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PHYSIOLOGIC AND METABOLIC EFFECTS OF SUPPLEMENTAL FRUCTOSE APPLIED TO VARIOUS TURFGRASSES UNDER SHADE

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Tara E. Valentino

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PHYSIOLOGIC AND METABOLIC EFFECTS OF SUPPLEMENTAL FRUCTOSE APPLIED TO VARIOUS TURFGRASSES UNDER SHADE

By

Tara E. Valentino

A THESIS

Submitted to
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ABSTRACT

PHYSIOLOGIC AND METABOLIC EFFECTS OF SUPPLEMENTAL FRUCTOSE APPLIED TO VARIOUS TURFGRASSES UNDER SHADE

By

Tara E. Valentino

Shaded conditions pose difficulties in establishing and maintaining high quality, persistent and hardwearing turfs. Exogenous fructose applications and supplemental light were examined as potential methods to counteract the negative effects of shade on turf. The effect of supplemental and ambient light levels in combination with exogenous fructose applications on chewings fescue *(Festuca rubra v. commutata)* 'SR5100', creeping red fescue (*Festuca rubra v. rubra*) 'Dawson', and Kentucky bluegrass (*Poa pratensis*) 'Cynthia' was examined in a simulated dome, controlled growth chamber, and greenhouse environment. Exogenous fructose applications had a significant positive impact on particular growth and metabolism variables of each of the three species. Species under ambient light had reduced growth compared to supplemental light; fructose and available light were not sufficient for these species to maintain growth under extreme shaded conditions. Light response curves suggest that exogenous fructose applications under ambient light could not supplement carbohydrates needed for growth; thus carbohydrate reserves were utilized to maintain respiration. Collectively, the supplemental low light produced better quality plants than any other treatment, and was sufficient to maintain overall photosynthesis to support turfgrass growth over a limited time interval.

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Turfgrass Introduction

Turfgrasses when regularly mowed form a dense growth of leaf blades and roots that are used for a variety of purposes. Multiple uses for turfgrasses range from home lawns, sports/athletic fields, and utility (soil stabilization) (Turgeon, 2002). Turfgrasses have been selected and bred for diverse environmental conditions. The underlying criteria for the selection of turfgrasses have been based on their quality and performance in the environmental and management system in which they are grown.

Domestication of livestock for agriculture was the first step in the domestication of turfgrasses (Casler and Duncan, 2002). Over time natural selection and breeding have improved turfgrass varieties (Long, 1972). The goal of breeding was to develop varieties that would perform best under certain turf situations. Turfgrasses were introduced to the United States from other continents that were adapted for seeding ranges and pastures (Hanson, 1972).

Turfgrasses are chosen based on their quality, functional utility, appearance, and playability (Turgeon, 2002). The characteristics of turfgrass quality include: visual quality, plant density, leaf texture, uniformity of the stand, color and smoothness, and overall quality. All of these characteristics may be maintained by selecting a well-adapted turfgrass that is compatible to the environment. Modifying the environment through cultural practices for example, mowing and fertilization, to promote survival and desired growth of the plants can alter turfgrass performance. Unfortunately the selected turfgrass does not always match the demands and/or management system in which it is

grown. As the demand for turfgrasses under less than ideal conditions or cultural practices increases, the margin of error to maintain acceptable turfgrass quality decreases (Turgeon, 2002). Due to this continued demand for the highest quality turfgrass new and innovative methods of improving turfgrasses performance have been investigated.

Environmental Demands on Turfgrasses

Light is essential for growth of turfgrasses, because it is the energy source for all plant life. Solar radiation that supports plant growth is within the spectral wavelengths from 400-700 nm known as photosynthetically active radiation (PAR) (Bell et al., 2000; Lambers et al., 1998; Johnson, 1993). Photosynthesis utilizes PAR to manufacture chemical energy using wavelengths from 400-500 nm, (blue light) and from 600-700 nm, (red light) being the most photosynthetically active (Beard, 1973; Bell et al., 2000).

Light can be measured in different units: footcandle, lux, Langleys, microeinstein, and micromole per second per square meter (Thimijan and Heins, 1983). Photosynthetic active radiation micromoles per second per square meter ($\mu mol\ m^{-2}\ s^{-1}$) is the most accurate unit when evaluating light energy. This unit of measure is based on the number of photons within the wavelengths utilized to drive photosynthesis based on a defined unit of time and a defined unit of area. The total quantity of light available over the course of the day is defined as the daily light integral (DLI $mol\ m^{-2}\ d^{-1}$). It is useful to consider the total PAR that is available over an entire photoperiod due to the natural variation that occurs in light energy due to weather events, season, and/or physical obstruction. DLI can be directly correlated to plant growth and crop yield. Bunnel et al. (2005a) used DLI to quantify the total amount of light needed to maintain TifEagle bermudagrass under golf green conditions. They found that as DLI declines there is a

negative decline to growth, quality, and metabolic responses in TifEagle. In addition, they also found that as DLI decreases so does the growth responses of Tifway, TifSport, and Celebration bermudagrass as well as Meyer zoysiagrass (Bunnell et al., 2005b).

DLI is an important measure of light intensity (photo flux density) because of its direct relationship with the rate of photosynthesis and ultimately carbohydrate accumulation. Turfgrass genera and species vary in their ability to survive or even maintain acceptable quality under different environmental stresses, including very low light. Even species that can withstand "low light" conditions can become stressed when they are grown under extremely low light, because a plant cannot survive when light intensity is below a threshold level needed to meet its respiratory requirements. The light intensity at which photosynthesis and respiration are at equilibrium is defined as the light compensation point (LCP). Plants maintained at PAR below their LCP can support the metabolic processes until carbohydrate reserves are exhausted; after which they die. The LCP for most cool-season turfgrasses is 2-3 % of full sunlight (2000 μmol m^{-2} s^{-1}) (Fry and Huang, 2004). Conversely, the maximum photosynthetic rate (Amax) of individual turfgrass leaves occurs at light intensities about 30% of full sunlight (Beard, 1973). The LCP and Amax vary dependent on species as well as the environment in which they are acclimated. Thus, both the species and environment to achieve high quality turfgrasses must be considered.

Shade is a major problem in turfgrass management because it associated with decreasing light absorption, quality and intensity. There are many reasons shade occurs on managed turfgrass sites such as buildings, trees, or shrubs. Shade caused by buildings result in an equal loss of intensity of all wavelengths, and shade caused by vegetation

results in a loss of only certain wavelengths. Beard (1973) estimated that at least 20 to 25% of the existing turfgrasses are maintained under some degree of shade. As shade increases, the light quality is altered and light intensity is decreased. Shade shifts light quality so that more blue and less red reaches the turf canopy; and red light is necessary for good plant health (Gaskin, 1964).

Phytochromes are the pigments that monitor various features of the light environment. They perceive the presence, the spectral composition, the direction, and the duration of light (Lambers et al., 1998). Phytochrome A absorbs far-red light, and phytochrome B absorbs red light (Lambers et al., 1998; Bell et al., 2000). In shaded conditions far-red light is available in greater proportions than other wavelengths under a canopy because PAR (400 to 700 nm) is less and far-red (730 nm) is more substantial (Lambers et al., 1998). This increase in the proportion of far-red light results in a reduction of carbohydrates for plant growth, because far-red light is less effective in photosynthesis compared to other wavelengths (Dunn et al., 1999). Far-red light also causes greater growth in the direction towards the light; resulting in a morphological trait of shade plants, stem elongation (Lambers et al., 1998; Bell et al., 2000).

Density of shade and the source of the shade are factors determining the magnitude of the change in both light quality and light intensity. For example, light transmittance through tree canopies can be less than 10% of full sunlight, resulting in a lower ration of red to far-red light (Lambers et al., 1998). For turfgrasses under vegetative shade, the amount of blue light decreased 1% while far-red light increased 2% compared to building shade (Bell et al., 2000). These results suggest that photosynthetic

performance was affected by both shade density and shade source when vegetative shade and building shade.

The impact of turfgrasses growing under shade results in decreased plant vigor, increased susceptibility to disease, reduced wear tolerance, and reduced turfgrass canopy density (McBee and Holt, 1966; Dudeck and Peacock, 1992). Many of these decreases in quality and performance are directly related to reduced photosynthesis that results in a decrease in available carbohydrates and stored total nonstructural carbohydrates (TNC) (Koh et al., 2003). As percent shade increased the levels of TNC decreased, which in turn resulted in low quality ratings, because low carbohydrate reserves also limit the growth of roots, shoots, rhizomes, and stolons (Bunnel, 2003). In addition, on 'Coastal' Bermudagrass roots and rhizomes decreased as shade increased (Burton et al., 1959). Carbohydrates are limited both by reduced biosynthesis via photosynthesis and because reserves are used at night during respiration (Beard, 1973; Burton et al., 1959; Johnson, 1993). When carbohydrate reserves are depleted because PAR is below the turfgrass LCP, plant quality declines. Interestingly, turfgrasses that are physiologically adapted to low light conditions have higher chlorophyll content per unit area to maximize the capability for light absorption compared to turfgrasses grown in full sunlight which may maximize the capability for light absorption and lower respiration rates which in turn lowers LCP, allowing the turfgrass to maintain positive rates of photosynthesis at lower light levels (Beard, 1973). This lower concentration in carbohydrate reserves due to lower photosynthesis rates triggers a cascade of changes in plant metabolism that include: lower carbohydrate-to-nitrogen ratio due to less nitrogen fixation; reduced transpiration rate due to reduced stomatal conductance; and higher tissue moisture content (Beard,

1973). Although plants possess similar responses, the responses can differ among plant or species. For example, LCP of 'Chardonnay' grapevine plants grown under three different levels of shade decreased as shade increased. Shaded leaves approached LCP more quickly and had reduced dark respiration rates compared to sun leaves, indicating that shaded leaves used available light more efficiently (Vanden Hueval et al., 2004). Kentucky bluegrass 'Merion' and red fescue 'Pennlawn' were also grown under three different levels of shade as both species LCP decreased as shade level increased (Wilkinson et al., 1974). Collectively, these results suggest that plants respond differently physiologically when under shade and the ability of a plant to adjust to its photosynthetic system is desired when choosing a plant for shaded sites.

Morphologically turfgrasses grown in shade are taller with thinner stems, lower dry weights, and decreased plant density than turfgrasses grown in full sun-light (Dudeck and Peacock, 1992; McBee and Holt, 1966). Anatomically grasses grown in shade display decreased cuticle thickness and stomatal density (Dudeck and Peacock, 1992) which results in more succulent leaves that are more susceptible to injury. The observed increase in disease infection for turfgrasses grown under low light intensities may be caused by germination of fungal spores in high humidity that is prevalent under shaded environments. The impact of disease tends to be the highest cause of death of turfgrasses under shade. This is because under shade there is a longer dew period, low evapotranspiration (ET) rate, and more succulent plant tissue all of which favor disease establishment and growth (Beard, 1973). Beard (1965) observed that the prominence of disease, enhanced by shade, reduced overall turfgrass performance.

Turfgrass species or cultivar selection, establishment, and maintenance of shade tolerant grasses are critical for producing high quality turfgrass (Tanskerly, 1999). Using the correct grass for a specific site will enhance the odds of better quality turf. In addition, there are many other key principles (mowing, traffic management, and nutrient and/or water applications) that must be considered when managing turfgrasses under shade. The management of the shaded site is as important as the adaptation capabilities of a specific turfgrass species. Raising the cutting height (5- 10 cm) allows more leaf area for absorption of light and productions of carbohydrates (Beard, 1973). Controlling traffic in a shaded site is important due to tissue weakness and sparse growth of turf under shade (Dunn et al., 1999; Tankersley, 1999). Also avoiding excess nitrogen fertilization is key since turfgrass growth rate is lower in shaded sites (Michigan State University (MSU) Extension Bulletin; GT1062, 1998). Burton et al. (1959) suggests that with heavy shade, high nitrogen fertilization decreased plant density and leaf area, contributing to a carbohydrate deficiency. Turfgrasses in shade posses' lower evapotranspiration rates so irrigate deeply and infrequently to control potential wet conditions (Danneberger, 2003). Irrigation techniques are important because large amounts of water on a shaded site may cause disease or other problems.

The management of trees and/or shrubs shading the site by pruning decreases shade canopy density to allow more sunlight to filter through for increased light reaching the turf (Beard, 1973; Tankserly, 1999). Pruning is the number one recommendation for reducing the negative impact of shade on turfgrass because of the increase in light penetration through the canopy, but also because it increases wind movement which assists the reduction of standing water on the turfgrass and high heat pockets due to

stagnant air movement (Beard, 1973; Danneberger, 2003; Dunn et al., 1999; Tankserly, 1999). All of these management practices are important because managing all parts of the turfgrass microenvironment is crucial to maintain better quality turf.

Carbohydrates: Fructans

When considering overall plant health and quality, carbohydrates are essential to turf growth and development. Carbohydrates are a source for re-growth and recovery, as well as survival when utilization exceeds supply and demand (Smith, 1972). Carbohydrates accumulated in excess of the level required for assimilation are called carbohydrate reserves (Beard, 1973). Fructans and oligosaccharides are the primary constituents of carbohydrate reserves in cool-season turfgrasses and contribute up to 45% of dry weight (Groteluxhen and Smith, 1968). Fructans also regulate: sucrose pool size in photosynthetic tissue, sucrose metabolism during phloem unloading, osmoregulation of cellular water potential, adaptation to low-temperature photosynthesis, and lowering of the freezing point of tissue water upon depolymerization to fructose (Nelson and Gorham, 1987; Pollock, 1986; Beard, 1973).

Fructans are made up of short-chain and long-chain fructosans. Long-chain fructose molecules are predominantly found in the lower sheath, lower internodes, and roots of cool-season turfgrass species, and act as the storage units for the carbohydrates (Smith, 1967 and 1972). Alternately, short-chain fructose molecules can be found in leaf blades and stem bases (Smith, 1967 and 1972), and are utilized for growth and maintenance of plant tissues.

The availability of these reserves and the concentration that are allocated to individual plant parts vary depending on tissue age, season of the year, environmental

factors that control supply and demand, and turfgrass management. Accumulation of carbohydrates is greatest during periods of minimal shoot growth and high light intensity as well as during late fall hardening prior to winter dormancy (Beard, 1973). The exhaustion of the reserves can occur when the plant is actively growing. Accumulation is favored by conditions like long photoperiods, infrequent cutting or grazing, low temperatures, and low amounts of fertilizer, and will be minimized with the opposite environmental and management conditions (Pollock, 1986).

When light intensities are below the optimum for efficient growth, carbohydrate reserves are utilized for respiration (Beard, 1973; Lambers et al., 1998). At medium light intensity, the rate of carbohydrate production can be less than 50% of that at high intensity, and that at low intensity there was almost no carbohydrate formation (Alberda, 1957). This supports the assumption that at higher light intensities, more photosynthesis takes place, which in turn creates more carbohydrates. When plants under experimental conditions are subjected to no light, there is a dramatic decline in available carbohydrates (Burris et al., 1967). Tomato plants placed in darkness stopped growing after 30-40 hours due to depletion of their carbohydrate reserves (Juhren and Went, 1949). However, when squash plants were grown in light then transferred to a darkroom, the plants were greatly affected by the amount and intensity of light that they had beforehand (Juhren and Went, 1949). This suggests that prior light intensity determines a plant's future due to the amount of allocated reserves that are then available to support metabolism under reduced light conditions.

Light Response Curves: Indication of Photosynthetic Efficiency

Although research is abundant on the interaction of shade and turfgrasses growth responses, the impact on turfgrass metabolism is not as well understood. Measuring photosynthesis of plants under shade provides an indication of the efficiency of the photosynthetic system (Peek and Russek-Cohen, 2002). In addition to light response curves (LRC), leaf reflectance measurements from a plant canopy detect plant stress (Carter and Miller, 1994). These indices provide information on the metabolic properties of a plant under shaded conditions.

Light response curves are used to measure a plant's photosynthetic responses to light by measuring carbon dioxide (CO_2) fixation in intact leaves at increasing light units ($\mu mol\ m^{-2}\ s^{-1}$). The LRC provides information on the photosynthetic properties of the plant to the changing light levels. The properties described by this series of measurements are the light compensation point (LCP), assimilation (A), apparent quantum efficiency (φ), dark respiration (Rd), and maximum assimilation or photosynthetic rate (Amax) (Figure 1.1). The response curves are calculated and fitted by the equation using Photosyn Assist Version 1.1 2004 (Dundee Scientific, Scotland, U.K.):

$$A = \frac{\varphi Q + Amax - \sqrt{(\varphi Q + Amax)^2 - 4\varphi Q k Amax}}{2k} - Rd$$

The φ is the linear portion of the curve and reveals the relationship between given light-dependent product and the number of absorbed photons known as quantum yield. These yields can vary from 0, where none of energy is used in photosynthesis, to 1, where all absorbed light is used (Taiz and Zeiger, 2002). The Rd is the measurement of CO_2 given

off by the plant due to respiration. As PAR continues to increase the photosynthetic response rate levels off and when the system becomes saturated Amax measures the photosynthetic response at the point where A no longer increases at a specific light level. At this point electron transport rate, rubisco activity, or the metabolism of triose phosphates, have become limiting to photosynthesis (Taiz and Zeiger, 2002).

Photosynthesis and LCP will vary depending on the light environment and plant species. For example, LCP of sun-grown light energy level plants ranges from 10-20 $\mu mol\ m^{-2}\ s^{-1}$ and shade grown light energy level plants the LCP ranges from 1-5 $\mu mol\ m^{-2}\ s^{-1}$ (Taiz and Zeiger, 2002). When photosynthetic rates of six different turfgrasses were compared, turfgrass genera varied ($p\text{-value} < 0.05$) in net photosynthetic rate. The differences were related to the individual features of growth habit: leaf elongation and surface cover, and carotenoid and chlorophyll content of the different genera (Van Huylenbroek and Van Bockstaele, 2001). Specifically, Amax was significantly higher for zoysiagrass compared to bentgrass, resulting in higher dry matter production in zoysiagrass (Agata et al., 1989). Thus, it is very important to consider the efficiency of genera and/or species photosynthetic apparatus when considering whether a turfgrass is suited for establishment for shaded sites.

There are three fates for light that is intercepted by a leaf: absorption, transmition, and/or reflection. Based on the fact that a fraction of the intercepted light is reflected, specific differences in reflected light quality between turfgrasses grown under environmental conditions which support normal metabolic conditions and turfgrasses grown under conditions in which induce stress metabolism can be used as an indication of metabolic efficiency or stress. Leaf reflectance measurements have been used to

measure wavelengths that correlate to plant stress (Carter and Miller, 1994). The following indices are used to provide information about various aspects of plant stress: water band index (WBI), narrow band index (NDVI), red-edge stress vegetation index (RVSI), and photosynthetic reflectance index (PRI). The WBI (WBI= R900/R970) values have been correlated with leaf water content, thus the values measure water-induced stress. The NDVI (NDVI1695= (R970-R695)/(R760+R695) and NDVI1700= (R840-R700)/(R840+R700)) measures the difference in reflected near infrared and red bands, and divided their sums, which have been positively related to plant health. The RVSI (RVSI= (R714+R759)/ 2-R733) value measures stress, which as the values become more negative this indicates reduced stress. The PRI (PRI= (R531-R570)/ (R531+R570)) values indicate photosynthetic radiation efficiency, which become increasingly negative with reduced radiation efficiency. Carter (1993) first defined the wavelengths at which leaf reflectance was most responsive to stress using plant competition in pines, disease on euonymus, fungi infection on pine, and oak senescence. The results suggested that changes in the wavelengths within the green and red areas of the spectrum increased in response to stress, and were most consistent over each stress regardless of plant genera (Carter, 1993). The usefulness of these indices in detecting and quantifying plant stress has been illustrated on a variety of plant systems. On soybeans, differences in leaf reflectance were measured in narrow stress-sensitive wavebands after herbicides were applied, showing that these measurements increased with herbicide damaged canopies (Carter and Miller, 1994). In addition, Lang et al. (2000) used leaf reflectance measurements to measure plant stress in relation to black leaf in grapes, and Penuelas et al. (1997) used the indices to measure plant stress in relation to water concentration.

Collectively, these studies suggest that leaf reflectance is a non-destructive tool in monitoring plant stress. Thus, combining LRC and leaf reflectance to explain the metabolic impact of shade on turfgrass growth and overall plant quality may provide important insights.

Turfgrass Biology

Selecting specific turfgrass species is important when growing turfgrass under shade. Turfgrasses have been specifically bred for shaded sites, to improve turfgrass performance by maintaining growth and quality better than previous turfgrasses available. Fine fescues are cool season grasses that are composed of over 100 species and cultivars within the *Festuca* tribe originating from Europe (Beard, 1973; Hanson, 1972). Fine fescues are known for their relatively high shade tolerance, not only due to their ability to grow well in the shade but also their ability to compete with surrounding plants. They are characterized as having a rhizomatous or "bunch type" growth habit, moderate wear tolerance (ability of grass to overcome traffic), good density (plants per unit area), and fine texture (estimate of leaf width). Fescues usually are grown in lawns, parks, and areas with shade (Murphy, 1996). Fescues are divided into two types based on leaf texture: coarse fescues or fine fescue (Turgeon, 2002). Coarse fescues include: tall fescue and meadow fescue. Fine fescues include creeping red fescue, chewings fescue, hard fescue, and sheep fescue. The diversity of fescues is based on their unique adaptation, cultural intensity, and plant description.

Chewings fescue (CF) (*Festuca rubra v. commutata*) is a fine fescue that forms a fine textured, erect growing, and high-density turf. The chewings fescue cv. 'SR 5100' is both shade and sun tolerant, which means this cultivar can grow well in sunny or shaded

sites (Beard, 1973). The cultivar has been evaluated in several research trials including the 1998 National Turf Evaluation Program (NTEP) fine fescue test (Morris, 2003). NTEP tests for quality, color, texture, density, percent ground cover, seedling vigor, drought tolerance, frost tolerance, and traffic tolerance of different cultivars to help breeders, researchers, and extension specialists determine what cultivar has the desired characteristics for their individual needs of their clientele. 'SR 5100' was ranked 6 on a 0 to 9 scale of 80 fine fescue cultivars that were evaluated (Graham Turf Seeds Ltd., Canada; Morris, 2003).

Creeping red fescue (CRF) (*Festuca rubra v. rubra*) is also a fine fescue that has a narrow texture, high shoot density, and good uniformity. The cultivar is a slender creeping red fescue that grows well in shaded sites (Beard, 1973; Turgeon, 2002). Based on the NTEP 1998 fine fescue test 'Dawson' received highest quality rating, which ranked it 16 out of 80 cultivars that were evaluated (Royal Brand Technical Report, 2003).

In Michigan, Kentucky bluegrass (KB) (*Poa pratensis*) is the most widely used cool season turfgrass. The original species of Kentucky bluegrass introduced to the United States originated from Eurasia (Beard, 1973). However, some scientists believe native populations existed along Cascade-Sierra Nevada Cordillera, the Rocky Mountain Cordillera, and northern Canada before the spread of European cultivars (Stebbins, 1972). Within the Kentucky bluegrass species there are both common and improved cultivars. Common cultivars are the original cultivars of Kentucky bluegrass, while improved cultivars are more disease resistant and more vigorous than common cultivars, and perform well in lawns under low maintenance (MSU Extension Bulletin; GT1062, 1998).

Its characteristics are: rhizomatous growth habit; medium wear tolerance (ability of grass to overcome traffic); 7-21 days to germinate; 1/8" leaf width; moderate to high thatch; and good shade, heat, drought, cold tolerance (Royal Brand Technical Report, 2003). Recommended cultural management for Kentucky bluegrass lawns include: mow frequently (one to two times per week) at 2.54 or 5 cm, 10-20g/ m^2 nitrogen fertilize in split applications, and irrigate to replace evapotranspiration rate. Kentucky bluegrass grows rapidly under cool and moist weather. The grass is widely used in lawns and also for commercial sites, golf course fairways, tees, roughs, and athletic sites. Kentucky bluegrass 'Cynthia' is a cultivar that was developed for its dark green color, fine leaf texture, and good density compared to other Kentucky bluegrass cultivars. The cultivar also has moderate shade tolerance, disease resistance, low water requirements, good wear recovery, and low input requirements.

Past Research

Extensive research has been done on turfgrasses grown in shade to correct problems and stress that the turfs encounter. Researchers have used different types of chemical applications to improve the quality of shade grown grasses. Types of chemical applications include: nitrogen, iron, trinexapac-ethyl (TE), and soluble carbohydrates such as sucrose, fructose, or combinations of each. Sucrose and fructose may supplement low carbohydrate reserves and compensate for low light conditions. For example, in tomatoes a 10% foliar sucrose solution increased dry weight, and in squash plants sucrose increased survival of plant when grown in darkness (Went, 1944; Juhren and Went, 1949; Berrie, 1960). Also in tomato plants, Went (1944) found that in darkness sucrose drops essentially to zero within 24-48 hours, but rises again upon immersion of 10% sucrose or

light exposure of 1000 μmol m^{-2} s^{-1}. Nelson and Gorham (1957) applied sucrose-C14 or glucose-C14 to trace carbohydrate partitioning in soybean seedlings and leaves. In the light they found that 1% of sucrose was translocated after 14 hours and that in dark 10% of glucose was translocated in 3 hours. In clover, 0.5 and 1% glucose stimulated nodule formulation both in absence and presence of light, and 2% glucose produced the highest number of nodules (Van Schreven, 1959). More recently, fructose was combined with post-emergent herbicides to enhance the action of the herbicide without decreasing tolerance of a plant to the herbicide (Penner et al., 1999). Fructose in solution was taken up in a plant between 1.25-11% weights per volume; however the combination of 1.25% fructose with herbicide and organisilicone as an adjuvant was sufficient to successfully kill weeds (Penner et al., 1999).

Use of exogenous fructose applications to counter act the negative effects of shade on turfgrass was first investigated under a sports turf management system (Sorochan, 2002). Due to the role of fructans as storage carbohydrate in cool season grasses, fructose applications could potentially supplement inadequate biosynthesis of fructans due to shaded environments and increase the quality of grasses grown under reduced light conditions. In these studies, fructose dissolved in water with an organisilicone adjuvant was applied on Supina bluegrass five times per week at 1.25% weight per volume and was also applied once per week at 1,2,4,6, and 8 times the application rate. Sorochan (2002) found that five applications per week caused leaf damage and that once a week at 1x rate (1.25% weight/volume) provided least amount of injury while demonstrating positive physiological responses. When investigating the translocation of exogenously applied fructose, exogenous fructose was successfully taken

up by the plant and used for metabolic processes (Sorochan, 2002). The quality of Supina bluegrass increased with exogenous applications of fructose compared to the control. However, the broader use of exogenous fructose on other turfgrasses and under varied shade conditions remains to be evaluated.

Growing turfgrasses in shade has been and currently is a challenge to the sports field industry as well as to the homeowner. Investigating innovative methods to increase the quality and health of turfgrasses grown under shaded conditions needs to be investigated. Knowledge about the effects of exogenous fructose on the metabolism is important to the understanding of how fructose is being utilized in turfgrass and if the fructose is producing a positive physiological response. Recommendations could also be made on the minimum DLI for each turfgrass required for exogenous fructose to have a positive response. The potential use of exogenous fructose applications and quantifying DLI can have great impact on the management of turfgrasses under shaded conditions.

Objectives of Study

1. Determine effects of exogenous fructose on CF, CRF, and KB
2. Determine effects of supplemental and ambient light levels on CF, CRF, and KB
3. Test the direct effects of the interaction of exogenous fructose applications and light level on CF, CRF, and KB
4. Determine metabolically (LRC and leaf reflectance) the effects of exogenous fructose and light levels on CF, CRF, and KB
5. Determine if fructose can substitute for light to maintain growth under supplemental and ambient shaded environments

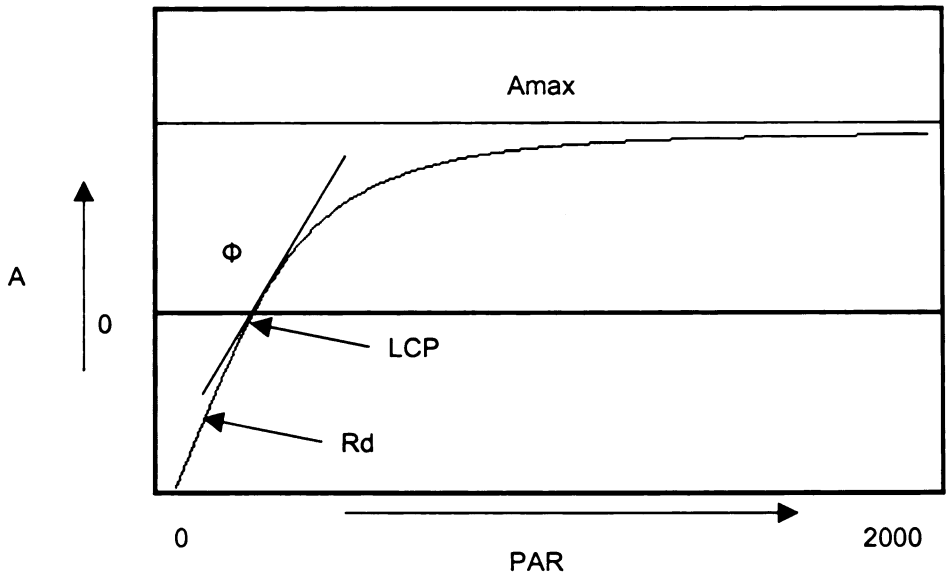

Figure 1.1 Light response curve: assimilation rate (A μmol CO_2 m^{-2} s^{-1}) measured over changing photosynthetic active radiation (PAR μmol m^{-2} s^{-1}) levels. Amax: maximum assimilation; LCP: light compensation point; Rd: dark respiration rate; and Φ: quantum efficiency.

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Chapter 2

Supplemental Fructose Applied to Chewings Fescue 'SR5100', Creeping Red Fescue 'Dawson', and Kentucky bluegrass 'Dawson' Under Shaded Conditions

Abstract

Shade poses difficulties in establishing and maintaining high quality, persistent and hardwearing turfs. Exogenous fructose applications were examined as a potential method to counteract the negative effects of shade on turf. We examined the effect of supplemental and ambient light levels in combination with exogenous fructose applications on chewings fescue *(Festuca rubra v. commutata)* 'SR5100' (CF), creeping red fescue (*Festuca rubra v. rubra*) 'Dawson' (CRF), and Kentucky bluegrass (*Poa pratnesis*) 'Dawson' (KB). Exogenous fructose treatments had a significant affect on KB clipping weight under 14 and 32 μmol m^{-2} s^{-1}, on CF water content under 14 μmol m^{-2} s^{-1}, on CRF photosynthetic efficiency under 73 μmol m^{-2} s^{-1}, on CRF plant health under 14 μmol m^{-2} s^{-1}, on CF plant stress under 73 μmol m^{-2} s^{-1}, on KB photosynthetic efficiency under 14 μmol m^{-2} s^{-1}, and on KB plant health under 32 μmol m^{-2} s^{-1}. Species grown under supplemental light had positive physiological responses compared to species grown under ambient light. This suggests that within the conditions of these experiments exogenous fructose was not an effective supplement for decreased carbohydrate reserves due to low rates of photosynthesis under ambient light. However, supplemental light (32 or 73 μmol m^{-2} s^{-1}) was sufficient to maintain turfgrass growth of CF, CRF, and KB. Species under ambient light became increasingly stressed compared to supplemental light, thus suggesting that these species do not maintain quality and growth well under extreme shaded conditions (40 to 200 μmol m^{-2} s^{-1}).

Introduction

Shaded environments are a major management problem for establishing high quality, persistent and hardwearing turfs (Wilson, 1997). Shading involves the partial or complete interception of direct solar radiation prior to being available for absorption by plant tissue. Growing many genera and species of turfgrass under shade decreases plant vigor, increases susceptibility to disease, reduces wear tolerance, and reduces density (McBee and Holt, 1966; Dudeck et al., 1992). With reduced light intensity the rate of photosynthesis is lowered, resulting in an immediate decrease in available carbohydrates and carbohydrate reserves (Koh et al., 2003). In addition, total nonstructural carbohydrates (TNC) decrease which are primarily stored in roots and crown tissue of grasses. Reduced light intensities that result in reduced levels of PAR limit growth and development of roots, stolons, shoots, and rhizomes (Dudeck and Peacock, 1992; Johnson, 1993; Bell et al., 2000; Danneberger, 2003; Wilson, 1997; Beard, 1973). Increasing the quality and health of turfgrasses under shaded conditions has been an ongoing goal. Exogenous fructose applications have been one of the newest methods to counteract the effects of turfgrasses grown in shade. It has been hypothesized that these applications are a way of supplementing low carbohydrate reserves to compensate for low light conditions (Sorochan, 2002).

In theory fructans may improve turfgrass growth since fructans have been identified as the primary carbohydrate reserve in cool-season turfgrasses (Sorochan, 2002; Groteluxhen et al., 1968). Fructans are polymers of fructose with a single molecule of glucose that forms a single molecule of sucrose as an end group. Fructose and other carbohydrate concentrations are greatly affected by light intensity. At high

light intensities, photosynthesis increases, which in turn creates more carbohydrates, and when plants are subjected to insufficient light there is a general decline in available carbohydrates (Burris et al., 1967). However, it remains unclear what threshold of light is sufficient to maintain turfgrass growth and development when supplemental fructose is applied. The objective of this work was to investigate the effect of different light levels in combination with exogenous fructose applications or no fructose applications on CF, CRF, and KB.

Materials and Methods

Experimental Site

This work took place during 2004 (year I) and 2005 (year II) inside the dome structure at the Hancock Turfgrass Research Center (HTRC) at Michigan State University (MSU) in East Lansing, Mich. The dome simulates an indoor sports facility that allows 2-10% of available photosynthetic active radiation (PAR) through fiberglass fabric. (Birdair®, Birdair Inc., Amherst, N.Y.).

The experimental design was split block design with three factors and four replications in year I, and four factors and three replications in year II. Replications decreased in year II due to additional treatments amid the same number of modules. The main factor was light level, which was a fixed effect: ambient light (AL, 2-10% PAR or 40 to 200 μmol m^{-2} s^{-1}, depending on weather) with ambient photoperiod duration, ambient light plus 73 μmol m^{-2} s^{-1} light supplemental high light (SHL) with 16-h photoperiod using high pressure sodium (HPS) lights, and ambient light plus 32 μmol m^{-2} s^{-1} supplemental low light (SLL) light with 16-h photoperiod using HPS lights. In year II only SLL and AL were tested. The supplemental light units were achieved by using

400W HPS lights located 2.3m above the turfgrass canopy. To achieve SHL a total of five 400W HPS lights were placed to cover a $5m^2$ area of turf. To achieve SLL four 400W HPS lights were placed to cover a $6m^2$ area of turf. Light intensity was measured with a CIRAS portable photosynthesis system (PP Systems, Amesbury, Mass.) at turf canopy height three times under each light treatment in random areas to verify consistent light intensity. A Watchdog Model 450 data logger (Spectrum Technologies, Plainfield, Ill.) recorded PAR under AL conditions instantaneously and calculated an average every 60-minutes. The output was used to calculate daily light integral (DLI mol m^{-2} d^{-1}) under AL over the duration of the experiment. Within each light treatment the second experimental factor consisted of fructose applied once per week (F1) or no fructose (NF) application (control). For the experiment initiated during year II, fructose applied two times per week (F2) was included as an additional treatment. The third experimental factor in both experiments was turfgrass cultivar type: CF and CRF in both years and KB in year II.

Forty-eight movable turf modules (GreenTech Inc®, Roswell, Ga.) were used to establish the CF, CRF, and KB. The modules measured four-by-four feet and 20cm deep creating a volume of $0.03m^3$. They are manufactured using high-density polyethylene material with a perforated base, pallet channels for easy repositioning, and foot locator pads for stability. The modules were placed in natural light outside the dome at the HTRC on a concrete area for proper drainage during establishment for both experiments. The modules contained a 5cm depth gravel base and 15cm soil depth that contained 10% Oshtemo sandy loam topsoil mixed with 90% well-graded sand (Great Lakes Gravel, Lake Odessa, Mich.). The turfgrass was seeded onto the modules at a rate of 15g/ m^2

(1000ft^2) on 23 July in year I. A starter fertilizer (16N-25P-13K) was applied at a rate of 3g phosphors (P)/ m^2 on the day of seeding. On the same day as seeding, germination blankets were placed over the top of the seeded area to accelerate germination and removed on 5 August. For the duration of the entire establishment period (from 23 July to 12 October) a total of 24g/ m^2 of (21N-3P-18K) fertilizer was applied to the modules on a weekly basis. Also during establishment, the modules were mowed starting 31 August at 7.6cm (3in) bench height, or set height of mower blades, with a Toro® walk mower (Bloomington, Minn.). Until 31 August the turf was mowed only when the height was 7.6cm tall and once per week thereafter until 16 October. Clippings were not removed and until 16 October, the turf was watered using an automated irrigation system four times a day for eight-minute periods.

Prior to moving the modules into the dome, all species were treated with a broad-spectrum fungicide (BannerMaxx®, Sygenta Corporation, Wilmington, Del.) at a rate of 1.2mL/ m^2 to prevent disease. Year I light and fructose treatments were initiated on 19 October 2005. Sixteen modules of CF or CRF per light treatment were placed inside the dome. The Agriculture Research Manager (ARM) statistics system (Gylling Data Management Inc., Brookings, S. Dak.) was used to randomly assign each module and treatment to its specific light treatment. The KB modules were left on the concrete area and were allowed to over winter under ambient outside light conditions.

In year II the KB modules were over seeded on 26 July at a rate of 10g/ m^2 and were fertilized with urea (46N-0P-0K) to increase coverage of KB at a rate of 5g/ m^2. After urea application, the KB modules were then fertilized a total of 23g/ m^2 of (21N-3P-18K) fertilizer applied weekly. Beginning 26 July the KB modules were watered four

times a day using an automated irrigation system and beginning 24 August KB was mowed as described in year I. On 15 September the KB modules were randomly assigned a light level and fructose treatment and placed into the simulated dome, as described in year I.

For year II on 26 July the modules from year I were cleaned of the old CF and CRF material and rebuilt with 90% sand and 10% soil mix. Once the modules were in place, CF and CRF cultivars were seeded, fertilized, and watered beginning on 26 July; mowing began on 6 September; and on 22 October the modules were randomly assigned a light level and fructose treatment and placed into the simulated dome, as described in year I.

Fructose Treatments

Fructose (Isoclear®, Cargill Sweeteners, Naperville, Ill.) treatments began on 21 October year I, 15 September year II KB, and 22 October year II CF and CRF. The treatments were applied once per week (year I and II) and twice per week (year II) to the corresponding modules. Fructose was mixed with an adjuvant (BreakThru®, Goldschmidt Chemical Corporation, Hopewell, Va.) and double distilled water. Fructose was applied at a rate of 1.25% v/v and the adjuvant was applied at a rate of 0.1% w/v (Penner et al., 1998). A carbon dioxide backpack sprayer (R&D Sprayers©, Opelousas, La.) was used to apply the fructose and adjuvant mixture to the corresponding modules.

Response Variables

Treatment effects were evaluated based on the interaction between light and fructose on the cultivars by measuring: clipping yield, turf density, and leaf-reflectance all species. Clippings were collected biweekly for CF and CRF in both years and weekly

for year II KB, and were stored at 5°C until placed in a forced air-drying oven. The clippings were dried at 100°C for 3 days and dry weight was measured and expressed as grams/m^2 of the plot area. Core samples were taken biweekly for CF and CRF in both years and weekly for year II KB with a 2.54cm diameter soil sampling tube to a depth of 3cm. For each sample the number of tillers were recorded and used to calculate turf density (tillers cm^{-2}).

Leaf-reflectance measurements were collected as close to solar noon as possible on a sunny day biweekly for CF and CRF both years and weekly for year II KB. Leaf-reflectance quantifies the amount and specific wavelength of light that is reflected off the turf canopy, which is then used to correlate to overall plant stress. The measurements indicate the effect of treatments on photosynthetic efficiency, metabolism of the plant, and the light absorbed that will be utilized for photosynthesis. A spectroradiometer (FieldSpec® Pro, Analytical Spectral Devices, Inc., Boulder, Colo.) was used to measure reflected light waves to calculate: water band index (WBI), narrow band index (NDVI), red-edge stress vegetation index (RVSI), and photosynthetic reflectance index (PRI). The WBI (WBI= R900/R970) values are correlated with leaf water content thus the values measured water-induced stress. The NDVI (NDVI1695= (R970-R695)/(R760+R695) and NDVI1700= (R840-R700)/(R840+R700)) measured the difference of near infrared and red bands, and divided their sums, resulting values are positively related to plant health. The RVSI (RVSI= (R714+R759)/ 2-R733) values indicate reduced stress and the greater negative numbers indicate reduced stress. The PRI (PRI= (R531-R570)/ (R531+R570)) indicated photosynthetic radiation efficiency, and the values decrease with reduced radiation efficiency.

Statistical Analysis

Species and fructose treatments for each light level were compared using Proc ANOVA with Tukey's adjustment (SAS, 2000). Measured light energy underneath all conditions was calculated into daily light integral (DLI mol m^{-2} d^{-1}) and used for statistical analysis for light treatment influence. Data from year I will only be reported due to similar results between CF and CRF for both years. Pearson's correlation was used to test the interactions between response variables.

Results

The application of fructose had a significant affect on KB clipping weight (grams m^{-2}) under AL and SLL (Table 2.2A), for PRI under AL (Table 2.11A), and NDVI695 under SLL (Table 2.12A). For CF and CRF, WBI, NDVI695, and NDVI700 were significantly different between fructose applications and control treatments under AL, whereas PRI and RVSI were significantly different under SHL (2.5A, 2.6A, 2.7A, 2.8A, 2.9A). There were no significant differences for CF and CRF clipping weight and tiller production (density). Due to the application of fructose there were no significant differences for KB tiller production or for WBI, NDVI700, and RVSI (Tables 2.1A, 2.3A, 2.4A, 2.10A, 2.13A, 2.14A). There were significant affects on growth and metabolism of CF, CRF, and KB due to available light energy (PAR). There were also significant interactions between species, fructose, and time for each of the parameters that were measured.

Daily Light Integral (DLI)

For each light treatment light levels were significantly different over time (weeks) (p-value < 0.05). Fluctuation in light levels was dependent on natural ambient conditions

(data not shown). There were no differences between the response parameters of the different turfgrass species and fructose treatments under the various light levels. However, SHL was found to have higher average DLI than SLL (Figure 2.1A), thus the SHL treatment was not included as a treatment in year II (Figure 2.1B). Supplemental low light treatments were also found to be more likely achieved under commercial management situations. Due to the time of year the KB experiment was conducted DLI was found to be higher than in both fescue experiments (data not shown). For KB light levels were not significantly different over time (weeks) (p-value < 0.01), however SLL maintained a higher DLI than compared to AL (Figure 2.2).

Clipping Weight

CF and CRF Experiment

Clipping weights (grams m^{-2}) for all species grown under all light energy levels were significantly different over time (weeks) (Table 2.1A). Clipping weights under AL decreased for all species, while increasing over the duration of the experiment when grown under SLL and SHL (Table 2.1B and Figure 2.3). There were significant differences between species when grown under AL and SLL (Table 2.1A); with CRF maintaining 30% higher clipping weights compared to CF (Table 2.1C). In addition, for plants grown under all light energy levels there was a significant interaction between species and time (Table 2.1A). Light energy available had a greater affect than exogenous fructose as illustrated by the one to five fold increase in clipping weight as light energy increased from AL to SHL (Table 2.1B).

Clipping weights for both CF and CRF under AL were positively correlated to density (p-value < 0.01, r = 0.84). For both CF and CRF, clipping weight was negatively

correlated to respective light DLI (p-value < 0.0001, r = -0.67). Under AL CRF clipping weight was positively correlated to NDVI695, NDVI700 and RVSI (p-value < 0.01, r = 0.503, 0.53, and 0.515 respectively).

KB Experiment

Exogenous fructose applications had a significant affect on KB clipping weight under AL and SLL (Table 2.2A). Under AL KB plants that received fructose had higher clipping weights compared to controls (NF) (Table 2.2B). Under SLL KB control plants (NF) had higher clipping weights than F2 and F1, respectively (Table 2.2B). Kentucky bluegrass clipping weight significantly differed over time (weeks) (Table 2.2A, C). Clipping weights for KB under AL fluctuated over time while clipping weights under SLL decreased by week four (Figure 2.4). Kentucky bluegrass clipping weights were 20% greater under SLL than under AL (Table 2.2B). Kentucky bluegrass grown under AL and SLL light levels maintained 25% higher clipping weights than both CRF and CF (data not shown). Under AL KB clipping weight was positively correlated to NDVI695 and NDVI700 (p-value < 0.01, r = 0.59).

Density

CF and CRF Experiment

Density (tillers cm^{-2}) was significantly different over the duration of the experiment for both CF and CRF species under both light energy levels (Table 2.3A), with density for both species decreasing over time (Table 2.3B and Figure 2.5). When CF and CRF were grown under SLL there was a significant interaction between fructose, species, and time (Table 2.3A). Each species responded differently to fructose applications over the duration of the experiment. There were slight differences in density

between light levels, with turfgrass species grown under SLL and SHL generally having higher densities than those grown under AL (Table 2.3B). For both CF and CRF density was negatively correlated to AL DLI (p-value < 0.0001, r = -0.63). For turfgrasses grown under AL density counts were positively correlated to clipping weight (p-value < 0.0001, r = 0.74).

KB Experiment

There were significant differences in density over time (weeks) for KB grown under SLL (Table 2.4A). Density increased over the duration of the experiment (Table 2.4B and Figure 2.6). Tiller production was found to be two times greater under SLL than under AL (Table 2.4B).

Leaf Reflectance

CF and CRF Experiment

Water Band Index

For CF grown under AL exogenous fructose had a significant affect on water band index (WBI R900/R970) (Table 2.5A), with the control plants (NF) maintaining higher WBI compared to F1 (Table 2.5B). Chewings fescue that did not receive fructose applications was less water-stressed compared to plants that received fructose applications. When plants were grown under AL and SLL there were significant differences in WBI over time (weeks) (Table 2.5A). At all points in time WBI under AL was consistently lower compared to measurements on turfgrasses grown under SLL (Table 2.5C).

Photosynthetic Reflective Index

Under SHL for CRF exogenous fructose applications significantly affected photosynthetic reflective index (PRI (R531-R570)/(R531+R570)) (Table 2.6A), with control plants maintaining higher PRI values compared to F1 plants (Table 2.6B). For CRF that did not receive fructose utilized PAR more efficiently compared to plants that received fructose applications. There was also a significant difference between species under SHL (Table 2.6A), with CRF maintaining one percent higher PRI compared to CF (Table 2.6D). Photosynthetic reflective index was significantly different over time for all species under all light energy levels (Table 2.6A). Photosynthetic reflective index was found to decrease under AL and SHL and increase under SLL over the duration of the experiment (Table 2.6C). Under AL conditions there was a significant interaction between species and time (Table 2.6A). Over time PRI responded differently depending on species type. Under SHL there was a significant interaction between fructose, species, and time (Table 2.6A). For both the control plants and F1 plants PRI decreased for both species over the duration of the experiment (data not shown).

Narrow-Band Vegetative Index

Exogenous fructose applications significantly affected narrow-band vegetative index 695 and 700 (NDVI695 and 700 (R970-R695)/(R970+R695) and (R840-R700)/(R840+R700)) for CRF grown under AL (Table 2.7A and 2.8A). Control plants maintained higher NDVI values than plants that received fructose (Table 2.7B and 2.8B). There were significant differences in NDVI under all light energy levels over time (weeks) (Table 2.7A and 2.8A), with NDVI decreasing over the duration of the experiment (Table 2.7C and 2.8C). For CF and CRF grown under SHL there were

significant differences in NDVI695 between species (Table 2.7A). Creeping red fescue possessed 1% higher NDVI values than CF (Table 2.7B). For CF and CRF grown under AL there was a significant interaction between fructose and species for NDVI695 (Table 2.7A). For plants grown under SHL there was a significant interaction between species and time for both NDVI695 and 700 (Tables 2.7A and 2.8A), with values decreasing over the duration of the experiment (Table 2.7C).

Under all light conditions NDVI695 and NDVI700 were highly correlated to one another (p-value < 0.0001, r = 0.94). For turfgrasses grown under SHL, NDVI695, NDVI700, and RVSI were all highly positively correlated (p-value < 0.0001, r = -0.83).

Red-edge Vegetative Index

Exogenous fructose applications for CF grown under SHL significantly affected red-edge vegetative index (RVSI (R714+R759)/(2-R733)) (Table 2.9A), with the control plants maintaining one point five percent higher RVSI vales than plants that received fructose (Table 2.9B). There were significant differences in RVSI over time for all turfgrass species and light conditions (weeks) (Table 2.9A). Red-edge vegetative index values were found to increase over the duration of the experiment (Table 2.9C). Under AL there was a significant interaction between species and fructose (Table 2.9A). Under SLL and SHL there was a significant interaction between fructose applications and species (Table 2.9A). Under all AL and SLL there was a significant interaction between fructose applications, species, and time (Table 2.9A). Each species responded differently over the duration of the experiment and to exogenous fructose (Appendix I).

KB Experiment

Water Band Index

Water band index (WBI) under both light energy levels significantly differed over time (weeks) (Table 2.10A), with WBI decreasing under AL and increasing under SLL (Table 2.10C). Water band index under AL maintained slightly higher values compared to WBI under SLL (Table 2.10B). Kentucky bluegrass grown under AL was under greater water stress than compared to KB grown under SLL.

Photosynthetic Reflective Index

Exogenous fructose applications for KB grown under AL significantly affected photosynthetic reflective index (PRI) (Table 2.11A). Plants that received fructose once per week (F1) maintained higher PRI values followed by NF and F2, respectively (Table 2.11B). Kentucky bluegrass that received F1 utilized PAR more efficiently than the two other treatments. Under both light energy levels there were significant differences in PRI over time (weeks) (Table 2.11A). Photosynthetic reflective index decreased over the duration of the experiment (Table 2.11C). Kentucky bluegrass grown under SLL maintained one percent greater PRI values compared to KB grown under AL (Table 2.11B).

Narrow-Band Vegetative Index

For KB grown under SLL exogenous fructose had a significant affect on narrow-band vegetative index 695 (NDVI695) (Table 2.12A), with control plants maintaining higher NDVI695 than plants that received fructose applications (Table 2.12B). Under both light energy levels, NDVI695 and 700 were significantly different over time (weeks) (Table 2.12A and 2.13A). Narrow-band vegetative index 695 and 700 decreased over the

duration of the experiment (Table 2.12C and 2.13C). Narrow-band vegetative index 695 values under both light levels were one to two percent higher than NDVI700 values (Table 2.12B and 2.13B). Under both AL and SLL NDVI695 and NDVI700 were positively correlated (p-value < 0.0001, r = 0.97).

Red-Edge Vegetative Index

Red-edge vegetative index (RVSI) was significantly different under both light energy levels over time (weeks) (Table 2.14A). Red-edge vegetative index increased over the duration of the experiment (Table 2.14C). Stress increased under both light levels over time. Red-edge vegetative index values were similar under both AL and SLL levels (Table 2.14B).

Discussion

Exogenous fructose had a significant affect on response variables measured under all light energy levels. For CF and CRF exogenous fructose applications negatively affected the plants when grown under ambient light by increasing water stress as measured by WBI and reducing health measured by NDVI compared to plants that did not receive exogenous fructose. When grown under supplemental high light, CF and CRF control plants utilized PAR more efficiently and were less stressed compared to plants that received exogenous fructose. These results suggest that under the light conditions within this experiment exogenous fructose may not have beneficial effects on the metabolic mechanisms of CF and CRF. In contrast, when KB was grown under ambient light exogenous fructose applications increased clipping weight and increased how efficient KB utilized PAR. However, when KB was grown under SLL fructose applications decreased overall health based on leaf reflectance indices. These results

indicate that exogenous fructose applications may have beneficial effects on growth and metabolism dependent on species and PAR light conditions.

When supplemental light was added under low light energy conditions higher positive responses in plant growth occurred compared to plants grown under ambient light. Thus, in contrast to previous work (Sorochan, 2002) supplementing ambient light under these simulated sports dome conditions with or without exogenous fructose, improved growth for CF, CRF, and KB over long periods of time.

Turfgrasses within this study were able to maintain consistent clipping weight and tiller production values under low supplemental light (daily light integral 3 ± 2 mol m^{-2} d^{-1}). This suggests that carbohydrates in CF, CRF, and KB produced by photosynthesis may have been preferentially allocated to shoots rather than tillers. This is consistent with Sorochan's (2002) data that suggested exogenous fructose applied to Supina bluegrass was allocated within the plant and was used for metabolic processes to support growth. However, clipping weights from CF, CRF, and KB turfgrasses grown under AL decreased early on and did not recover over time, suggesting that carbohydrates were rapidly depleted under this level of PAR and even exogenous fructose could not supplement for the required carbohydrate concentrations for growth (i.e. dry weight accumulation).

Under AL all leaf reflectance values decreased over time. This suggests that the metabolic processes of CF, CRF, and KB became increasingly less efficient as the duration of shaded conditions was extended. Turfgrasses grown under AL non-fructose plants had higher NDVI values than fructose treated plots. In addition, Rd increased as exogenous fructose applications increased for turfgrasses grown under AL. These results

suggests that exogenous fructose treatments under AL may have contributed to the turfgrasses overall stress by reducing health and increasing respiration, possibly contributing to reduced photosynthetic efficiency by altering other metabolic processes (i.e. mitochondrial respiration) resulting in overall reduced growth. Trinexapac-ethyl (TE) treatments on Supina and Kentucky bluegrass in ambient light conditions reduced clipping weights in comparison to plots not treated with TE, indicating increased stress on TE treated plots (Stier, 2001). A treatment intended to reduce one specific stress actually triggers another, but related metabolic stress was observed in Stier's work (2001). In this work under SLL and SHL for CF and CRF and under SLL for KB species leaf reflectance indicated water stress index and overall stress (RVSI) increased while overall plant health (NDVI) and radiation efficiency (PRI) decreased over time, regardless of fructose treatment. Based on light reflectance data, all species were continually metabolically stressed; they were still able to maintain some shoot growth under these conditions. In addition, DLI was positively correlated to overall plant health, which supports the general hypothesis that with higher DLI there is a positive effect on plant health. Collectively, the correlations suggest that when species had better overall health, then overall growth was higher, regardless of fructose treatment.

Conclusion

In summary, exogenous fructose treatments had a positive effect on some response variables for all three turfgrass species. However, light energy (PAR) had a greater positive affect on growth compared to exogenous fructose although turfgrasses responded differently to exogenous fructose treatments. Some species (KB) achieve a better physiological status than other species (CF and CRF) with fructose applications. In

addition, supplemental PAR as low as 3-10 ± 2 mol m^{-2} s^{-1} appears to be sufficient to maintain overall growth and quality of the KB, CF, and CRF species tested in this experiment. This research causes one to speculate how exogenous fructose impacts different metabolic responses within the plant and how the application of exogenous fructose interacts with light.

Table 2.1A Analysis of variance for clipping weight (grams m^{-2}) under ambient light (AL 5-10 µmol m^{-2} s^{-1}), supplemental low light (SLL 32 µmol m^{-2} s^{-1}), and supplemental high light (SHL 73 µmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*) and creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*).

	AL			SLL			SHL		
Source	df	MS	F	df	MS	F	df	MS	F
F	1	1.01	1.79ns	1	0.48	0.38ns	1	0.006	0ns
W	5	46.3	75.6**	5	22.1	17.3**	5	8.69	6.70**
S	1	26.1	42.6**	1	28.7	22.5**	1	0.33	0.26ns
F*W	5	1.80	2.95*	5	1.37	1.08ns	5	1.60	1.23ns
F*S	1	0.005	0.01ns	1	0.77	0.61ns	1	0.23	0.18ns
S*W	5	15.36	25.1**	5	14.8	11.6**	5	3.99	3.08*
F*W*S	5	0.09	0.15ns	5	0.25	0.18ns	5	1.31	1.01ns
Error	72	0.61		72	1.27		72	1.29	

Note: Significance levels for repeated measures are given as probability: ns, $p > 0.05$; *, $p < 0.05$; **, $p < 0.01$.
F, fructose; W, week; S, Species.

Table 2.1B Means specific clipping weight (grams m^{-2}) over time (week) under ambient light (AL 5-10 µmol m^{-2} s^{-1}), supplemental low light (SLL 32 µmol m^{-2} s^{-1}), and supplemental high light (SHL 73 µmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*) and creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*).

	AL		SLL		SHL	
Week	CF	CRF	CF	CRF	CF	CRF
1	2.06a	6.9a	1.71ab	6.32a	1.99b	3.24b
3	0.62b	2.1b	1.62ab	3.52b	3.23ab	3.65ab
5	0.25b	0.10c	0.89b	0.77c	1.83b	1.15b
9	0.23b	0.20c	1.5ab	1.46cb	4.27ab	2.54ab
12	0.34b	0.40bc	1.74a	1.21cb	2.13ab	2.20ab
15	0.19b	0.20c	2.58a	1.71cb	2.22ab	2.36ab

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.

Table 2.1C Means specific clipping weight (grams m^{-2}) by species under ambient light (AL 5-10 µmol m^{-2} s^{-1}), supplemental low light (SLL 32 µmol m^{-2} s^{-1}), and supplemental high light (SHL 73 µmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*) and creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*).

Species	AL	SLL	SHL
CF	0.62b	1.67b	2.16a
CRF	1.66a	2.77a	2.49a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.

Table 2.2A Analysis of variance for clipping weight (grams m^{-2}) under ambient light (AL 5-10 µmol m^{-2} s^{-1}) and supplemental low light (SLL 32 µmol m^{-2} s^{-1}) for Kentucky bluegrass 'Cynthia' (KB *Poa pratensis*).

		AL			SLL	
Source	df	MS	F	df	MS	F
F	2	6.02	3.71*	2	7.80	6.23**
W	3	19.05	11.8**	3	27.4	21.9**
F*W	6	0.50	0.31ns	6	0.30	0.24ns
Error	36	1.62		36	1.25	

Note: Significance levels for repeated measures are given as probability: ns, $p > 0.05$; *, $p < 0.05$; **, $p < 0.01$.
F, fructose; W, week; S, species.

Table 2.2B Means specific for clipping weight (grams m^{-2}) at week four under ambient light (AL 5-10 µmol m^{-2} s^{-1}) and supplemental low light (SLL 32 µmol m^{-2} s^{-1}) for Kentucky bluegrass 'Cynthia' (KB *Poa pratensis*).

	AL	SLL
Trt	KB	KB
F1	2.52a	3.53b
F2	2.46ab	3.87b
NF	1.79b	4.72a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.
F1, fructose 1x/week; NF, no fructose (control).

Table 2.2C Means specific for clipping weight (grams m^{-2}) over time under ambient light (AL 5-10 µmol m^{-2} s^{-1}) and supplemental low light (SLL 32 µmol m^{-2} s^{-1}) for Kentucky bluegrass 'Cynthia' (KB *Poa pratensis*).

Week	AL	SLL
1	4.98a	2.75c
2	3.62b	3.65bc
3	4.81ab	6.30a
4	2.26c	4.04b

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.

Table 2.3A Analysis of variance for density (tillers cm^{-2}) under ambient light (AL 5-10 µmol m^{-2} s^{-1}), supplemental low light (SLL 32 µmol m^{-2} s^{-1}), and supplemental high light (SHL 73 µmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*) and creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*).

	AL			SLL			SHL		
Source	df	MS	F	df	MS	F	df	MS	F
F	1	0.74	0.12ns	1	0.47	0.99ns	1	0.88	0.22ns
W	3	13.4	22.6**	3	5.11	10.5**	3	3.03	7.74**
S	1	0.32	0.54ns	1	0.29	0.61ns	1	0.09	0.22ns
F*W	3	0.02	0.03ns	3	0.21	0.44ns	3	0.12	0.31ns
F*S	1	0.38	0.64ns	1	0.02	0.05ns	1	0.62	1.59ns
S*W	3	0.06	0.11ns	3	0.29	0.61ns	3	0.86	0.22ns
F*W*S	3	1.48	2.49ns	3	1.41	2.92*	3	0.30	0.78ns
Error	48	0.59		48	0.48		48	0.39	

Note: Significance levels for repeated measures are given as probability: ns, $p > 0.05$; *, $p < 0.05$; **, $p < 0.01$.
F, fructose; W, week; S, Species.

Table 2.3B Means specific density (tillers cm^{-2}) over time under ambient light (AL 5-10 µmol m^{-2} s^{-1}), supplemental low light (SLL 32 µmol m^{-2} s^{-1}), and supplemental high light (SHL 73 µmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*) and creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*).

	AL		SLL		SHL	
Week	CF	CRF	CF	CRF	CF	CRF
1	3.16a	3.50a	3.11a	3.10a	2.99ab	3.03a
5	1.63b	1.70b	2.57ab	2.60a	3.26a	3.16a
10	1.68b	1.70b	2.29ab	2.30a	2.66ab	2.39a
15	1.18b	1.30b	1.48b	2.00a	2.45ab	2.27a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.

Table 2.4A Analysis of variance for density (tillers cm^{-2}) under ambient light (AL 5-10 µmol m^{-2} s^{-1}) and supplemental low light (SLL 32 µmol m^{-2} s^{-1}) for Kentucky bluegrass 'Cynthia' (KB *Poa pratensis*).

		AL			SLL	
Source	df	MS	F	df	MS	F
F	2	0.10	1.83ns	2	0.006	0.12ns
W	3	0.002	0.40ns	3	0.59	12.7**
F*W	6	0.02	0.35ns	6	0.04	0.82ns
Error	36	0.06		36	0.46	

Note: Significance levels for repeated measures are given as probability: ns, $p > 0.05$; *, $p < 0.05$; **, $p < 0.01$.
F, fructose; W, week; S, species.

Table 2.4B Means specific density (tillers cm^{-2}) over time under ambient light (AL 5-10 µmol m^{-2} s^{-1}) and supplemental low light (SLL 32 µmol m^{-2} s^{-1}) for Kentucky bluegrass 'Cynthia' (KB *Poa pratensis*).

Week	AL	SLL
1	0.58a	0.59b
2	0.62a	0.54b
3	0.53a	0.51b
4	0.55a	0.99a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.

Table 2.5A Analysis of variance for water band index (R900/R970) under ambient light (AL 5-10 μmol m^{-2} s^{-1}), supplemental low light (SLL 32 μmol m^{-2} s^{-1}), and supplemental high light (SHL 73 μmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*) and creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*).

	AL			SLL			SHL		
Source	df	MS	F	df	MS	F	df	MS	F
F	1	0.04	4.44*	1	0.002	0.57ns	1	0.001	0.45ns
W	4	0.14	15.5**	4	0.03	11.2**	4	0.006	1.81ns
S	1	0.13	1.42ns	1	0.00009	0.03ns	1	0.0003	0.10ns
F*W	1	0.009	0.93ns	1	0.006	2.22ns	1	0.007	2.05ns
F*S	4	0.005	0.51ns	4	0.01	3.40ns	4	0.007	2.18ns
S*W	4	0.009	1.07ns	4	0.002	0.65ns	4	0.001	0.22ns
F*W*S	4	0.009	0.99ns	4	0.003	1.14ns	4	0.001	0.53ns
Error	219	0.009		219	0.003		219	0.003	

Note: Significance levels for repeated measures are given as probability: ns, $p > 0.05$; *, $p < 0.05$; **, $p < 0.01$.
F, fructose; W, week; S, Species.

Table 2.5B Mean specific water band index (R900/R970) at week fifteen under ambient light (AL 5-10 μmol m^{-2} s^{-1}), supplemental low light (SLL 32 μmol m^{-2} s^{-1}), and supplemental high light (SHL 73 μmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*) and creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*).

	AL		SLL		SHL	
Trt	CF	CRF	CF	CRF	CF	CRF
NF	0.93a	0.89a	1.01a	1.02a	0.98a	1.01a
F1	0.94b	0.90a	0.99a	1.01a	0.99a	1.02a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.
NF, no fructose (control); F1, fructose 1x/week.

Table 2.5C Mean specific water band index (R900/R970) over time under ambient light (AL 5-10 μmol m^{-2} s^{-1}) and supplemental low light (SLL 32 μmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*) and creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*).

	AL		SLL	
Week	CF	CRF	CF	CRF
3	1.02ab	1.02a	0.97bc	0.97ab
6	1.03a	1.04a	1.02a	0.99ab
9	1.05a	1.05a	0.96bc	0.96b
12	1.05a	1.00a	0.94c	0.97ab
15	0.93b	0.90b	1.00ab	1.02a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.

Table 2.6A Analysis of variance for photosynthetic reflective index ((R531-R571)/(R531+R570)) under ambient light (AL 5-10 µmol m^{-2} s^{-1}), supplemental low light (SLL 32 µmol m^{-2} s^{-1}), and supplemental high light (SHL 73 µmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*) and creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*).

	AL			SLL			SHL	
Source	df	MS	F	df	MS	F	df	MS	F
F	1	0.04	6.11ns	1	0.00009	0.01ns	1	0.97	4.53*
W	4	0.71	121**	4	0.18	23.2**	4	3.27	153**
S	1	0.0004	6.11*	1	0.00006	0.01ns	1	0.13	4.53*
F*W	1	0.003	0.58ns	1	0.003	0.42ns	1	0.03	1.55ns
F*S	4	0.0002	0.05ns	4	0.002	0.24ns	4	0.07	3.46ns
S*W	4	0.01	2.43*	4	0.008	1.02ns	4	0.04	1.85ns
F*W*S	4	0.01	2.02ns	4	0.006	0.76ns	4	0.09	4.21**
Error	219	0.006		214	0.008		222	0.02	

Note: Significance levels for repeated measures are given as probability: ns, $p > 0.05$; *, $p < 0.05$; **, $p < 0.01$.
F, fructose; W, week; S, Species.

Table 2.6B Mean specific photosynthetic reflective index ((R531-R571)/(R531+R570)) at week fifteen under ambient light (AL 5-10 µmol m^{-2} s^{-1}), supplemental low light (SLL 32 µmol m^{-2} s^{-1}), and supplemental high light (SHL 73 µmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*) and creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*).

	AL		SLL		SHL	
Trt	CF	CRF	CF	CRF	CF	CRF
NF	-0.13a	-0.15a	-0.05a	-0.09a	-0.17a	-0.07a
F1	-0.09a	-0.09a	-0.12a	-0.08a	-0.14a	-0.11b

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.
NF, no fructose (control); F1, fructose 1x/week.

Table 2.6C Mean specific photosynthetic reflective index ((R531-R571)/(R531+R570)) over time under ambient light (AL 5-10 µmol m^{-2} s^{-1}), supplemental low light (SLL 32 µmol m^{-2} s^{-1}), and supplemental high light (SHL 73 µmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*) and creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*).

	AL		SLL		SHL	
Week	CF	CRF	CF	CRF	CF	CRF
3	0.04a	0.04a	-0.04b	-0.04b	0.36a	0.34a
6	0.05a	0.02a	-0.09b	-0.06b	-0.41d	-0.33d
9	0.01a	-0.01a	-0.04b	-0.05b	-0.04bc	0.07b
12	-0.25c	-0.26c	-0.04b	-0.05b	-0.02b	0.01bc
15	-0.12b	-0.12b	0.09a	0.09a	-0.16c	-0.09c

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.

Table 2.7A Analysis of variance for narrow band vegetative index 695 ((R970-R695)/(R970+R695)) under ambient light (AL 5-10 µmol m^{-2} s^{-1}), supplemental low light (SLL 32 µmol m^{-2} s^{-1}), and supplemental high light (SHL 73 µmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*) and creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*).

	AL			SLL			SHL	
Source	df	MS	F	df	MS	F	df	MS	F
F	1	0.05	8.9**	1	0.00003	0ns	1	0.01	1.41ns
W	4	0.28	50.3**	4	0.25	35.9**	4	4.82	585**
S	1	0.007	1.28ns	1	0.001	0.17ns	1	0.04	5.31*
F*W	1	0.009	1.58ns	1	0.004	0.61ns	1	0.003	0.35ns
F*S	4	0.02	4.3*	4	0.002	0.25ns	4	0	0ns
S*W	4	0.007	1.35ns	4	0.004	0.59ns	4	0.03	3.06*
F*W*S	4	0.009	1.67ns	4	0.004	0.56ns	4	0.006	0.75ns
Error	219	0.006		214	0.007		222	0.008	

Note: Significance levels for repeated measures are given as probability: ns, $p > 0.05$; *, $p < 0.05$; **, $p < 0.01$.
F, fructose; W, week; S, Species.

Table 2.7B Mean specific narrow band vegetative index 695 ((R970-R695)/(R970+R695)) at week fifteen under ambient light (AL 5-10 µmol m^{-2} s^{-1}), supplemental low light (SLL 32 µmol m^{-2} s^{-1}), and supplemental high light (SHL 73 µmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*) and creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*).

	AL		SLL		SHL	
Trt	CF	CRF	CF	CRF	CF	CRF
NF	0.51a	0.63b	0.62a	0.64a	0.01a	-0.02a
F1	0.58a	0.57a	0.61a	0.58a	-0.07a	-0.10a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.
NF, no fructose (control); F1, fructose 1x/week.

Table 2.7C Mean specific narrow band vegetative index 695 ((R970-R695)/(R970+R695)) over time under ambient light (AL 5-10 µmol m^{-2} s^{-1}), supplemental low light (SLL 32 µmol m^{-2} s^{-1}), and supplemental high light (SHL 73 µmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*) and creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*).

	AL		SLL		SHL	
Week	CF	CRF	CF	CRF	CF	CRF
3	0.74a	0.75a	0.66ab	0.69ab	0.69a	0.68a
6	0.60b	0.61b	0.69a	0.69a	0.66a	0.61a
9	0.73a	0.71a	0.55d	0.52d	0.69a	0.69a
12	0.70a	0.69a	0.54cd	0.53cd	0.65a	0.62a
15	0.54b	0.59b	0.61bc	0.61bc	0.04b	0.10b

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.

Table 2.8A Analysis of variance for narrow band vegetative index 700 ((R840-R700)/(R840+R700)) under ambient light (AL 5-10 µmol m^{-2} s^{-1}), supplemental low light (SLL 32 µmol m^{-2} s^{-1}), and supplemental high light (SHL 73 µmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*) and creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*).

	AL			SLL			SHL	
Source	df	MS	F	df	MS	F	df	MS	F
F	1	0.05	15.7**	1	0.002	0.56ns	1	0.02	3.83ns
W	4	0.32	94.0**	4	0.16	37.7**	4	5.34	958**
S	1	0.004	1.27ns	1	0.005	1.23ns	1	0.04	7.35**
F*W	1	0.006	1.49ns	1	0.003	0.80ns	1	0.003	0.60ns
F*S	4	0.008	2.41ns	4	0.00001	0ns	4	0.00003	0.06ns
S*W	4	0.003	0.98ns	4	0.0008	0.21ns	4	0.01	2.60*
F*W*S	4	0.007	2.04ns	4	0.005	1.11ns	4	0.002	0.33ns
Error	219	0.003		241	0.004		222	0.005	

Note: Significance levels for repeated measures are given as probability: ns, $p > 0.05$; *, $p < 0.05$; **, $p < 0.01$.
F, fructose; W, week; S, Species.

Table 2.8B Mean specific narrow band vegetative index 700 ((R840-R700)/(R840+R700)) at week fifteen under ambient light (AL 5-10 µmol m^{-2} s^{-1}), supplemental low light (SLL 32 µmol m^{-2} s^{-1}), and supplemental high light (SHL 73 µmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*) and creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*).

	AL		SLL		SHL	
Trt	CF	CRF	CF	CRF	CF	CRF
NF	0.46a	0.54a	0.57a	0.55a	-0.07a	-0.12a
F1	0.50a	0.48b	0.57a	0.59a	-0.13a	-0.19a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.
NF, no fructose (control); F1, fructose 1x/week.

Table 2.8C Mean specific narrow band vegetative index 700 ((R840-R700)/(R840+R700)) over time under ambient light (AL 5-10 µmol m^{-2} s^{-1}), supplemental low light (SLL 32 µmol m^{-2} s^{-1}), and supplemental high light (SHL 73 µmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*) and creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*).

	AL		SLL		SHL	
Week	CF	CRF	CF	CRF	CF	CRF
3	0.69a	0.71a	0.62ab	0.64a	0.68a	0.67a
6	0.57c	0.57c	0.64a	0.64a	0.58b	0.54c
9	0.67ab	0.66ab	0.52cd	0.51c	0.64ab	0.63ab
12	0.62bc	0.62b	0.51d	0.54bc	0.60b	0.58bc
15	0.47d	0.51d	0.57bc	0.57c	0.10c	0.10d

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.

Table 2.9A Analysis of variance for red-edge vegetative index ((R714+R759)/(2-R733)) under ambient light (AL 5-10 µmol m^{-2} s^{-1}), supplemental low light (SLL 32 µmol m^{-2} s^{-1}), and supplemental high light (SHL 73 µmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*) and creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*).

	AL			SLL			SHL	
Source	df	MS	F	df	MS	F	df	MS	F
F	1	0.00008	0.95ns	1	0.0001	1.56ns	1	0.004	4.1*
W	4	0.003	32.1**	4	0.003	37.9**	4	0.10	100**
S	1	0.0001	1.79ns	1	0.000002	0.02ns	1	0.003	2.88ns
F*W	1	0.00006	0.68ns	1	0.004	5.1**	1	0.0003	0.23ns
F*S	4	0.0006	6.39*	4	0.00009	1.16ns	4	0.0008	0.90ns
S*W	4	0.00005	0.62ns	4	0.0003	3.81**	4	0.009	9.71**
F*W*S	4	0.0002	2.74*	4	0.0001	2.47*	4	0.004	0.51ns
Error	219	0.00009		214	0.00008		222	0.0009	

Note: Significance levels for repeated measures are given as probability: ns, $p > 0.05$; *, $p < 0.05$; **, $p < 0.01$.
F, fructose; W, week; S, Species.

Table 2.9B Mean specific red edge vegetative index ((R714+R759)/(2-R733)) at week fifteen under ambient light (AL 5-10 µmol m^{-2} s^{-1}), supplemental low light (SLL 32 µmol m^{-2} s^{-1}), and supplemental high light (SHL 73 µmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*) and creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*).

	AL		SLL		SHL	
Trt	CF	CRF	CF	CRF	CF	CRF
NF	-0.03a	-0.03a	-0.04a	-0.05a	0.02b	0.03b
F1	-0.03a	-0.02a	-0.03a	-0.04a	0.07a	0.09a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.
NF, no fructose (control); F1, fructose 1x/week.

Table 2.9C Mean specific red edge vegetative index ((R714+R759)/(2-R733)) over time under ambient light (AL 5-10 µmol m^{-2} s^{-1}), supplemental low light (SLL 32 µmol m^{-2} s^{-1}), and supplemental high light (SHL 73 µmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*) and creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*).

	AL		SLL		SHL	
Week	CF	CRF	CF	CRF	CF	CRF
3	-0.03a	-0.02a	-0.02a	-0.02a	-0.05b	-0.04b
6	-0.02a	-0.02a	-0.03a	-0.02a	-0.06b	-0.05b
9	-0.04b	-0.04b	-0.02a	-0.02a	-0.03b	-0.03b
12	-0.04b	-0.04b	-0.03a	-0.02a	-0.04b	-0.04b
15	-0.03a	-0.03a	-0.04b	-0.04b	0.05a	0.06a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.

Table 2.10A Analysis of variance for water band index (R900/R970) under ambient light (AL 5-10 µmol m^{-2} s^{-1}) and supplemental low light (SLL 32 µmol m^{-2} s^{-1}) for Kentucky bluegrass 'Cynthia' (*Poa pratensis*).

		AL		SLL	
Source	df	MS	F	MS	F
F	2	0.001	2.76ns	0.003	3.96ns
W	2	0.001	3.51*	0.02	26.2**
F*W	4	0.0007	1.89ns	0.0002	0.30ns
Error	99	0.0004		0.0008	

Note: Significance levels for repeated measures are given as probability: ns, $p > 0.05$; *, $p < 0.05$; **, $p < 0.01$.
F, fructose; W, week.

Table 2.10B Mean specific water band index (R900/R970) at week four under ambient light (AL 5-10 µmol m^{-2} s^{-1}) and supplemental low light (SLL 32 µmol m^{-2} s^{-1}) for Kentucky bluegrass 'Cynthia' (*Poa pratensis*).

Trt	AL	SLL
NF	1.06a	1.05a
F1	1.07a	1.03a
F2	1.07a	1.05a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.
NF, no fructose (control); F1, fructose 1x/week; F2, fructose 2x/week.

Table 2.10C Mean specific water band index (R900/R970) over time under ambient light (AL 5-10 µmol m^{-2} s^{-1}) and supplemental low light (SLL 32 µmol m^{-2} s^{-1}) for Kentucky bluegrass 'Cynthia' (*Poa pratensis*).

Week	AL	SLL
1	1.06a	1.08a
2	1.06a	1.03b
3	1.07a	1.04b

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.

Table 2.11A Analysis of variance for photosynthetic reflective index ((R531-R571)/(R531+R570)) under ambient light (AL 5-10 μmol m^{-2} s^{-1}) and supplemental low light (SLL 32 μmol m^{-2} s^{-1}) for Kentucky bluegrass 'Cynthia' (*Poa pratensis*).

		AL		SLL	
Souce	df	MS	F	MS	F
F	2	0.05	4.99**	0.003	0.42ns
W	2	0.37	40.5**	0.85	128**
F*W	4	0.01	1.50ns	0.004	0.66ns
Error	99	0.009		0.007	

Note: Significance levels for repeated measures are given as probability: ns, $p > 0.05$; *, $p < 0.05$; **, $p < 0.01$.
F, fructose; W, week.

Table 2.11B Mean specific photosynthetic reflective index ((R531-R571)/(R531+R570)) at week four under ambient light (AL 5-10 μmol m^{-2} s^{-1}) and supplemental low light (SLL 32 μmol m^{-2} s^{-1}) for Kentucky bluegrass 'Cynthia' (*Poa pratensis*).

Trt	AL	SLL
NF	-0.08a	-0.01a
F1	-0.19b	-0.006a
F2	-0.10ab	-0.009a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.
NF, no fructose (control); F1, fructose 1x/week; F2, fructose 2x/week.

Table 2.11C Mean specific photosynthetic reflective index ((R531-R571)/(R531+R570)) over time under ambient light (AL 5-10 μmol m^{-2} s^{-1}) and supplemental low light (SLL 32 μmol m^{-2} s^{-1}) for Kentucky bluegrass 'Cynthia' (*Poa pratensis*).

Week	AL	SLL
1	0.04a	-0.3a
2	-0.2b	0.03b
3	-0.1b	0.02b

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.

Table 2.12A Analysis of variance for narrow band vegetative index 695 ((R970-R695)/(R970+R695)) under ambient light (AL 5-10 µmol m^{-2} s^{-1}) and supplemental low light (SLL 32 µmol m^{-2} s^{-1}) for Kentucky bluegrass 'Cynthia' (*Poa pratensis*).

		AL		SLL	
Source	df	MS	F	MS	F
F	2	0.0006	0.45ns	0.007	3.20*
W	2	0.01	8.31**	0.06	33.4**
F*W	4	0.0006	0.45ns	0.001	0.66ns
Error	99	0.001		0.002	

Note: Significance levels for repeated measures are given as probability: ns, $p > 0.05$; *, $p < 0.05$; **, $p < 0.01$.
F, fructose; W, week.

Table 2.12B Mean specific narrow band vegetative index 695 ((R970-R695)/(R970+R695)) at week four under ambient light (AL 5-10 µmol m^{-2} s^{-1}) and supplemental low light (SLL 32 µmol m^{-2} s^{-1}) for Kentucky bluegrass 'Cynthia' (*Poa pratensis*).

Trt	AL	SLL
NF	0.81a	0.81a
F1	0.83a	0.78b
F2	0.81a	0.77b

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.
NF, no fructose (control); F1, fructose 1x/week; F2, fructose 2x/week.

Table 2.12C Mean specific narrow band vegetative index 695 ((R970-R695)/(R970+R695)) over time under ambient light (AL 5-10 µmol m^{-2} s^{-1}) and supplemental low light (SLL 32 µmol m^{-2} s^{-1}) for Kentucky bluegrass 'Cynthia' (*Poa pratensis*).

Week	AL	SLL
1	0.85a	0.87a
2	0.84a	0.80b
3	0.82b	0.79b

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.

Table 2.13A Analysis of variance for narrow band vegetative index 700 ((R840-R700)/(R840+R700)) under ambient light (AL 5-10 µmol m^{-2} s^{-1}) and supplemental low light (SLL 32 µmol m^{-2} s^{-1}) for Kentucky bluegrass 'Cynthia' (*Poa pratensis*).

		AL		SLL	
Source	df	MS	F	MS	F
F	2	0.0006	0.36ns	0.006	2.97ns
W	2	0.01	5.77**	0.08	38.2**
F*W	4	0.001	0.61ns	0.001	0.58ns
Error	99	0.002		0.002	

Note: Significance levels for repeated measures are given as probability: ns, $p > 0.05$; *, $p < 0.05$; **, $p < 0.01$.
F, fructose; W, week.

Table 2.13B Mean specific narrow band vegetative index 700 ((R840-R700)/(R840+R700)) at week four under ambient light (AL 5-10 µmol m^{-2} s^{-1}) and supplemental low light (SLL 32 µmol m^{-2} s^{-1}) for Kentucky bluegrass 'Cynthia' (*Poa pratensis*).

Trt	AL	SLL
NF	0.73a	0.74a
F1	0.77a	0.71a
F2	0.74a	0.71a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.
NF, no fructose (control); F1, fructose 1x/week; F2, fructose 2x/week.

Table 2.13C Mean specific narrow band vegetative index 700 ((R840-R700)/(R840+R700)) over time under ambient light (AL 5-10 µmol m^{-2} s^{-1}) and supplemental low light (SLL 32 µmol m^{-2} s^{-1}) for Kentucky bluegrass 'Cynthia' (*Poa pratensis*).

Week	AL	SLL
1	0.78b	0.80a
2	0.77ab	0.72b
3	0.75a	0.72b

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.

Table 2.14A Analysis of variance for red-edge vegetative index ((R714+R759)/(2-R733)) under ambient light (AL 5-10 µmol m^{-2} s^{-1}) and supplemental low light (SLL 32 µmol m^{-2} s^{-1}) for Kentucky bluegrass 'Cynthia' (*Poa pratensis*).

		AL			SLL	
Source	df	MS	F	df	MS	F
F	2	0	0.03ns	2	0.00005	0.63ns
W	2	0.001	22.9**	2	0.0009	11.6**
F*W	4	0.00003	0.47ns	4	0.00006	0.72ns
Error	99	0.00006		99	0.00008	

Note: Significance levels for repeated measures are given as probability: ns, $p > 0.05$; *, $p < 0.05$; **, $p < 0.01$.
F, fructose; W, week.

Table 2.14B Mean specific red-edge vegetative index ((R714+R759)/(2-R733)) at week four under ambient light (AL 5-10 µmol m^{-2} s^{-1}) and supplemental low light (SLL 32 µmol m^{-2} s^{-1}) for Kentucky bluegrass 'Cynthia' (*Poa pratensis*).

Trt	AL	SLL
NF	-0.03a	-0.03a
F1	-0.03a	-0.03a
F2	-0.03a	-0.03a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.
NF, no fructose (control); F1, fructose 1x/week; F2, fructose 2x/week.

Table 2.14C Mean specific red-edge vegetative index ((R714+R759)/(2-R733)) over time under ambient light (AL 5-10 µmol m^{-2} s^{-1}) and supplemental low light (SLL 32 µmol m^{-2} s^{-1}) for Kentucky bluegrass 'Cynthia' (*Poa pratensis*).

Week	AL	SLL
1	-0.03a	-0.02a
2	-0.04b	-0.03b
3	-0.03a	-0.03b

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.

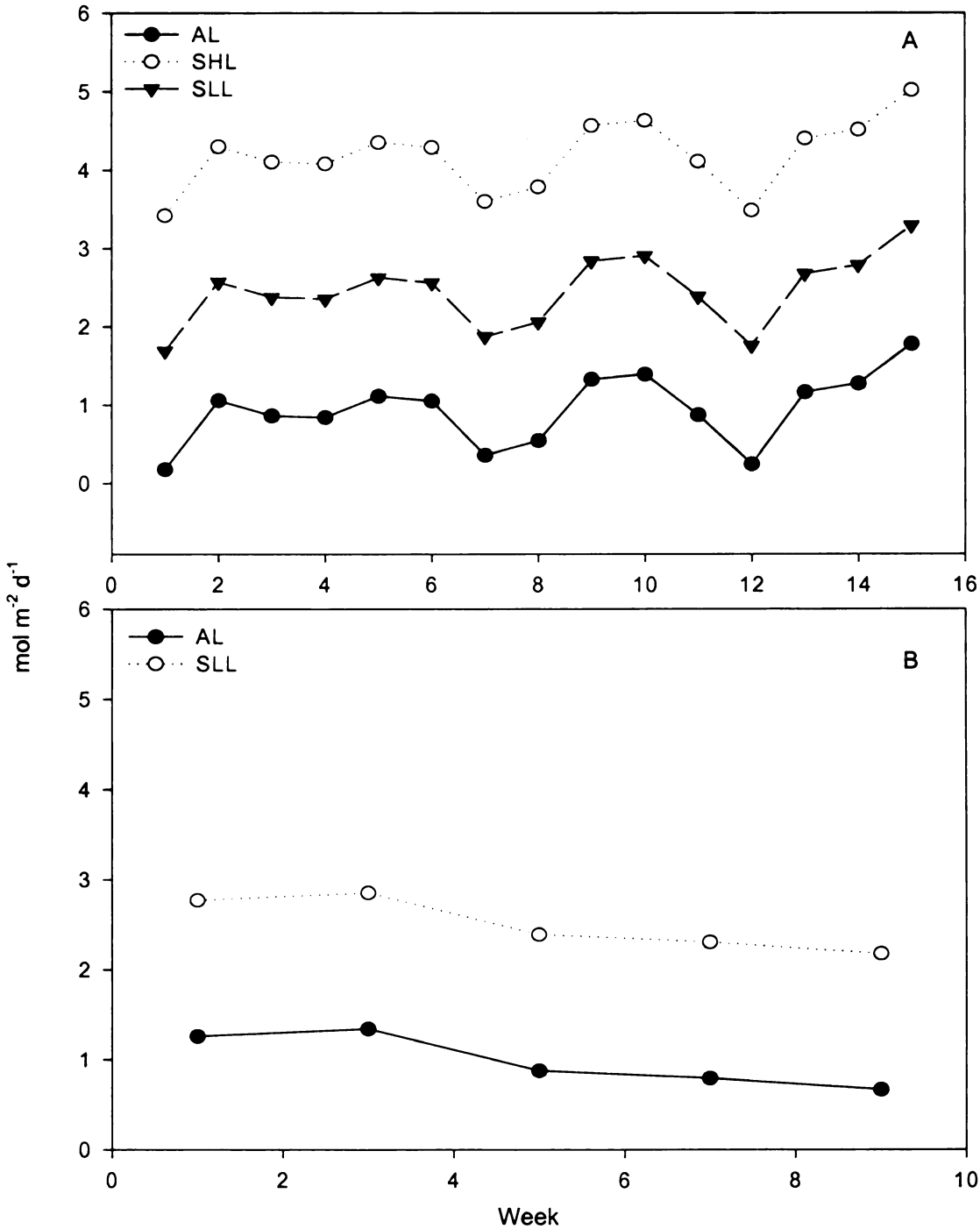

Figure 2.1 A) Year I beginning October 19, 2004 and B) year II beginning October 24, 2005 over time (week) daily light integrals (DLI) mol m^{-2} d^{-1} under ambient light (AL 40-200 µmol m^{-2} s^{-1} ambient photoperiod); supplement high light (SHL ambient light plus 73 µmol m^{-2} s^{-1} 16-h photoperiod using high pressure sodium (HPS) lights); and supplemental low light (SLL ambient light plus 32 µmol m^{-2} s^{-1} 16-h photoperiod using HPS lights).

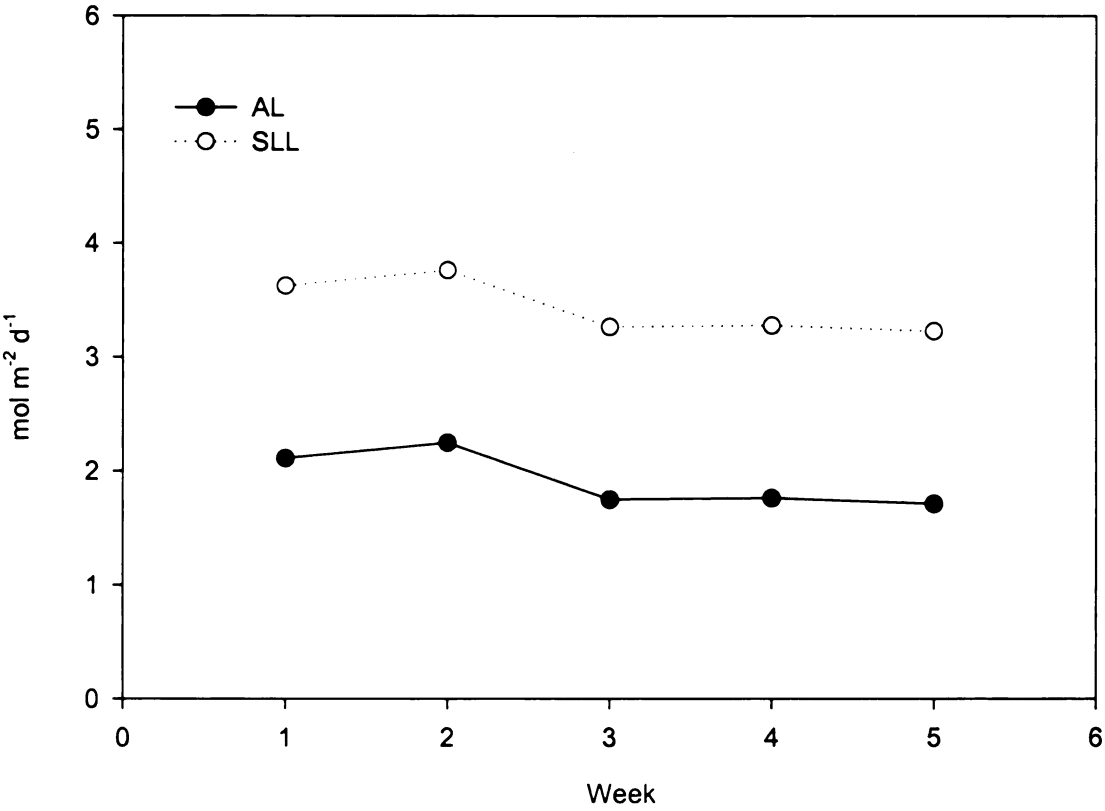

Figure 2.2 Kentucky bluegrass 'Cynthia' (KB) (*Poa pratensis*) daily light integral (DLI) mol m^{-2} d^{-1} ambient light (AL 40-200 µmol m^{-2} s^{-1} ambient photoperiod) and supplemental low light (SLL ambient light plus 32 µmol m^{-2} s^{-1} 16-h photoperiod using high pressure sodium lights) over time (week).

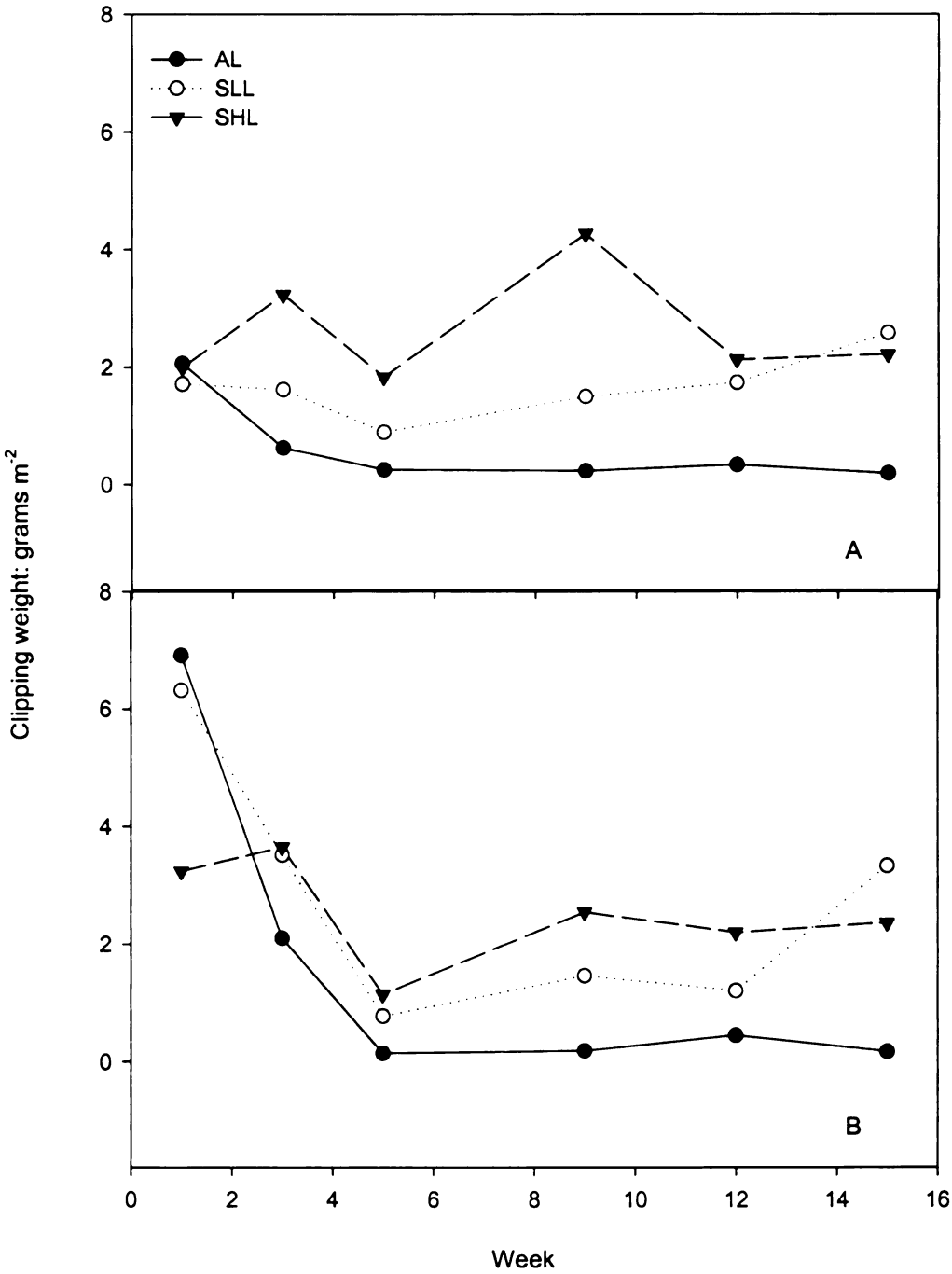

Figure 2.3 A) Chewings fescue 'SR 5100' (*Festuca rubra v. commutata*) and B) creeping red fescue 'Dawson' (*Festuca rubra v. rubra*) clipping weight (grams m^{-2}) under ambient light (AL 40-200 µmol m^{-2} s^{-1} ambient photoperiod), supplemental low light (SLL ambient light plus 32 µmol m^{-2} s^{-1} 16-h photoperiod using high pressure sodium lights), and supplemental high light (SHL ambient light plus 73 µmol m^{-2} s^{-1} 16-h photoperiod using HPS lights) over time (week).

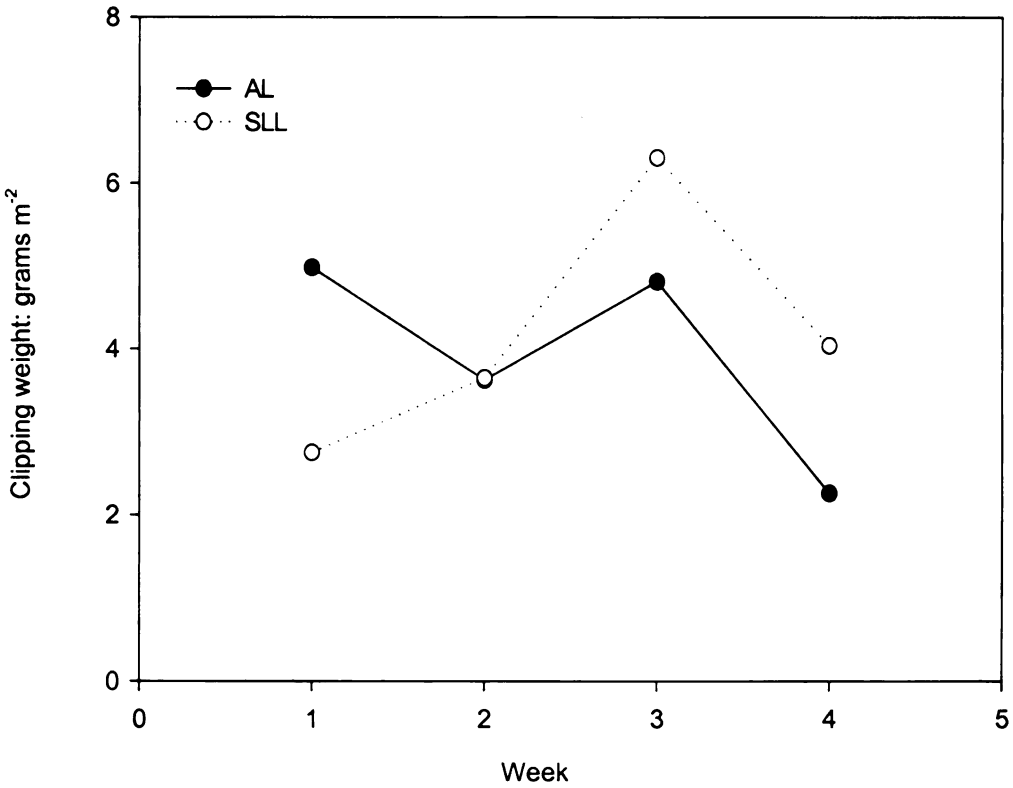

Figure 2.4 Kentucky bluegrass 'Cynthia' (*Poa pratensis*) clipping weight (grams m^{-2}) under ambient light (AL 40-200 µmol m^{-2} s^{-1} ambient photoperiod) and supplemental low light (SLL ambient light plus 32 µmol m^{-2} s^{-1} 16-h photoperiod using high pressure sodium lights) over time (week).

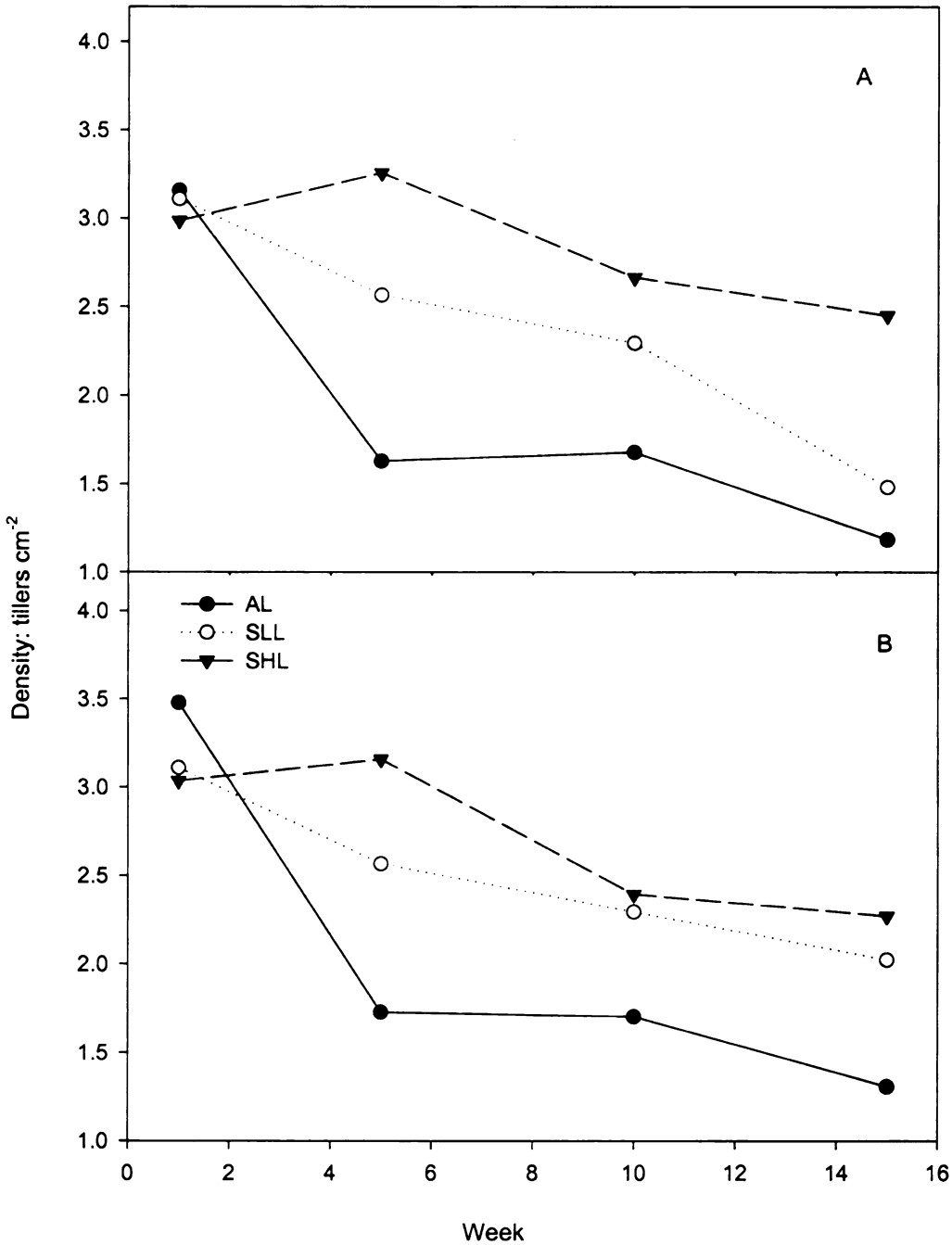

Figure 2.5 A) Chewings fescue 'SR 5100' (*Festuca rubra v. commutata*) and B) creeping red fescue 'Dawson' (*Festuca rubra v. rubra*) density (tillers cm^{-2}) under ambient light (AL 40-200 µmol m^{-2} s^{-1} ambient photoperiod), supplemental low light (SLL ambient light plus 32 µmol m^{-2} s^{-1} 16-h photoperiod using high pressure sodium lights), and supplemental high light (SHL ambient light plus 73 µmol m^{-2} s^{-1} 16-h photoperiod using HPS lights) over time (week).

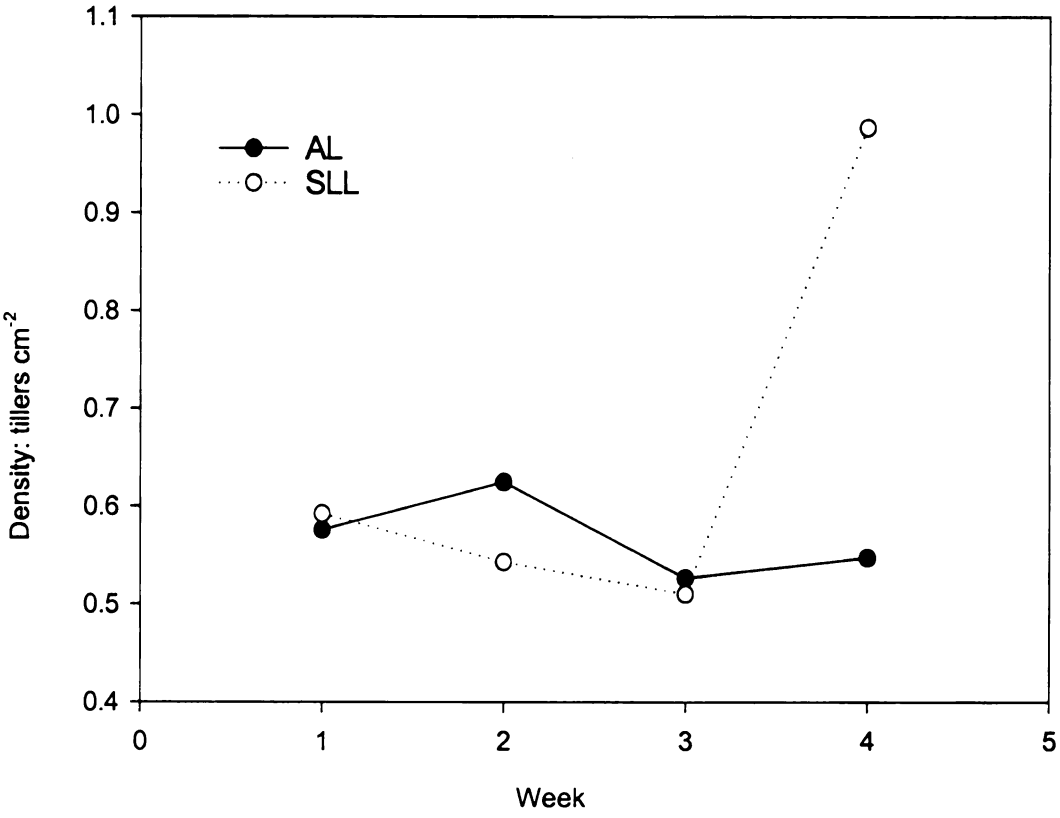

Figure 2.6 Kentucky bluegrass 'Cynthia' (*Poa pratensis*) density (tillers cm^{-2}) under ambient light (AL 40-200 µmol m^{-2} s^{-1} ambient photoperiod) and supplemental low light (SLL ambient light plus 32 µmol m^{-2} s^{-1} 16-h photoperiod using high pressure sodium lights) over time (week).

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Chapter 3

Physiologic and Metabolic Effects on Various Turfgrasses Under Shaded Conditions within a Growth Chamber

Abstract

Maintaining growth and quality of turfgrasses under shaded conditions is challenging. Exogenous fructose applications were tested under low ambient light (14 μmol m^{-2} s^{-1}) and supplemental low light (40 μmol m^{-2} s^{-1}) levels using chewings fescue 'SR 5100' *(Festuca rubra v. commutata)*, creeping red fescue 'Dawson' (*Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (*Poa pratensis*) as model plant systems. Results from this experiment suggest exogenous fructose applications had an effect on density and dark respiration for the three species. Overall growth was positively affected by supplemental low light compared to ambient light regardless of species. In addition, light response curves suggest that exogenous fructose applications decrease photosynthesis over time (week) regardless of light level. These data suggest that exogenous fructose applications under ambient light (14 μmol m^{-2} s^{-1}) could not supplement carbohydrates needed to maintain growth; and thus carbohydrate reserves were being utilized to maintain respiration. Overall, supplemental low light (35 μmol m^{-2} s^{-1}) produced better quality plants than any other treatment, suggesting the light energy level was sufficient to maintain overall growth and photosynthesis. Species under ambient light became increasingly stressed as indicated by metabolic indices, thus suggesting that ambient light cannot sustain physiological and metabolic processes as measured by these indices.

Introduction

Low light conditions impact physiological and metabolic qualities of turfgrasses. Growing under shade decreases plant vigor, increases susceptibility to disease, reduces wear tolerance, and reduces density (McBee, 1966; Dudeck et al., 1972). These changes are associated with reduced light intensity because photosynthesis is reduced resulting in a decrease in available total nonstructural carbohydrates (TNC) (Koh, 2003; Bunnell, 2005). Reduced light intensities (e.g. photosynthetic active radiation (PAR)) result in detrimental growth and development that limit growth of roots, stolons, shoots, and rhizomes (Dudeck et al., 1992; Johnson, 1993; Bell, 2000; Danneberger, 2003; Wilson, 1997; Beard, 1973).

To counteract the effects of low light conditions, applications of exogenous fructose have been examined as a way to supplement low amount of carbohydrates. In turfgrasses, fructans are the primary carbohydrate reserve in cool-season turfgrasses (Sorochan, 2002; Groteluxhen et. al., 1968). Exogenous fructose applications may supplement the loss of carbohydrates, specifically fructans, due to reduced photosynthesis in low light conditions.

Understanding the impact of low light energy level can be difficult in a field-type environment because there are many other factors that may interact with each other. Thus, using controlled environments (e.g. growth chambers) to study reduced light conditions on turfgrasses allows one to isolate the influence of specific environmental factors on growth. For example, when Kentucky bluegrass and Zoysiagrass were grown under three different PAR levels (11.1, 2.2, and 0.9 mol m^{-2} d^{-1}) clipping weights were directly related to daily light integral (DLI); clipping weights decreased as DLI decreased

(Cockerham et al., 2002). The objective of this experiment was to examine the direct interaction of light level, species, and exogenous fructose treatments on chewings fescue 'SR5100' *(Festuca rubra v. commutata)*, creeping red fescue 'Dawson' (*Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (*Poa pratensis*) under controlled light environments.

Materials and Methods

Experimental Site

Experiments were conducted using Econair® (Ecological Chambers Inc., Manitoba, Canada) growth chambers located on Michigan State University (MSU) campus in East Lansing, Mich. The experiment was replicated in time with experiment I initiated on 24 October 2005 and concluding 7 weeks later, experiment II initiated on 5 December 2005 and concluding 7 weeks later. The experiment was a split block design with fixed blocks and repeated measures.

Fifty-four four-inch square plastic pots (volume 1.05L) were filled with an 80:20 soil to sand mix and placed into research greenhouses on 26 September and 14 November for experiment I and II, respectively. The greenhouse was set to 21°C and 45% RH. To provide a constant soil temperature of 13°C the pots were placed onto a germination pad that was thermostatically controlled. The pots were seeded with chewings fescue 'SR5100' (CF), creeping red fescue 'Dawson' (CRF), and Kentucky bluegrass 'Cynthia' (KB) at a rate of 15g/ m^2. At seeding a starter fertilizer was applied at a rate of 3g phosphors (P)/ m^2 and biweekly fertilizing (16N-25P-13K) took place thereafter. CF and CRF species germinated within three weeks and KB germinated within three and half weeks of seeding. During germination the pots were watered two to three times per week

to maintain consistent soil moisture. Each pot within each turfgrass species was randomly assigned to a corresponding treatment. The treatments consisted of no fructose (control- NF), exogenous fructose application one time per week (F1); and exogenous fructose application two times per week (F2). Once the grasses were 75% germinated, or ¾ of the pot was covered with turfgrass, the pots were placed into the growth chamber and treatments were initiated. The pots were randomly placed into their respective light level and allowed to acclimate for one week to their environment, prior to response variable measurements, which began after the acclimation period. The growth chamber was set to a temperature of 10°C, relative humidity of 70%, and a 12-hour photoperiod using four 400W high-pressure sodium (HPS) lights. Inside the growth chamber two structures were built so that shade cloth could be arranged for specific light energy levels. The light energy levels achieved were 14 μmol m^{-2} s^{-1} using 70% shade cloth (Ludvig Svennson, Charlotte, N.C.) folded over twice (ambient light - AL) and 40 μmol m^{-2} s^{-1} using 70% shade cloth folded over once (supplemental low light- SLL), both of which correspond to light energy levels that were obtained under a simulated sports dome environment (Chapter 2). A hand-held light meter (Spectrum Technologies, Model BQM, Plainfield, Ill.) was used to verify consistent light energy levels for each light treatment. There were three replications of each treatment and turfgrass species giving a total of nine pots per grass and 27 pots per light treatment.

Fructose Treatment

Fructose (Isoclear®, Cargill Sweeteners, Naperville, Ill.) treatments began on 24 October and 5 December for experiments I and II, respectively, and were applied once or twice per week depending on treatment specification. Fructose was mixed with an

adjuvant (BreakThru®, Goldschmidt Chemical Corporation, Hopewell, Va.) and double distilled water. The fructose was applied at a rate of 1.25% v/v and the adjuvant was applied at a rate of 0.1% w/v. A hand held 2mL sprayer was used to apply the fructose and adjuvant mixture to the turfgrass canopy of designated pots.

Response Variables

The following data were collected to determine the interaction between DLI, fructose treatment, and/or turfgrass species: clipping yield, density, leaf area, and light response curves. Collection of data began on 25 October and 5 December for experiments I and II, respectively. Clipping yields correspond to cutting each individual pot to a pre-determined height of 7.62cm above the soil line of the container. Although the pots were cut weekly, clippings were collected for analysis on a biweekly basis. The clippings were then dried at 100°C in an oven for three days and weighed for dry content that is expressed as grams/m^2. To measure density tillers per cm^2 were counted on an identical pre-determined section measuring 5x5 cm of the 10.16x10.16 cm pot biweekly.

Light response curves were evaluated using a LICOR 6400 portable photosynthesis system biweekly beginning on 24 October and 5 December for experiments I and II, respectively (LICOR® Biosciences, Lincoln, Nebr.). These measurements are a non-destructive technology to evaluate the affects of fructose on photosynthetic responses to varying light energy levels. The parameters of the LICOR cuvette were: chamber 2x3 cm opaque needles light emitting diode (LED) light source, carbon dioxide (CO_2) maintained at 400 µmol/mol constant concentration, 10°C constant temperature, and flow rate 250 parts per million (ppm). These specific parameters were used because the "needle" chamber measures a small amount of area, which corresponds

to the small area of turfgrass leaves measured. Six turfgrass leaves from each pot were placed within the chamber of the LICOR and subjected to the AutoProgram 'Light Curve' to determine photosynthesis rates at varying light levels. The program parameters for each light level were: 1) photosynthetic active radiation (PAR) 500 250 100 60 45 30 15 0 μmol m^{-2} s^{-1}, 2) minimum wait time 30 seconds, 3) maximum wait time 100 seconds, 4) coefficient of variation (total CV%) 0.05 to maintain mean stability, and 5) match if reference CO_2 0 ppm different from CO_2 sample.

Gas exchange measurements were converted for actual leaf area since the grasses did not cover the entire leaf chamber. Six leaves in the chamber were removed from each plant and stored for calculation of leaf area. Leaf area was calculated by measuring the width of the leaves under a dissecting microscope set at 64x for each leaf and an average was calculated to determine leaf area per plant. The leaf area equation used to determine correction factors is as follows:

100 units at 64x= *A* mm

B units x (*A* mm/100) = *C* mm /10= *D* cm

6 leaves x *D* cm x 3cm (width chamber) = *E* cm^2

A corresponds to millimeter length of samples as measured by the microscope; *B* corresponds to how many units the sample measured from the microscope ruler; *C* corresponds to the sample measurement now in millimeters; *D* corresponds to the sample in centimeters; and *E* corresponds to the total sample area within the chamber. Each individual correction was recorded for used to process LICOR output for each measurement.

Once all measurements were taken using the LICOR AutoProgram, the data was downloaded using the LICOR software and inputted into Microsoft Excel (Microsoft Corp., Redmond, Wash.). The following parameters were calculated using the LICOR 'Light Curve' program: photosynthetic rate (photo), area $2cm^2$ constant, and photosynthetically active radiation (PAR) in (PARi).

Once all leaf measurements were calculated, light response curves were determined using the following equation:

$$A = \frac{\varphi Q + Amax - \sqrt{(\varphi Q + Amax)^2 - 4\varphi Q k Amax}}{2k} - Rd$$

with Photosyn Assistant (Dundee Scientific, Scotland, U.K.). From the 'Light Curve' output from Excel photo, PARi, and light level (Q μmol m^{-2} s^{-1}) were used to determine assimilation (A μmol CO_2 m^{-2} s^{-1}): apparent quantum efficiency (φ μmol CO_2 fixed/mol PPF), maximum assimilation (Amax mmol CO_2 m^{-2} s^{-1}), convexity (*k*), dark respiration (Rd μmol m^{-2} s^{-1}), and light compensation point (LCP μmol CO_2 m^{-2} s^{-1}). Using the variables calculated and the 'Light Curve' output, Photosyn Assistant calculated corresponding light response curves for each turfgrass.

Statistical Analysis

Species and fructose treatments were compared within each light energy level using Proc ANOVA with Tukey's adjustment (SAS, 2000). The light energy level measured was calculated into daily light integral (DLI mol m^{-2} d^{-1}) and used for statistical analysis for light treatment influence. Clipping weights between experiments I and II were significantly different. However, over time experiments I and II showed similar trends, therefore, only results from experiment I will be reported. There were no

significant differences between experiments I and II for all other variables, therefore means were combined. In addition, Pearson's correlation coefficients were prepared to assess the relationship of the response variables (SAS, 2000).

Results

The application of exogenous fructose had a significant affect on CF, CRF, and KB tiller production (density) and dark respiration (Rd) under AL (Tables 3.2A and 3.8A). However, there were no significant differences in clipping weight, leaf area, net photosynthesis (Pn), maximum photosynthetic rates (Amax), and quantum efficiency (Q) for turfgrass species treated with exogenous fructose (Tables 3.1A, 3.3A, 3.4A, 3.5A, 3.6A, 3.7A). There were significant affects on growth and metabolism of CF, CRF, and KB due to available light energy (PAR). There were also significant interactions between species, fructose, and time for each of the parameters measured.

Daily Light Integral

Daily light integral (DLI mol m^{-2} d^{-1}) was not significantly different over time (weeks) regardless of experiment and light level (data not shown). SLL had two point five percent higher DLI values than AL regardless of week (Figure 3.1). Under AL DLI was positively correlated to turfgrass leaf area for CF ($r = 0.76$) and KB ($r = 0.74$) (p-value < 0.0001) and negatively correlated to turfgrass quality for CF (p-value < 0.0001, $r = -0.53$); and under SLL DLI was positively correlated to leaf area for KB (p-value < 0.01, $r = 0.55$).

Clipping Weight

Clipping weights (gm m^{-2}) were significantly different for all species over the duration of the experiment when grown under AL and SLL (Table 3.1A). Clipping

weights for all species decreased over time under both light levels (Table 3.1C and Figure 3.2). Species was significantly different under SLL (Table 3.1A). Kentucky bluegrass maintained greater clipping weights compared to CF and CRF (Table 3.1B). There was a two fold increase in clipping weights as light energy level increased from AL to SLL for all turfgrass species (Table 3.1B). Under AL clipping weight was negatively correlated to leaf area for species CRF (p-value < 0.01, $r = -0.51$).

Density

Tiller production (density) for plants grown under AL responded significantly to the application of exogenous fructose (Table 3.2A). For CF, density was greatest for the control plants (NF), followed by F1 and F2, respectively (Table 3.2B). Density for CRF and KB was greatest for plants that received F1 treatments, followed by F2 and NF treatments, respectively (Table 3.2B).

For plants grown under SLL tiller production was significantly different over the duration of the experiment (Table 3.2A). Densities for all species increased over time (Table 3.2C and Figure 3.3). Under both light levels there was a significant difference between species (Table 3.2A). Kentucky bluegrass maintained two percent higher tiller production then CF and CRF (Table 3.2B). Under both light levels there was a significant interaction between fructose applications and species (Table 3.2A). Available light had a greater impact on density than exogenous fructose applications as illustrated by the one to three fold increase in density as light energy level increased from AL to SLL (Table 3.2B). Under SLL density was positively correlated to turfgrass leaf area for CRF and KB (p-value < 0.0001, $r = 0.53$), suggesting that under SLL as density increased, turfgrass leaf area was positively affected.

Leaf Area

Leaf area (cm^2) for all plants grown under AL and SLL were significantly different over the duration of the experiment (Table 3.3A and 3.3C). Leaf area for both CF and CRF decreased over time under both light energy levels. While KB grown under AL decreased and KB grown under SLL increased over time (Table 3.3C and Figure 3.4). Under both light energy levels there was a significant difference between species (Table 3.3A). Kentucky bluegrass maintained one to two percent greater leaf area than CF and CRF (Table 3.3B). There was an approximate two fold increase in leaf area as light energy level increased from AL to SLL for CRF and KB (Table 3.3B). Under AL, leaf area was negatively correlated to clipping weight CRF (p-value < 0.01, $r = -0.51$).

Light Response Curves

Amax

Maximum assimilation (Amax mmol CO_2 m^{-2} s^{-1}) for plants grown under AL was significantly different over time (weeks) (Table 3.4A and 3.4C). Maximum assimilation decreased for CF and KB and increased for CRF over the duration of the experiment (Table 3.4C). The interaction between exogenous fructose applications and time for plants grown under SLL was significant (Table 3.4A). Maximum assimilation increased over time for plants applied with fructose once per week and the controls, while Amax decreased for plants applied with fructose two times per week (Appendix II). There was a significant interaction between species and time for plants grown under SLL (Table 3.4A). Maximum assimilation increased within the first week and then decreased over the following weeks of the experimentation (Appendix II). Under each light energy level, KB maintained two percent higher Amax compared to CF and CRF (Table 3.4B).

There was a one to four fold increase in Amax as light energy level increased from AL to SLL for all species (Table 3.4B).

Quantum Efficiency

Plants grown under AL had a significant difference in quantum efficiency (Q μmol CO_2 m^{-2} s^{-1}/mol PPF) over time (weeks) (Table 3.5A). The efficiency of quantum utilization decreased over time for all species (Table 3.5C) under the earlier specified levels of PAR. There were slight differences in Q between AL and SLL for all turfgrass species (Table 3.5B).

Light Compensation Point

Light compensation point (LCP μmol m^{-2} s^{-1}) for plants grown under AL was significantly different over time (weeks) (Table 3.6A). Light compensation point increased for all species over the duration of the experiment (Table 3.5C). There was a one to three fold increase in LCP as light energy level increased from AL to SLL for KB and CF (Table 3.6B).

Dark Respiration

Dark respiration (Rd μmol CO_2 m^{-2} s^{-1}) for KB grown under AL responded significantly to applications of exogenous fructose (Table 3.7A). The control (NF) plants maintained greater Rd rates, followed by F1 and F2, respectively (Table 3.7B). Dark respiration rate for plants grown under AL were significantly different over time (weeks) (Table 3.7A and 3.7C). Dark respiration rate decreased within the first two weeks and then increased over the following experimentation (Table 3.7C). There were significant differences between species Rd (Table 3.7A). Kentucky bluegrass maintained two to five percent higher Rd rates when grown under AL, and maintained two percent higher Rd

rates when grown under SLL than CF and CRF (Table 3.7B). There was a five fold increase in Rd as light energy level increased from AL to SLL for all species (Table 3.7B).

Light Response Curves

Under AL all turfgrasses were able to maintain positive assimilation (A μmol CO_2 m^{-2} s^{-1}) rates through week five of the experiment (Figure 3.5). However, each individual turfgrass species varied in A rates week by week. At week three and five there were no significant differences in A between the three turfgrass species (data not shown). At week three CF maintained higher A rates compared to KB and CRF (Figure 3.5A). By week five all three species decreased in A (Figure 3.5B). By week seven, there were significant difference in turfgrass species (p-value < 0.01), with CRF and CF possessing two point five percent higher A rates compared to KB (Figure 3.5C).

Under SLL all turfgrass species were able to maintain positive rates of photosynthesis through the seven weeks of the experiment (Figure 3.6). Over the duration of the experiment there were significant differences between turfgrass species (p-value < 0.01) (data not shown). At week three CF possessed two percent higher A rates compared to both KB and CRF (Figure 3.6A). By week five KB possessed one point five percent higher A rates compared to CRF and three percent higher A rates compared to CF (Figure 3.6B). By week seven CRF and KB possessed three percent higher A rates compared to CF (Figure 3.6C).

Discussion

Exogenous fructose treatments had a positive affect on plant density and dark respiration rate under 14μmol m^{-2} s^{-1} for all three turfgrass species. Dark respiration was

highest for the control plants of all three species, suggesting that exogenous fructose applications assisted the turfgrass species adaptation to extreme low light conditions. This supports the improved metabolic efficiency of the species under simulated dome conditions (Chapter 2).

Turgrass growth increased as available PAR increased; when the turfgrasses were grown under supplemental light of 40 μmol m^{-2} s^{-1} a greater significant positive response occurred. As measured under simulated dome conditions, the minimum critical PAR for turfgrass maintenance and growth appears to be greater than 3-10 μmol m^{-2} s^{-1} and may fall between the light energy level provided in the AL (14 μmol m^{-2} s^{-1}) and SLL (40 μmol m^{-2} s^{-1}) levels.

When the three turfgrasses were grown under AL, KB initially had improved efficient utilization of available PAR compared to CF and CRF. Over time CF and CRF were able to acclimate to the low light conditions within this experiment, while KB did not acclimate as illustrated by the negative assimilation rates obtained by KB by week seven. This supports the research of the turfgrasses under shaded conditions that showed the photosynthetic features of the turfgrass species were associated with differences in shade tolerance (Van Huylenbroeck and Van Bockstaele, 2001). This suggests that the idea that species selection may be the largest factor in determining turfgrass success for shaded conditions.

When turfgrasses were grown under supplemental low light for long periods of time they were able to maintain positive assimilation rates over the duration of the experiment. The results from this work supports similar results from sports simulated dome work (Chapter 2), which showed that growth and metabolism of turfgrasses grown

under the light energy level of SLL were higher than the same variable measured under lower (AL) light energy (Chapter 2). In addition, total non-structural carbohydrates were greatly influenced by turfgrass species under shaded conditions supporting the idea that improved photosynthetic capacity of the individual species greatly affects improved shade tolerance (Bunnell, 2003). This is supported by the fact that under both AL and SLL the individual A rates of the three turfgrass species decreased as the experiment lengthened (Figure 3.5 and 3.6), suggesting that the three turfgrass species adapted to the low light conditions (AL), thus decreasing their individual potential Amax.

In addition, it was observed that the LCP for each individual turfgrass decreased as the experiment lengthened. This result is expected, since an adaptation to low light conditions (i.e. shade) is lower LCP and ultimately lower Amax potential (Beard, 1973). In fact, Kentucky bluegrass 'Merion' and red fescue 'Pennlawn' grown under three different levels of shade had decreased LCP values as shade level increased (Wilkinson et al., 1974). The differences in photosynthetic rates between species may be due to total leaf area of each turfgrass species. Jones (2006) found that net photosynthesis (μmol CO_2 m^{-2} s^{-1}) of various firs (*Abies spp.*) increased with needle thickness and shape, resulting in different photosynthetic measurements among species. In this study, KB had larger leaf area and consistently higher photosynthetic rates than either of the fescue turfgrasses regardless of light treatment.

The results combined suggest that KB grown under shaded conditions initially was able to maintain photosynthesis more efficiently than the other turfgrasses and that carbohydrate reserves were being utilized to maintain growth, regardless of exogenous fructose treatment and light energy level. Collectively, the results suggest that SLL is

more efficient to maintain growth regardless of species and treatment, and that increasing light levels at these low PAR values have a positive effect on the plant.

Conclusion

In summary, exogenous fructose applications positively affected density and dark respiration rate of the turfgrass species under AL, but did not significantly affect any of the other response variables measured under the two light energy levels within this work. Supplemental low light was sufficient to maintain overall growth of the species, although initially KB performed better than CF and CRF, thus species can be a large factor in determining light and exogenous fructose application efficiency.

Light response curve data suggests CF and CRF were able to acclimate to ambient light (14 μmol m^{-2} s^{-1}) conditions compared to KB regardless of exogenous fructose applications. Additionally, the data indicate that under supplemental low light (40 μmol m^{-2} s^{-1}) all three turfgrass species within this experiment were able to maintain overall photosynthesis over the duration of the experiment, thus increasing growth compared to turfgrasses grown under ambient light (14 μmol m^{-2} s^{-1}).

In conclusion, exogenous fructose applications had little positive physiological response regardless of species under ambient light (14 μmol m^{-2} s^{-1}). Species type and light energy level to drive photosynthesis had the most influence on growth and metabolism and suggest that species is a contributing factor in determining overall growth and quality under shaded conditions. This research suggests there may be a light energy level threshold between 14 and 40 μmol m^{-2} s^{-1} that exogenous fructose applications may be most efficient in increasing growth of the three species.

Table 3.1A Analysis of variance for clipping weight (grams m^{-2}) under ambient light (14 µmol m^{-2} s^{-1}) and supplemental low light (40 µmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB *Poa pratensis*).

		AL		SLL	
Source	df	MS	F	MS	F
F	2	7.2	0.84ns	4.56	1.06ns
W	2	143.6	16.8**	23.6	5.51*
S	3	16.6	1.94ns	55.0	12.8**
F*W	6	17.2	2.01ns	1.37	0.32ns
F*S	4	0.73	0.08ns	4.50	1.05ns
S*W	6	7.24	0.84ns	6.90	1.61ns
F*W*S	12	5.02	0.59ns	2.25	0.53ns
Error	180	8.57		4.29	

Note: Significance levels for repeated measures are given as probability: ns, $p > 0.05$; *, $p < 0.05$; **, $p < 0.01$.
F, fructose; W, week; S, species.

Table 3.1B Mean specific clipping weight (grams m^{-2}) at week seven under ambient light (14 µmol m^{-2} s^{-1}) and supplemental low light (40 µmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB *Poa pratensis*).

	AL			SLL		
Trt	CF	CRF	KB	CF	CRF	KB
NF	0.61a	0.41a	0.69a	1.69a	1.84a	3.96a
F1	0.38a	0.54a	0.61a	1.18a	2.46a	4.26a
F2	0.25a	0.35a	0.49a	0.81a	1.78a	3.60a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.
F1, fructose 1x/week; F2, fructose 2x/week; NF, no fructose (control).

Table 3.1C Mean specific clipping weight (grams m^{-2}) over time and by species under ambient light (14 µmol m^{-2} s^{-1}) and supplemental low light (40 µmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB *Poa pratensis*).

Week	AL	SLL	Species	AL	SLL
1	4.04a	3.78a	CF	1.92a	1.93b
3	2.66a	2.85ab	CRF	1.63a	2.94a
5	0.98b	2.39b	KB	2.56a	3.67a
7	0.47b	2.36b			

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.

Table 3.2A Analysis of variance for density (tillers cm^{-2}) under ambient light (14 µmol m^{-2} s^{-1}) and supplemental low light (40 µmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB *Poa pratensis*).

		AL		SLL	
Source	df	MS	F	MS	F
F	2	1.04	6.44*	0.18	1.00ns
W	2	0.30	1.84ns	6.00	33.7*
S	3	9.13	56.4**	19.5	109*
F*W	6	0.22	1.37ns	0.05	0.31ns
F*S	4	0.65	3.99*	0.91	5.13*
S*W	6	0.07	0.42ns	0.26	1.45ns
F*W*S	12	0.15	0.90ns	0.09	0.53ns
Error	180	0.16		0.18	

Note: Significance levels for repeated measures are given as probability: ns, $p > 0.05$; *, $p < 0.05$; **, $p < 0.01$.
F, fructose; W, week; S, species.

Table 3.2B Analysis of variance for density (tillers cm^{-2}) at week seven under ambient light (14 µmol m^{-2} s^{-1}) and supplemental low light (40 µmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB *Poa pratensis*).

	AL			SLL		
Trt	CF	CRF	KB	CF	CRF	KB
NF	0.97a	0.54b	1.62b	1.51a	1.16a	2.04a
F1	0.90ab	0.99a	1.59a	1.26a	1.29a	2.64a
F2	0.65b	0.57a	1.21ab	1.15a	1.31a	2.72a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.
F1, fructose 1x/week; F2, fructose 2x/week; NF, no fructose (control).

Table 3.2C Analysis of variance for density (tillers cm^{-2}) over time and by species under ambient light (14 µmol m^{-2} s^{-1}) and supplemental low light (40 µmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB *Poa pratensis*).

Week	AL	SLL	Species	AL	SLL
1	0.84a	0.86c	CF	0.80b	1.00b
3	0.99a	1.25b	CRF	0.64b	0.95b
5	0.88a	1.31b	KB	1.32a	1.87a
7	1.00a	1.68a			

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.

Table 3.3A Analysis of variance for leaf area (cm^2) under ambient light (14 µmol m^{-2} s^{-1}) and supplemental low light (40 µmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB *Poa pratensis*).

		AL		SLL	
Source	df	MS	F	MS	F
F	2	0.002	0.13ns	0.002	0.17ns
W	2	0.07	6.30*	0.06	5.16*
S	2	0.09	7.72*	0.23	18.3**
F*W	4	0.01	0.90ns	0.01	0.65ns
F*S	4	0.02	1.47ns	0.01	0.87ns
S*W	4	0.01	0.73ns	0.01	0.86ns
F*W*S	8	0.01	0.70ns	0.01	0.95ns
Error	135	0.01		0.01	

Note: Significance levels for repeated measures are given as probability: ns, $p > 0.05$; *, $p < 0.05$; **, $p < 0.01$.
F, fructose; W, week; S, species.

Table 3.3B Mean specific leaf area (cm^2) at week seven under ambient light (14 µmol m^{-2} s^{-1}) and supplemental low light (40 µmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB *Poa pratensis*).

	AL			SLL		
Trt	CF	CRF	KB	CF	CRF	KB
NF	0.40a	0.34a	0.47a	0.43a	0.41a	0.53a
F1	0.45a	0.40a	0.43a	0.39a	0.39a	0.48a
F2	0.40a	0.33a	0.50a	0.39a	0.37a	0.63a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.
F1, fructose 1x/week; F2, fructose 2x/week; NF, no fructose (control).

Table 3.3C Mean specific leaf area (cm^2) over time and by species under ambient light (14 µmol m^{-2} s^{-1}) and supplemental low light (40 µmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB *Poa pratensis*).

Week	AL	SLL	Species	AL	SLL
3	0.47a	0.50a	CF	0.42b	0.43b
5	0.39b	0.44b	CRF	0.38b	0.41b
7	0.41b	0.44b	KB	0.47a	0.53a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.

Table 3.4A Analysis of variance maximum assimilation (mmol CO_2 m^{-2} s^{-1}) under ambient light (14 µmol m^{-2} s^{-1}) and supplemental low light (40 µmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB *Poa pratensis*).

		AL		SLL	
Source	df	MS	F	MS	F
F	2	0.63	1.76ns	1.44	1.77ns
W	2	2.73	7.67*	1.79	2.20ns
S	2	0.05	0.01ns	0.68	0.84ns
F*W	4	0.38	1.06ns	3.03	3.72*
F*S	4	0.25	0.69ns	0.59	0.72ns
S*W	4	0.34	0.97ns	2.9	3.60*
F*W*S	8	0.43	1.22ns	0.34	0.42ns
Error	135	0.36		0.81	

Note: Significance levels for repeated measures are given as probability: ns, $p > 0.05$; *, $p < 0.05$; **, $p < 0.01$.
F, fructose; W, week; S, species.

Table 3.4B Mean specific maximum assimilation (mmol CO_2 m^{-2} s^{-1}) at week seven under ambient light (14 µmol m^{-2} s^{-1}) and supplemental low light (40 µmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB *Poa pratensis*).

	AL			SLL		
Trt	CF	CRF	KB	CF	CRF	KB
NF	0.71a	0.48a	0.52a	0.68a	0.88a	1.23a
F1	0.46a	1.45a	0.41a	0.56a	1.61a	1.51a
F2	0.47a	0.24a	0.28a	0.73a	0.91a	1.08a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.
F1, fructose 1x/week; F2, fructose 2x/week; NF, no fructose (control).

Table 3.4C Mean specific maximum assimilation (mmol CO_2 m^{-2} s^{-1}) over time under ambient light (14 µmol m^{-2} s^{-1}) chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB *Poa pratensis*).

Week	AL
3	0.71a
5	0.26b
7	0.55ab

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.

Table 3.5A Analysis of variance quantum efficiency (μmol CO_2 m^{-2} s^{-1}/mol PPF) under ambient light (14 μmol m^{-2} s^{-1}) and supplemental low light (40 μmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB *Poa pratensis*).

		AL		SLL	
Source	df	MS	F	MS	F
F	2	0.004	0.08ns	5429	1.00ns
W	2	0.51	10.9**	5388	1.00ns
S	2	0.011	0.24ns	5422	1.00ns
F*W	4	0.003	0.07ns	5396	1.00ns
F*S	4	0.01	0.27ns	5422	1.00ns
S*W	4	0.01	0.21ns	5403	1.00ns
F*W*S	8	0.01	0.30ns	5399	1.00ns
Error	135	0.47		5407.	

Note: Significance levels for repeated measures are given as probability: ns, $p > 0.05$; *, $p < 0.05$; **, $p < 0.01$.
F, fructose; W, week; S, species.

Table 3.5B Mean specific quantum efficiency (μmol CO_2 m^{-2} s^{-1}/mol PPF) at week seven under ambient light (14 μmol m^{-2} s^{-1}) and supplemental low light (40 μmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB *Poa pratensis*).

	AL			SLL		
Trt	CF	CRF	KB	CF	CRF	KB
NF	0.06a	0.001a	0.0004a	0.007a	0.14a	0.02a
F1	0.001a	0.01a	0.001a	0.15a	0.01a	0.28a
F2	0.001a	0.0001a	0.001a	0.01a	0.01a	0.01a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.
F1, fructose 1x/week; F2, fructose 2x/week; NF, no fructose (control).

Table 3.5C Mean specific quantum efficiency (μmol CO_2 m^{-2} s^{-1}/mol PPF) over time under ambient light (14 μmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (*Festuca rubra v. commutata*), creeping red fescue 'Dawson' (*Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (*Poa pratensis*).

Week	AL
3	0.01b
5	0.17a
7	0.01b

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.

Table 3.6A Analysis of variance light compensation point (μmol m^{-2} s^{-1}) under ambient light (14 μmol m^{-2} s^{-1}) and supplemental low light (40 μmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB *Poa pratensis*).

		AL		SLL	
Source	df	MS	F	MS	F
F	2	1402	0.72ns	1643	1.92ns
W	2	10074	5.19*	79.9	0.09ns
S	2	307	0.16ns	55.2	0.06ns
F*W	4	1693	0.87ns	565	0.66ns
F*S	4	1484	0.76ns	694	0.81ns
S*W	4	743	0.38ns	416	0.49ns
F*W*S	8	594	0.31ns	265	0.31ns
Error	85	1942		855	

Note: Significance levels for repeated measures are given as probability: ns, $p > 0.05$; *, $p < 0.05$; **, $p < 0.01$.
F, fructose; W, week; S, species.

Table 3.6B Mean specific light compensation point (μmol m^{-2} s^{-1}) at week seven under ambient light (14 μmol m^{-2} s^{-1}) and supplemental low light (40 μmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB *Poa pratensis*).

	AL			SLL		
Trt	CF	CRF	KB	CF	CRF	KB
NF	45.6a	24.5a	28.3a	25.2a	22.3a	16.8a
F1	71.8a	71.6a	69.8a	11.0a	33.1a	39.4a
F2	32.3a	65.4a	39.5a	35.3a	31.8a	24.3a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.
F1, fructose 1x/week; F2, fructose 2x/week; NF, no fructose (control).

Table 3.6C Mean specific light compensation point (μmol m^{-2} s^{-1}) over time under ambient light (14 μmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (*Festuca rubra v. commutata*), creeping red fescue 'Dawson' (*Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (*Poa pratensis*).

Week	AL
3	23.4b
5	21.8b
7	52.8a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.

Table 3.7A Analysis of variance for dark respiration (μmol CO_2 m^{-2} s^{-1}) under ambient light (14 μmol m^{-2} s^{-1}) and supplemental low light (40 μmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB *Poa pratensis*).

		AL		SLL	
Source	df	MS	F	MS	F
F	2	0.27	4.05*	0.17	1.10ns
W	2	1.25	18.7**	0.06	0ns
S	2	0.22	3.26*	0.06	0.38ns
F*W	4	0.11	1.64ns	0.0001	0.29ns
F*S	4	0.05	0.79ns	0.26	1.69ns
S*W	4	0.04	0.61ns	0.05	0.30ns
F*W*S	8	0.03	0.46ns	0.10	0.64ns
Error	135	0.67		0.16	

Note: Significance levels for repeated measures are given as probability: ns, $p > 0.05$; *, $p < 0.05$; **, $p < 0.01$.
F, fructose; W, week; S, species.

Table 3.7B Mean specific dark respiration (μmol CO_2 m^{-2} s^{-1}) at week seven under ambient light (14 μmol m^{-2} s^{-1}) and supplemental low light (40 μmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB *Poa pratensis*).

	AL			SLL		
Trt	CF	CRF	KB	CF	CRF	KB
NF	-0.47a	-0.18a	-0.65b	-0.15a	-0.21a	-0.48a
F1	-0.21a	-0.24a	-0.31ab	-0.12a	-0.58a	-0.19a
F2	-0.18a	-0.04a	-0.13a	-0.57a	-0.22a	-0.20a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.
F1, fructose 1x/week; F2, fructose 2x/week; NF, no fructose (control).

Table 3.7C Mean specific dark respiration (μmol CO_2 m^{-2} s^{-1}) over time and by species under ambient light (14 μmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (*Festuca rubra v. commutata*), creeping red fescue 'Dawson' (*Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (*Poa pratensis*).

Week	AL	Species	AL
3	-0.27 b	CF	-0.21 b
5	-0.01 a	CRF	-0.11 a
7	-0.27 b	KB	-0.23 b

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.

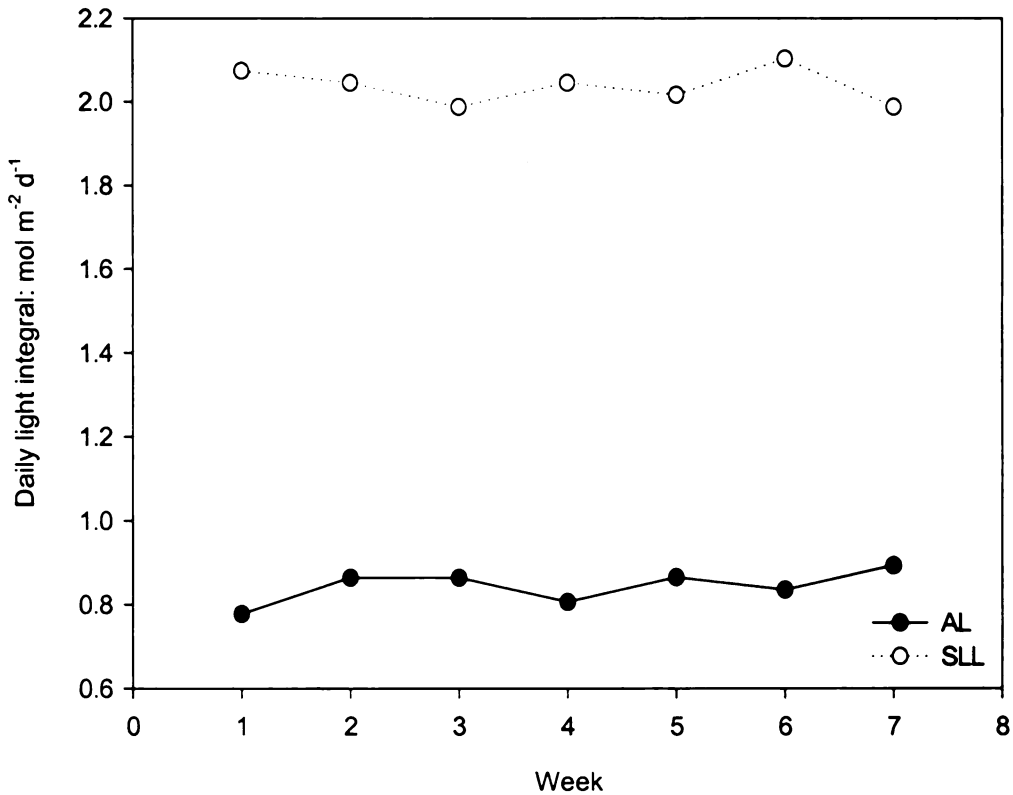

Figure 3.1 Daily light integral (DLI mol m^{-2} d^{-1}) combined experiment means of ambient light (AL- 14 µmol m^{-2} s^{-1}) and supplemental low light (SLL- 40 µmol m^{-2} s^{-1}) with 12 hour photoperiod using high pressure sodium lights in Econair® growth chamber.

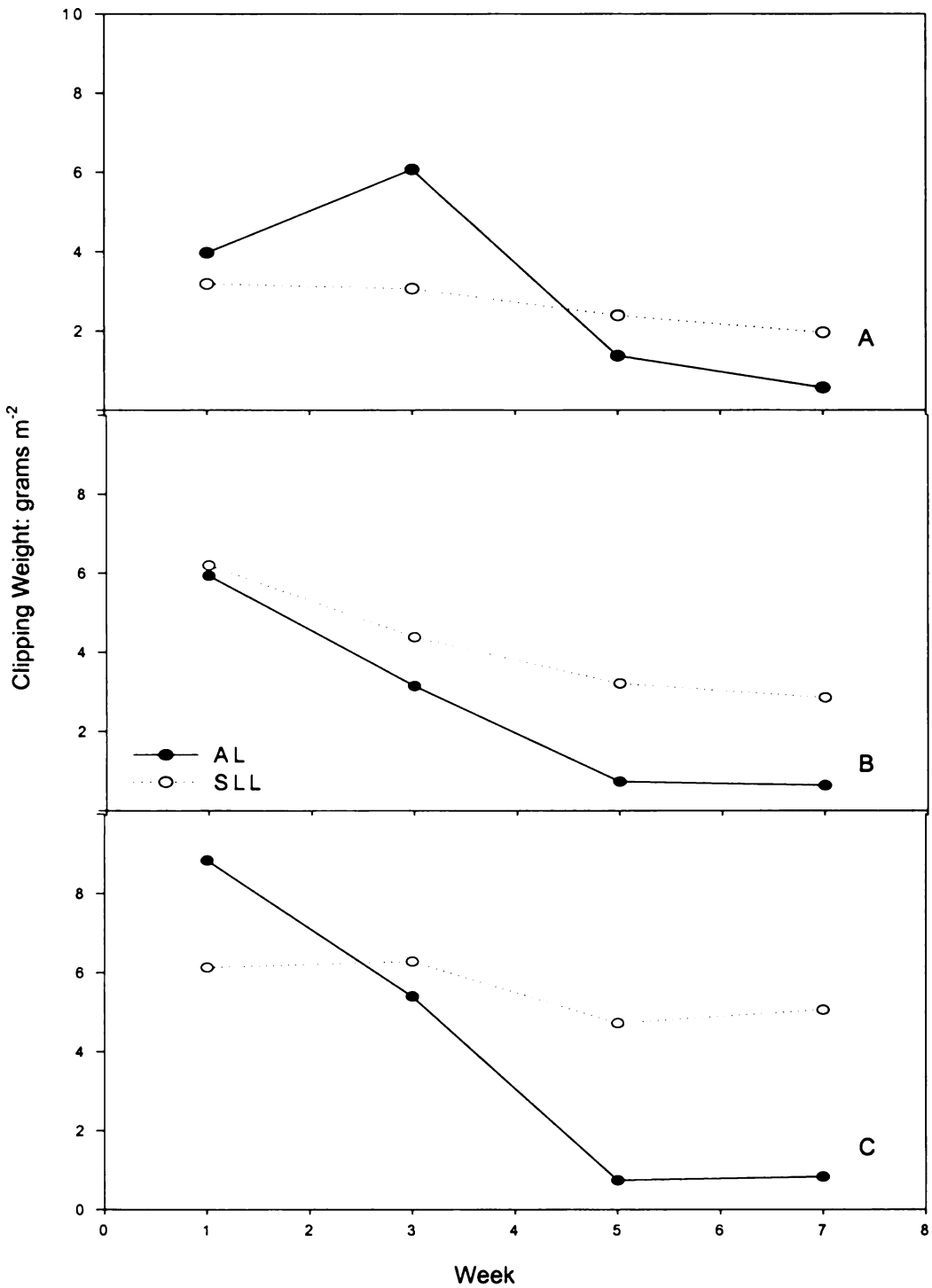

Figure 3.2 Clipping weights (grams/m^2) experiment I combined fructose and control treatment under ambient light (AL- 14 µmol m^{-2} s^{-1}) and supplemental low light (SLL- 40 µmol m^{-2} s^{-1}) for A) chewings fescue 'SR 5100' (CF) (*Festuca rubra v. commutata*), B) creeping red fescue 'Dawson' (CRF) (*Festuca rubra v. rubra*), and C) Kentucky bluegrass 'Cynthia' (KB) (*Poa pratensis*).

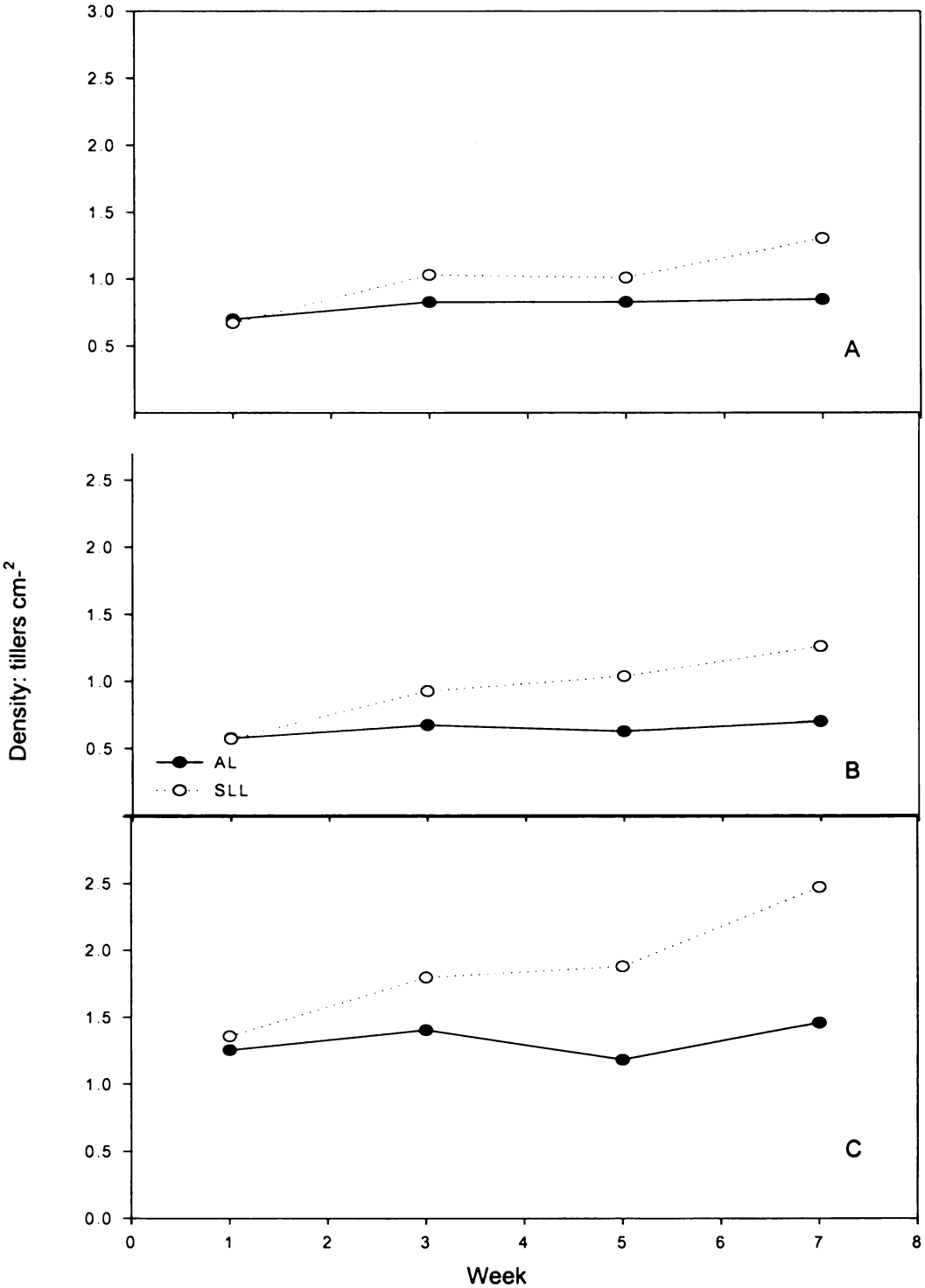

Figure 3.3 Density (tillers/cm^2) combined fructose and control treatment and experiment under ambient light (AL- 14 µmol m^{-2} s^{-1}) and supplemental low light (SLL- 40 µmol m^{-2} s^{-1}) for A) chewings fescue 'SR 5100' (CF) (*Festuca rubra v. commutata*), B) creeping red fescue 'Dawson' (CRF) (*Festuca rubra v. rubra*), and C) Kentucky bluegrass 'Cynthia' (KB) (*Poa pratensis*).

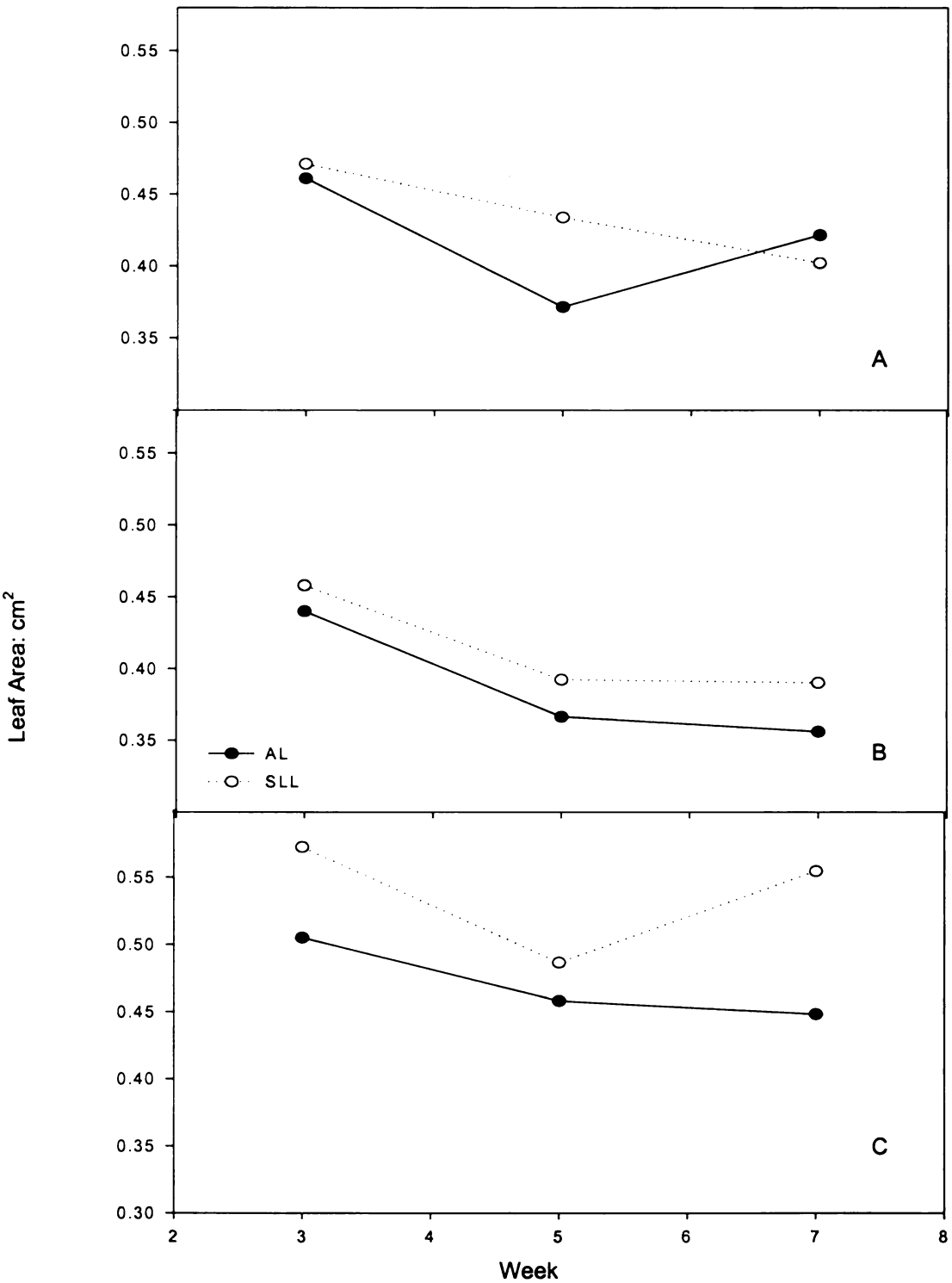

Figure 3.4 Leaf area (cm^2) Combined fructose and control treatments and experiment under ambient light (AL- 14 µmol m^{-2} s^{-1}) and supplemental low light (SLL- 40 µmol m^{-2} s^{-1}) for A) chewings fescue 'SR 5100' (CF) (*Festuca rubra v. commutata*), B) creeping red fescue 'Dawson' (CRF) (*Festuca rubra v. rubra*), and C) Kentucky bluegrass 'Cynthia' (KB) (*Poa pratensis*).

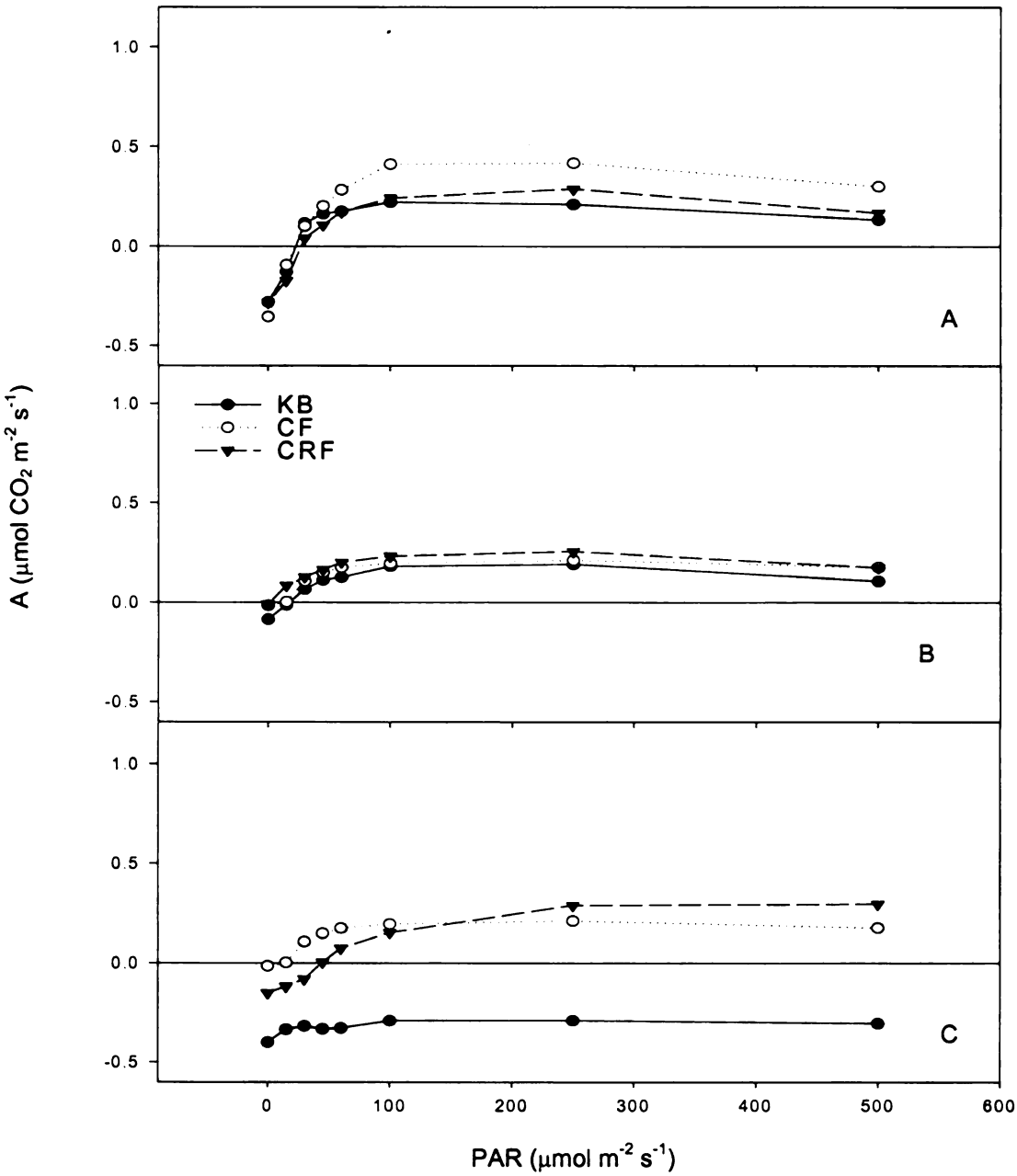

Figure 3.5 Combined experiment and fructose and control treatments assimilation (A µmol CO_2 m^{-2} s^{-1}) rates under ambient light (AL- 14 µmol m^{-2} s^{-1}) at A) week three, B) week five, and C) week seven for chewings fescue 'SR 5100' (CF) (*Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF) (*Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB) (*Poa pratensis*) over photosynthetic active radiation (PAR µmol m^{-2} s^{-1}).

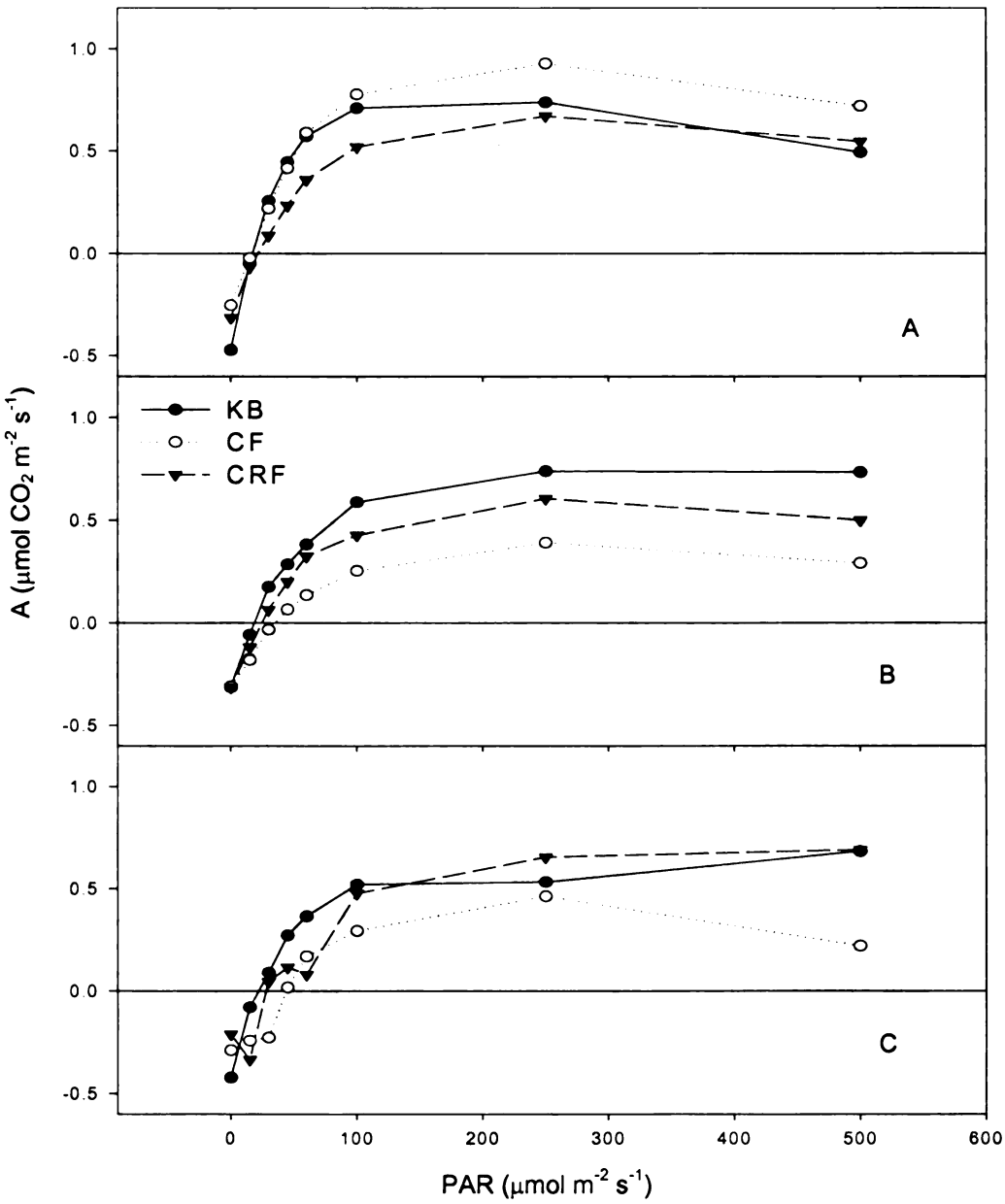

Figure 3.6 Combined experiment and fructose and control treatment photosynthesis (A µmol CO_2 m^{-2} s^{-1}) rates under supplemental low light (SLL- 40 µmol m^{-2} s^{-1}) at A) week three, B) week five, and C) week seven for chewings fescue 'SR 5100' (CF) (*Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF) (*Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB) (*Poa pratensis*) over photosynthetic active radiation (PAR µmol m^{-2} s^{-1}).

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Chapter 4

Physiologic and Metabolic Effects Due to Three Daily Light Integrals and Supplemental Fructose on Various Turfgrasses Under Shaded Conditions

Abstract

It is difficult to maintain overall quality and growth of turfgrasses under shaded conditions. Exogenous fructose applications were tested under low ambient light and supplemental low light levels using chewings fescue *(Festuca rubra v. commutata)* 'SR5100', creeping red fescue (*Festuca rubra v. rubra*) 'Dawson', and Kentucky bluegrass (*Poa pratenesis*) 'Dawson' as model plant systems. Results from this experiment suggest that exogenous fructose did not have significant impact on clipping weight for any of the three genera, although, fructose treatments significantly interacted with species clipping weight under 8 mol m^{-2} d^{-1} for KB and CF with clipping weight decreasing for CF as fructose was applied and increasing for KB as fructose was applied. Fructose treatments did have a significant affect on density on KB under 8 and 4 mol m^{-2} d^{-1} and for CRF under 4 mol m^{-2} d^{-1}, increasing tillers cm^{-2}. Species grown under daily light integral's (DLI) of 8 and 10 mol m^{-2} d^{-1} light levels were able to maintain and increase overall growth and photosynthesis over time for all species. In contrast, data suggest that exogenous fructose applications under a DLI of 4 mol m^{-2} d^{-1} could not supplement carbohydrates needed to sustain essential metabolic functions and that carbohydrate reserves were being utilized to maintain respiration. Collectively, the results suggest there is a threshold light level between 4 and 8 mol m^{-2} d^{-1} light energy required to maintain growth and photosynthesis for the species and genera included in this work.

Introduction

The amount of light energy a plant receives during the course of a day has a major impact on its growth and quality. One way of measuring the total amount of light energy a plant receives during the photoperiod is based upon daily light integral (DLI), which accounts for the total moles of light energy per day per squared meter (mol m^{-2} d^{-1}) (Faust, 2004). In greenhouse studies, the recommended DLI to support growth and development is 10 moles per day on various types of floriculture plants (Faust, 2004). Plants grown in less than 10 moles per day may have enough light to support adequate growth for a limited time, but extended periods under low light eventually will have negative physiology impacts on the metabolism of the plant that translates into reduced growth and resistance to stress. This is because low light conditions not only decrease plant vigor, but also increase susceptibility to disease, reduces wear tolerance, and reduces density (McBee, 1966; Dudeck et al., 1972). With reduced light intensity the rate of photosynthesis is lowered resulting in a decrease in available carbohydrates, carbohydrate reserves, and total nonstructural carbohydrates (TNC) (Koh, 2003; Bunnell et al., 2005a).

Maintaining growth and quality of turfgrasses under low light conditions (<10 mol m^{-2} d^{-1}) remains a challenge. Growth of turfgrasses is dependent upon carbohydrates that are produced via the light-dependent reactions of photosynthesis. Bunnell et al. (2005b) found that as DLI decreased for three Bermudagrass cultivars and 'Meyer' Zoysiagrass there was a corresponding decrease in total non-structural carbohydrates (TNC) in both roots and shoots. This relationship is important to consider when determining how turfgrass growth can be enhanced under low light conditions.

Application of exogenous fructose has been examined as a way to supplement the low amounts of carbohydrates due to low light conditions. Sorochan (2002) found that on Supina bluegrass, applications of exogenous fructose one time per week had positive physiological impacts, i.e. increased growth (clipping weight-grams/m^2) and quality, under low light conditions (400 ± 40 μmol m^{-2} s^{-1}), and that the carbon from the exogenous fructose was partitioned to different locations within the turfgrass. However, further studies using chewings fescue 'SR5100', creeping red fescue 'Dawson', and Kentucky bluegrass 'Cynthia' suggest exogenous fructose applications did not improve growth and quality under low light conditions, but had some beneficial effects under supplemental low light conditions (Chapter 2 and 3). Thus, the hypothesis that there is a threshold light energy level in which exogenous fructose applications would benefit turfgrasses needs to be tested. The objective of this work was to measure the effects of three low light energy daily light integrals (DLI- mol m^{-2} d^{-1}) levels that can occur under ambient shaded environments in combination with exogenous fructose applications to determine physiologic and metabolic impacts for chewings fescue 'SR5100' *(Festuca rubra v. commutata)* and creeping red fescue 'Dawson' (*Festuca rubra v. rubra*) which are two shade tolerant turfgrass species, as well as Kentucky bluegrass 'Cynthia' (*Poa pratensis*) that is commonly grown in North Central United States.

Materials and Methods

Experimental Site

The investigation took place within Michigan State University (MSU) research greenhouses located in East Lansing, Mich. The experiment was replicated in time with experiment one (I) initiated 27 October 2005 and concluding 7 weeks later, and

experiment two (II) initiated 12 December 2005 and concluding 7 weeks later. Supplemental lights were used to ensure identical light energy and photoperiod duration for both experiments. The experiment was a split block design with fixed blocks (light energy level) and repeated measures.

Eighty-one four-inch square pots (volume 1.05L) were filled with an 80:20 sand to soil mix and placed into the research greenhouses on 26 September and 14 November for experiments I and II, respectively. The greenhouse was set to at 21°C and 45% RH. To obtain a constant soil temperature of 13°C the pots were placed onto a germination pad that was thermostatically controlled. The pots were seeded with chewings fescue 'SR5100' (CF), creeping red fescue 'Dawson' (CRF), and Kentucky bluegrass 'Cynthia' (KB) at a rate of 15g/ m^2. At seeding a starter fertilizer (16N-25P-13K) was applied at a rate of 2.5g/ m^2 and biweekly fertilizing took place thereafter. CF and CRF species germinated within three weeks and KB germinated within three and half weeks of seeding. During germination the pots were watered two to three times per week to ensure media retained uniform moisture. Each pot within the specific turfgrass species was randomly assigned to a corresponding treatment. The treatments consisted of no fructose (control- NF), exogenous fructose application one time per week (F1); and exogenous fructose application two times per week (F2); and then randomly assigned to one of three benches. The three benches were set to obtain the following daily light integrals (DLI mol m^{-2} d^{-1}): 10 mol m^{-2} d^{-1} using high pressure sodium (HPS) lights with a 16-h photoperiod; 8 mol m^{-2} d^{-1} using incandescent lights with a 16-h photoperiod; and 4 mol m^{-2} d^{-1} using HPS lights and 50% shade cloth (Ludvig Svennson, Charlotte, N.C.) with a 16-h photoperiod. Once the grasses were 75% germinated, or ¾ of the pot contained

turfgrass, the pots were placed under the DLI treatments that have been described previously to initiate the experiment. Greenhouse indices were maintained by an environmental computer (Priva CD 750 Computer System, Vineland Station, Ontario), that controlled roof vents, exhaust fans, evaporative cooling pads, and heating as needed, to maintained temperature at 20 ± 5°C during both experiments. Light intensity was maintained by quantum sensors (Apogee Instruments, Logan, Utah) that were located at plant height on each bench. Hourly averages were recorded by a CR-10 datalogger (Campbell Scientific, Logan, Utah). The three light energy levels of 10, 8, and 4 mol m^{-2} d^{-1} were used to determine a threshold light energy level that could benefit from exogenous fructose treatments. The pots were assigned a light energy level and randomly placed onto each bench and allowed to acclimate to their assigned light energy level for one week, in which response variable measurements began after the acclimation period. Each bench contained three replications of each fructose treatment for each grass species giving a total of nine pots per grass and 27 pots per bench.

Fructose Treatment

Fructose (Isoclear®, Cargill Sweeteners, Naperville, Ill.) treatments began on 27 October and 9 December for experiments I and II, respectively, and were applied once or twice per week depending on treatment specification. Fructose was mixed with an adjuvant (BreakThru®, Goldschmidt Chemical Corporation, Hopewell, Va.) and double distilled water. The fructose was applied at a rate of 1.25% v/v and the adjuvant was applied at a rate of 0.1% w/v. A hand held 2 L sprayer was used to apply the fructose and adjuvant mixture to the corresponding pots.

Response Variables

Data were collected to determine the interaction between DLI, fructose treatment, and/or turfgrass species: clipping yield, density, light response curves, and leaf area. Data collection began on 1 November and 13 December for experiment I and II, respectively. Clipping yields correspond to cutting each individual turfgrass species to a pre-determined height of 7.62cm above the soil line of the container. Although the turfgrass species were cut weekly, clippings were collected for analysis on a biweekly basis. The clippings were dried at 100°C in an oven for three days and weighed for dry content that is expressed as grams/m^2. To measure density tillers per cm^2 were counted on an identical pre-determined section measuring 5x5cm of the 10.16x10.1cm pot biweekly.

Light response curves under the environmental conditions that have been described were measured using a LICOR 6400 portable photosynthesis system biweekly beginning on 1 November and 13 December for experiment I and II, respectively (LICOR® Biosciences, Lincoln, Nebr.). These measurements are a non-destructive mean of evaluating the effects of fructose and light energy level on photosynthetic responses of each turfgrass species. The parameters of the LICOR were: chamber 2x3 opaque needles light emitting diode (LED) light source, carbon dioxide (CO_2) maintained at 400 µmol/mol constant concentration, temperature constant 20°C, and flow rate 250 parts per million (ppm). Six turfgrass leaves from each pot were placed within the chamber of the LICOR and subjected to the AutoProgram 'Light Curve' to determine photosynthesis rates at varying light levels. The program parameters were: 1) photosynthetic active radiation (PAR)- 2000, 1000, 500, 250, 100, 60, 45, 30, 15, 0 µmol m^{-2} s^{-1} and PAR- 500,

250, 100, 60, 45, 30, 15, 0 μmol m^{-2} s^{-1}; 2) minimum wait time 30 seconds; 3) maximum wait time 100 seconds; 4) coefficient of variation (total CV%) 0.05 to maintain mean stability; and 5) match if CO_2 sample 0 ppm different from CO_2 reference.

After measurements the six leaves in the chamber were removed from each plant and stored for calculation of leaf area correction for each measurement. Leaf area correction was calculated by using a microscope set at 64x; leaf width was recorded for each leaf and an average was calculated to determine leaf area per plant. The following equation was used to determine corrected leaf area:

100 units at 64x= *A* mm

B units x (*A* mm/100) = *C* mm /10= *D* cm

6 leaves x *D* cm x 3cm (width chamber) = *E* cm^2

A corresponds to millimeters length of samples as measured by the microscope; *B* corresponds to how many units the sample measured from the microscope ruler; *C* corresponds to the sample measurement now in millimeters; *D* corresponds to the sample in centimeters; and *E* corresponds to the total sample area within the chamber. Each correction was recorded for use to process LICOR output for each measurement.

Once all measurements were taken using the LICOR program, the data was downloaded using the LICOR software and inputted into Microsoft Excel (Microsoft Corp., Redmond, Wash.). The following parameters were calculated using the LICOR 'Light Curve' program: photosynthetic rate (photo), conductance (cond), internal CO_2 concentration (Ci), leaf vapor pressure deficit (VpdL), leaf area 2cm^2 constant, stomatal ratio (StmRat), air temperature (Tair), leaf temperature (Tleaf), block temperature (TBlk),

reference CO_2 (CO_2R), sample CO_2 (CO_2S), reference H_2O (H_2OR), sample H_2O (H_2OS), flow, photosynthetically active radiation (PAR) in (PARi), and PAR out (PARo).

Once all leaf measurements were collected with the LICOR photo, PARi, and light energy level (Q μmol m^{-2} s^{-1}) were used to calculate light response curves. The data were fitted to the following equation to calculate total photosynthesis or assimilation rates (*A* μmol CO_2 m^{-2} s^{-1}) at the various light levels:

$$A = \frac{\varphi Q + Amax - \sqrt{(\varphi Q + Amax)^2 - 4\varphi Q k Amax}}{2k} - Rd$$

using Photosyn Assistant (Dundee Scientific, Scotland, U.K.).

The following indices were used to calculate *A* and to determine the effects of light level and fructose treatments on the various turfgrasses: apparent quantum efficiency (φ μmol CO_2 fixed/mol PPF), maximum assimilation (Amax mmol CO_2 m^{-2} s^{-1}), convexity (k), dark respiration (Rd μmol CO_2 m^{-2} s^{-1}), and light compensation point (LCP μmol CO_2 m^{-2} s^{-1}).

Statistical Analysis

To test the objectives of the experiment species and fructose treatments within each light level were compared using Proc ANOVA with Tukey's adjustment. Experiment I and II were significantly different for clipping weight (p-value < 0.01), with experiment I containing significantly higher clipping weights compared to experiment II. This difference may be due ambient light levels due to time of year (October vs. December) the experiments began. Although, trends between experiments I and II were similar, so only experiment I clipping weight representative data are presented. All other variables were not significantly different between experiment I and II, thus, means were

combined and presented together. In addition, Pearson's correlation coefficients were prepared to assess the relationship of the response variables (SAS, 2000).

Results

The application of exogenous fructose had a significant affect on KB and CF clipping weights (grams m^{-2}) and tiller production (density) (Tables 4.1A and 4.2A). However, there were no significant differences in leaf area, net photosynthesis, maximum photosynthetic rates (Amax), quantum efficiency (Q), or dark respiration (Rd) due to the application of exogenous fructose to the canopies of these three turfgrass species (Tables 4.3A, 4.4A, 4.5A, 4.6A, 4.7A, and 4.8A). There were significant affects on the growth and metabolism of KB, CF, and CRF due to available light energy (PAR) and significant interactions between species, fructose, and time that will be reported for each of the parameters that were measured.

Clipping Weight

Plants grown under a daily light integral (DLI) of 10 mol m^{-2} d^{-1} did not significantly respond to the application of fructose (Table 4.1B). However, for CF and KB plants that received 8 mol m^{-2} d^{-1} PAR clipping weights were greatest for the controls (NF), followed by F1 and F2 treatments, respectively (Table 4.1B). The same pattern occurred for CF plants that received 4 mol m^{-2} d^{-1} PAR. There was a significant interaction between species and exogenous fructose for turfgrass grown under 8 mol m^{-2} d^{-1} indicating that the three species responded in different ways to the availability of an exogenous supply of carbohydrate (Appendix III).

Additionally, there were significant differences in clipping weights over the duration of the experiment (Table 4.1A), with clipping weights for all species increasing

over time under both the 10 and 8 mol m^{-2} d^{-1} DLI energy levels (Table 4.1C and Figure 4.1). Under 4 mol m^{-2} d^{-1} clipping weights did not significantly change over the duration of the experiment (Figure 4.1). There was a significant interaction between fructose applications, species and time (weeks) for plants grown under 8 mol m^{-2} d^{-1} PAR (Table 4.1A), which suggests that clipping weights for all species increased as exogenous fructose application continued over the duration of the experiment. However, light had a greater impact on clipping weights than exogenous fructose applications as can be seen by the two to 15 fold decrease in clipping weights as PAR decreased from 10 mol m^{-2} d^{-1} to 4 mol m^{-2} d^{-1} (Table 4.1B).

Density

Plants grown under 8 and 4 PAR of 10 mol m^{-2} d^{-1} did have significant differences in density (tiller production) under all fructose application rates compared to controls (NF, no fructose) (Table 4.2A). For plants grown under 4 mol m^{-2} d^{-1} both CRF and KB plants that received exogenous fructose had higher density compared to controls. Once again, fructose applications did not significantly influence turfgrass density under a PAR of 10 mol m^{-2} d^{-1} (Tables 4.2A and 4.2B). There was a significant difference between species with KB possessing 1.5% greater densities compared to CF and CRF under all light energy levels (Table 4.2C).

There were significant differences in densities over the duration of the experiment (Table 4.2A), with densities for all species increasing over time under both the 10 and 8 mol m^{-2} d^{-1} light energy levels (Table 4.2C and Figure 4.2). Under 4 mol m^{-2} d^{-1} there was a significant interaction between species and time (weeks), which suggests that each species tiller production responded differently over the duration of the experiment (Table

4.2A). Both CF and CRF maintained similar densities over the duration of the experiment, while KB tiller production increased over the duration of the experiment (Figure 4.2). Light had a greater impact on density than exogenous fructose applications as can be seen with the one to three fold decrease in density as light energy decreased from 10 to 4 mol m^{-2} d^{-1} (Table 4.2B).

Leaf Area

There were significant increases in leaf area (cm^2) for plants grown under 10 and 8 mol m^{-2} d^{-1} (Table 4.3A), with all species increasing in leaf area over the duration of the experiment (Figure 4.3). There was a significant interaction between species and time (weeks) for plants grown under 10 and 8 mol m^{-2} d^{-1} (Table 4.3A). Each species responded differently to their respective light treatment over the duration of the experiment (Table 4.3C). Plants grown under 4 mol m^{-2} d^{-1} maintained consistent leaf areas over the duration of the experiment, although KB increased slightly over the duration of the experiment while CF and CRF decreased (Figure 4.3). There were significant differences in leaf area under all light energy levels between species (Table 4.3A). Kentucky bluegrass maintained two to three percent higher leaf areas compared to CF and CRF under all light energy levels (Table 4.3B and C), which is most likely influenced by the morphological differences in KB and fine leaf fescue turfgrass species. As found for other growth responses, available light energy had a greater impact on leaf area than exogenous fructose applications as seen by the one point five to greater than two fold decrease in leaf area as light energy decreased from 10 to 4 mol m^{-2} d^{-1} (Table 4.3B).

Light Response Curves

Amax

For all species grown under DLI of 10 and 8 mol m^{-2} d^{-1} maximum assimilation (Amax mmol CO_2 m^{-2} s^{-1}) was significantly different over time (weeks) (Table 4.4A), with Amax increasing under both light energy levels (Table 4.4C; Figures 4.4 and 4.5). Under 4 mol m^{-2} d^{-1} Amax decreased over the duration of the experiment for all species (Figure 4.6). Species was significantly different under all light energy levels (Table 4.4A), with KB maintaining one to three times higher Amax compared to CF and CRF (Table 4.4C). There was a significant interaction between exogenous fructose, time, and species for plants grown under 10 mol m^{-2} d^{-1} (Table 4.4A).

Light Compensation Point

There were significant differences in the light compensation point (LCP μmol m^{-2} s^{-1}) for plants grown under DLI of 10 and 8 mol m^{-2} d^{-1} over time (weeks) (Table 4.5A), with KB and CF decreasing in LCP and CRF increasing over time (Table 4.5C; Figures 4.4 and 4.5). For all species grown under 4 mol m^{-2} d^{-1} the LCP increased for CF and KB and decreased for CRF over the duration of the experiment (Figure 4.6).

Quantum Efficiency

There were significant differences in quantum efficiency (Q μmol CO_2 m^{-2} s^{-1}/mol PPF) over time (weeks) (Table 4.6A), with Q increasing over time for all species grown under DLI of 10 and 8 mol m^{-2} d^{-1} and decreasing for all species grown under DLI of 4 mol m^{-2} d^{-1} (Table 4.6C; Figure 4.4, 4.5, and 4.6). The three species grown under DLI of 10 and 8 mol m^{-2} d^{-1} had a significant difference in Q between species and there was a significant interaction between species and time (Table 4.6A). Under both of the higher

light energy levels the efficient use of light energy to drive Pn increased over time for all species, although KB maintained three to five percent higher Q compared to CRF and CF respectively (Table 4.6B and C). For plants grown under 4 mol m^{-2} d^{-1} there was a significant interaction between exogenous fructose, species, and time (Table 4.6A), suggesting that each species responded differently to the various treatments over the duration of the experiment.

Dark Respiration

For plants grown under 10 mol m^{-2} d^{-1} dark respiration rate (Rd μmol CO_2 m^{-2} s^{-1}) was greatest for the controls (NF), followed by F2 and F1 treatments respectively (Table 4.7B). In contrast, for plants grown under DLI of 4 mol m^{-2} d^{-1} Rd was greatest for treatment F1, followed by F2 and NF, respectively (Table 4.7B). For all species grown under 10 and 8 mol m^{-2} d^{-1} DLI Rd significantly decreased over the duration of the experiment (Table 4.7C; Figures 4.4 and 4.5). In contrast, for plants grown under 4 mol m^{-2} d^{-1} Rd increased over the duration of the experiment (Figure 4.6). There was a significant difference in Rd between species under all light energy levels (Table 4.7A), with KB possessing three to six percent higher Rd rates compared to CF and CRF (Table 4.7C). In addition, for plants grown under 10 mol m^{-2} d^{-1} there was a significant interaction between species and time (weeks) (Table 4.7A).

Light Response Curves

Under DLI of 10 mol m^{-2} d^{-1} all turfgrasses were able to maintain positive assimilation (A μmol CO_2 m^{-2} s^{-1}) rates throughout the seven weeks of the experiment. However, each individual turfgrass species varied in A rates over time. At week three there were no significant differences in A between the three turfgrass species, with all

species maintaining similar A rates at all PAR intensities (Figure 4.4A). By week five there were significant differences in turfgrass species (p-value < 0.01), with CRF possessing two percent higher A rates compared to KB and five percent higher A rates compared to CF (Figure 4.4B). By week seven, there were significant differences in turfgrass species (p-value < 0.01), with KB possessing two percent higher A rates compared to CF and CRF (Figure 4.4C).

Under DLI of 8 and 4 mol m^{-2} d^{-1} all turfgrasses were able to maintain positive A rates throughout the seven weeks of the experiment. However, each individual turfgrass species varied in A rates over time. Under both of these DLI levels at week three there were no significant differences between turfgrass species, with all turfgrasses responding similarly to the changing PAR levels (Figure 4.5A and 4.6A, respectively). Kentucky bluegrass was able to maintain 0.5% higher A rates compared to CF and CRF under both light energy levels (Figures 4.5A and 4.6A). By week five, there were significant differences between the three turfgrass species (p-value < 0.01). Under 8 and 4 mol m^{-2} d^{-1} DLI KB possessed 1-3%, respectively, higher A rates compared to CRF and CF (Figure 4.5B and 4.6B, respectively). By week seven, there were significant differences between the turfgrass species (p-value < 0.01), with KB possessing three point five percent higher A rates under 8 mol m^{-2} d^{-1} and two percent higher A rates under 4 mol m^{-2} d^{-1} compared to CF and CRF (Figure 4.5C and 4.6C, respectively). As expected, for all turfgrass species A rates were higher under DLI of 10 and 8 mol m^{-2} d^{-1} compared to DLI of 4 mol m^{-2} d^{-1} (data not shown).

Discussion

As with the simulated dome and control environment, exogenous fructose had a significant positive influence on growth under different DLI. When KB and CRF were grown under 8 and 4 mol m^{-2} d^{-1} there was a significant effect of fructose on clipping weight and density. Clipping weight decreased with increasing exogenous fructose applications while density increased, suggesting that carbohydrates from exogenous fructose applications were allocated to the tillers rather than the shoots of KB and CRF. This is in contrast to previous results where carbohydrates were allocated to the shoots rather than the tillers (Chapter 2; Sorochan, 2002), and similar to previous results where carbohydrates were allocated to tillers rather than shoots (Chapter 3).

Daily light integral impacted growth and metabolism as illustrated by the increase in response variables as light energy level increased across the three DLI (4 to 10 mol m^{-2} d^{-1}). Under DLI of 10 and 8 mol m^{-2} d^{-1} light energy had a positive effect on the metabolism of the three species. Although, the lowest DLI (4 mol m^{-2} d^{-1}) was able to maintain some growth over time (week), this amount of light energy was not enough to incur a positive physiological or metabolic response for any of the turfgrass species. For all species clipping weight, density, and leaf area increased over time under DLI of 10 and 8 mol m^{-2} d^{-1}, while under a DLI of 4 mol m^{-2} d^{-1} growth remained static in value over time or sometimes even decreased. This response is similar to other common observations of turfgrass growth responses to extreme shaded conditions. Under these shade conditions the number of leaves were reduced was directly related to reduced clipping weight and tillers (Dudeck and Peacock, 1992). In the present work KB had higher response variable than CF and CRF regardless of light level or treatment. These

results are similar to the sports simulated dome experiment and the growth chamber experiment, where all variables measured were higher for KB compared to CF and CRF (Chapter 2 and 3).

In addition, KB possessed higher Rd, Q, Amax, LCP, and A than CF and CRF in all light levels suggesting that photosynthesis for KB was driven by higher respiration rates (Rd) and use additional carbohydrates to maintain growth over time in shaded conditions. For all species, net photosynthesis increased over time under 10 and 8 mol m^{-2} d^{-1} while remaining similar over time in 4 mol m^{-2} d^{-1}, suggesting a threshold light level between 4 and 8 mol m^{-2} d^{-1}. Also, light response curves under 10 and 8 mol m^{-2} d^{-1}, regardless of species that received fructose and control treatments that did not receive fructose, possessed higher photosynthetic rates for all PAR levels compared to 4 mol m^{-2} d^{-1}. This relationship supports the previous observation that shaded plants approach the light compensation point more quickly and net photosynthesis is lower in shaded verses full sun plants (Vanden Hueval et al., 2004; Wilkinson et al., 1974). Again, KB maintained higher photosynthetic values than CF and CRF for all PAR points over time regardless of light level and treatment, which may indicate a difference in the genetic potential of photosynthesis among the species that were compared.

The present work indicates CF and CRF did not possess a surplus of carbohydrate reserves regardless of exogenous fructose applications in quantities that were sufficient to maintain acceptable growth under all light levels, although all species performed better under higher DLI (10 and 8 mol m^{-2} d^{-1}) than DLI compared with extreme shaded conditions (4 mol m^{-2} d^{-1}). These results support the hypothesis that various types of turfgrasses under shaded conditions show that the photosynthetic capacity of the turfgrass

species determines differences in shade tolerance (Van Huylenbroeck and Van Bockstaele, 2001). Collectively, the outcome of the present work suggests that some turfgrasses grown under DLI within the 10 and 8 mol m^{-2} d^{-1} treatments were able to maintain and/or increase growth over time. Additionally, threshold light level for these species may exist between 10/8 mol m^{-2} d^{-1} and 4 mol m^{-2} d^{-1}.

Conclusion

In summary, exogenous fructose impacted growth and development as shade tolerant turfgrass species. In addition, the results suggest that DLI within 10 and 8 mol m^{-2} d^{-1} were sufficient to maintain acceptable growth for all species. Light response curve data suggests that species grown under 4 mol m^{-2} d^{-1} light level could not produce enough carbohydrates through photosynthesis to reach acceptable growth over time.

Exogenous fructose had some affects on the physiologic and metabolic response on species grown under low light shaded conditions of this experiment. Specific DLI research is essential to understand the minimum light levels these turfgrasses can maintain and increase overall growth, quality, and photosynthetic capabilities.

Table 4.1A Analysis of variance for clipping weight (grams m^{-2}) under 10, 8, 4 mol m^{-2} d^{-1} for chewings fescue 'SR 5100' (CF) (*Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF) (*Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB) (*Poa pratensis*).

		10 mol m^{-2} d^{-1}		8 mol m^{-2} d^{-1}		4 mol m^{-2} d^{-1}	
Source	df	MS	F	MS	F	MS	F
F	2	187	0.41ns	116	1.09ns	29.72	1.20ns
W	3	44546	96.60**	10238	96.80**	229.1	9.25**
S	2	669	1.45ns	205.3	1.94ns	21.1	0.85ns
F*W	6	62.4	0.14ns	36.7	0.35ns	11.5	0.46ns
F*S	4	620	1.34ns	558.1	5.28**	33.2	1.34ns
S*W	6	288	0.62ns	235.6	2.23*	24.3	0.98ns
F*W*S	12	224	0.49ns	249.8	2.36*	15.2	0.62ns
Error	180	461		105.7		24.7	

Note: Significance levels for repeated measures are given as probability: ns, $p > 0.05$; * $p < 0.05$; and ** $p < 0.01$.
F, fructose; W, week; S, species.

Table 4.1B Mean specific clipping weight (grams m^{-2}) at week seven under 10, 8, 4 mol m^{-2} d^{-1} for chewings fescue 'SR 5100' (CF) (*Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF) (*Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB) (*Poa pratensis*).

	10 mol m^{-2} d^{-1}			8 mol m^{-2} d^{-1}			4 mol m^{-2} d^{-1}		
Trt	CF	CRF	KB	CF	CRF	KB	CF	CRF	KB
F1	72.9a	55.3a	80.1a	29.6ab	37.3a	54.6a	4.42ab	7.12a	10.9a
F2	62.8a	57.5a	82.8a	20.3b	33.2a	51.3ab	2.63b	6.25a	10.1a
NF	74.9a	83.2a	64.3a	46.7a	40.4a	29.9b	10.6a	7.75a	7.43a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.
Trt, treatment; F1, fructose 1x/week; F2, fructose 2x/week; NF, no fructose (control).

Table 4.1C Mean specific clipping weight (grams m^{-2}) over time under 10, 8, 4 mol m^{-2} d^{-1} for chewings fescue 'SR 5100' (CF) (*Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF) (*Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB) (*Poa pratensis*).

Week	10 mol m^{-2} d^{-1}	8 mol m^{-2} d^{-1}	4 mol m^{-2} d^{-1}
1	11.1bc	9.53a	9.64b
3	8.96c	5.18b	10.8b
5	21.3b	5.31b	11.6b
7	70.2a	7.46ab	38.2a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.

Table 4.2A Analysis of variance for density (tillers cm^{-2}) under 10, 8, 4 mol m^{-2} d^{-1} for chewings fescue 'SR 5100' (CF) (*Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF) (*Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB) (*Poa pratensis*).

		10 mol m-2 d-1		8 mol m-2 d-1		4 mol m-2 d-1	
Source	df	MS	F	MS	F	MS	F
F	2	0.50	0.84ns	7.05	9.29**	1.49	3.32*
W	3	81.6	88.1**	15.5	34.2**	8.51	18.9**
S	2	20.9	22.6**	25.9	20.5**	17.3	38.6**
F*W	6	0.44	0.82ns	0.77	2.15ns	0.26	0.75ns
F*S	4	1.49	0.17ns	1.63	2.15ns	0.97	0.08ns
S*W	6	0.50	0.77ns	0.43	0.56ns	1.01	0.04*
F*W*S	12	0.09	1.00ns	0.47	0.62ns	0.15	0.98ns
Error	180	0.92		0.76		80.8	

Note: Significance levels for repeated measures are given as probability: ns, $p > 0.05$; *, $p < 0.05$; and **, $p < 0.01$.
F, Fructose; W, week; S, species.

Table 4.2B Mean specific density (tillers cm^{-2}) at week seven under 10, 8, 4 mol m^{-2} d^{-1} for chewings fescue 'SR 5100' (CF) (*Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF) (*Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB) (*Poa pratensis*).

	10 mol m-2 d-1			8 mol m-2 d-1			4 mol m-2 d-1		
Trt	CF	CRF	KB	CF	CRF	KB	CF	CRF	KB
F1	4.32a	1.61a	4.66a	2.76a	2.71a	4.43a	1.61a	1.60a	3.08a
F2	3.88a	1.60a	4.19a	2.40a	1.96a	3.02ab	1.60a	1.26ab	2.95ab
NF	4.50a	1.83a	4.04a	2.79a	2.04a	2.24b	1.83a	0.83b	2.28b

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.
Trt, treatment; F1, fructose 1x/week; F2, fructose 2x/week; NF, no fructose (control).

Table 4.2C Mean specific density (tillers cm^{-2}) over time and by species under 10, 8, 4 mol m^{-2} d^{-1} for chewings fescue 'SR 5100' (CF) (*Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF) (*Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB) (*Poa pratensis*).

Week	10 mol m^{-2} d^{-1}	8 mol m^{-2} d^{-1}	4 mol m^{-2} d^{-1}
1	1.12c	1.04c	0.98b
3	1.59c	1.61b	1.68a
5	2.51b	1.93b	1.66a
7	3.9a	2.71a	1.89a

Species	10 mol m^{-2} d^{-1}	8 mol m^{-2} d^{-1}	4 mol m^{-2} d^{-1}
CF	2.49a	1.76b	1.44b
CRF	1.67b	1.39c	1.13c
KB	2.69a	2.32a	2.09a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.

Table 4.3A Analysis of variance for leaf area (cm^2) under 10, 8, 4 mol m^{-2} d^{-1} for chewings fescue 'SR 5100' (CF) (*Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF) (*Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB) (*Poa pratensis*).

		10 mol m-2 d-1		8 mol m-2 d-1		4 mol m-2 d-1	
Source	df	MS	F	MS	F	MS	F
F	2	0.0003	0.66ns	0.0005	0.6ns	0.003	1.12ns
W	2	0.04	78.4**	0.02	24.1**	0.002	0.76ns
S	2	0.07	126**	0.017	19.3**	0.02	6.21*
F*W	4	0.009	1.86ns	0.0001	0.14ns	0.006	1.74ns
F*S	4	0.003	0.67ns	0.0003	0.37ns	0.005	1.63ns
S*W	4	0.008	15.7**	0.004	4.86*	0.007	2.33ns
F*W*S	8	0.0006	1.16ns	0.0005	0.51ns	0.002	0.72ns
Error	135	0.0005		0.0009		0.003	

Note: Significance levels for repeated measures are given as probability: ns, $p > 0.05$; *, $p < 0.05$; and **, $p < 0.01$.
F, Fructose; W, week; S, species.

Table 4.3B Mean specific leaf area (cm^2) at week seven under 10, 8, 4 mol m^{-2} d^{-1} for chewings fescue 'SR 5100' (CF) (*Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF) (*Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB) (*Poa pratensis*).

	10 mol m-2 d-1			8 mol m-2 d-1			4 mol m-2 d-1		
Trt	CF	CRF	KB	CF	CRF	KB	CF	CRF	KB
F1	0.08a	0.08a	0.17a	0.06a	0.08a	0.13a	0.05b	0.04a	0.08a
F2	0.07a	0.07a	0.16a	0.09a	0.07a	0.14a	0.04b	0.05a	0.09a
NF	0.09a	0.08a	0.18a	0.08a	0.08a	0.14a	0.07a	0.15a	0.09a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.
Trt, treatment; F1, fructose 1x/week; F2, fructose 2x/week; NF, no fructose (control).

Table 4.3B Mean specific leaf area (cm^2) over time and by species 10, 8, 4 mol m^{-2} d^{-1} for chewings fescue 'SR 5100' (CF) (*Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF) (*Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB) (*Poa pratensis*).

Week	10 mol m^{-2} d^{-1}	8 mol m^{-2} d^{-1}	4 mol m^{-2} d^{-1}
3	0.06c	0.06c	0.06a
5	0.09b	0.07b	0.07a
7	0.11a	0.10a	0.08a

Species	10 mol m^{-2} d^{-1}	8 mol m^{-2} d^{-1}	4 mol m^{-2} d^{-1}
CF	0.06b	0.06b	0.05b
CRF	0.07b	0.06b	0.07ab
KB	0.13a	0.10a	0.09a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.

Table 4.4A Analysis of variance for Amax (μmol CO_2 m^{-2} s^{-1}) under 10, 8, 4 mol m^{-2} d^{-1} for chewings fescue 'SR 5100' (CF) (*Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF) (*Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB) (*Poa pratensis*).

		10 mol m-2 d-1		8 mol m-2 d-1		4 mol m-2 d-1	
Source	df	MS	F	MS	F	MS	F
F	2	10.2	3.14ns	0.71	1.88ns	0.08	1.03ns
W	2	33.2	10.2**	18.1	48.1**	0.22	2.84ns
S	2	14.7	4.49*	12.2	32.7**	1.74	22.8**
F*W	4	4.9	1.51ns	0.04	0.12ns	0.005	0.07ns
F*S	4	4.79	1.47ns	0.31	0.85ns	0.06	0.83ns
S*W	4	7.57	2.32ns	0.87	2.32ns	0.13	1.67ns
F*W*S	8	6.72	2.06*	0.17	0.44ns	0.05	0.61ns
Error	132	3.26		0.37		0.08	

Note: Significance levels for repeated measures are given as probability: ns, $p > 0.05$; *, $p < 0.05$; and **, $p < 0.01$.
F, Fructose; W, week; S, species.

Table 4.4B Mean specific Amax (μmol CO_2 m^{-2} s^{-1}) at week seven under 10, 8, 4 mol m^{-2} d^{-1} for chewings fescue 'SR 5100' (CF) (*Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF) (*Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB) (*Poa pratensis*).

	10 mol m-2 d-1			8 mol m-2 d-1			4 mol m-2 d-1		
Trt	CF	CRF	KB	CF	CRF	KB	CF	CRF	KB
F1	1.86a	2.02a	3.42a	1.38a	1.68a	3.17a	0.16a	0.35a	0.56a
F2	1.45a	1.92a	3.25a	1.26a	1.35a	2.77a	0.39a	0.31a	0.58a
NF	1.82a	1.86a	4.05a	1.71a	1.89a	2.61a	0.46a	0.38a	0.60a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.
Trt, treatment; F1, fructose 1x/week; F2, fructose 2x/week; NF, no fructose (control).

Table 4.4C Mean specific Amax (μmol CO_2 m^{-2} s^{-1}) over time and by species under 10, 8, 4 mol m^{-2} d^{-1} for chewings fescue 'SR 5100' (CF) (*Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF) (*Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB) (*Poa pratensis*).

Week	10 mol m^{-2} d^{-1}	8 mol m^{-2} d^{-1}	4 mol m^{-2} d^{-1}
3	0.82b	0.88b	0.31a
5	1.72ab	1.08b	0.42a
7	2.41a	1.98a	0.42a

Species	10 mol m^{-2} d^{-1}	8 mol m^{-2} d^{-1}	4 mol m^{-2} d^{-1}
CF	1.15b	1.03b	0.27b
CRF	1.67ab	1.10b	0.29b
KB	2.21a	1.92a	0.59a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.

Table 4.5A Analysis of variance for light compensation point (μmol m^{-2} s^{-1}) under 10, 8, 4 mol m^{-2} d^{-1} for chewings fescue 'SR 5100' (CF) (*Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF) (*Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB) (*Poa pratensis*).

		10 mol m-2 d-1		8 mol m-2 d-1		4 mol m-2 d-1	
Source	df	MS	F	MS	F	MS	F
F	2	3.03	0ns	317	1.03ns	1341	0.58ns
W	2	16626	21.9**	1331	4.58*	3450	1.49ns
S	2	1010	1.33ns	564	1.94ns	3285	1.42ns
F*W	4	174	0.23ns	41.8	0.14ns	1186	0.51ns
F*S	4	237	0.31ns	572	1.97ns	1598	0.69ns
S*W	4	58.7	0.08ns	80.3	0.28ns	1241	0.53ns
F*W*S	8	201	0.27ns	28.7	0.98ns	1294	0.56ns
Error	132	757		290		2321	

Note: Significance levels for repeated measures are given as probability: ns, $p > 0.05$; *, $p < 0.05$; and **, $p < 0.01$.
F, Fructose; W, week; S, species.

Table 4.5B Mean specific light compensation point (μmol m^{-2} s^{-1}) at week seven under 10, 8, 4 mol m^{-2} d^{-1} for chewings fescue 'SR 5100' (CF) (*Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF) (*Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB) (*Poa pratensis*).

	10 mol m-2 d-1			8 mol m-2 d-1			4 mol m-2 d-1		
Trt	CF	CRF	KB	CF	CRF	KB	CF	CRF	KB
F1	50.7a	52.3a	47.7a	19.5a	16.4a	19.5a	34.7a	8.14a	27.3a
F2	57.7a	57.7a	50.7a	23.9a	24.5a	12.5a	24.0a	33.8a	15.9a
NF	66.6a	59.9a	46.1a	19.7a	24.0a	19.9a	17.5a	25.9a	20.3a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.
Trt, treatment; F1, fructose 1x/week; F2, fructose 2x/week; NF, no fructose (control).

Table 4.5C Mean specific light compensation point (μmol m^{-2} s^{-1}) over time under 10 and 8 mol m^{-2} d^{-1} for chewings fescue 'SR 5100' (CF) (*Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF) (*Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB) (*Poa pratensis*).

Week	10 mol m^{-2} d^{-1}	8 mol m^{-2} d^{-1}
3	38.1b	20.5b
5	19.3c	19.8b
7	54.4a	28.9a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.

Table 4.6A Analysis of variance for quantum efficiency (μmol CO_2 m^{-2} s^{-1}/mol PAR) under 10, 8, 4 mol m^{-2} d^{-1} for chewings fescue 'SR 5100' (CF) (*Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF) (*Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB) (*Poa pratensis*).

		10 mol m-2 d-1		8 mol m-2 d-1		4 mol m-2 d-1	
Source	df	MS	F	MS	F	MS	F
F	2	0.00002	2.78ns	0.000004	1.31ns	0.01	0.94ns
W	2	0.0005	55.7**	0.0002	55.2**	0.05	3.44*
S	2	0.0005	57.4**	0.0002	51.7**	0.02	1.25ns
F*W	4	0.000004	0.28ns	0	0ns	0.01	1ns
F*S	4	0.000002	1.41ns	0.00003	0.88ns	0.03	2.11ns
S*W	4	0.00005	6.43**	0.000002	4.85*	0.01	0.98ns
F*W*S	8	0.00004	1.73ns	0.000005	0.14ns	0.03	2.19*
Error	132	0.000008		0.000004		0.01	

Note: Significance levels for repeated measures are given as probability: ns, $p > 0.05$; *, $p < 0.05$; and **, $p < 0.01$.
F, Fructose; W, week; S, species.

Table 4.6B Mean specific quantum efficiency (μmol CO_2 m^{-2} s^{-1}/mol PAR) at week seven under 10, 8, 4 mol m^{-2} d^{-1} for chewings fescue 'SR 5100' (CF) (*Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF) (*Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB) (*Poa pratensis*).

	10 mol m-2 d-1			8 mol m-2 d-1			4 mol m-2 d-1		
Trt	CF	CRF	KB	CF	CRF	KB	CF	CRF	KB
F1	0.004a	0.005a	0.01a	0.004a	0.005a	0.01a	0.002a	0.002a	0.29a
F2	0.004a	0.006a	0.01a	0.003a	0.004a	0.01a	0.001a	0.17a	0.005a
NF	0.005a	0.006a	0.01a	0.004a	0.005a	0.01a	0.002a	0.007a	0.003a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.
Trt, treatment; F1, fructose 1x/week; F2, fructose 2x/week; NF, no fructose (control).

Table 4.6C Mean specific quantum efficiency (μmol CO_2 m^{-2} s^{-1}/mol PAR) over time and by species under 10, 8, 4 mol m^{-2} d^{-1} for chewings fescue 'SR 5100' (CF) (*Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF) (*Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB) (*Poa pratensis*).

Week	10 mol m^{-2} d^{-1}	8 mol m^{-2} d^{-1}	4 mol m^{-2} d^{-1}
3	0.002c	0.002c	0.001b
5	0.006b	0.003b	0.003b
7	0.008a	0.006a	0.05a

Species	10 mol m^{-2} d^{-1}	8 mol m^{-2} d^{-1}	4 mol m^{-2} d^{-1}
CF	0.003b	0.003b	0.001a
CRF	0.004b	0.003b	0.02a
KB	0.009a	0.006a	0.04a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.

Table 4.7A Analysis of variance for dark respiration rate (μmol CO_2 m^{-2} s^{-1}) under 10, 8, 4 mol m^{-2} d^{-1} for chewings fescue 'SR 5100' (CF) (*Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF) (*Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB) (*Poa pratensis*).

		10 mol m-2 d-1		8 mol m-2 d-1		4 mol m-2 d-1	
Source	df	MS	F	MS	F	MS	F
F	2	0.70	2.48ns	0.005	0.49ns	0.0009	0.2ns
W	2	1.42	50.3**	0.06	5.94*	0.007	1.56ns
S	2	0.05	17.0**	0.09	9.19*	0.01	4.08*
F*W	4	0	1ns	0.005	0.48ns	0.003	0.61ns
F*S	4	0.02	0.07ns	0.01	1.11ns	0.005	1.18ns
S*W	4	0.18	6.65**	0.01	0.98ns	0.003	0.77ns
F*W*S	8	0.05	0.56ns	0.005	0.51ns	0.008	1.87ns
Error	132	0.03		0.01		0.004	

Note: Significance levels for repeated measures are given as probability: ns, $p > 0.05$; *, $p < 0.05$; and **, $p < 0.01$.
F, Fructose; W, week; S, species.

Table 4.7B Mean specific dark respiration rate (μmol CO_2 m^{-2} s^{-1}) at week seven under 10, 8, 4 mol m^{-2} d^{-1} for chewings fescue 'SR 5100' (CF) (*Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF) (*Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB) (*Poa pratensis*).

	10 mol m-2 d-1			8 mol m-2 d-1			4 mol m-2 d-1		
Trt	CF	CRF	KB	CF	CRF	KB	CF	CRF	KB
F1	-0.18a	-0.22a	-0.55a	-0.07a	-0.08a	-0.20a	-0.03a	-0.06a	-0.11a
F2	-0.21a	-0.29a	-0.67a	-0.01a	-0.12a	-0.11a	-0.02a	-0.06a	-0.05a
NF	-0.31a	-0.31a	-0.64a	-0.01a	-0.05a	-0.16a	-0.02a	-0.06a	-0.07a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.
Trt, treatment; F1, fructose 1x/week; F2, fructose 2x/week; NF, no fructose (control).

Table 4.7C Mean specific dark respiration rate (μmol CO_2 m^{-2} s^{-1}) over time and by species under 10, 8, 4 mol m^{-2} d^{-1} for chewings fescue 'SR 5100' (CF) (*Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF) (*Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB) (*Poa pratensis*).

Week	10 mol m^{-2} d^{-1}	8 mol m^{-2} d^{-1}	4 mol m^{-2} d^{-1}
3	-0.07 a	-0.04 a	-0.02 a
5	-0.12 a	-0.08 b	-0.03 a
7	-0.38 b	-0.11 ab	-0.04 a

Species	10 mol m^{-2} d^{-1}	8 mol m^{-2} d^{-1}	4 mol m^{-2} d^{-1}
CF	-0.12 a	-0.04 a	-0.02 a
CRF	-0.15 a	-0.07 ab	-0.02 a
KB	-0.31 b	-0.13 b	-0.05 b

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.

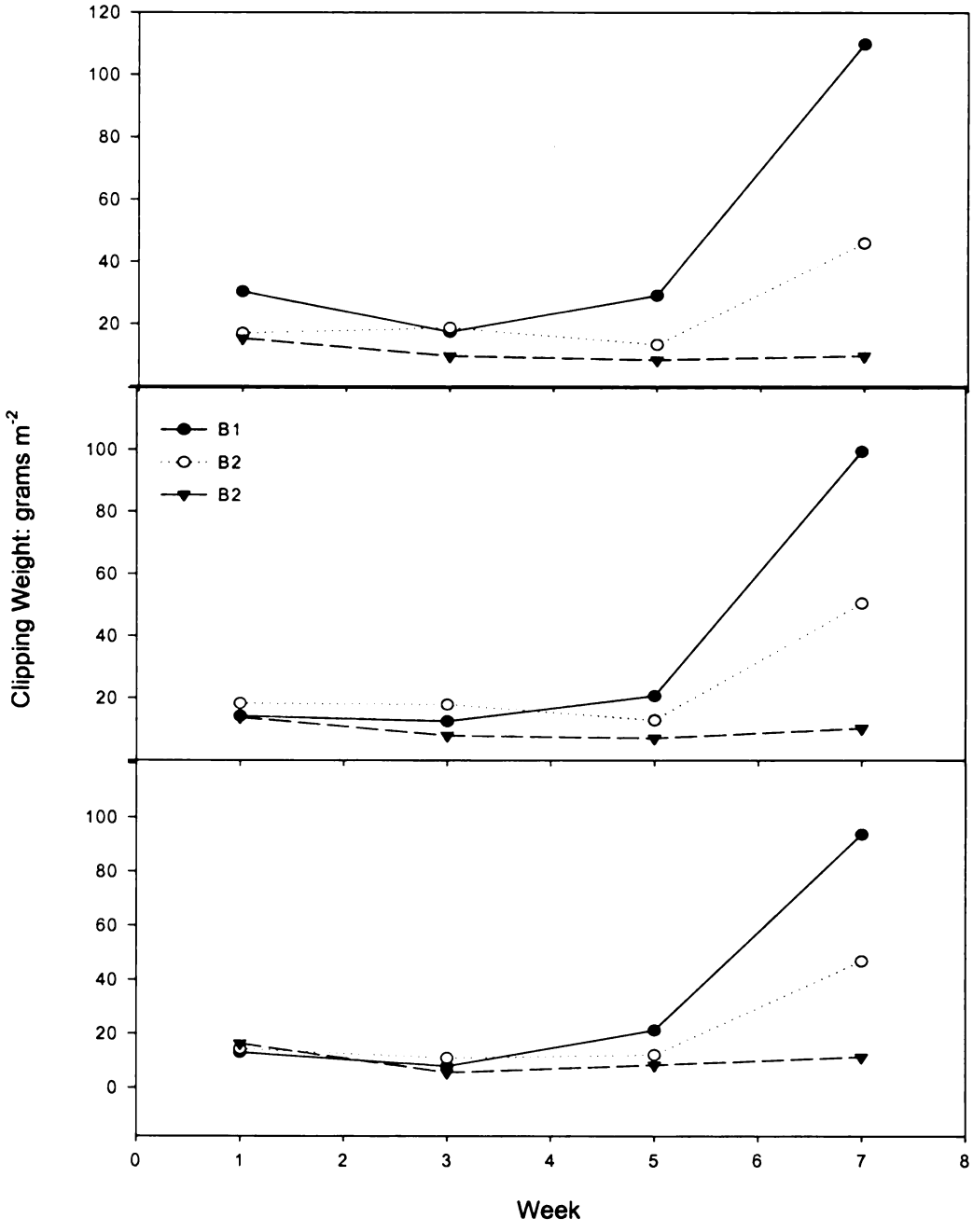

Figure 4.1 Clipping weights (grams/m^2) experiment I combined fructose and control treatment under bench one (B1- 10 mol m^{-2} s^{-1}), bench two (B2- 8 mol m^{-2} s^{-1}), and bench three (B3- 4 mol m^{-2} s^{-1}) for A) chewings fescue 'SR5100' (*Festuca rubra v. commutata*), B) creeping red fescue (*Festuca rubra v. rubra*), and C) Kentucky bluegrass 'Cynthia' (*Poa pratensis*).

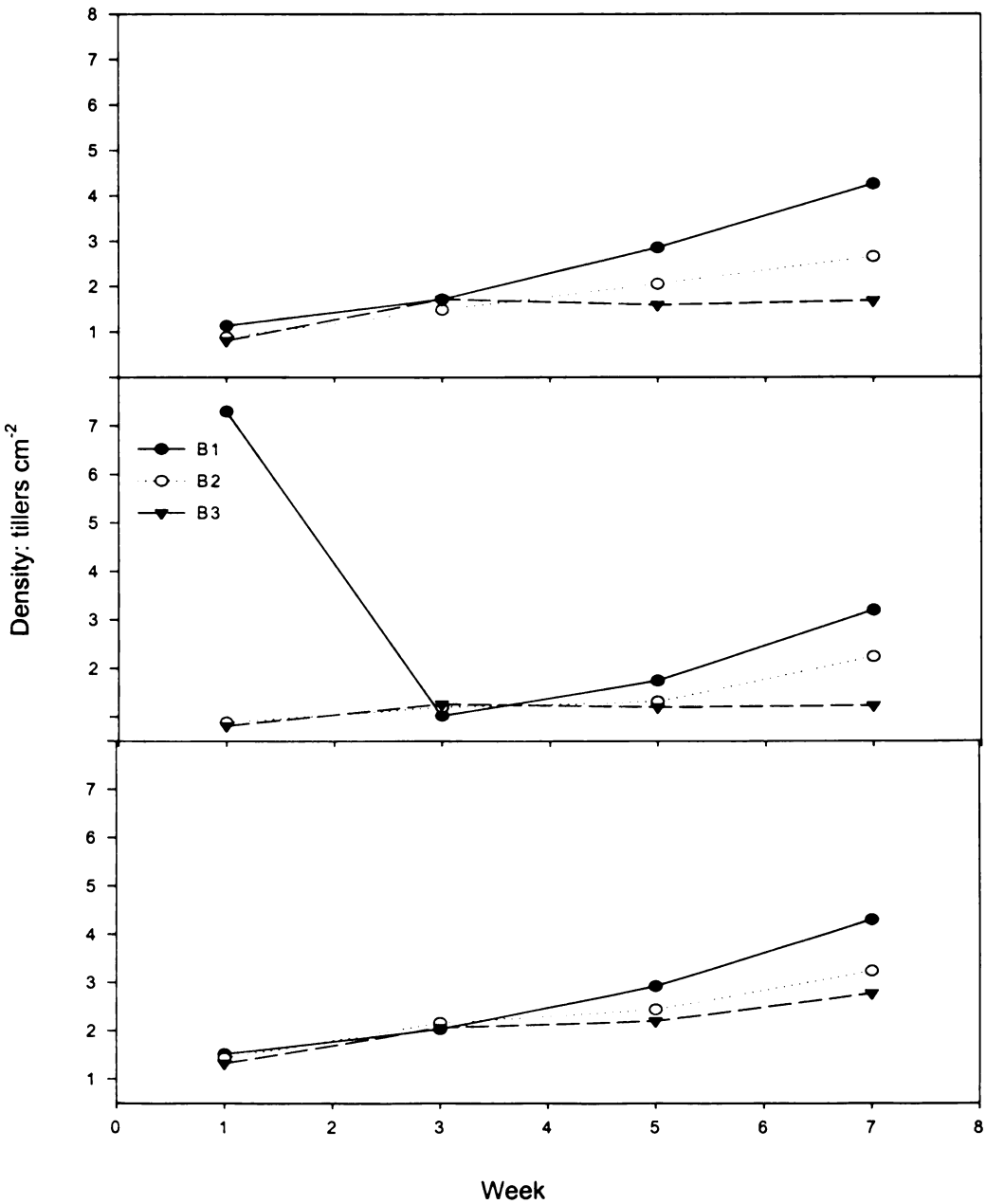

Figure 4.2 Density (tillers/cm^2) combined fructose and control and experiment under bench one (B1- 10 mol m^{-2} s^{-1}), bench two (B2- 8 mol m^{-2} s^{-1}), and bench three (B3- 4 mol m^{-2} s^{-1}) for A) chewings fescue 'SR5100' (*Festuca rubra v. commutata*), B) creeping red fescue (*Festuca rubra v. rubra*), and C) Kentucky bluegrass 'Cynthia' (*Poa pratensis*).

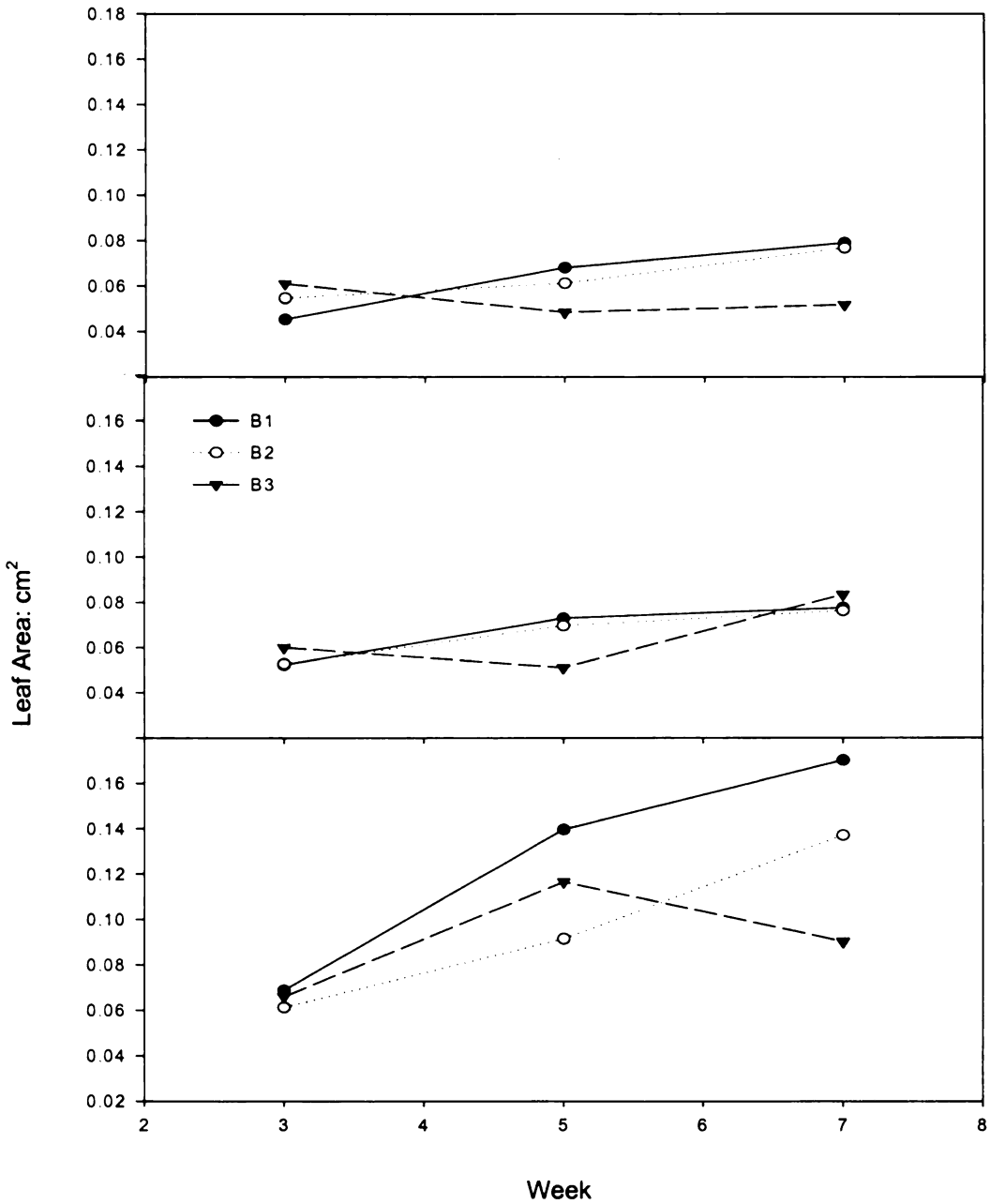

Figure 4.3 Leaf area (cm^2) from combined fructose and control treatment and experiment under bench one (B1- 10 mol m^{-2} s^{-1}), bench two (B2- 8 mol m^{-2} s^{-1}), and bench three (B3- 4 mol m^{-2} s^{-1}) for A) chewings fescue 'SR5100' (*Festuca rubra v. commutata*), B) creeping red fescue 'Dawson' (*Festuca rubra v. rubra*), and C) Kentucky bluegrass 'Cynthia' (*Poa pratensis*).

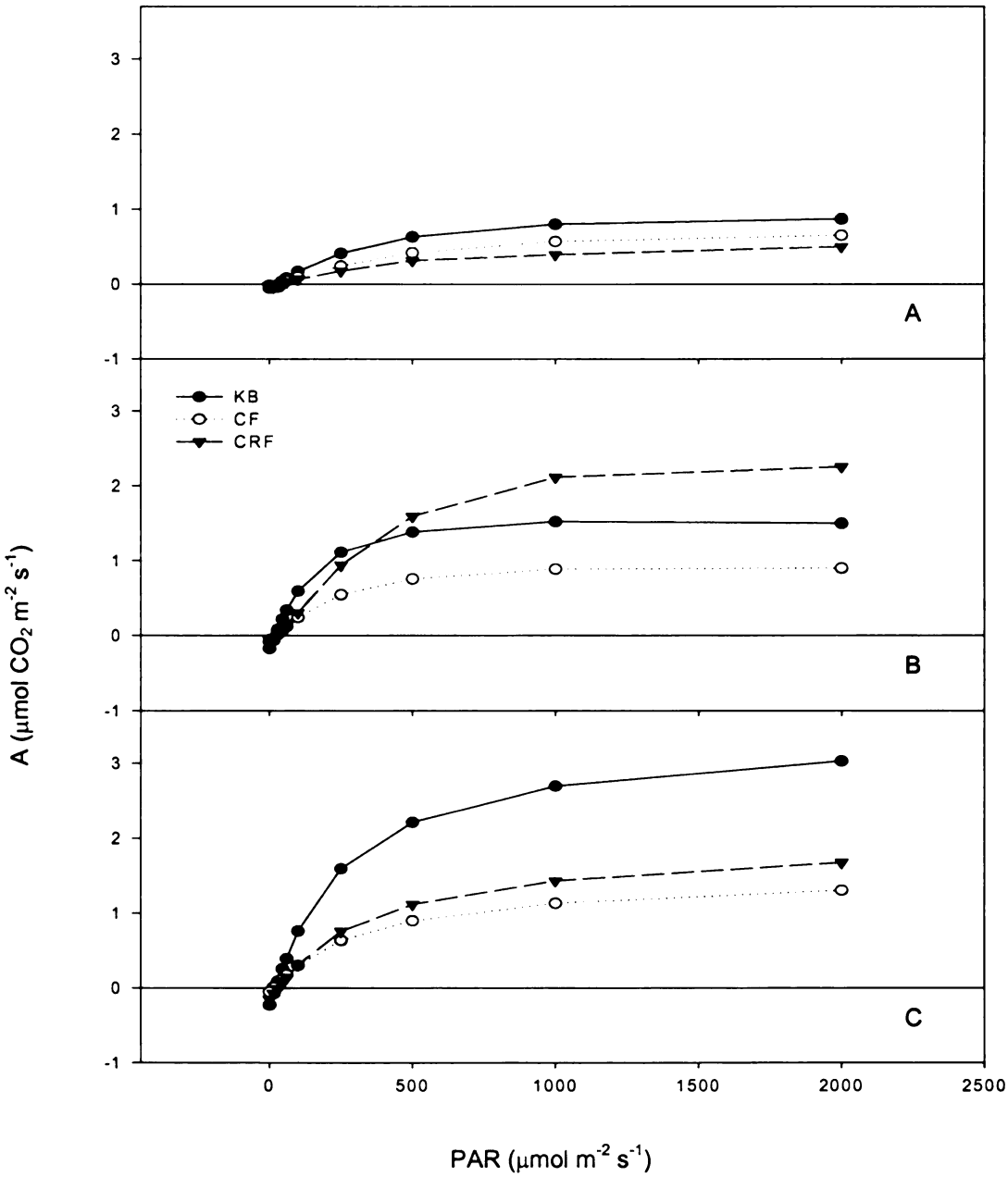

Figure 4.4 Combined fructose and control assimilation (A μmol CO_2 m^{-2} s^{-1}) over varying photosynthetic active radiation (PAR μmol m^{-2} s^{-1}) under 10 mol m^{-2} d^{-1} light response curves at a) week three, b) week five, and c) week seven for chewings fescue 'SR5100' (CF) (*Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF) (*Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB) (*Poa pratensis*).

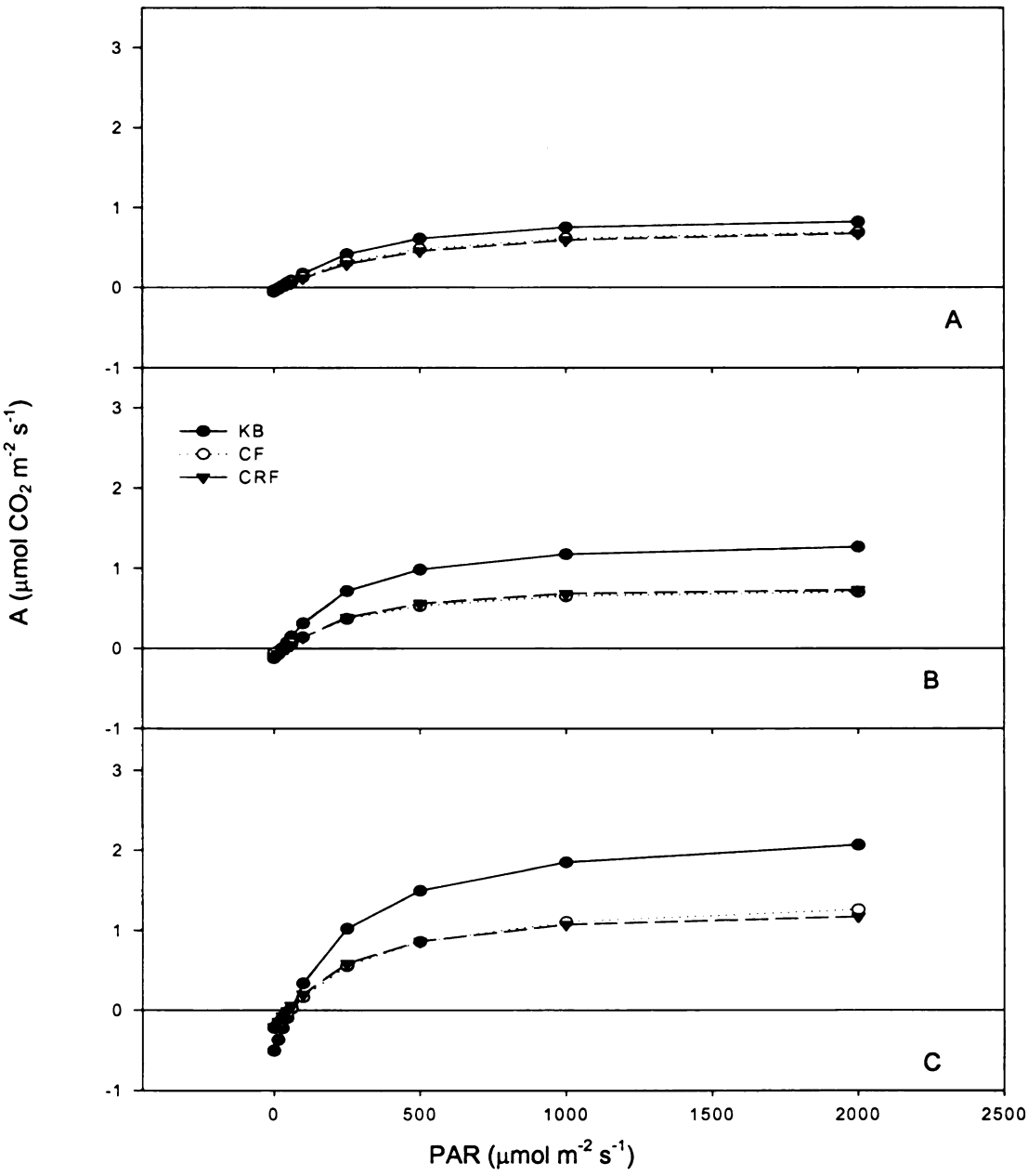

Figure 4.5 Combined fructose and control assimilation (A µmol CO_2 m^{-2} s^{-1}) over varying photosynthetic active radiation (PAR µmol m^{-2} s^{-1}) under 8 mol m^{-2} d^{-1} light response curves at A) week three, b) week five, and c) week seven for chewings fescue 'SR5100' (CF) (*Festuca rubra v. commutata*), creeping red fescue 'Dawson' (KB) (*Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB) (*Poa pratensis*).

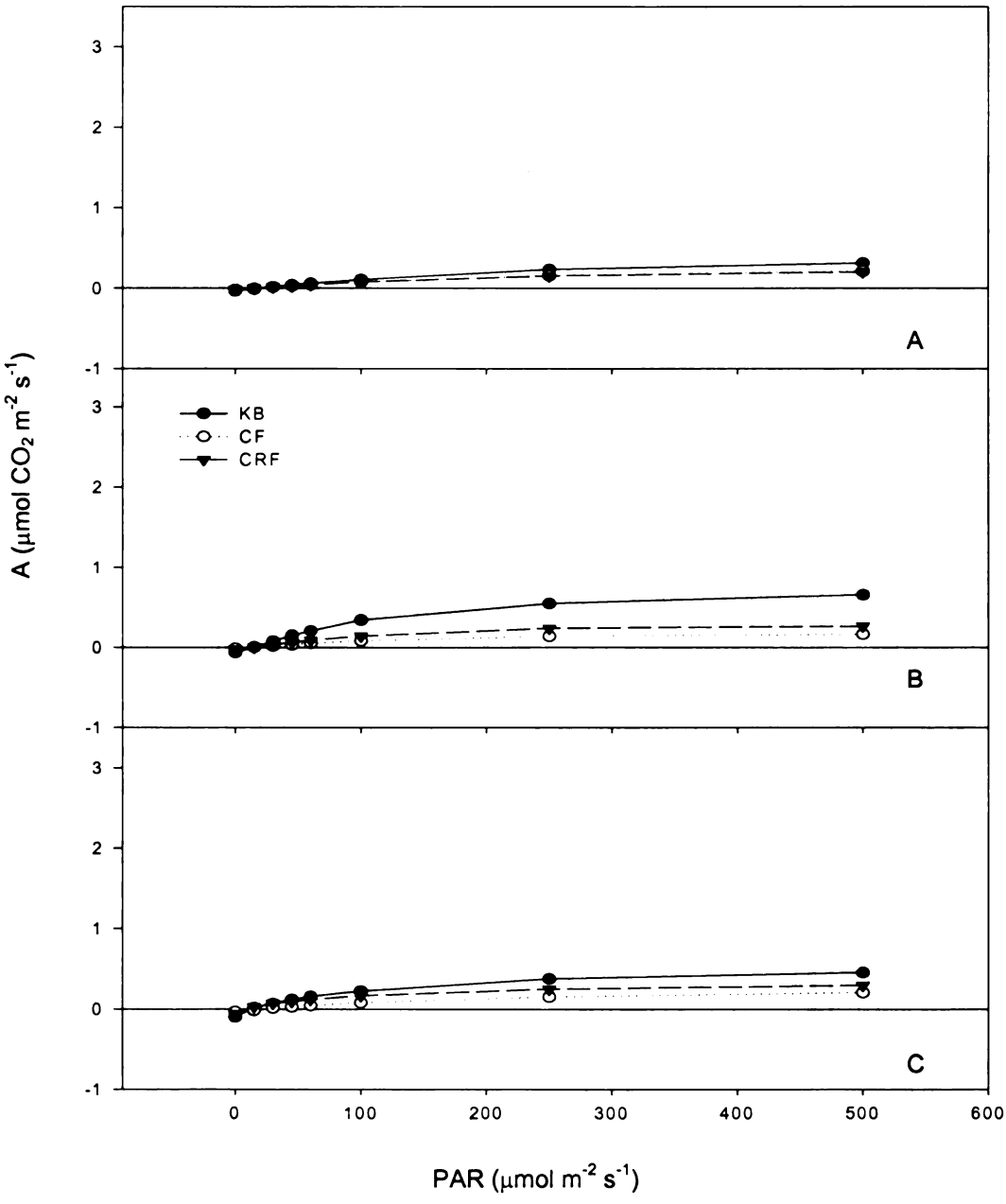

Figure 4.6 Combined fructose and control assimilation (A µmol CO_2 m^{-2} s^{-1}) over varying photosynthetic active radiation (PAR µmol m^{-2} s^{-1}) under 4 mol m^{-2} d^{-1} light response curves at A) week three, b) week five, and c) week seven for chewings fescue 'SR5100' (CF) (*Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF) (*Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB) (*Poa pratensis*).

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Thesis Conclusion

Throughout each experiment exogenous fructose applications had a significant positive impact on particular growth and metabolism variables of each of the three species under the various shaded growth environments (i.e. simulated dome, controlled environment growth chamber, or greenhouse). Additionally, exogenous fructose applications were found to increase photosynthesis initially after application under supplemental light for chewings fescue 'SR5100', creeping red fescue 'Dawson', and Kentucky bluegrass 'Cynthia'. In these combinations, the effects of exogenous fructose were species and light dependent.

Available light energy greatly impacted growth and metabolism in each experiment, as illustrated by the increase in response variables from ambient or low light conditions to supplemental or higher light conditions. These results indicate a light threshold level required to maintain growth under shaded conditions, which is not maintained under ambient light conditions under sports dome conditions. Also, this work suggests the required light threshold may differ by species due to species being a dependent factor.

This research raises many questions relating to exogenous fructose applications on turfgrasses under shaded conditions. If exogenous fructose applications increase photosynthesis initially, can we time the applications in the fall so that the stored excess fructose from the applications will increase reserves in the spring? Can the previous altering of storage reserves prior to winter dormancy determine how long fructose is stored in the plant? Can timing of fructose applications provide practical usage for short interval applications, with extended benefits?

Appendix I

Dome Experiment Significant Tables

Table I-I Means specific clipping weight (grams m^{-2}) at week fifteen under ambient light (AL 5-10 µmol m^{-2} s^{-1}), supplemental low light (SLL 32 µmol m^{-2} s^{-1}), and supplemental high light (SHL 73 µmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*) and creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*).

	AL		SLL		SHL	
Fructose	CF	CRF	CF	CRF	CF	CRF
F1	0.22a	0.17a	2.36a	3.14a	1.89a	2.30a
NF	0.16a	0.17a	2.80a	3.52a	2.55a	2.43a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.
F1, fructose 1x/week; NF, no fructose (control).

Table I- II Means specific clipping weight (grams m^{-2}) week and fructose treatment interaction under ambient light (AL 5-10 µmol m^{-2} $s^{-1}$for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*) and creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*).

Week	Fructose	AL
1	F1	3.72a
3	F1	1.54b
5	F1	0.28c
9	F1	0.23c
12	F1	0.29c
15	F1	0.19c
1	NF	5.24a
3	NF	1.18b
5	NF	0.16c
9	NF	0.18c
12	NF	0.52c
15	NF	0.16c

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.
W, week; F, fructose.
F1, fructose 1x/week; NF, no fructose (control).

Table I-III Means specific density (tillers cm^{-2}) at week fifteen under ambient light (AL 5-10 µmol m^{-2} s^{-1}), supplemental low light (SLL 32 µmol m^{-2} s^{-1}), and supplemental high light (SHL 73 µmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*) and creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*).

	AL		SLL		SHL	
Fructose	CF	CRF	CF	CRF	CF	CRF
F1	1.13a	1.18a	1.48a	1.88a	2.27a	2.27a
NF	1.23a	1.43a	1.49a	2.17a	2.22a	2.27a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.
F1, fructose 1x/week; NF, no fructose (control).

Table I-IV Means specific density (tillers cm^{-2}) for week by fructose by species interaction supplemental low light (SLL 32 µmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*) and creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*).

		SLL	
Week	Fructose	CF	CRF
1	F1	2.86a	3.55a
5	F1	2.61a	2.91a
10	F1	2.76a	2.07a
15	F1	1.48b	1.87b
1	NF	3.35a	2.66ab
5	NF	2.51a	2.22b
10	NF	1.82b	2.51ab
15	NF	1.48b	2.17b

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.
F1, fructose 1x/week; NF, no fructose (control).

Table I-V Means specific density (tillers cm^{-2}) at week four under ambient light (AL 5-10 µmol m^{-2} s^{-1}) and supplemental low light (SLL 32 µmol m^{-2} s^{-1}) for Kentucky bluegrass 'Cynthia' (KB *Poa pratensis*).

	AL	SLL
Fructose	KB	KB
F1	0.54a	1.03a
F2	0.59a	1.04a
NF	0.49a	0.88a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.
F1, fructose 1x/week; NF, no fructose (control).

Table I-VI Means specific narrow band vegetative index 695 ((R970-R695)/(R970+R695)) for fructose and species interaction under ambient light (AL 5-10 µmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*) and creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*).

	AL	
Fructose	CF	CRF
F1	-0.25	-0.24
NF	-0.24	-0.28

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.
F1, fructose 1x/week; NF, no fructose (control).

Table I-VII Means specific red-edge vegetative index ((R714+R759)/(2-R733)) for week, fructose, and species interaction under ambient light (AL 5-10 µmol m^{-2} s^{-1}) and supplemental low light (SLL 32 µmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*) and creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*).

		AL		SLL	
Week	Fructose	CF	CRF	CF	CRF
3	F1	-0.02a	-0.02a	-0.02 a	-0.02a
6	F1	-0.02a	-0.03a	-0.02 a	-0.03a
9	F1	-0.04c	-0.03a	-0.02 a	-0.02a
12	F1	-0.05c	-0.04b	-0.03 a	-0.02a
15	F1	-0.03a	-0.02a	-0.04 b	-0.04b
3	NF	-0.03a	-0.02a	-0.02 a	-0.02a
6	NF	-0.03a	-0.03a	-0.02 a	-0.02a
9	NF	-0.04b	-0.04b	-0.01 a	-0.01a
12	NF	-0.04b	-0.04b	-0.02 a	-0.01a
15	NF	-0.04b	-0.03a	-0.04 b	-0.02a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.
F1, fructose 1x/week; NF, no fructose (control).

Appendix II

Growth Chamber Experiment Significant Tables

Table II-I Mean specific maximum assimilation (mmol CO_2 m^{-2} s^{-1}) for week by fructose interaction under supplemental low light (SLL 40 µmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB *Poa pratensis*).

		SLL	
Week	F1	F2	NF
3	0.76a	0.53a	0.83a
5	0.22b	0.31b	0.27b
7	0.77a	0.32b	0.57ab

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.
F1, fructose 1x/week; F2, fructose 2x/week; NF, no fructose (control).

Table II-II Mean specific maximum assimilation (mmol CO_2 m^{-2} s^{-1}) for week by species interaction under supplemental low light (SLL 40 µmol m^{-2} s^{-1}) for chewings fescue 'SR 5100' (CF *Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF *Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB *Poa pratensis*).

		SLL	
Week	CF	CRF	KB
3	1.78a	0.95b	1.09a
5	0.71b	0.88b	1.21a
7	0.66b	1.11a	1.28a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.

Appendix III

Greenhouse Experiment Significant Tables

Table III-I Mean specific clipping weight (grams m^{-2}) for fructose by species interaction under 8 mol m^{-2} d^{-1} for chewings fescue 'SR 5100' (CF) (*Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF) (*Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB) (*Poa pratensis*).

	8 mol m^{-2} d^{-1}		
Trt	CF	CRF	KB
F1	15.7a	18.9a	22.3a
F2	11.6b	15.5b	22.4a
NF	20.2a	18.3a	12.9b

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.
Trt, treatment; F1, fructose 1x/week; F2, fructose 2x/week; NF, no fructose (control).

Table III-II Mean specific clipping weight (grams m^{-2}) for fructose, week, and species interaction under 8 mol m^{-2} d^{-1} for chewings fescue 'SR 5100' (CF) (*Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF) (*Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB) (*Poa pratensis*).

Week	Trt	CF	CRF	KB
1	F1	11.6b	15.5b	4.9c
3	F1	11.2b	12.7b	13.3b
5	F1	10.3b	9.48c	16.5b
7	F1	29.6a	37.36a	54.7a
1	F2	8.39b	7.31b	10.1b
3	F2	9.84b	10.6b	11.2b
5	F2	8.11b	10.8b	17.1b
7	F2	20.3a	33.2a	51.3a
1	NF	9.29c	8.39c	10.9b
3	NF	12.1b	13.2b	3.1c
5	NF	12.7b	11.3b	7.8b
7	NF	46.7a	40.4a	29.9a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.
Trt, treatment; F1, fructose 1x/week; F2, fructose 2x/week; NF, no fructose (control).

Table III-III Mean specific density (tillers cm^{-2}) week and species interaction and by species under 4 mol m^{-2} d^{-1} for chewings fescue 'SR 5100' (CF) (*Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF) (*Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB) (*Poa pratensis*).

Week	CF	CRF	KB
1	0.81b	0.81b	1.32b
3	1.71a	1.26a	2.06a
5	1.59a	1.19a	2.2a
7	1.68a	1.23a	2.77a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.

Table III-IV Mean specific Amax (µmol CO_2 m^{-2} s^{-1}) for week, fructose, and species interaction under 10 mol m^{-2} d^{-1} for chewings fescue 'SR 5100' (CF) (*Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF) (*Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB) (*Poa pratensis*).

		10 mol m^{-2} d^{-1}		
Week	Trt	CF	CRF	KB
3	F1	0.83b	0.44b	1.06b
5	F1	0.89b	0.68b	1.66b
7	F1	1.86c	2.03a	3.43a
3	F2	0.65b	0.64b	1.24b
5	F2	0.88b	0.79b	1.83b
7	F2	1.45a	1.92a	3.25a
3	NF	0.66b	0.69c	1.48b
5	NF	1.31a	5.94a	1.51b
7	NF	1.81a	1.86b	4.04a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.
Trt, treatment; F1, fructose 1x/week; F2, fructose 2x/week; NF, no fructose (control).

Table III-V Mean specific quantum efficiency (μmol CO_2 m^{-2} s^{-1}/mol PAR) for week, fructose, and species interaction under 4 mol m^{-2} d^{-1} for chewings fescue 'SR 5100' (CF) (*Festuca rubra v. commutata*), creeping red fescue 'Dawson' (CRF) (*Festuca rubra v. rubra*), and Kentucky bluegrass 'Cynthia' (KB) (*Poa pratensis*).

		4 mol m^{-2} d^{-1}		
Week	Trt	CF	CRF	KB
3	F1	0.0008b	0.001a	0.001b
5	F1	0.0008b	0.002a	0.004b
7	F1	0.001a	0.002a	0.29a
3	F2	0.0009b	0.001b	0.001a
5	F2	0.001a	0.002b	0.005a
7	F2	0.001a	0.17a	0.004a
3	NF	0.0008b	0.0009b	0.003a
5	NF	0.001a	0.002a	0.004a
7	NF	0.001a	0.007a	0.003a

Note: Means within column followed by the same letter are not significantly different at the 0.05 level. Mean differences were determined by Tukey's studentized range test.
Trt, treatment; F1, fructose 1x/week; F2, fructose 2x/week; NF, no fructose (control).

Appendix IV

Commercial Products and Suppliers

Apogee Instruments Inc. 82 Crockett Ave., Logan, Utah 84321. Phone: (435) 792-4700.

BannerMaxx®. Sygenta Corporation. 2200 Concord Pike, PO Box 8353, Wilmington, Delaware 19803. Phone: (302) 425-2000.

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Gylling Data Management Inc. Agriculture Research Manager (ARM). 405 Martin Boulevard, Brookings, South Dakota 57006.

Isoclear®. Cargill Sweeteners. Box 1400A, Dayton, Ohio 45413. Phone: (937) 237-1268.

LICOR® Biosciences, 4421 Superior St., Lincoln, NB 68504, USA.

Ludvig Svennson Inc. 1813 Associates Ln. Suite E., Charlotte, North Carolina 28217. Phone: (704) 357-0457.

Microsoft Corporation. One Microsoft Way. Redmond, Wash. 98052.

PP Systems. CIRAS Portable Photosynthesis System. 110 Haverville Road, Suite 301, Amesbury, Mass. 01913 Phone: (978) 834-0505.

Priva CD 750. Priva Computers Inc. 3468 South Service Road, Vineland Station, Ontario, Canada. Phone: (905) 562-7351.

R&D Sprayers. 419 Highway 104, Opelousas, Louisiana 70570. Phone: (337) 942-1001.

SAS (Statistical Analytical Software). 2002. SAS Institute Inc., 100 SAS Campus Drive, Cary, North Carolina 27513. Phone: (919) 677-8000.

Spectrum Technologies, Inc. Watchdog Data Logger Model 450. 12360 South Industrial Dr., East - Plainfield, Illinois 60585.

Toro Company. Consumer Division, 8111 Lyndale Avenue South, Bloomington, Minn. 55420.


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