomized complete block design where ten cultivars of bermudagrass were replicated four times in each light treatment block. Shade treatments were applied for three consecutive years from 2014 through 2016. The replications were created along north-south direction to control the potential gradients. All data were analyzed using analysis of variance (ANOVA) with the general linear model procedure (GLM) in SAS software version 9.4 (SAS Institute, 2012). Treatment means were separated using Fisher’s protected Least Significant Difference (LSD) test at $p \leq 0.05$ level. Cultivars were also assessed using a turf performance index (TPI) which aggregates multiple assessment dates and parameters to determine the most consistent performer across dates and environments (Wherley et al., 2011). A cumulative TPI score was generated for each cultivar, representing the number of times it occurred in the top statistical group as determined by least significant differences across all parameters and all sampling dates.

Cultural management

Grasses were mowed once per week at a 5cm height to simulate the mowing height of a golf course rough. Fertilization was applied at a rate of 24 kg N ha^{-1} (urea) biweekly during the active growing season during the first two years of the study. A total of 246 kg N ha^{-1} yr^{-1} and 172 kg N ha^{-1} yr^{-1} were applied in 2014 and 2015, respectively. During 2016, the fertilizer rate was reduced to 24 kg N ha^{-1} once per month (123 kg N ha^{-1} yr^{-1}) because of substantial scalping in the previous year. Fields were irrigated as needed to prevent visible drought stress. A mix of 2,4-D, Mecoprop-p, and Dicamba (Strike 3, Winfield Solutions) at a rate of 3.5 L of product ha^{-1} and glyphosate at a rate of 1.75 L ha^{-1} were applied in the winter (Feb, 2014; Jan, 2015; Jan 2016) of each year for post-emergence control of annual and perennial weeds. Oxadiazon (Ronstar Flo, Bayer Environmental Science) was sprayed at a rate of 2.2 kg ha^{-1} before spring green up in each year (Feb 2014; March 2015; Feb 2016) to control summer annual weeds. Pendimethalin (Pendulum 3.3 EC, BASF) was applied at a rate of 2 kg ha^{-1} in the fall (September, 2014; Aug 2015). Imidacloprid (Merit 2F, Bayer Environmental Science) was applied once at a rate of 0.45 kg ha^{-1} in Oct 2014 to control grubs. Glyphosate was sprayed in borders between cultivars as needed to prevent contamination.

Data collection

Data collection was performed in June through September for each treatment year (i.e., 2014, 2015, and 2016). In each treatment block, photosynthetically active radiation (PAR) was measured every 30 min using quantum sensors installed approximately at 0.5m above the ground (Spectrum Technologies, Plainfield, IL). In 2014 and 2015, data were measured from a single sensor per block. In 2016, three additional sensors were placed within the severe shade treatment to assess variation in shade across replication. In 2016, a WatchDog 2550 micro-weather station (Spectrum Technologies, Plainfield, IL) was also installed on the severe shade and open sun treatment blocks to record wind speed, air temperature, and relative humidity.

Turf quality (TQ) was evaluated biweekly in the growing season using the National Turfgrass Evaluation Program (NTEP) visual scale of 1 to 9, where 1 = brown dead turf and 9 = ideal green healthy turf and 6 = minimally acceptable turf (Morris and Shearman, 2000). Spring green-up was similarly evaluated using NTEP methodology each April.

Canopy spectral reflectance was collected using an active sensor reflectance meter (Trimble Navigation Inc., Sunnyvale, CA) to calculate a normalized difference vegetation index (NDVI) using the following formula:

$$\text{NDVI} = (\text{NIR} - \text{Red}) / (\text{NIR} + \text{Red}) \qquad \text{(Eq. 1)},$$

where Red and NIR are spectral reflectance measurements acquired in the red (visible) and near-infrared regions, respectively. Measurements were made monthly as a single pass across the middle of the plots. The NDVI has been shown to be an objective measure of turfgrass color and density for assessing turfgrass performance in shade (Bell et al., 2002).

Digital images of each plot were taken monthly during 2016 to assess the turfgrass cover using a camera (Canon Power Shot G16, Melville, NY) mounted on the top of an enclosed light box illuminated with four fluorescent lamps following the methods of Richardson et al. (2001). The images were then analyzed using SigmaScan Pro version 5.0 (Systat Software, Inc., San Jose, CA) to determine the percent green cover (Karcher and Richardson, 2005). While analyzing the images, hue and saturation threshold settings ranged from 30 to 140 and 0 to 100 respectively.

Results

The cultivar x year interactions were significant for TQ and spring green-up in open sun and moderate shade (Appendix I), so the data were analyzed separately for individual year. Data were analyzed individually for each light treatment as a separate experiment because there was no replication of light treatment. The response of each cultivar under open sun, moderate shade and severe shade was analyzed from June through September.

Micro-environment

In 2014, compared to open sun, the severe shade received on average 21% of open sun (8.9 mol m^{-2} d^{-1}) and moderate shade received on average 41% of open sun (17.2 mol m^{-2} d^{-1}) (Table 2). In 2016, compared to open sun, severe shade received average 20% sunlight (9.2 mol m^{-2} d^{-1}) and moderate shade received 39% sunlight (17.7 mol m^{-2} d^{-1}) (Table 2). In severe shade, average mean temperature was 0.4^0 C lower, relative humidity was 1.2 % higher, wind speed was 0.9 mph lower, and wind gust was 1.9 mph lower than in open sun (Table 2). Light data from the 2015 growing season were lost during a computer crash, but the micro-environments were likely similar to those measured in other years of the study.

Open sun

Under open sun, cultivars differed significantly in TQ, NDVI, spring green up, and percent green cover in each year (Table 3-5). In 2014, Latitude 36 and Northbridge had similar average TQ to each other but a significantly higher average TQ than other entries (Table *6*). In 2015, Northbridge had the highest average TQ; while in 2016, Latitude 36 and Northbridge demonstrated the highest average TQ (Table 7-8). TifGrand and OKS 2011-4 had the lowest average TQ in each year (Table 6-8). The average TQ scores were above minimally acceptable in each year for each cultivar except TifGrand and OKS 2011-4 in 2016 (Table 6-8).

In 2014, Latitude 36 showed the highest numerical average NDVI but was statistically not different from OKS 2011-1, Northbridge and Riviera (Table *6*). The lowest average NDVI in 2014 was observed in OKS 2011-4 but it was similar to Celebration, Patriot, Princess 77, or TifGrand (Table *6*). In 2015, Latitude 36 had the highest numerical average NDVI but it was statistically similar to Northbridge and OKS 2011-1 (Table 7). The lowest average NDVI in 2015 was observed in Patriot and Princess 77, but each was not different from OKS 2011-4, Celebration, TifGrand or Yukon (Table 7). In 2016, OKS 2011-1 had the highest average NDVI, and Patriot had the lowest (Table 8).

Cultivars in the top statistical group for spring green-up were Latitude 36 and Northbridge in 2014; OKS 2011-1, Riviera, and Yukon in 2015; and Latitude 36 in 2016 (Table 6-8). In 2016, Latitude 36 and Northbridge had the highest green coverage (90% and 89% respectively) and TifGrand and Yukon had the least green coverage (66% for each) (Table *9*). Overall performance of the cultivars using the TPI was ranked as follows: Latitude 36 > Northbridge > OKS 2011-1 > Riviera > Yukon > Celebration > Princess 77 > 2011-4 = Patriot > TifGrand.

Moderate shade

In 2014, Latitude 36 and Riviera demonstrated the highest average TQ rating and average NDVI rating, respectively, while each cultivar maintained TQ greater than the minimally acceptable threshold (Table *10*). In 2014, Latitude 36 and Northbridge had a similar green-up rating to each other but better than other entries. In 2015, each cultivar maintained minimally acceptable turfgrass quality, but no significant differences were observed among cultivars, although TifGrand showed a poor spring green-up capability (Table *11*). In 2016, cultivars were not significantly different based on average TQ or NDVI ratings and were below the minimally acceptable quality threshold (Table *12*). Northbridge and Latitude 36 had the highest average green coverage (65 % and 63% respectively), while OKS 2011-4 and TifGrand had the lowest average green coverage (39% for each) (Table *13*). That same year, TifGrand and Princess 77 were the slowest to green-up in spring compared to other cultivars. Overall performance of cultivars using the TPI was ranked as follows: Northbridge > Latitude 36 > Princess 77 > OKS 2011-1 = Riviera > Celebration > Yukon > Patriot > OKS 2011-4 > TifGrand.

Severe shade

In 2014, only three cultivars (Latitude 36, Northbridge, and Celebration) demonstrated average TQ above a minimally acceptable rating (Table *14*). That same year, Patriot had the lowest average NDVI rating, and Latitude 36 had the best spring green-up rating. By 2015, none of the cultivars could maintain an acceptable turfgrass quality, although Celebration showed the highest quality and Patriot the lowest (Table *15*). Similarly, Patriot and Princess 77 were the slowest to green-up each in spring, while Riviera was the fastest. Princess 77 and Yukon had the highest average NDVI ratings but were similar to OKS 2011-1, Celebration, Latitude 36, and Northbridge. By 2016, Celebration showed the highest average TQ among other cultivars tested and demonstrated the fastest spring green-up, while Patriot had the least average TQ and the slowest to green-up in spring (Table 16). Celebration, OKS 2011-1, Northbridge and Princess 77 showed statistically similar average NDVI among each other but were better than the other cultivars tested (Table 16). Latitude 36, Celebration, and Northbridge had similar green coverage (40%, 38% and 36% respectively) but better than others in 2016 (Table *17*). Overall performance of cultivars using the TPI was ranked as follows: Celebration > Northbridge > Latitude 36 > OKS 2011-1 > Riviera = Princess 77 = Yukon > OKS 2011-4 > TifGrand > Patriot (Table *18*).

Seeded entries

Because of differences in establishment methods and the presence of more genetic variation in seeded cultivars (as compared to clonal cultivars), targeted comparisons among seeded cultivars was of interest. Among seeded cultivars, OKS 2011-1 demonstrated the best TPI for open sun and severe shade, while Princess 77 was the best in moderate shade (Table *18*). However, even the best seeded entry in moderate shade or severe shade did not maintain an acceptable TQ at the end of study. OKS 2011-4 was consistently the worst seeded type in each environment and each year.

Discussion

This study was different from several previous shade studies due to the incorporation of shade from both natural vegetation and neutral shade fabric. Furthermore, these methods created additional stressors such as tree-root competition and restricted air-flow. Although it is likely that these additional changes could have increased random error within the experiment, the environment was a more realistic simulation of actual shaded sites. Along with the reduced irradiance, these factors are likely to have contributed to worsening the turf quality and performance. Koh et al. (2002) found airflow restriction of creeping bentgrass (*Agrostis palustris* Huds.) putting greens reduced turf color, density and root mass and restriction alone caused greater reduction in turf color and density than shade.

Due to the limited space and resources, it was not feasible to replicate the light treatment. By analyzing each light block as a separate experiment, we were still able to quantify the relative performance for each individual shade environment. Overall, the performance of each cultivar gradually declined as duration of shade increased within each year. Cultivars in moderate shade were poorer than in open sun and cultivars in severe shade were poorer than in moderate shade and open sun. The quality and performance of cultivars (based on NDVI and percent green cover) was affected by the cumulative shade duration effect as well. Several studies have reported similar decline in turf quality, density and color due to prolonged shade (Baldwin et al., 2008; Bell and Danneberger, 1999; Bunnell et al., 2005; Dunne et al., 2015; Jiang et al., 2004).

Cultivars TifGrand and Patriot were consistently in the lowest statistical group in each year and light treatment block. The poor turf quality and overall performance of TifGrand and Patriot, regardless of light treatment, suggests these two cultivars were not well-adapted to the present study site or management conditions. Specifically, the taller mowing height (5cm) may have exceeded the ideal range for these two cultivars, which presumably could have led to reduced plant density and poorer turf quality. The poor performance of TifGrand in shade contradicts prior research by Hanna et al., (2010) and Baldwin et al., (2008) who reported TifGrand did better than other bermudagrass cultivars under 70% shade and 64% shade respectively. Furthermore, TifGrand was especially developed for use in shaded turf sites (Hanna et al., 1997). On the other hand, the poor performance of Patriot in shade is in agreement with previous reports that Patriot is highly shade sensitive and the poorest among bermudagrass cultivars under 64%, 60%, or 49% continuous shade (Baldwin et al., 2008; Hanna and Mow, 2007; and Trappe et al., 2011).

Cultivars performing better in open sun were better than others in moderate shade or severe shade as well. For instance, Latitude 36 and Northbridge were well adapted to our study sites and had ranked in top three group in each light environment based on cumulative TPI table. Interestingly, Celebration had demonstrated varying shade tolerance in terms of TQ and NDVI in different shade densities. In open sun, it had maintained fairly good quality in each year but was behind the top performing cultivars, such as Northbridge and Latitude 36. In moderate shade, the performance of Celebration was at acceptable level for first two years but was not ranked in the top group. In severe shade, although it was below acceptable quality, it had outcompeted all other cultivars as shade intensified. The better shade tolerance of Celebration in severe shade agrees with prior studies by Bunnell et al., (2005) and Baldwin et al., (2008) who reported Celebration outcompeted TifSport and Tifway under 71% shade and Celebration was top performer under 64% shade among 42 bermudagrass cultivars tested respectively. Baldwin et al., (2008) had ranked the relative shade tolerance of bermudagrass as Celebration > TifGrand > Princess 77 > Riviera > Yukon > Patriot. Excluding TifGrand, this ranking is in close agreement with the results found in this study.

The relatively better turf quality demonstrated by Celebration in severe shade could have been associated with a lower light compensation point. Previous work by Miller et al., (2005) using bermudagrass putting greens reported difference in light compensation point between Tifdwarf and Floradwarf cultivars. The same authors had also noticed the prostate growth habit of Floradwarf, which could have benefitted in tolerating more shade. Utilizing carbohydrate reserves in lateral spread rather than in vertical growth might help grass to maintain green cover while saving more photosynthetic materials being clipped off. Research working towards finding alternative ways to differentiate shade tolerance among large numbers of cultivars are needed.

Conclusion

This study confirmed that variability exists among bermudagrass cultivars in terms of shade tolerance although none maintained acceptable turf quality under the most severe shade treatment. The seeded experimental cultivars evaluated in this experiment did not perform better than commercially available cultivars in moderate or severe shade suggesting further recurrent selection is required.

Table 1. Bermudagrass genotypes evaluated in the three-year shade study.

Genotypes	Species	Propagation material[z]
OKS 2011-1	*C. dactylon*	Seed
OKS 2011-4	*C. dactylon*	Seed
Riviera	*C. dactylon*	Seed
Yukon	*C. dactylon*	Seed
Princess 77	*C. dactylon*	Seed
Latitude 36	*C. dactylon* x *C. transvaalensis*	Plugs
Northbridge	*C. dactylon* x *C. transvaalensis*	Plugs
Patriot	*C. dactylon* x *C. transvaalensis*	Plugs
TifGrand	*C. dactylon* x *C. transvaalensis*	Plugs
Celebration	*C. dactylon*	Plugs

[z] Cultivars were propagated using seeds and plugs for seeded and clonal types respectively.

Table 2. Daily mean accumulated PAR[z] in 2014 and daily mean accumulated PAR, air temperature, relative humidity, wind speed, and wind gust in 2016 shade study.

Blocks	June	July	Aug	Sept	Avg
	2014 PAR (mol m^{-2} d^{-1})				
Full Sun	43.8 ± 10.6	43.8 ± 16.1	46.9 ± 6.2	32.4 ± 11.6	41.7 ± 11.1
Moderate shade	17.8 ± 5.4	18.1 ± 8.2	17.5 ± 7.7	15.5± 7.4	17.2 ± 7.1
Severe shade	9.3 ± 6.4	9.8 ± 9.7	9.1 ± 5.9	7.5 ± 6.5	8.9 ± 7.1
	2016 PAR (mol m^{-2} d^{-1})				
Full Sun	50.7 ± 14.8	51.7 ± 10.9	42.4 ± 11.0	37.1 ± 9.4	45.5 ± 11.5
Moderate shade	21.4 ± 5.0	19.9 ± 5.2	18.6 ± 4.5	15.2 ± 3.4	18.8 ± 4.5
Severe shade	11.1 ± 2.4	9.5 ± 2.9	7.0 ± 3.2	7.0 ± 2.4	8.7 ± 2.7
	2016 Mean air temperature (^{0} C)				
Full Sun	26.7 ± 5.2	28.0 ± 5.0	26.7 ± 4.9	23.3 ± 5.5	26.2 ± 5.2
Severe shade	26.2 ± 5.3	27.7 ± 4.5	26.4 ± 4.8	23.0 ± 5.9	25.8 ± 5.1
	2016 Mean relative humidity (%)				
Full Sun	72.0 ± 18.2	73.8 ± 17.7	73.4 ± 18.4	75.8 ± 17.9	73.8 ± 18.0
Severe shade	73.3 ± 19.8	75.3 ± 17.4	74.6 ± 17.2	76.9 ± 18.3	75.0 ± 18.2
	2016 Mean wind speed (m s^{-1})				
Full Sun	0.6 ± 0.2	0.8± 0.2	0.5 ± 0.2	0.6 ± 0.2	0.6 ± 0.2
Severe shade	0.2 ± 0.4	0.3 ± 0.4	0.2 ± 0.4	0.2 ± 0.4	0.2 ± 0.4
	2016 Mean wind gust (m s^{-1})				
Full Sun	2.3 ± 1.3	2.9 ± 1.4	2.1 ± 1.3	2.2 ± 1.3	2.4 ± 1.3
Severe shade	1.5 ± 1.4	1.9 ± 1.6	1.4 ± 1.3	1.5 ± 1.4	1.6 ± 1.4

[z] Photosynthetically active radiation (PAR) was recorded every 30 min intervals using quantum light sensor and data aggregated per month.

Table 3.Analysis of variance for turf quality, normalized difference vegetation index, and spring green-up across months in open sun, moderate shade, and severe shade environments in 2014 at Oklahoma State University Turfgrass Research Center.

		Turf quality					Normalized difference vegetation index					Spring green-up
Source	df	June	July	Aug	Sept	Avg	June	July	Aug	Sept	Avg	April
		Pr > F										
		Full Sun										
Cultivar	9	**	***	***	***	***	***	***	*	***	***	***
Block	3	NS	NS	NS	NS	NS	***	NS	NS	*	NS	***
Error	27											
		Moderate Shade										
Cultivar	9	**	***	***	***	***	***	NS	*	***	***	***
Block	3	**	*	***	**	***	***	NS	*	***	**	NS
Error	27											
		Severe Shade										
Cultivar	9	***	***	***	***	***	***	NS	***	***	***	***
Rep	3	*	*	*	**	**	NS	NS	NS	NS	NS	NS
Error	27											

*, **, ***, and NS= $P < 0.001$, $P < 0.01$, $P < 0.05$, and $P > 0.05$, respectively.

Table 4. Analysis of variance for turf quality, normalized difference vegetation index, and spring green-up across months in open sun, moderate shade, and severe shade environments in 2015 at Oklahoma State University Turfgrass Research Center.

		Turf quality					Normalized difference vegetation index					Spring green-up
Source	df	June	July	Aug	Sep	Avg	June		Aug	Sep	Avg	April
		Pr > F										
		Full Sun										
Cultivar	9	***	***	***	NS	***	**		*	NS	***	***
Block	3	NS	NS	NS	NS	NS	***		***	NS	NS	NS
Error	27											
		Moderate Shade										
Cultivar	9	***	***	***	***	NS	***		***	NS	**	NS
Block	3	***	***	***	***	*	***		***	***	NS	**
Error	27											
		Severe Shade										
Cultivar	9	***	***	***	***	***	***	***	***	*	***	***
Block	3	NS	NS	**	NS	NS	*	NS	NS	***	**	NS
Error	27											

*, **, ***, and NS= P < 0.001, P < 0.01, P < 0.05, and P > 0.05, respectively.

Table 5. Analysis of variance for turf quality, normalized difference vegetation index, spring green-up, and percent green cover across months in open sun, moderate shade, and severe shade environments in 2016 at Oklahoma State University Turfgrass Research Center.

		Turf quality					Normalized difference vegetation index					Spring green-up	Percent green cover			
Source	df	June	July	Aug	Sep	Avg	June	July	Aug	Sep	Avg	April	June	July	Aug	Avg
		Pr > F														
		Full Sun														
Cultivar	9	***	***	***	**	***	**	NS	**	*	*	***	***	***	***	***
Block	3	NS	**	***	***	***	NS	NS	NS	*	***	NS	NS	NS	NS	NS
Error	27															
		Moderate Shade														
Cultivar	9	**	NS	NS	*	NS	*	NS	**	*	NS	**	***	***	***	***
Block	3	**	*	NS	***	**	*	NS	*	***	*	NS	***	***	NS	***
Error	27															
		Severe Shade														
Cultivar	9	*	**	**	*	**	***	*	***	*	***	***	***	***	***	***
Block	3	NS	**	***	*	**	*	***	***	NS	**	NS	NS	NS	***	NS
Error	27															

*, **, ***, and NS= P < 0.001, P < 0.01, P < 0.05, and P > 0.05, respectively.

Table 6. Turf quality, normalized difference vegetative index, and spring green-up ratings in open sun study of bermudagrass in 2014 at Oklahoma State University Turfgrass Research Center.

	TQ[z]					NDVI[y]					Spring	
Cultivars	June	July	Aug	Sept	Avg	June	July	Aug	Sept	Avg	green-up[x]	TPI[w]
OKS 2011-1	7.0b[v]	7.0cd	7.0d	6.9dc	7.0cd	0.860a	0.848ab	0.821a	0.862de	0.848ab	4.7bc	4
OKS 2011-4	6.2c	7.0cd	7.0d	6.7d	6.7d	0.841bc	0.824d	0.789abc	0.836f	0.822d	4.5c	1
Celebration	6.7bc	7.0cd	7.2cd	7.4ab	7.0bcd	0.840c	0.832cd	0.797abc	0.858e	0.832cd	4.2c	2
Latitude 36	7.7a	7.9a	8.0a	7.4ab	7.7a	0.860a	0.851a	0.798abc	0.895a	0.851a	7.0a	11
Northbridge	7.7a	7.9a	8.0a	7.6a	7.8a	0.843bc	0.845ab	0.804ab	0.887ab	0.845ab	6.7a	10
Patriot	6.5bc	6.9d	7.5bc	7.0bcd	7.0cd	0.836c	0.830cd	0.781bc	0.871cd	0.829cd	4.7bc	0
Princess 77	7.0b	7.1cd	7.0d	7.2abc	7.0cd	0.842bc	0.829cd	0.787abc	0.856e	0.828cd	3.2d	2
Riviera	6.7bc	7.0cd	7.4bcd	7.6a	7.2bc	0.853ab	0.840abc	0.786abc	0.878bc	0.839abc	5.2b	5
TifGrand	6.7bc	7.5b	7.5bc	6.1e	7.0cd	0.840c	0.830cd	0.765c	0.876bc	0.828cd	4.7bc	0
Yukon	7.0b	7.2bc	7.7ab	7.5a	7.4b	0.861a	0.836bc	0.791abc	0.856e	0.836bc	7.7bc	4
LSD$_{0.05}$	0.7	0.4	0.4	0.5	0.3	0.012	0.013	0.037	0.011	0.013	0.7	

[z] TQ: Turf visual quality ratings recorded bi-weekly and data aggregated per month; 9= ideal healthy turf; 6=minimally acceptable quality; 1= brown dead turf.

[y] NDVI is the normalized difference vegetative index gives the measure of turf color plus density.

[x] Spring green-up rating measures the transition from dormant to active growth stage in the spring. It was recorded in early April on 1 to 9 scale where 1= brown dormant turf and 9=fully green turf.

[w] TPI is the turf performance index representing the number of times an entry occurred in the top statistical group "a".

[v] Values within a column followed by the same letter are not significantly different at $P \leq 0.05$ by Fisher's protected least significant difference (LSD).

Table 7. Turf quality, normalized difference vegetative index, and spring green-up ratings in open sun study of bermudagrass in 2015 at Oklahoma State University Turfgrass Research Center.

	TQ[z]					NDVI[y]				Spring	
Cultivars	June	July	Aug	Sept	Avg	June	Aug	Sept	Avg	green-up[x]	TPI[w]
OKS 2011-1	8.0abc[v]	7.6b	8.0a	7.5	7.8bc	0.845abc	0.837ab	0.814	0.832abc	6.8ab	6
OKS 2011-4	7.0d	7.3cd	7.3bc	7.0	7.1f	0.822e	0.800ab	0.806	0.821cde	7.0a	2
Celebration	7.8bc	7.5bc	7.4bc	7.3	7.5de	0.843abcd	0.827bc	0.800	0.823cde	4.3d	1
Latitude 36	8.3ab	8.3a	8.0a	7.5	8.0ab	0.852ab	0.851a	0.821	0.841a	5.8c	7
Northbridge	8.5a	7.5bc	7.9a	7.5	8.1a	0.859a	0.841ab	0.815	0.838ab	6.0bc	6
Patriot	7.5cd	7.4bcd	7.6ab	6.9	7.4def	0.821e	0.834ab	0.792	0.816e	3.3e	2
Princess 77	7.0d	7.5bc	7.6ab	7.3	7.3ef	0.824e	0.813c	0.806	0.814e	2.3f	1
Riviera	7.8bc	7.1d	7.9a	7.4	7.6cd	0.834bcde	0.834ab	0.818	0.829bcd	7.0a	3
TifGrand	7.0d	7.5bc	7.3bc	7.0	7.1f	0.826de	0.829bc	0.812	0.822cde	3.0ef	0
Yukon	7.8bc	8.5a	7.1c	7.1	7.4def	0.834cde	0.826bc	0.795	0.818de	7.0a	2
$LSD_{0.05}$	0.6	0.3	0.4	NS	0.3	0.018	0.017	NS	0.012	0.9	

[z] TQ: Turf visual quality ratings recorded bi-weekly and data aggregated per month; 9= ideal healthy turf; 6=minimally acceptable quality; 1= brown dead turf.

[y] NDVI is the normalized difference vegetative index gives the measure of turf color plus density.

[x] Spring green-up rating measures the transition from dormant to active growth stage in the spring. It was recorded in early April on 1 to 9 scale where 1= brown dormant turf and 9=fully green turf.

[w] TPI is the turf performance index representing the number of times an entry occurred in the top statistical group “a”.

[v] Values within a column followed by the same letter are not significantly different at $P \leq 0.05$ by Fisher’s protected least significant difference (LSD).

Table 8. Turf quality, normalized difference vegetative index, and spring green-up ratings in open sun study of bermudagrass in 2016 at Oklahoma State University Turfgrass Research Center.

	TQ^z					NDVI^y					Spring
Cultivars	June	July	Aug	Sept	Avg	June	July	Aug	Sept	Avg	green-up^x
OKS 2011-1	5.8b^w	5.8c	6.3bc	6.4abc	6.0cd	0.853abc	0.780	0.829a	0.798a	0.815a	6.8bc
OKS 2011-4	5.8b	5.8c	6.0cd	6.3bc	5.9d	0.836cd	0.773	0.788bc	0.779abc	0.794bc	6.5c
Celebration	6.0b	6.0c	6.3bc	6.5abc	6.2bcd	0.845bcd	0.776	0.775cd	0.783ab	0.795bc	7.0ab
Latitude 36	7.5a	6.8ab	6.8a	6.9a	7.0a	0.851abc	0.786	0.790bc	0.785ab	0.803ab	7.3a
Northbridge	7.5a	6.9a	6.5ab	6.3bc	6.8a	0.869a	0.762	0.794bc	0.793ab	0.805ab	7.0ab
Patriot	7.0a	6.3bc	5.9d	6.0cd	6.3bc	0.862ab	0.781	0.756d	0.757c	0.789c	6.0d
Princess 77	6.0b	6.0c	6.4b	6.8ab	6.3bc	0.829d	0.780	0.794bc	0.798a	0.800bc	6.0d
Riviera	6.3b	6.1c	6.5ab	6.6ab	6.4b	0.830d	0.770	0.814ab	0.782ab	0.800bc	7.0ab
TifGrand	5.0c	5.0d	5.4e	5.6d	5.3e	0.852abc	0.788	0.804abc	0.774bc	0.805ab	6.0d
Yukon	5.8b	5.9c	6.4b	6.4abc	6.1bcd	0.846bcd	0.765	0.806abc	0.797a	0.804ab	6.8bc
LSD$_{0.05}$	0.5	0.5	0.4	0.6	0.3	0.018	NS	0.031	0.023	0.012	0.4

[z] TQ: Turf visual quality ratings recorded bi-weekly and data aggregated per month; 9= ideal healthy turf; 6=minimally acceptable quality; 1= brown dead turf.

[y] NDVI is the normalized difference vegetative index gives the measure of turf color plus density.

[x] Spring green-up rating measures the transition from dormant to active growth stage in the spring. It was recorded in early April on 1 to 9 scale where 1= brown dormant turf and 9=fully green turf.

[w] Values within a column followed by the same letter are not significantly different at $P \leq 0.05$ by Fisher’s protected least significant difference (LSD).

Table 9. Percent green cover in open sun study of bermudagrass in 2016 at Oklahoma State University Turfgrass Research Center.

	Percent green cover[z]				
Cultivars	June	July	Aug	Average	TPI[y]
OKS 2011-1	85.3ab[x]	68.9bc	77.3b	77.1b	6
OKS 2011-4	71.6c	68.0bc	44.8g	61.5f	1
Celebration	74.0c	75.2b	61.1c	70.1c	3
Latitude 36	89.4a	90.7a	89.8a	90.0a	13
Northbridge	92.9a	86.5a	86.4a	88.6a	12
Patriot	78.4bc	67.9c	50.9ef	65.7de	2
Princess 77	76.3c	73.9bc	48.8fg	66.3de	2
Riviera	74.6c	73.2bc	60.1c	69.3cd	5
TifGrand	71.7c	68.0bc	56.8cd	65.5e	3
Yukon	75.7c	66.9c	54.5de	65.7e	3
$LSD_{0.05}$	8.8	7.3	4.3	3.6	

[z] Percent green cover was generated analyzing the digital images through SigmaScan Software.

[y] TPI is the turf performance index representing the number of times an entry occurred in the top statistical group “a”.

[x] Values within a column followed by the same letter are not significantly different at $P \leq 0.05$ by Fisher’s protected least significant difference (LSD).

Table 10. Turf quality, normalized difference vegetative index, and spring green-up ratings in moderate shade study of bermudagrass in 2014 at Oklahoma State University Turfgrass Research Center.

	TQ[z]					NDVI[y]					Spring	
Cultivars	June	July	Aug	Sept	Avg	June	July	Aug	Sept	Avg	green-up[x]	TPI[w]
OKS 2011-1	6.2cde[v]	6.8cde	6.5cd	6.4bcd	6.5cd	0.861a	0.825	0.776ab	0.838cd	0.825ab	5.0b	2
OKS 2011-4	6.0de	6.3e	6.3d	6.3cde	6.2de	0.838bc	0.833	0.746abc	0.801e	0.805c	4.0c	1
Celebration	6.7abc	7.0bcd	6.8bc	6.9a	6.8b	0.842abc	0.823	0.76abc	0.852bc	0.819abc	5.0b	5
Latitude 36	7.2a	7.6a	7.4a	6.9a	7.3a	0.851ab	0.829	0.761abc	0.871a	0.828ab	6.0a	10
Northbridge	6.7abc	7.5ab	7.0ab	6.9a	7.0ab	0.829c	0.832	0.731c	0.857ab	0.812bc	6.8a	7
Patriot	5.7e	6.5de	6.4cd	6.0de	6.2e	0.794d	0.809	0.720c	0.828d	0.788d	4.5bc	0
Princess 77	5.7e	6.8cde	7.0ab	6.5abc	6.5c	0.849ab	0.829	0.781a	0.841bcd	0.825ab	2.3d	5
Riviera	6.5bcd	7.0bcd	6.8bc	6.8ab	6.8bc	0.858ab	0.828	0.784a	0.854bc	0.831a	5.0b	4
TifGrand	6.5bcd	7.3abc	6.4cd	5.9e	6.5c	0.849ab	0.833	0.741abc	0.855ab	0.82abc	4.8bc	5
Yukon	7.0ab	7.0bcd	6.6bcd	6.6abc	6.8b	0.861a	0.821	0.738bc	0.849bc	0.817abc	5.0b	4
$\text{LSD}_{0.05}$	0.7	0.5	0.4	0.5	0.3	0.020	NS	0.043	0.017	0.016	1.0	

[z] TQ: Turf visual quality ratings recorded bi-weekly and data aggregated per month; 9= ideal healthy turf; 6=minimally acceptable quality; 1= brown dead turf.

[y] NDVI is the normalized difference vegetative index gives the measure of turf color plus density.

[x] Spring green-up rating measures the transition from dormant to active growth stage in the spring. It was recorded in early April on 1 to 9 scale where 1= brown dormant turf and 9=fully green turf.

[w] TPI is the turf performance index representing the number of times an entry occurred in the top statistical group “a”.

[v] Values within a column followed by the same letter are not significantly different at $P \le 0.05$ by Fisher’s protected least significant difference (LSD).

Table 11. Turf quality, normalized difference vegetative index, and spring green-up ratings in moderate shade study of bermudagrass in 2015 at Oklahoma State University Turfgrass Research Center.

	TQ[z]					NDVI[y]				Spring	
Cultivars	June	July	Aug	Sept	Avg	June	Aug	Sept	Avg	green-up[x]	TPI[w]
OKS 2011-1	7.3cde[v]	7.3a	6.3ab	6.3abc	6.8	0.786ab	0.737a	0.712	0.745ab	6.8	6
OKS 2011-4	7de	6.4c	6.1bc	6.0c	6.4	0.785ab	0.708a	0.699	0.731ab	6.8	3
Celebration	7.8bc	6.8b	5.9c	6.1bc	6.6	0.786ab	0.749a	0.720	0.752ab	4.3	3
Latitude 36	8.5a	7.4a	6.1bc	6.5ab	7.1	0.803a	0.741a	0.676	0.740ab	6.5	6
Northbridge	8.0ab	7.4a	6.1bc	6.5ab	7.0	0.787ab	0.711a	0.653	0.717abc	6.5	6
Patriot	7.0de	6.4c	6.0bc	6.0c	6.3	0.696c	0.695a	0.613	0.668c	3.8	1
Princess 77	7.3cde	7.4a	6.5a	6.4abc	6.9	0.786ab	0.668a	0.679	0.711abc	3.3	6
Riviera	7.3cde	6.8b	6.5a	6.6a	6.8	0.812a	0.745a	0.738	0.765a	6.5	5
TifGrand	7.5bcd	6.6bc	6.0bc	6.1bc	6.6	0.746b	0.654a	0.686	0.695bc	3.0	1
Yukon	6.8e	6.5bc	6.1bc	6.0c	6.3	0.783ab	0.749a	0.617	0.716bc	6.3	2
LSD$_{0.05}$	0.5	0.3	0.3	0.5	NS	0.042	0.113	NS	0.058	NS	

[z] TQ: Turf visual quality ratings recorded bi-weekly and data aggregated per month; 9= ideal healthy turf; 6=minimally acceptable quality; 1= brown dead turf.

[y] NDVI is the normalized difference vegetative index gives the measure of turf color plus density.

[x] Spring green-up rating measures the transition from dormant to active growth stage in the spring. It was recorded in early April on 1 to 9 scale where 1= brown dormant turf and 9=fully green turf.

[w] TPI is the turf performance index representing the number of times an entry occurred in the top statistical group “a”.

[v] Values within a column followed by the same letter are not significantly different at P ≤ 0.05 by Fisher’s protected least significant difference (LSD).

Table 12. Turf quality, normalized difference vegetative index, and spring green-up ratings in moderate shade study of bermudagrass in 2016 at Oklahoma State University Turfgrass Research Center.

	TQ[z]					NDVI[y]					Spring
Cultivars	June	July	Aug	Sept	Avg	June	July	Aug	Sept	Avg	green-up[x]
OKS 2011-1	5.0b[w]	5.0	5.1	5.4ab	5.1	0.721ab	0.618	0.682abc	0.676a	0.674	6.0ab
OKS 2011-4	5.0b	5.0	5.5	5.4ab	5.2	0.690d	0.622	0.673bc	0.670a	0.664	6.3ab
Celebration	5.0b	5.1	5.5	5.6ab	5.3	0.714abc	0.625	0.665c	0.665ab	0.667	5.5bc
Latitude 36	5.5a	5.4	5.4	5.4ab	5.4	0.722ab	0.630	0.685abc	0.679a	0.679	6.0ab
Northbridge	5.5a	5.4	6.0	5.8a	5.7	0.716abc	0.652	0.694ab	0.663ab	0.681	6.3ab
Patriot	5.5a	5.0	4.9	5.0bc	5.1	0.711abcd	0.627	0.631d	0.606c	0.643	5.8ab
Princess 77	4.8b	5.0	5.4	5.5ab	5.2	0.704bcd	0.615	0.703a	0.679a	0.675	4.8c
Riviera	5.0b	4.9	5.3	5.8a	5.2	0.71abcd	0.636	0.687bc	0.676a	0.670	6.5a
TifGrand	4.8b	4.8	4.6	4.6c	4.7	0.696cd	0.620	0.673bc	0.678bc	0.652	4.8c
Yukon	5.0b	5.0	5.4	5.4ab	5.2	0.732a	0.626	0.674bc	0.667a	0.675	5.8ab
LSD$_{0.05}$	0.5	NS	NS	0.7	NS	0.022	NS	0.028	0.048	NS	0.8

[z] TQ: Turf visual quality ratings recorded bi-weekly and data aggregated per month; 9= ideal healthy turf; 6=minimally acceptable quality; 1= brown dead turf.

[y] NDVI is the normalized difference vegetative index gives the measure of turf color plus cover.

[x] Spring green-up rating measures the transition from dormant to active growth stage in the spring. It was recorded in early April on 1 to 9 scale where 1= brown dormant turf and 9=fully green turf.

[w] Values within a column followed by the same letter are not significantly different at $P \leq 0.05$ by Fisher's protected least significant difference (LSD).

Table 13. Percent green cover in moderate shade study of bermudagrass in 2016 at Oklahoma State University Turfgrass Research Center.

	Percent green cover[z]				
Cultivars	June	July	Aug	Avg	TPI[y]
2011-1	56.1cd[x]	39.9cd	32.0c	42.7cd	5
2011-4	51.0d	37.9cd	28.3c	39.0d	3
Celebration	58.6cd	48.7bc	43.1ab	50.1b	4
Latitude 36	79.1ab	58.2ab	51.8a	63.0a	6
Northbridge	89.5a	63.6a	47.8a	65.0a	10
Patriot	67.3bc	38.5cd	24.0c	43.3bcd	7
Princess 77	62.7cd	44.7c	32.6bc	46.7bc	3
Riviera	62.9cd	40.0cd	27.3c	43.4bcd	4
TifGrand	57.1cd	31.9d	27.0c	38.7d	0
Yukon	62.1cd	42.4cd	25.5c	43.4bcd	4
$LSD_{0.05}$	12.5	11.7	10.7	7.2	

[z] Percent green cover was generated analyzing the digital images through SigmaScan Software.

[y] TPI is the turf performance index representing the number of times an entry occurred in the top statistical group “a”.

[x] Values within a column followed by the same letter are not significantly different at $P \leq 0.05$ by Fisher’s protected least significant difference (LSD).

Table 14. Turf quality, normalized difference vegetative index, and spring green-up ratings in severe shade study of bermudagrass in 2014 at Oklahoma State University Turfgrass Research Center.

	TQ[z]					NDVI[y]						
Cultivars	June	July	Aug	Sept	Avg	June	July	Aug	Sept	Avg	Spring green-up[x]	TPI[w]
OKS 2011-1	5.5bc[v]	5.8ab	5.9b	5.8ab	5.7bcd	0.787ab	0.828	0.759ab	0.808a	0.795ab	3.3c	6
OKS 2011-4	5.0c	5.4bc	5.6b	5.3bc	5.3de	0.764bc	0.819	0.733bc	0.750ab	0.767ab	3.0c	2
Celebration	5.8ab	6.1a	6.1ab	5.8ab	5.9abc	0.799ab	0.827	0.771a	0.794ab	0.798a	3.0c	9
Latitude 36	6.3a	6.4a	6.6a	5.8ab	6.3a	0.827a	0.799	0.727bc	0.811a	0.791ab	5.0a	9
Northbridge	5.8ab	6.1a	6.6a	6.0a	6.1ab	0.796ab	0.819	0.725c	0.798a	0.785ab	4.3b	8
Patriot	3.5d	4.1d	4.4c	4.3d	4.1f	0.614d	0.791	0.648e	0.639c	0.673c	2.0d	0
Princess 77	4.0d	4.8cd	5.9b	5.8ab	5.1e	0.727c	0.831	0.780a	0.784ab	0.781ab	2.0d	4
Riviera	5.5bc	5.8ab	6.1ab	5.6ab	5.8abcd	0.790ab	0.797	0.758ab	0.772ab	0.779ab	3.0c	8
TifGrand	5.5bc	5.9ab	5.8b	4.9c	5.5cde	0.796ab	0.824	0.692d	0.735b	0.762b	3.0c	2
Yukon	6.0ab	6.0ab	6.0ab	5.8ab	5.9abc	0.800ab	0.809	0.733bc	0.784ab	0.782ab	4.0b	8
$LSD_{0.05}$	0.7	0.7	0.6	0.6	0.5	0.049	NS	0.032	0.062	0.035	0.6	

[z] TQ: Turf visual quality ratings recorded bi-weekly and data aggregated per month; 9= ideal healthy turf; 6=minimally acceptable quality; 1= brown dead turf.

[y] NDVI is the normalized difference vegetative index gives the measure of turf color plus density.

[x] Spring green-up rating measures the transition from dormant to active growth stage in the spring. It was recorded in early April on 1 to 9 scale where 1= brown dormant turf and 9=fully green turf.

[w] TPI is the turf performance index representing the number of times an entry occurred in the top statistical group “a”.

[v] Values within a column followed by the same letter are not significantly different at $P \leq 0.05$ by Fisher’s protected least significant difference (LSD).

Table 15. Turf quality, normalized difference vegetative index, and spring green-up ratings in severe shade study of bermudagrass in 2015 at Oklahoma State University Turfgrass Research Center.

	TQ[z]					NDVI[y]				Spring	
Cultivars	June	July	Aug	Sept	Avg	June	Aug	Sept	Avg	green-up[x]	TPI[w]
OKS 2011-1	5.0cd[v]	5.6bc	4.8abc	4.1bcd	4.9bcd	0.709ab	0.654abc	0.615a	0.659ab	5.5ab	6
OKS 2011-4	4.5de	4.9de	4.0def	4.0cd	4.3e	0.636cd	0.602cde	0.552abc	0.597cd	5.5ab	2
Celebration	6.3a	6.5a	5.3a	4.9a	5.7a	0.714ab	0.656ab	0.586a	0.652ab	4.3cd	9
Latitude 36	5.8abc	5.8b	4.5cd	4.0cd	5.0bc	0.707ab	0.681a	0.571ab	0.653ab	4.8bc	5
Northbridge	6.0ab	5.8b	5.1ab	4.5ab	5.3ab	0.708ab	0.666ab	0.608a	0.661ab	5.5ab	9
Patriot	3.8e	4.1f	3.6f	3.5e	3.8f	0.588d	0.560e	0.511bc	0.553d	3.0e	0
Princess 77	4.5de	5.4bcd	4.6bc	4.3bc	4.7cde	0.750a	0.704a	0.619a	0.691a	3.3e	4
Riviera	5.0cd	5.6bc	4.9abc	4.1bcd	4.9bcd	0.669bc	0.628bcd	0.556abc	0.618bc	6.0a	3
TifGrand	5.3bcd	5.1cde	3.9ef	3.8de	4.5de	0.631cd	0.601de	0.484c	0.572cd	3.8de	0
Yukon	4.8d	4.8e	4.4cde	4.0cd	4.5de	0.750a	0.698a	0.570ab	0.673a	5.5ab	5
$LSD_{0.05}$	0.9	0.6	0.5	0.5	0.5	0.054	0.053	0.074	0.054	0.8	

[z] TQ: Turf visual quality ratings recorded bi-weekly and data aggregated per month; 9= ideal healthy turf; 6=minimally acceptable quality; 1= brown dead turf.

[y] NDVI is the normalized difference vegetative index gives the measure of turf color plus density.

[x] Spring green-up rating measures the transition from dormant to active growth stage in the spring. It was recorded in early April on 1 to 9 scale where 1= brown dormant turf and 9=fully green turf.

[w] TPI is the turf performance index representing the number of times an entry occurred in the top statistical group “a”.

[v] Values within a column followed by the same letter are not significantly different at $P \leq 0.05$ by Fisher’s protected least significant difference (LSD).

Table 16. Turf quality, normalized difference vegetative index, and spring green-up ratings in severe shade study of bermudgrasses in 2016 at Oklahoma State University Turfgrass Research Center.

Cultivars	TQ[z]					NDVI[y]					Spring green-up[x]
	June	July	Aug	Sept	Avg	June	July	Aug	Sept	Avg	
OKS 2011-1	3.4bc[w]	3.0bc	2.8b	3.4ab	3.1b	0.640bc	0.525ab	0.652a	0.608a	0.606a	4.5ab
OKS 2011-4	2.6bc	2.6bc	2.4bc	2.6bc	2.6bc	0.608bcd	0.443bc	0.570ab	0.551a	0.543ab	3.5bcd
Celebration	5.3a	5.8a	4.9a	4.9a	5.2a	0.753a	0.549a	0.602ab	0.586a	0.623a	5.0a
Latitude 36	3.8ab	3.4bc	3.0b	2.8bc	3.2b	0.631bcd	0.527ab	0.563bc	0.558a	0.570ab	3.5bcd
Northbridge	3.8ab	3.2bc	3.2b	3.4ab	3.4b	0.684abc	0.541a	0.636ab	0.574a	0.609a	4.3abc
Patriot	1.9c	1.9c	1.5c	1.5c	1.7c	0.419e	0.395c	0.441d	0.402b	0.414c	2.0e
Princess 77	3.8ab	3.8b	3.4b	3.4ab	3.6b	0.708ab	0.553a	0.616ab	0.583a	0.615a	3.3cd
Riviera	2.6bc	2.6bc	2.6bc	2.8bc	2.7bc	0.615bcd	0.499ab	0.581ab	0.565a	0.565ab	4.5ab
TifGrand	2.3bc	2.3bc	2.6bc	2.6bc	2.4bc	0.522de	0.467abc	0.483cd	0.520a	0.498b	2.5de
Yukon	2.6bc	2.6bc	2.6bc	3bc	2.7bc	0.575cd	0.493ab	0.567b	0.548a	0.546ab	3.5cd
LSD$_{0.05}$	1.8	1.5	1.3	1.6	1.4	0.114	0.089	0.084	0.107	0.081	1.1

[z] TQ: Turf visual quality ratings recorded bi-weekly and data aggregated per month; 9= ideal healthy turf; 6=minimally acceptable quality; 1= brown dead turf.

[y] NDVI is the normalized difference vegetative index gives the measure of turf color plus cover.

[x] Spring green-up rating measures the transition from dormant to active growth stage in the spring. It was recorded in early April on 1 to 9 scale where 1= brown dormant turf and 9=fully green turf.

[w] Values within a column followed by the same letter are not significantly different at $P \leq 0.05$ by Fisher’s protected least significant difference (LSD).

Table 17. Percent green cover in severe shade study of bermudgrasses in 2016 at Oklahoma State University Turfgrass Research Center.

	Percent green cover[z]				
Cultivars	June	July	Aug	Average	TPI[y]
2011-1	33.8bc[x]	32.4bc	12.6cde	26.3b	6
2011-4	22.7cd	19.4ef	7.5f	16.5cd	3
Celebration	46.7a	41.0ab	27.7a	38.5a	15
Latitude 36	50.7a	46.0a	23.7ab	40.1a	8
Northbridge	47.0a	41.5ab	20.4b	36.3a	11
Patriot	17.7d	13.2f	9.5ef	13.4d	0
Princess 77	40.0ab	30.8cd	14.6c	28.5b	8
Riviera	26.5cd	23.2cde	14.3cd	21.3bc	5
TifGrand	25.9cd	16.2ef	9.7def	17.3cd	2
Yukon	31.0bc	22.6def	11.4cdef	21.6bc	3
$LSD_{0.05}$	11.7	9.8	4.6	7.4	

[z] Percent green cover was generated analyzing the digital images through SigmaScan Software.

[y] TPI is the turf performance index representing the number of times an entry occurred in the top statistical group “a”.

[x] Values within a column followed by the same letter are not significantly different at $P \le 0.05$ by Fisher’s protected least significant difference (LSD).

Table 18. Cumulative turf performance index (TPI) in open sun, moderate shade, and severe shade in 2014, 2015, and 2016 at Oklahoma State University Turfgrass Research Center.

	Cumulative Turf Performance index (TPI)^z									
	Latitude 36	Northbridge	OKS 2011-1	Celebration	Riviera	Princess 77	Yukon	OKS 2011-4	TifGrand	Patriot
				Full Sun						
2014	11	10	4	2	5	2	4	1	0	0
2015	7	6	6	1	3	1	2	2	0	2
2016	13	12	6	3	5	2	3	1	3	2
Total TPI	31	28	16	6	13	5	9	4	3	4
				Moderate Shade						
2014	10	7	2	5	4	5	4	1	5	0
2015	6	6	6	3	5	6	2	3	1	1
2016	6	10	5	4	4	3	4	3	0	7
Total TPI	22	23	13	12	13	14	10	7	6	8
				Severe Shade						
2014	9	8	6	9	8	4	8	2	2	0
2015	5	9	6	9	3	4	5	2	0	0
2016	8	11	6	15	5	8	3	3	2	0
Total TPI	22	28	18	33	16	16	16	7	4	0

^{z}TPI is the turf performance index representing the number of times an entry occurred in the top statistical group “a”.

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CHAPTER III

INVESTIGATIONS INTO THE INTERACTIONS OF SHADE AND DROUGHT ON BERMUDAGRASS TURF

Introduction

Turfgrasses require water for maintaining acceptable quality and need to be irrigated when precipitation is inadequate. Amid increasing water demand, water use rates of turfgrass is a concerning issue. It is estimated that 31 million acres of irrigated turfgrass are maintained in the United States (Milesi et al., 2005). Irrigation can be a significant component of domestic water demand, particularly in summer. The water use rates of bermudagrasses (*Cynodon* spp.) varied from 4.8 to 5.5 mm d^{-1} in Oklahoma during the growing season (Moss and Martin, 2014). However, water use rates can depend on climatic conditions, cultural regimes, species and cultivar adaptation (Huang, 2008; Kopp and Jiang, 2013). Although bermudagrasses as a group exhibit good drought resistance, water use rates and drought resistance can vary by cultivar (Baldwin et al., 2006; Carrow, 1996; Qian et al., 1997; Steinke et al., 2011).

An estimated 25% of the turfgrass is grown under shade (Beard, 1973). Bermudagrass performs poorly in shade in compared to other warm-season species, such as zoysiagrass (Bunnell et al., 2005a). Variability among the bermudagrass cultivars in shade tolerance has been reported (Baldwin et al., 2008; Gaussoin et al. 1998; Trappe et al., 2011).

Turfgrass water use rates are sensitive to solar radiation and therefore can be much lower in shaded environments. Under full-sun conditions, ‘Midlawn’ hybrid bermudagrass [*C. dactylon* (L.) Pers. x *C. transvaalensis* Burtt-Davy], maintained acceptable turf quality with irrigation level at 60% actual ET replacement in a mobile rainout shelter. In southern California, ET of lawns under trees was lower than without trees by 0.9 to 3.9 mm d^{-1} (Litvak et al., 2014). A study from Israel found that turfgrass shaded either by trees or by shade mesh reduced total water use rate by at least 50% (Shashua-Bar et al., 2009).

In a turfgrass system, shade stress often co-exists with drought stress. Sack and Grubb (2002) synthesized five hypotheses to explain the relationship between shade and drought stress in a plant community. First, the influential trade-off hypothesis predicts that drought has a stronger negative effect on shade-weakened plants. This could be more important for plants having lower root: shoot ratio, resulting in greater sensitivity to drought stress a high specific leaf area and leaf area ratio for efficient irradiance capture at the expense of their root allocation as indicated by Smith and Huston (1989). Second, the above-ground facilitation hypothesis predicts that shade-induced temperature moderation reduces the effect of drought stress by alleviating the evaporative demand at the leaf. Third, the primary limitation hypothesis predicts that the impact of drought will be less in dense shade because water will have less role in growth due to limitation of light. The fourth is the interplay hypothesis, which predicts that moderate shade reduces the effect of drought stress while dense shade can worsen it. Shade reduces the effect of drought stress in a linear relationship with the severity of shade. Finally, a null hypothesis predicts that effects of shade and drought are orthogonal.

Although there have been numerous studies on individual effect of either shade stress or drought stress on turf quality, there is limited prior research to study the combined effects of shade and drought on turfgrasses. Thus, a greenhouse study was conducted to evaluate the effects of combined drought and shade stress on bermudagrass performance and water use rate. The objectives of this research were 1) to measure the effect of drought stress on shaded and non-shaded bermudagrass turf quality and water use rate and 2) to determine if the response to shade, drought, or combined shade and drought differ among bermudagrass cultivars.

Materials and methods

Establishment:

Two greenhouse experiments were conducted at the Oklahoma State University Horticulture Research Greenhouse located in Stillwater, OK (lat. 36^0 8’ N, long. 97^0 5’ W). The first experiment was conducted from March 19, 2017 through May 20, 2017 (hereafter referred to as Expt. 1). A second experiment was conducted from July 16, 2017 through September 02, 2017 (hereafter referred to as Expt. 2).

Grasses were established in growth tubes [10 cm diameter x 46 cm long polyvinyl chloride pipe (PVC) with a flat bottom cap] from washed plugs on July 19, 2016 and March 16, 2017 for Expt. 1 and Expt. 2, respectively. Soil was air-dried in the sun, sieved through a 2-mm screen and uniformly mixed in equal volume with silica sand using electric concrete mixer to obtain a 1:1 v/v root-zone medium. Pots were well-watered to avoid drought stress during establishment and before starting treatments. Fertilizer was applied at 12 kg N ha^{-1} every week using 20-20-20 water soluble fertilizer (Jr Peters Inc., Allentown, PA) throughout the study. Grasses were clipped at a height of 5cm once a week and clippings were removed.

The whole experiment was divided into two separate light treatment blocks: 'Non-shade’ and ‘Shade’. Non-shade treatment block received natural sunlight inside the greenhouse plus supplemental lighting from a 400-watt high pressure sodium lamp (Rudd Lighting Inc., Racine, WI). Shade treatment block received filtered light passing through a black shade fabric that was anchored to a 2.5cm diameter PVC pipe frame (1m x 1m x 1m). The fabric was 0.5m above the turf canopy at its center but was allowed to drape over the sides of the frame to a height 0.34m above the turf canopy to reduce light during low sun angles while maintaining air movement.

Expt. 1 was arranged as a 2 x 2 factorial completely randomized design with three replications. Two bermudagrass cultivars and two irrigation levels were randomized within each light treatment block. The two cultivars, ‘Celebration’, a common bermudagrass [*Cynodon dactylon* (L.) Pers.] and ‘Latitude 36’, a hybrid bermudagrass [*C. dactylon* (L.) Pers. x *C. transvaalensis* Burtt-Davy], were selected as industry standards for their respective types. Water was applied to replace 100% actual ET in all pots for the first two weeks under light treatments. After two weeks of acclimation to light treatments, irrigation treatments were applied twice per week to replace either 100% actual ET or 50% actual ET based on the average of water loss of all experimental units for a given treatment combination. Measurements were taken for a period of eight weeks after the onset of light treatments.

Expt. 2 was similar to Expt. 1 with the subsequent differences. The experiment was arranged as 3 x 2 factorial completely randomized design. A shade-sensitive hybrid bermudagrass cultivar ‘Patriot’ was added along with Celebration and Latitude 36 from Expt. 1. The supplemental lighting was removed from the Non-shade treatment due to anticipation of greater solar radiation and higher temperatures during this period. Grasses were kept well-watered for four weeks to allow for acclimation to shade, and drought treatment was applied after four weeks of shading. Water was applied once a week based on 100% and 50% actual ET replacement. Measurements were taken for a period of six weeks after drought treatment was initiated. Other materials and methods remained same as in Expt. 1.

Measurements:

Photosynthetically active radiation (PAR) was recorded using a quantum light sensor (Spectrum Technologies, Inc., Plainfield, IL) and data logged every 30 mins in µmol m^{-2} s^{-1} using a Watchdog 1000 (Spectrum Technologies, Inc., Plainfield, IL). The PAR data were converted to a daily light integral (DLI) and averaged over treatment period for each cycle of trial. Relative humidity and air temperature were also recorded at a similar resolution using the same instrumentation.

Visual turf quality was assessed weekly following National Turfgrass Evaluation Program (NTEP) guidelines (Morris and Shearman, 2000). Ratings were taken on a scale of 1 to 9 (9 = ideal turf, 6= minimum acceptable turf, and 1= brown dead turf). Normalized difference vegetation index (NDVI) was measured every week using a Spectral Reflectance Sensor (Decagon Devices Inc., Pullman, WA). This gives the measure of turf density plus color and the value ranges from 0 to 1. Measurements were taken by hand at a height 5cm above the turf canopy to ensure consistency across all measurements and ensure sampling area remained within the 10cm pot diameter.

Leaf relative water content was measured at 0, 2, 4, 6 and 8 weeks after treatment (WAT) in Expt. 1 and at 0, 4, and 6 WAT in Expt. 2. From each pot, shoots were randomly harvested and transported to lab in freezer bags stored on ice in a cooler. For each pot, ten leaves of similar physiological age (third or fourth fully expanded) were separated from shoots and weighed using an analytical balance (XS64, Mettler Toledo). For turgid weight, leaves were placed in covered petri-dishes, hydrated in de-ionized water for 4 h at room temperature and dried with kimwipes before weighing. Finally, leaves were dried in oven at 80 ^{0}C for 48 h and dry weights were recorded. Leaf relative water content (RWC) was determined gravimetrically using the following equation:

$$RWC= (FW-DW) / (TW-DW) \times 100 \qquad \text{(Eq. 2)}$$

Where FW is fresh weight of leaf samples, DW is dry weight of leaves after being dried in oven at 80 ^{0}C for 48 h, and TW is turgid weight of leaves after hydration at 4 ^{0}C for 4 h (Barrs and Weatherly, 1962).

Cell membrane stability was determined by measuring leaf relative electrolyte leakage (EL) following the methods of Abraham et al. (2004). Measurements were taken at 0, 4, 6 and 8 WAT in Expt. 1 and at 0, 4 and 6 WAT in Expt. 2. Shoots were sampled from each pot, placed in freezer bags and transported in ice-cooler. For each pot, ten leaves of similar physiological age were detached from shoots, rinsed three times in distilled deionized water, and placed in a test tube containing 20 mL of distilled deionized water. After the leaves were shaken for 24 h at 120 rpm, the initial conductivity of the solution ($C_{initial}$) was measured using a conductance meter (Model 32, Yellow Spring Instruments Co.., Yellow Springs, OH). Leaves were then killed by autoclaving at 120 ^{0}C for 30 min. The test tubes were again shaken for 24 h at 120 rpm before measuring the final conductivity (C_{max}). Relative EL was calculated as the percentage of $C_{initial}$ over C_{max}.

Evapotranspiration (ET) rates were measured gravimetrically by weighing the pots in each treatment combination (Bremer, 2003). Before shade initiation, pots were fully saturated by placing them in a plastic tub filled with water to approximately 10cm below the top of the pot until free water was visible at the soil surface (24 h). Pots were then allowed to drain freely for another 24 h to achieve soil moisture at apparent field capacity, at which point drainage holes were sealed with cork, dried with a towel, and weighed. In Expt. 1, pots were weighed again after every 2 or 3 days and the difference in mass attributed to ET. In Expt. 2, pots were weighed every 7 days. Cumulative water use (mm) for each treatment was determined as the sum of all water applied during the entire study. Measurement days for each parameter were different in each week and are presented separately for each experiment (Table 19).

Table 19. Timeline for parameter measurements in Expt. 1 and Expt. 2.

Parameters	Week 0	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8
…………………………..………..……Expt. 1………...……………………..………									
TQ	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun	Sun
NDVI	Mon	Mon	Mon	Mon	Mon	Mon	Mon	Mon	Mon
RWC	Mon		Mon		Mon		Mon		Mon
EL	Mon				Mon		Mon		Mon
ET	Tue/Fri	Tue/Fri	Tue/Fri	Tue/Fri	Tue/Fri	Tue/Fri	Tue/Fri	Tue/Fri	Tue/Fri
…………………………..………..……Expt. 2……...……………………..………									
TQ	Sun	Sun	Sun	Sun	Sun	Sun	Sun		
NDVI	Mon	Mon	Mon	Mon	Mon	Mon	Mon		
RWC	Mon				Mon		Mon		
EL	Mon				Mon		Mon		
ET	Fri	Fri	Fri	Fri	Fri	Fri	Fri		

Results

Statistical analysis:

The study was arranged in 2 x 2 completely randomized factorial design in Expt. 1 and 3 x 2 completely randomized factorial design in Expt. 2. For each trial, data were analyzed separately by light treatment. All data were analyzed using analysis of variance (ANOVA) with the general linear model procedure (GLM) in SAS software version 9.4 (SAS Institute, 2012). ANOVA was conducted for the main effects of cultivar, water, date and their two-way and three-way interactions. The date x water interaction was significant for each parameter and therefore data were subsequently analyzed within each date for both trials. Data were pooled across treatments when there was no significant interaction effect. Treatment means were separated by Fisher's protected least significant difference (LSD) test at $p \leq 0.05$.

Micro-environment of light treatments

In Expt. 1, the Non-shade block received an average of 20.8 mol m^{-2} d^{-1} PAR, while the Shade block received an average of 10.1 mol m^{-2} d^{-1} (49% of Non-shade) PAR during the treatment period. The daily mean air temperature and relative humidity was 31.8 ^{0}C and 65.0% in Non-Shade and 30.7 ^{0}C and 67.5% in Shade, respectively (Table 20).

In Expt. 2, the Non-shade block received an average of 26.8 mol m^{-2} d^{-1} PAR, while the Shade block received an average of 9.7 mol m^{-2} d^{-1} (36% of Non-shade) PAR during the treatment period. The daily mean air temperature and relative humidity were 27.5 ^{0}C and 47.7% in Non-shade and 26.4 ^{0}C and 49.6% in Shade, respectively.

Expt. 1

Turf quality (TQ)

There was no significant effect of cultivar or any higher order interaction involving cultivar; thus, data were pooled across cultivar to estimate main effects of water treatment (Table 21 and 22). In the Non-shade block, the 50% ET treatment maintained a minimally acceptable rating until 5 weeks after treatment (WAT) (Table 23). Leaf rolling and firing thereafter reduced turf quality until grasses were completely brown at 8 WAT. Compared to the 100% ET treatment, the 50% ET treatment resulted in lower TQ at 3 WAT and remained lower thereafter. In Shade, the 100% ET treatment maintained an acceptable rating of 6 through the duration of the study (Table 23). The 50% ET treatment was similar to 100% ET treatment until 4 WAT and maintained a minimally acceptable rating until 6 WAT.

Normalized difference vegetation index (NDVI)

Data were pooled across cultivar in Non-shade due to lack of cultivar effect; whereas, in Shade, cultivars were analyzed separately due to a significant effect of cultivar or higher order interaction involving cultivar (Table 21 and 22). In Non-shade, the 100% ET treatment consistently had a high NDVI (NDVI ≥ 0.922) that was significantly greater than the 50% ET treatment starting 2 WAT (Table 24). In Shade, the 100% ET treatment demonstrated a greater NDVI than the 50% ET treatment starting at 4 WAT and thereafter. In shade, cultivars demonstrated similar NDVI under the 100% ET treatment, but within the 50% ET treatment, Latitude 36 had a higher NDVI than Celebration at 4 and 8 WAT.

Leaf relative water content (RWC):

Data were pooled across cultivars due to lack of a significant effect of cultivar (Table 21 and 22). In Non-shade, the 100% ET treatment demonstrated a significantly higher RWC than the 50% ET treatment at 4, 6, and 8 WAT (Table 25). By the end of study, the 50% ET treatment had 12.1% RWC. In Shade, the 100% ET treatment had a significantly higher RWC than the 50% ET treatment at 4, 6, and 8 WAT (Table 25). By the end of the study, the RWC in 100% and 50% ET treatments was 66.6% and 28.3%, respectively.

Leaf relative electrolyte leakage (EL):

Data were pooled across cultivar due to lack of a significant effect of cultivar (Table 21 and 22). In Non-shade, the 50% ET treatment had a significantly higher EL than the 100% ET treatment at 4, 6, and 8 WAT, reaching 66.8% EL by the end of the study (Table 25). In Shade, the 50% ET treatment had significantly higher EL than the 100% ET treatment at 4, 6, and 8 WAT (Table 25). At 8 WAT, EL in 100% and 50% ET treatments was 16.6% and 36.9%, respectively.

Evapotranspiration (ET) rate:

Due to a significant cultivar x water interaction, further analysis was conducted within water treatment (Table 21 and 22). In Non-shade plus the 100% ET treatment, Celebration and Latitude 36 had ET rates that ranged from 7.2 to 8.4 mm d^{-1} and 6.2 to 7.3 mm d^{-1}, respectively (Table 26). The ET rate of the 50% ET treatment was similar to the 100% ET treatment until 23 days after treatment (DAT) at which time they sharply declined. In Shade plus the 100% ET treatment, Celebration and Latitude 36 had ET rates that ranged from 3.5 - 6.2 mm d^{-1} and 3.2 - 6.1 mm d^{-1}, respectively (Table 26). Similar to the results in Non-shade, the Shade plus 50 % ET treatment had a sharp decline in ET beginning at 23 DAT.

Cumulative water use rate (CW):

In Non-shade plus the 100% ET treatment, Celebration had a higher CW rate (443.8 mm) than Latitude 36 (389.0 mm) (Fig. 1). In contrast, no differences were observed between cultivars under the Non-shade plus the 50% ET treatment. Under Shade, Celebration had similar CW rates to Latitude 36 in both the 100% ET and 50% ET treatments (Fig. 2).

Expt. 2

Turf quality (TQ)

There was no significant effect of the cultivar x water interaction; thus, data were to estimate main effects of water or cultivar treatment (Table 27 and 28). In the Non-shade block, the 50% ET treatment maintained a minimally acceptable rating until 3 weeks after treatment (WAT) (Table 29). Latitude 36 maintained acceptable TQ until 5 WAT, while Celebration and Patriot maintained acceptable TQ until 4 WAT. In Shade, 100% and 50% ET treatments maintained acceptable turf quality until 5 WAT and 3 WAT, respectively (Table 29). Starting 0 WAT (4 weeks after shade), Celebration and Latitude 36 had similar but significantly higher TQ than Patriot and remained significantly different thereafter.

Normalized difference vegetation index (NDVI)

In Non-shade, the 100% ET treatment was significantly greater than the 50% ET treatment starting 2 WAT and remained greater thereafter (Table 30). Differences among cultivars were observed only at 4 and 6 WAT, where Celebration and Latitude 36 were similar to each other and superior to Patriot. As early as 0 WAT (4 weeks after shade), Celebration and Latitude 36 were similar and superior to Patriot.

Leaf relative water content (RWC):

There was no significant effect of cultivar x water interaction; thus, data were to estimate main effects of cultivar or water treatments (Table 27 and 28). In Non-shade, the 100% ET treatment had significantly higher RWC than the other at 4 and 6 WAT (Table 31). By the end of study, the 50% ET treatment had a 17.7% RWC. At 4 and 6 WAT, Celebration and Latitude 36 had a similar RWC to each other but higher than Patriot. In Shade, the 100% ET treatment had a higher RWC than the 50% ET treatment at 4 and 6 WAT. By the end of study, the 50% ET treatment had a 31.5% RWC. At 4 and 6 WAT, Celebration and Latitude 36 had RWC similar to each other but higher than Patriot.

Electrolyte leakage (EL):

There was no significant effect of the cultivar x water interaction; thus, data were to estimate main effects of water or cultivar treatment (Table 27 and 28). In Non-shade, the 50% ET treatment had significantly higher EL than the 100% ET treatment at 4 and 6 WAT (Table 31). By the end of study, EL from the 50% ET treatment reached 71.9%. At 4 and 6 WAT, Celebration and Latitude 36 had similar EL to each other but less than Patriot. In Shade, the 50% ET treatment had significantly higher EL than the 100% ET treatment at 4 and 6 WAT. By the end of study, EL of the 50% ET treatment reached 59.3%. At 4 WAT, Patriot and Latitude 36 had similar EL to each other but higher than Celebration. At 8 WAT, Celebration had less EL than Patriot but was similar to Latitude 36.

Evapotranspiration (ET) rate:

Due to a significant cultivar x water and cultivar x water x date interaction further analysis was conducted for cultivar x water treatment combination (Table 27 and 28). In Non-shade plus the 100% ET treatment, ET rates varied from 5.0 to 6.0 mm d^{-1}, 3.9 to 5.2 mm d^{-1}, 5.7 to 6.5 mm d^{-1} for Celebration, Latitude 36, and Patriot, respectively (Table 32). ET rates in the 50% ET treatment sharply declined at 5 DAT and continued to decline as drought stress intensified. In Shade plus 100% ET treatment, ET rates varied from 2.0 to 5.3 mm d^{-1}, 1.7 to 5.0 mm d^{-1}, 1.0 to 5.7 mm d^{-1} for Celebration, Latitude 36, and Patriot, respectively.

Cumulative water use rate (CW):

In Non-shade plus the 100% ET treatment, Patriot had the highest CW rate (230.0 mm), followed by Celebration (213.5 mm) and Latitude 36 (181.2 mm) (*Fig. 3*). Within the 50% ET treatment, Patriot had similar a CW rate (77.6 mm) to Celebration (74.9 mm) but higher than that of Latitude 36 (66.3 mm). Under Shade plus the 100% ET treatment, Celebration had the highest CW rate (139.7 mm), followed by Latitude 36 (127.7 mm) and Patriot (115.9 mm) (*Fig. 4*). Within the 50% ET treatment, Latitude 36 and Patriot had similar CW rates (50.6 mm and 50.0 mm, respectively) but less than that of Celebration (58.2 mm).

Discussion

Differences in micro-climate between the two trials were apparent. Use of supplemental lighting in the Non-shade block only in Expt. 1 resulted greater PAR in compared to Expt. 2. However, use of the same shade structure in both trials provided nearly similar PAR in shaded block.

Drought treatment replacing 50% ET had progressively lowered the TQ and NDVI throughout the treatment period in both trials. Reduction of TQ and NDVI due to shade alone or drought alone stress have been reported in previous studies (Baldwin et al., 2009; Bunnell et al., 2005a; Fu et al., 2004; Jiang et al., 2009). The apparent delay in drought stress under shaded conditions is related to a similar delay in soil water depletion due to the lower evaporative demand. Litvak et al. (2014) suggested tree shade could reduce ET rate of turf while the combined ET rate of tree plus turf remained less than that of turf without trees in open sun. Whether these findings hold true for all tree-turf interactions is beyond the scope of project.

Shade stress reduced the RWC for 100% ET treatments, but increased RWC for 50% ET treatments. Within 50% ET treatment, non-shaded grasses showed more leaf desiccation than shaded grasses possibly due to high evaporative demand. In a previous study, lower RWC in zoysiagrass was related to decline in canopy net photosynthesis (Fu, 2003). In contrast, Shade promoted drought avoidance which resulted in improved TQ compared to Non-shade. Likewise, Patriot's lower RWC is likely related to its poor performance under shade or drought in this study.

Patriot has been reported as having poor shade tolerance even among other bermudagrasses (Baldwin et al., 2008; Trappe et al., 2011). In contrast, Celebration was reported as having superior shade tolerance among several bermudagrass cultivars (Baldwin et al., 2008; Bunnell et al., 2005a). In recent field trials, Latitude 36 was reported to have good performance relative to other cultivars under 55% shade (20.5 µmol m^{-2} d^{-1}) (Chapter II). The present study is in agreement with much of these previous reports suggesting Patriot as being inferior to Celebration or Latitude 36 in regards to shade tolerance. The implications for this on water relations were evidenced by the relatively high water use of Patriot in the Non-shade block and the relatively low water use in the Shade block. Higher demand for water in Patriot could be one of the reasons for poor performance when subjected to individual or combined stress.

The effect of increasing drought stress on ET rate differed between shaded and non-shaded turfgrasses. Shaded grasses showed gradual decline in ET rates but non-shaded grasses had sharp decline in ET rates. Reductions in ET or transpiration among turfgrass with increasing drought have been reported by a few previous researchers (Cathey et al., 2013; Qian and Fry, 1997; Zhang et al., 2017).

The present study did not consider the impact of tree-root competition or vegetative shade that can possibly alter the relationship between shade and drought stress. Future studies investigating the interaction of shade and drought in field condition under tree canopy that simulates the real-world scenario may bring new useful information to turf industry.

Conclusion

The modification of the above-ground environment reduced the severity of drought stress to some extent suggesting reduced water demand in shade could lead to maintenance of green cover during prolonged drought. There is evidence that shade tolerance of the turfgrass can have a role in tolerance of the combined shade and drought stress as well. The present study was among the first to directly investigate the combined effects of shade and drought stress on bermudagrass turf. Results will contribute towards improving irrigation management of shaded turf sites and the long-term sustainability of turfgrass management.

Table 20.Weather data retrieved from micro-weather station installed during light and shade study.

Study period	Daily Light Integral (DLI)	Mean Air temperature (^{0}C)			Relative humidity
	mol m^{-2} d^{-1}	High	Low	Mean	(%)
	Non-shade				
Expt. 1	26.8 ± 8.0^z	36.9 ± 4.7	21.7 ± 1.3	27.5 ± 1.9	47.7 ± 13.1
Expt. 2	20.8 ± 5.7	43.3 ± 4.9	25.5 ± 1.2	31.8 ± 2.2	65.0± 8.0
	Shade				
Expt. 1	9.7 ± 4.3	32.4 ± 2.8	21.8 ± 1.4	26.3 ± 1.5	49.6 ± 13.5
Expt. 2	10.1 ± 3.0	39.2 ± 3.8	25.5 ± 1.1	30.7 ± 1.9	67.5 ± 11.8

^{z}Mean ± standard deviation calculated from each day of measurement.

Table 21. Analysis of variance for the effects of cultivar, water, date and their interactions on turf quality (TQ), normalized difference vegetation index (NDVI), leaf relative water content (RWC), leaf relative electrolyte leakage (EL), and evapotranspiration rate (ET) under non-shade combined with drought stress in Expt. 1 in bermudagrass.

		TQ	NDVI		RWC		EL		ET
Source	df	Sign	Sign	df	Sign	df	Sign	df	Sign
Cultivar (C)	1	NS	NS	1	NS	1	NS	1	***
Water (W)	1	***	***	1	***	1	***	1	***
Date (D)	8	***	***	4	***	3	***	17	***
C x W	1	NS	NS	1	NS	1	NS	1	***
C x D	8	NS	NS	4	NS	3	NS	17	NS
W x D	8	***	***	4	***	3	***	17	***
C X W X D	8	NS	NS	4	NS	3	NS	17	NS
Error	72			40		32		144	

*, **, ***, and NS= $P < 0.001$, $P < 0.01$, $P < 0.05$, and $P > 0.05$, respectively.

Table 22. Analysis of variance for the effects of cultivar, water, date and their interactions on turf quality (TQ), normalized difference vegetation index (NDVI), leaf relative water content (RWC), leaf relative electrolyte leakage (EL), and evapotranspiration rate (ET) under shade combined with drought stress in Expt. 1 in bermudagrass.

		TQ	NDVI		RWC		EL		ET
Source	df	Sign	Sign	df	Sign	df	Sign	df	Sign
Cultivar (C)	1	NS	***	1	NS	1	NS	1	***
Water (W)	1	***	***	1	***	1	***	1	***
Date (D)	8	***	***	4	***	3	***	17	***
C x W	1	NS	***	1	NS	1	NS	1	NS
C x D	8	NS	***	4	NS	3	NS	17	NS
W x D	8	***	***	4	***	3	***	17	***
C X W X D	8	NS	***	4	NS	3	NS	17	NS
Error	72			40		32		144	

*, **, ***, and NS= P < 0.001, P < 0.01, P < 0.05, and P > 0.05, respectively.

Table 23. Turf quality of bermudagrasses as affected by shade, drought, or combined shade and drought in Expt. 1.

		Weeks after treatment								
Light	Treatments	0	1	2	3	4	5	6	7	8
		Turf quality[z] (1-9, 9= green ideal turf)								
Non-shade	100% ET	9.0	9.0	9.0	9.0a[x]	9.0a	9.0a	9.0a	8.0a	8.0a
	50% ET	9.0	9.0	9.0	8.0b	7.0b	6.3b	4.3b	3.2b	1.0b
	$LSD_{0.05}$	NS[y]	NS	NS	0.00	0.00	0.46	0.46	1.06	0.00
Shade	100% ET	9.0	9.0	8.0	8.0	7.2a	7.3a	7.0a	6.0a	6.0a
	50% ET	9.0	9.0	8.0	8.0	6.3b	6.0b	6.0b	5.3b	4.3b
	$LSD_{0.05}$	NS	NS	NS	NS	0.59	0.47	0.00	0.47	0.47

[z] Turf quality ratings recorded on a scale of 1-9; 9= ideal healthy turf; 6=minimally acceptable quality; 1= brown dead turf.

[y] NS= Not significant at p=0.05.

[x] Values within a column followed by the same letter are not significantly different at P = 0.05 by Fisher's protected least significant difference.

Table 24. Normalized Difference Vegetation Index (NDVI) of bermudagrasses as affected by shade, drought, or combined shade and drought in Expt. 1.

			Weeks after treatment								
			0	1	2	3	4	5	6	7	8
Light	Water	Cultivars	Normalized difference vegetation index[z]								
Non-shade	100% ET		0.936	0.936	0.937a[x]	0.937a	0.937a	0.936a	0.934a	0.928a	0.922a
	50% ET		0.937	0.936	0.932b	0.925b	0.822b	0.725b	0.611b	0.555b	0.372b
	LSD$_{0.05}$		NS[y]	NS	0.002	0.002	0.003	0.013	0.042	0.031	0.053
Shade	100% ET	Celebration	0.938	0.937	0.936	0.932	0.931a	0.916a	0.91a	0.876a	0.748a
	100% ET	Latitude 36	0.936	0.937	0.934	0.932	0.931a	0.92a	0.911a	0.868a	0.763a
	50% ET	Celebration	0.936	0.937	0.936	0.930	0.83c	0.805c	0.731c	0.678b	0.593c
	50% ET	Latitude 36	0.939	0.936	0.936	0.935	0.853b	0.835b	0.788b	0.767b	0.689b
	LSD$_{0.05}$		NS	NS	NS	NS	0.011	0.012	0.036	0.041	0.027

[z] Normalized difference vegetative index (NDVI) gives the measure of turf color plus %GC and ranges from 0 to 1.

[y] NS= Not significant at p=0.05.

[x] Values within a column followed by the same letter are not significantly different at P = 0.05 by Fisher's protected least significant difference.

Table 25. Leaf relative water content and leaf relative electrolyte leakage of bermudagrasses as affected by shade, drought, or combined shade and drought in Expt. 1.

		Weeks after treatment				
Light	Treatments	0	2	4	6	8
		Leaf relative water content[z]				
		…………………………%..				
Non-shade	100% ET	87.9	85.9	85.0a[x]	86.4a	82.0a
	50% ET	88.7	89.1	75.9b	45.3b	12.1b
	$LSD_{0.05}$	NS[y]	NS	2.8	6.7	6.4
Shade	100% ET	88.5	85.4	82.8a	70.6a	66.6a
	50% ET	89.5	86.1	77.9b	68.8b	28.3b
	$LSD_{0.05}$	NS	NS	3.0	4.4	11.2
		Leaf relative electrolyte leakage[w]				
		..…………………………%.......................................				
Non-shade	100% ET	5.6	-	6.3b	7.3b	10.6b
	50% ET	5.8	-	13.1a	43.5a	66.8a
	$LSD_{0.05}$	NS		1.3	6.7	7.2
Shade	100% ET	5.7	-	6.4b	11.3b	16.6b
	50% ET	5.6	-	9.2a	24.3a	36.9a
	$LSD_{0.05}$	NS		0.5	4.4	5.6

[z] Leaf relative water content was measured gravimetrically and expressed in percentage.

[y] NS= Not significant at p=0.05.

[x] Values within a column followed by the same letter are not significantly different at P = 0.05 by Fisher's protected least significant difference.

[w] Leaf relative electrolyte leakage gives the measure of membrane stability and expressed in percentage.

Table 26. Evapotranspiration rates (mm d^{-1}) ^{z} over days after treatment as affected by shade, drought, or combined shade and drought in Expt. 1.

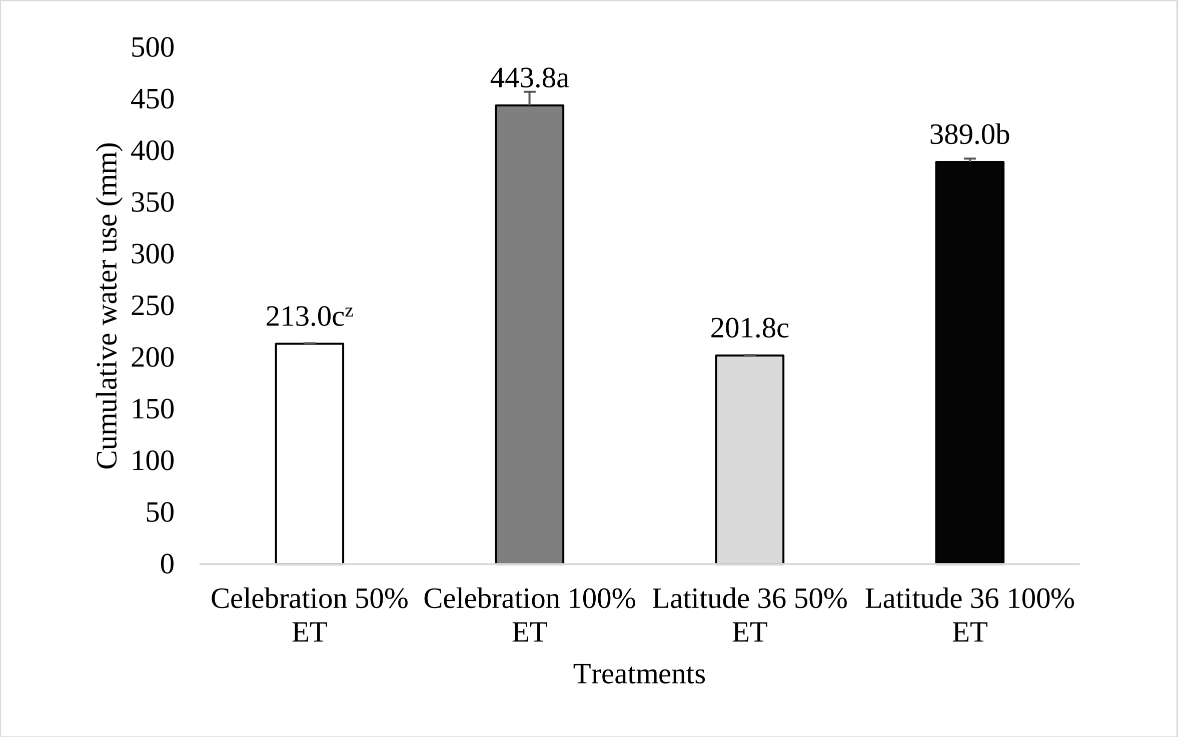
	Days after treatment																	
Cultivars	2	5	9	12	16	19	23	26	30	33	37	40	44	47	51	54	58	61
Non-shade- 100% ET																		
Celebration	8.4a^{yx}	8.1a	7.8a	7.9a	7.7a	8.0a	7.7a	7.9a	7.7a	7.7a	7.5a	7.7a	7.6a	7.5a	7.3a	7.7a	7.2a	7.4a
Latitude 36	7.3b	7.1c	6.8b	7.1b	6.6c	7.0c	6.4b	6.6b	6.2b	6.6b	6.6b	7.0a	6.9a	7.1a	6.6b	6.9b	6.6b	6.8b
Non-shade- 50% ET																		
Celebration	8.2ab	7.9ab	7.8a	7.8a	7.6a	7.7ab	6.3b	5.7c	5.4c	5.8c	4.8c	3.7c	3.5c	3.4b	2.1c	1.7c	1.6c	1.2c
Latitude 36	7.7b	7.6abc	7.5a	7.4b	7.2b	7.3bc	6.2b	5.7c	4.8d	5.3c	4.7c	3.6c	3.3d	2.9b	1.9d	1.5c	1.4c	1.1c
LSD$_{0.05}$	0.69	0.60	0.48	0.39	0.37	0.50	0.80	0.83	0.48	0.70	0.46	0.41	0.37	0.40	0.28	0.36	0.21	0.41
Shade- 100% ET																		
Celebration	6.2	6.1	6.0a	6.0	5.7a	5.7a	5.4a	5.2a	5.1a	5.1a	5.0a	5.3a	4.7a	4.7a	4.4a	4.1a	4.1a	3.5a
Latitude 36	6.1	6.0	5.9ab	5.7	5.6a	5.5b	5.0a	5.2a	4.8b	4.9a	4.8a	4.7b	4.7a	4.5a	4.1b	3.8a	3.6b	3.2a
Shade- 50% ET																		
Celebration	5.6	5.6	5.7ab	6.0	5.7a	5.7a	4.7ab	4.3b	3.4d	3.3b	3.1b	3.0c	2.8b	2.5b	2.3c	2.0b	1.7c	1.5b
Latitude 36	5.3	5.3	5.1b	5.2	4.9b	4.8ab	4.4b	4.0b	3.7c	3.5b	3.0b	3.0c	2.7b	2.4b	2.1c	2.0b	1.6c	1.5b
LSD$_{0.05}$	0.77	0.82	0.84	0.79	0.63	0.62	0.59	0.38	0.26	0.35	0.43	0.53	0.45	0.51	0.42	0.64	0.49	0.49

[z] Mean evapotranspiration rate (ET) was calculated by water balance method.

[y] ET rate was divided by number of days between water applications to generate ET in mm day^{-1}.

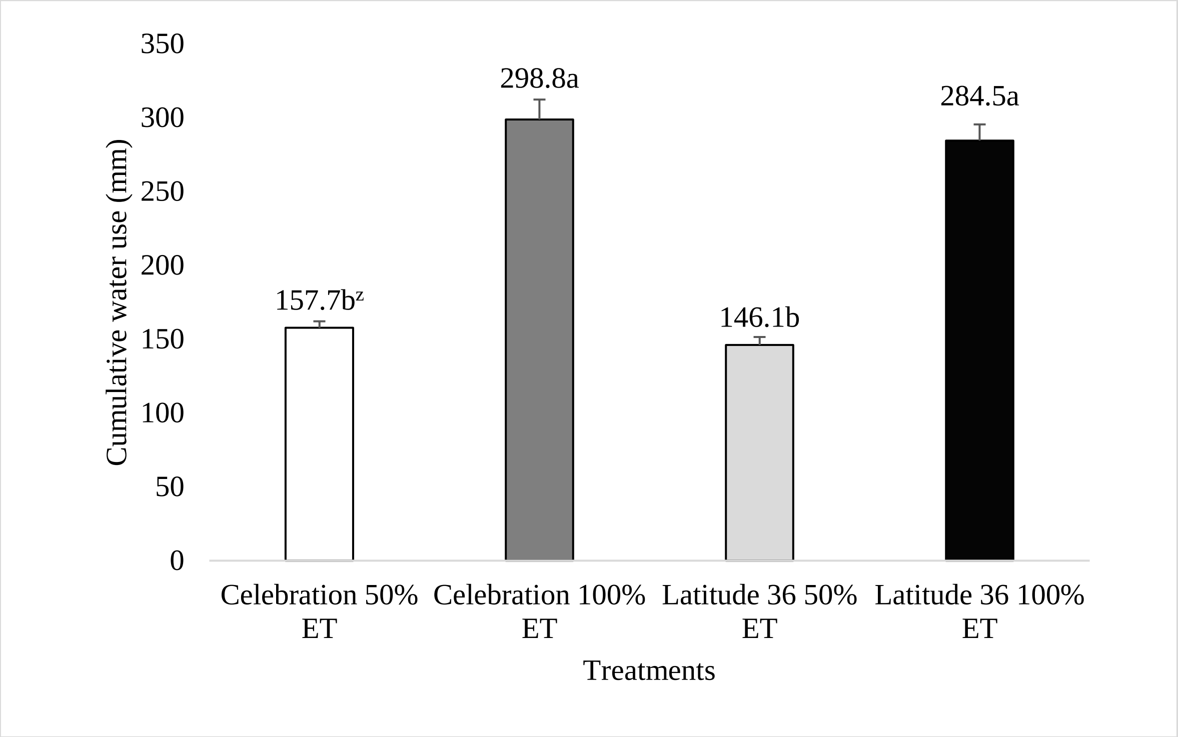
[x] Values within a column followed by the same letter are not significantly different at P = 0.05 by Fisher's protected least significant difference.

Fig. 1. Cumulative water use rates of two non-shaded bermudagrasses as affected by drought stress in Expt. 1.



[z]Means with the same letter are not significantly different at P = 0.05 by Fisher’s protected least significant difference.

Fig. 2. Cumulative water use rates of two shaded bermudagrasses as affected by drought stress in Expt. 1.



^{z}Means with the same letter are not significantly different at P = 0.05 by Fisher's protected least significant difference.

Table 27. Analysis of variance for the effects of cultivar, water, date and their interactions on turf quality (TQ), normalized difference vegetation index (NDVI), leaf relative water content (RWC), leaf relative electrolyte leakage (EL), and evapotranspiration rate (ET) under non-shade combined with drought stress in Expt. 2 in bermudagrass.

		TQ	NDVI		RWC		EL		ET
Source	df	Sign	Sign	df	Sign	df	Sign	df	Sign
Cultivar (C)	2	***	**	2	***	2	***	2	***
Water (W)	1	***	***	1	***	1	***	1	***
Date (D)	6	***	***	2	***	2	***	6	***
C x W	2	NS	NS	2	**	2	NS	2	***
C x D	12	*	NS	4	**	4	*	12	NS
W x D	6	***	***	2	***	2	***	6	***
C X W X D	12	NS	NS	4	NS	4	NS	12	***
Error	84			36		36		84	

*, **, ***, and NS= $P < 0.001$, $P < 0.01$, $P < 0.05$, and $P > 0.05$, respectively.

Table 28. Analysis of variance for the effects of cultivar, water, date and their interactions on turf quality (TQ), normalized difference vegetation index (NDVI), leaf relative water content (RWC), leaf relative electrolyte leakage (EL), and evapotranspiration rate (ET) under shade combined with drought stress in Expt. 2 in bermudagrass.

		TQ	NDVI		RWC		EL		ET
Source	df	Sign	Sign	df	Sign	df	Sign	df	Sign
Cultivar (C)	2	***	***	2	***	2	***	2	***
Water (W)	1	***	***	1	***	1	***	1	***
Date (D)	6	***	***	2	***	2	***	6	***
C x W	2	NS	**	2	NS	2	NS	2	*
C x D	12	NS	***	4	NS	4	NS	12	***
W x D	6	***	***	2	***	2	***	6	***
C X W X D	12	NS	NS	4	NS	4	NS	12	**
Error	84			36		36		84	

*, **, ***, and NS= $P < 0.001$, $P < 0.01$, $P < 0.05$, and $P > 0.05$, respectively.

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Table 29. Turf quality of three bermudagrasses as affected by shade, drought, or combined shade and drought in Expt. 2.

Light	Treatment	Weeks after treatment						
		0	1	2	3	4	5	6
		Turf quality[z] (1-9, 9= green ideal turf)						
Non-shade	100% ET	9.0	9.0	8.4a[x]	8.5a	8.7a	8.0a	8.0a
	50% ET	9.0	9.0	7.6b	7.5b	5.0b	3.4b	2.3b
	$LSD_{0.05}$	NS[y]	NS	0.34	0.34	0.34	0.99	0.64
Non-shade	Celebration	9.0	9.0	7.7b	7.9b	7.2a	5.7	5.0
	Latitude 36	9.0	9.0	8.5a	8.5a	7.4a	6.0	5.5
	Patriot	9.0	9.0	7.7b	7.5b	6.0b	5.4	4.9
	$LSD_{0.05}$	NS	NS	0.42	0.42	0.42	NS	NS
Shade	100% ET	7.7	7.5	7.0a	6.9	6.9a	6.0a	5.4a
	50% ET	7.7	7.5	6.5b	6.5	5.7b	5.2b	3.3b
	$LSD_{0.05}$	NS	NS	0.54	NS	0.34	0.54	0.42
Shade	Celebration	8.0a	7.5a	7.0a	6.9a	6.7a	6.0a	4.9a
	Latitude 36	8.0a	8.0a	7.2a	7.2a	6.7a	6.0a	4.9a
	Patriot	7.0b	6.9b	6.0b	6.0b	5.5b	4.7b	3.2b
	$LSD_{0.05}$	0.00	0.51	0.66	0.78	0.42	0.66	0.51

[z] Turf quality ratings recorded on a scale of 1-9; 9= ideal healthy turf; 6=minimally acceptable quality; 1= brown dead turf.

[y] NS= Not significant at p=0.05.

[x] Values within a column followed by the same letter are not significantly different at P = 0.05 by Fisher’s protected least significant difference.

Table 30. Normalized Difference Vegetation Index (NDVI) of three bermudagrasses as affected by shade, drought, or combined shade and drought in Expt. 2.

Light	Water	Weeks after treatment						
		0	1	2	3	4	5	6
Non-shade	100% ET	0.902	0.895	0.870a[x]	0.878a	0.859a	0.809a	0.806a
	50% ET	0.899	0.888	0.849b	0.831b	0.770b	0.555b	0.489b
	LSD$_{0.05}$	NS[y]	NS	0.016	0.018	0.030	0.056	0.054
	Celebration	0.897	0.899	0.859	0.854	0.833a	0.701	0.651ab
	Latitude 36	0.905	0.889	0.859	0.855	0.830a	0.688	0.683a
	Patriot	0.900	0.886	0.860	0.855	0.782b	0.657	0.608b
	LSD$_{0.05}$	NS	NS	NS	NS	0.037	NS	0.066
Shade	100% ET	0.816a	0.858a	0.849a	0.834a	0.759a	0.719a	0.706a
	50% ET	0.858b	0.806b	0.777b	0.772b	0.741b	0.654b	0.608b
	LSD$_{0.05}$	0.027	0.023	0.017	0.022	NS	0.051	0.046
	Celebration	0.862a	0.857a	0.832a	0.834a	0.771a	0.717a	0.713a
	Latitude 36	0.835ab	0.839a	0.835a	0.801b	0.784a	0.728a	0.714a
	Patriot	0.814b	0.801b	0.772b	0.774b	0.694b	0.615b	0.544b
	LSD$_{0.05}$	0.033	0.029	0.021	0.027	0.037	0.062	0.056

[z] Normalized difference vegetative index (NDVI) gives the measure of turf color plus %GC and ranges from 0 to 1.

[y] NS= Not significant at p=0.05.

[x] Values within a column followed by the same letter are not significantly different at P = 0.05 by Fisher’s protected least significant difference.

Table 31. Leaf relative water content and leaf relative electrolyte leakage of three bermudagrasses as affected by shade, drought, or combined shade and drought in Expt. 2.

Light	Treatments	Weeks after treatment		
		0	4	6
		Leaf relative water content[z]		
		------------------------%------------------------		
Non-shade	100% ET	94.6	94.2a[x]	80.1a
	50% ET	95.4	54.4b	17.7b
	$LSD_{0.05}$	NS[y]	2.8	2.4
Non-shade	Celebration	95.2	77.1a	50.3a
	Latitude 36	95.1	75.9a	50.5a
	Patriot	94.8	69.8b	45.8b
	$LSD_{0.05}$	NS	3.4	3.0
Shade	100% ET	78.6	70.5a	49.7a
	50% ET	78.4	49.0b	31.5b
	$LSD_{0.05}$	NS	6.4	4.2
Shade	Celebration	81.8a	61.0a	46.8a
	Latitude 36	78.9ab	68.2a	41.5b
	Patriot	74.9b	50.1b	33.6c
	$LSD_{0.05}$	4.3	7.9	5.2
		Electrolyte leakage[w]		
		------------------------%------------------------		
Non-shade	100% ET	4.5	6.2a	7.7a
	50% ET	4.6	15.7b	71.9b
	$LSD_{0.05}$	NS	1.4	3.4
Non-shade	Celebration	4.5	9.3b	38.0b
	Latitude 36	4.5	10.6b	38.3b
	Patriot	4.6	13.1a	43.0a
	$LSD_{0.05}$	NS	1.7	4.2
Shade	100% ET	15.7	24.8b	38.9b
	50% ET	15.1	31.0a	59.3a
	$LSD_{0.05}$	NS	3.2	9.0
Shade	Celebration	12.4b	24.9a	42.8b
	Latitude 36	15.8ab	26.2b	47.8ab
	Patriot	18.1a	32.6b	56.7a
	$LSD_{0.05}$	3.9	3.9	11.0

[z] Leaf relative water content was measured gravimetrically and expressed in percentage.

[y] NS= Not significant at p=0.05.

[x] Values within a column followed by the same letter are not significantly different at P = 0.05 by Fisher's protected least significant difference.

[w] Leaf relative electrolyte leakage gives the measure of membrane stability and expressed in percentage.

Table 32. Evapotranspiration rates (mm d^{-1})^z over days after treatment as affected by shade, drought, or combined shade and drought in Expt. 2.

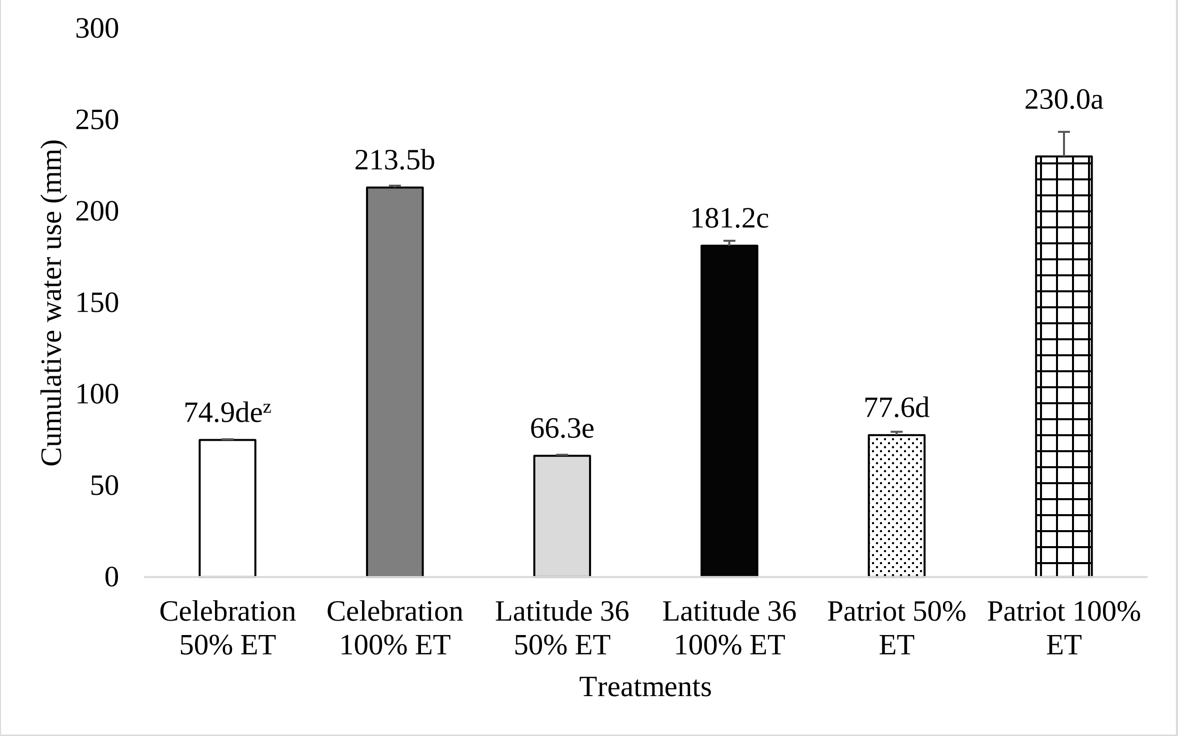
Light	Water	Cultivars	Days after treatment						
			5	12	19	26	33	40	46
Non-shade	100% ET	Celebration	6.0b^{yx}	5.3ab	5.4ab	5.0b	5.4a	5.4a	5.2b
	100% ET	Latitude 36	5.2c	4.7a-d	4.7bc	4.4c	4.7b	3.9b	4.0c
	100% ET	Patriot	6.5a	5.7a	5.8a	5.5a	5.8a	5.7a	5.7a
	50% ET	Celebration	6.1b	4.4cd	4.1cd	3.6e	2.8c	2.3c	1.4d
	50% ET	Latitude 36	5.5c	3.9d	3.6d	2.9f	2.6c	2.3c	1.4d
	50% ET	Patriot	6.5a	4.9abc	4.3cd	3.9d	2.7c	2.0c	1.2d
	$LSD_{0.05}$		0.32	0.80	0.72	0.26	0.59	0.68	0.34
Shade	100% ET	Celebration	5.3b	4.2b	4.2a	3.1a	2.5a	2.4a	2.0a
	100% ET	Latitude 36	5.0c	4.1b	3.5ab	2.9b	2.5a	2.0b	1.7b
	100% ET	Patriot	5.7a	4.7a	2.7bc	2.0d	1.8c	1.4c	1.0c
	50% ET	Celebration	5.3b	4.1b	3.2bc	2.4c	2.0b	1.5c	1.0c
	50% ET	Latitude 36	4.9c	3.8c	2.6bc	2.0d	1.6d	1.3c	0.7d
	50% ET	Patriot	5.5ab	4.3b	2.3c	1.6e	1.3e	1.0d	0.6d
	$LSD_{0.05}$		0.27	0.26	0.92	0.19	0.16	0.26	0.22

[z] Mean evapotranspiration rate (ET) was calculated by water balance method.

[y] ET rates was divided by number of days between water applications to generate ET in mm day^1.

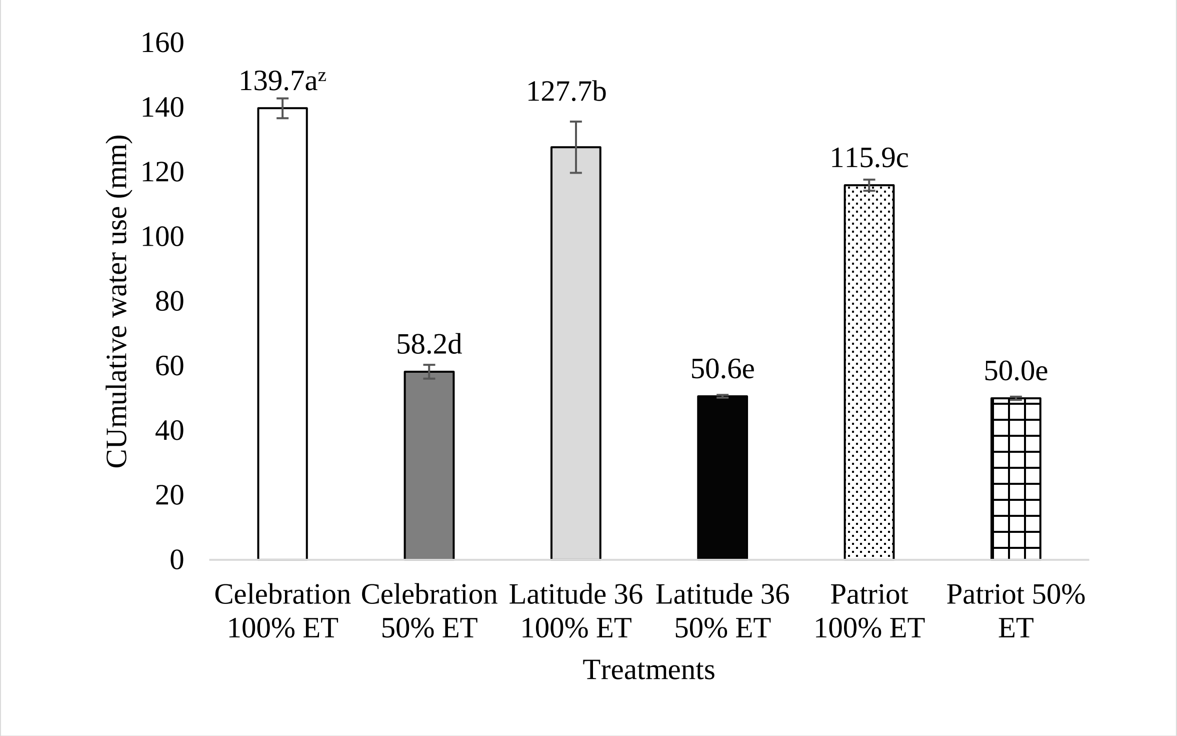
[x] Values within a column followed by the same letter are not significantly different at P = 0.05 by Fisher’s protected least significant difference.

Fig. 3. Cumulative water use rates of three non- shaded bermudagrasses as affected by drought stress in Expt. 2.



[z]Means with the same letter are not significantly different at $P = 0.05$ by Fisher's protected least significant difference.

Fig. 4. Cumulative water use rates of three shaded bermudagrasses as affected by drought stress in Expt. 2.



[z] Means with the same letter are not significantly different at P = 0.05 by Fisher's protected least significant difference.

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CONCLUSION

Bermudagrass, a widely popular warm-season turfgrass shows relatively poor tolerance to shade. It suffers from change in physiology, morphology, and eventual decline in turf health when grown under low-light conditions. Variability among bermudagrass cultivars in terms of shade tolerance have been reported previously and thus, there is a critical need for developing shade tolerant genotypes and understanding the shade tolerance mechanism at the plant level. The research presented herein was designed to contribute to the long-term goal of developing best management practices for shaded landscapes in regards to grass selection and water management.

A three-year field experiment demonstrated that variability exists among bermudagrass cultivars in terms of shade tolerance although none of the tested genotypes maintained acceptable turf quality under the most severe shade treatment. The seeded experimental cultivars evaluated in this experiment did not perform better than commercially available cultivars in moderate or severe shade suggesting further recurrent selection is required.

Two greenhouse experiments conducted in spring and summer of 2017 demonstrated that the severity of drought stress can be alleviated by the presence of shade due to decreased water use rates. No differences were observed between cultivars Latitude 36 and Celebration; however, the poor performance of the shade sensitive cultivar Patriot provides evidence that shade tolerance of the turfgrass can have a role in tolerance of the combined shade and drought stress as well. The present study was among the first to directly investigate the combined effects of shade and drought stress on bermudagrass turf.

One aspect of shade environment that was not possible to address in this greenhouse study was the tree-turf interaction. Because of the greenhouse setting of this experiment, the results from this study will likely differ when conducted in field where tree-root competition, alteration of light quality, restricted air-flow, and sunflecks might interact differently. Results from this study will contribute towards improving irrigation management of shaded turf sites and the long-term sustainability of turfgrass management.

APPENDICES

Appendix I: Analysis of variance for effect of cultivar x year on turf quality, normalized difference vegetation index, and spring green-up.

Source	df	Turf Quality	df	NDVI[z]	df	Spring green up
		Pr > F				
		Full Sun				
Cultivar (C)	9	***	9	***	9	***
Year (Y)	2	***	2	***	2	***
Block	3	***	3	*	3	NS
C x Y	18	**	18	NS	18	***
Error	87		87		87	
		Moderate shade				
Cultivar (C)	9	***	9	***	9	***
Year (Y)	2	***	2	***	2	***
Block	3	***	3	***	3	NS
C x Y	18	**	18	NS	18	***
Error	87		87		87	
		Severe shade				
Cultivar (C)	9	***	9	***	9	***
Year (Y)	2	***	2	***	2	***
Block	3	*	3	***	3	NS
C x Y	18	NS	18	NS	18	***
Error	87		87		87	

[z] Normalized difference vegetative index (NDVI) gives the measure of turf color plus density.

*, **, ***, and NS= $P < 0.001$, $P < 0.01$, $P < 0.05$, and $P > 0.05$, respectively.

Appendix II: Analysis of variance for effect of cultivar x date on turf quality, normalized difference vegetation index, and spring green-up.

Source	df	Turf Quality	df	NDVI[z]	df	Percent green up[y]
		Pr > F				
		2014				
Cultivar (C)	9	***	9	***		
Date (D)	3	***	3	***		
Block	3	***	3	NS		
C x D	27	NS	27	NS		
Error	437		437			
		2015				
Cultivar (C)	9	***	9	NS		
Date (D)	3	***	2	*		
Block	3	NS	3	NS		
C x D	27	NS	18	NS		
Error	437		327			
		2016				
Cultivar (C)	9	***	9	*	9	***
Date (D)	3	NS	3	***	2	***
Block	3	NS	3	NS	3	NS
C x D	27	NS	27	NS	18	NS
Error	437		437		327	

[z] Normalized difference vegetative index (NDVI) gives the measure of turf color plus density.

[y] Percent green up data were collected only in the year 2016.

*, **, ***, and NS= $P < 0.001$, $P < 0.01$, $P < 0.05$, and $P > 0.05$, respectively.

Appendix III: Methods for percent green cover, canopy photosynthesis, and chlorophyll content.

Digital images were taken weekly using a Power Shot G15 camera (Canon USA Inc., Melville, NY) mounted on a light box. A standard light box was illuminated by two 5-watt lamps connected to an external portable 600-watt power source (Duracell Powerpack Pro 1300). Images were then processed and analyzed for percent green cover (GC) using SigmaScan Pro 5.0 (SysStat Software, 1999) and the methods of Karcher and Richardson (2003) and Richardson et al. (2001).

Canopy photosynthesis rate was measured with a LI-6400XT portable gas exchange system (LI-COR Inc., Lincoln, NE) using a custom built clear top plexiglass chamber. Measurements were taken at 2, 4, 5, 6, 7 and 8 WAT in Expt. 1 and weekly in Expt. 2. Measurements occurred between 1100 to 1400 h from a single replication within both Non-shade and Shade block. After each measurement, the chamber was shaded by covering with a black cloth to completely block solar radiation to the chamber. Canopy gross photosynthesis (μmol CO_2 m^{-2} s^{-1}) was obtained using an equation: Gross photosynthesis = Sunlit chamber + Shaded chamber (Bremer and Han, 2005).

Chlorophyll content in clippings was measured at 0, 4 and 8 WAT for Expt. 1 and 0, 4, and 6 WAT for Expt. 2. Fresh clippings were harvested from each pot using scissors and transported in freezer bags stored on ice in a cooler. Clippings were weighed (approx. 0.1 g) and placed in a glass test tube with 7 mL N, N- Dimethylformamide. Samples were then shaken in horizontal shaker for 24 h at a low setting for extraction (Inskeep and Bloom, 1985). Upon completion of extraction, samples were passed through Whatman 41 filter paper and brought to volume in a 10-mL volumetric flask. Absorbance values were recorded at 665 nm and 647 nm wavelengths using a spectrophotometer (Genesys 20, ThermoSpectronic, Rochester, NY). The following formulae were used to calculate concentrations of chlorophyll a, chlorophyll b and total chlorophyll following the methods of Inskeep and Bloom (1985).

Chla (mg/L) = $12.7 * A_{665} – 2.79 * A_{647}$ (Eq. 1)

Chlb (mg/L) = $20.7 * A_{647} – 4.62 * A_{665}$ (Eq. 2)

Total Chl (mg/L) = $17.9 * A_{647} + 8.08 * A_{665}$ (Eq. 3)

Chlorophyll contents (mg g^{-1}) were calculated as:

$$\frac{Chlorophyll\ concentration\ \left(\frac{mg}{L}\right) x\ Volume\ of\ extract\ (mL)}{g\ of\ leaf\ tissue} = Chlorophyll\ content\ (mg\ g-1)$$

(Eq. 4)

Appendix IV: Analysis of variance for the effects of cultivar, water, date and their interactions on percent ground cover (%GC), canopy gross photosynthesis rate (P_g), chlorophyll a content (Chla), chlorophyll b content (Chlb), and total chlorophyll content (TChl) under shade combined with drought stress in Expt. 1 in bermudagrass.

	……………..………. Non-shade…………..…………						…………………………………Shade…………………………					
		%GC		Chla	Chlb	TChl		%GC		Chla	Chlb	TChl
Source	df	Sign	df	Sign	Sign	Sign	df	Sign	df	Sign	Sign	Sign
Cultivar (C)	1	NS	1	NS	NS	NS	1	NS	1	**	NS	**
Water (W)	1	***	1	***	***	***	1	***	1	***	***	***
Date (D)	8	***	2	***	***	***	8	***	2	***	***	***
C x W	1	NS	1	NS	NS	NS	1	NS	1	NS	NS	NS
C x D	8	NS	2	NS	NS	NS	8	NS	2	***	**	***
W x D	8	***	2	***	***	***	8	***	2	***	***	***
C X W X D	8	NS	2	NS	NS	NS	8	NS	2	NS	NS	NS
Error	72		24				72		24			

*, **, ***, and NS= $P < 0.001$, $P < 0.01$, $P < 0.05$, and $P > 0.05$, respectively.

Appendix V: Percent green cover (%GC), and canopy gross photosynthesis rate leakage of bermudagrasses as affected by shade, drought, or combined shade and drought in Expt. 1.

		Weeks after treatment								
Light	Treatments	0	1	2	3	4	5	6	7	8
		Percent green %GC[z]								
Non-shade	100% ET	95.5a[y]	94.7a	94.1a	94.1a	94.6a	94.7a	94.5a	88.2a	84.1a
	50% ET	96.3a	93.9a	93.5a	85.5b	75.3b	55.6b	53.6b	31.2b	12.3b
	$\text{LSD}_{0.05}$	NS	NS	NS	3.45	1.57	3.85	2.53	2.64	1.62
Shade	100% ET	93.2	94.1	92.1	88.0	84.7a	70.4a	73.4a	64.3a	45.8a
	50% ET	93.1	93.7	92.0	88.0	78.5b	63.9b	64.9b	55.4b	41.2b
	$\text{LSD}_{0.05}$	NS	NS	NS	NS	2.66	5.96	2.46	3.79	4.62

		Canopy gross photosynthesis rate[x]					
		Weeks after treatment					
		2	4	5	6	7	8
Non-shade	100% ET	25.9	25.8	32.6	26.1	29.3	16.9
	50% ET	26.2	10.5	8.2	5.9	1.1	-0.01
Shade	100% ET	18.6	21.5	21.3	18.0	10.7	5.1
	50% ET	18.3	14.9	14.9	8.7	4.8	3.4

[z] Percent green %GC was generated analyzing the digital images through SigmaScan Software.

[y] Values within a column followed by the same letter are not significantly different at P = 0.05 by Fisher's protected least significant difference.

[x] Canopy gross photosynthesis rate was measured using LI-6400 XT portable gas exchange chamber by adding gas exchange rates in sunlit and shade chamber.

Appendix VI: Mean chlorophyll a, chlorophyll b, and total chlorophyll content in mg g^{-1} of fresh clippings in bermudagrasses as affected by shade, drought, or combined shade and drought in Expt. 1.

		Weeks after treatment		
Light	Treatments	0	4	8
		Chlorophyll a content (mg g^{-1}) [z]		
Non-shade	100% ET	1.88	1.80a[y]	0.95a
	50% ET	1.90	1.51b	0.07b
	$LSD_{0.05}$	NS	0.17	0.27
Shade	100% ET	1.98	2.22a	1.73a
	50% ET	2.08	1.19b	1.38b
	$LSD_{0.05}$	NS	0.250	0.09
Shade	Celebration	1.85b	1.78	1.46b
	Latitude 36	2.21a	1.63	1.65a
	$LSD_{0.05}$	0.18	NS	0.09
		Chlorophyll b content (mg g^{-1}) [x]		
Non-shade	100% ET	0.66	0.69a	0.53a
	50% ET	0.70	0.58b	0.09b
	$LSD_{0.05}$	NS	0.088	0.083
Shade	100% ET	0.67	0.75a	0.63a
	50% ET	0.70	0.51b	0.51b
	$LSD_{0.05}$	NS	0.080	0.04
Shade	Celebration	0.63b	0.66	0.55
	Latitude 36	0.74a	0.61	0.59
	$LSD_{0.05}$	0.05	NS	NS
		Total Chlorophyll content (mg g^{-1}) [w]		
Non-shade	100% ET	2.53	2.48a	1.47a
	50% ET	2.59	2.09b	0.16b
	$LSD_{0.05}$	NS	0.178	0.206
Shade	100% ET	2.65	2.97a	2.35a
	50% ET	2.77	1.69b	1.89b
	$LSD_{0.05}$	NS	0.25	0.12
Shade	Celebration	2.47b	2.43	2.01b
	Latitude 36	2.94a	2.23	2.23a
	$LSD_{0.05}$	0.23	NS	0.13

[z] Chlorophyll a content was determined in mg per g of fresh clippings using the equation described by Inskeep and Bloom (1985).

[y] Values within a column followed by the same letter are not significantly different at P = 0.05 by Fisher's protected least significant difference.

[x] Chlorophyll b content was determined in mg per g of fresh clippings using the equation described by Inskeep and Bloom (1985).

[w] Total Chlorophyll content is the sum of chlorophyll a and chlorophyll b content.

Appendix VII: Analysis of variance for the effects of cultivar, water, date and their interactions on percent ground cover (%GC), canopy gross photosynthesis rate (P_g), chlorophyll a content (Chla), chlorophyll b content (Chlb), and total chlorophyll content (TChl) under shade combined with drought stress in Expt. 2 in bermudagrass.

		………………Non- shade…………………					………………………… Shade……………………………					
		%GC		Chla	Chlb	TChl		%GC		Chla	Chlb	TChl
Source	df	Sign	df	Sign	Sign	Sign	df	Sign	df	Sign	Sign	Sign
Cultivar (C)	2	***	2	NS	NS	NS	2	***	2	***	NS	***
Water (W)	1	***	1	***	***	***	1	***	1	*	**	***
Date (D)	6	***	2	***	***	***	6	***	2	***	***	***
C x W	2	*	2	NS	NS	NS	2	NS	2	NS	NS	NS
C x D	12	NS	4	NS	NS	NS	12	***	4	NS	NS	***
W x D	6	***	2	***	***	***	6	***	2	**	NS	***
C X W X D	12	NS	4	NS	NS	NS	12	NS	4	**	NS	**
Error	84		36				84		36			

*, **, ***, and NS= $P < 0.001$, $P < 0.01$, $P < 0.05$, and $P > 0.05$, respectively.

Appendix VIII: Mean percent green cover (%GC) and canopy gross photosynthesis rates of three bermudagrasses as affected by shade, drought, or combined shade and drought in Expt. 2.

Light	Treatment	Weeks after treatment						
		0	1	2	3	4	5	6
		Percent green %GC^{z}						
Non-shade	100% ET	95.8	95.2a^{y}	93.5a	93.7a	93.2a	85.8a	84.5a
	50% ET	95.7	93.0b	88.3b	59.5b	52.8b	20.6b	17.4b
	LSD$_{0.05}$	NS	1.5	2.4	1.8	3.6	4.7	3.9
Non-shade	Celebration	96.0	93.7	91.6	77.7a	74.4a	52.6	50.8ab
	Latitude 36	95.6	94.9	91.9	78.3a	74.9a	55.2	54.4a
	Patriot	95.6	93.6	89.2	73.8b	69.6b	52.0	47.5b
	LSD$_{0.05}$	NS	NS	NS	2.2	4.4	NS	4.8
Shade	100% ET	75.8	73.5a	71.0a	65.4a	58.2a	48.5a	47.1a
	50% ET	74.9	71.1b	62.8b	53.5b	51.1b	26.8b	33.6b
	LSD$_{0.05}$	NS	2.17	3.09	4.11	4.34	3.74	3.31
Shade	Celebration	77.2a	74.2a	69.7a	66.4a	61.1a	47.8a	54.7a
	Latitude 36	77.3a	72.9a	68.6a	62.7a	58.8a	42.3b	46.8b
	Patriot	71.6b	69.8b	62.4b	49.3b	44.2b	23.0c	19.6c
	LSD$_{0.05}$	2.75	2.66	3.78	5.03	5.31	4.58	4.05
		Canopy gross photosynthesis rates^{x}						
Non-shade	100% ET	33.5	34	32.8	32.4	29.3	25.2	25.6
	50% ET	33.5	35.6	28.8	18.7	6.5	1.1	-5.7
Shade	100% ET	22.7	22.3	19.3	18.6	14.0	8.7	7.1
	50% ET	24.0	22.3	16.5	13.0	10.1	2.7	-1.7

[z] Percent green %GC was generated analyzing the digital images through SigmaScan Software.

[y] Values within a column followed by the same letter are not significantly different at P = 0.05 by Fisher's protected least significant difference.

[x] Canopy gross photosynthesis rate was measured using LI-6400 XT portable gas exchange chamber by adding gas exchange rates in sunlit and shade chamber.

Appendix IX: Mean chlorophyll a and chlorophyll b contents in mg g^{-1} of fresh clippings of three bermudagrasses as affected by shade, drought, or combined shade and drought in Expt. 2.

Light	Treatments	Chlorophyll a content (mg g^{-1})[z]		
		0	4	6
Non-shade	100% ET	2.62	1.71a[y]	1.86a
	50% ET	2.58	1.02b	0.19b
	LSD $_{0.05}$	NS	0.26	0.28
Shade	100% ET	2.6	1.64	0.83a
	50% ET	2.81	1.46	0.34b
	LSD$_{0.05}$	NS	NS	0.08
Shade	Celebration	3.10a	1.88a	0.69a
	Latitude 36	2.67b	1.41b	0.67a
	Patriot	2.35b	1.36b	0.40b
	LSD$_{0.05}$	0.40	0.26	0.09
		Chlorophyll b content (mg g^{-1})[x]		
Non-shade	100% ET	0.83	1.69a	0.88a
	50% ET	0.84	0.44b	0.26b
	LSD $_{0.05}$	NS	0.24	0.09
Shade	100% ET	1.16	0.96a	0.54
	50% ET	1.02	0.58b	0.49
	LSD$_{0.05}$	NS	0.20	NS
Shade	Celebration	1.26	0.77ab	0.51
	Latitude 36	1.02	0.95a	0.51
	Patriot	0.99	0.58b	0.52
	LSD$_{0.05}$	NS	0.25	NS

[z] Chlorophyll a content was determined in mg per g of fresh clippings using the equation described by Inskeep and Bloom (1985).

[y] Values within a column followed by the same letter are not significantly different at P = 0.05 by Fisher's protected least significant difference.

[x] Chlorophyll b content was determined in mg per g of fresh clippings using the equation described by Inskeep and Bloom (1985).

Appendix X: Total chlorophyll content in mg g^{-1} of fresh clippings of three bermudagrasses as affected by shade, drought, or combined shade and drought in Expt. 2.

Light	Treatments	Total chlorophyll content (mg g^{-1}) ^{z}		
		0	4	6
Non-shade	100% ET	3.49	3.39a	2.74a
	50% ET	3.44	1.46b	0.44b
	LSD $_{0.05}$	NS	0.16	0.26
Shade	100% ET	3.75	2.59a	1.36a
	50% ET	3.83	2.03b	0.83b
	LSD$_{0.05}$	NS	0.13	0.07
Shade	Celebration	4.35a	2.65a	1.2a
	Latitude 36	3.68b	2.35b	1.18a
	Patriot	3.33c	1.94c	0.91b
	LSD$_{0.05}$	0.29	0.16	0.09

^{z}Total Chlorophyll content is the sum of chlorophyll a and chlorophyll b content.

VITA

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