EFFECTS OF LIGHT QUALITY ON THE GROWTH AND DEVELOPMENT OF TWO HORTICULTURAL CROPS

By

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EFFECTS OF LIGHT QUALITY ON THE GROWTH AND DEVELOPMENT OF TWO HORTICULTURAL CROPS

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Abstract: The effect of various light environments on the growth of two horticultural crops was investigated. The growth and development of plants is affected by light quality, light periodicity, light quantity, and phototropism. These parameters can be controlled by photoselective filters or shade nets to induce morphological and physiological responses in plants. Two sets of greenhouse experiments were conducted by selectively screening sunlight for two horticultural crops, turfgrass and romaine lettuce (*Lactuca sativa* L. var. *longifolia*). Treatments for the turfgrass study included a blue polyester gel filter, 40% black poly-woven fabric, and a combination thereof to create reduced R:FR, reduced PPF, and reduced R:FR plus reduced PPF conditions to reproduce vegetative and neutral shade and observe shade avoidance responses under each treatment. Each shade treatment resulted in longer leaves, symptomatic of shade avoidance responses for both turfgrass species. Bermudagrass (*Cynodon dactylon* (L.) Pers. 'JSC2009-6') had a strong response to each shade treatment and exhibited a decrease in tillers and leaf count. However, there is little evidence that the reduced R:FR ratio in this study initiated responses in bermudagrass over responses to a reduced PPF. Treatments for the lettuce study included four commercial shade nets: Chromatinet® pearl, Chromatinet® red, aluminet ®, and standard black. Applied shade nets (all rated to decrease solar radiation by 30%) significantly reduced PPF from 1033 µmol m^{-2} s^{-1} under ambient light to 617 – 733 µmol m^{-2} s^{-1} under nets. Lettuce grown under pearl-+ shade net had the highest number of leaves. Lettuce grown under aluminet in the summer produced plants with a greater leaf area. Lettuce grown under red shade net had the greatest total dry weight. The results of both studies indicates that managing light quality with photoselective filters and spectrally modified shade nets does impact the growth and development of turfgrass and romaine lettuce.

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CHAPTER I

LITERATURE REVIEW

Introduction

Plants need light to grow, develop, and adapt to environmental conditions. Light captured by chlorophyll in plants provides the energy for photosynthesis, the process in which plants combine carbon dioxide and water to produce oxygen and carbohydrates. Light also operates as a signal of environmental conditions that impact plant growth and development. Plants are responsive to light quantity, light quality, the intervals with which light occurs, also known as periodicity, and the direction of light, also known as phototropism (Illic & Fallik, 2017). Within plants, there are several light-absorbing compounds referred to as photoreceptors that attain energy in various regions of the electromagnetic spectrum. These photoreceptors allow plants to perceive any alterations in light environment, which then will initiate physiological and morphological changes necessary for the plant to adapt to the environment (Demotes-Mainard et al., 2016).

Light quantity and quality

The quality and the quantity of light determines how well plants grow (Kubota et al., 2016). Light quantity, as it relates to plants, is the amount of photons available for photosynthesis and is typically reported as photosynthetic photon flux (PPF) with units of micromoles of photons per square meter per second (μmol m^{-2} s^{-1}), which is considered more relevant for biological processes than irradiance (Chen et al., 2014; Darko et al., 2014; Ouzounis et al., 2015). A daily light integral (DLI) is the accumulation of PPF over the course of a day and provides a simple metric for quantifying light quantity across locations and time periods (Faust & Logan, 2018).

Light quality refers to the spectral distribution of light, or the relative number of photons of each wavelength within a light spectrum. Plants are responsive to the spectrum of light ranging from ultraviolet (UV) to infrared. These specific regions include UV (< 400 nm), visible (400-700 nm), far-red (700-800 nm), and infrared (>800 nm) (Sudhakar et al., 2013). The visible region of light is often termed photosynthetically active radiation (PAR) as this region of the light spectrum provides energy for photosynthesis in plants. The rate of photosynthesis is determined by the amount of PAR. Photosynthetically active radiation can further be divided into regions of blue (400-500 nm), green (500-600 nm), and red (600-700 nm) (Sudhakar et al., 2013). The primary photosynthetic pigment, chlorophyll, has absorbance of light in the blue (peak absorbance at 430 nm) and red regions (peak absorbance at 660 nm), with very little absorption in the green region of light (Carvalho et al., 2011). The blue, red, and far-red regions of the light spectrum also play an integral role in the photomorphogenesis of plants (Demotes-Mainard et al., 2016). Photomorphogenesis is the process by which plants perceive changes in the light spectrum that then influence growth and development. These changes in the light spectrum are captured by several light-absorbing compounds, such as photoreceptors, including cryptochromes, chlorophylls, phototropins, and phytochromes

(Cerny et al., 2003). Cryptochromes and phototropins are both blue-light photoreceptors. Cryptochromes regulate plant development and photomorphogenesis. Phototropins are involved in phototropism, which is the orientation of a plant in response to the direction of light (Briggs et al., 2001). Phytochromes are photoreceptors sensitive to light in the R:FR region of the visible spectrum of light. There are two forms of phytochrome: the active form, which is stimulated by far-red light (705–740 nm) and the inactive form, which is stimulated by red light (650–670 nm) (Kreslavski et al., 2018). These photoreceptors trigger responses in the growth and development of the plant that allow it to adapt to the change in the environment.

Plant responses to light

The R:FR region of the spectrum (650-740 nm) stimulates several plant responses, including leaf expansion, stem elongation, and flowering (Demotes-Mainard et al., 2016). The blue region of the spectrum (420-450 nm) influences phototropism, cell elongation, and shoot elongation (Huché-Thélier et al., 2016) The R:FR wavelengths of the light spectrum is important in plant development and regulates phytochrome activity (Demotes-Mainard et al., 2016). Light quality fluctuates based on the time of day and the season. At dawn and dusk, shorter wavelengths are filtered due to the lesser angle of incident light.

Phytochromes play an important role in the regulation of photosynthetic processes under stress conditions in both C3 and C4 plants (Kreslavski et al., 2018). In C3 plants, the first carbon compound produced during photosynthesis comprises three carbon atoms. Under stress conditions, such as high temperature and light intensity, C3 plants close stomata causing the oxygen concentration in the leaf to be higher than the carbon dioxide concentration, which leads to oxygen binding with the photosynthetic enzyme rubisco instead of carbon dioxide in a process called photorespiration (Furbank & Taylor, 1995). Photorespiration reduces the photosynthetic efficiency in C3 plants and results in the net loss of carbon from the plant. The C4 plants have evolved mechanisms to avoid photorespiration using the enzyme PEP carboxylase, which does not bind to oxygen, to concentrate carbon dioxide within specialized bundle sheath cells. As a result, C4 plants typically have greater photosynthetic efficiency during periods of high temperature and light intensity (Furbank & Taylor, 1995). However, during periods of low light intensity, the rate of CO^2 leakage (expressed as the relative rate of phosphoenolpyruvate (PEP) carboxylation) increases, due to a possible partial suppression of photorespiration (Cousins et al., 2008; Hendersons et al., 1992; Tazoe et al., 2008). Light quality and quantity can each have an impact on carbon assimilation and plant development in both C3 and C4 plants (Sun et al., 2011).

Applications of light response in turfgrass management

Approximately 20% - 25% of cultivated turf in the United States grows under shade from trees, shrubs, or buildings (Beard, 1997). Shaded environments are complex in that “vegetative shade” and/or “neutral shade” can be produced, with the latter referring to shade derived from buildings or other non-vegetative objects. While neutral and vegetative shade are common sources of shade, additional changes in the light spectra further influence plant physiology and morphology (Wherley et al., 2005). Both neutral and vegetative shade reduce light intensity, however, vegetative shade also alters the spectral quality, most often characterized by a reduction in the R:FR ratio. A reduction in the R:FR reaching a turfgrass canopy under a shaded environment is caused by a higher transmittance of far red light due to the trees' absorption of red and blue wavelengths (Bell et al., 2000). The R:FR of full sunlight ranges from 1.15 – 1.28, while the R:FR under vegetative shade has been reported to be from 0.36 to 0.97, with the R:FR under vegetative shade more commonly reported as ranging ~0.7 (Petrella & Watkins, 2020; Studzinska et al., 2012; Wherley et al., 2005). Reductions in R:FR ratio correlate with changes in plant growth and development termed shade avoidance responses. Shade avoidance responses will trigger reduced tillering, increased leaf length, decreased leaf width, thinner leaves, vertical stem elongation, and a lower chlorophyll content in plants (Allard et al., 1991; Ballare et al., 2017; Casal et al., 1990; Wherley et al., 2005). Morphological changes associated with the shade avoidance responses can also result in loss of carbohydrate stores due to excessive leaf removal during mowing. Lower carbohydrate levels reduce tillering and density, thus light quality affects biomass production of the plant (Baldwin et al., 2009). Plants that are more shade-tolerant will display reductions in stem and leaf elongation and greater tillering compared to shade-intolerant plants which will display responses that are contrary to shade-tolerant plants (Valladares, 2008). Shade-tolerant plants will also demonstrate reductions in specific leaf area and increases in the amounts of chlorophyll (Beard, 1997; Valladares, 2008).

A reduction in the R:FR ratio can influence plant growth and development beyond a reduction in light intensity or PPF alone. A growth chamber experiment studying annual ryegrass (*Lolium multiflorum* Lam.) growth and development found that annual ryegrass displayed an increase in leaf length and had fewer tillers under simulated reduced R:FR ratio combined with reduced PPF conditions compared to reductions in

PPF alone (Casal et al., 1985). Similarly, in another growth chamber experiment, perennial ryegrass (*Lolium perenne* L.) plants grown under a combination of low PPF and reduced R:FR had fewer tillers compared to perennial ryegrass plants grown under low PPF conditions alone (Gautier et al., 1999). In a field study, tall fescue (*Schedonorus arundinaceus* Schreb.) grown under vegetative shade had thinner leaves, fewer tillers, and a lower chlorophyll concentration compared to tall fescue grown in reduced PPF conditions alone (Wherley et al., 2005).

A tool researchers have been using to evaluate shade responses in plants is to utilize neutral-density shade nets in field studies, greenhouses, and through reducing PPF in growth chambers (Bahmani et al., 2000; Devkota et al., 1998; Li et al., 2017; Meeks et al., 2015; Richardson et al., 2019). However, using only neutral-density shade nets in these research studies disregards changes in spectral quality that is found under vegetative shade. To evaluate the effects of vegetative shade, researchers have used far-red light emitting diodes (LEDs) in growth chambers or photoselective filters in greenhouses to simulate spectral changes under vegetative canopies (Casal et al., 1985; Gautier et al., 1999; Petrella & Watkins, 2020; Studzinska et al., 2012). In a greenhouse experiment, a photoselective filter was used that reduced the R:FR ratio to 0.70 in combination with a 30% reduction in PPF to simulate vegetative shade on creeping bentgrass (*Agrostis stolonifera* L.) (Studzinska et al., 2012). In another greenhouse experiment, a blue polytheylene photoselective filter along with a black shade net that reduced light intensity by 30% placed on top of the filter was used to simulate vegetative shade and evaluate the effects of this combination shade on Chewings fescue (*Festuca rubra* L. ssp. *commutata* Gaudin), hard fescue (*Festuca brevipila* Tracey), and strong creeping red fescue (*Festuca rubra* ssp. *rubra* Gaudin) (Petrella & Watkins, 2020). Photoselective filters have been used to evaluate the effects of altered light quality on plant growth and development in other plant species (Clifford et al., 2004; Lara et al., 2021; Li et al., 2000; Lykas et al., 2008; Runkle et al., 2001).

Applications of light response to the growth and development of lettuce

Lettuce (*Lactuca sativa* L.) is a common cool season crop grown worldwide, either cultivated in the fields or in greenhouses using hydroponics. Various factors impact the growth and development of lettuce grown in hydroponic systems including light, ambient temperature, electrical conductivity (EC) of the nutrient solution, pH of the nutrient solution, and temperature of the nutrient solution (Gent, 2017). Light and temperature play an integral role in the year-round production of lettuce, especially in locations where temperatures and photoperiod are the highest. Lettuce yield and marketability are negatively affected as planting dates progress toward longer days and warmer temperatures (Dufault et al., 2006). The reason for this reduction in marketability is attributed to the formation of loose heads, tipburn, and bolting (Zhao and Carey, 2009). Tipburn is a common physiological disorder of lettuce caused by sub-optimal environmental factors in field production and hydroponics (Holmes et al., 2019). Tipburn is induced by a calcium deficiency in the youngest developing leaves of lettuce. Calcium is essential for the creation of the cell membrane and cell walls (Saure, 1998). Sub-optimal temperatures, light intensity, nutrient solution concentration, and air flow are factors that contribute to tipburn (Swaef et al., 2015). Also, high light intensity and an extended photoperiod increase the incidence and severity of tipburn (Mashego, 2001; Saure, 1998; Sago, 2016). These factors also induce another physiological disorder of lettuce bolting. Bolting is referred to as the transition from the vegetative to reproductive stage. Symptoms of bolting include rapid stem elongation, followed by flowering. In lettuce, stem elongation is undesired as it deems the plant unmarketable. Higher temperatures may allow the plant to grow faster and flower earlier, however this usually allows bitter flavors to accumulate (Zhao & Carey, 2009). In order to overcome or decrease the impacts of high light intensity in places with warmer climates during summer months, cool-season vegetables, such as lettuce should be grown under shaded conditions.

Photoselective shade nets are a relatively new agricultural tool used to protect crops using different filtration of solar radiation (Shahak, 2008). Researchers have studied the effect of photoselective filters on plant physiology and morphology (Díaz-Pérez & St. John, 2019). The application of many of these prior studies has been on production within greenhouse environments (Cerny et al., 2003). Recently, colored shade cloths or netting have been designed for the specific purpose of manipulating plant growth and development in a manner that also increases yield (Zare et al., 2019). Photo-selective nets affect environmental conditions such as temperature, light intensity, and humidity (Díaz-Pérez and St. John, 2019). Photo-selective nettings also selectively filter light creating targeted spectra that can be perceived by plant photoreceptors. The ability of photoselective nets to transform direct light to scattered light allows the diffusion of light into the inner plant canopy, possibly initiating a moderate cooling effect (Shahak, 2008; Stamps, 2009). The color of photoselective nets can also influence physiological processes in the plants as well as the yield and quality (Illic et al., 2017). In a study conducted on lettuce in South Africa, plants grown under photo-selective pearl and yellow nets with 40% shading enhanced the fresh weight and percentage of marketable yield at harvest (Ntsoane et al., 2016). The pearl net is designed to scatter light to a greater extent than other types of photoselective shade nets (Rajapakse & Shahak, 2007). Black shade nets are most commonly used in the horticulture industry, however, it does not modify spectral quality or have the ability to scatter light (Arthurs et al., 2013; Selahle et al., 2014) The most important reason for using photoselective netting is to decrease the potential for physiological disorders of cool-season vegetable crops in places with warmer climates.

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CHAPTER II

EFFECTS OF REDUCED R:FR RATIO ON TURFGRASS SEEDLING GROWTH

Abstract

Warm-season turfgrasses can be highly sensitive to reductions in light quantity, but less is known about their response to light quality. A greenhouse project was conducted to investigate the morphological response of bermudagrass (*Cynodon dactylon* (L.) Pers. ‘JSC2009-6’) and perennial ryegrass (*Lolium perenne* L.) seedlings to four shade treatments under non-mown conditions. Grasses were planted as a single seed within 2.5 cm cone-tainers filled with soilless media. After seedling emergence, shade was applied using a blue polyester gel filter, 40% black poly-woven fabric, or a combination thereof to create reduced red to far red (R:FR), reduced photosynthetic photon flux (PPF), and reduced R:FR plus reduced PPF conditions. Data collected included chlorophyll content, progressive canopy height, leaf angle, leaf area, specific leaf area, tiller count, and above-ground and below-ground dry mass. Each shade treatment resulted in longer leaves, symptomatic of shade avoidance responses for both species. Bermudagrass had a stronger response to each shade treatment and exhibited a decrease in tillers and leaf count. However, there was little evidence that the reduced R:FR ratio initiated additional responses in bermudagrass over responses to a reduced PPF alone.

INTRODUCTION

Light having wavelengths between 400 and 700 nm is referred to as photosynthetically active radiation (PAR) and is considered the only light that can be used by plants for assimilation of carbon. Photosynthetically active radiation is measured in terms of photosynthetic photon flux (PPF). Approximately 25% of cultivated turf in the United States is grown under some level of shade (Beard, 1997). Shade reduces PPF therefore disrupting the energy available to assimilate carbon (Wherley et al., 2005). Shade has most commonly been defined as either “vegetative shade” (qualitative) or “neutral shade” (quantitative), with the latter referring to shade derived from buildings or other non-vegetative objects. Quantitative shade leads to a reduction in all light uniformly. Under quantitative shade, turfgrasses respond to the reduction of light intensity (Studzinka et al, 2012). Qualitative shade can include vegetative canopies, such as trees, that reduce light intensity and filters light. Vegetative shade from trees selectively absorbs red and blue wavelengths while transmitting far red wavelengths, thus reducing the ratio of red light to far red light (R:FR ratio) reaching the turfgrass canopy (Bell et al., 2000). The R:FR ratio is an indicator of change in light quality and is detected by phytochromes within the plant (Ruberti et al., 2012). The R:FR ratio for full sunlight averages 1.15 (Holmes & Smith, 1977), while values for vegetative shade from trees have ranged between 0.43 and 0.91 (Bell et al., 2000). A reduction in the R:FR ratio stimulates changes in plant growth and development, referred to as shade avoidance responses (Casal, 2013; Ruberti et al., 2012; Smith, 1982). Shade avoidance responses include vertical stem elongation, lower chlorophyll concentration, a reduction in leaf thickness, and reduced tillering (Allard et al., 1991; Ballare et al., 2017; Casal et al., 1990; Wherley et al., 2005). Previous research shows evidence of shade avoidance responses to a reduction in R:FR ratio in cool-season grasses. In a growth chamber experiment, perennial ryegrass (*Lolium perenne* L.) produced fewer tillers under a combination of reduced PPF and reduced R:FR ratio compared to a reduced PPF (Gautier et al., 1999). Two tall fescue (*Schedonorus arundinaceus* Schreb.) cultivars, Plantation and Equinox, responded to vegetative shade (reduced R:FR ratio) with a decrease in tillering, lower chlorophyll concentrations, and narrower and thinner leaves compared to the tall fescue grown in only reduced PPF conditions (Wherley et al., 2005). In another growth chamber experiment, annual ryegrass (*Lolium multiflorum* Lam.) exhibited an increase in leaf length and a decrease in tillering due to a combined reduction in the R:FR ratio and a reduction in PPF compared to a reduction in PPF (Casal et al., 1985). Previous research evaluating the effects of a reduced R:FR ratio has focused mainly on cool-season grasses. Warm-season turfgrasses can be highly sensitive to reductions in light quantity, but less is known about their response to a change in R:FR ratio.

Bermudagrass (*Cynodon dactylon* (L.) Pers.), a popular warm-season turfgrass used for its many desirable traits including drought resistance, traffic tolerance, and disease resistance (Barrios et al., 1986; Beard, 1973). Despite these desirable characteristics, bermudagrass is often limited by its poor shade tolerance (Zhang et al., 2017). Multiple studies have reported light quantity (PPF) is critical to performance of bermudagrass and other warm-season turfgrasses (Chhetri et al., 2019; Zhang et al., 2017). Whether shade stress is worsened by changes in light quality is less well-documented. This study aimed to study the effect of a reduction in R:FR ratio on the morphology of bermudagrass seedlings under different shade treatments.

MATERIALS AND METHODS

Plant materials and growing conditions

An eight-week greenhouse study was conducted at the Oklahoma State University Horticulture Research Greenhouse in Stillwater, Oklahoma. The study was conducted from 23 January 2020 to 19 March 2020 and then repeated 27 August 2020 to 22 October 2020. The study used bermudagrass (*Cynodon dactylon* (L.) Pers. 'JSC2009-6') and a perennial ryegrass (*Lolium perenne* L.) mixture of 'Palmer III', 'Prelude IV', and 'Line Drive II' (Palmer's Pride Par III, Green Seed Company, Springfield, MO). Both species were planted as a single seed within a 4 mm diameter cone-tainer filled with a soilless growing medium (Metro-Mix 360, Sun Gro Horticulture, Agawam, MA). Pots were watered from below and maintained under saturated conditions until germination. After germination, water was maintained in the tubs to ensure the soil surface was visibly moist but not saturated. At weeks 3, 5, and 7 after shade treatment initiation, a water soluble fertilizer (20N-20P_2O_5-20K_2O, Harrell's LLC, Lakeland, FL) was applied to each cone-tainer at a rate of 1.1 g m^{-2} N. Preventative application of 8.8% azoxystrobin (Heritage TL, Syngenta Crop Protection, Inc., Greensboro, NC) was applied three weeks after planting and then every two weeks at 20 mL per cone-tainer of 0.4 mL Heritage TL/1.5 gallons of water.

Experimental design and treatment

The study was arranged in a randomized complete block, split-plot design in which the shade treatment served as the whole main plot and the species served as sub-plots. Shade treatments included greenhouse ambient conditions, photoselective blue polyethylene film (LEE Filters, Burbank, CA) chosen to reduce R:FR with minimal reduction in PPF (hereafter referred to as qualitative shade), polywoven black shade cloth (Greenhouse Megastore. Model #SC-BL40, Danville, IL.) chosen to reduce PPF without affecting R:FR (hereafter referred to as quantitative shade), and combined blue polyethylene film with black shade cloth (hereafter referred to as combination shade) (Studzinka et al, 2012). The shade treatments were implemented once seeds had germinated by wrapping a 152x122 cm strip the corresponding material(s) around the top of a wooden frame approximately 60 cm tall and centered over the pots. Shade treatments were replicated three times, while species had ten subsamples within each shade structure.

Data collection

The PPF was recorded on a 60 min resolution using a quantum sensor and temperature and humidity were recorded with a datalogger (WatchDog 1450, Spectrum Technologies, Inc., Plainfield, IL). A daily light integral (DLI) was calculated as accumulated PPF reaching pots within a day. Spectral radiation under each treatment was measured using a spectrometer fastened with a two-meter optical fiber and a cosine-corrected head (Flame-S-VIS-NIR-ES, Ocean Optics Inc, Dunedin, FL) near the end of the study on a sunny day at solar noon.

At 2, 4, 6 and 8 weeks after treatment (WAT) initiation, samples from each experimental unit were selected to measure leaf chlorophyll concentration, free standing canopy height, and tiller count. Leaf chlorophyll concentration was analyzed mid-morning using a handheld chlorophyll content meter (CCM-300, Opti-Sciences, Inc.) by selecting the third fully expanded leaf from the oldest tiller of three subsamples per species. Free standing canopy height was taken by raising the plant to its highest point and measuring with a ruler on all experimental units.

At the conclusion of the study, three subsamples of each experimental unit were used to measure the following parameters: leaf count, leaf angle, leaf area, specific leaf area, and above-ground and below-ground dry mass. Plants were clipped at the soil line and roots washed free of growing media. Images of the shoots were collected using a camera (Canon Power Shot G16, Melville, NY) mounted 25 cm above the samples. An image was taken of the second or third fully developed or oldest tiller of the sample and placed onto a sheet of standard white copy paper. Subsequently, leaves were excised from all shoots and scattered onto the sheet of standard white copy paper before collecting a second image. The images were then analyzed using ImageJ version 1.53 (National Institutes of Health, Bethesda, MD, USA). Leaf angle was measured using the "angle tool" for each second or third fully expanded leaf on tiller images. Leaf count was measured using the "analyze particles" feature in ImageJ to calculate total number of leaves. Leaf area was measured as the number of green pixels within leaf images converted to area using a ruler within each image for calibration. After collecting images, leaves, the remainder of the shoots, and roots were separately oven-dried at 60°C for 48 hours before being weighed to obtain dry mass. Specific leaf area was calculated as the leaf area divided by the leaf dry mass (Fontanier & Steinke, 2017).

Data were subjected to a generalized linear mixed model (PROC GLIMMIX) using SAS (SAS v9.4; SAS Inst. Inc., Cary, NC). Means were separated using Fisher's protected LSD. All statistical tests were performed using a significance level of $P \leq 0.05$.

Experimental run did not interact with treatment; therefore, data are pooled across experiments. Correlation analysis was conducted using MS Excel (Microsoft Corporation, Redmond, WA) to quantify the linear relationship between each response variable mean and mean light quantity (DLI).

RESULTS AND DISCUSSION

Light modification

Each shade treatment reduced PPF compared to ambient conditions ($P \leq 0.0001$). In the first experiment, qualitative shade resulted in 8.8 mol m^{-2} d^{-1} (79% of ambient), quantitative shade received 5.6 mol m^{-2} d^{-1} (50% of ambient), and combination shade received 3.6 mol m^{-2} d^{-1} (32% of ambient) (Table 2.1). In the second experiment, qualitative shade received 13.9 mol m^{-2} d^{-1} (71% of ambient), quantitative shade received 9.0 mol m^{-2} d^{-1} (46% of ambient), and combination shade received 7.0 mol m^{-2} d^{-1} (35% of ambient) (Table 2.1).

Spectral analysis of light reaching the turfgrass revealed difference among shade treatments. Qualitative shade and the combination treatment reduced transmittance in the R:FR regions of the spectra (Fig. 2.1). In both experiments, the R:FR ratio of both qualitative and combination shade was 0.99 compared to ambient and quantitative shade, which had a R:FR ratio of 1.15 (Table 2.1). Studzinska et al. (2012), using a similar blue filter, reported a R:FR ratio of 1.28 for ambient and quantitative shade and a R:FR ratio of 0.7 for qualitative and combination shade. Another study using a similar blue polythethylene photoselective filter reported a R:FR ratio of 0.66-0.67 for qualitative shade and a R:FR ratio of 1.07-1.08 for full sun (Petrella & Watkins, 2020). In initial testing under laboratory conditions, the filter had demonstrated similar R:FR (0.73) as those reported in the literature. Differences in the product performance during the experiments may be related to light conditions in the greenhouse or discrepancies between product performance under initial testing conditions (indoors) and this study (greenhouse).

Chlorophyll concentration

Chlorophyll concentration was significantly affected by treatment resulting in significantly greater concentrations in plants grown under ambient conditions than plants grown under quantitative and combination shade (Fig. 2.2). Plants grown under qualitative shade were not significantly different from plants grown under ambient, as well as plants grown under quantitative and combination shade (Fig. 2.2). Petrella & Watkins (2020) reported greater chlorophyll concentrations under full sun for Chewings fescue (*Festuca rubra* L. ssp. *commutata* Gaudin), hard fescue (*Festuca brevipila* Tracey), and strong creeping red fescue (*Festuca rubra* ssp. *rubra* Gaudin) compared to plants grown under qualitative shade. Baldwin et al. (2009) reported few differences among shade treatments (blue, red, yellow, and black nets) for chlorophyll concentration for bermudagrass (*Cynodon dactylon* (L.) Pers. X *C. transvaalensis* Burtt Davy) and zoysiagrass (*Zoysia matrella* (L.) Merr). In a study conducted by Wherley et al. (2005), tall fescue (*Schedonorus arundinaceus* Schreb.) grown under quantitative shade had a higher chlorophyll concentration compared to tall fescue grown under qualitative shade. Results from previous research combined with results from the present study indicate there is some variation in the plants response to shade for chlorophyll concentration.

Plant morphology

Canopy height was affected by significant species and week main effects (Table 2.2). Ryegrass had the highest canopy height compared to bermudagrass (Table 2.4). Tillering provides for better establishment and lateral spreading, producing many additional roots essential for the growth of bermudagrass. In the present study, bermudagrass grown under shade treatments had a substantial reduction in the tiller count compared to ambient, with quantitative and combination shade having a more severe reduction in tillers (Table 2.5). Ryegrass grown under shade treatments also displayed a reduction in tillers compared to ambient, with the combination shade being most severe (Table 2.5). A growth chamber experiment conducted on annual ryegrass (*Lolium multiflorum* Lam.) reported fewer tillers under reduced R:FR ratio combined with reduced PPF conditions compared to reductions in PPF alone (Casal et al., 1985). Similarly, in another growth chamber experiment, perennial ryegrass plants grown under a combination of low PPF and reduced R:FR had fewer tillers compared to perennial ryegrass plants grown under low PPF conditions alone (Gautier et al., 1999). In a field study, tall fescue grown under vegetative shade had fewer tillers than tall fescue grown under reduced PPF conditions alone (Wherley et al., 2005). Wan & Sosebee (1998) observed a decrease in tillering for weeping lovegrass (*Eragrostis curvula* (Schrad.) Nees.), a perennial warm-season grass, when exposed to a R:FR ratio of 0.7 compared to a R:FR ratio of 1.3. Similarly, the present study suggests that bermudagrass is sensitive to reductions in the R:FR ratio combined with reductions in PPF for tillering.

The species by shade treatment interaction was significant for leaf count, leaf length, and leaf area (Table 2.3). In general, bermudagrass leaf count had a stronger response to shade treatments than ryegrass with each type of shade reducing leaf count compared to ambient and the qualitative shade producing more leaves than the combination treatment (Table 2.5). Each shade treatment also increased bermudagrass leaf length compared to ambient (Table 2.5). In contrast, ryegrass only showed a significant reduction in leaf count under the combination shade and an increase in leaf length under the quantitative and combination shade treatments (Table 2.5). For leaf area, the treatments were not significantly different from each other for bermudagrass, while quantitative and combination shade had a greater leaf area than qualitative shade and ambient for ryegrass (Table 2.5). Stuefer and Huber (1998) reported a greater leaf area for *Potentilla* spp. grown under spectral shade compared to the plants grown under neutral shade. Similarly, Allard et al. (1991) reported tall fescue grown under a dense shade environment had a greater leaf area than those grown in partial shade or full sun.

In most plants, specific leaf area (SLA) increases in response to shade, which allows the plant to expand leaf area to capture more light (Dwyer et al., 2014). Similarly, a greater SLA is indicative of thinner leaves typical of shaded plants (Vile et al., 2005). In this experiment, specific leaf area (SLA) was affected by a significant treatment main effect (Table 2.6). Plants grown under the combination shade had the greatest SLA when compared to plants grown under ambient light, quantitative shade, or qualitative shade (Table 2.6). Valladares et al. (2008) reported SLA to be greater in shade-intolerant grasses, such as bermudagrass. In an experiment done on barley (*Hordeum vulgare*), it was found that reducing the light available to the plant from 400 µmol $m^{-2} s^{-1}$ to 90 µmol $m^{-2} s^{-1}$ increased the SLA of the fully expanded leaves (Gunn et al., 1999).

The species by shade treatment interaction was significant for shoot dry weight (Table 2.6). Perennial ryegrass had a stronger response to all shade treatments compared to ambient. Perennial ryegrass grown under all shade treatments had significantly lower shoot dry weights when compared to ambient (Table 2.7). Bermudagrass grown under quantitative and combination shade had significantly lower shoot dry weights compared to ambient and qualitative shade, which were not significantly different from each other (Table 2.7). The treatment main effect was significant for leaf dry weight, shoot dry weight, and root dry weight (Table 2.6). Grasses grown under combination shade had the lowest leaf dry weight compared to ambient light, quantitative shade, and qualitative shade (Table 2.8). Jiang et al. (2004) reported a reduction in leaf dry weight in bermudagrass cultivars grown under low light conditions compared to full sun. Combination shade produced grasses with the lowest shoot dry weight when compared to qualitative shade and ambient (Table 2.8). However, qualitative shade was not significantly different from ambient or quantitative shade (Table 2.8). Grasses grown under ambient and qualitative shade had higher root dry weights when compared to quantitative and combination shade (Table 2.8). Baldwin et al. (2009) reported root growth reduction of warm-season turfgrasses ‘Diamond’ zoysiagrass (*Zoysia matrella* (L.) Merr.), ‘Sea Isle 2000’ seashore paspalum (*Paspalum vaginatum* Swartz.), and ‘Tifway’ and ‘Celebration’ bermudagrasses under reduced R:FR ratio conditions of blue shade net.

There was little evidence that R:FR ratio enhanced shade avoidance responses for either species. Rather, most variables were strongly correlated to the DLI (Table 2.9). The linear response of bermudagrass to DLI, regardless of R:FR ratio, suggests R:FR ratio may not be as important for warm-season turfgrasses as it is for cool-season turfgrasses. However, additional study is needed to confirm this response is not simply an artifact of experimental conditions. For example, incremental decreases in light appeared to be too severe to isolate the qualitative shade response in bermudagrass. Furthermore, the underperformance of the photoselective filter (higher R:FR than initial screening indicated) may also have inhibited a true simulation of qualitative shade. Using a more shade tolerant warm-season species or different selective filter is needed to confirm results of the present study.

CONCLUSION

This study represents the first effort to isolate the effect of R:FR on warm-season turfgrass morphological response. A reduction in the R:FR ratio induced few morphological changes in bermudagrass compared to ambient conditions. Previous research concludes cool-season grass grown under simulated vegetative (combination) shade reduces chlorophyll concentration and this study concludes warm-season grass also experiences a reduction in chlorophyll concentration when grown under combination shade. The reduced R:FR ratio combined with reduction in PPF was most detrimental to both bermudagrass and perennial ryegrass. However, a reduction in the R:FR ratio induced few morphological changes in bermudagrass compared to ambient conditions. The responses of both turfgrass species used in this study are largely attributed to the differences in PPF. This response indicates further potential for selecting warm-season grasses, perhaps less shade intolerant, for improved responses to a reduction in the R:FR ratio.

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TABLES AND FIGURES

Table 2.1 The daily light integral (DLI) and red to far red (R:FR) of light treatments used in the greenhouse studies.

Experiment	Treatment[z]	DLI	R:FR[y]
		------mol/m^{-2}/d^{-1}------	
Experiment 1	Ambient	11.1	1.15
	Qualitative	8.8	0.99
	Quantitative	5.6	1.15
	Combination	3.6	0.99
Experiment 2	Ambient	19.6	1.15
	Qualitative	13.9	0.99
	Quantitative	9.0	1.15
	Combination	7.0	0.99

[z] Treatments include: full light (ambient), reduced R:FR (qualitative), reduced PPF (quantitative), and reduced PPF and R:FR (combination).

[y] Red to far red ratio (R:FR) calculated from the wavelengths of 650-670 and 720-740 nm.

Table 2.2. Analysis of variance for the effects of treatment, species, week, and their interactions on chlorophyll concentration, canopy height, and tiller count of bermudagrass and perennial ryegrass grown in greenhouse conditions.

	Chlorophyll Concentration	Canopy Height	Tiller Count
Treatment (T)	*	NS	***
Species (S)	***	***	*
Week (W)	NS	***	***
S*T	NS	NS	*
W*T	NS	NS	*
W*S	NS	NS	**
W*S*T	NS	NS	NS

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

Table 2.3. Analysis of variance for the effects of treatment, species, week, and their interaction on leaf count, leaf length, and leaf area of bermudagrass and perennial ryegrass grown in greenhouse conditions.

Source of Variation	Leaf Count	Leaf Length	Leaf Area
		------cm------	-----cm^2-----
Treatment (T)	***	**	*
Species (W)	***	***	***
T*W	*	*	*

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

Table 2.4. Effect of species and week main effects on canopy height of bermudagrass and perennial ryegrass grown in greenhouse conditions.

Species	Canopy Height
	-------cm--------
Bermudagrass	10.04b[z]
Ryegrass	16.34a
Week	**Canopy Height**
	-------cm-------
2	9.41d
4	12.91c
6	14.70b
8	15.75a

[z] Means (n=240) within a column followed by same lowercase letter are not significantly different at 0.05 significance level.

Table 2.5. Interaction between species and treatment for leaf count, leaf length, leaf area, and tiller count of bermudagrass and perennial ryegrass grown in greenhouse conditions.

Species	Treatment[z]	Leaf count	Leaf length	Leaf area	Tiller count
			-----cm-----	----cm^2----	
Bermudagrass	Ambient	99a[y]	2.47b	0.40a	4.61a[x]
	Qualitative	67b	3.08a	0.45a	3.14b
	Quantitative	52bc	3.07a	0.40a	1.82c
	Combination	33c	3.62a	0.45a	1.32c
Perennial Ryegrass	Ambient	35a	5.92b	0.87b	2.34a
	Qualitative	28b	6.80b	1.10b	2.14a
	Quantitative	23b	8.98a	1.65a	2.03a
	Combination	18c	9.37a	1.50a	1.09b

[z] Treatments represent full light (ambient), reduced R:FR (qualitative), reduced PPF (quantitative), and reduced PPF and R:FR (combination).

[y] Means (n=72) within a column followed by same lowercase letter are not significantly different at 0.05 significance level.

[x] Means (n=240) within a column followed by same lowercase letter are not significantly different at 0.05 significance level.

Table 2.6. Analysis of variance for the effects of treatment, species, and their interaction on specific leaf area, leaf dry weight, shoot dry weight, and root dry weight of bermudagrass and perennial ryegrass grown in greenhouse conditions.

Source of Variation	Leaf dry weight	Shoot dry weight	Root dry weight	Specific leaf area
	----------------------	g	---------------------	----cm^{-2} g^{-1}----
Treatment (T)	*	**	**	***
Species (S)	*	**	*	NS
S*T	NS	*	NS	NS

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

Table 2.7. Interactions between species and treatment for shoot dry weight of bermudagrass and perennial ryegrass grown in greenhouse conditions under ambient, qualitative, quantitative, and combination treatments.

Species	Treatment[z]	Shoot dry weight
		--------g--------
Bermudagrass	Ambient	0.64a[y]
	Qualitative	0.46a
	Quantitative	0.18b
	Combination	0.16b
Perennial Ryegrass	Ambient	0.25a
	Qualitative	0.16b
	Quantitative	0.16b
	Combination	0.11b

[z] Treatments represent full light (ambient), reduced R:FR (qualitative), reduced PPF (quantitative), and reduced PPF and R:FR (combination).

[y] Means (n=240) within a column followed by the same letter are not significantly different at 0.05 significance level.

Table 2.8. Main effects of treatment on specific leaf area, leaf dry weight, shoot dry weight, and root dry weight of bermudagrass and perennial ryegrass grown in greenhouse conditions.

Treatment	Leaf dry weight	Shoot dry weight	Root dry weight	Specific leaf area
	----------------------	g	---------------------	----cm^{-2} g^{-1}----
Ambient	0.13a	0.44a	0.22a	5.91c^{z}
Qualitative	0.10a	0.31ab	0.17a	8.39bc
Quantitative	0.13a	0.17bc	0.08b	13.21b
Combination	0.05b	0.13c	0.05b	23.48a

^{z}Means (n=72) within a column followed by same lowercase letter are not significantly different at 0.05 significance level.

Table 2.9. Correlation (r) between daily light integral (DLI) and specific leaf area (SLA), leaf dry weight (DW), shoot DW, root DW, leaf count, leaf length, leaf area, and tiller count of bermudagrass and perennial ryegrass grown in greenhouse conditions.

Variable	r
SLA	-0.89
Leaf DW	0.62
Shoot DW	1.00
Root DW	0.99
Leaf Count	0.99
Leaf Length	-0.99
Leaf Area	-0.95
Tiller Count	0.99

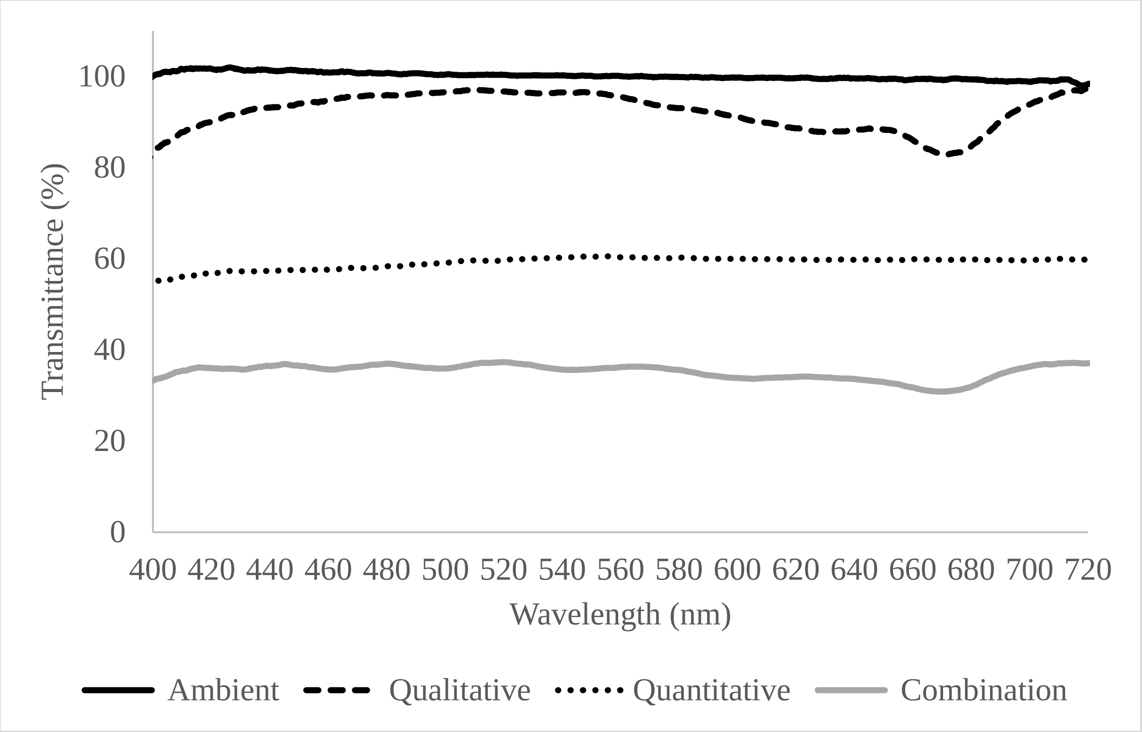

Figure 2.1. Light modification (spectra of transmittance) under qualitative, quantitative, combination shade treatments, and ambient (no shade).

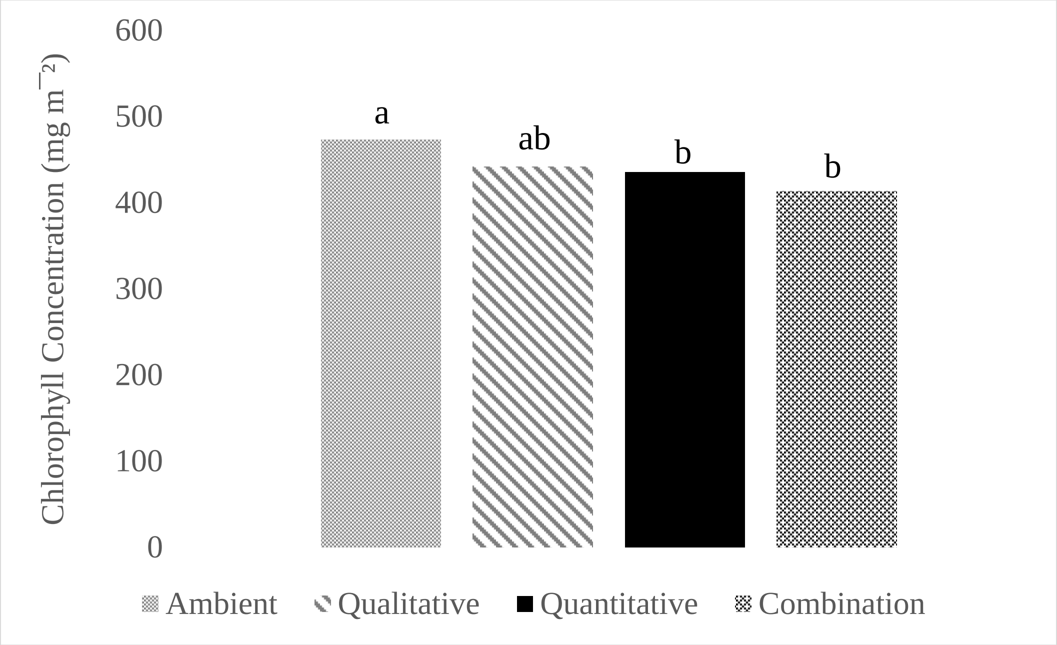

Figure 2.2. Main effect of shade treatment on leaf chlorophyll concentration. Data were pooled across perennial ryegrass and bermudagrass plants.

CHAPTER III

EFFECTS OF LIGHT QUALITY ON THE GROWTH AND DEVELOPMENT ON HYDROPONICALLY GROWN ROMAINE LETTUCE

ABSTRACT

In places with warmer climates during the summer, shade nets are typically used to cover greenhouses that produce cool-season crops. A greenhouse study was conducted to investigate the effects of four commercial shade nets on the growth and development of ‘Coastal Star’ green leaf romaine lettuce and ‘Super Red’ red leaf romaine lettuce during the summer and fall growing seasons using an ebb and flow hydroponic system. The commercial shade nets used were Chromatinet® pearl, Chromatinet® red, aluminet ®, and a standard polywoven black. Applied shade nets (all rated to decrease solar radiation by 30%) significantly reduced photosynthetic photon flux density from 1033 μmol m^{-2} s^{-1} under ambient light to 617 – 733 μmol m^{-2} s^{-1} under shade nets. The shade nets affected the morphology and composition of the romaine lettuce during its growing period. Lettuce grown under pearl shade nets had the greatest number of leaves. Lettuce grown under aluminet in the summer produced plants with a greater leaf area. ‘Coastal Star’ green leaf romaine lettuce grown under pearl shade nets produced plants with a greater total soluble solids content. ‘Super Red’ red leaf romaine lettuce grown under aluminet produced plants with a greater total sugar content. The results of this study suggest that managing light quality with spectrally modified shade nets does impact the growth, development, and quality of romaine lettuce grown in a greenhouse hydroponics system.

INTRODUCTION

Lettuce (*Lactuca sativa* L.) is a common cool season crop grown worldwide, either cultivated in field production or in greenhouses using hydroponics. Lettuce yield and marketability are negatively affected as planting dates progress toward longer days and warmer temperatures (Dufault et al., 2006). Lettuce grown in a greenhouse may be limited during summer months in locations with warmer climates due to a higher light intensity and longer photoperiod (Gaudreau et al., 1994). The growth and development of lettuce also depends on light quality (Ilić et al., 2017). Incident solar radiation includes ultraviolet (UV) (wavelength less than 400 nm), photosynthetically active radiation (PAR) (wavelength ranging from 400 to 700 nm), and infrared radiation (wavelength greater than 700 nm) (Sudhakar et al., 2013). Spectrums within PAR cause various morphological and physiological responses. Photoautotrophic organisms, such as lettuce, use photoreceptors to detect properties of incident light, such as: light intensity, light quality, and photoperiod. Phytochromes are types of photoreceptors which perceive light in the red and far red wavelengths, while cryptochromes perceive light in the blue and UVA regions. The information received from the photoreceptors is used to regulate plant growth and development, also referred to as photomorphogenesis, and can influence morphological and physiological changes. Light intensity affects lettuce growth, nutrient content, and can cause physiological disorders (Gaudreau et al., 1994). The optimal value of light intensity for lettuce is 400-600 μmol m^{-2} s^{-1} (Fu et al., 2012). Light intensity in summer months can reach up to 2000 μmol m^{-2} s^{-1}, which combined with temperatures exceeding 30/16 °C day/night, increase the risk of premature flower initiation (bolting) (Simonne et al., 2002), leaf bitterness (Zhao and Corey, 2009), and tip burn.

Shade nets can prove to be an efficient method to minimize the undesirable physiological and morphological changes that happen in cool-season vegetables such as lettuce. Shade nets are comprised of different fibers, knitting designs, densities, and thread pigmentations that modify the light spectrum in the visible and far red regions (Shahak, 2004) and provide combinations of dispersed, spectrally modified light and natural, unmodified light (Shahak et al., 2009). Researchers have been studying the effect of photoselective filters on plant physiology and morphology (Díaz-Pérez & St. John, 2019). The application of many of these prior studies has been on production within greenhouse environments (Cerny et al., 2003). Recently, colored shade cloths or netting have been designed for the specific purpose of manipulating plant growth and development in a manner that also increases yield (Zare, et al., 2019). Photo-selective nets affect environmental conditions such as temperature, light intensity, and humidity (Díaz-Pérez & St. John, 2019). Photo-selective nettings also selectively filter light creating targeted spectra that can be perceived by plant photoreceptors. Managing light quality can improve the economic value of hydroponic lettuce production. The objective of this research was to evaluate the effect of shade net color on the morphology and nutritional indicators of two cultivars of hydroponically grown romaine lettuce.

MATERIALS AND METHODS

Plant Material and Growth Conditions

Two greenhouse experiments were conducted at the Department of Horticulture and Landscape Architecture Research Greenhouses in Stillwater, OK. ‘Coastal Star’ green leaf romaine lettuce (Johnny’s Selected Seeds, Winslow, MN) and ‘Super Red’ red leaf romaine lettuce (Everwilde Farms, Fallbrook, CA) were selected for the studies. Seeds were sown in Oasis Rootcubes (2×2×3.5 cm) having 276 cubes per tray (BFG Supply, Burton, OH) on 23 June 2020 for the first experiment and 10 August 2020 for the second experiment. Plants were transplanted into Ebb and Flow recirculating hydroponic systems and shade treatments were initiated on 14 July 2020 and 31 August 2020 for the first and second experiment, respectively. The initial nutrient solution was made by adding 147 g of a complete soluble fertilizer (Jack’s 15-12-26, J.R. Peters, Allentown, PA) and 98 g of calcium nitrate (American Plant Products, Oklahoma City, OK) to 40 gallons of water (Singh et al., 2019). The nutrient solution’s electrical conductivity (EC) for each system was maintained between 1.5 and 2.5 mS/cm and the pH was maintained between 5.5 and 6.5. The pH and EC of each system’s solution was checked daily with a portable pH/EC meter (HI9813-6 Hanna Instruments, Smithfield, RI). Harvest occurred on 6 August 2020 (23 days after transplanting) and 28 September 2020 (28 days after transplanting) for the first and second experiment, respectively.

Experimental Design and Treatment Structure

The experiments were conducted as a split plot design in which the shade treatment served as the whole main plot and the cultivars served as sub-plots. Shade treatments included a control (greenhouse ambient conditions) and four commercial shade polyethylene (HDPE) fabrics nominally rated to reduce radiation by 30% but each varying in color: standard black (Green-Tek, Janesville, WI), aluminet (Green-Tek, Janesville, WI), Chromatinet pearl (Green-Tek, Janesville, WI), and Chromatinet red (Green-Tek, Janesville, WI). Shade fabrics were suspended approximately 165.1 cm above tables using a 2.44 × 2.74 m structure made of polyvinyl chloride pipe.

Data collection

Temperature and relative humidity were recorded on a 60 min resolution using a datalogger (WatchDog 1450, Spectrum Technologies, Inc., Plainfield, IL) on each table. Photosynthetic photon flux (PPF) was measured at solar noon three days per week during the study with a handheld quantum sensor (Spectrum Technologies, Aurora, IL).

Each plant was scanned weekly using a chlorophyll meter (SPAD- 502, Konica Minolta, Japan). For each plant, the average SPAD reading from three leaves representing the base, middle, and top of the plant was used for subsequent analysis. °Brix, leaf coloration, plant fresh weight, leaf count, leaf length, leaf width, plant height, plant length, and plant width were measured at harvest. Brix values were measured using a handheld refractometer (Westover 0-32 Degree ATC Brix Refractometer #RHB-32ATC). For leaf color analysis, the second or third fully developed leaf from three plants were placed onto a 20 x 30 cm white polystyrene sheet and digital images were collected using a camera (Canon Power Shot G16, Melville, NY) mounted 25.4 cm away from the samples. The images were then analyzed using ImageJ version 1.35 software (National Institutes of Health, Bethesda, MD, USA) and the “RGB Measure” plugin before calculating a dark green color index (DGCI) using the methods of Karcher & Richardson (2003). After completing fresh sample measurements, plants were cut at the base and dried for 2 days at 60°C before measuring dry mass. Subsequently, three randomly selected plants (replicates) of each treatment combination were analyzed for plant essential nutrient content by the Oklahoma Soil Water and Forage Analytical Laboratory.

Data Analysis:

Data were analyzed using a generalized linear mixed model (SAS 9.4) with all effects treated as fixed. For SPAD readings, sequential measurements were modeled using a repeated measures analysis. Means were separated using Fisher's least significant difference. All statistical tests were assessed at a significance level of $p \leq 0.05$.

RESULTS AND DISCUSSION

Light modification by shade nets

Spectral quality of light passing through shade netting can promote different photosynthetic responses in plants (Illic et al., 2019). In the present study, treatment was significant for PPF with each shade net reducing PPF compared with ambient in both summer and fall productions (Table 3.1) The maximum PPF for the treatments in summer were 866, 862, 921, 780, and 1215 μmol m^{-2} s^{-1} for pearl, red, aluminet, black, and ambient, respectively, which corresponded to 71%, 71%, 76%, and 64% of ambient under pearl, red, aluminet, and black, respectively. For the fall production of lettuce, the maximum PPF for the treatments were 501, 442, 463, 386, and 720 μmol m^{-2} s^{-1} for pearl, red, aluminet, black, and ambient, respectively, which corresponded to 70%, 61%, 64%, and 54% of ambient under pearl, red, aluminet, and black, respectively. Arthurs et al. (2013) found similar reductions in PPF under black nets rated to reduce solar radiation by 50%. However, the reductions in PPF for pearl and red nets reported by Arthurs et al. (2013) were more severe than the present study.

Spectral analysis of light reaching the lettuce revealed differences among shade nets. The red shade net reduced transmittance in the blue, green, and yellow spectra to a greater degree than wavelengths greater than 580 nm in the red and far red regions. The other three shade nets did not alter relative spectral composition in the visible range (Fig. 3.1). The shade nets did not affect the R:FR ratio compared to ambient.

Chlorophyll concentration, pigmentation, and total sugar content

Chlorophyll concentration corresponds to the rate of photosynthesis (Fleischer, 1935) and is commonly used as an indicator of plant growth and health (Ni et al., 2009). Chlorophyll concentration was significantly affected by treatment (Table 3.2) resulting in greater concentrations in plants grown under ambient, aluminet, and pearl nets than plants grown under the black net (Table 3.3). Plants grown under the red net were not significantly different from plants grown under pearl or black nets. Plants grown under the black shade net had the lowest chlorophyll concentration (Table 3.3). These results are consistent with Tafoya et al. (2018) in which cucumbers grown under aluminet and pearl nets had significantly higher chlorophyll concentrations than plants grown under black nets. Nsoante et al. (2016) reported higher chlorophyll concentrations for lettuce grown under pearl and yellow shade nets. The results support the fact that light quality does influence chlorophyll concentrations in romaine lettuce.

According to Barrett et al. (2010), color is considered a visual indicator of quality in vegetables, such as romaine lettuce, as it affects preference and acceptability to consumers. In the present studies, DGCI was used as an indicator of visual quality. The data resulted in a three-way interaction between treatment, cultivar, and season (Table 3.2). In the summer study, 'Super Red' under the red shade net had a greater DGCI than under ambient, pearl, or black which indicates the red color of 'Super Red' was more vibrant (Table 3.4). Other comparisons for DGCI were not affected by shade treatment (Table 3.4).

Soluble solid content (SSC), measured in °Brix, is an important indicator of quality in lettuce. °Brix was significantly affected by cultivar and treatment (Table 3.2). 'Coastal Star' green leaf romaine lettuce grown under pearl shade nets produced plants with a greater °Brix value (Fig. 3.2). 'Super Red' red leaf romaine lettuce grown under aluminet produced plants with a higher °Brix value (Fig. 3.2). Mastilovic et al. (2019), who reported butter lettuce (*Lactuca sativa* L. var. *capitata*) grown in the summer under ambient light as having a higher °Brix value than pearl, red, blue, and black shade nets. However, another light quality experiment done on marigold (*Calendula officinalis* L.) and violet (*Viola tricolor*) reported a greater °Brix value under yellow and red shade nets compared to non-shaded or ambient conditions (Zare et al., 2019). The results of previous studies along with the present study indicate the effects of light quality on °Brix value varies for various horticultural crops. Water temperature, air temperature, and lettuce cultivar also influence °Brix values for various horticultural crops.

Leaf morphology of romaine lettuce at harvest

Shaded plants tend to have a larger leaf area more under low light intensities in order to capture light for photosynthesis. In the present study, there was a three-way interaction between treatment, cultivar, and season for leaf area (Table 3.2). In summer, 'Coastal Star' leaf area was greatest under aluminet, red, and black and lowest under ambient and pearl (Table 3.6). 'Super Red' leaf area was greatest under aluminet and lower for all other treatments. In fall, leaf area was the greatest for 'Coastal Star' under ambient compared to all shade nets, while there was no significant difference among treatments for 'Super Red'. Illic et al. (2017) reported a higher leaf area in lettuce grown under red and pearl nets in the summer and a lower leaf area for lettuce grown under ambient and black nets, with all shade nets rated to reduce solar radiation by 50%. Lara et al. (2021) also reported a higher leaf area in spinach grown under red nets compared to blue and gray shade nets, with shade nets reducing solar radiation by 65%, for summer production in a greenhouse. In a field study conducted in the summer, lettuce grown under red nets, rated to reduce solar radiation by 50%, resulted in a higher leaf area than non-shaded conditions (Li et al., 2017). For the summer production of lettuce, red shade nets produce larger leaf areas, which affect yield and marketability. These results are consistent with previous research indicating that plants have a greater leaf area when grown under shade.

Treatment was significant for number of leaves, plant height, head width, growth index, leaf width, and leaf length (Table 3.5). Lettuce grown under pearl nets had the greatest number of leaves, while lettuce under black nets had the least number of leaves (Table 3.7). Lettuce grown under all shade nets had a significant increase in plant height compared to lettuce grown under ambient, with black, aluminet, and red shade nets having the greatest plant height. Lettuce grown under black shade nets had a greater head width than lettuce grown under ambient (Table 3.7). These results are similar to Illic et al. (2017) in which lettuce grown under ambient had the smallest head width compared to lettuce grown under black nets. Lettuce grown under red and aluminet were not significantly different from lettuce grown under black shade nets or pearl shade nets. The growth index for lettuce grown under ambient was significantly lower compared to lettuce grown under black and red shade nets. McElhannon (2007) reported a smaller growth index for lettuce grown under pearl and red nets compared to lettuce grown under ambient light. Lettuce grown under black nets had the greatest leaf length and leaf width compared to lettuce grown under aluminet and pearl nets (Table 3.7). Lara et al. (2021), in which there was no significant difference between ambient, red, and gray nets. The effects of photoselective nets on number of leaves, plant height, head width, growth index, leaf width, and leaf length varies and needs further research conducted to determine the effects of each color net on these parameters.

Yield and productivity

Light conditions have a significant effect on the quality and yield of vegetables (Fu et al., 2017). Treatment was significant for root, shoot, and total dry weight (Table 3.8). Lettuce grown under ambient had a greater root dry weight than all shade nets (Table 3.9). Li et al. (2017) reported dry weight of lettuce unaffected by black and red shade nets compared to ambient light. However, in the present study, lettuce grown under ambient and red nets had a greater shoot dry weight then lettuce grown under black nets. Lettuce grown under black nets had the lowest total dry weight when compared to ambient and red nets that had the greatest total dry weight. (Table 3.9).

For fresh weight, there were no significant interactions for treatment or cultivar, however there was a significant difference between seasons. The average yields for fresh weight ranged from 75.22 g and 239.53 g for summer and fall, respectively. Sublett et al. (2018) reported a greater fresh weight for lettuce grown in summer than lettuce grown in the fall in a deep-water culture production system. In the present study, however, shade nets did not impact fresh yield between seasons.

Nutrient content

Nutritional quality is a key factor when it comes to determining the quality of lettuce. Researchers have indicated that light alters the uptake of multiple elements as plants detect changes in light quality, quantity, and intensity (Liu et al., 2020; Neocleous & Savvas, 2019; Xu et al., 2021). In leaf nutrient analysis for mineral content in the present study, there was a significant season by treatment interaction for potassium (K), calcium (Ca), sulfur (S), manganese (Mn), zinc (Zn), and boron (B) (Table 3.10) with variations among treatments (Table 3.10). For summer production, romaine lettuce grown under aluminet had a higher K content of 5.45% DW compared to romaine lettuce grown under ambient (4.78% DW) and pearl (4.26% DW), but was comparable to romaine lettuce grown under red (5.13% DW) and black (5.15% DW) nets (Table 3.12). However, for fall production, lettuce grown under aluminet had the lowest K content of 9.08% DW compared to all other treatments (Table 3.12). Baslam et al. (2013) reported K content levels ranging from 5.37–8.76% DW for romaine lettuce grown in a greenhouse in Spain while romaine lettuce consumed in the United States claimed K content ranging from 2.8-5.0 % DW (USDA, 2015) in which the present study is well within range of both. Similar to the present study, Koudela and Petrikova (2008) reported K contents of green leaf lettuces (4.8–12% DW) were not significantly different from those in red leaf lettuces (5–13% DW). In the present study, K content between growing seasons varied with the summer production of romaine lettuce having a lower K content compared to the fall production of romaine lettuce (Table 3.12). In romaine and green and red leaf lettuces, Ca content ranged from 0.4–0.8% DW (USDA, 2015). By comparison, in our study, Ca content for lettuce grown under pearl in the summer and lettuce grown under red in the fall had contents of 0.90% DW and 1.00% DW compared to all other shade nets (Table 3.12). Similar to the present study, Koudela & Petrikova (2008) reported no significant differences for Ca content in green leaf lettuces from red leaf lettuces. Iron is essential for plants as it is involved in photosynthetic processes and the production of chlorophyll (Roosta, 2009). Lettuce grown under aluminet had a significantly lower Fe content than all other treatments in both summer and fall, while lettuce grown under red nets had a significantly higher Fe content when compared to aluminet (Table 3.12). Ochieng (2018) reported a lower Fe content for spiderplant (*Chlorophytum comosum*) and african nightshade (*Solanum scabrum* Mill**.)** grown under gray net compared to yellow and blue shade nets used in the study. Fe content has been reported as ranging from 59.9-248 mg L^{-1} in romaine lettuce, in which the present study is well within range for both summer and fall production (Baslam et al., 2013; USDA, 2015). While treatment was significant for Ca, Mg, S, Fe, Mn, Zn, and B concentrations, cultivar was significant for N and Cu concentrations (Table 3.9). ‘Super Red’ had higher N content of 5.02% DW and Cu content of 17.3 mg L^{-1} than ‘Coastal Star’, which had an N content of 4.59% DW and Cu content of 14.6 mg L^{-1}. There was an interaction between treatment and cultivar for phosphorus (Table 3.9). Phosphorus is integral part of photosynthesis metabolism in plant cells (Pieters et al., 2001). In the present study, ‘Coastal Star’ under ambient and aluminet had the lowest amount of phosphorus, while pearl nets had greater phosphorus content than black nets (Table 3.11). ‘Super Red’ grown under black nets had a greater amount of phosphorus than ‘Super Red’ grown under aluminet (Table 3.11). Overall, shade net color and time of year did have an impact on plant nutrient content of hydroponically grown romaine lettuce.

CONCLUSION

The production of cool-season vegetables, such as romaine lettuce, during periods of high light intensity and warm temperatures represent a challenge to growers. In this experiment, shade nets varied in their effect on lettuce morphology, yield, and nutrient content. Chlorophyll concentration was greatest for ‘Coastal Star’ grown under aluminet, but greatest for ‘Super Red’ grown under pearl net. °Brix was greater for ‘Super Red’ grown under aluminet, but for ‘Coastal Star,’ was greater when grown under pearl. The interaction between season and the shade net color suggests time of year is critical to selecting the appropriate shade net. Lettuce grown under aluminet in the summer had the greatest leaf area for both cultivars compared to all other shade nets. In the summer production, the overall content for Ca, P, and K was greater for lettuce grown under pearl than when grown in the fall. Pearl and red photoselective nets seem to be most useful when utilized in the summer production of lettuce for optimal marketability. However, further research is needed to investigate the effects of color shade nets on limiting physiological disorders and improving lettuce quality for year-round greenhouse production of cool-season crops.

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TABLES AND FIGURES

Table 3.1. Photosynthetic photon flux (PPF) under each treatment for the summer and fall production of two cultivars of romaine lettuce (‘Coastal Star’ and ‘Super Red’) grown in an ebb and flow hydroponics systems.

Season	Treatment	PPF
		---µmol m^{-2} s^{-1}---
Summer	Ambient	1215
	Pearl	866
	Red	862
	Aluminet	921
	Black	780
Fall	Ambient	720
	Pearl	501
	Red	442
	Aluminet	463
	Black	386

Table 3.2. Analysis of variance for the effects of season, cultivar, treatment, and their interactions on chlorophyll concentration, pigmentation, °Brix, and leaf area of two cultivars of romaine lettuce grown in ebb and flow hydroponic systems.

Source of Variation	Chlorophyll Concentration	Pigmentation	°Brix	Leaf area
	-----SPAD-----	-----DGCI-----		-----cm^2-----
Season (S)	***	NS	***	NS
Cultivar (C)	***	*	***	*
Treatment (T)	*	*	***	NS
C*T	**	*	*	NS
S*C*T	NS	*	NS	*

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

Table 3.3. Interaction between cultivar and treatment on leaf chlorophyll concentration (SPAD) of two cultivars of romaine lettuce grown in ebb and flow hydroponic systems.

Treatment	Coastal Star
Ambient	34.16a[z]
Pearl	31.61bc
Red	31.98b
Aluminet	34.43a
Black	29.86c
	Super Red
Ambient	29.87a
Pearl	30.38a
Red	27.89b
Aluminet	29.51ab
Black	28.75ab

[z] Means (n=60) within a column followed by same lowercase letter are not significantly different at 0.05 significance level.

Table 3.4. Interaction between season, treatment, and cultivar for dark green color index of two cultivars of romaine lettuce grown in ebb and flow hydroponic systems.

		Dark Green Color Index
Season	Treatment	Coastal Star
Summer	Ambient	0.729ab[z]
	Pearl	0.711ab
	Red	0.755ab
	Aluminet	0.731ab
	Black	0.724ab
Fall	Ambient	0.613b
	Pearl	0.632ab
	Red	0.632ab
	Aluminet	0.629ab
	Black	0.628ab
		Super Red
Summer	Ambient	0.587b
	Pearl	0.368c
	Red	0.829a
	Aluminet	0.790ab
	Black	0.172c
Fall	Ambient	0.643ab
	Pearl	0.644ab
	Red	0.643ab
	Aluminet	0.647ab
	Black	0.622ab

[z] Means (n=60) within a column followed by same lowercase letter are not significantly different at 0.05 significance level.

Table 3.5. Analysis of variance for the effects of season, cultivar, treatment, and their interactions on plant growth and quality of two cultivars of romaine lettuce grown in ebb and flow hydroponic systems.

Source of Variation	Leaf width	Leaf length	Height	Head width	Growth index	Leaf count
	------------------------cm	-------------------------				
Season (S)	***	***	***	***	***	***
Cultivar (C)	*	**	*	***	***	***
Treatment (T)	***	NS	*	*	***	*
S*T	**	*	NS	*	*	NS
S*C	NS	*	NS	***	***	NS

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

Table 3.6. Interaction between season, cultivar, and treatment on leaf area of two cultivars of romaine lettuce grown in ebb and flow hydroponic systems.

Season	Cultivar	Treatment	Leaf area
			-----cm^2-----
Summer	Coastal Star	Ambient	89.68b
		Pearl	103.75b
		Red	116.66a
		Aluminet	156.95a
		Black	150.13a
	Super Red	Ambient	83.43b
		Pearl	104.61b
		Red	90.37b
		Aluminet	124.36a
		Black	84.61b
Fall	Coastal Star	Ambient	163.75a
		Pearl	103.83b
		Red	98.66b
		Aluminet	90.02b
		Black	70.16b
	Super Red	Ambient	104.47b
		Pearl	81.19b
		Red	74.86b
		Aluminet	72.75b
		Black	108.23b

[z] Means (n=60) within a column followed by same lowercase letter are not significantly different at 0.05 significance level.

Table 3.7. Main effects of treatments on plant growth and quality of two cultivars of romaine lettuce grown in ebb and flow hydroponic systems.

Treatment	Leaf width	Leaf length	Height	Head width	Growth index	Leaf count
	-------------------------	cm	---------------------------			
Ambient	7.1a	14.1b	20.9c	27.9c	24.8c	18.8bc[z]
Pearl	6.1c	12.8c	21.9bc	28.3bc	26.0bc	20.5a
Red	6.4bc	13.8bc	22.9ab	29.9ab	27.3a	19.6abc
Aluminet	6.2c	13.6bc	22.7ab	29.8ab	26.8ab	20.3ab
Black	6.9ab	15.2a	23.5a	31.2a	27.7a	18.4c

[z] Means (n=120) within a column followed by same lowercase letter are not significantly different at 0.05 significance level.

Table 3.8. Analysis of variance for the effects of season, cultivar, treatment, and season by treatment interaction for root, shoot, and total dry weight (g) of two cultivars of romaine lettuce grown in ebb and flow hydroponic system.

Source of Variation	Root	Shoot	Total
	-----------------g------------------		
Season (S)	*	***	***
Cultivar (C)	***	*	*
Treatment (T)	***	NS	NS
S*T	**	NS	NS

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

Table 3.9. Main effects of treatments on root, shoot, and total dry weight (g) for romaine lettuce grown in hydroponic ebb and flow systems.

Treatment	Root	Shoot	Total
	-----------------g-----------------		
Ambient	1.66a[z]	7.52a	9.18a
Pearl	1.36cd	7.03ab	8.39ab
Red	1.51b	7.73a	9.24a
Aluminet	1.45bc	7.16ab	8.61ab
Black	1.24d	6.52b	7.97b

[z] Means (n=120) within a column followed by same lowercase letter are not significantly different at 0.05 significance level.

Table 3.10. Analysis of variance for the effects of season, cultivar, treatment, and their interactions for nutrient element content of two cultivars of romaine lettuce grown in ebb and flow hydroponic systems.

Source of Variation	N	P	K	Ca	Mg	S	Fe	Mn	Zn	B	Cu
Season (S)	***	***	***	*	***	NS	NS	***	***	***	*
Cultivar (C)	***	NS	NS	***	*	**	NS	*	*	***	*
Treatment (T)	NS	NS	NS	*	*	*	**	***	*	*	NS
C*T	NS	*	NS	NS	NS	NS	NS	NS	NS	NS	NS
S*T	NS	**	***	***	NS	***	NS	**	*	*	NS

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

Table 3.11. Main effects of treatment on phosphorus of two cultivars of romaine lettuce grown in ebb and flow hydroponic systems.

Cultivar	Treatment	Phosphorus
		-------% dry wt-------
Coastal Star	Ambient	0.90c[z]
	Pearl	1.06a
	Red	1.04ab
	Aluminet	0.93c
	Black	0.97b
Super Red	Ambient	1.00ab
	Pearl	0.98ab
	Red	0.97ab
	Aluminet	0.96b
	Black	1.02a

[z] Means (n=6) within a column followed by same lowercase letter are not significantly different at 0.05 significance level.

Table 3.12. Main effects of season and treatment on nutrient element content of two cultivars of romaine lettuce grown in ebb and flow hydroponic systems.

		Nutrient Element Content										
		Macronutrients						Micronutrients				
		------% dry wt------						------mg L^{-1}------				
Season	Treatment	N	P	K	Ca	Mg	S	Fe	Mn	Zn	B	Cu
Summer	Ambient	4.20ab[z]	0.72b	4.78bc	0.66d	0.49b	0.28c	116.53b	95.08b	69.68ab	47.92ab	17.08abc
	Pearl	3.82b	0.86a	4.26c	0.90a	0.57a	0.36a	175.37a	103.58b	74.42ab	40.58c	14.32c
	Red	4.28a	0.74b	5.13ab	0.7bc	0.52ab	0.29c	187.10a	110.32b	69.78ab	44.03bc	17.25abc
	Aluminet	4.51a	0.82ab	5.45a	0.78b	0.49b	0.32b	73.38b	106.40b	68.68b	52.45a	18.62ab
	Black	4.40a	0.74b	5.15ab	0.67cd	0.50b	0.31b	109.33b	128.20a	80.13a	45.52b	20.25a

		Nutrient Element Content										
		Macronutrients						Micronutrients				
		------% dry wt------						------mg L^{-1}------				
Season	Treatment	N	P	K	Ca	Mg	S	Fe	Mn	Zn	B	Cu
Fall	Ambient	5.57a	1.19a	10.50a	0.76cd	0.62a	0.33a	122.4b	105.2a	79.95c	30.93a	14.53a
	Pearl	5.26a	1.18a	10.13ab	0.67d	0.61a	0.32a	123.08b	104.68a	91.47ab	29.46a	14.75a
	Red	5.33a	1.27a	9.89b	1.00a	0.58ab	0.32a	198.33a	82.55b	99.90a	31.45a	15.97a
	Aluminet	5.18a	1.07b	9.08c	0.76cd	0.53b	0.31a	97.00c	66.07c	69.35c	30.37a	12.07a
	Black	5.53a	1.25a	9.95ab	0.97ab	0.53b	0.31a	143.17ab	110.45a	88.35bc	29.55a	14.67a

[z] Means (n=6) within a column followed by same lowercase letter are not significantly different at 0.05 significance level.

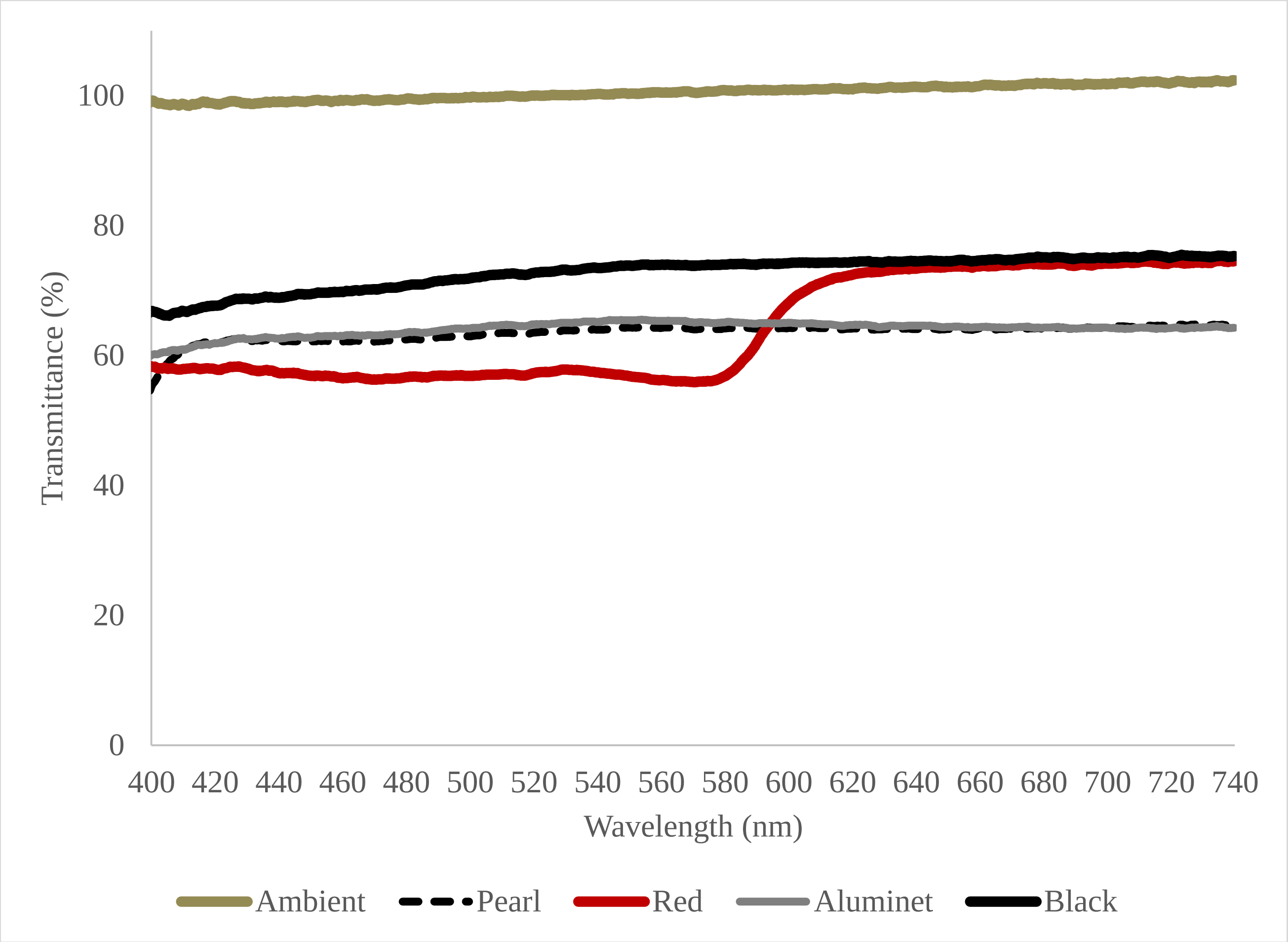

Figure 3.1. Spectra of transmittance for pearl, red, aluminet, and black shade nets compared to ambient.

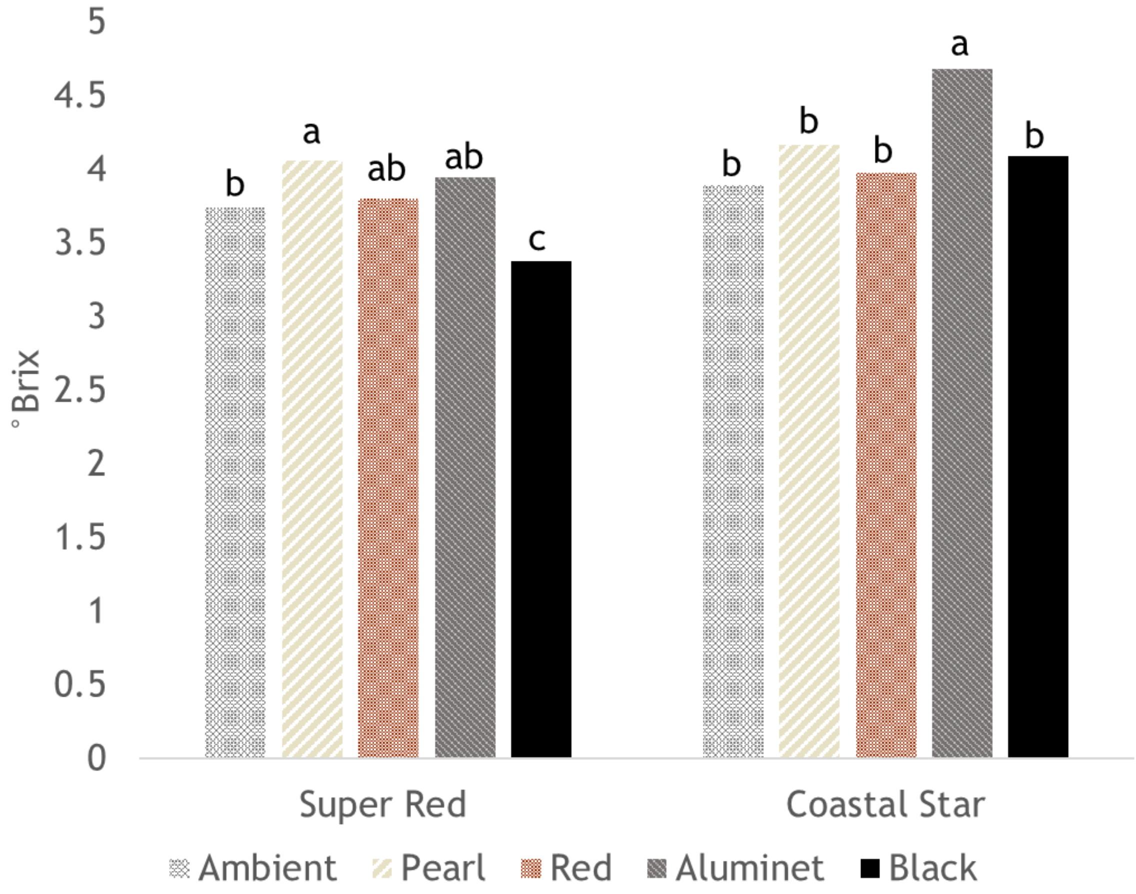

Figure 3.2. Total soluble solid content measured in °Brix of two romaine lettuce cultivars (‘Super Red’ and ‘Coastal Star’) grown under each ambient, pearl, red, aluminet, and black shade nets.

CHAPTER IV

CONCLUSION

Spectral modification, either by photoselective nets or filters, is becoming a great tool for horticulturists to use to manipulate plant growth and development. Greenhouse horticultural production is becoming more important globally, and therefore the need for adopting new technologies and advanced cultivation practices are needed for successful production in the competitive global environment. The global implications of using photoselective nets and filters is far-reaching.

Photoselective filters can be used to simulate changes in the R:FR ratio that plants underneath vegetative canopies experience. A reduction in the R:FR ratio combines with a reduction in PPF was detrimental to both warm-season bermudagrass and cool-season perennial ryegrass, however there is little to support that the reduction in the R:FR ratio initiated shade avoidance responses in both species over responses to the reduction in PPF. Whether the underperformance of the photoselective filter (greater R:FR than initial screening indicated) inhibited a true simulation of qualitative shade is not clear and further research in this field is needed to confirm the response.

The production of cool-season vegetables, such as romaine lettuce, during periods of high light intensity and warm temperatures represent a challenge to growers. Photoselective shade nets are a useful tool in managing light quality manipulation in warmer climates. All shade nets in this study decreased light intensity, which is favorable for lettuce growth and development for summer production. There is variability among photoselective shade nets and their effect on lettuce morphology, physiology, and plant nutrient content. There is also a large variability on using shade nets in this study on time of year. Further research is warranted to investigate the effects of photoselective shade nets on the growth and development of lettuce grown in the summer, perhaps with shade nets that reduce solar radiation by more than 30%.

APPENDICES

Appendix A

Additional Tables and Figures

Table A.1: Main effects of species on leaf angle, leaf count, leaf length, and leaf area of bermudagrass and perennial ryegrass grown in greenhouse conditions under ambient, qualitative, quantitative, and combination treatments.

Species	Leaf angle	Leaf count	Leaf length	Leaf area
	-----°-----		-----cm-----	----cm^2----
Bermudagrass	120b[z]	63a	3.06b	0.43b
Perennial Ryegrass	135a	26b	7.77a	1.28a

[z] Values within a column followed by the same lowercase letter are not significantly different at 0.05 significance level.

Table A.2: Main effects of species on leaf dry weight, root dry weight, shoot dry weight, and R:S ratio of bermudagrass and perennial ryegrass grown in greenhouse conditions under ambient, qualitative, quantitative, and combination treatments.

Species	R:S ratio	Leaf	Shoot	Root
		-----------------g-----------------		
Bermudagrass	0.32b[z]	0.08b	0.36a	0.32b
Perennial Ryegrass	1.16a	0.12a	0.17b	0.16a

[z] Means (n=240) within a column followed by the same lowercase letter are not significantly different at 0.05 significance level.

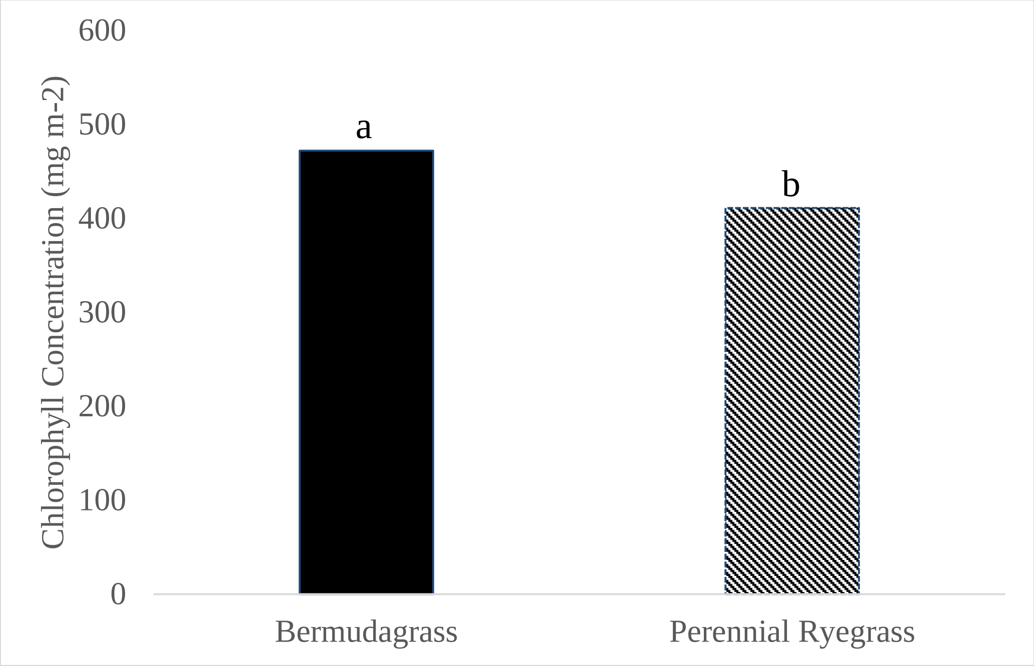

Figure A.1. Main effects of species on leaf chlorophyll concentration for bermudagrass and perennial ryegrass grown in greenhouse conditions under ambient, qualitative, quantitative, and combination treatments.

Appendix B

Illustrations

Illustration B.1. Overview of a shade structure to investigate the response of bermudagrass and perennial ryegrass to a reduction in R:FR ratio with minimal PPF reduction with a photoselective blue polyester gel filter (Lee Filters, Burbank, CA).

Illustration B.2. Overview of a shade structure to investigate the response of bermudagrass and perennial ryegrass to a reduction in R:FR ratio combined with a reduction in PPF with a photoselective blue polyester gel filter and 40% black shade net.

Illustration B.3. Subsamples of bermudagrass (left) and perennial ryegrass (right) grown under ambient conditions in the greenhouse at Oklahoma State University.

Illustration B.4. Subsamples of bermudagrass (left) and perennial ryegrass (right) grown under qualitative shade in the greenhouse at Oklahoma State University.

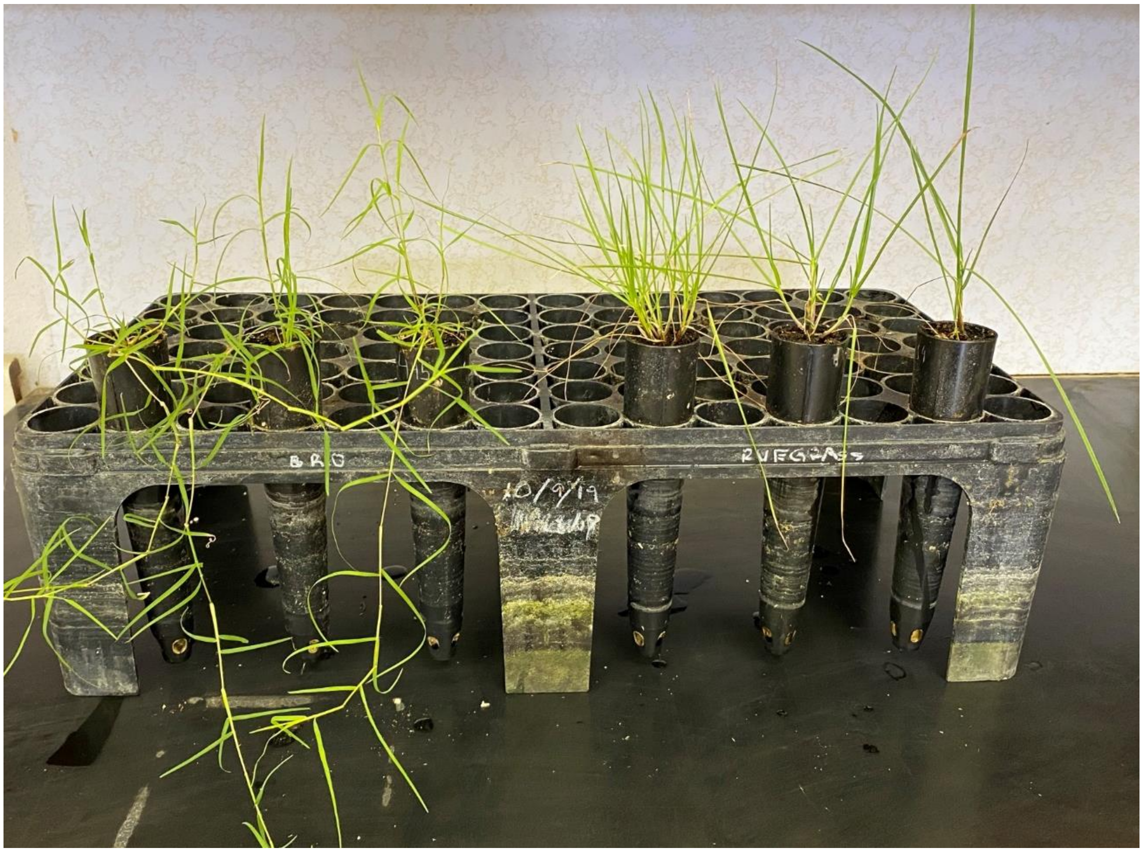

Illustration B.5. Subsamples of bermudagrass (left) and perennial ryegrass (right) grown under quantitative shade in the greenhouse at Oklahoma State University.

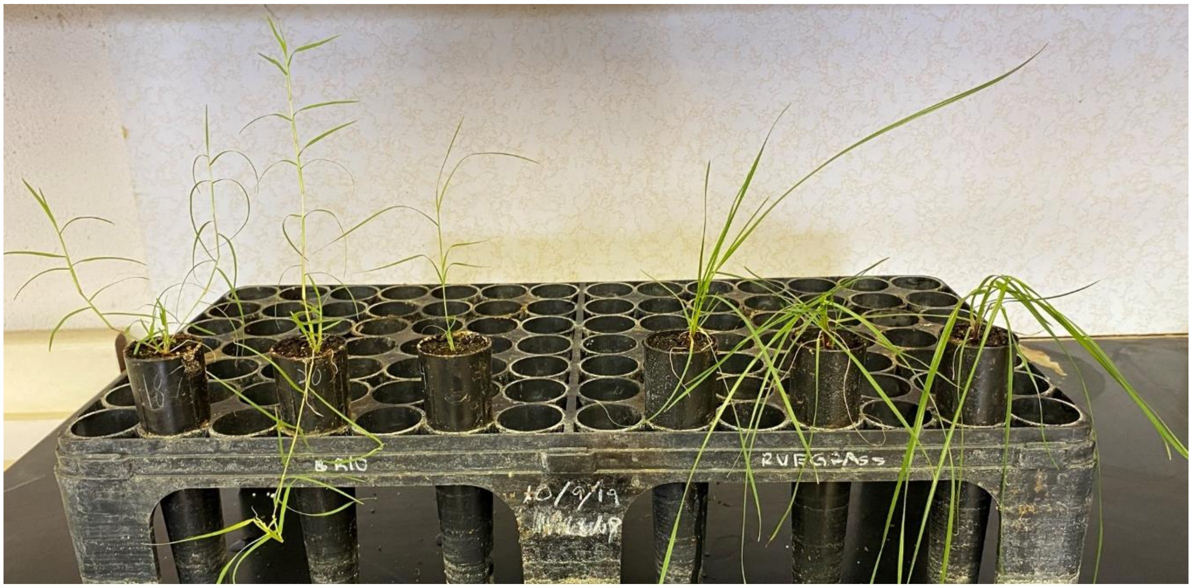

Illustration B.6. Subsamples of bermudagrass (left) and perennial ryegrass (right) grown under combination shade in the greenhouse at Oklahoma State University.

Illustration B.7. ‘Coastal Star’ and ‘Super Red’ romaine lettuce grown under pearl net in the greenhouse at Oklahoma State University.

Illustration B.8. ‘Coastal Star’ and ‘Super Red’ romaine lettuce grown under red net in the greenhouse at Oklahoma State University.

Illustration B.9. ‘Coastal Star’ and ‘Super Red’ romaine lettuce grown under aluminet in the greenhouse at Oklahoma State University.

Illustration B.10. ‘Coastal Star’ and ‘Super Red’ romaine lettuce grown under black net in the greenhouse at Oklahoma State University.

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