Utah State University

DigitalCommons@USU

All Graduate Theses and Dissertations

Graduate Studies

5-2014

Deficit Irrigation of Kentucky Bluegrass for Intermountain West Urban Landscapes

Hang T. T. Duong
Utah State University

Follow this and additional works at: https://digitalcommons.usu.edu/etd

Part of the Plant Sciences Commons

This Thesis is brought to you for free and open access by the Graduate Studies at DigitalCommons@USU. It has been accepted for inclusion in All Graduate Theses and Dissertations by an authorized administrator of DigitalCommons@USU. For more information, please contact digitalcommons@usu.edu.

Utah State University
MERRILL-CAZIER LIBRARY

DEFICIT IRRIGATION OF KENTUCKY BLUEGRASS FOR

INTERMOUTAIN WEST URBAN LANDSCAPES

by

Hang T.T. Duong

A thesis proposal submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Plant Science

Approved:

_____	_____
Dr. Roger K. Kjelgren	Dr. Lawrence E. Hipps
Major Professor	Committee member
_____	_____
Dr. Paul G. Johnson	Mark R. McLellan
Major Professor	Vice President for Research and
	Dean of the School of Graduate Studies

UTAH STATE UNIVERSITY
Logan, Utah

2014

ABSTRACT

Deficit Irrigation of Kentucky Bluegrass (Poapratensis L.) for Intermountain West
Urban Landscapes

By

Hang T.T. Duong, Master of Science

Utah State University, 2014

Co-Major Professors: Dr. Roger K. Kjelgren and Dr. Paul G. Johnson

Department: Plants, Soils, and Climate

Due to end users irrigating with excess water, water conservation of turfgrass can make a large impact in urban water conservation by reducing water applied while still maintaining visual appearance. This study was conducted to determine if Kentucky bluegrass (*Poapratensis* L.) can be deficit irrigated to maintain minimum acceptable appearance while conserving water. The study investigated water stress in terms of stomatal conductance, chlorophyll index, leaf temperature and predawn leaf water potential at the point of water stress, or where visual quality no longer meets expectations during dry down conditions. Water use was measured over well established Kentucky bluegrass with an eddy covariance system that was validated with soil water measurements. Turfgrass was irrigated at 80% of reference evapotranspiration based on allowable depletion of 12 mm of soil water during growing season that was considered to be well-watered. Two dry downs were conducted over a two-year period (early and late summer). Turfgrass was allowed to dry down without irrigation

until visual quality reached the minimum acceptable points (score ≤ 6). During drying periods, visual rating, chlorophyll index, predawn leaf water potential, and leaf temperature with stomatal conductance rapidly decreased once stomatal conductance fell to approximately half of well-watered levels. Both soil water content and evapotranspiration had weak correlation with stomatal conductance; however, stomatal conductance tended to have higher correlation with the change in soil moisture than with the change in crop evapotranspiration. Soil water use and eddy covariance data in terms of crop evapotranspiration had high correlation. The plant water use factor ranged from around 0.8 to 1.1 under well-watered condition corresponding to visual rating from 7 to 9. At the minimum acceptable point of visual rating, which is 5.5 to 6, the plant factor ranged from 0.65 to 0.87. This value of plant factor is quite high at this point. Even when Kentucky bluegrass went below acceptable visual quality, the grass still used significant amounts of water with the plant factor value ranging from 0.6 to 0.8. The data suggested that deficit irrigation cannot be applied with Kentucky bluegrass in the Intermountain West area.

(67pages)

PUBLIC ABSTRACT

Deficit Irrigation of Kentucky Bluegrass (Poapratensis L.) in Intermountain

West Urban Landscapes

Hang T.T Duong

In the western United States, water shortages are more severe than in other parts of the country. An average of 40% to 60% of potable water is used for irrigating landscape plantings (Kjelgren et al., 2000), especially turfgrass. Therefore, conservation on these turf areas can make a large impact in urban water conservation by reducing water use and still maintaining visual appearance.

This research is a two-year project to determine whether deficit irrigation can be used in maintenance of Kentucky bluegrass in the Intermountain West to achieve water conservation by identifying: 1. How much water does Kentucky bluegrass use when water is optimal and limited? 2. What is the level of plant water stress of Kentucky bluegrass where visual quality falls before acceptable level? 3. What is the water use of Kentucky bluegrass at the point when it is approaching less than acceptable visual quality?

Two dry downs were conducted over a two-year period (early and late summer). Turfgrass was allowed to dry down without irrigation until visual quality reached the minimum acceptable points (score ≤ 6). During dry down periods, visual rating, chlorophyll index, predawn leaf water potential, and leaf temperature with stomatal conductance rapidly decreased once stomatal conductance fell to approximately half of well-watered levels.

Even when Kentucky bluegrass went below acceptable visual quality, the grass still used significant amounts of water with the plant factor value ranging from

0.6 to 0.8. This is based on immediate water use measurements. Under actual irrigation practice, however, well managed KBG has been shown provide adequate quality under deficit irrigation as low as 0.7, where the grasses access additional soil water storage. These data indicate that KBG cannot be deficit irrigated and maintain acceptable quality in the Intermountain West urban landscape where rootzones limit the ability to access additional soil water.

ACKNOWLEDGMENTS

<p style="text-align:center">CONTENTS</p>

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

By 2050, the global population is expected to increase to 9.2 billion, 86% of whom will live in less-developed countries and 70% in rapidly growing urban areas. In parallel with the increasing of population, global water consumption from irrigation, domestic, industrial, and livestock uses is expected to grow by 21% by 2050. Global agriculture water consumption is expected to increase at 0.7% per year, from 6400 km^3 in 2000 to 8600 km^3 by 2025 and to 9060 km^3 by 2050 (Sulser et al., 2010). Agriculture uses about 70% of all the accessible water extracted from the Earth's rivers, lakes, and underground aquifers, and as much as 90% in many developing countries. Recent projections indicate that by 2025 many river basins and countries globally will face a situation in which 30% or more of the irrigation demands will be unmet because of water shortages. As water becomes increasingly scarce, seeking new and sustainable solutions to water conservation is very important.

In dry areas crop production requires efficient irrigation techniques to achieve water conservation. For example, grain yields can often be sustained with 25% less irrigation water than normally applied as long as the crops receive sufficient water during critical growth stages. Called deficit irrigation, this practice is becoming a necessity in some water-short areas. On the North China plain, for example, farmers now irrigate wheat three times a season rather than five because less frequent irrigation did not affect the yield. Many studies have shown that the traditional practice of flooding rice fields throughout the growing season is not essential for high yields. Applying less water or even letting rice fields dry out between irrigations can in some cases reduce water applications by 40–70% without significantly lowering yields (Guerra et al., 1998).

In the western United States, the water shortages are more severe than in other parts of the country. Utah and Nevada are the two driest states in terms of precipitation in the United States. However, per capita water use in Utah is the second largest in the nation. In 2002, average per capita water use for Utah was approximately 765 liters per day. Water conservation in urban agriculture, specifically urban landscapes, is also vitally important to stretch water supplies as much as possible.

Throughout the West, an average of 40% to 60% of potable water is used for irrigating landscape plantings (Kjelgren et al., 2000). However, some of this water is wasted because of the poor water management. Turfgrass, specifically Kentucky bluegrass (KBG) is a very important plant growing in many landscapes and serving important functional roles. It is the most widely used cool-season turf grass species for lawns, golf course, and athletic fields (Turgeon, 2002) due to its high quality appearance and desirable growth characteristics (Beard, 1973). Turfgrass provides functional benefits, such as reduced soil erosion, dust prevention, heat dissipation, wildlife habitat and many recreational benefits that contribute to physical and mental well-being. Additional functions include aesthetic qualities, impacts on quality of life, increased property values and other benefits to society and environment (Fender, 2006). Therefore, because of the many benefits of using this species or other grass species, the potential for water conversation in irrigated turfgrass landscape exists in only applying what the plants require. Conservation on these turf areas can make a large impact in urban water conservation by reducing water use and still maintaining visual appearance.

How do we estimate amount of water needed? Evapotranspiration (ET) is mostly used to schedule irrigation for turfgrass, and represents the combined processes of evaporation (from the soil and plant surfaces) and plant transpiration. Reference

evapotranspiration (ET_{ref} or ET_o) is the rate at which readily available soil water is vaporized from hypothetical specified vegetated surfaces (Jensen et al., 1990). The specific surface is a uniform surface of dense, actively growing well-watered cool-season turf clipped at 10 cm over an area of at least 100 m of the same or similar vegetation (Allen et al., 2005). A plant factor (K_p) is the ratio of actual plant evapotranspiration (ET_p) to the reference evapotranspiration (ET_o), varying in time based on growth and horticulture practices. ET_o allows comparison among places and between times. Actual ET use is estimated as the product by K_p x ET_o. K_p values vary over time for crop plants, so monthly averaged coefficients are normally used in scheduling timing and amount of irrigation (Carrow, 1996). The plant factor is essential for efficient irrigation to conserve yet maintain visual quality and appearance. Measuring actual plant transpiration is not easy. Many methods such as soil moisture depletion are accurate but spatially limited.

There are several empirical methods to measure actual plant ET or identify K_p values. Direct methods include use of lysimeter, water balance, and eddy covariance. Indirect methods involve estimating plant water use, such as through energy balance, mass transfer, or a combination of energy and heat. Among those methods, the eddy covariance technique is an ideal method used when calculating water usage of plants in large areas and for long period of times.

There are a number of research studies on ET rates and plant factors (K_p) in KBG under well-watered conditions. Turfgrass ET rates generally range from 3.6-6.3 mm d^{-1} (Aronson et al., 1987a; Feldhake et al., 1984; Fernandez and Love, 1993; Keeley and Koski, 2001; Shearman, 1986). However, according to Fernandez et al. (1993), ET of turfgrass range up to 7.5 mm day^{-1} under varying climatic, edaphic (varying drainage, texture and soil chemical), and management conditions. Aronson et

al. (1987b) reported that seasonal plant factor values in the humid Northeast, based on the Penman equation for KBG, ranges from 0.7-1 for cool season turf and 0.6-0.8 for warm season turf.

To achieve efficient irrigation, what is the minimum K_p value to maintain acceptable appearance of turfgrass? For crops, reducing water and maintaining acceptable yield is already done through deficit irrigation. Deficit irrigation is defined as supplying water in amounts less than actual ET measured under well-watered conditions. However, turfgrass is not typically evaluated on quantifiable yield but instead on visual characteristics.

Deficit irrigation has become an increasingly popular conservation technique in turfgrass maintenance (Feldhake et al., 1984; Fry and Butler, 1989; Qian and Englke, 1999). Many researchers have found that turfgrasses require water in amounts less than ET to maintain acceptable visual quality (Feldhake et al., 1984; Fry and Butler, 1989; Fu et al., 2004; Qian and Engelke, 1999). Deficit irrigation in the transition zone of the United States is often practiced on tall fescue (TF; *Festucaarundinacea*Schreb.) (Fu et al., 2007). TF watered twice between June and September maintained-acceptable quality at deficit irrigation levels of 40% or 60% ET (Fu et al., 2004). Banuelos et al. (2011) reported that deficit irrigation on bermudagrass (*Cynodondactylon*) at a range of 66% to 75% of ET_o and at 75% to 80% of ETo on seashore paspalum (*Paspalumvaginatum*) could maintain acceptable quality turfgrass (quality rating ≥ 6). However, for KBG, there is no research at the field scale in the Intermountain West to determine if it can be deficit irrigated using eddy covariance to integrate over larger areas, which is an accurate system to measure ET.

Objectives

Overall goal:

    To determine whether deficit irrigation can be used in maintenance of Kentucky bluegrass in the Intermountain West to achieve water conservation.

Specific objectives:

    1. How much water does Kentucky bluegrass use when water is optimal and limited?

    2. What is the level of plant water stress of Kentucky bluegrass where visual quality falls before acceptable level?

    3. What is the water use of Kentucky bluegrass at the point when it is approaching less than acceptable visual quality?

CHAPTER 2

LITERATURE REVIEW

Evaporation theoretical consideration. Evapotranspiration (ET) is the process whereby liquid water from vegetation, soil, and free water surfaces is evaporated into water vapor. The process is complex, and is governed by the following factors: available energy, turbulence intensity, saturation deficit of the air, and the stomatal resistance of the vegetation. If exposed soil is present, then the evaporation of the soil surface must be treated separately. The process can be expressed by the well-known Penman-Monteith equation (FAO#56):

$$E = \frac{s(R_n - G) + \rho c_p D / r_a}{s + \gamma(1 + r_c / r_a)} \quad (1.1)$$

where R_n is net radiation, G is soil heat flux (W m^{-2}), c_p is specific heat capacity of air (J kg^{-1} K^{-1}), s is the slope of the saturation vapor pressure vs. temperature curve (Pa K^{-1}), ρ is the density of moist air (kg m^{-3}), r_a is an aerodynamic resistance (s m^{-1}), r_c is bulk canopy resistance (s m^{-1}), e_s is saturation vapor pressure at the air temperature (Pa) and e_a is the atmospheric vapor pressure (Pa). So, D is the saturation deficit of the air, and γ is the pyschrometric constant.

$$\gamma = \frac{P c_p}{L \varepsilon} \quad (1.2)$$

where P is atmospheric pressure, L is latent heat of vaporization, and ε is the ratio of the molecular weights of water vapor to dry air, equal to 0.622.

Available energy is defined by Rn-G, since some of the net radiation is consumed by soil heat flux (G). This energy is available to drive the fluxes of sensible heat and evapotranspiration.

The surface–atmosphere interactions term depends on the aerodynamic characteristics of the surface and it expresses the conversion of sensible heat of the surrounding air into latent heat. As a rough surface interacts more strongly with the atmosphere it is able to extract more sensible heat from the passing air than a fairly smooth surface. The degree of atmosphere–vegetation interaction can be estimated by a decoupling coefficient (Ω), defined by McNaughton and Jarvis (1983), based on the Penman–Monteith equation. The decoupling coefficient sets the relative importance of the equilibrium term to the overall ET and it varies from 0 (a perfect coupling condition with the atmosphere providing all the needed energy for the ET) to 1 (a complete isolation being the radiation the only contributor to the ET process).

Estimating water use from reference ET: plant factors. Since the estimation of ET with the Penman-Monteith type of equations described above is often difficult, another approach is to relate actual ET to some measure of the maximum value that could ideally occur under the given environmental conditions. This led to the definition of Reference ET (ET_o). It is defined as the evapotranspiration rate of a hypothetical grass reference surface that fully shades the ground, and is well supplied with water. The following assumptions are made: vegetation height is 0.12 m; albedo is 0.23; and the stomatal resistance is assumed to be minimal, having a value of 70 s m^{-1}. See Allen et al. (1998).

This idea led to a simplified approach to estimate actual ET. It simply assumes that the actual ET will be some fraction of the reference value, depending on the actual vegetation, stage of growth, soil water content etc. This can be written as:

$$ET = k_c \, ET_0 \qquad 1.3 \quad \text{(FAO\#56)}$$

ET is the actual ET, where k_c is a coefficient that represents all the factors that would cause the ET to differ from the ideal case, and is functionally the same as the plant factor Kp. It is often referred to as the "crop coefficient", since most work has been in crops. ET_o is the reference ET defined above.

A definition is still required for the reference ET value. An equation that is commonly used is described in a FAO report by Allen et al. (1998). Using the assumed values for albedo and stomatal resistance of the idealized surface given above, they derived an expression for daily reference ET:

$$E = \frac{0.408 s (R_n - G) + \gamma \dfrac{900}{T + 273} u_2 D}{s + \gamma(1 + 0.34 * u_2)} \qquad 1.4$$

All variables have already been defined except for u_2, which is the average wind speed at a height of 2 m. Note that this expression is for daily ET in mm d^{-1}. For other units and time periods, the equation has to be derived accordingly.

To get actual ET, the value of K_c (K_p for more variable landscape plants such as turf) must be determined empirically. According to FAO #56, K_p values for cool season turfgrass are 0.9, 0.95 (with maximum crop height =1 m) for initial, mid and

late seasons, respectively. However, it is not clear that these estimates came from high quality measurements of actual ET of turf. Data are lacking for estimates of K_p values for irrigated turf using very high quality measurements of actual ET.

    Eddy covariance technique directly measures plant water use. This method measures the covariance between fluctuations of vertical wind velocity, heat, water vapor.Eddy covariance overcomes the need to determine each component in the water balance by using the energy balance approach. Because it integrates over turf areas, eddy covariance also avoids soil surface heterogeneity issues by placing the sensors above the crop canopy and the evapotranspiration can be measured from various types of vegetation.

    Eddy covariance is based on the idea that upward and downward gusts of air due to turbulence are the mechanism that moves mass, heat and water vapor between the surface and atmosphere. It assumes that steady-state conditions exist, i.e., that general atmospheric conditions are not changing rapidly over the averaging period, and that upwind areas are homogeneous, so that it can be assumed that the flux measured just above the canopy is equal to that at the canopy surface and fluxes are constant within certain range of height (Moncrieff et al., 1997).

    Eddy covariance flux measurements reflect the upwind surface. However, the relative contribution of the surface changes with the distance upwind. In order to know that the fluxes being calculated are from the Kentucky bluegrass (*Poapratensis* L.) surface, and not other upwind surfaces, the contribution of different distances to the flux must be known. This may be termed the "footprint" of the flux measurement (Gash, 1986), "effective fetch" (Pasquill, 1972), or "source of area of sensor" (Schmid and Oke, 1990). Basically, the footprint of a measurement is a transfer function for the characteristics of the surrounding terrain (Schmid, 2002).

Three cases can represent a large range of atmospheric conditions. These include: slightly unstable, unstable, and near-neutral. Unstable air is defined by rapid decrease of temperature with height caused by surface becoming much warmer than air; in this case air rising motion is enhanced by strong heating of surface. Stable air is defined by slow decrease or increase of temperature with height, air rising motion is suppressed, and may even cause sinking motion.

Plant physiology responses to drought stress. Drought resistance is the capability of growing and surviving under drought stress conditions. Drought resistance is classified into 3 categories: drought avoidance, drought tolerance, and drought escape. Drought tolerance can be defined as plant's ability to maintain physiological functions when very little or no water is available to the plant. Drought avoidance is the ability of a plant to maintain normal physiological function by postponing tissue dehydration. This mechanism may be achieved by increasing water uptake of the root system and reducing water loss from transpiring leaves. Drought escape is when a plant completes its life cycle prior to drought exposure or becomes dormant during drought stress.

One important drought avoidance mechanism is the ability of plants to reduce water loss through leaf transpiration. Stomatal closure is one of the most sensitive responses to drought stress, which increases resistance to water diffusion out of leaves, hence resulting in reduced transpiration. Stomatal closure has been found to be caused by the increase in the concentration of ABA in leaf that is transported from roots exposed to drying soils (Davies et al., 1994, 2002). ABA is synthesized in roots, then is transported to shoots and initiates a signal cascade in guard cells that alters the membrane transport of several ions, and as a result, guard cells lose their turgor and lead to stomatal closure. Stomatal closure causes changes in stomatal conductance (g_s)

to water vapor, and hence transpiration rate and ultimately photosynthesis (Bohnertand Jensen, 1996; Zhang and Davies, 1987). According to Wang et al. (2003), KBG cultivars tolerant of drought showed slower ABA accumulation rate than drought-sensitive cultivars under short-term drought stress, suggesting that low accumulation rate of ABA in leaves would be beneficial for the maintenance of photosynthesis during short-term drought, and allow dry matter to accumulate to support plant survival during prolonged drought. Lower ABA accumulation and less severe decline in leaf water potential, photosynthesis, g_s, and turf quality during drought stress characterized the drought tolerance of KBG (Wang et al., 2003). DaCosta and Huang (2006) showed that decline in g_s and shoot growth was independent of leaf water status and could be hormonally—ABA—controlled which could help maintain favorable leaf water status by reducing water loss under soil drying conditions with KBG.

Furthermore, drought-avoidant plants can shed or fold leaves, or develop a thick cuticle to reduce transpiration. Renard et al. (1987) and Johnston et al. (2002) reported that transpiration can also be reduced by decreasing light intensity (solar heating) via rolling leaves in both TF and *Eragrostiscurvula* (Schrad.) Nees, complex cv. Consol., a temperature zone C4 grass. TF, which performed better under drought stress, had positive correlation to leaf thickness, epicuticular wax content, and tissue density but had negative correlation to stomatal density and leaf width. Drought avoidance in plants might lead to increases in water use efficiency (WUE). It is reported that drought-avoidant turfgrass species had higher WUE than the drought-sensitive ones (DaCosta and Huang, 2006).

Water stress also can be determined by the ET rate – the sum of the amount of water transpired from leaves and evaporated from soil under the canopy within a giv-

en period of time. Turfgrass species which have low ET can delay tissue desiccation (reduce the rate of soil water depletion) and survive longer under limited water supply. Actual plant water use varies with plant species, with cultivars within species, and with climate conditions. The amount of water lost through transpiration is a function of the rate of plant growth and environmental factors such as soil, moisture, temperature, solar radiation, humidity, and wind. Transpiration rates are higher in arid climates than in humid climates because of the greater water vapor deficit between the leaf and the atmosphere in dry air. Thus, transpiration losses may be as high as 10 mm of water per day in desert environments during summer months, whereas in humid climate under similar temperature conditions, the daily losses may be only 5 mm of water per day (Duble, 2006).

According to Beard and Green (1994), the application of water to turfgrass in excess of its requirements can be attributed to human factors, not plant needs. Current estimates of ET of well-watered turfgrass range from 2.5 to 7.5 mm day^{-1} (Fernandez and Love, 1993), depending on environmental conditions. Research has indicated that ET rate of KBG generally ranges from 3.6 to 6.3 mm d^{-1} under varying climatic, edaphic (resulting from the soil) , and management conditions (Aronson et al., 1987; Feldhake et al., 1984a; Fernandez and Love, 1993; Keeley and Koski, 2001; Shearman, 1986).

The plant factor (K_p) used in irrigation scheduling is the ratio of actual ET (ET_p) to reference ET. Reference ET (ET_o) is calculated from the surface of actively growing turfgrass that is maintained at 12 cm and is well-watered (Allen et al., 1998). Once K_p has been determined, only calculations of ET_o are required to estimate ET_p needed for scheduling irrigation (Allen et al., 1998). However, according to Carrow (1996), plant factors can vary substantially over short time periods, so monthly aver-

aged values are normally used for irrigation scheduling. These values can be averaged to yield quarterly, semi-annual, or annual plant K_p values (Richie et al., 1997) although averaging K_p reduces precision and turfgrass may be under-irrigated during stressful summer months.

Factors that influence K_p in turfgrasses are seasonal changes in canopy properties, rate of growth and soil moisture stress that would cause decreased water use relative to ET, and overall turf management practices (Carrow, 1996; Gibeault et al., 1989). Scientific irrigation scheduling regimes which calculate irrigation water requirements based on ET_p have been suggested as one means to improve irrigation management for turfgrass (Brown et al., 2001). ET_o data is available from public weather networks in different regions of US; however, access to reliable $K_p$values becomes a limiting factor when implementing scientific irrigation scheduling systems for turfgrass. A study by Carrow conducted in Georgia in 1989 and 1990 (Carrow,1996) showed that cool season turfgrassK_ps ranged from 0.79 to 0.82 monthly under moderate to moderately severe water stress. Meyer and Gibeault (1987) conducted a similar study as Carrow in California to develop a set of plant factors for turfgrass including KBG, where the results were that K_p for cool-season turfgrass ranged from 0.6 to above 1.1. Ervin and Koski (1998) conducted an experiment applying deficit irrigation using cool-season turfgrasses in Fort Collin, CO. Turfgrasses (KBG and TF) were subjected to increasing levels of drought through the use of a line-source irrigation system with the idea to develop water conserving K_ps to be used with water conservation while still maintaining acceptable turfgrass quality by irrigating every 3 days, with K_p values in the range of 0.60 to 0.80 for KBG and 0.50 to 0.80 for TF. They concluded that in Colorado, water can be conserved while maintaining acceptable turfgrass quality by irrigating these two turfs every 3 days by adjusting ET,

with a KBG coefficient of 0.70 and a TF coefficient of 0.60. Aronson et al. (1987b) reported that seasonal K_p values in the humid Northeast, based on the Penman equation, was 0.9-1.2 for Kentucky bluegrass, cv. Baron and 0.9-1.2 for KBG, cv. Enmundi in July-September.

*Leaf temperature and drought stress.*Plant temperature is a major determining factor in surface energy fluxes and provides insight into plant water status. Tanner (1963) first proposed that plant temperature be used to quantify water stress. Plant temperature indicates plant water status because stomates respond to drying soil and plant water status, prevailing meteorological conditions, and control evaporative cooling of leaves. As stomates close in response to soil water depletion and a decrease in water uptake, plant temperature increases and convective energy transfer increases to balance the decrease in transpiration. As stomates close, photosynthesis is reduced because CO_2 absorption is reduced. Idso et al. (1981) developed an empirical crop water stress index (CWSI) related to air vapor pressure deficit (VPD), and Jackson et al. (1981) derived a theoretically based CWSI from the energy balance for a plant canopy. Both CWSI methods provide a relative indication of plant stress by comparing the measured canopy to air temperature difference to lower (non-water-stressed) and upper (water-stressed) limits of the canopy to air temperature difference. Jackson et al. (1981) showed that the limits, or baselines, are dependent on meteorological and plant factors. Many studies has been developed from those studies to refine the calculation/estimation of the baselines to improve the CWSI, such as the research of Jackson et al. (1988), Jones (1999), Payero and Irmark (2006), and Payero et al. (2005), and Wang et al. (2003).

Most temperature-based plant water stress indices have provided only a relative indication of water stress and have relied on empirical measurements. For this

reason, Campbell and Norman (1990) suggested abandoning the use of empirically established indices in favor of a direct determination of canopy resistance calculated from environment measurements and energy balance principles. Hatfield (1985) and Amer and Hatfield (2004) showed that the calculation of canopy stomatal resistance can indicate plant response to available soil water and prevailing meteorological conditions. However, some of the methods for calculation of canopy stomatal resistance still relied on empirical measurements (Jones, 1999; Leinonen et al., 2006), until Blonquist et al. (2009) derived an equation to calculate canopy conductance from measured meteorological and plant variables conducted on turfgrass and alfalfa. Their results showed that g_s is directly related to stomatal aperture and plant water status.

Continuous measurement of canopy conductance throughout the plant life cycle should also be a powerful tool in the quest to select plants for increased water uses efficiency (Condon et al., 2004), to measure responses of turfgrass to water deficiency (Jiang et al., 2009) and to select for improved drought tolerance (Jones, 1999). The other measurements or estimates required to calculate canopy conductance are air temperature, relative humidity, net radiation divergence in the canopy, wind speed, and canopy height. It is also necessary to estimate the zero plane displacement height and roughness lengths for momentum, heat, and water vapor. Their sensitive analysis showed that canopy conductance is highly sensitive to small changes in canopy and air temperature. It also showed canopy conductance is most sensitive to the roughness length for the momentum, followed by water vapor, and least sensitive to the roughness length for heat. It is less sensitive to all the roughness lengths as the wind speed and canopy height increase.

Turfgrass canopy temperature changes according to the moisture level and transpiration rates, with leaf canopy temperature exceeding ambient air temperature

under turfgrass drought stress as a result of transpiration reduction (Jiang et al., 2009). Canopy temperatures for well-watered crops have been found to be lower (2 to 3 ºC) than a stressed plant under water deficit in a study using peas (Clark and Hiller, 1973). The difference between plant canopy temperature and ambient air temperature (ΔT) has been studied as a tool to manage irrigation scheduling in Kentucky bluegrass because it relates to the water potential in turf leaves (Throssell et al., 1987).

*Deficit irrigation.*Deficit irrigation is defined as supplying water in amounts less than actual ET measured under well-watered conditions and has become an increasingly popular conservation technique in turfgrass maintenance (Feldhake et al., 1984; Fry and Butler, 1989; Qian and Engelke, 1999). Many researchers have found that turfgrasses require water in amounts less than ET to maintain acceptable visual quality (Feldhake et al., 1984; Fry and Butler, 1989; Fu et al., 2004; Qian and Engekle, 1999). Deficit irrigation in the transition zone of the United States is often practiced on TF (Fu, 2007). When watered twice between June and September, TF maintained acceptable quality at deficit irrigation levels of 40% or 60% ET (Fu et al., 2004). Several studies have been conducted on bermudagrass in the Desert Southwest under suboptimal irrigation. Meyer and Gibeault (1987) reported that annual $K_p$ranged from 0.5 to 0.8 for warm season grasses, and that acceptable quality was maintained with a K_p of 0.60. Garrot and Mancino (1994) evaluated water use of Texturf-10, Tifgree, and MidIronbermudagrasses. Grasses were irrigated deeply and infrequently (when visible wilt was observed). Water use was presented as a fraction of ET_o and varied around 0.55 for MidIron to around 0.65 for Texturf-10 during the growing season. High water use fractions in the range of 0.70 to 0.80 were observed during the first few days after irrigation. Banuelos et al. (2011) reported that deficit irrigation on bermudagrass at a range of 66% to 75% of ET_o and at 75% to 80% of

ET_o on seashore paspalum could maintained acceptable quality turfgrass (quality rating $\geq$ 6).

CHAPTER 3

MATERIALS AND METHODS

Study site - experimental design. A field experiment was conducted at the

Greenville research farm (45°45'58''N, 111°48'37''W, elevation 1412 m), in North

Logan, Utah. The experiment area was a large plot of well-established (8 years) KBG

turf planted on a Millville silt loam, pH = 7.8. The turf area was roughly a triangle

measuring approximately 176 m north to south, 164 m east to west, and 225 m

northwest to southeast. A central portion of the plot, measuring 100 m x 90 m was

planted with a sod comprised of a proprietary blend of 10 KBG varieties (Chanshare

Turf Farms, Tremonton, Utah). The remaining corners of the plot area were planted

into 'Park' KBG. The central and sodded portion of the study area was divided into

four blocks, east to west, to account for soil and irrigation variability. Each block was

divided into 12 grids of 7.6 x 7.6 m, with three grids randomly selected within each

block. Plant physiological measurements were carried out within these areas. This

created a randomized complete block design for all the plot measurements with 12

plots throughout the experimental area (Fig. 2.1).

Application of nitrogen fertilizer (48-0-0) was split into two applications each

year of the study with 49 kg N ha^{-1} applied in late May and an equal amount applied

in early September. Phosphorous and potassium were not applied because a soil test

indicated adequate to excessive amounts present. Mowing was done weekly at 7.6 cm.

No pesticides were applied during the two-year study period. Irrigation was assumed

to be Kp of 80% of ET$_o$ based on depletion of 12 mm of soil water during growing

season that was considered to be well-watered, using an ET$_o$-based smart controller

(model WR-1, Irrisoft Inc., Logan, UT) that automatically schedules irrigations based

on ET. Application rate is approximately 0.5 inches (1.2 cm) per hour corrected up-
wards for a distribution uniformity of approximately 70%.

A weather station located approximately 60 m to the south of this research plot
was used to collect hourly temperature and rainfall. Meteorological parameters and
flux data were collected from an eddy covariance system set up on the NE corner of
the main plot area (sodded turfgrass area). With a predominant SW wind direction,
this created fetch of 126 m diagonally across the plot area to measure turbulence flux-
es. The eddy covariance consisted of a LiCor 7500 sensor (LI-COR Biosciences, Lin-
coln, NE) – a fast-response water vapor and CO_2 sensor was mounted at the height of
1.6 m to measure CO_2 and water vapor density, and a 3-D sonic anemometer (CSI-
CSAT3; Campbell Scientific Inc., Logan, UT) to measure the three dimensions of
wind speeds and sonic temperature was placed 1.6 m above the surface. A tempera-
ture and humidity sensor (Vaisala HMP45C; Campbell Scientific, Inc.) was mounted
at a height slightly above the eddy covariance sensors, to record air temperature and
humidity values.

For energy balance calculations, two soil heat flux plates were placed at a
depth of 0.08 m near the instrument tower. Soil temperature probes were installed at 2
cm and 6 cm depth to measure average soil temperature changes in the layer above
plates. Soil moisture was measured in the upper 8 cm of the soil with a CSI-616 probe
(Campbell Scientific Inc.). A Kipp&Zonen net radiometer (model CNR02,
Kipp&Zonen, Delft, Netherlands) was mounted 1.2 m above the surface in 2009. In
2010, a second radiometer (NR-Lite; Kipp&Zonen) was installed at the height of 2.5
m. Measurements from the latter net radiometer were used to correct the measure-
ments of net radiation in 2009 and the early half of 2010. Data were sampled at 20 Hz
and recorded by a CR 5000 data logger (Campbell Scientific, Inc.). Values obtained

when winds came from behind the instrumentwhich is north and northeast direction where there was no turf or when wind directions created an upwind fetch that was too small were discarded from the analyses. Likewise, data obtained during the days with thunderstorms or showers were also removed.

*Soil moisture data.*To validate eddy covariance (EC) measurements, particularly in regards to the spatial fetch-footprint analysis, soil moisture content in each of the 12 plot areas was measured using a capacitance soil water measurement system (Diviner 2000; Sentek Sensor Technologies, Stepney, South Australia, Australia). A PVC access tube was inserted in the center within each block and the sensor was manually inserted in the tube to scan the profile. This instrument measured volumetric water content (VWC) at 10 cm intervals to a 100 cm depth. Soil moisture was measured at 10 AM every other day when the KBG was well-watered or not drought stressed, then, every day when evidence of some stress was observed.

Plant data collection. In response to drought, plant measurements are a very important indicator to determine when turf is stressed. Plots were evaluated for visual quality on the basis of color, shoot density, and uniformity of stand on a scale of 1 to 9 (1 = no live grass, 6 = minimum acceptable, and 9 = dark-green dense, uniform grass (Emmons, 2000).

Leaf $g_s$was measured by a porometer (model SC-1 porometer; Decagon Devices, Pullman, WA). The porometer measured g_s from vapor flux from the leaf through stomates and into ambient atmosphere. Five measurements were taken per plot. Three leaf blades of grass were excised and arranged before clamping side by side with the adaxial side of the leaves facing the porometer chamber. Stomatal conductance was measured on the abaxial—bottom—side of the leaf because this side has higher stomatal density than does the other side (this was indicated by a testing meas-

urement to compare g_s between two sides and the abaxial side has much higher g_s values, approximately 6 times higher).

Canopy temperature was measured using a digital thermometer (Model 52-II Dual Input Digital Thermometer; Fluke Corporation, Everett, WA) connected with infrared (IR) temperature sensors (Model SI-111; Apogee Instruments, Inc., Logan, UT) at the same time g_s was measured. Five measurements were taken per plot. Chlorophyll index was measured using a Field Scout CM 1000 chlorophyll meter (Spectrum Technologies, Inc., Aurora, IL), ambient and reflected 700 nm and 840 nm light used to calculate the relative chlorophyll index. Ten readings were taken per plot. Predawn leaf water potential was measured using pressure chamber model PSI 1000 (PMS Instrument Company, Albany, OR). Five leaf blades per plot were taken at predawn, covered by aluminum foil, put inside a plastic bag and stored in a cooler and measured right after collection inside a barn 200 m away from the plot. The samples were measured 15 minutes after being taken from the field.

Data analysis.Net radiation values of the permanent NR-Lite sensor were corrected using the results of the calibration with the CNR02 sensor with the equation below:

CRN02 = 13.63 + 1.22 NR-Lite – 0.00027383 x (NR-Lite)^2

Calculation of reference ET (ET_o) based on Penman - Monteith equation (UN FAO-56).

Footprint is an upwind area where the atmospheric flux measured by an instrument is generated;i.e., flux footprint describes an upwind area "seen" by the instruments measuring vertical turbulent fluxes. These are quantified in each graph with

the value of z/L, whereL is the Monin-Obukov length scale; LE is directly collected from eddy covariance, it is ET_p which is unforced $ET_{p:}$

$$LE = \overline{Lw'\rho_v'}$$

Lis the latent heat of vaporization, w is the vertical wind, and ρvis water vapor density. The prime symbol represents the fluctuation from the mean over the defined averaging period.

The energy balance of a surface must obey the conservation of energy. If all measurements were perfect and assumptions were met, then the equation would be balanced:

H + LE = Rn – G

where H is the sensible heat flux, LE is the latent heat flux, Rnis net radiation and G issoil heat flux.

Generally, fluxes can be either overestimated or underestimated depending on local atmospheric conditions, measurement errors in the sensible heat or net radiation, and the ability of the instrument to measure small values of temperature and humidity. The problem is nearly always underestimation of the fluxes. Any errors reduce a covariance value. Lack of steady state conditions, inappropriate flux averaging periods and imperfect frequency corrections have also been found to cause an imbalance between the calculated fluxes and available energy. This underestimation results in the sum of H and LE being smaller than the difference of Rnand G. The ability to account for all the energy is termed energy balance closure. Energy balance closure is an accepted process in assessing data reliability. The reliability of the flux estimates can be examined by looking at the ability to close the energy balance equation. If all the measurements were made perfectly, and all assumptions were valid, the energy balance should be equal to 1 (Liu et al., 2006). Even though there are daily variations,

the daily average K_p values were very similar to the values currently being used if energy balance closure was not forced to obtain the ET values. But when the energy balance closure was forced the plant factor was near a value of 1.0. Therefore, in this research, unforced ET_p was used.

The plant factor was calculated as:

$$K_p = LE/ET$$

where LE is latent heat, ET_o is reference evapotranspiration and calculated following FAO56, and K_p is the plant factor.

Soil water depletion over 40 cm and 100 cm was summed and averaged for 10 out of 12 plots over the field for four dry-downs over two years(depth of two plotswas limited by a shallow impermeable layer). Soil water depletion was regressed on EC water loss to assess correlation between the two independent measures of water loss.

Stomatal conductance was regressed on the difference of Tl and Ta (Tl-Ta), leaf water potential, chlorophyll index, and visual rating, for each dry-down in each year (2009 and 2010)to assess how plant transpiration related to other plant parameters.

K_p of two dry-downs for two years (2009 and 2010) was plotted by linear regression with visual rating, and R was calculated for the correlation between the two parameters. The second dry-down in 2010 was interrupted by rain in the middle of the dry-down, and due to this measurements were halted until the soil moisture reached the same level as the day before the rain; therefore, it is still considered a full dry-down. All graphs were created using SigmaPlot 12 software (Systat Software, Chicago, IL).

CHAPTER 4

RESULTS AND DISCUSSION

Flux Footprints. Fig. 2-2 shows relative contribution of the land surface area

to the flux for three different cases: slightly unstable (2-2 A); unstable (2-2 B); and

near-neutral (2-2 C). Most studies consider the value where 80% of the cumulative

flux is reached, but here both the 80% and 85% values are marked on the graphs. In

the unstable cases (nearly always the case), the footprint of the flux measurement was

well within the 126 m fetch of the KGB. On the rare cases of near-neutral or slightly

unstable, the footprint extended upwind. However, the surface upwind of the study

plot consisted of small irrigated turf plots for a different study. Hence, there was not a

large discontinuity in surface characteristics as the wind traversed towards the sen-

sors. The results show that the fetch in this study was adequate, and that the flux esti-

mates represent the KBG surface.

Weather data. In general, average maximum temperature and saturation defi-

cit through the whole season were very similar in both years 2009 and 2010 (average

maximum temperatures were around 25.5°C and saturation deficit were around 1.9

KPa) **(**Fig. 2-3**).**However, 2010 was 5 $^{\circ}$C cooler than the historical average in May

and 2.5 $^{\circ}$C warmer than the historical average in September (Table 2-1). Total precipi-

tation was higher in 2009 than in 2010 (162 mm and 134 mm, respectively). Early

summer (May and June) in 2009 and 2010 had higher precipitation than historical

weather data. However, there was little to no rain in the middle of summer (July) in

both years of research which is the typical summer pattern of the region (Table 2-1).

Precipitation returned again in August of both years, but September precipitation rec-

orded in both years, especially in 2010, was lower compared to historical weather da-

ta.

Correlation between Soil moisture depletion and ET_p from Eddy covariance.
Soil water use and eddy covariance correlated to each other, although the relationship
was closer for the 0 to 40 cm depth than the entire depth from 0 to 100 cm, with $R^2 =$
0.72 and 0.49, respectively (Fig. 2-4 A and B). Although R^2 for the entire depth from
0-100 cm was lower than the R^2 for the surface profile (0 to 40 cm), it was closer to
the 1:1 line. Therefore the correlation between ET_p and soil depletion of the entire
depth was more reliable than this correlation between ET_p and soil water depletion
from the surface profile. This gives assurance that they are measuring the same thing.
Eddy covariance ET was somewhat greater than soil water depletion, possibly due to
the inability to accurately measure water content of the soil near the surface and the
thatch layer. The relationship was closer over the range of water use rates taken dur-
ing the dry down when turf was water stressed, possibly because surface soil water
was greatly reduced and changes in soil water content were more accurately meas-
ured. The results give confidence in both ways of water measurement used on KBG.
This result supports the footprint analysis, and the fetch in this study was adequate
and the flux estimates represent the KBG surface.

*Soil moisture data over time.*Fig. 2-5 displays the change in soil moisture wa-
ter content at various depths vs. day after irrigation stopped for both seasons. The re-
sults showed that water was mainly extracted from the 0 to 40 cm layer. These find-
ings are similar to previous studies; Bonos and Murphy (1999) reported that KBG cul-
tivars had greater root mass in the upper 30 cm of the root zone after stress had oc-
curred compared to cultivars that lacked stress tolerance. In addition, they reported
that stress-tolerant types had greater root mass in the 30 to 45 cm profile when sam-
pled before stress. This is in agreement with the result that mostly the change in soil

water content is seen in the depth of 0 to 40 cm. This means that the root systems of KBG in this study mainly extracted water from shallower soil profile depths.

The beginning and end of each dry down experiment are noted in each graph. The changes of soil moisture content were different in the early vs. late season dry down periods in both years. In early season (early summer), soil moisture content changed quickly and at a significantly higher rate compared to the later season dry down period. This isin terms of the total days needed for the KBG turf to show drought stress and reduction in theshallow soil layers (0 to 10 cm and 0 to 20cm). During late season, (late summer into early fall), water content decreased more slowly and with similar rates of drying observed in the multiple depths (0 to 10, 10 to 20, 20 to 30, and 30 to 40 cm layers) at the same time. Additionally, water content at 40 cm in late season was lower than in early season. This means that in early seasons, KBG extracted water from the upper layers more than the deeper layers while in late seasons, KBG used water deeper in the soil. This is can be explained that in early season, the root system of KBG was not as deeply established as in late season; deeper roots appeared to allow the turf to extract water from deeper soil profile after the peak summer season. Even though KBG had roots deeper in the soil (down to 40 cm), the availability of that deeper water did not slow down water stress (indicating that KBG g_s appears most sensitive to soil drying in the upper soil layers).

Previous research in seasonal rooting characteristics of turfgrass showed that: root length and number decreased throughout the summer and then slightly increased in late summer or early spring. Work by Liu and Huang (2005) showed midsummer decline of root production and increased mortality of existing roots were related closely to changes in soil temperature. Cool-season turfgrass maintains optimal root growth between 10 and 18 $^{\circ}$C (Beard, 1973). Root growth of KBG was shown to be inhibited

as soil temperature increased to 25 ^{o}C (Aldous and Kaufmann, 1979). In this study, in late season the air temperature decreased and as a consequence soil temperature also decreased (data shown in Fig. 2-5). Because of the decrease in temperature and photoperiod in late season, and the growth of roots in this season, the plant could extract water from deeper soil and maintained turgor under low soil water potential and resulted in longer visual quality maintenance. This result is in agreement with the findings of Esmaili and Salehi (2012), that decreasing temperature and photoperiod decreased verdure fresh and dry weight, shoot height, tiller density, leaf area and chlorophyll, and relative water contents. However, rooting depth and fresh weight of roots increased and changed the root/shoot ratio of *Zoysia japonica* 'Lanyin No. III' (Li, 2002; Xi and Zhang, 2005). Rooting depth under long day length and intermediate day length conditions compared to short day length treatment increased 55% and 30%, respectively (Esmaili and Salehi, 2012).

KBG may have osmotically adjusted to help it to extract water deeper in the soil. Turfgrasses are constantly subjected to changing and interactive environmental stresses. Previous growing conditions can influence responses and adaptation of plants exposed to subsequent environmental stress (Ackerson, 1980; Bennett and Sullivan, 1981; Eamus, 1987). In this study, the late dry down could be considered to have been drought-preconditionedbyearly dry down and the recovery time after that. Jiang and Huang (2000) found that drought-preconditioned KBG had higher canopy photosynthesis and turgor potential than non-preconditioned plants during subsequent heat stress. Brown and Thomas (1980) reported that drought-preconditioned plants had lower dark respiration rate. In a study by Jiang and Huang (2001), drought-preconditioning enhanced heat tolerance in KBG, which could be related to maintenance of higher osmotic adjustment associated with accumulation of ion solutes and

water soluble carbohydrates and development of extensive roots deeper in the soil profile. In addition, ET_o in late season was lower so the plants were not using water as quickly as in summer 2009 and 2010, explaining why days to unacceptable appearance was much greater.

Plant Factors. Values of K_p are displayed in Fig. 2-6 A and B and Table 2-2. The results show that average plant factors for the whole season in 2009 was higher than in 2010; in 2009 K_p ranged from 0.75 to 1.2, while 2010 ranged from .75 to 1. K_p decreased to 0.82 early summer and 0.65 late summer during summer 2009, when KBG no longer met the visual quality expectation. During summer 2010, K_p decreased to 0.72 early summer and late summer were 0.71 as KBG no longer met the acceptable visual quality rating. These results agree in general with the range of results presented by Ervin and Koski (1998) in Fort Collins, CO. Their research indicated that water conservation can be encouraged while still maintaining acceptable turfgrass quality by irrigating every 3 days with K_p values in the range of 0.60 to 0.80 for KBG. Fenton (2010) conducted an experiment in well-watered conditions in the same field as the study reported here where K_p values were determined to be 0.75 and 0.81 during 2007 and 2008, respectively. The change in the amount of water lost (used by grasses, transpiration, or drainage) in 0 to 40 cm soil profile tended to be lower than ET measured by eddy covariance system in both years but significantly lower in 2009 (Fig. 2-6 A and B). The lower value in soil water depletion could be explained by a less than full coverage of the turfgrass causing evaporation, however the plots consistently had full cover throughout the experiments. Water extracted from deeper soil layers could also explain these differences.

Turfgrass responses to drought stress. Previous research (Jarvis, 1976; Jones and Higgs, 1989; Stewart, 1988) showed that g_s is sensitive to leaf temperature (Tleaf)

and time of day. In this study, the changes in g_s during the dry down are shown in Fig.2-7. The results showed that g_s decreased with time after irrigation was stopped. During the dry down, g_s at 2 PM was reduced more than that at 10 AM. Stomates are more sensitive to drought stress in the afternoon than in the morning. In the afternoon, leaf temperature increased, therefore, g_s values at 2 PM were more reflective of the water stress. This is related to partial recovery of plant water potential during the night and the higher saturation deficit in the afternoon causing stomatal closure to avoid the drought condition; it took longer to arrive at the water stress levels in later seasons (Fig. 2-7). For the first three dry downs, mid morning and mid afternoong_s was nearly the same, suggesting that g_s is not sensitive to vapor deficits when well-watered, but as it became more stressed, sensitivity of leaf to air vapor deficits appeared to increase.

During the dry down, differences between leaf and average maximum air temperature increased along with the increasing drought stress levels, while water potential decreased in this process (became more negative because the turf had less evaporative cooling due to stomatal closure). According to Shackel et al. (1997), physically, as a plant tissue loses water, any reduction in the total water potential of the tissue must be reflected in a corresponding reduction in the water potential of the cells in that tissue, meaning that either cell turgor or cell osmotic potential must decline. For most tissues, the decline is most apparent in cell turgor, and since important plant processes such as stomatal opening are believed to be turgor dependent, it is expected that overall plant growth should be reduced as plant water deficits become more severe (Fig. 2-8).

To limit transpiration during dry down, plants must close stomata to prevent the lost of water via transpiration which resulted in leaf surfaces heating up (Fig. 2-9).

These graphs show that T_{leaf}-T_{airmax} increased very fast when the turfgrass went into drought stress. As the turfgrass leaf heats up, there is more turbulence at the turf canopy, decreasing boundary layer resistance (increasing conductance), connecting the turf stomata closure to the atmosphere and increasing leaf-air vapor pressure deficit.

Leaf water potential decreased faster in early summer season in both years (Fig. 2-9). In fact, this result matched with the result for soil moisture changing in early and late season. This may be due to the cooler temperature and the deeper soil water extraction by roots in late season, allowing plants to maintain water potential, so it decreased gradually slowly in comparison to that in early season. Chlorophyll content and visual rating decreased over time during the dry down (Fig. 2-10). Like g_s, chlorophyll index and the visual rating decreased gradually until it reached the point ofminimum visual quality (around 6 to 5.5), it decreased faster from that point. At this point, grass color turned brown in many parts of a plot, and subsequently the entire plot entered dormancy and became brown.Stomatal conductance has a trend of decreasing when soil moisture decreases, but within that decrease there are still ups and downs with the constant decrease of soil moisture due to atmospheric conditions. In other words, $g_s$is governed not only by soil moisture but also atmospheric conditions. Unlike g_s, chlorophyll index and visual rating decrease with the decrease of soil moisture, and the speed of that decrease depends on atmospheric conditions. Visual rating was based on turfgrass color, density and uniformity.

Correlations among measurements. Stomatal conductance was highly correlated with predawn leaf water potential. Likewise, leaf temperature was highly correlated with g_s during the dry down. (Fig. 10). There was more scatter (less correlation) at water potentials less negative than -0.6 MPa, but the relationship became much closer at -0.6 to -0.7 MPa in corresponding to g_s of 260 mmol m^{-1} s^{-1}. The decline in leaf water po-

tential was more responsive to the decline in g_s than other parameters measured (Fig. 10D). This result contrasts to the findings of Sheffer (1979) and Aronson et al. (1987a), who noted that leaf water potential in cool-season turfgrasses (*Poapratensis* L. 'Baron', *Loliumperenne* L. 'Yorktown II', *Festucarubra*var. *commutate* Gaud. 'Jamestown' and *Festucaovina* var. *duriuscula* (L.) Koch were not as sensitive to drought stress as ET and growth rate, and the results of DaCosta and Huang (2006) showed that a decline in $g_s$and shoot growth was independent of leaf water status. The experiments that both Aronson and DaCosta conducted were in a greenhouse, therefore all of the environmental conditions were controlled; additionally, dew points in this experiment ranged from 12 to 18 ^{o}C, which was much more humid than in Utah. The result may suggest that, in the conditions of dry soil and dry air, leaf water potential of KBG is greatly responsive to drought stress. This might be explained by the increase in leaf temperature and the dry air of Utah that may have caused reduced boundary layer resistance, increasing coupling of stomata to the atmosphere and imposing the very dry air on the turf leaves.

Visual rating had a fairly good correlation with g_s (Fig. 10C). When visual rating went below 5, $g_s$dropped very quickly and reached very low values at ratings of 2 to 3. Additionally, the relationship between visual rating and g_s became much closer when $g_s$went down to the value of around 260 mmol m^{-1} s^{-1}. Chlorophyll content had somewhat lower correlation with $g_s$than did visual rating (Fig. 10B). When $g_s$decreased to 260 mmol m^{-2} s^{-1}, the grasses began to show wilting, and visual rating was at 5.5. When chlorophyll index went below 200, the g_s essentially went to zero (Fig. 10B).

All the parameters above, including predawn leaf water potential, leaf temperature, visual rating, and chlorophyll index showed similar patterns. None of the fac-

tors started to decrease until g_s dropped to about 50% of well-watered levels or approximately 260 mmol m^{-1} s^{-1}. KBG has the ability, when extended dry conditions occur, to go into summer dormancy or quiescence, like a number of other grass species. While dormant, the crowns of grass plants are living but existing leavessenesce, and no new leaves are produced. Regrowth occurs when temperatures and moisture is again favorable for growth. The data showed that when KBG is exposed to dry conditions and g_s drops to half the level of well-watered turf, KBG starts to go into summer dormancy.

Correlation between plant factor *and visual rating.* Visual rating is not tightly correlated with plant factors through the dry downs over both years with $R^2 = 0.26$ which is not high. This result is shown in Fig. 2-11. The impact of drought stress via visual quality relatively mirrored the trend observed for K_p. Visual rating decreased when the Kp – grass coefficient decreased.

$K_p$ranged from around 0.8 to 1.1 under well-watered conditions, corresponding to visual rating from 7 to 9. At the minimum acceptable point of visual rating, which is 5.5 to 6, K_p went from 6.5 to 0.87. This value of K_p is quite high at this point,even when KBG went below the acceptable visual quality..

When g_s gets low enough to restrict turf water use, leaf temperature goes up, which maintains water use due to high leaf air vapor pressure deficit, and water potential go down very quickly, pushing the grass into dormancy where chlorophyll and visual quality fall quickly. This could explain the high water use of KBG even under drought conditions in the dry and hot Intermountain West area.

CHAPTER 5

SUMMARY AND CONCLUSION

Plant`s parameters and evapotranspiration of Kentucky Bluegrass were measured by Eddy covariance over two dry downs periods in two years 2009 and 2010 in the intermountain west region Utah. The values of these parameters at the minimum acceptable point were determined.

Visual rating, chlorophyll index, predawn leaf water potential and leaf temperature with g_s decreased very quickly and the relationship between these factors and g_s become much closer when g_s fell to approximately half of well-watered levels.

Both soil water content and ET had weak correlation with g_s; however, g_s tended to have higher correlation with the change in soil moisture than that with the change in crop ET. Soil water use and eddy covariance data in terms of crop ET had a high correlation.

K_p ranged from around 0.8 to 1.1 under well-watered conditions, corresponding to visual rating from 7 to 9. At the minimum acceptable point of visual rating, which is 5.5 to 6, K_p went from 0.65 to 0.87. This value of K_p is quite high at this point. Even when KBG went below the acceptable visual quality, the grass still uses significant amounts of water with the value of K_p ranging from 0.6 to 0.8. This is based on immediate water use measurements. Under actual irrigation practice however, well managed KBG has been shown provide adequate quality under deficit irrigation as low as 0.7, where the grasses access additional soil water storage.

These data indicate that KBG cannot be deficit irrigated and maintain acceptable quality in the Intermountain West urban landscape where rootzones limit the ability to access additional soil water.

REFERENCES

Ackerson, R.C. 1980. Stomatal responses to water stress and abscisic acid as affected by water stress history. Plant Physiol. 65: 455-459.

Aldous, D.E., and J.E. Kaufmann. 1979. Role of root temperature on shoot growth of two Kentucky bluegrass cultivars. Agron. J. 71:545-547.

Allen, R.G., I.A. Walter, R.L. Elliott, T.A. Howell, D. Itenfisu, M.E. Jensen, and R.L. Snyder. 2005. The ASCE standardized reference evapotranspiration equation. The American Society of Civil Engineers, Reston, VA.

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration, guidelines for computing crop water requirements. FAO Irrig. and Drain. Paper 56, Food and Agric. Orgn. of the United Nations, Rome, Italy. pp300.

Amer, K.H., Hatfield, J.L., 2004. Canopy resistance as affected by soil and meteorological factors in potato. Agron. J. 96:978-985.

Aronson, L.J., A.J. Gold, R.J. Hull, and J.L Cisar. 1987a. Cool-season turfgrass responses to drought stress. Crop Sci. 27:1261-1266.

Aronson, L.J., A.J. Gold, R.J. Hull, and J.L Cisar. 1987b. Evapotranspiration of cool-season turfgrasses in the humid Northeast. Agron. J. 79:901-905.

Banuelos, J.B., J.L. Walworth, P.W. Brown, and D.M. Kopec. 2011. Deficit irrigation of Seashore Paspalum and Bermudagrass. Agron. J. 103:1567-1577.

Beard, J.B. 1973. Turfgrass: Science and Culture. Prentice-Hall, Englewood Cliffs, NJ.

Beard, J.B., and R.L. Green. 1994. The role of turfgrasses in environmental protection and their benefits to humans. J. Environ. Quality 23(3):452-460.

Bennett, J.M., and C.Y. Sullivan. 1981. Effects of water stress preconditioning on

net photosynthetic rate of grain sorghum. Photosynthetica 15: 330-337.

Blonquist, J.M. Jr., J.M. Norman, and B. Bugbee. 2009. Automated measurement of canopy stomatal conductance based on infrared temperature. Agr. Forest Meteorol. 149:1931-1945.

Bohnert, H.J., and R.G. Jensen. 1996. Strategies for engineering water-stress tolerance in plants. Trends Biotech. 14:89-97.

Bonos, S.A., and J.A Murphy. 1999. Growth responses and performance of Kentucky bluegrass under summer stress. Crop Sci. 39:770-774.

Brown, K.W., and J.C. Thomas. 1980. The influence of water stress preconditioning on dark respiration. Physiol. Plant. 49:205–209.

Brown, P.W., C.F. Mancino, M.H. Young, T.L. Thompson, P.J. Wierenga, and D. Kopec. 2001. Penman-Monteith crop coefficients for use with desert turf systems. Crop Sci. 41:1197-1206

Campbell, G.S., J.M.Norman. 1990. Estimation of plant water status from canopy temperature: An analysis of the inverse problem. In: Steven, M.D., Clark, J.A. (Eds.). Applications of Remoting Sensing in Agriculture. Butterworths, London, UK, pp. 255-271.

Carrow, R.N. 1996. Drought avoidance characteristics of diverse tall fescue cultivars. Crop Sci. 36:371-377.

Clark, R.N., and E.A. Hiler. 1973. Plant measurements as indicators of crop water deficit. Crop Sci. 13: 466-469.

Condon, A.G., R. Richards, G. Rbetzke, G. Farquhar, and G. Farquhar. 2004. Breeding for high water use efficiency. J. Exper.Botany 55: 2447-2460.

DaCosta, M., and B. Huang. 2006. Minimum water requirements for creeping, colonial, and velvet bentgrass under fairway conditions. Crop Sci. 46(1):81-

89.

Davies, W.J., S. Wilkinson, and B. Loveys. 2002. Stomatal control by chemical
    signalling and the exploitation of this mechanism to increase water use
    efficiency in agriculture. New Phytol. 153: 449–460.

Davies, W.J., F. Tardieu, and C.L. Trejo. 1994. How do chemical signals work in
    plants that grow in drying soil? Plant Physiol. 104(2):309-314.

Duble, R. L. 2006. Water management on turfgrasses. Available online:
    [http://plantanswers.tamu.edu/turf/publications/water.html]. Verified: Nov
    21st, 2006

Eamus, D. 1987. Influence of preconditioning upon the changes in leaf conductance
    and leaf water potential of soybean, induced by chilling, water stress and
    abscisic acid. Aust. J. Plant physiol. 14: 331-339.

Emmons, R.D. 2000. Turfgrass Science and Management. 3rd ed. Delmar Publish-
    ers, Albany, NY.

Ervin, E.H., and A.J. Koski. 1998. Drought avoidance aspects and crop coefficients
    of Kentucky bluegrass and Tall fescue turfs in the semiarid west. Crop Sci.
    38:788-795.

Esmaili, S., and H. Salehi. 2012. Effects of temperature and photoperiod on post-
    poning bermudagrass (Cynodondactylon [L.] Pers.) turf dormancy. J. Plant
    Phys. 169:851–858.

Feldhake, C.M., R.E. Danielson, and J.D. Butler. 1984. Turfgrass evapotranspira-
    tion. 11. Responses to deficit irrigation. Agron. J. 76:85-89.

Fender, D. 2006. Urban perennial grasses in times of a water crisis: benefits and
    concerns. Council for Agricultural Science and Technology (CAST). Water
    Quality &Quantity Issues for Turfgrasses in Urban Landscapes, Las Vegas,

NV.

Fenton, L.L. 2009. Evapotranspiration of Kentucky bluegrass. MS Thesis, Utah State University.

Fernandez, G. and B. Love. 1993. Comparison of turfgrass cumulative evapotranspiration curves. HortSci. 28:732–734.

Fry, J.D., and J.D. Butler. 1989. Response of tall and hard fescue to deficit irrigation. Crop Sci. 29: 1536-1541.

Fu, J. 2007. Tall fescue rooting as affected by deficit irrigation. HortScience 42:688-691.

Fu, J., J. Fry, and B. Huang. 2004. Minimum water requirements of four turfgrasses in the transition zone. HortSci. 39:1740-1744.

Fu, J., J. Fry, and B. Huang. 2007. Tall fescue rooting as affected by deficit irrigation. HortSci. 42:688-691.

Garrot, D.J., and C.F. Mancino. 1994. Consumptive water use of three intensively managed bermudagrasses growing under arid conditions. Crop Sci. 34:215-221.

Gash, J. 1986. A note on estimating the effect of limited fetch on micrometeorological evaporation measurements. BoundaryLayer Meteorol. 35:409-413.

Gibeault, V.A., S. Cockerham, J.M. Henry, and J. Meyer. 1989. California Turfgrass: its use, water requirement and irrigation. California Turfgrass Culture Vol. 39, numbers 3 and 4. Cooperative Extension, University of California.

Hatfield, J.L. 1985. Wheat canopy resistance determined by energy balance techniques. Agronomy Journal 77:279-283.

Idso, S.B.,R.D.Jackson, P.J.Printer Jr., R.J. Reginato, and J.L. Hatfield. 1981. Nor-

malizing the stress-degree-day parameter for environmental variability. Agricultural Meteor. 24:45-55.

Jackson, R.D., S.B.Idso, R.J.Reginato, P.J.Printer Jr. 1981. Canopy temperature as a crop water stress indicator. Water Resour. Res. 17:1133-1138.

Jackson, R.D., W.P.Kustas, B.J. Choudhury. 1988. A reexamination of the crop water stress index. Irrigation Science 9:309-317.

Jarvis, P.G. 1976. The interpretations of the variation in leaf water potential and stomatal conductance found in canopies in the field. Philos. Trans. R. Soc. London. Ser.B. 273:593-610.

Jensen, M.E., R.D. Burman, and R.G. Allen. 1990. Evapotranspiration and Irrigation Water Requirements. ASCE Manuals and Reports on Engineering Practice No. 70, Am. Soc. Civil Engr., New York, NY.

Jiang, Y., and B. Huang. 2000. Effects of drought or heat stress alone and in combination on Kentucky bluegrass. Crop Sci. 40:1358–1362.

Jiang, Y., and B. Huang. 2001. Osmotic adjustment and root growth associate with drought preconditioning-enhanced heat tolerance in Kentucky bluegrass. Crop Sci. 41:1168–1173.

Jiang, Y., H. Liu, and V. Cline. 2009. Correlations of leaf relative water content, canopy temperature, and spectral reflectance in perennial ryegrass under water deficit conditions. J. Amer. Soc. Hort. Sci. 44:459–462.

Johnston, W.H., T.B. Koen, and V.F. Shoemark. 2002. Water use, completion and temperate-zone C4 grass. (Eragrostiscurvula (Schrad.) Nees. Complex) cv. Consol. Aust. J. Res. 53(6):715-728.

Jones, H.G. and K.H.Higgs. 1989. Empirical models of the conductance of leaves in apple orchards. Plant Cell Environ. 12:301-308.

Jones, H.G. 1999. Use of infrared thermometry for estimation of stomatal conductance as a possible aid to irrigation scheduling. Agric. Forest Meteorology 95:139-149.

Keeley, S.J., and A.J. Koski. 2001. Dehydration avoidance of diverse Poapratensis cultivars and cultivar groups in a semiarid climate. Int. Turf. Soc. Res.J.9:311-316.

Kjelgren, R., L. Rupp, and D. Kilgren. 2000. Water conversation in urban landscapes. HortSci. 35:1037-1040.

Leinonen, I., O.M.Grant, C.P. Tagliavia, M.M.Chaves, H.C.Jones. 2006. Estimating stomatal conductance with thermal imagery. Plant, Cell and Environ. 29:1508-1518.

Liu, H, J.T. Randerson, J. Lindfors, W.J. Massman, and T. Foken. 2006. Consequences of incomplete surface energy balance closure for CO_2 fluxes from open-path CO_2/H_2O infrared gas analyzers. Boundary-Layer Meteor. 120(1):65-85.

Liu, X. Z.,and B. R. Huang. 2005. Root physiological factors involved in cool-season grass response to high soil temperature. Environ. Exp. Bot. 53:233-245.

McNaughton, K.G., Jarvis, P.G. 1983. Predicting effects of vegetation changes on transpiration and evaporation. In: Kozlowski, T.T. (Ed.), Water Deficits and Plant Growth Vol.VII. Academic Press.pp.1–47.

Meyer, J.L. and Gibeault, V.A. 1987. Turfgrass performance when underirrigated. Applied Agricultural Research Vol. 2, No. 2, pp.117-199. Springer Verlag New York Inc.

Moncrieff, J., R. Valentini, S. Greco, G. Seufert, and P. Ciccioli. 1997. Trace gas

exchange over terrestrial ecosystems: Methods and perspectives in micro-meteorology.J. Exp. Bot. 48:1133-1142.

Pasquill, F.: 1972. Some Aspects of Boundary Layer Description. Quart. J. Royal Meteorol. Sot. 98: 469-494

Payero, J.O., Irmak, S. 2006. Variable upper and lower crop water stress index baselines for corn and soybean. Irrigation Science 25: 21-32.

Payero, J.O., Neale, C.M.U., Wright, J.L. 2005. Non-water-stressed baselines for calculating crop water stress index (CWSI) for alfafa and tall fescue grass. Transactions of the ASAE. 48: 653-661.

Qian, Y.L. and M.C. Engelke. 1999. Turfgrass selection: Comparing three turfgrasses for minimum irrigation requirements, drought resistance and long-term performance. Turfgrass Trends 8:4-8.

Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D.K, and Yoder, D.C., coordi-nators. 1987. Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Soil Loss Equation (RUSLE). U.S. Dept. of Ag-riculture, Agric. Handbook No.703:404.

Richie, W. E., Green, R. L. and Gibeault, V.A. 1997. Using ETo (Reference Evapo-transpiration) for turfgrass irrigation efficiency. California Turfgrass Culture Vol. 47, Nos. 3 & 4. University of California.

Schimid, H.P. 2002. Footprint modeling for vegetation atmosphere exchange stud-ies, a review and perspective. Agric for Meteorol. 113: 159-183.

Schmid, H. P. and T. R. Oke. 1990. A model to estimate the source area contrib-uting to surface layer turbulence at a point over patchy terrain. Quarterly Journal Royal Meteorological Society 116: 965-988.

Shackel, K.A., H. Ahmadi, W. Biasi, R. Bucher, D. Goldhamer, S. Gurusingle, J.

Hasey, D. Kester, B. Krueger, B. Lampinen, G. McBourty, W. Micke, E. Mitcham, B. Olson, K. Pelletrau, H. Phillips, D. Ramos, L. Schwankl, S. Sibbett, R Snyder, S Southwick, M. Stevenson, M. Thorpe, S. Weinbaum, and J. Yeager. 1997. Plant water status as an index of irrigation need in deciduous fruit trees. HortTechnology 7(1): 23-29.

Sheffer, K.M. 1979. Responses of three cool-season turfgrass species to heat and moisture stress. PhD. diss. Univ. of Missouri, Columbia (Diss. Abstr. 80-07193).

Shearman, R. C. 1986. Kentucky bluegrass cultivar evapotranspiration rates. Hortscience 21(3):455-457.

Stewart, J.B. 1988. Modeling surface conductance of pine forests. Agric. For. Meteorol. 43: 19-35.

Sulser, T.B., C. Ringler, T. Zhu, S. Msangi, E. Bryan and M. Rosegrant. 2010. Green and blue water accounting in the Ganges and Nile basins: implications for food and agricultural policy. J. Hydrol. 284:276-291.

Sumner, D. M. 2006. Adequacy of selected evapotranspiration approximations for hydrologic simulation. J. Amer. Water Resour. Assoc. 42:699-711.

Tanner, C.B. 1963. Plant temperatures. Agronomy journal 55:210-211.

Throssell, C.S., R.N. Carrow, and G.A. Milliken. 1987. Canopy temperature-based irrigation scheduling indices for Kentucky bluegrass turf. Crop Sci. 27:126-131.

Turgeon,A.J. 2002.Turfgrass management(Prentice Hall, Englewood Cliffs, NJ), 6th Ed.

Wang, Z., B. Huang, and Q. Xu. 2003. Effect of abscisic acid on drought response of Kentucky bluegrass. J. Am. Soc. Hort. Sci. 128(1):36-41.

Xi, J.B. and H.X. Zhang. 2005. Winter-green technology on Zoysia japonica Lanyin No. 3 sport field turf in south subtropic region. J. Zhongshan Univ. 44(4):93–95.

Zhang, J. and Davies, W.J. 1987. Increased synthesis of ABA in partially dehydrated root tips and ABA transport from roots to leaves. J. Exp. Bot. 38(12):2015-2023.

Table 1. Average maximum temperature and average precipitation from May to September from 1956 to 2010.

Month	1956-2010		2009		2010	
	Precipitation (mm)	Maximum air temperature (°C)	Precipitation (mm)	Maximum air temperature (°C)	Precipitation (mm)	Maximum air temperature (°C)
May	46.2	20.6	43.4	20.8	73.4	15.3
Jun	34.0	26.3	72.9	23.2	27.4	23.9
Jul	16.5	31.9	0.0	30.5	0.0	30.8
Aug	21.8	30.8	28.2	29.0	23.1	29.1
Sep	34.5	24.9	32.5	27.2	10.2	26.4

Table 2. Monthly average K_p from May to September in 2009 and 2010

Month	Kp - 2009	Kp-2010
May	0.90 ± 0.10	0.89 ± 0.16
June	1.01 ± 0.10	0.82 ± 0.13
Jul	0.92 ± 0.08	0.76 ± 0.07
Aug	0.90 ± 0.09	0.82 ± 0.09
Sep	0.97 ± 0.09	0.81 ± 0.81

Fig. 1. Plot layout of Kentucky bluegrass field experiment design.
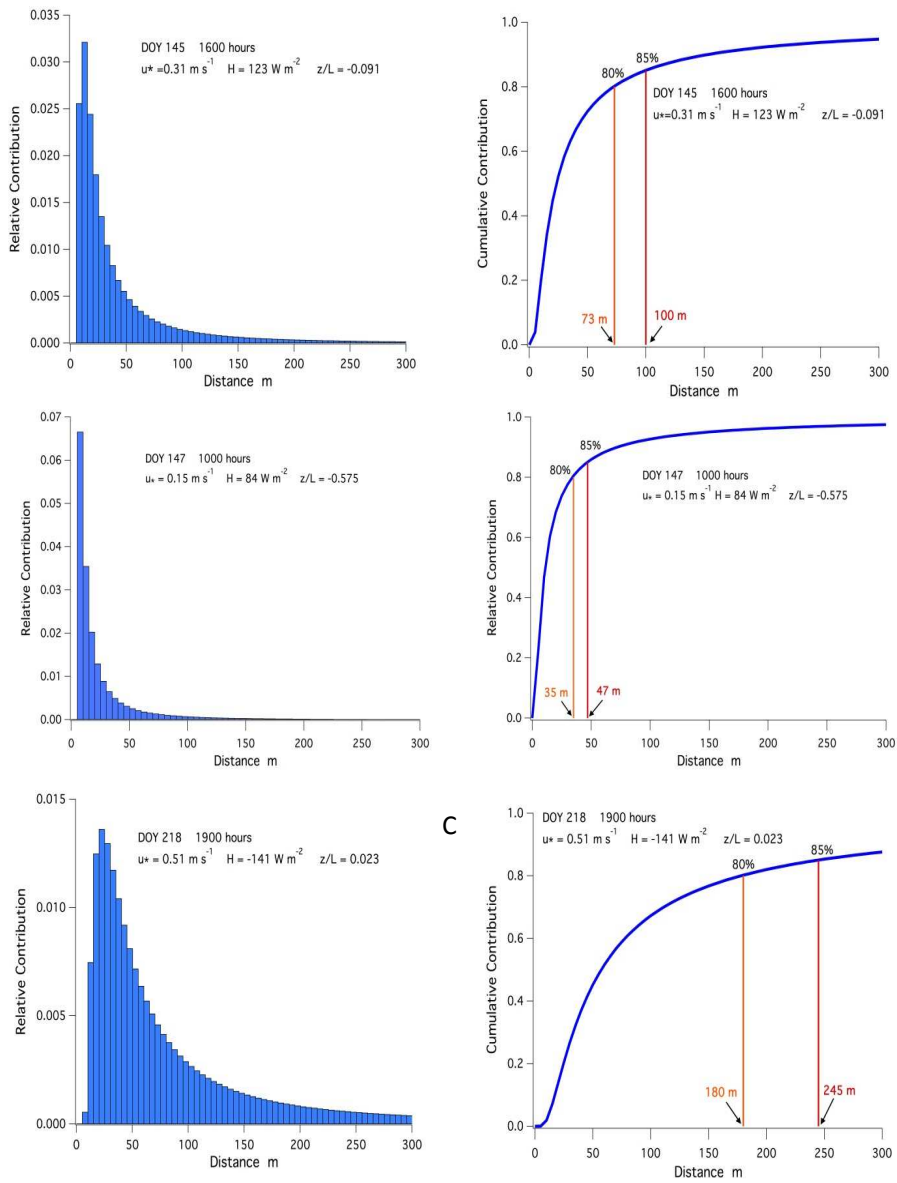
Fig.2. Footprint of the Kentucky bluegrass field: 1A – DOY 145: slightly unstable, 1B – DOY 147: unstable, 1C – DOY 218: near neutral.
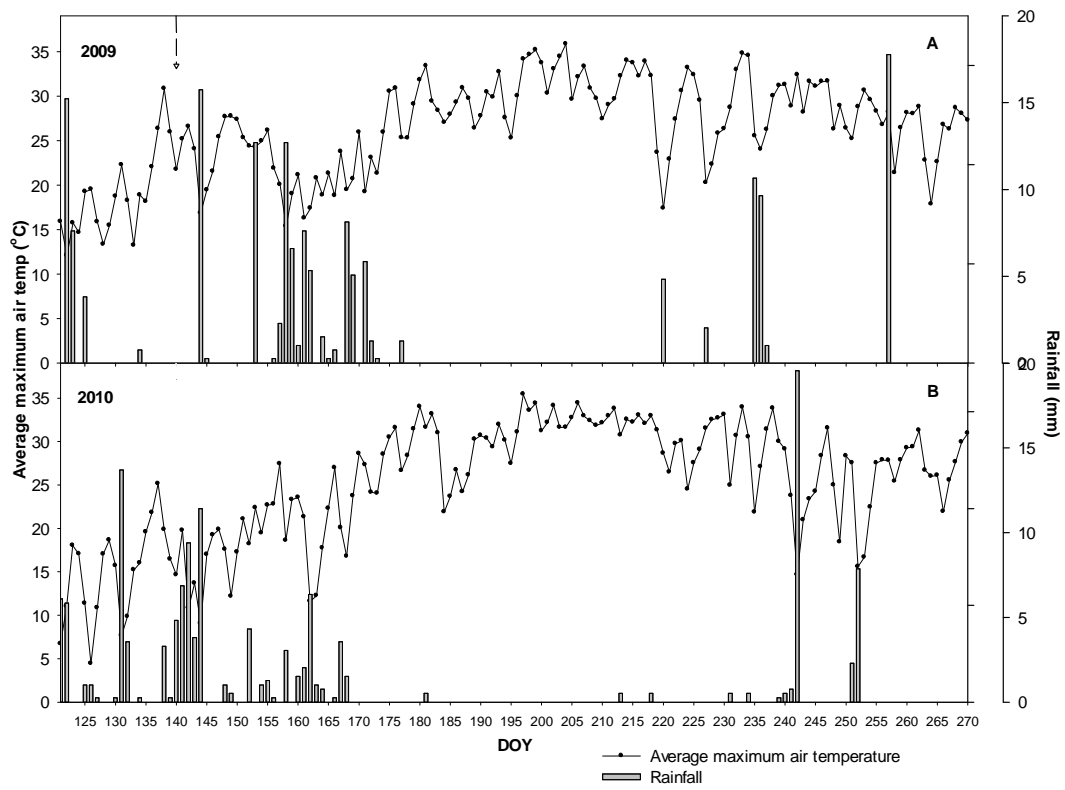
Fig. 3. Seasonal weather data at the Utah State University Research Farm: rainfall, maximum temperature from May to September (DOY 125 to DOY 270). A-2009, B-2010.
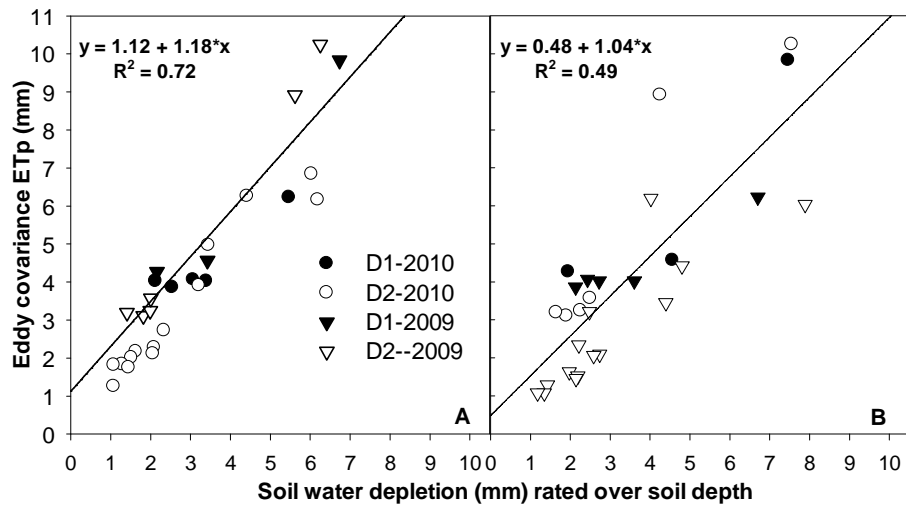
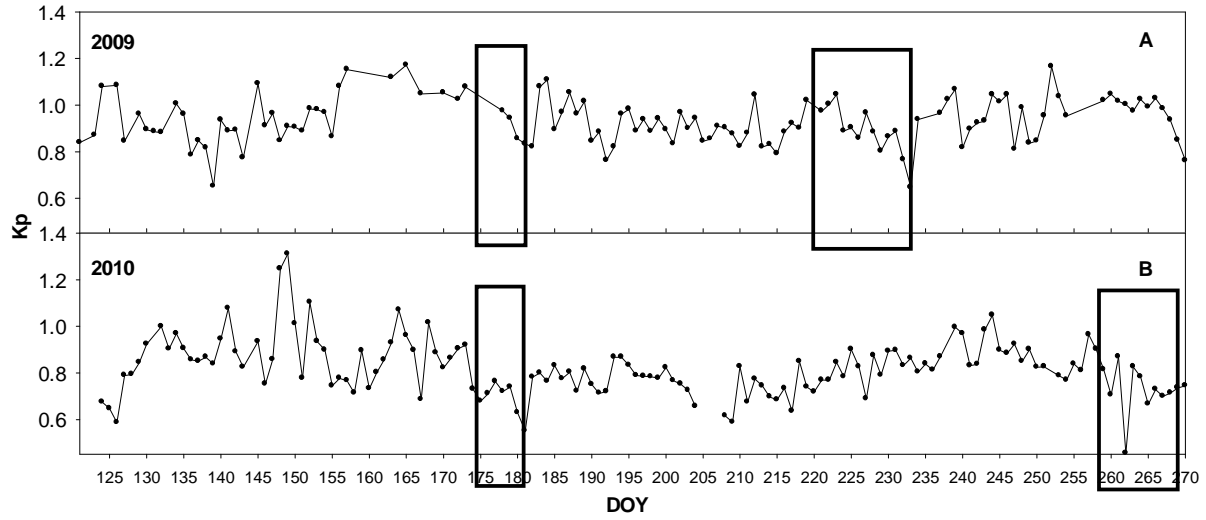Fig.4. Correlation between eddy covariance and soil water depletion over depth: A: depth 0 to 40cm, B: depth 0 to 100cm.

Fig.5. Kentucky bluegrass depletion/soil water during drydown period in Utah over 2 years at the depth of 10 cm to 40cm.A: dry down 1, 2009. B: dry down 2, 2009. C: dry down 1, 2010. D: dry down 2, 2010. Days 8to18 after irrigation in dry down 2 in 2010 were interrupted due to rain.
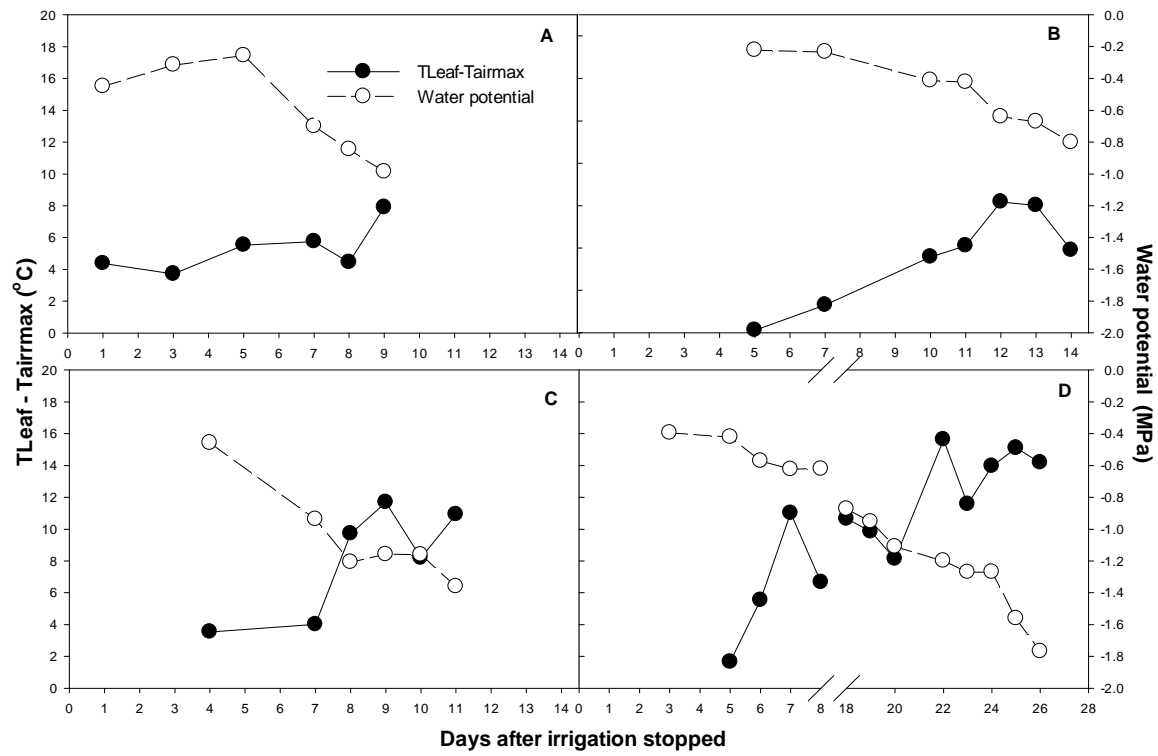
Fig.6. Kentucky bluegrass coefficient values throughout the season from May to September (from DOY 125 to DOY 270). A:2009, B:2010.
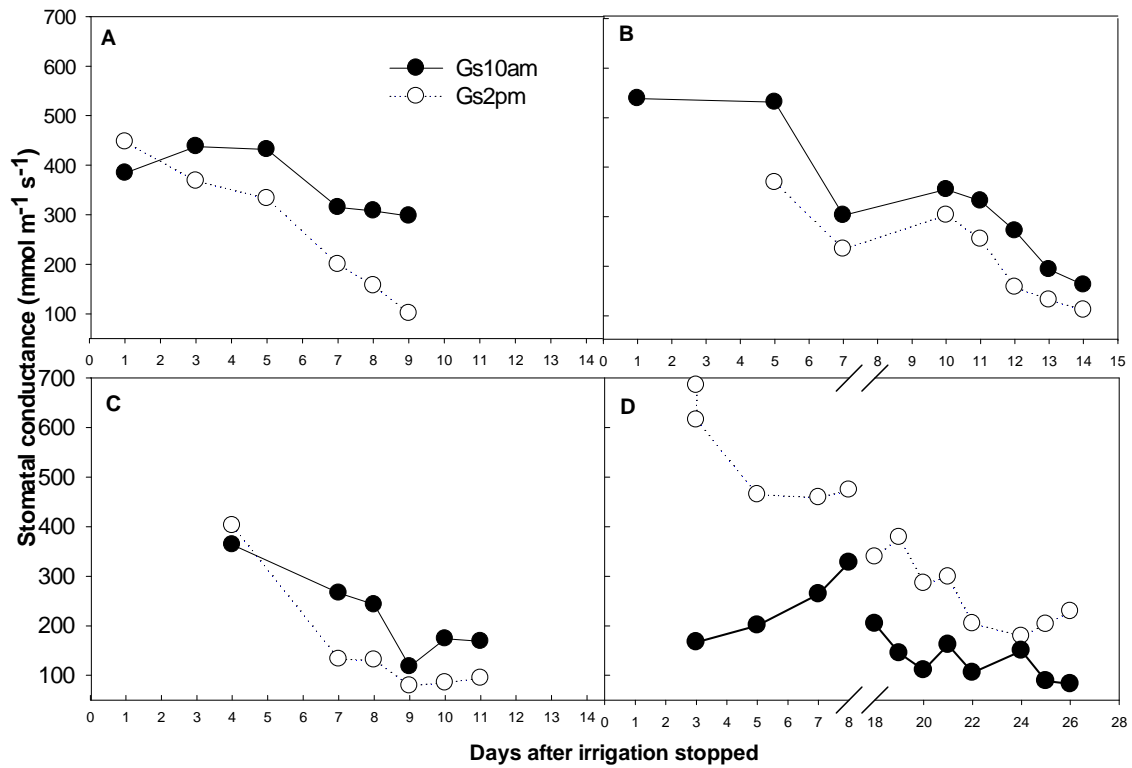
Fig. 7. Stomatal conductance performance during dry down period at 10 AM and 2 PM. A: dry down 1, 2009. B: dry down 2, 2009. C: dry down 1, 2010. D: dry down 2, 2010. Days 8 to18 after irrigation in dry down 2 in 2010 were interrupted due to rain.

Figure. 8. Tleaf-Tairmax and water potential during dry down. A: dry down 1, 2009. B: dry down 2, 2009. C: dry down 1, 2010. D: dry down 2, 2010. Days 8 to18 after irrigation in dry down 2 in 2010 were interrupted due to rain.
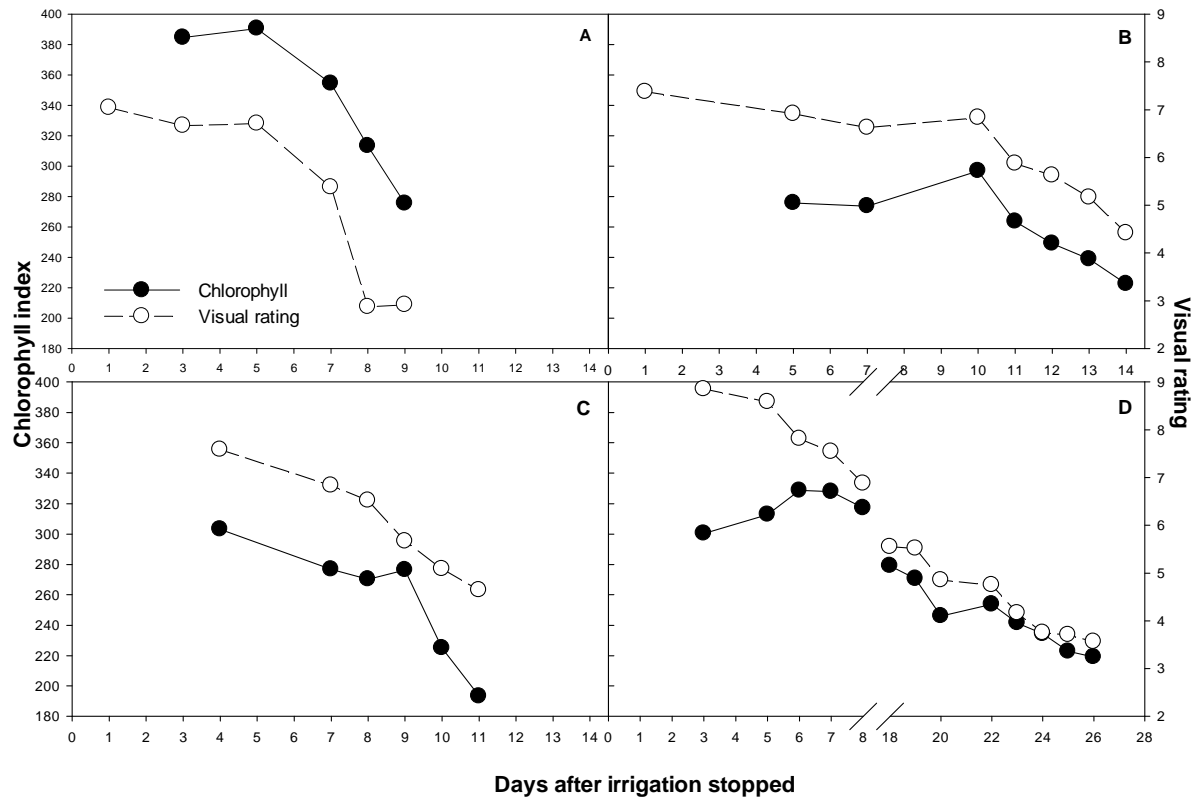
Fig.9. Chlorophyll content and visual rating during dry down throughout the season. A: dry down 1, 2009. B: dry down 2, 2009. C: dry down 1, 2010. D: dry down 2, 2010. Days 8 to18 after irrigation in dry down 2 in 2010 were interrupted due to rain.
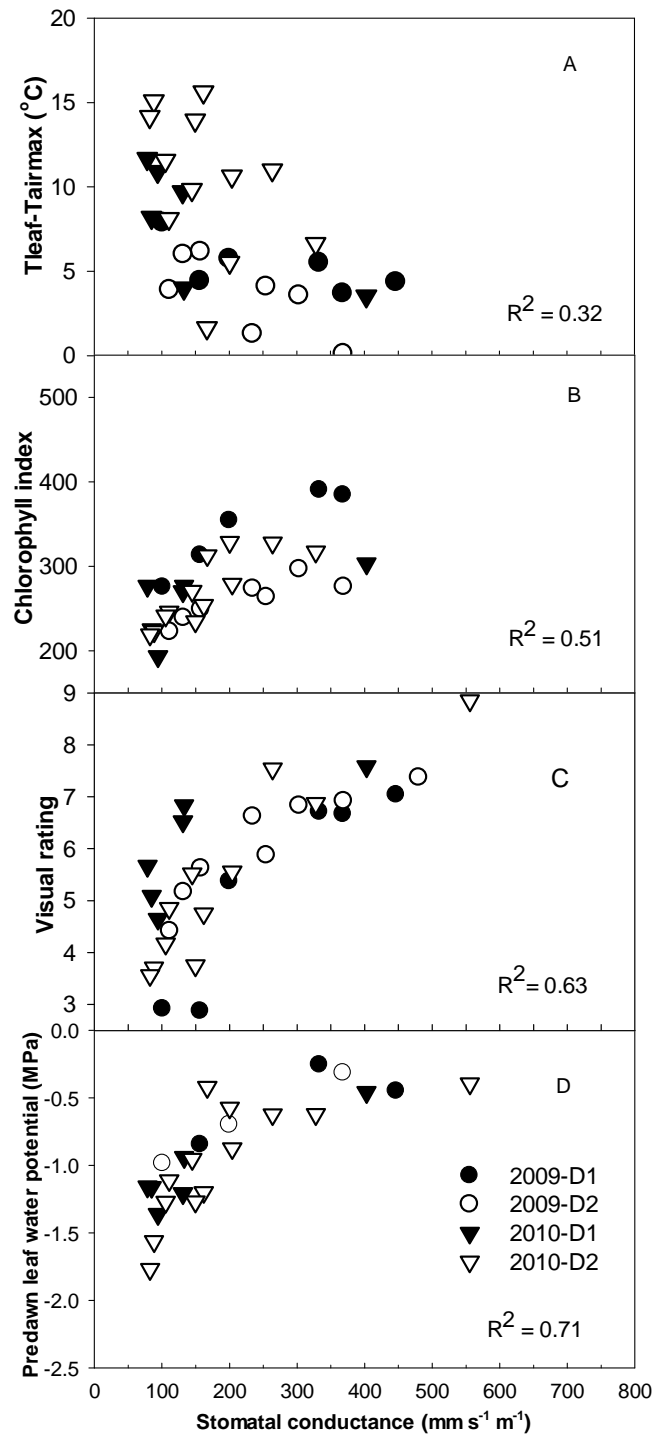
Fig.10. Stomatal conductance vs. other factors during drydown periods in both 2009 and 2010. A:stomatal conductance vs.(TLeaf-Tairmax);B:stomatal conductance vs. chlorophyll index;C:stomatal conductance vs. visual rating;D: stomatal conductance vs. leaf water potential.
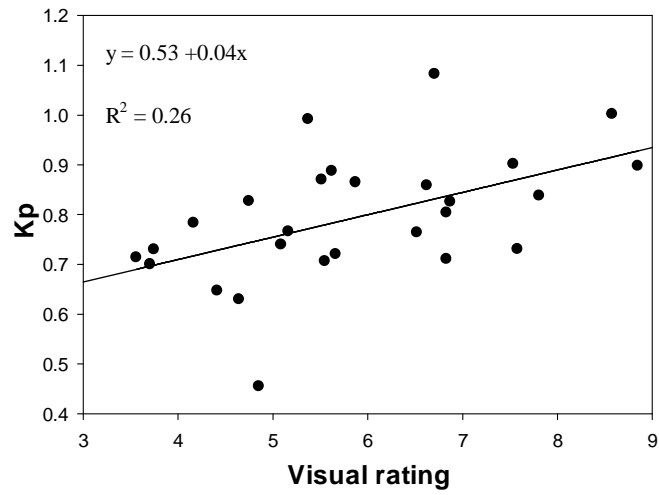
Fig.11. Turfgrass plant factor (actual use / reference evapotranspiration) versus visual rating occurring over periods in 2009 and 2010.