Turfgrass Water Use and Photosynthesis in Controlled Environments

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Abstract

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Water use by turfgrasses is important because it impacts land use decisions and the potential use of natural turfgrasses in enclosed stadia. To determine turfgrass water use the evapotranspiration (ET) and photosynthesis rates were measured for different turfgrasses under different soil water conditions in a controlled environment with artificial lights. Application of abscisic acid reduced Kentucky bluegrass (KBG) ET, photosynthesis rates and it also reduced turfgrass growth and turfgrass greenness. Amongst tall fescue, Kentucky bluegrass and perennial ryegrass, tall fescue had the highest ET and photosynthesis rates. Five KBG cultivar blends varied in ET and photosynthesis rates when maintained at bin capacity, analogous to field capacity, and below bin capacity conditions. The KBG cultivar blend with the lowest ET in both conditions was the 'Turfgrass Water Conservation Alliance (TWCA)' blend. The KBG cultivar blend with the highest ET at bin capacity was Lowmow, while at below bin capacity was 4-Way. Turfgrasses in bins maintained at bin capacity used less water during daytime than turfgrasses in bins below bin capacity and had higher relative night time ET rates: 44.8% of daytime compared to 34.7 % for below bin capacity. The KBG cultivar blend bred for staying green in drought conditions, TWCA, had lower ET and photosynthesis rates than standard KBG cultivar blends.

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Table of Abbreviations

Abbreviation	Description
CB	Creeping Bentgrass
CHS	Canopy Height Sensor
DCO_2	Light Off Carbon Dioxide Balance
DET	Light Off Evapotranspiration
ET	Evapotranspiration
ET_a	Actual Evapotranspiration
ET_c	Calculated Evapotranspiration
ET_{Day}	Full day Evapotranspiration
ET_e	Estimated Evapotranspiration
KBG	Kentucky Bluegrass
LCO_2	Light On Carbon Dioxide Balance
LET	Light On Evapotranspiration
NCER	Net Carbon Exchange Rate
PR	Perennial Ryegrass
RWC	Relative Water Content
TF	Tall Fescue
VPD	Vapour Pressure Deficit
VWC	Volumetric Water Content
WM_B	Water Mass Below Capacity
WM_c	Water Mass Capacity
ΔWM	Change Water Mass
$\%WM\Delta$	Percent Water Mass Change
WUE	Water Use Efficiency

Chapter 1: Introduction

The study of plant transpiration is necessary with global climate change and population distribution changes altering the distribution of water resources (Pickard et al. 2017). At the local and regional levels, water availability will change with time and result in water irrigation restrictions (Mashhadi Ali et al. 2016; Milman and Polsky 2016). Evapotranspiration is the combination of water lost from the plant by transpiration and water lost from the surface by evaporation. The plant transpiration rate is influenced by a range of abiotic and biotic factors. In urban areas, plants grown in both polycultures and monocultures are often irrigated to maintain plant quality and function (Pannkuk 2015). One of the most prevalent plant types in urban areas is turfgrass (Milesi et al. 2005). Turfgrasses form key components of urban areas in the form of lawns, park greenspaces, golf courses and sports fields (Milesi et al. 2005). ET rates of turfgrass are important for understanding water needs and for developing corresponding restrictions and legislation based on agronomic needs.

Participants in major sporting events indoors and outdoors desire natural turfgrasses on which to play (Roberts et al. 2014). Modern indoor stadia have been engineered to handle the humidity produced by turfgrasses although actual ET rates of turfgrasses growing in the indoor environment are not known. The limited ability to control humidity makes retrofitting older stadia to grow turfgrass difficult. It is important to understand transpiration of natural turfgrass in controlled environments such as greenhouses and indoor stadia in the context of plant health and structural longevity of the stadia.

Transpiration and photosynthesis rates of a turf stand can be dependent on biotic and abiotic factors. Within cool-season grasses, ET rates differ by species and by cultivar within the same species (Green et al. 1990; Zhang et al. 2007). Studies that examined ET rates of different cultivars of Kentucky bluegrass showed differences among cultivars (Shearman 1986; Ebdon et al. 1998b). Plant-available soil water content can also affect ET rates. The higher the plant-available soil water content the higher the ET rate, while lower plant available soil water content decreases the ET rate for six turfgrass species (Zhang et al. 2007).

Certain plant hormones can have an effect on ET rates, as shown by Elansary and Yessoufou (Elansary and Yessoufou 2015), who found that the application of abscisic acid (ABA) reduced ET rates relative to the untreated control in the warm-season turfgrass species seashore paspalum (cv. Sea spray). This was the case for most cutting heights and irrigation conditions that were tested. In cool-season turfgrasses, there is little research on how the application of ABA influences the ET rate when not subjected to a drought condition (McCann and Huang 2008).

Turfgrass ET rates are traditionally recorded over long time intervals. Most studies record ET rates at time course measurements from a single day (Aronson et al. 1987b; Sun et al. 2013) and upwards to a whole growing season or duration of the experiment (Cathey et al. 2011; McGroary et al. 2011). There are few turfgrass studies that measure ET rates or photosynthesis on an hourly basis within a twenty-four-hour time-course. The measurement of ET and photosynthesis on an hourly basis would allow for a more accurate understanding of fluctuations within a day, which is important for maintaining a stable humidity in an enclosed environment. The current literature for turfgrass lacks a comparison between day/light-on and night/light-off environments, which does not allow for the adjustment to different humidity loads in a controlled environment. Additionally, previous studies that measured cool-season turfgrass ET rates used an uncommon rootzone of fritted clay (Shearman 1986; Kim and Beard 1988; Green et al. 1990;

Bowman and Macaulay 1991; Salaiz et al. 1991; Fernandez and Love 1993; Qian et al. 1996; Ebdon et al. 1998b; Huang and Fu 2000).

This thesis was designed to add to limited existing information about turfgrass ET rates and photosynthesis. Both ET and photosynthesis rates are reported at hour-long intervals over a number of days. This thesis also reported the differences in turfgrass ET rates when subjected to day and night conditions. The usefulness of application of ABA to reduce ET rates in turfgrasses in KBG when grown under non-drought conditions was also determined.

Experiment 1 examined the impact of ABA application on turf stand ET and photosynthesis rates by comparing the ET and photosynthesis rates of turfgrass before and after ABA application.

Experiment 2 examined the differences in ET and photosynthesis rates of three seeded cool-season grasses: Kentucky bluegrass (KBG), perennial ryegrass (PR), and tall fescue (TF) subjected to field capacity conditions.

Experiments 3 and 4 examined the differences in ET and photosynthesis rates between different sodded cultivar blends of KBG subjected to either field capacity conditions (Experiment 3) or below field capacity (Experiment 4). The results from Experiment 3 and Experiment 4 were compared to determine the effect of soil water content on turfgrass ET rates.

Chapter 2: Literature Review

In urban areas water use restrictions are becoming more common based on either real or perceived local water shortages (Kenney et al. 2004; Atwood et al. 2007; Beal et al. 2014; Tsuda et al. 2014; Milman and Polsky 2016; Choi et al. 2017; Manago and Hogue 2017). The plant species composition in an urban environment can determine the amount of water consumed in a given landscape area (Lowry et al. 2011; Nouri et al. 2013; Litvak et al. 2017). Models of plant ET rates in urban environments rely on estimates of ground cover of each type of plant and crop coefficients in a given geographical area (Lowry et al. 2011; Nouri et al. 2013; Litvak et al. 2017). Plants with lower water use needs that can remain visually acceptable under dry conditions might become preferred plants in an urban setting (Domenghini et al. 2013).

2.1 ET Rate Determinations

ET rates are determined in a number of different ways. A common way of predicting turfgrass watering needs that is currently in use by turfgrass managers is to calculate ET rates using the Penman-Montieth Equation, or a derivation of this equation, with a previously calculated crop coefficient. This leads to an estimated ET rate, or ET_e. Another method is to calculate ET based on a water-balance using a modifiable base equation, leading to a calculated ET rate, or ET_c. The most accurate method of determining ET rate is gravimetrically measuring water loss from a container directly, resulting in an actual ET rate, or ET_a. The method used to calculate or determine ET rate can impact the regulation of water use in managed turfgrasses in the landscape. Recent work shows that ET rates can vary based on a number of factors that are not included in the current methods for calculating ET, including the Penman-Montieth Equation (Poro et al. 2017).

2.1.1 The Penman-Montieth Equation

$$\lambda E^{*} = \frac{c_v\lfloor e_{sat}(T_s) - e_a \rfloor}{\gamma r_V}$$

The Penman-Montieth Equation is used to determine the amount of water evaporation from a leaf canopy at a given time. The Penman-Montieth Equation provides a calculation tool to estimate potential ET rates (Widmoser 2009). In the equation shown above, λ (J kg^{-1}) is the latent heat of vaporization, c_v (Jm^{-3} K^{-1}) is the volumetric heat capacity of moist air at constant atmospheric pressure, T_s (ºC) is the surface temperature, e_{sat} is the vapour pressure of the air at saturation, e_a (Pa) is actual vapour pressure, γ (Pa K^{-1}) is the psychrometric coefficient that is dependent on surface temperature and atmospheric pressure, and r_v (s m^{-1})is the mass transfer resistance for water vapour (Widmoser 2009).

The Penman-Montieth Equation can also be written as:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2(e_s - e_a)}{\Delta + \gamma \cdot (1 + 0.34u_2)}$$

In this equation, ET_o (mm/d) is the potential evapotranspiration per day, R_n (MJ m^{-2} day^{-1}) is the net radiation at the surface of the crop, G (MJ m^{-2} day^{-1}) is the soil heat flux density, T (ºC) is the mean air temperature at 2m above the surface, Δ (kPa $°C^{-1}$) is the slope of the saturation of vapour pressure vs temperature curve, γ (Pa K^{-1}) is the psychrometric coefficient, e_s (Pa) is the vapour pressure of the air at saturation, e_a (Pa) is actual vapour pressure, and μ is the horizontal wind speed (m s^{-1}) (Malamos et al. 2015). This estimation of ET rates using climatic variables has been used extensively to predict water use of turfgrasses (Qian et al. 1996; Barton et al. 2009; Pannkuk et al. 2010; Aamlid et al. 2016). The equation assumes that turfgrass canopies behave similarly despite differences in density and canopy height, but recently this has been shown to be inaccurate (Poro et al. 2017). In addition, these estimations assume natural radiation, measured temperatures and wind speeds above the canopy, none of which are useful for enclosed environments such as growth chambers, greenhouses, and indoor stadia (Zhang et al. 2010). Water use in growth chamber experiments cannot be used to determine the Penman-Montieth Equation because the height of the growing surface to the top of many growth chambers is often less than the 2m, which is typically required for measurement of temperature and wind speed. In addition, it is difficult to measure wind speed indoors, particularly in a growth chamber, thus making the Penman Montieth Equation not applicable.

2.1.2 Calculated ET (ET_c)

Calculated ET (ET_c) rates rely on the measurement of primary and secondary variables to determine ET rates. The primary measured variables usually include irrigation (I), precipitation (P) and soil moisture or soil water storage changes (ΔSW, ΔW, or ΔS) (Carrow 1995; McGroary et al. 2011; Candogan et al. 2015; Aydinsakir et al. 2016). Irrigation measurements are recorded by water meters (Candogan et al. 2014, 2015; Aydinsakir et al. 2016). In most experiments the precipitation data are collected from an onsite or nearby weather station (Candogan et al. 2014, 2015; Aydinsakir et al. 2016). Soil moisture or soil water storage values are measured with permanent or portable devices including neutron probes with installed tensiometers (Candogan et al. 2014, 2015) or Time-Domain Reflectometer (Carrow 1995; Aydinsakir et al. 2016). The secondary variables that are initially in the ET rate equations include deep percolation (Dp), surface runoff (RO), capillary rise (CR), drainage loss (L), ground water storage ($\Delta G'$), and water transferred in or out of the root zone horizontally by subsurface flow (ΔSF) (Candogan et al. 2015). However, these variables are often removed because the measurements are too impractical to measure. In Carrow (1995) the original ET rate equation was:

$ET = P + I - (RO + \Delta G' + \Delta W - L)$, but was then revised to $ET = I + \Delta W$, based on conditions of the study and removal of the secondary variables. This is considered acceptable as previous research has shown water does not leave the soil column below 60cm, allowing the removal of $\Delta G'$ and L from the ET rate equation. Additionally, the applied irrigation rates do not result in any observable RO, allowing this variable to also be removed from the equation (Carrow 1995).. Aydinsakir et al. (2016) used the following equation to calculate ET:$ET_a = I + P - Dp \pm \Delta SW$. The equation was left unchanged for the calculation of ET (Aydinsakir et al. 2016). Irrigation remained in the equation because it was measured using water meters. Precipitation remained because it was measured at the onsite weather station. Deep percolation remained because the effective rooting depth was assumed to be 0.3 m. Soil water content remained because average rootzone water uptake in Bermudagrass occurred at a depth of 15 cm and was the length of the soil probes.

Candogan et al. (2015) used the following equation initially to determine ET:

$ET = I + P - RO - DP + CR \pm \Delta SF \pm \Delta SW$. RO was removed from the equation because sprinkling rate was below infiltration rate. The variables CR and ΔSF were effectively considered zero based on the difficulties in measuring each one. With the consideration of some values being effectively zero, the functional equation was reduced to (Candogan et al. , 2015):

$ET = I + P - DP \pm \Delta SW$. The equation from Candogan et al. (2014) was: $ET_c = I + P + \Delta S - R - D$

In turfgrass research Fernandez and Love (1993) used the Gompertz model to analyze ET rates of different species and cultivars in dry-down experiments.

> "Gompertz model is, Y =aexp[-bexp(-kt)]; where Y = predicted ETcum, t = adjusted days (ETcum at ith day/mean pan evaporation/day); a = the asymptote, theoretical maximum value for Y; and b and k are constants with different values for different cultivars. The Gompertz model is a sigmoid curve and is asymmetrical about the inflection point where the change in ET rate is zero. ETcum components can be estimated from the Gompertz model parameters a, b, and k. ET rate is kYloge(aY-1). ETmax in the Gompertz model occurs when the rate of change in ET rate is 0 at the curve, ti= (loge b)k-1and its value is ETmax= (ka)e-1 (Tipton, 1984).(Fernandez and Love 1993)".

2.1.3 Actual ET (ET_a)

One of the ways of determining ET_a rate is the gravimetric method. The procedure for this method is outlined in Bowman and Macaulay (1991) and begins with recording the initial weight of each turfgrass container on a balance, followed by adding water to each container to maintain non water-limiting conditions. The containers are then weighed again once drainage stops and then weighed again the following day. The time difference between the second measurement and the one from the previous day was assumed to be twenty-four hours when it was functionally twenty-two hours. In controlled environments such as greenhouses, growth chambers, or field conditions under a rain-out shelter, the amount of added water is controlled through human or mechanical means. In field trials that are conducted without rainout shelters, either days with precipitation are included within the applied water value (Feldhake et al. 1983), or the lysimeters are weighed at the next available date with two consecutive days without rain. The rootzone containers or lysimeters can range in size depending on the study. The rootzone materials used in this method can also vary and can include fritted clay (Shearman 1989, 1986; Aronson et al. 1987b; Kim and Beard 1988; Green et al. 1990, 1991; Atkins et al. 1991; Bowman and Macaulay 1991; Salaiz et al. 1991; Beard et al. 1992; Ebdon et al. 1998b), sand with peat moss (Feldhake et al. 1983; Fry and Butler 1989) and local soil (Aronson et al. 1987b; Kopec et al. 1988; DaCosta and Huang 2006; Zhang et al. 2007; Cathey et al. 2013; Domenghini et al. 2013; Fuentealba et al. 2016).

2.2 Factors affecting ET rates

Evapotranspiration is the combination of water loss from the growing medium through evaporation and the plant through transpiration. In the natural environment, there are many factors that can affect evapotranspiration. These include environmental conditions, water availability, stomatal density, nutrient availability, increased carbon dioxide concentration, relative shoot density, different plant hormones and the salinity of irrigation water. Factors that contribute to altered evapotranspiration include relative plant age, vapour pressure deficit, nutrients and temperature (Su et al. 2007; Barton et al. 2009; Wherley and Sinclair 2009; Erickson and Kenworthy 2011). One of the most important factors that influences ET rate is soil water content (Irmak 2015). In general, the factors that affect ET rates can be classified as either abiotic or biotic.

2.2.1 Abiotic factors

Abiotic conditions that affect ET rates include wind speed, solar radiation, non-differentiated environmental factors, air temperature and air vapour pressure, air CO_2 concentrations, soil nutrients, and soil water content with plant available soil moisture. Each is discussed below in greater detail.

2.2.1.1 Wind Speed, Solar radiation

Solar radiation and wind speed have both been shown to increase ET rates as they increase. Increasing wind speed from 0.3 m/s to 1.0 m/s led to an increase in ET_c rates in young tomato (*Solanum lycopersicum* cv. Momotaro) transplants (Thongbai et al. 2010). In the

Penman-Monteith equation, if incoming radiation is above a given threshold combined with increased wind speeds, there is a decline in transpiration rates. Similarly, greenhouse-grown cucumber (*Cucumis sativus* L. *cv.* Jinyan 4) ET_a rates were positively correlated with increased solar radiation (Zhang et al. 2010).

2.2.1.2 Temperature and Vapour Pressure Deficit

Air temperature and vapour pressure deficit (VPD) are two linked environmental conditions that can influence plant ET rates. VPD is the difference between the actual vapour pressure and the saturated vapour pressure at a given air temperature (Wherley and Sinclair 2009). VPD is calculated using relative humidity and air temperature (Cathey et al. 2013; Weaver and van Iersel 2014). The VPD can be changed by varying the temperature (Ebdon et al. 1998a, 1998b) or humidity (Leonardi et al. 2001; Wherley and Sinclair 2009) of the study area. Sermons et al. (2012) studied the effects that temperature and vapour pressure deficit had on tall fescue's ability to regulate water use. The warmer temperatures resulted in a greater ET_a rate, regardless of VPD. This is due to the stomata acclimating to increased VPD to maintain homeostatic carbon balance (Marchin et al. 2016). Also, the tall fescue cultivars tested were able to acclimate by increasing their ET_a rates at increased VPD when VPD was raised from 0.75 kPa to 1.8 kPa. Wherley and Sinclair (2009) showed that ET_a rate increased linearly in response to increased VPD in C4 grasses. In comparison, C3 grasses showed a linear increase in ET_a in response to increasing VPD initially, but then rates levelled off, leading to a plateau portion of the curve. In a semi-controlled greenhouse environment, the variation in temperature contributed to 64% of the variation in ET_a rates for all eleven KBG cultivars tested (Ebdon et al. 1998b). In hybrid Texas-KBG 'Thermal Blue', Apollo KBG, and Dynasty TF species, a high temperature environment (35/25°C,day/night) increased well-watered turfgrass ET_a rate when compared to the control temperature environment (22/15°C, day/night) (Su et al. 2007). In conclusion, increasing air temperature and VPD positively impact ET rate of turfgrasses.

2.2.1.3 CO_2 Concentrations

Some studies investigated the effects of increased carbon dioxide levels on plant evapotranspiration to simulate the effects of climate change. When examining rice fields treated with a controlled level of CO_2, Shimono et al. (2013) found the increased CO_2 concentrations and accompanying temperature increases to reduce ET_c rate by 5%. In areas with increased CO_2 the ET_c rates of vascular plants were reduced (Heijmans et al. 2001). Wilson et al. (1999) found increased CO_2 levels decreased stomatal gas exchange primarily at the leaf level . Conley et al. (2001) found increases in CO_2 levels decreased ET_c of sorghum in both well-watered and dry conditions and both temperature environments. In young tomato (*Solanum lycopersicum* cv. Momotaro) transplants grown in a growth chamber, increased CO_2 resulted in significant decreases in ET_c rates (Thongbai et al. 2010). These various studies suggest that increases in localized atmospheric levels of CO_2 can reduce ET rates of plants.

2.2.1.4 Nutrients

The addition of nutrients can have positive effect on overall ET rate, especially nitrogen, potassium, and phosphorus. Barton et al. (2009) found that increased nitrogen application on Kikuyu turfgrass resulted in increased ET_a rates. Rudnick and Irmak (2014) found increased application of nitrogen resulted in increased ET_c rates in field-grown corn. Erickson and Kenworthy (2011) found nitrogen application resulted in increased ET_a rates of two Zoysiagrass cultivars studied. The plants that received a single application of nitrogen resulted in a reduced quality of turf and lower ET_a rates than the plants that received two applications. ET_a rates per unit area decreased with a single nitrogen application. The plants that received a second nitrogen application had increased water use efficiency compared to the plants that received a single application of nitrogen. Candogan et al. (2015) showed that increased nitrogen application in non-water limiting situations increased ET_c rates of perennial ryegrass in addition to providing visual quality and increased clipping yields. Hernández et al. (2015) found increasing nitrogen applications in non-water limiting situations led to increased ET_c rates in corn, and Motalebifard et al. (2013) found the addition of phosphorus to a potato plant increased the ET_a/ET_c rates. Ebdon et al. (1999) studied the effects of different rates of N, P, and K independently and in combination on Majestic KBG in a field experiment under rain shelter conditions. When applied alone, nitrogen at five different rates resulted in increases in ET_a rates and turfgrass growth that correlated positively with increased application rate. In the subsequent study by Ebdon et al. (1999)that examined five rates of the three primary nutrients in combination, increased applications of K resulted in increased ET_a rates when N and P were applied at medium to high rates (294 kg/ha/year N and 43 kg P/ha/year to 589 kg/ha/year N and 86 kg/ha/year P). However, when increasing rates of K were applied to the turf while keeping KBG-recommended rates of N and P constant, the ET_a rates decreased which were related to decreased shoot growth (Ebdon et al. 1999). When studying the effect of N application on three cool season grass species (KBG, CB and PR), the crop coefficients of PR increased by 16% compared to the untreated control (Poro et al. 2017), while the N application did not affect it. Consequently, changes in either N or P availability to plants affected plant ET rates.

2.2.1.5 Soil Water Content and Plant Available Soil Water

Soil water content and plant available soil water are two abiotic factors that can impact ET rates of plants. Githinji et al. (2009) tested the water use of various tall fescue and hybrid bluegrass cultivars under different watering regimens, including 100% ET_c, 80% ET_c and 60% ET_c rates. The greatest ET_c rate was at the 100% ET replacement and the lowest was for the 60% ET watering treatment. Fernandez and Love (1993) tested the water use of a range of cool season turfgrasses under a gradual soil dry down. After the ninth day of gradual soil drying, based on the Gompertz model, the turfgrass ET_a rate steadily decreased. In an irrigation trial of a mango orchard, the rates of irrigation to percent pan evaporation were 70%, 80%, 90%, and 100% (da Silva et al., 2009). The lower the irrigation level the lower the ET_a rate (da Silva et al., 2009). Irmak (2015) found increases in soil water availability resulted in increased corn ET_c rates. Kuster et al. (2013) tested the effect of drought and soil type effects on simulated oak stands. When the soil dried out, the ET_c rate was reduced. Nektarios et al. (2014) found tall fescue ET_a rates to decline with reduced water availability. Djaman et al. (2013) found years with greater precipitation or fields with greater irrigation frequency had greater ET_c rates than those in fields with less precipitation or lower irrigation frequency. Fuentealba et al. (2016) found warm season turfgrass ET_a rates decreased after a critical point in the soil plant available water content was reached, and it varied between genera, species and cultivars of the same species. Overall, decreased soil water content and plant available soil water had a negative impact on the plant ET_a or ET_c rate.

2.2.2.1 Biotic factors: Plant Structure, Health and Cutting Height

Plant structure characteristics can impact on ET rates in turfgrasses. Kim and Beard (1988) found leaf structure to be a factor in Buffalograss (cv. Texas Common), Centipedegrass (cv Georgia Common), Bermudagrass (cv. Arizona Common) Bermudagrass (cv. Tifgreen), Bermudagrass (cv. Tifway), Seashore paspalum (cv. Adalayd), Zoysiagrass (cv. Meyer), St. Augustinegrass (cv.Texas Common), Zoysiagrass (cv. Emerald), Bluegrama (cv. Common), Bahiagrass (cv. Argentine) and Tall rescue (cv. Kentucky 31). Some factors that influenced the reduction of ET_a rates were shoot density, the number of leaves per unit area and leaf orientation. Leaf width and vertical leaf extension rate were factors that determined total evaporative surface. Turf canopies with increased horizontal growth and increased shoot or leaf densities decreased the movement of water from roots to leaf tips. The increased density and horizontal growth had reduced eddy covariant movements and resulted in a rise in the canopy internal humidity reducing VPD. Kim and Beard (1988) determined that increased shoot density of turfgrasses reduces ET_a rates in warm season grasses. Bowman and Macaulay (1991) found that ET_a rate differences between tall fescue cultivars increased with days after mowing. As the days after mowing increased, the size of the leaves increased, possibly leading to increased ET_a rates. Wherley et al. (2015) determined warm season grasses that remain healthy had increased ET_a rates relative to less healthy plants. Barton et al. (2009) found older (20 years) turfgrass stands had higher ET_a rates than younger ones (20 weeks). When studying 10 different St Augustine grass genotypes in the field, Atkins et al. (1991) found that shoot density was positively correlated to increased turfgrass ET_a rates. When studying the effect of cutting height on ET_a rates for three cool season grass species, Poro et al. (2016) noted that ET_a increased with increasing mowing height. Overall, plant morphology, plant health, and turfgrass height all have an impact on ET rate in turfgrass plants.

2.3 ET of Greenhouse Plants

Greenhouse environmental conditions range from semi-controlled to fully-controlled through automated climate systems. The studied responses for plants grown in greenhouse environments should be similar to growth-chamber-grown plants. The differences in abiotic conditions can affect plant ET rate. Tomatoes, cucumbers and sweet peppers are three of the most common commercially-grown food plants in greenhouse production. In a study of tomato ET rates in a greenhouse, the ET_a was greater for plants grown in the middle of the group at 248 $\mu g\ H_2Og^{-1}s^{-1}$ while plants on the perimeter had and ET_a of 191 $\mu g\ H_2Og^{-1}s^{-1}$ (Papadopoulos and Ormrod 1991). In a glasshouse study on closely related wild and cultivated tomato lines, night time ET rates under ambient conditions ranged from 8–33% of maximum daytime ET_a rates (Caird et al. 2007). Over the course of two 3-week greenhouse trials, cumulative transpiration of tomato plants (cv. Pannovy) under an actively-cooled environment was 713 L/m^2 compared to a passively cooled environment transpiration rate of 506-713 L/m^2 (Dannehl et al. 2014). In cucumbers (cv. Mustang) grown under greenhouse conditions, daily ET_a rates ranged from 1.83-3.12 L/m^2 of ground area during the day and night time hourly ET_a rates were 0.015-0.025 $Lh^{-1}m^{-2}$ of ground area (Yang et al. 1990). Over the course of a 115-day greenhouse trial on rock wool grown paprika (*Capsicum annuum* L. cv. Fiesta), plants treated with a low irrigation frequency at 160 J/cm^2 radiation had a cumulative ET rate of 130 L/m^2 versus plants treated with a high irrigation frequency at 120 J/cm^2 radiation that had a cumulative ET rate of 138 L/m^2 (Ta et al. 2012). The transpiration of rockwool-grown paprika (*Capsicum annuum* L. cv. Fiesta), with moisture content ranges of 80, 70, 60, and 50%, were 0.0038, 0.0038, 0.0035, and 0.0011 g/(cm^2·s) (Shin and Son 2015). The different ET rates of greenhouse plants indicated diversity of ET rates within controlled abiotic conditions.

2.4 Water Use of Turfgrasses by Species

Turfgrass ET rates are often determined in controlled growth chambers, greenhouses, and uncontrolled field conditions. Turfgrasses are divided into cool season and warm season grasses. The main metabolic difference between the two types of turfgrass is the type of photosynthetic pathways used to obtain carbon from the atmosphere. Cool season grasses use C3 photosynthesis, while warm season grasses use C4 photosynthesis.

2.4.1 Between Species ET Comparisons

The comparison of ET rates between species is well studied. These comparisons between species could be used to formulate recommendations on the species most suited for the intended growing region.

In a field trial in Colorado, Feldhake et al. (1983) maintained KBG (cv. Merion), Bermudagrass (cv.Tifway), TF (cv. Rebel) and Buffalograss (common) at a 2cm cutting height in bucket lysimeters under well-watered conditions. During the first two years of only growing KBG and Bermudagrass under the same conditions, Bermudagrass had ET rates 24% lower than KBG. Feldhake et al. (1983) noted that the differences in ET_a rates were connected to the differences in turfgrass morphology. The Bermudagrass grew in a compact mat with short horizontally growing leaves, while the KBG had an upright growth habit that was more open to air flow (Feldhake et al. 1983). The warm season grasses (Bermudagrass and Buffalograss) had ET_a rates that were about 20% less than the cool season grasses (KBG and TF) (Feldhake et al. 1983).

In a two-year field trial conducted in Rhode Island under well-watered conditions, the ET_a rates of KBG (cv. Baron and cv. Enmundi), PR (cv. Yorktown II), Chewings red fescue (cv. Jamestown) and hard fescue (cv. Tournament) were measured by weighing (Aronson et al. 1987b). The ET_a rates in the first year were highest for KBG (cv. Baron) at 3.50 mm/d and lowest for hard fescue (cv. Tournament) at 2.25 mm/day. The ET_a rates for KBG (cv. Enmundi), PR (cv. Yorktown II) and Chewings red fescue (cv. Jamestown) were the same in the first year of the study ranging from 3.38 to 3.40 mm/d. In the second year of the study, KBG (cv. Enmundi) had the highest ET_a rate at 4.14 mm/d and Chewings red fescue (cv. Jamestown) had the lowest ET_a rate at 3.58 mm/d. The ET_a rates of PR (cv. Yorktown II) and hard fescue (cv. Tournament) were the second highest at 3.96 mm/d and 3.93 mm/day, respectively. KBG (cv. Baron) had the third lowest ET_a rate of 3.65 mm/d in the second year. The weather during both study years was different and was assumed to be the reason for the relative change in ranking of the ET_a rates. Aronson et al. (1987b) state that the ET_a rates in the first were greater based on evaporative demand.

In a growth chamber study with well-watered conditions, nine species of cool season turfgrass had their ET_a rates measured. As a group KBG (cv.'s Bensun, Majestic, Merion) had the highest ET_a rates of 12.4 mm/day (cv. Bensun and Merion) and 11.9 mm/day (cv. Majestic) (Green et al. 1990). The group of fine fescues excluding sheep fescue had the lowest ET_a rates with hard fescue (cv. Waldina) at 7.4 mm/day and Chewings fescue (cv. Jamestown) at 7.7 mm/day. The other species had intermediate ET_a rates ranging from 8.4 mm/day for rough bluegrass (cv. Sabre) to 11.4mm/day for TF (cv.'s Rebel). The ET_a rates for the other turfgrasses were 9.1 mm/day for perennial ryegrass (cv. Manhattan II), 9.9 mm/day for TF (cv. Kentucky

31), 10.1 mm/day for creeping bentgrass (CB) (cv. Pencross), 9.8 mm/day for annual bluegrass and 9.3 mm/day for sheep fescue (cv. Big Horn) (Green et al. 1990).

In a well-watered and dry-down field experiment in Beijing City, China, the ET_a rates of three cool season grasses and three warm season grasses were measured. The three cool season grasses were KBG (cv. Nuglade), TF (cv. Hundog-5) and PR (cv. Advent), and the three warm season grasses were Bermudagrass (cv. Pers.), *Zoysiagrass japonica*(Japanese lawngrass) and Buffalograss (cv. Engelm) (Zhang et al. 2007); the experiment ran from May to December. The cool season turfgrasses had higher total ET_a than the warm season grasses for both irrigation treatments. The cool season grass with the highest total ET_a was TF (cv. Hundog-5) and the lowest was PR (cv. Advent). The warm season grass with the highest total ET_a was Bermudagrass and the lowest was *Zoysiagrass japonica*.

Kim and Beard (1988) conducted a field study comparing the ET_a rates of one cool season grass and eleven warm season grasses. The warm season grasses were Bermudagrass (cv. Arizona Common), Bermudagrass (cv.Tifgreen), Bermudagrass (cv.Tifway), Zoysiagrass (cv. Meyer), Zoysiagrass (cv. Emerald), Augustinegrass (cv. Texas Common), Centipedegrass (cv. Georgia Common), Seashore paspalum (cv. Adalayd), Bluegrama (cv. Common), Buffalograss (cv. Texas Common) and Bahiagrass (cv. Argentine). The only cool season grass was TF (cv. Kentucky 31). The turfgrass with the highest ET_a rate was TF (cv. Kentucky 31) for both study years at 7.1 and 5.1 mm/day. The warm season grasses had ET_a rates ranging from 5.3 mm/day for Buffalograss (cv. Texas Common) to 6.5 mm/day for Zoysiagrass (cv. Emerald) at the first year. During the second measurement period, warm season turfgrass ET_a ranged from 4.1 mm/day for Bermudagrass (cv.Tifway) to 5.1 mm/day for Seashore paspalum (cv. Adalayd).

Carrow (1995) studied the ET_c rates of turfgrasses in the Piedmont region of the US over a two-year period and irrigated the grasses when the soil moisture dropped below 14% volumetric soil water content. The turfgrasses studied were TF (cv. Kentucky-31 and cv. Rebel II), Bermudagrass (cv. Common and cv. Tifway), Zoysiagrass (cv. Meyer), St. Augustine (cv. Raleigh) and centipedegrass (common). Over the study period, the Bermudagrasses had significantly lower ET_c rates than both centipedegrass and TF (cv. Kentucky-31). Climatic conditions, soil moisture and turfgrass growth were determined to be the contributing factors to the differences in ET_c rates of each turfgrass. The maximum ET_c rates were up to 3.7 times greater than the minimum ET_c rates for any of the grasses grown.

Under well-watered and dry-down conditions in a greenhouse environment, Fuentealba et al. (2016) studied the ET_a rates of nineteen genotypes and cultivars within five species of warm season turfgrasses. The species studied were African Bermudagrass (cv. UFCT33 and cv. UFCT42), hybrid Bermudagrass (cv. TifSport), five common Bermudagrasses (cv. Celebration, cv. PI289922, cv. UFCD12, cv. UFCD295, cv. UFCD347 and cv. UFCD481), *Zoysia japonica* (cv. cv. DALZ4360, cv. DALZ5269-24, cv. Empire, cv. JaMur and cv. UF182) and Zoysia matrella (cv. PristineFlora, cv. UF374, cv. Zeon and cv.UF336). The daily ET_a rates were different both between and within species. In general, the well-watered St. Augustinegrass had the highest ET_a rates at 5.44 mm/day and the species with the lowest ET_a rates were African bermudagrass, *Zoysia japonica* and *Zoysia matrella* with ET_a rates of 4.25 mm/day, 4.28 mm/day and 4.34 mm/day, respectively. The differences in ET_a rates were attributed to differences in the morphology of the turfgrasses studied.

DaCosta and Huang (2006) studied the effect of different irrigation rates on different bentgrass species CB (cv.L-93), colonial bentgrass (cv. Tiger 2), and velvet bentgrass (cv.

Greenwich). At 100% ET_a replacement, colonial bentgrass had the highest ET_a during July and August. The ET_a rates of the field studied were different within and between years based on the seasonal climate.

2.4.2 Within Species ET Comparisons

When studying the ET rates within a single species, there are known cultivar differences. Cultivar ET differences for cool season grasses have been studied for Kentucky bluegrass (KBG), tall fescue (TF) and perennial ryegrass (PR).

Sod cuttings of twenty KBG cultivars that were grown on a fritted clay rootzone under well-watered conditions with ambient air temperature of 25ºC had an ET rate range of 3.86 mm/day (cv. Enoble) to 6.34 mm/day (cv.'s Birka, Sydsport and Merion) (Shearman, 1986). Under well-watered field conditions at college station Texas, twenty-four Bermudagrass cultivars over the course of three years had ET_a rates that ranged from 4.2 mm/day to 5.2 mm/day (Beard et al. 1992).

In a field trial, twelve cultivars of PR were seeded into mini-lysimeters and placed into field plots of the same cultivar (Shearman 1989). Under wilt-based irrigation conditions and a 50 mm cutting height, turfgrass ET_a was measured daily for four days at six periods from June of 1985 to May of 1986 (Shearman 1989). The mean daily ET_a rates varied seasonally with the cultivar (cv. Prelude) with the lowest ET rate having 4.93 mm/day in mid-september 1985 and the cultivar (cv. Linn) having the highest ET rate in 9.98 in mid-May 1986.

In a field trial, four turf-type and two forage-type cultivars of TF were seeded into minilysimeters and placed into field plot of the same cultivar (Kopec et al. 1988). Under wilt-based irrigation conditions and a 76 mm cutting height, turfgrass ET rate was measured daily for four days at four periods in a single growing season (Kopec et al. 1988). The mean daily ET_a rates of the turf types ranged from 21.0 mm/4days (cv. Rebel) in early September to 32.9 mm/4days (cv. Hounddog) in mid-July (Kopec et al. 1988).

In a greenhouse study, Bowman and Macaulay (1991) grew twenty TF cultivars to determine the weekly ET_a rates when the turfgrass was cut once a week at 50 mm. Over the seven-day period there was variation in the ET_a rates of the TF cultivars, and the forage-types cv. Alta and cv. Penngrazer having the highest ET_a rates of 70.1 mm/week and 67.9 mm/week, respectively. The cultivars with the lowest ET_a rates were the turf-types cv. Murietta, cv. Shortstop, and cv. Silverado at 61.6 mm/week, 61.5 mm/week and 60.2 mm/week, respectively.

2.4.3 Turfgrass ET Summary

The various research data presented in this section suggest that ET rates of turfgrasses are influenced by the species or cultivar within a turfgrass stand and their environment.. This genetic variability within and between turfgrass species allows for differences in plant functions, including ET. Many of these functions are regulated by plant hormones. Therefore, the final section of this review examines how plant hormone regulation, and specifically abscisic acid (ABA), affects ET rates in different turfgrass species.

2.5 ET and ABA Plant Hormone Regulation

One plant hormone that can affect ET rates of turfgrass and plants in general is ABA, a plant hormone that works to regulate various plant functions when the plant is under stress (Suzuki et al. 2016). ABA is upregulated in plants that are grown in stressful environments (Suzuki et al. 2016). The abiotic stresses that result in the upregulation of ABA include excess salt (NaCl) (Suzuki et al. 2016), heat (Li et al. 2014; Suzuki et al. 2016), drought (Zeevaart 1971, 1983; Schurr et al. 1992; Wang and Huang 2003; Wang et al. 2004; DaCosta and Huang 2007; Li et al. 2014), and cold (Talanova and Titov 1994; Bravo et al. 1998). ABA applied to plants can modify plant structure, and specifically it can reduce the size of the stomatal aperature (Franks 2001). Correspondingly, increased levels of ABA in plants can reduce stomatal conductance (Franks 2001; Wan and Zwiazek 2001; Aasamaa and Sõber 2011; Rogiers et al. 2012; Li et al. 2015) and ET_a (Aasamaa and Sõber 2011; Rogiers et al. 2012; Li et al. 2015), and this can lead to a decrease in relative water use (Li et al. 2015). Overall, ABA can affect the plant ET rate, photosynthesis rate and structural development.

2.5.1 ABA and Changes to Plant Water Use

ABA applications on plants have led to reduced plant water use (Reynolds and Bewley 1993; Kim and van Iersel 2011; Elansary and Yessoufou 2015; Li et al. 2015). Fern fronds soaked in ABA had reduced water use compared to non-soaked fronds and recovered better from drought (Reynolds and Bewley 1993). ABA application on Seaspray turfgrass reduced water use at all mowing heights and irrigation treatments except 30% rewatering under drought conditions (Elansary and Yessoufou 2015). When ABA was applied through irrigation, plants had reduced ET_a (Kim and van Iersel 2011; Li et al. 2015). The use of higher concentrations of ABA resulted in lower stomatal conductance rates (Li et al. 2015). ABA drenches at different rates (0, 250, 500, 1000, and 2000 mg/L) in 50 mL applications reduced leaf gas exchange and ET_a in *Salvia splendens* in a dry-down experiment (Kim and van Iersel 2011). When examining different KBG cultivar responses to drought, cultivars with more endogeneous ABA had lower ET_a rates (Wang et al. 2004). Trinexapac-ethyl (TE) application on turfgrass reduced ABA production within the plant under drought conditions, but TE application did not reduce water use in well-watered conditions (Krishnan and Merewitz 2015)

2.5.2 Changes to Plant Gas Exchange with ABA

ABA applications on plants can decrease stomatal gas exchange. ABA application on wild type tomatoes resulted in decreased carbon assimilation within 30 minutes of application (Herde et al. 1997). After application of ABA, the plant can take two hours to reach a steady-state rate of carbon assimilation (Herde et al. 1997). When comparing the effect of ABA on carbon assimilation versus transpiration, transpiration decreased more than assimilation (Herde et al. 1997). When exposed to heat stress with an ABA treatment, CB had reduced photosynthesis compared to the control (Larkindale and Huang 2004). ABA application on pansies resulted in reduced photosynthesis for up to fourteen days (Weaver and van Iersel 2014).

Different crop and horticultural plant gas exchange can be negatively impacted with the application of ABA. ABA applications to leaf cuttings resulted in gas exchange decreases across species (corn, common bean, *Xanthium strumarium*, beet, *Rumex obtusifolius*, rose.), and the greatest reductions were from biologically-sourced ABA compared to synthetic analogues (Kriedemann et al. 1972). The different species had different response times to the ABA applications, such that bean had the shortest time to complete stomatal closure at 30 minutes compared to rose at 108 minutes (Kriedemann et al. 1972). When comparing the effect of industrial analogue ABA to biological ABA on musk melon seedlings under drought stress, both applications reduced gas exchange for the first three days. The ABA-treated plants recovered better than non-treated upon irrigation (Agehara and Leskovar 2012).

The amount of gas exchange reduction is directly proportional to the concentration of ABA applied. In poplar seedlings ABA applications reduced stomatal conductance by 19% within the first four hours (Wan and Zwiazek 2001).

2.5.3 ABA Alters Plant Structure

Application of ABA can alter plant structure and growth. Reduced leaf growth of KBG cultivars Midnight and Brilliant occurred for only the first six days after the ABA application under well-watered conditions (Wang et al. 2003). On detached ears of winter wheat (*Triticum aestivum* L. cv. 'Wanmai 38'), ABA applications did not reduce photosynthetic activity, but it reduced the amount of chlorophyll in the leaves compared to the control (Xie et al. 2004). Foliar application of ABA to two *Malus* species (*M. sieversii* and *M. hupehensis*) using one-year-old seedlings under well-watered conditions increased plant root/shoot ratio, specific leaf area, endogenous ABA concentration, water use efficiency and it significantly decreased height growth, total biomass, total leaf area, net photosynthesis and stomatal conductance (Ma et al. 2008). ABA applied twice daily to new leaves on well-watered *Tradescantia virginiana* reduced the size of the stomata, increased stomata density in the lower epidermis, and lowered stomatal conductance compared to the untreated control (Franks 2001).

2.6 Summary

Abiotic factors that affect plant ET rates include wind speed, air temperature, VPD, CO_2 concentration, soil nutrient availability and plant available soil water content. Biotic factors that influence the plant ET rate include differences in growth habit, plant health and plant height. Plants grown in greenhouse environments can have different ET rates based on genetic and abiotic factors. Within turfgrasses, ET rates can differ both within and between species when grown in identical abiotic conditions. The genetics of each plant can regulate the hormone ABA in times of stress to alter plant functions. The altered plant functions include ET rates, photosynthesis rates and plant growth.

2.7 Hypothesis

In a controlled environment with artificial lights, the ET rates and NCER will be affected by turfgrass species and cultivar blend, soil water conditions, and the application of ABA.

2.8 Objectives and Experimentation

The objectives of the studies in this thesis are:

1) to examine the impact of ABA application on turf stand ET and photosynthesis rates by comparing the ET and photosynthesis rates of turfgrass before and after ABA application.
2) to examine the differences in ET and photosynthesis rates of three seeded cool-season grasses: Kentucky bluegrass (KBG), perennial ryegrass (PR), and tall fescue (TF) subjected to field capacity conditions
3) to examine the differences in ET and photosynthesis rates between different sodded cultivar blends of KBG subjected to either field capacity conditions (Experiment 3) or below field capacity (Experiment 4). The results from Experiment 3 and Experiment 4 were compared to determine the effect of soil water content on turfgrass ET rates.

Chapter 3: Methods

3.1 Overview

This thesis is composed of four different experiments, each focusing on ET rates and net CO_2 assimilation. Experiment 1 studied the effects of an ABA application on KBG sod physiology. Experiment 2 studied the ET rates of three seeded cool season grasses. Experiment 3 examined the ET rates of different sodded KBG blends when grown under well-watered conditions. Experiment 4 examined the ET rates of different sodded KBG blends when grown under dry conditions. Methods common to each Experiment are described in sections 3.2-3.6, and methods specific to each Experiment are described in section 3.7.

3.2 Bin construction

Rectangular plastic bins (40.7 cm long x 28.0 cm wide x 16 cm deep) (Sterlite® Ultra™ Latch, Sterlite Corporation, Townsend, MA) were painted glossy white (Krylon Products Group) to reduce the effects of ambient light on rootzone temperature. Each of the grow bins had five holes (0.32 cm) drilled for drainage, including one in each corner and one in the center, and covered with filter paper (Whatman 3, Sigma-Aldrich Canada Co. Oakville, ON). The base layer (5.3 cm) of the bins consisted of expanded clay pebbles (Hydrocorn, De Rijp, The Netherlands) as a drainage layer to create a perched water table. The growing medium consisting of USGA-specification sand and peat (80:20 v/v Hutcheson Sand and Mixes, Huntsville, ON) filled the remaining depth (11 cm) in the bins. The filled bins were watered to settle the sand so there was a level surface for the sod and seed establishment. The rectangular plastic bins that were not drilled with holes were used as drainage bins. The drainage bins were placed under allowed for excess water in the grow bins to drain freely to prevent flooded conditions in the rootzone and the captured excess water from the grow bin so volume would not evaporate. Black PVC (5.08 cm diameter) was cut into 7.6 cm lengths to act as spacers between the drainage bins and growing bins. The spacer pipes allowed for the separation of both the grow and drainage bins from each other to allow for the removal of excess water.

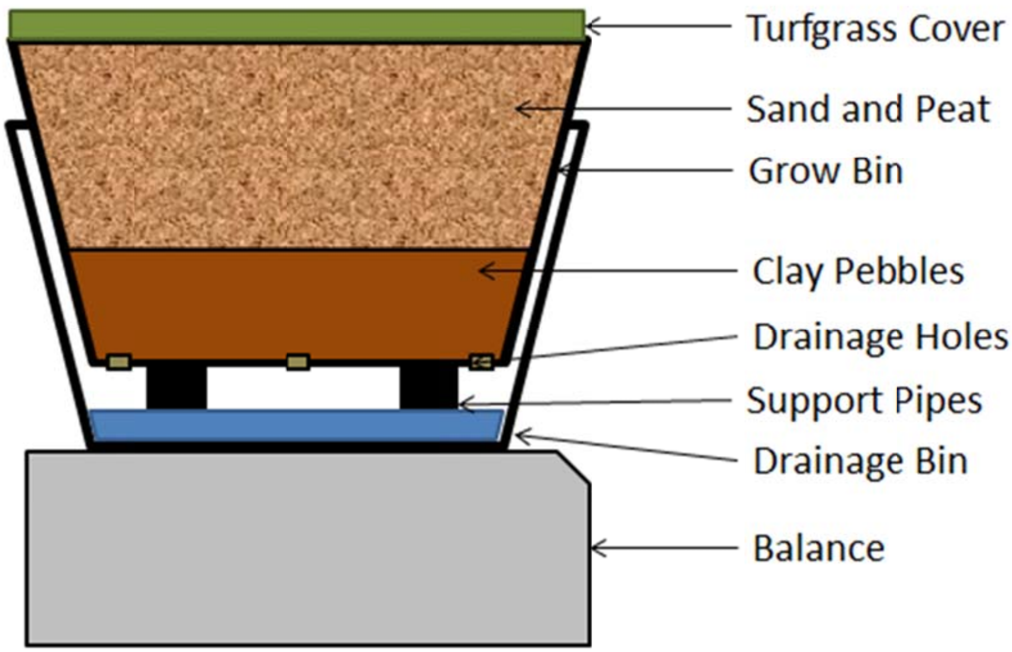

Figure 3.1: Schematic diagram of the turfgrass bin configuration used in all experiments

3.3 Turfgrass Establishment

Sodded bins were established for Experiments 1, 3 and 4, while seeded bins were established for Experiment 2 to allow for the inclusion of turfgrasses that do not form a sod once mature. Turfgrass establishment started with the harvest of mature Kentucky bluegrass sod rolls that were shipped to the Edmund C. Bovey building at the University of Guelph. The mature KBG sods were composed of cultivars determined by sod growers that would meet the quality standards required for professional sports fields. The rolls were trimmed with a stencil to fit in the bins. Each sod piece had the incoming rootzone material removed to reduce background variation from the soil that the sod was produced. Each sod piece was placed into a marked bin denoting the sample replicate and bin class (cultivar blend). The sodded bins were watered twice daily for one week to allow for root establishment. In total, there were five different Kentucky bluegrass sod compositions designated as a KBG bin class (Table 7.5). For the seeded experiment, TF (50 g/m^2, cv Summer, Jacklin Seed, JR Simplot), PR (30 g/m^2, cv Accent II, Jacklin Seed, JRSimplot), and KBG (16 g/m^2, cv Action, Jacklin Seed JR Simplot) were seeded in six bins of each species on September 3, August 21 and August 6, 2015 respectively. The relative ET rate of each the cultivar from each species was not known at the time of the experiment. The seeded bins were mist-watered twice a day until most seeds germinated (14 days).

3.4 Maintenance Conditions

The turfgrass bins were maintained in the greenhouse facility at the University of Guelph in the Edmund C. Bovey Building (43.3º 15′ L.N.) from July of 2015 to February 2016 at an average temperature of 21.64 / 18.36 º C (day/night) and a 16-hour photoperiod between 6 am to 10 pm using supplemental high-pressure sodium (HPS) lights when natural levels dropped below 200 µmol photons m^{-2} s^{-1}. The turfgrass bins were watered every second day to field capacity until the end of September 2015. Starting October 2015, the bins were fertilized weekly with 2.38 L of soluble 20-8-20 including micro nutrients [0.15% magnesium, 0.100% iron, 0.050% manganese,0.050% zinc, 0.050% copper, 0.020% boron, 0.015% molybdenum] (Plant-Prod 20-8-20 All Purpose High Nitrate, Plant Products, Brampton, ON) at a concentration of 250 ppm N. For three weeks from late October to November, weekly fertilization was replaced with watering. Insecticides and fungicides were applied to the turfgrass in each bin on a regular schedule to reduce the impact of insects and fungicides as outlined in Tables 7.1 and 7.2, respectively.

3.5 Testing Conditions

A custom growth chamber located in the Controlled Environment Systems Research Facility at the University of Guelph was the testing chamber (4.5 m x 3 m x 2.5 m (LxWxH)) for ET rates and NCER. The walls and floors were stainless steel with a tempered glass roof. Carbon dioxide and humidity were measured with a LiCor L16262 Gas Analyzer for CO_2/H_2O vapour, Instrumar Custom Gas Analyzer for CO_2/O_2, Gas Chromatograph/Mass Spectrometer (HP-5890/HP-5971) and Dionex DX500 HPLC Ion Chromatograph. The light was provided by the alternation of nine 600 Watt HPS and six 400 Watt metal halide (MH) lamps. These lights provided 500 μmol m^{-2} s^{-1} PAR at canopy height. The layout of the growth chamber is shown in Figure 7.1. The average temperature in the chamber was 22±0.7°C day & night). The photoperiod was 12h/12h (light/dark) for all experiments.

3.6 Physiological Measurements

The water use of turfgrass in each bin was measured gravimetrically using a New Classic MF scale (#MS32001L/03) (Mettler-Toledo, Switzerland) with live recording software each minute for all experiments. The gravimetric water use was determined by the difference in mass in hour long time segments. In the ABA trial only (Experiment 1), the volumetric water content (VWC) was measured with a moisture meter to determine a consistent chamber entry range. Each bin was weighed to have a mass that corresponded with each bin VWC. The corresponding bin mass (g) to VWC was used to maintain a consistent bin mass when the bins were irrigated before each chamber entry. ET was reported in mm for the conversions to mols m^{-2}=1000 * mmH_2O * (18.015 g $mol^{-1})^{-1}$. The experimental unit for ET rates was a single turfgrass bin.

Vertical shoot growth was measured by a custom-built Canopy Height Sensor (CHS) developed in our lab by K. Chang. To measure vertical shoot growth per bin, the average height (mm) at exit was compared to average height of entry. The experimental unit for vertical shoot growth was a single turfgrass bin.

Turfgrass green cover (%) was tracked throughout the experiments by analysing photos taken with an EOS Rebel XT camera (Canon Canada Inc. Mississauga, ON) in a controlled light booth before and after each chamber treatment. The pictures were analysed using ImageJ digital imaging software to determine green area with images cropped at 3456 x 2304 to 2607 x 1629 pixels. The experimental unit for turfgrass green cover was a single turfgrass bin.

Net carbon exchange rate (NCER) of the turfgrass bins was monitored by a LiCor L16262 Gas Analyzer, and the data was analyzed in one-hour time segments. The CO_2 levels in the chamber were drawn down by the plants and then CO_2 was replaced. To assure that the linear draw down of CO_2 levels were being used to calculate the hourly NCER, the data within each hour segment had 30-minute lines of regression put on the data set at 1-minute intervals. When a line of regression had an R^2 of 0.90 or greater, the rest of the hour was tested for the longest time length with an R^2 of 0.90 or greater to maximize the total time contained in the NCER measurement. This allowed for the NCER to be within a reasonable zone of fluctuation for the time period of a given hour. If an hour had two slopes that had regressions of R^2 of 0.90 or greater, a weighted average was taken. The calculated NCER are stated in units of mmol $CO_2 m^{-2} hour^{-1}$. The experimental unit for NCER was the growth chamber.

Water use efficiency was calculated by comparing the mean water use of all bins in the chamber in mol/m^2 to the NCER in the chamber at mmol CO_2/m^2 (WUE= mmol CO_2/ mol H_2O).

3.7 Specific Experiments and Treatments

3.7.1 Experiment 1: ABA Treatment

3.7.1.1 Pre-experiment 1

For Experiment 1, bin mass and relative water content were measured the day before chamber entry (Day 0). The volumetric water content (VWC) was measured in the top 7.6 cm of the bins with a moisture meter (Theta probe MLX2/HH2 moisture meter, delta-T Devices, Cambridge England,) at five locations and bin mass was measured using a balance (New Classic MF scale) (#MS32001L/03, Mettler-Toledo, Switzerland). The bin masses were recorded with the matching VWC to have a corresponding mass. The night before chamber entry the bins were weighed to determine the current mass and had their VWC measured. If the turfgrass bin's VWC was below 20%, the turfgrass bin were watered until the VWC was 20%. When the bin mass reached 20% VWC, this final was determined to be the corresponding mass.

3.7.1.2 Experiment 1: Experimental Design

There were three repetitions separated by time. Each repetition was of a single KBG bin class. For ET there were six experimental units per repetition. CO_2 and WUE had one experimental unit per repetition.

The 3 KBG bin classes used in this experiment were grown under greenhouse conditions for six to eight months.

3.7.1.3 The Effects of ABA on KBG Turfgrass Physiology Procedure

The ABA trial had three different treatments applied to the same bins, separated by time. The three treatments were Untreated Control, ABA Application, and Recovery. Each bin set was placed in the chamber for one week. One day was defined as a 24-hour period that started when the lights turned on at 10:00am EST for 12 hours followed by 12 hours when the lights were turned off. The physiological parameters measured in this experiment were ET rate, NCER, green cover, and turfgrass height change. At the time of each chamber entry, the turfgrass in each of the bins was trimmed to 3 cm. The control treatment lasted two days (Day 1 & Day 2). Plants were watered initially to a VWC of 20±5% based on moisture meter readings. CHS readings were taken to determine turfgrass height and photos were taken for digital imaging analysis prior to placing the bins in the chamber. Bins entered the chamber on Day 1 at 10:00 am and on Day 3 the bins were removed from the chamber at 10:00 am. Plant height measurements and photographs were taken again as described for Day 1. Each bin was weighed and soil moisture was measured to determine changes in VWC. The turfgrass in the bins were trimmed to 3 cm and had CHS readings taken to determine turfgrass height and photos taken for digital imaging analysis. For the ABA treatment, the bins were then watered to approximately 300 g below entry mass. Following the watering, the foliar application of ABA occurred at a rate of 2.7 L/m^2 at a concentration of 200 µM (Sigma-Aldrich, St. Louis, MO) (300 ml per bin) with a motorized pump system (designed by K. Chang) resulting in the original entry mass. Before returning the bins to the chamber, each bin was weighed and soil moisture was measured to determine entry VWC and then bins were kept in the chamber for 2 days (Day 3 & Day 4). On Day 5 the bins were removed from the chamber at 10:00 am, each bin had CHS readings taken to determine turfgrass height, and photos were taken for digital imaging analysis followed by measurement of weight and soil moisture to determine VWC. Turfgrass in each bin was trimmed to a height of 3 cm. The trimmed turfgrass had CHS readings taken for determining turfgrass height and photos taken for digital imaging analysis on the trimmed bins. Before re-entry, the bins were watered to initial entry mass and soil moisture was measured to determine VWC and then bins were placed back in the chamber for a total of 3 days for recovery. On Day 8, the bins were removed from the chamber and CHS readings were taken to determine turfgrass height. Additionally, photos were taken for digital imaging analysis and then the samples were weighed and soil moisture was measured to determine final VWC.

3.7.2 Experiment 2: Seeded Turfgrass Species at Bin Capacity Conditions

3.7.2.1 Pre-experiment 2

The mass at bin capacity was determined two days before chamber entry. Bin capacities were determined by watering turfgrass bins to the point of overflow and after an hour period of covered draining the bins were weighed. During the draining period, the turfgrass area was covered by unused painted bins to halt transpiration by creating an assumed 100% relative humidity (RH). At the time of the experiment, the turfgrass in the seeded bins were three to four months old.

3.7.2.2 Experiment 2: Experimental Design

Each turfgrass species was replicated one time. Each replication had six experimental units for ET. There was one experimental unit for NCER and WUE. Day 1 and Day 3, the day plants were watered were treated as replicates. Day 2 and Day 4, the day plants were not watered were treated as replicates. This allowed for replication and statistical analysis.

3.7.2.3 Experiment 2 Seeded Species at Bin Capacity Procedure

The Seeded Capacity trial measured ET rates, NCER, green cover, and turfgrass height change for three cool season turfgrasses, including TF, KBG, and PR. The turfgrass was trimmed to 3 cm the day before entry (Day 0). On the day of entry (Day1), the bins were watered to bin capacity and had VWC measured with the moisture meter. Before chamber entry, the turfgrass bins had CHS readings taken to determine turfgrass height and photos taken for digital imaging analysis. The layout of the bins in the chamber is depicted in Figure 3. On Day 2, the bins remained in the chamber and were not watered. On Day 3, the bins were watered to bin capacity. On Day 4, the bins remained in the chamber and were not watered. On Day 5, the bins were removed from the chamber and the turfgrass bins had CHS readings taken to determine turfgrass height, VWC was measured with the moisture meter, and photos were taken for digital imaging analysis.

3.7.3 Experiment 3: Sodded KBG Turfgrass Grown in Bin Capacity Conditions

3.7.3.1 Pre-experiment 3

Experiment 3 with sodded KBG followed the same preparation procedure as Experiment 2. At the time of the experiment, the KBG bin classes were established three weeks to two months beforehand.

3.7.3.2 Experiment 3: Experimental Design

Each KBG bin class had one or two true replications. There were initially two replications for all KBG bin classes, but an issue with the CO_2 supply resulted in the loss of a replication for two KBG bin classes. Each replication had six experimental units for ET. There was one experimental unit for NCER and WUE. Day 1 and Day 3, the day plants were watered were treated as replicates. Day 2 and Day 4, the day plants were not watered were treated as replicates. This allowed for replication and statistical analysis.

3.7.3.3 Experiment 3 Procedure

In Experiment 3, ET rate, NCER, and green cover for five different KBG blended sods were measured. The turfgrass was trimmed to 3 cm the day before entry (Day 0). Photos were taken of each bin for digital imaging analysis the day before entry (for round 1) or the day of entry (for round 2). On the day of entry (Day1), the bins were watered to bin capacity and then entered the chamber. The layout of the bins in the chamber is depicted in Figure 3. On Day 2, the bins remained in the chamber and were not watered. On Day 3, the bins were watered to bin capacity. On Day 4, the bins remained in the chamber and were not watered. On Day 5, the bins were removed from the chamber to have photos taken for digital imaging analysis.

3.7.4 Experiment 4: Sodded KBG Turfgrass Grown in Below Bin Capacity Conditions

3.7.4.1 Pre-experiment 4

In Experiment 4 (below capacity treatment) the bins were weighed the day before entry to determine relative water content (RWC). The mass of each bin was compared to the previously determined bin capacity mass to determine RWC. To allow for a consistent RWC for a KBG bin class, the RWC for each bin was determined. Then the entry RWC for the KBG bin class was determined by the turfgrass bin with the highest RWC. The highest RWC was then rounded to the closest 5% value. For example, when the turfgrass bin with the highest RWC was 72% the designated RWC for chamber entry was 75%. All KBG of a bin class entering the chamber would be watered to the same RWC as the turfgrass bin with the highest RWC.

Water mass capacity (WM_c) was defined as the maximum mass of water in the turf bins at bin capacity and was calculated by the following:

(1) Water mass Capacity (WM_c) = Maximum Mass – Sod Mass – Bin Mass Dry,

where Maximum Mass is mass of a bin at bin capacity; Sod mass is the mass of the sod before being placed into the bin; and Bin Mass Dry is the combined mass of the pipes, grow bin, bottom bin, clay substrate, and the sand with peat mixture.

Water mass below capacity (WM_B) was defined as the amount of water in the turf bins when not at bin capacity and was calculated by the following:

(2) Water mass below capacity (WM_B) = Current mass – Sod Mass – Bin Mass Dry

Current Mass is the mass of a bin at the time of weighing; Sod mass is the mass of the sod before being placed into the bin; Bin Mass Dry is the combined mass of the pipes, grow bin, bottom bin, clay substrate, and the sand with peat mixture.

Change in water mass (ΔWM) is the difference between water mass at bin capacity and water mass at below capacity and was calculated by the following:

(3) Change Water mass (ΔWM) = $WM_c - WM_B$

% Water mass change ($\%WM\Delta$) is the change in water mass (ΔWM) divided by water mass at bin capacity multiplied by 100% and was calculated by the following:

(4) % Water Δ ($\%WM\Delta$) = $(\Delta WM / WM_c)*100$;

(5) RWC=% Water present (%WP) = 100 - $\%WM\Delta$.

At the time of the experiment, the KBG bin classes ranged in establishment time of three to five months. Four KBG bin classes were used in this experiment.

3.7.4.2 Experiment 4 Experimental Design

Each KBG bin class had one replication. There were initially two replications per KBG bin class, but there was issue with the data logger that resulted in having a single replication per bin class. Each replication had six experimental units for ET. There was one experimental unit for NCER and WUE. Day 1 and Day 3, the day plants were watered were treated as replicates. Day 2 and Day 4, the day plants were not watered were treated as replicates. This allowed for replication and statistical analysis.

3.7.4.3 Experiment 4 Procedure

In Experiment 4, the sodded below-bin capacity treatment a similar method as Experiment 3 for four different KBG blends was followed. This experiment measured ET rates, NCER, green cover, and turfgrass height. On the day of entry (Day 1), the bins were watered to the determined RWC. Before chamber entry, the turfgrass bins had CHS readings taken to determine turfgrass height and photos taken for digital imaging analysis. On Day 2, the bins remained in the chamber and were not watered. On Day 3, the bins were watered to the determined bin RWC. On Day 4 the bins remained in the chamber and were not watered. On Day 5, the bins were removed from the chamber and the turfgrass bins had CHS readings taken to determine turfgrass height and photos taken for digital imaging analysis.

3.8 Terminology

A day in this study was defined as a 24-hour time frame with a 12-hour period of the lights on followed by a 12-hour period of the lights off. ET rate data were divided into both lights on ET (LET) and lights off ET (DET). The NCER data were divided into lights on CO_2 (LCO_2) and lights off CO_2 (DCO_2).

3.9 Data Analysis

Experiment 1 data was analysed by analysis of variance using the ProcGlimmix procedure in SAS Studio 3.7 and a Tukey's HSD means separation test at a p-value of 0.05. For data analysis of Experiments 2-4, data from Day1 with Day 3 were treated as Day 1 at capacity and Day 2 with Day 4 were treated as Day 2 at below capacity. The experiment was designed with each bin as an experimental unit. Each set of six bins was a repetition. Experiments 2 - 4 were analysed by analysis of variance using the ProcGLM procedure in SAS Studio 3.7 and a Tukey's test at a *p*-value of 0.05. The results of Experiment 3 and 4 were compared using ProcGLM procedure in SAS Studio 3.7 and a Tukey's test at a p-value of 0.05. For the comparison of Experiment 3 and Experiment 4 there was true replication.

Chapter 4: Results

4.1 The Effects of ABA on KBG Turfgrass Physiology

The difference between treatments was significant for all measured variables except for DET (Table 4.1.1). There was a significant interaction between day and treatment for all measured parameters with lights on and respiration (DCO_2) with the lights off (Table 4.1.1). In general, the change in green cover was not different between entering and exiting (EE) the chamber and there was no interaction with the treatment effect (Table 4.1.1).

All treatments had increased values for net photosynthesis (LCO_2) and water use efficiency (LWUE) from Day 1 to Day 2 (Table 4.1.2). The LCO_2 rates on Day 1 were 18.2% lower than those on Day 2. The LWUE of Day 1 was 16.9% lower than Day 2.

The Control treatment had the highest LET, while Day 2 of the ABA Application treatment had the lowest LET (Table 4.1.3). The Day 2 ABA LET rates were 19.2% lower than Day 2 of the Control treatment. The highest LCO_2 was on Control Day2 and the lowest LCO_2 was Day1 of the Application treatment (Table 4.1.3). The Day 1 Application LCO_2 rates were 40.4% lower than Day 2 of the Control. There was no difference between the Day 2 LWUE among all treatments (Table 4.1.3). Green area decreased consistently from the beginning of the experiment, when the bins were placed in the chamber, to the end of the experiment when they were removed from the chamber through all treatment periods (Table 4.1.3). The ABA application treatment resulted in negative growth for the turfgrasses in contrast to the two other treatments (Table 4.1.3).

Table 4.1.1: Analysis of variance (ANOVA) for turfgrass physiological responses in Experiment 1 (ABA effect on ET)

	ET[1]		CO_2		Mean WUE	Green Cover	Δ Canopy Height
	Light On[2]	Light Off	Light On	Light Off	Light On		
Effect	Pr > F	Pr > F	Pr > F	Pr > F	Pr > F	Pr > F	Pr > F
Treatment[3]	<.0001	0.547	<.0001	<.0001	<.0001	0.041	<.0001
Day[4]	<.0001	0.2736	<.0001	0.0076	<.0001		
Time[5]						0.2035	
Hour	<.0001	0.029	0.0002	0.1533	<.0001		
Day*Hour	<.0001	0.2804	<.0001	0.2075	<.0001		
Day*treatment	<.0001	0.8874	<.0001	0.0059	<.0001		
Day*Hour*treatment	<.0001	0.9651	<.0001	0.0886	<.0001		
treatment*time						0.7504	

[1]ET is evapotranspiration, CO_2 is net CO_2 exchange, Mean WUE is mean water use efficiency, Green cover is the mean green cover of a turfgrass bin between treatments, Δ Canopy Height is the difference in turfgrass height on growth chamber entry and on growth chamber exit.
[2]Light On is the 12 hour period when the lights were on in the growth chamber, Lights Off) is the 12 hour period when the lights were off in the growth chamber
[3]Treatment is the comparison between the three treatment applied to the turfgrass: Untreated Control, ABA Application, and Recovery
[4]Day is the 24 hour period that each treatment was divided into
[5]Time is the difference between chamber Entry and Exit Values

Table 4.1.2: The effect of time in the growth chamber across treatments for the ABA Experiment

Day	Mean CO_2[1] ($mmol/m^2/hour$) Light On[2]		Mean WUE ($mmolCO_2/molH_2O$) Light On	
1	26.1	b[3]	2.50	b
2	31.9	a	3.01	a

[1]Mean net CO_2 exchange, Mean WUE is mean water use efficiency
[2]Light On is the 12 hour period when the lights were on in the growth chamber
[3]lowercase letters in each column that are the same have means that are not statistically different at $p<0.05$ Tukey's test

Table 4.1.3: The effect of the application of ABA on measured turfgrass physiological parameters

Treatment[2]	Day[3]	ET[1] (mm/h) Light On[4]	ET[1] (mm/h) Light Off	(%) Off/On	CO_2 (mmol/m^2/hour) Light On	CO_2 (mmol/m^2/hour) Light Off	Mean WUE (mmolCO_2/molH_2O) Light On	Green Cover (%)	Δ Canopy Height (mm)
Control	1	0.2137 a[5]	0.0697 a	32.6	31.2b	-7.270 a	2.65 b	55.97 a	7.50 a
	2	0.2156 a	0.0681 ab	31.6	34.4a	-7.610 a	2.92 a		
Application	1	0.1844 b	0.0618 ab	33.5	20.5e	-7.696 a	2.15 c	51.08 ab	-14.94 b
	2	0.1743 c	0.0619 ab	35.5	28.9c	-7.540 a	3.03 a		
Recovery	1	0.1829 bc	0.0597 b	32.6	26.7d	-7.600 a	2.69 b	49.08 b	1.56 a
	2	0.1901 b	0.0621 ab	32.7	32.2b	-8.295 b	3.09 a		

The data was pooled by treatment for all 3 KBG bin classes.
[1]ET is evapotranspiration, CO_2 is net CO_2 exchange, Mean WUE is mean water use efficiency, Green cover is the mean green cover of a turfgrass bin between treatments, Δ Canopy Height is the difference in turfgrass height on growth chamber entry and on growth chamber exit.
[2]Treatment is composed of three treatments separated by time: Untreated Control, ABA Application, and Recovery.
[3]Day is the 24-hour period in which each treatment was divided.
[4]Light On is the 12 hour period when the lights were on in the growth chamber, and Light Off is the 12 hour period when the lights were off in the growth chamber.
[5]lowercase letters in each column that are the same have means that are not statistically different at $p<0.05$ Tukey's test.

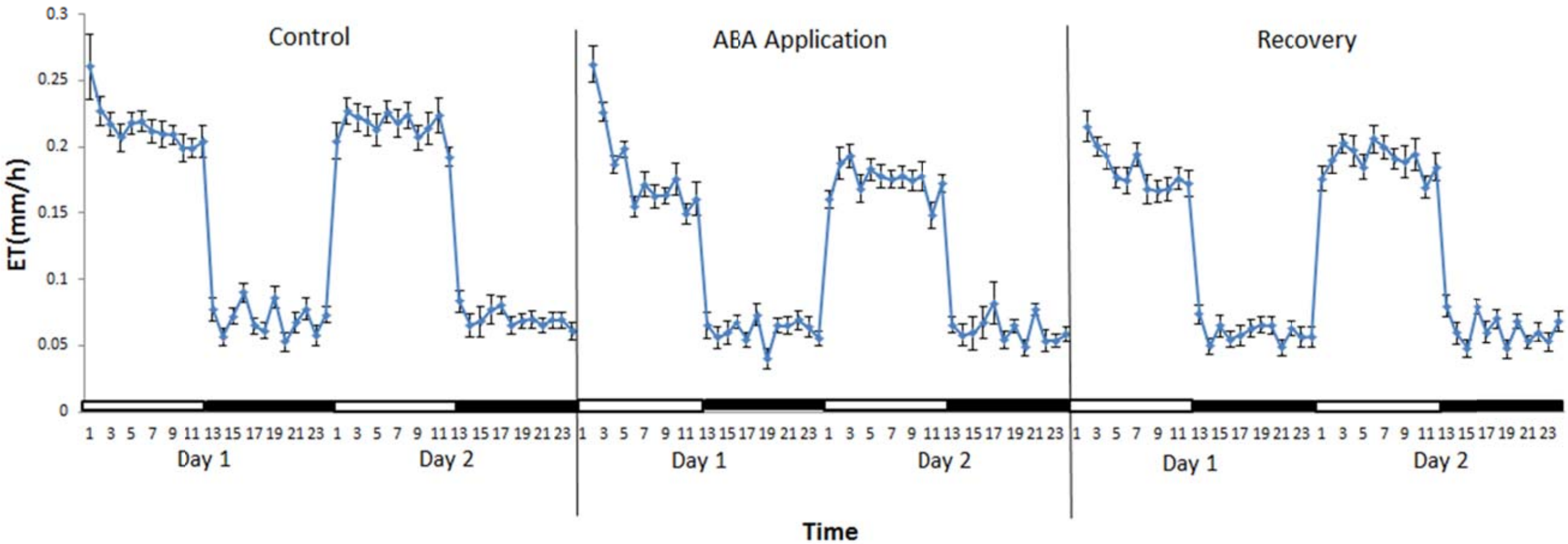

Figure 4.1.1: Turfgrass Evapotranspiration during the Control, ABA Application, and Recovery Treatments. The experiment was divided into three distinct periods of 2 days each for Control (Day 1-2), ABA Application (Day 3-4), Recovery (Day 5-6) for a combined number of 6 days. Data were recorded once per hour. Data were pooled to treatment and day

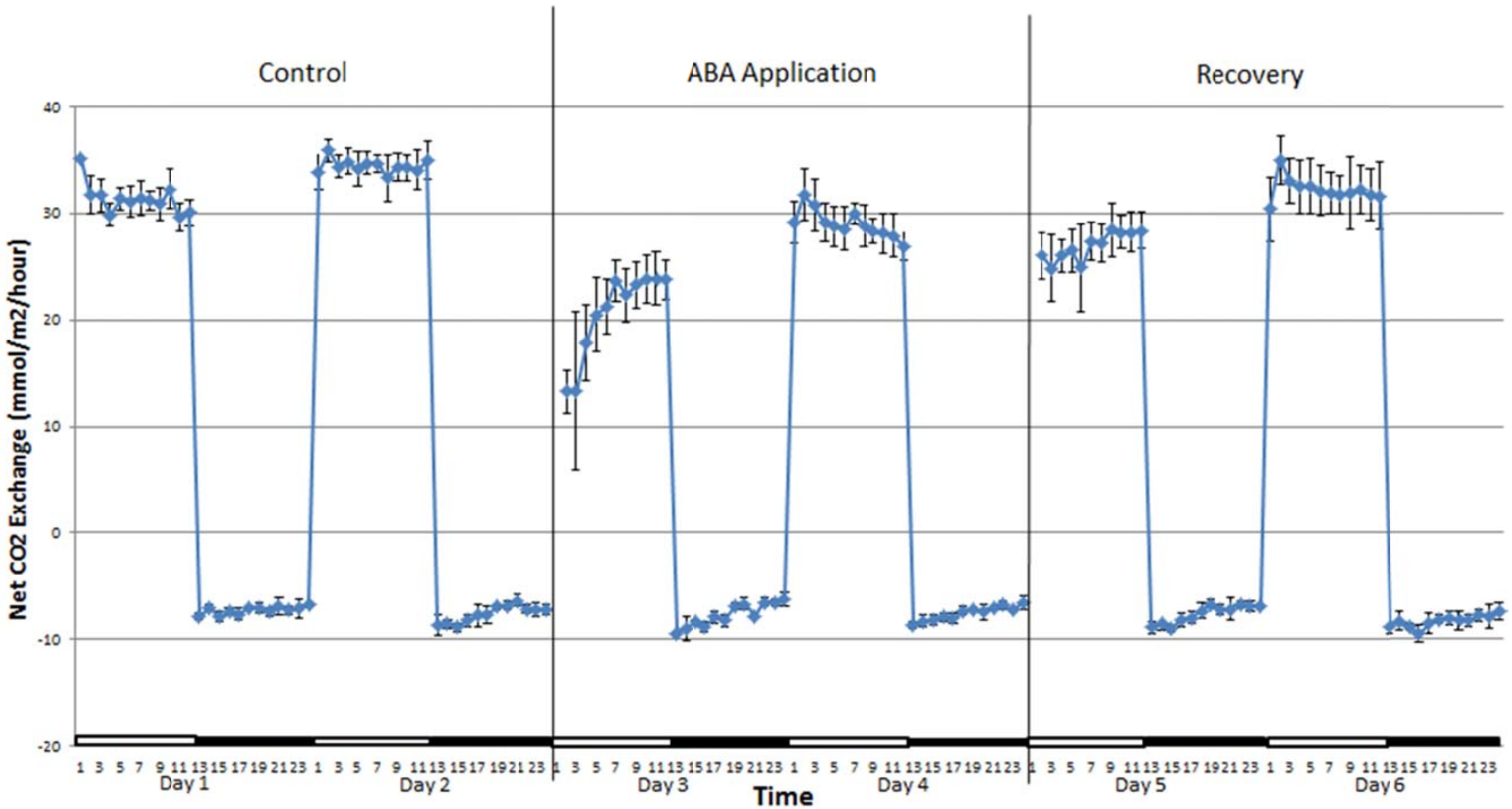

Figure 4.1.2: Net CO_2 Exchange during the Control, ABA Application and Recovery Treatments. The experiment was divided into three distinct periods of 2 days each for Control (Day 1-2), ABA Application (Day 3-4), Recovery (Day 5-6) for a combined number of 6 days. Data were recorded once per hour. Data were pooled to treatment and day.

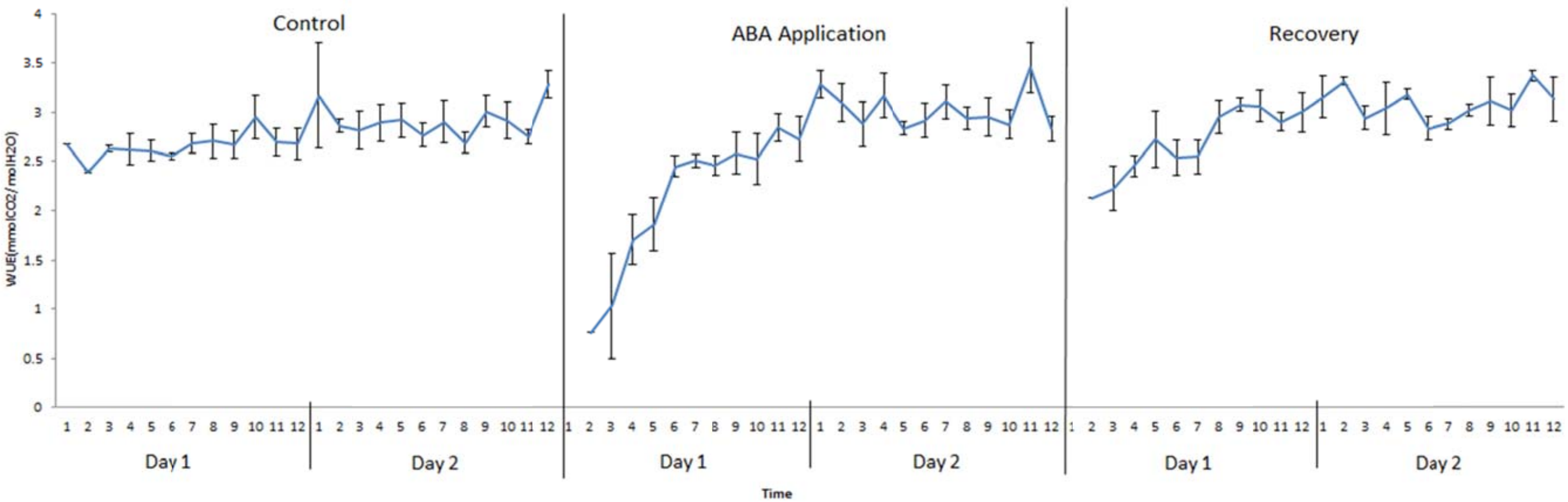

Figure 4.1.3: Water use efficiency during the Control, ABA application and Recovery Treatments. The experiment was divided into three distinct periods of 2 days each for Control (Day 1-2), ABA Application (Day 3-4), Recovery (Day 5-6) for a combined number of 6 days. Data were recorded once per hour. Data were pooled to treatment and day.

4.2 Seeded Turfgrass Species at Bin Capacity Conditions

The seeded bins that compared turfgrass species (Species) showed differences in all measured physiological responses (Table 4.2.1). The DET did not vary based on whether the plant was watered the same day (DAY 1) versus the day not watered (DAY 2), but did vary for the other measured parameters regardless of species (Table 4.2.2). The LET rates of Day 1 were 5.8% lower than Day 2. The species with the highest LET was TF and the lowest was KBG, 0.4205 mm/h, and 0.3222 mm/h respectively (Table 4.2.3). The LET rate of KBG was 23.4% less than TF. TF had the highest DET value that was higher than both PR and KBG (Table 4.2.3).TF DET rates were 25.7% and 27.6% greater than PR and KBG, respectively. TF had the highest LCO_2 value and KBG had the lowest LCO_2 value (Table 4.2.3). The TF LCO_2 rate was 33% greater than KBG. The LWUE was highest for PR and KBG being the least efficient (Table 4.2.3).

Table 4.2.1: Analysis of Variance (ANOVA) for the seeded turfgrass physiological responses of ET, net CO_2 exchange, WUE and green area to watering at bin capacity. Day is Day1 (irrigated) vs Day 2 (non-irrigated), Species is the species of turfgrass used, Species*Day is the interaction of each species by each day

Interactions	ET[1] (mm/h)		CO_2 (mmol/m^2/h)		WUE (mmolCO$_2$/molH$_2$O)	Green Cover (%)	Δ Canopy Height mm
	Light[2] On	Light Off	Light On	Light Off	Light On		
Species	<.0001	<.0001	<.0001	0.0004	<.0001	<.0001	<.0001
Day[3]	0.0259	0.8021	0.0265	<.0001	0.0216		
Species*Day	0.3928	0.2735	0.3901	0.9546	0.594		
Time[4]						0.2001	
Species*Time						0.96	

[1]ET is evapotranspiration, CO_2 is net CO_2 exchange, Mean WUE is mean water use efficiency, Green cover is the mean green cover of a seeded turfgrass bin, Δ Canopy Height is the difference in turfgrass height on growth chamber entry and on growth chamber exit.
[2]Day is the 24-hour period in which each treatment was divided.
[3]Light On is the 12 hour period when the lights were on in the growth chamber, and Light Off is the 12 hour period when the lights were off in the growth chamber.
[4]Time is the chamber Entry to Exit difference

Table 4.2.2: The Differences between Day 1 and Day 2 for the measured turfgrass physiological parameters of seeded turfgrasses. Also include Lights Off data for ET.

Day[2]	ET[1] (mm/h)		(%)	CO_2 (mmol/m$_2$/h)		WUE (mmolCO$_2$/molH$_2$O)
	Light On[3]	Light Off	Off/On	Light On	Light Off	Light On
1	0.3682a[4]	0.1795 a	48.8	62.0 b	-11.72a	3.05 b
2	0.3620b	0.1802 a	49.8	65.8 a	-14.09b	3.26 a

[1]ET is evapotranspiration, CO_2 net CO_2 exchange,, Mean WUE is mean water use efficiency
[2]Day is the 24-hour period in which each treatment was divided.
[3]Light On is the 12 hour period when the lights were on in the growth chamber, and Light Off is the 12 hour period when the lights were off in the growth chamber.
[4]lowercase letters in each column that are the same have means that are not statistically different at $p<0.05$ Tukey's test.

Table 4.2.3: Seeded Turfgrass Species Physiological responses to being well-watered

Species	ET[1]			CO_2		WUE	Δ Canopy Height	Green Cover
	(mm/h)		(%)	(mmol/m^2/h)		(mmolCO_2/molH_2O)	(mm)	(%)
	Light On[2]	Light Off	Off/On	Light On	Light Off	Light On		
Tall Fescue	0.4205 a[3]	0.2186a	52.0	74.2a	-12.83ab	3.19b	-19.36b	95.63 a
Perennial Ryegrass	0.3526 b	0.1625b	46.1	67.7b	-14.22a	3.47a	2.65a	90.63 b
Kentucky Bluegrass	0.3222 c	0.1583b	49.1	49.7c	-11.67b	2.80c	2.97a	81.14 c

[1]ET is evapotranspiration, CO_2 is net CO_2 exchange, Mean WUE is mean water use efficiency, Green cover is the mean green cover of a seeded turfgrass bin, Δ Canopy Height is the difference in turfgrass height on growth chamber entry and on growth chamber exit.
[2]Light On is the 12 hour period when the lights were on in the growth chamber, and Light Off is the 12 hour period when the lights were off in the growth chamber.
[3]lowercase letters in each column that are the same have means that are not statistically different at $p<0.05$ Tukey's test.

Table 4.2.4: Seeded Turfgrass Species calculated ET_{day} rates from mean hourly Light On and Light Off conditions.

Species	ET_{day} mm/day
Tall Fescue	7.67
Perennial Rye	6.18
Kentucky Bluegrass	5.77

The ET_{day} rates were calculated with the formula:
ET_{day}=12*(ET Light On) + 12*(ET Light Off)

4.3 Sodded KBG Turfgrass Grown in Bin Capacity Conditions

At bin capacity, all measured physiological responses were impacted by being watered (Day1) or not watered (Day2) (Table 4.3.1). All measured physiological responses were different based on KBG bin class (Table 4.3.1).

The KBG bin class that consistently had the highest LET was Lowmow (Table 4.3.2). The KBG bin class with the lowest consistent LET values was TWCA (Table 4.3.2). On a per day basis, LET was greater in round 1 than round 2 (Table 4.3.2). The KBG bin class with the highest DET was 4-Way (Table 4.3.2). The KBG bin class with the lowest DET was TWCA (Table 4.3.2). The LET rates of Lowmow were 19.5% to 35% greater than TWCA of the same round and day. The DET rates for 4-Way was 21.2% and 31.2 % greater than TWCA for both round 1 and round 2, respectively.

The KBG bin classes with the highest LCO_2 were Impact and Lowmow (Table 4.3.2). The KBG bin classes with the lowest LCO_2 were TWCA and 100% Dwarf (Table 4.3.2). CO_2 exchange in Round2 was significantly less than Round 1 (Table 4.3.2). In general, the KBG bin class with the greatest DCO_2 loss was Impact (Table 4.3.2). The KBG bin classes with the smallest DCO_2 losses were TWCA and 4-Way (Table 4.3.2). The KBG bin classes with two rounds of data had higher per day DCO_2 in round 1 than round 2 (Table 4.3.2). The KBG bin class that usually had the highest LWUE was Impact (Table 4.3.2). The KBG bin classes with the lowest LWUE were TWCA and 100% Lowmow (Table 4.3.2). The LWUE for Impact was about 31% greater than 100% Dwarf.

Table 4.3.1: Analysis of variance for turfgrass physiological responses of Kentucky bluegrass sods to watering at bin capacity

Interactions	ET[1] (mm/h)		CO_2 (mmol/m^2/h)		WUE (mmolCO_2/molH_2O)	Green Cover (%)
	Light On[2]	Light Off	Light On	Light Off	Light On	
Day[3]	<.0001	<.0001	<.0001	<.0001	<.0001	
Bin Class[4]	<.0001	<.0001	<.0001	0.0072	<.0001	<.0001
Day*Bin Class	0.0051	0.1163	<.0001	<.0001	<.0001	0.9124
Time[5]						0.5344

[1]ET is evapotranspiration, CO_2 is net CO_2 exchange, Mean WUE is mean water use efficiency, Green cover is the mean green cover of a turfgrass bin.
[2]Light On is the 12 hour period when the lights were on in the growth chamber, and Light Off is the 12 hour period when the lights were off in the growth chamber.
[3]Day is the 24-hour period in which each treatment was divided.
[4]Bin Class is the term used to classify the 5 KBG cultivar blends: 100% Dwarf, 4-Way, Impact, Lowmow, and TWCA.
[5]Time is the chamber Entry to Exit difference
Each Bin Class was in the growth chamber for a four day cycle with Day1 and Day 3 combined together and Day2 and Day 4 were combined together.

Table 4.3.2: The differences for the bin capacity treatment on Kentucky bluegrass Bin Class, Round, and Day for all measured turfgrass physiological parameters

Bin Class	Round	Day[3]	ET[1] (mm/hour) Light On[2]	ET[1] (mm/hour) Light Off	(%) Off/On	CO_2 (mmol/m^2/hour) Light On	CO_2 (mmol/m^2/hour) Light Off	Mean WUE (mmolCO_2/molH_2O) Light On	Green Cover (%)
100% Dwarf	1	1	0.3246ef[4]	0.1572 bc	49.3	39.5ij	-14.20de	2.20 hi	77.49c
		2	0.3131fg			38.1j	-14.75def	2.20 hi	
4-Way	1	1	0.3890ab	0.1796 a	47.0	47.6fg	-13.74d	2.22 hi	76.86c
		2	0.3746bc			52.6de	-12.50c	2.53 cdefg	
Impact	1	1	0.3747bc	0.1468 cd	40.0	60.4bc	-20.78h	2.93 ab	92.11a
		2	0.3584cd			64.8a	-20.12h	3.23 a	
	2	1	0.3302def	0.1426 cd	44.0	45.5gh	-17.77g	2.36 efgh	88.82ab
		2	0.3185ef			49.2efg	-17.83g	2.83 bc	
Lowmow	1	1	0.4152a	0.1711 ab	41.4	56.5cd	-18.36g	2.47 defgh	86.70b
		2	0.4106a			60.8b	-19.89h	2.68 bcde	
	2	1	0.3454de	0.1426 cd	41.0	49.4efg	-15.11ef	2.55 cdefg	79.72c
		2	0.3507cd			51.0ef	-15.77f	2.62 bcde	
TWCA	1	1	0.3342def	0.1380 de	44.4	36.6j	-13.89d	2.20 hi	NA
		2	0.2869gh			42.6hi	-11.51c	2.76 bcd	
	2	1	0.2569hi	0.1236 e	50.3	27.2k	-9.20b	1.90 i	NA
		2	0.2342hi			29.4k	-7.93a	2.35 fgh	

[1]ET is evapotranspiration, CO_2 is net CO_2 exchange, Mean WUE is mean water use efficiency, Green cover is the mean green cover of a seeded turfgrass bin.
[2]Light On is the 12 hour period when the lights were on in the growth chamber, and Light Off is the 12 hour period when the lights were off in the growth chamber.
[3]Day is the 24-hour period in which each treatment was divided.
Each Bin Class was in the growth chamber for a four day cycle with Day1 and Day 3 combined together and Day2 and Day 4 were combined together.
[4]lowercase letters in each column that are the same have means that are not statistically different at $p<0.05$ Tukey's test.

Table 4.3.3: ET_{day} for each Kentucky bluegrass bin class at bin capacity.

Bin Class	Round	Day	ET mm/day
100% Dwarf	1	1	5.78
		2	5.64
4-Way	1	1	6.82
		2	6.65
Impact	1	1	6.26
		2	6.06
	2	1	5.67
		2	5.53
Lowmow	1	1	7.04
		2	6.98
	2	1	6.08
		2	6.15
TWCA	1	1	5.67
		2	5.10

The ET_{day} rates were calculated with the formula:
ET_{day}=12*(ET Light On) + 12*(ET Light Off)

4.4 Sodded KBG Turfgrass Grown in Below Bin Capacity Conditions

At below capacity, all measured turfgrass physiological responses were impacted by KBG bin class (Type) (Table 4.4.1). The impact of when the bins were watered on the same day versus watered on the day previous contributed to differences in LET, LCO_2, LWUE, and Green Area (Table 4.4.1).

Day 2 had a greater LET, LCO_2, and LWUE than Day1 (Table 4.4.2). Green Area on growth chamber entry was higher than chamber exit (Table 4.4.2). LCO_2 was 7.5% greater on Day 2 than Day 1.

The KBG blend with the greatest LET was 4-Way and the lowest was TWCA, (Table 4.4.3). The LET rates for 4-Way were 18.3% greater than the LET rates for TWCA. The KBG bin class with the highest DET was 4-Way (Table 4.4.3) being 30.8 to 35.1% greater than the other three KBG bin classes. Lowmow had the lowest LCO_2 values compared to the other three KBG bin classes (Table 4.4.3) being 12.9% to 16.7% lower. The KBG blend with the highest DCO_2 loss was 4-Way and the least was Lowmow (Table 4.4.3). The two KBG blends with the highest LWUE were TWCA and Impact (Table 4.4.3). The two KBG blends with the lowest LWUE were Lowmow and 4-Way (Table 4.4.3). 4-Way had a negative canopy height change of 7.44mm growth during it time in the growth chamber (Table 4.4.3). The KBG blends with the highest green area were TWCA and Impact (Table 4.4.3). 4-Way and Lowmow had the lowest green (Table 4.4.3).

Table 4.4.1: Analysis of variance of turfgrass physiological responses of Kentucky bluegrass sods to watering at below bin capacity

Interactions	ET[1] (mm/h)		CO_2 (mmol/m^2/h)		WUE (mmolCO_2/molH_2O)	Δ Canopy Height (mm)	Green Cover (%)
	Light On[2]	Light Off	Light On	Light Off	Light On		
Bin Class[4]	<.0001	<.0001	<.0001	<.0001	<.0001	0.0034	<.0001
Day[3]	0.0004	0.1013	<.0001	0.2103	<.0001		
Bin Class*Day	0.2221	0.731	0.6392	0.1543	0.8449		
Bin Class*Time							0.6392
Time[5]							<.0001

[1]ET is evapotranspiration, CO_2 is net CO_2 exchange, WUE is mean water use efficiency, Green cover is the mean green cover of a turfgrass bin, Δ Canopy Height is the difference in turfgrass height on growth chamber entry and on growth Green cover is the mean green cover of a seeded turfgrass bin, Light Off is the 12 hour period when the lights were off in the growth chamber.
[3]Day is the 24-hour period in which each treatment was divided.
[4]Bin Class is the term used to classify the 4 KBG cultivar blends: 4-Way, Impact, Lowmow, and TWCA.
[5]Time is the chamber Entry to Exit difference

Table 4.4.2: The differences between Day 1 and Day 2 for the measured turfgrass physiologies of Kentucky bluegrass sods at below bin capacity

Day[3]	ET[1] (mm/h)		(%)	CO_2 (mmol/m^2/h)	WUE (mmolCO_2/molH_2O)	Green Cover (%)
	Light On[2]	Light Off	Off/On	Light On	Light On	
1	0.3597b[4]	0.1303a	36.2	58.9b	2.92b	90.76 a
2	0.3741a	0.1258a	33.6	63.7a	3.12a	87.60 b

[1]ET is evapotranspiration, CO_2 is net CO_2 exchange, WUE is mean water use efficiency, Green cover is the mean green cover of a turfgrass bin, Δ Canopy Height is the difference in turfgrass height on growth chamber entry and on growth chamber exit.
[2]Light On is the 12 hour period when the lights were on in the growth chamber, and Light Off is the 12 hour period when the lights were off in the growth chamber.
[3]Day is the 24-hour period in which each treatment was divided.
[4]lowercase letters in each column that are the same have means that are not statistically different at $p<0.05$ Tukey's test.

Table 4.4.3: The differences for below bin capacity treatment by Kentucky bluegrass Bin Class on all measured turfgrass physiological parameters

Bin Class[3]	ET[1] (mm/h) Light On[2]	ET[1] (mm/h) Light Off	(%) Off/On	CO_2 (mmol/m^2/h) Light On	CO_2 (mmol/m^2/h) Light Off	WUE (mmol CO_2/mol H_2O) Light On	Δ Height (mm)	Green Cover (%)
Impact	0.3536 b[4]	0.1139 b	32.2	63.7 a	-14.8 b	3.20 a	1.21 a	90.33 a
4-Way	0.4125 a	0.1701 a	41.2	64.2 a	-16.3 a	2.86 b	-7.44 b	86.58 b
Lowmow	0.3646 b	0.1104 b	30.3	55.0 b	-12.0 c	2.73 b	-1.83 a	87.26 b
TWCA	0.3369 c	0.1177 b	34.9	62.1 a	-14.6 b	3.30 a	0.53 a	92.54 a

[1]ET is evapotranspiration, CO_2 is net CO_2 exchange, WUE is mean water use efficiency, Green cover is the mean green cover of a turfgrass bin, Δ Canopy Height is the difference in turfgrass height on growth chamber entry and on growth chamber exit.
[2]Light On is the 12 hour period when the lights were on in the growth chamber, and Light Off is the 12 hour period when the lights were off in the growth chamber.
[3]Bin Class is the term used to classify the 4 KBG cultivar blends: 4-Way, Impact, Lowmow, and TWCA.
[4]lowercase letters in each column that are the same have means that are not statistically different at $p<0.05$ Tukey's test.

Table 4.4.4: ET_{day} for each Kentucky bluegrass bin class of the Below Bin Capacity Treatment.

Bin Class	ET mm/day
Impact	5.61
KBG 4-way	6.99
Lowmow	5.70
TWCA	5.45

The ET_{day} rates were calculated with the formula:
ET_{day}=12*(ET Light On) + 12*(ET Light Off)

4.5 Sodded KBG Physiological Responses to Bin Capacity Compared to Below Bin Capacity

Difference in water content was an important factor for all measured turfgrass physiological parameters (Table 4.5.1). The water content by KBG bin class interaction was important for all measured turfgrass physiological parameters (Table 4.5.1). The Water Content by day interaction was important for all measured turfgrass physiological parameters (Table 4.5.1). The interaction between Water Content, KBG type, and Day was significant for LET, DCO_2 and LWUE (Table 4.5.1).

The Below Capacity treatment had a higher LET, LCO_2, LWUE, and green cover than the Capacity treatment (Table 4.5.2). The DET rates for turfgrass grown at Capacity were 15.7% greater than turfgrasses grown at Below Capacity. The LCO_2 rates for turfgrasses grown at Below Capacity were 21.5% greater than turfgrasses grown at Capacity. The Bin Capacity treatment had greater DET, DCO_2 values (Table 4.5.2). The Below Capacity treatment had reduced green cover on exit compared to entry (Table 4.5.2).

LET was the same for both treatments on Day1, but the Below Capacity increased on Day 2 and Capacity decreased on Day 2 (Table 4.5.3). The DET of the capacity treatment decreased from day 1 to day 2, while it was constant for the below treatment (Table 4.5.3). The DET rates for turfgrasses grown at Capacity were 12.3% to 18.9% greater than turfgrasses grown a Below Capacity. In both water treatments the LCO_2 of Day 2 exceeded the values of Day 1 (Table 4.5.3). On both days, the below treatment had LCO_2 values about 21.4% greater than the capacity treatment (Table 4.5.3). The DCO_2 of the below treatment was consistently lower than the capacity treatment for both days and the capacity treatment had a greater loss on Day1 than

Day 2 (Table 4.5.3). The LWUE was greater on Day2 than Day 1 for both water treatments and below capacity was greater than the capacity (Table 4.5.3). The LWUE rates for turfgrasses grown at Below Capacity were 13.1% to 18.8% greater than turfgrasses grown at Capacity.

The two KBG types with higher Below Capacity LET than Capacity LET rates were TWCA and 4-Way (Table 4.5.4). For Lowmow and Impact DET was higher in Capacity treatment compared to the Below Capacity (Table 4.5.4). TWCA and 4-Way DET was not different between water treatments (Table 4.5.4). For LCO_2, TWCA and 4-Way had higher values in the below capacity treatment compared to the capacity treatment (Table 4.5.4). Lowmow and Impact lost less DCO_2 in the below capacity treatment compared to the capacity treatment (Table 4.5.4). TWCA and 4-Way lost more DCO_2 in the below capacity treatment than in the capacity treatment (Table 4.5.4). TWCA and 4-Way had higher LWUE in the below capacity treatment than in the capacity treatment (Table 4.5.4).

Table 4.5.1: Analysis of variance of turfgrass physiological responses of Kentucky bluegrass sods to the different water treatments (Bin Capacity/Below Bin Capacity)

Interaction	ET[1]			CO_2		WUE	Green Cover
	Lights On[2] (mm/h)	Lights Off (mm/h)	Light OFF/Light ON (%)	Lights On (mmol/m^2/h)	Lights Off (mmol/m^2/h)	Lights On (mmolCO_2/molH_2O)	(%)
Water[5]	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Water*Bin Class[4]	<.0001	<.0001		<.0001	<.0001	<.0001	<.0001
Water*Day[3]	<.0001	0.0029	0.0003	<.0001	0.0113	<.0001	0.0046
Water*Bin Class*Day	0.0049	0.8133		0.256	<.0001	0.0177	0.9005

*colour change did not include TWCA

[1]ET is evapotranspiration, CO_2 is net CO_2 exchange, WUE is mean water use efficiency, Green cover is the mean green cover of a turfgrass bin.

[2]Light On is the 12 hour period when the lights were on in the growth chamber, and Light Off is the 12 hour period when the lights were off in the growth chamber.

[3]Day is the 24-hour period in which each treatment was divided.

[4]Bin Class is the term used to classify the 4 KBG cultivar blends: 4-Way, Impact, Lowmow, and TWCA.

[5]Water represents the two water conditions: Bin Capacity and Below Bin Capacity

Table 4.5.2: The effect of water treatment (Below Bin Capacity vs Bin Capacity) on the measured turfgrass physiologies for Kentucky bluegrass

Treatment	ET[1]			CO_2		WUE	Green Cover
	(mm/h)		(%)	(mmol/m^2/h)		(mmolCO_2/molH_2O)	(%)
	Light ON[2]	Light OFF	Light OFF/Light ON	Light ON	Light OFF	Light ON	
Below Bin Capacity[3]	0.3669a[4]	0.1280 b	34.7 b	61.3a	-14.4a	3.02 a	88.06 a
Bin Capacity	0.3414b	0.1519 a	44.8 a	48.1b	-15.3b	2.54 b	84.84 b

[1]ET is evapotranspiration, CO_2 is net CO_2 exchange, WUE is mean water use efficiency, Green cover is the mean green cover of a turfgrass bin. Δ Canopy Height is the difference in turfgrass height on growth chamber entry and on growth chamber exit.
[2]Light On is the 12 hour period when the lights were on in the growth chamber, and Light Off is the 12 hour period when the lights were off in the growth chamber.
[3]Below Bin Capacity is all of the bin classes pooled together when grown at below bin capacity conditions, Bin Capacity is all of the bin classes pooled together when grown at bin capacity conditions
[4]lowercase letters in each column that are the same have means that are not statistically different at $p<0.05$ Tukey's test.

Table 4.5.3: The effect of water treatment (Below Capacity vs At Capacity) and Day(Day1 vs Day2) on measured turfgrass physiologies of Kentucky bluegrass sods

Water	Day[3]	ET[1]			CO_2		WUE
		(mm/h)		(%)	(mmol/m^2/h)		(mmolCO_2/molH_2O)
		Light ON[2]	Light OFF	Light OFF/Light ON	Light ON	Light OFF	Light ON
Below[4]	1	0.3597 b[5]	0.1303 c	36.0b	58.9b	-14.3a	2.92b
Below	2	0.3741 a	0.1258 c	33.4b	63.7a	-14.5a	3.12a
Capacity	1	0.3494 b	0.1552 a	44.7a	46.26d	-15.65c	2.37d
Capacity	2	0.3334 c	0.1485 b	45.0a	50.1c	-15.1b	2.71c

[1]ET is evapotranspiration, CO_2 is net CO_2 exchange, WUE is mean water use efficiency, Green cover change is the change in green cover of the turfgrass bins from the time before being entered into the growth chamber and the time the turfgrass bins were removed from the grown chamber, Δ Canopy Height is the difference in turfgrass height on growth chamber entry and on growth chamber exit.
[2]Light On is the 12 hour period when the lights were on in the growth chamber, and Light Off is the 12 hour period when the lights were off in the growth chamber.
[3]Day is the 24-hour period in which each treatment was divided.
[4]Below is all of the bin classes pooled together when grown at below bin capacity conditions, Capacity is all of the bin classes pooled together when grown at bin capacity conditions
[5]lowercase letters in each column that are the same have means that are not statistically different at $p<0.05$ Tukey's test.

Table 4.5.4: The effect of KBG bin class, water treatment by round on measured turfgrass physiologies

Bin Class[5]	Treatment[4]	Round[3]	ET[1] (mm/h)		CO_2 (mmol/m^2/h)		WUE (mmolCO_2/molH_2O)	Green Cover (%)
			Light ON[2]	Light OFF	Light ON	Light OFF	Light ON	
Impact	Capacity	1	0.3665bc[6]	0.1468 c	62.6 a	-20.45h	3.08 bc	92.11 a
		2	0.3244fg	0.1426 c	47.4 d	-17.80f	2.59 ef	88.82 abc
	Below	1	0.3536cde	0.1139 e	63.7 a	-14.77d	3.20 ab	90.33 abc
4-Way	Capacity	1	0.3818b	0.1780 a	50.1 d	-13.12c	2.37 g	76.86 d
	Below	1	0.4125a	0.1701 ab	64.2 a	-16.30e	2.86 cd	86.58 c
Lowmow	Capacity	1	0.4129a	0.1711 ab	58.6 b	-19.12g	2.57 efg	86.70 c
		2	0.3481de	0.1615 b	50.2 d	-15.44de	2.73 de	79.72 d
	Below	1	0.3646bcd	0.1104 e	55.0 c	-11.97b	2.59 efg	87.26 bc
TWCA	Capacity	1	0.3105g	0.1380 cd	39.6 e	-12.70bc	2.48 fg	NA
		2	0.2455h	0.1236 de	28.3 f	-8.56a	2.12 h	NA
	Below	1	0.3369ef	0.1177 e	62.1 a	-14.55d	3.30 a	NA

[1]ET is evapotranspiration, CO_2 is net CO_2 exchange, WUE is mean water use efficiency, Green cover is the mean green cover of a turfgrass bin.
[2]Light On is the 12 hour period when the lights were on in the growth chamber, and Light Off is the 12 hour period when the lights were off in the growth chamber.
[3]Round is the 4 day period that each bin class was in the growth chamber
[4]Treatment is divided into either below or capacity: Below is the treatment the bin classes were grown at below bin capacity conditions, Capacity is the treatment the bin classes were grown capacity conditions
[5]Bin Class is the term used to classify the 4 KBG cultivar blends: 4-Way, Impact, Lowmow, and TWCA.
[6]lowercase letters in each column that are the same have means that are not statistically different at $p<0.05$ Tukey's test.

Chapter 5: Discussion

5.1 Sodded ABA Application

In the ABA Experiment, the application of ABA to sodded KBG turfgrass resulted in reduced ET rates and NCER (Table 4.1.3). In previous work, the application of ABA on various plants reduced stomatal conductance, photosynthesis and transpiration (Wan and Zwiazek 2001; Yin et al. 2004; Ma et al. 2008; Waterland et al. 2010; Agehara and Leskovar 2012; McArtney et al. 2014; Weaver and van Iersel 2014; Li et al. 2015). In general, previous studies supported the findings in our ABA study. The studies varied in the types of plants used including perennial woody plants (Wan and Zwiazek 2001; Yin et al. 2004; Ma et al. 2008; McArtney et al. 2014), annual plants (Waterland et al. 2010; Kim and van Iersel 2011; Agehara and Leskovar 2012; Weaver and van Iersel 2014), or perennial bedding plants that share morphological likeness to grasses (Li et al. 2015). The previous studies applied ABA to different parts of the plant, including the leaves (Yin et al. 2004; Ma et al. 2008; Waterland et al. 2010; Agehara and Leskovar 2012; McArtney et al. 2014; Weaver and van Iersel 2014), roots (Wan and Zwiazek 2001; Waterland et al. 2010; Kim and van Iersel 2011; Li et al. 2015), or open stem cuttings (Wan and Zwiazek 2001); in the current study it was assumed that the excess ABA from the foliar application would be taken up by the roots.

In previous ABA research, the age of the plant specimens ranged from young seedlings to mature annuals or trees. In comparison, the current ABA study examined the effect on mature sods of varying ages grown in a greenhouse environment for six to eight months that exposed them lower levels of UV light and less air movement potentially resulting in different cuticle composition and stomatal morphology. Wan and Zwiazek (2001) applied ABA to intact aspen

(*Populus tremuloides*) seedlings and excised shoots, and gas exchange was reduced in treated plants compared to untreated plants and it was correlated to an increase in ABA concentrations of the xylem sap. Ginger plants that had ABA irrigated at increasing concentrations had stomatal conductance that was significantly reduced compared to the untreated control (Li et al. 2015). In the current study, both LET (Light On ET) and LCO_2 (Light On NCER) rates were reduced compared to the untreated control (Table 4.1.3). The foliar application of ABA on two apple (*Malus sp*) species significantly reduced photosynthesis and stomatal conductance in both the well-watered and drought treatments (Ma et al. 2008). Application of ABA to young vegetative propagations of poplar resulted in decreased net photosynthesis, transpiration, and stomatal conductance (Yin et al. 2004). The LET and LCO_2 were both reduced when ABA was applied to the turfgrasses (Table 4.1.3). Unlike LCO_2, the LET reduction from the ABA application treatment did not reverse in the present study. These findings support the reduction of LWUE, LCO_2, and LET of ABA-treated KBG turfs (Table 4.1.3). To have a reduction in LET and LCO_2 during the ABA application period, the increased levels of ABA within the plant could have led to a reduction in the number of open stomata or the relative opening size of the stomata (Waterland et al. 2010; Aasamaa and Sõber 2011).

The effect of the application of ABA can be either reversible or not reversible. The application of ABA on Salvia (cv. 'Bonfire Red') reduced gas exchange within three hours for all treated plants and lasted for the remainder of the study relative to the untreated control (Kim and van Iersel 2011). The spraying and drenching of chrysanthemums (cv. Festive Ursula) resulted in decreased stomatal conductance on day 1 to day 3 for both irrigated and drought-stressed plants (Waterland et al. 2010). The drought stressed plants that were watered on day six and plants that were continually irrigated had stomatal conductance return to pre-application rates (Waterland et al. 2010). Seedlings of muskmelon (cv. 'Caravelle') were treated with increasing concentrations of ABA, which were negatively correlated with carbon assimilation and gas exchange (Agehara and Leskovar 2012). The effects of reduced carbon assimilation and gas exchange mitigated by ABA can be reversed by time (Agehara and Leskovar 2012). The application of ABA to mature apple trees resulted in reduced gas exchange within the first three hours of application, and had residual impact lasting up to nineteen days (McArtney et al. 2014). Thus, the residual impact of the ABA application treatment was greatest on LET (Table 4.1.3). The application of ABA to pansies (*Viola wittrockiana*) (cv. 'Delta Premium Deep Blue') significantly reduced the gas exchange and net photosynthesis from the day of application to twelve days after application (Weaver and van Iersel 2014). These findings support the reduction of LCO_2 of ABA-treated KBG turfs was reversible in time, and LET rates were not reversable (Table 4.1.3).

In the current study, the foliar application of ABA resulted in reduced leaf extension (Table 4.1.3). The application of ABA to two apple species (*Malus sp*) resulted in reduced height growth and total leaf area (Ma et al. 2008). The application of 3.8 mM ABA on young pepper transplants reduced shoot elongation for up to seven days (Agehara and Leskovar 2015). The growth of KBG cultivars 'Midnight' and 'Barron' was reduced for those treated with ABA under well-watered conditions (Wang et al. 2003). KBG treated with ABA took six days to return to a growth rate similar to untreated plants (Wang et al. 2003). The application of ABA on bell pepper plants reduced plant growth that was reversible with time (Agehara and Leskovar 2015). The reduced growth in treated plants relative to untreated plants in the three studies was similar to the reduction in photosynthetic rates (Table 4.1.3). The application of ABA to pansies (*Viola wittrockiana*) (cv. 'Delta Premium Deep Blue') significantly caused chlorosis on treated leaves relative to the control (Weaver and van Iersel 2014). The chlorosis of the pansy leaves treated with ABA was similar to the results in Table 4.1.3 of the reduction of turfgrass green area after the ABA application. These findings support the results found in the current ABA study where ABA application reduced turfgrass growth and green area (Table 4.1.3). The reduction of plant growth rate and green area coincided with the drop in photosynthesis. The reduction in turfgrass canopy growth after ABA application could be associated with possible stomatal closures (Kriedemann et al. 1972; Rogiers et al. 2012; Pantin et al. 2013; Li et al. 2015), reduced stomatal conductance (Wan and Zwiazek 2001; McArtney et al. 2014) and reduced net carbon assimilation rates (Ma et al. 2008; Lu et al. 2009).

When KBG and CB were treated with ABA pre-drought, the treated plants had less early growth than untreated plants, but had sustained growth longer into the drought period compared to the untreated control (McCann and Huang 2008). In the current study, canopy growth was reduced when ABA was applied (Table 4.1.3). Canopy growth returned to rates similar to the control treatment during the recovery treatment (Table 4.1.3). The treated plants used less water earlier in the drought treatment compared to the untreated control (McCann and Huang 2008). In Experiment 1 the ABA application reduced canopy growth compared to the control period (Table 4.1.3). The reduction in turfgrass canopy growth after ABA application would be associated with possible stomatal closures (Kriedemann et al. 1972; Rogiers et al. 2012; Pantin et al. 2013; Li et al. 2015), reduced stomatal conductance (Wan and Zwiazek 2001; McArtney et al. 2014) and reduced net carbon assimilation rates (Ma et al. 2008; Lu et al. 2009).

5.2 Seeded Turfgrass Species at Bin Capacity Conditions

Previous studies measured turfgrass water use on a daily to monthly basis with varying methods. One method to determine water use was the mass-balance/gravimetric method on a daily basis using a few measurements at two day intervals over the course of a growing season (Shearman 1986; Ebdon et al. 1998b). The other main method of determining water use was the Penman-Montieth equation (Section 2.1.1) either directly or using some derivations of the equation (Carrow 1995; McGroary et al. 2011; Candogan et al. 2014, 2015; Aydinsakir et al. 2016). The method used in the current experiments for measuring water loss was the mass-balance/gravimetric method at hourly ET rate intervals. This method allowed for a more accurate result than the other methods of ET rate measurement because it allowed LET and DET to be measured independently for a more accurate understanding of daily ET rate allotment. When studying ET rates of tomatoes in a closed environment with a live recording scale during both day and night conditions, night ET rates were about 30% of day time ET rates (Caird et al. 2007). This supported the general findings in all of the experiments in this study of DET being about one third to a half of the given LET value for the same species or KBG type within the same experiment (Table 4.3.2; Table 4.2.3; Table 4.4.3).

In the current study, the rootzone of the seeded bins was as an 80:20(by volume) sand and peat moss mixture of 11cm. Previous research examining ET in seeded cool season turfgrass used either fritted clay in the rootzone (Shearman 1986; Kim and Beard 1988; Green et al. 1990; Bowman and Macaulay 1991; Salaiz et al. 1991; Fernandez and Love 1993; Qian et al. 1996; Ebdon et al. 1998b; Huang and Fu 2000), field soil, or a sand and peat moss mixture. Also, previous research was conducted using a range of environments in either growth chambers (Green et al. 1990; Ebdon et al. 1998b), greenhouses (Bowman and Macaulay 1991), or field trials (Kopec et al. 1988; Zhang et al. 2007). Use of similar conditions in previous work would allow for the best comparison between species to the current seeded study. In a growth chamber study with fritted clay, KBG ET_{day} was 11.2 and 12.4 mm/day (cv. Majestic, Bensun and Merion), PR (cv. Manhattan II) ET_{day} was 9.1mm/day (cv. Manhattan II), and TF ET_{day} was 9.9 and 11.4 mm/day (cv. Kentucky 31, and Rebel) (Green et al. 1990). In the growth chamber study, PR (cv. Manhattan II) had ET rates lower than all three KBG cultivars, and both TF cultivars had ET rates that were not different than the three KBG cultivars or PR (Green et al. 1990). The ET_{day} rates in the current study for KBG were 51.5% to 53.5% less than those reported by Green et al. (1990). TF ET_{day} rates in the current study were 22.5% to 32.7% lower than Green et al. (1990).The ET_{day} rates in the current study for PR were 32.1% lower than Green et al. (1990). In the current study, TF had the highest LET, DET and ET_{day} rates and KBG had the lowest LET and ET_{day} rates (Table 4.2.3; Table 4.2.4). In a field study with field soil, well-watered TF ET_{day} rate was 4.08mm/day(cv. Hundog-5), KBG ET_{day} rate was 8.87 mm/day (cv. Nuglade), and PR ET_{day} rate was 3.86 mm/day (cv. Advent) (Zhang et al. 2007). In a field trial with sand and peat, the ET_{day} day was 5.68 mm/day for KBG (cv. Merion) and was not different than TF (cv. Rebel) at 5.18 mm/day (Feldhake et al. 1983). The results in the current study had TF (cv. Summer) LET (0.4205 mm/h), DET (0.2186 mm/h) and ET_{day} (7.67 mm/day) rates being greater than KBG LET (0.3222 mm/h), DET (0.1583 mm/h) ET_{day} (5.77 mm/day) (cv. Action) (Table 4.2.3; Table 4.2.4) were not supported by Feldhake et al. (1983). When comparing the cumulative ET rates under well-watered conditions, there was no difference between KBG (cv. Apollo) and TF (cv. Dynasty) (Su et al. 2007). To allow for the comparison of the data from the current study to the previously reported research on turfgrass ET rates, ET_{day} rate values in mm/day for each species were calculated to be 7.67 mm/day for TF (cv. Summer), 6.18 mm/day for PR (cv. Accent II), and 5.76mm/day for KBG (cv. Action) (Table 4.2.4). In terms of relative ET_{day} comparisons between species, there was no definitive pattern in the difference turfgrass species ET_{day} rates relative with the current study. The differences between turfgrass species ET rates in the current study could be caused by differences in green cover and plant genetic parameters.

5.3 Untreated Sodded Turfgrass

5.3.1 Turfgrass ET

In the current study, there were differences in LET and DET based on KBG bin class (Table 4.3.2). When comparing ET_a rates in the current study to those in the literature, one important difference was that the current study used KBG blends not single KBG cultivars. In a growth chamber study on KBG sourced from sod plugs grown on fritted clay subjected to a temperature environment of 25ºC, ET_a rates ranged from 4.15-7.15 mm/day with a mean of 6.076 mm/day (Shearman 1986). The ET_a rates of the current study were 5.10-7.04 mm/day (Table4.3.3), which were within the range of Shearman (1986). The two main differences between the studies were the depth of the rootzone (11.5cm vs 25 cm) and rootzone growth medium (sand and peat vs fritted clay). In a two year field study using KBG sods grown on field soil, the ET_a rates for cv. Baron were 3.50 and 3.68 mm/day and cv. Enmundi were 3.38 and 4.14 mm/day (Aronson et al. 1987a). The lower ET_a rates measured by Aronson et al. (1987a) compared to the current study could attributed to the variability of growth conditions of a field study. As a whole, KBG ET_a rates would be most comparable when the plants were grown under similar conditions.

In general, the ET_a rates for the bin capacity treatment were lower during the Light On (LET) period and had higher Light Off ET_a (DET) rates than the below bin capacity treatment (Table 4.5.2). The drought treatment on KBG cultivars 'Midnight' and 'C-74' had decreased transpiration relative to the well-watered control (Abraham et al. 2008). In the current study, the bins were put into the chamber at either bin capacity or below bin capacity and had the mass recorded on an hourly basis. In contrast, Abraham et al. (2008) had the turfgrass lysimeters put into the chamber at capacity and allowed the drought containers to dry down fourteen days before measuring ET_a with a portable single leaf gas exchange system (LI-6400; LI- COR, Inc., Lincoln, NE). Sodded TF had lower ET_c rates and gas exchange when irrigated once a day compared to the less frequently irrigated plots (Brown et al. 2004). Brown et al. (2004) stated that the water use and gas exchange differences were the result of wetter soils not having sufficient aeration to function normally. Even with the use of a sand and peat mixture as the growing medium in the current study, the higher soil water content of the current study hindered the ability of the KBG sods to function optimally compared to the below capacity treatment. TF sods under different irrigation treatments, ranging from 100% water loss replacements to 20% water loss replacements, did not have different rates of gas exchange (Domenghini et al. 2013). In contrast, the current study had both ET_a rates and NCER affected by the different soil water content treatments. Plant ET rates and stomatal conductance can be reduced by water logged soil conditions (Huang et al. 1994; Shao et al. 2013). The reduction in ET rates in winter wheat grown in water logged conditions was attributed to the greater closing of stomata than plants grown in drier soil conditions (Shao et al. 2013). The difference between Day 1 and Day 2 ET rates in the bin capacity study were similar to Shao et al. (2013) where ET rates increased three days after the waterlogging stress was lifted. The difference in KBG bin class ET rates in the bin capacity study could be based on how each cultivar responded to the water logging stress.

In the current below capacity study, ET_a rates were different based on KBG bin class (Table 4.4.3). In a drought dry down treatment comparing KBG cultivars of the highest and lowest 5% ET_a rate cultivars as determined in Ebdon et al. (1998b), the ET rate was different between cultivar groups in both years during days 1-4, and the low ET rate cultivars were less (Ebdon and Kopp 2004). When comparing the ET rates of cultivars defined as being part of either a low and high ET rate group, KBG cultivar groups during days 5-9 of the dry-down showed a difference in ET rates only in the first year and the low ET rate group used less water (Ebdon and Kopp 2004). During days 1-4, the within group ET rate was only different for the low ET rate KBG group in the second year (Ebdon and Kopp 2004). Over days 5-9 of the dry-down the differences within each group were significant except for year 2 of the high ET rate group (Ebdon and Kopp 2004). These findings support the results of the below bin capacity study, where TWCA, composed of low water use cultivars, had lower LET compared to the KBG types with higher ET rates (Table 4.4.3). Turfgrass bred for longer green cover (TWCA) had lower ET rates in the current experiment. The KBG bin class ET rates were dependent on how the cultivar blends in each KBG bin class responded to soil water conditions (Ebdon and Kopp 2004).

5.3.2 Turfgrass CO_2 Balance

In a turfgrass study comparing the differences between morphology and class of different Bermuda grass cultivars to either well-watered or deficit irrigation treatments, a LI-COR 6400XT was used to measure both CO_2 and H_2O exchange rates of two to three attached leaves (Husmoen et al. 2012). The cultivars had different CO_2 exchange rates and the plants under deficit irrigation had lower CO_2 exchange rates than those that were well watered (Husmoen et al. 2012). When comparing CO_2 balance data of KBG bin classes watered to capacity to those watered to below capacity, the data show that the below bin capacity plants had higher CO_2 balance rates than the capacity treatment (Table 4.5.2, Table 4.5.3). The differences between Husmoen et al. (2012) and the current study include a greenhouse versus growth chamber environment, the use of a LI-COR 6400XT analyzer on 2-4 attached leaves at peak physiological activity versus the use of a LiCor L16262 Gas Analyzer for the whole study unit over a 24 hour time cycle, and the use of a single cultivar in each stand versus the use of a cultivar blend. Under drought conditions, there was a cultivar difference for single leaf photosynthesis between KBG 'Midnight' and 'C-74'when using a portable gas exchange system (Abraham et al. 2008). When comparing well-watered KBG to drought treatments, the well-watered plant had higher net photosynthesis rates. The drought treatment on KBG 'Midnight' and 'C-74' had decreased net photosynthesis relative to the well-watered control (Abraham et al. 2008). In contrast to the current study, Abraham et al. (2008) imposed a drought treatment while the current study imposed a drier soil environment that was irrigated.

When comparing the effect of mowing height on two CB cultivars ('Pencross' and 'Denshaw') there was no cultivar difference in photosynthesis, but there was a difference in night time respiration (Liu and Huang 2003). In Experiments 2-4 there were differences in both species and KBG bin class (KBG cv blends) dark period respiration that were also found in Liu and Huang (2003). The sealed nature of the respiration measurements in Liu and Huang (2003) with a 10 cm diameter tube over the canopy allowed for a relative equivalence of measurement to the current experiment total stand NCER. In the current study, the hourly measurement of NCER balances showed differences between cultivars in Experiment 3 (Table 4.3.2), Experiment

4 (Table 4.4.3), and between water treatments (Table 4.5.2; Table 4.5.3; Table 4.5.4). The lower photosynthesis rates in the bin capacity treatment relative to the below bin capacity treatment were also found in waterlogging of winter wheat (Huang et al. 1994; Shao et al. 2013). Waterlogged winter wheat had reduced photosynthesis relative to the non-waterlogged control plants (Huang et al. 1994; Shao et al. 2013). The turfgrasses in the bin capacity treatment were maintained in the greenhouse at or near waterlogged conditions before and after entering the growth chamber for study by being watered every second day. In contrast, the turfgrasses in the below bin capacity treatment were maintained in the greenhouse at below bin capacity conditions with a single weekly watering. The winter wheat cultivar photosynthesis rates found by Huang et al. (1994) was similar to the different KBG bin classes with different cultivar blends in response to waterlogging conditions (Table 4.3.2). The photosynthetic efficiency of the turfgrass in the bin capacity study could have been lower than the below bin capacity study due to limitations in stomatal activity (Shao et al. 2013). The day difference in photosynthesis rates (Table 4.5.3), such that Day 2 rates were greater than Day 1 were similar to Shao et al. (2013), where photosynthesis rates took up to three days to return to normal after the waterlogging treatment ended. Shao et al. (2013) suggested that the reduction in winter wheat photosynthesis rates were the result of increased stomatal closure. Based on the finding of both Huang et al. (1994) and Shao et al. (2013), the reduction in photosynthesis rates in the bin capacity treatment compared to the below capacity treatment were the result of the closure of stomata in response to waterlogged conditions.

5.3.3 Turfgrass WUE

In Experiments 1-4 water use efficiency (WUE) was defined as the ratio of NCER ($mmol/m^2/hour$) of all turfgrass bins in the chamber to the mean ET rate ($mol/m^2/hour$) of all of the bins in the growth chamber. Ebdon and Kopp (2004) found that WUE was different based on KBG cultivar and the time period of the dry down experiment. KBG cultivars during the early period of the dry down (Day 1-4) had higher WUE than the same plants during the water limited period (Day 5-8) (Ebdon and Kopp 2004). In contrast, when comparing the WUE values of Experiment 3 to Experiment 4, the KBG bin classes had a higher WUE when not under bin capacity conditions (Table 4.5.2; Table 4.5.3; Table 4.5.4). The difference between the WUE of the well-watered and water-limited conditions was attributed to the 75% decline in growth under the drier soil conditions (Ebdon and Kopp 2004). Ebdon and Kopp (2004) defined WUE as the dried leaf biomass from cuttings above 5cm over a four-day period to the water use over the same four-day period (mg/mL). The limitation with this method was acknowledged by Ebdon and Kopp (2004)based on the unaccounted carbon allocation to the roots and rhizome structures, and to new leaves below the 5 cm cutting height.

The WUE of warm season turfgrass grown in shallow soil profiles was defined as cumulative clipping yields to cumulative ET and was estimated by the linear regression of cumulative clipping yields to cumulative ET (Zhou et al. 2012). In the soil dry down, there was a species difference associated with WUE (Zhou et al. 2012). The turfgrasses grown under drought conditions had a higher WUE than turfgrasses grown under well-watered conditions (Zhou et al. 2012). A comparison of the WUE of Experiment 3 (Bin Capacity) to Experiment 4 (Below Bin Capacity) supports the study by Zhou et al. (2012), where KBG sods grown at below bin capacity had higher WUE than those grown at bin capacity (Table 4.5.2; Table 4.5.3; Table

4.5.4). The KBG bin class Lowmow did not follow the general trend (Table 4.5.4) compared to all species and cultivars in Zhou et al. (2012). In terms of winter wheat, waterlogged soil conditions reduced WUE (Shao et al. 2013). Shao et al. (2013) defined WUE as µmol CO_2/mmol H_2O by using a gas-exchange analyzer. The differences in WUE between KBG bin class grown at either bin capacity or below bin capacity conditions would be dependent on how the cultivars in each blend responded to their growing conditions as supported by Shao et al. (2013).

Instantaneous WUE was determined from fresh cut leaf photosynthetic rate and leaf transpiration rate (Abraham et al. 2008). Well-watered KBG cultivars ‘Midnight’ and ‘C-74’ did not have different WUE (Abraham et al. 2008). When comparing well-watered KBG to drought treatments, the well-watered plants had higher WUE (Abraham et al. 2008). The drought treatment on KBG ‘Midnight’ maintained similar WUE relative to the well-watered treatment, while KBG ‘C-74’ had decreased WUE relative to the well-watered control (Abraham et al. 2008). The difference in KBG bin class WUE responses were not consistently affected by water treatment (Table 4.5.4). The differences in KBG bin class WUE in Experiment 3 and Experiment 4 could be attributed to how the cultivar blends physiology differed as noted in Abraham et al. (2008).

Chapter 6: Conclusions

In Experiment 1, ABA application reduced ET and photosynthesis rates as expected. The ET rates never returned to the level of the control, while photosynthesis returned to the level of the control. The application of ABA to plants may not have a consistent effect over time for plant WUE. These finding could allow managers of sports stadia to apply ABA before an event to reduce humidity loads for consecutive days, although reduced growth and recovery of the turfgrass system could occur.

In Experiment 2, the ET, photosynthesis and WUE rates were different based on the species of seeded cool season turfgrass. TF had the highest ET and photosynthetic rates. KBG had the lowest ET and photosynthetic rates. PR had the highest WUE rate. The results of Experiment 2 reinforce the assumption that different species of cool season grasses have different ET rates when watered to bin capacity. If turfgrass managers prefer a low water-use, seeded turfgrass, KBG would be preferred over both TF and PR when watered to field capacity. In context, the root zones in this experiment had a maximum depth of 16cm that are not realistic in normal turfgrass field conditions. The use of a relatively shallow rootzone did not optimize the deep root growth capabilities of tall fescue. In the field, turfgrass managers would normally not maintain their rootzone water status at field capacity. Future research in this area could focus on ET and photosynthesis rates at varying soil water content levels.

In Experiment 3, sodded KBG cultivar blends grown at bin capacity had different ET, photosynthesis and WUE based on cultivar differences. Water loss from blends of KBG cultivars varied in LET, DET, and photosynthesis. Grass bred to stay green longer during prolonged drought (TWCA) had both the lowest ET rates during both light and dark periods, and generally lower photosynthetic rates compared to other KBG cultivars. This indicated a potential to select for KBG blends that use less water in the urban setting. In Experiment 4 with variable soil water content, sodded KBG blend had different ET, photosynthesis and WUE rates based on cultivar differences. The LET, DET and photosynthesis rates varied by KBG cultivar blends in this study. Kentucky bluegrass cultivars bred to stay greener during drought conditions (TWCA) had the lower light on ET rates than other cultivars. The difference in ET rates indicates the potential for the urban setting to use less water based on KBG cultivar blend selection.

When comparing the results of Experiment 3 to Experiment 4, KBG sods grown under variable soil water content conditions had higher LET, LCO_2 and WUE rates than those grown under bin capacity conditions. KBG blends grown under capacity conditions had higher DET and DCO_2 rates than those grown under variable soil water conditions. KBG turfgrasses grown under bin capacity conditions could have hindered physiological function relative to those grown under variable soil water content conditions. Reduced irrigation of sand and peat rootzones below field capacity would allow for healthier plants. To maximize WUE of turfgrasses, areas with turfgrass should not be irrigated to field capacity.

One of the shortcomings of this research was the lack of proper replication for Experiments 2-4. The availability of one suitable growth chamber and a tight timeframe imposed by the project sponsor limited the number of true replications. In an ideal situation, there would have been a second identical growth chamber with light settings staggered in time from the first chamber. The use of a second chamber would have allowed for a greater number of replications in Experiments 2-4. If the project timeframe was extended, proper repetitions could occur. The maintenance of the turfgrasses in greenhouse conditions during autumn and winter coincided with fungicide applications and reduced green cover. In future research, turfgrasses grown in greenhouse or growth chamber environments should use conditions that result in optimal turfgrass health. The application of the fungicides and insecticides might have negatively affected the health of the turfgrasses over the course of all experiments. In the ABA study (Experiment 1), the turfgrass bins used had initial green covers ranging from 36.4-77.1% with a mean of 57.6%. In ideal conditions, the turfgrasses undergoing the ABA experiment would have a minimum starting green area greater than those in the current experiment.

Future research on turfgrass ET in controlled environments would include different light quality conditions. The current study grew turfgrasses under HPS and nickel metal halide lights, which may have resulted in reduced green area in Experiment 1 and Experiment 4. To mitigate the reduction of turfgrass green area in controlled environments, ideal lighting conditions and cultivars or blends needs to be determined. In the case of lighting, the turfgrasses could be subjected to different wavelength combinations at different intensities. The ET rates and turfgrass health measurements should be compared for individual cultivars or known cultivar blends in a range of lighting conditions. Different cultivar bends may respond differently to the various lighting conditions. The different cultivars of each species should have the ET rates measured at different soil water content levels. In terms of ABA, future research should determine the amount and concentration of ABA that reduces ET rates with limited impacts to green cover.

ET rates of turfgrasses are not the same. They are affected by the genetics of species and cultivars. Also, ET rates are determined by available soil water content. To properly control water use in urban environments, the water use of each type of plant from species to cultivar should be studied to have precise measurements. Once the precise water use measurements are made in each urban environment area, governments can table motions for laws that determine which plants and cultivars should be grown in certain jurisdictions.

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Appendix

Table 7.1: Order of operations for Experiment 3

Day	Step	Action
-1	1	Turfgrass bins were soaked and allowed to drain for about 2 hours.
		Bins were covered with opaque bins to create an environment of 100% relative humidity.
	2	Bottom drain bins were emptied of water; bins were weighed to determine bin capacity
0	1	Turfgrass in each bin was cut to 3 cm
	2	Bins had photos taken for digital imaging analysis (round 1 only)
1	1	Bottom bins were drained of any excess water
	2	Bins were weighed to determined water needed to bring bins to bin capacity
	3	Bins were watered to bin capacity
	4	Bins had photos taken for digital imaging analysis (round 2 only)
	5	Bins were put on scales in the growth chamber
2	1	Maintained in chamber
3	1	Mass of bins recorded
	2	Bins watered to capacity
4	1	Maintained in chamber
5	1	Bins were removed from the chamber
	2	Bins had photos taken for digital imaging analysis

Table 7.2: Order of operations for Experiment 1 ABA treatment on KBG sod

Day	Step	Action
0	1	Bins were weighed to have a reference mass
	2	Bins moisture probed to determine mean VWC across all six bins
1	1	Turfgrass trimmed to 2.9± 0.3cm
	2	Bins were moisture probed to determine if watering was need
	3	Bins were watered to reference mass if below 20%±5
	4	Bins had photos taken in a light controlled booth to determine entry green cover
	5	Bins had Canopy height sensor treatment to measure height
	6	Bins entered the chamber and placed on scales at 10:00(except 1 round at 11:00)
2	1	Maintained in chamber
3	1	Bins removed from chamber at 10:00
	2	Bins had Canopy height sensor readings to measure exit height
	3	Bins had photos taken in light controlled booth to determine exit green cover
	4	Bins weighed on scaled to determine exit mass and the amount of watering required for chamber entry
	5	Bins were moisture probed to determine exit VWC
	6	Bins were trimmed to 2.9± 0.3cm
	7	Bins had Canopy height sensor readings to measure entry height
	8	Bins had photos taken in light controlled booth to determine entry green cover
	9	Bins were watered to about 304 g below initial entry mass
	10	Bins were sprayed with ABA at a rate of 2.7L/m^2 at concentration of 200 μM (Sigma-Aldrich, St. Louis, MO?) with a motorized pump system (designed by M. Chang).
	11	Bins had a sitting period
	12	Bins were weighed to determine entry mass
	13	Bins were moisture probed to determine entry VWC
	14	Bins entered chamber at about 11:00,
4	1	Maintained in chamber
5	1	Bins removed from the chamber at 10:00
	2	Bins had Canopy height sensor readings to measure exit height
	3	Bins had photos taken in light controlled booth to determine exit green cover
	4	Bins weighed on scaled to determine exit mass and the amount of watering required for chamber entry
	5	Bins were moisture probed to determine exit VWC
	6	Bins were trimmed to 2.9± 0.3cm
	7	Bins had Canopy height sensor readings to measure entry height
	8	Bins had photos taken in light controlled booth to determine entry green cover
	9	Bins watered to initial entry mass
	10	Bins were weighed after a sitting period to determine current entry mass
	11	Bins were moisture probed to determine entry VWC
	12	Bins entered the chamber at 11:00, except tall fescue at 11:35
6	1	Bins maintained in the chamber
7	1	Bins maintained in the chamber
8	1	Bins removed from the chamber at 10:00
	2	Bins had Canopy height sensor readings to measure exit height
	3	Bins had photos taken in light controlled booth to determine exit green cover
	4	Bins weighed on scaled to determine exit mass
	5	Bins were moisture probed to determine exit VWC

Table 7.3: Applied Insecticides

Date	Trade Name	Active Compound	Rate
9-Jul-15	Beleaf	flonicamid	0.3 gm /L
15-Jul	Pirlis	pirimicarb	0.5 gm/L
22-Jul	Dimlin	diflubenzuron	0.15 gm/L
30-Jul	Intercept	imidacloprid	0.25 gm/L
6-Aug	Beleaf	flonicamid	0.3 gm /L
13-Aug	Dimlin	diflubenzuron	0.15 gm/L
20-Aug	Impower	imidacloprid	0.25 gm/L
28-Aug	Intercept	imidacloprid	0.25 gm/L
3-Sep	Beleaf	flonicamid	0.3 gm /L
11-Sep	Dimlin	diflubenzuron	0.15 gm/L
18-Sep	Beleaf	flonicamid	0.3 gm /L
25-Sep	Pylon	chlorfenapyr	1.5 ml/L
8-Oct	Beleaf	flonicamid	0.3 gm /L
15-Oct	Pylon	chlorfenapyr	1.5 ml/L
12-Nov	Dimlin	diflubenzuron	0.15 gm/L
16-Nov	Beleaf	flonicamid	0.3 gm /L
4-Dec	Pylon	chlorfenapyr	1.5 ml/L
15-Jan-16	Dimlin	diflubenzuron	0.15 gm/L

Table 7.4: Applied Fungicides

Application Date	Trade Name	Active Compound	Rate
24-Oct	Banner	Propiconazole	(Eric applied)
30-Oct	Zerotol	Hydrogen peroxide	10 ml/L coarse spray
6-Nov	Zerotol	Hydrogen peroxide	10 ml/L coarse spray
12-Nov	Myco stop	Streptomyces griseoviridis	1 gm/ 10L
26-Nov	Zerotol	Hydrogen peroxide	10 ml/L coarse spray
1-Dec	Zerotol	Hydrogen peroxide	10 ml/L coarse spray
10-Dec	Heritage MAXX	azoxystrobin	63 ml 100 m-2 (~0.07 ml/bin) in 0.5 L of water per bin

Table 7.5: Turfgrass bin classes and Cultivar(s) in each bin class

Bin Class	Cultivars
Poa supina	Pre mixed
KBG low mow (Green Horizons/Compact)	Pre mixed
Impact (Pick seed)	Pre mixed
100% Dwarf KBG (Pick Seed)	Pre mixed
Pick Seed KBG 4-way	America, Armada, Mercury, SR 2100
Turfgrass Water Conservation Alliance(TWCA)	Mallard, Ridgeline, Monto Carlo
Seeded KBG	Action
Seeded tall fescue	Summer
Seeded perennial ryegrass	Accent II

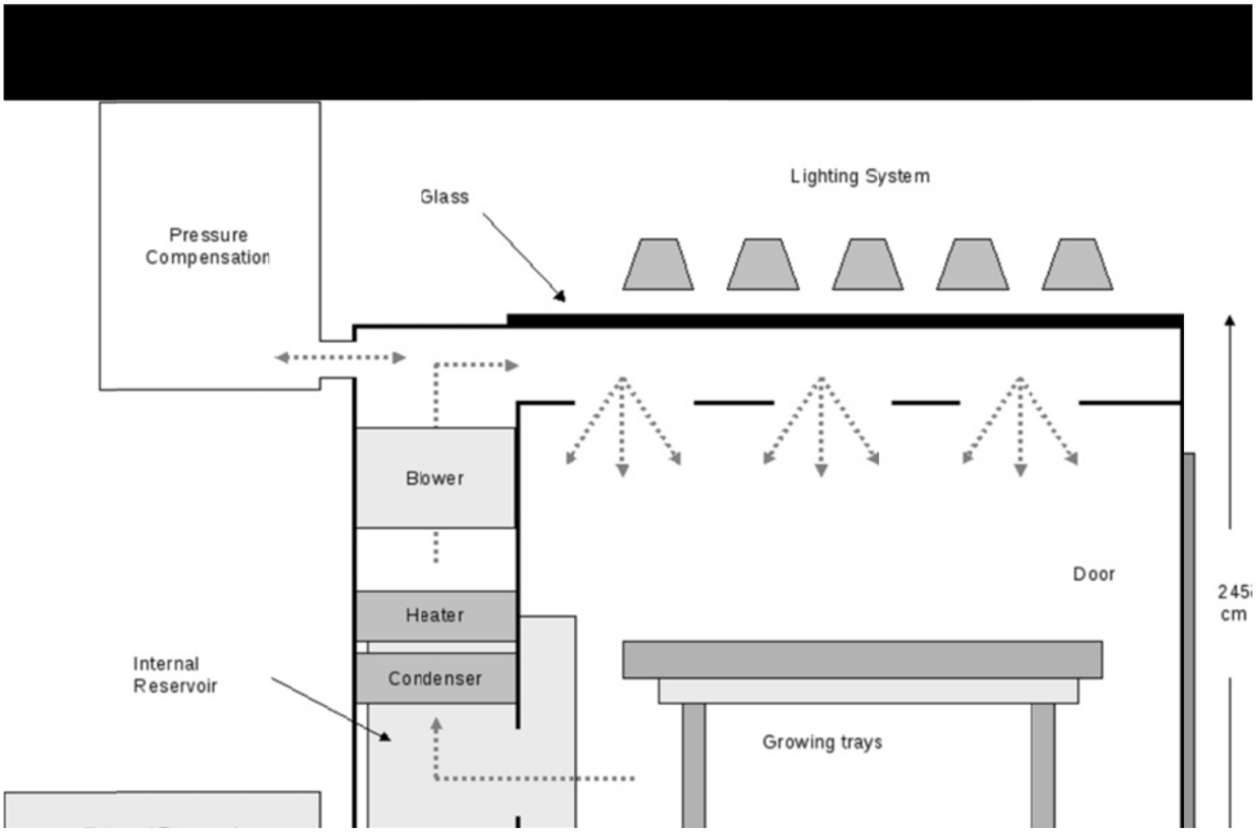

Figure 7.1: Schematic diagram of growth chamber set up (supplied by M. Stasiak (Stasiak et al. 2012))

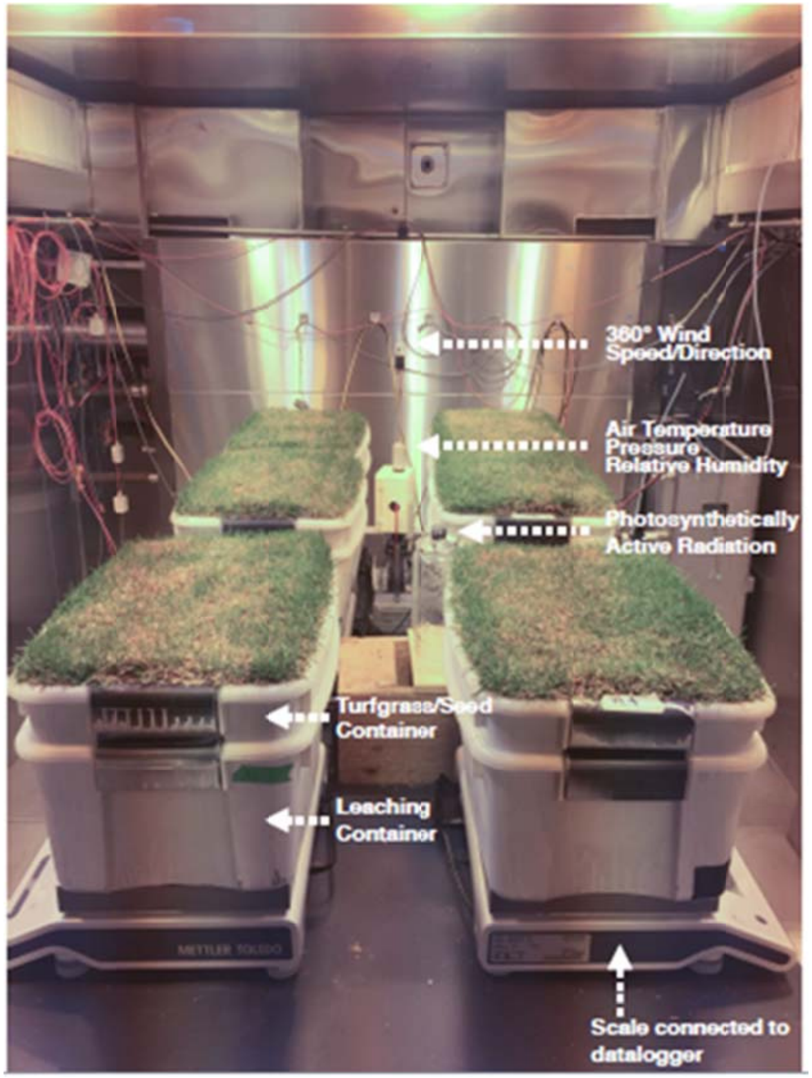

Figure 7.2: Turfgrass container (bins) set up in the Growth chamber (Supplied by Michael Chang): Six turfgrass bins located within the controlled environment chamber. The bins were placed onto balances to monitor ET_a. The chamber was equipped with following environmental sensors: wind speed/direction, temperature/pressure/humidity, and light quality