THESIS

IRRIGATION EFFECTS ON GROWTH, STRESS, VISUAL QUALITY AND EVAPOTRANSPIRATION OF ORNAMENTAL GRASSES

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ABSTRACT

IRRIGATION EFFECTS ON GROWTH, STRESS, VISUAL QUALITY AND EVAPOTRANSPIRATION OF ORNAMENTAL GRASSES

Deficit irrigation research has proven extremely effective for reducing the amount of irrigation applied to various types of landscape plants including trees, shrubs, and herbaceous ornamental plants. This research has yet to delve in to one of the most common classes of drought tolerant plants, ornamental grasses. Deficit irrigation treatments were based on evapotranspiration of a short reference crop (Kentucky bluegrass evapotranspirtation, ET_o). In 2012 three ornamental grass species were planted, and an on-site atmometer was used to estimate ET_o. The three species used for trialing were *Panicum virgatum* 'Rotstrahlbusch' (Rotstrahlbusch Switchgrass), *Schizachyrium scoparium* 'Blaze' (Blaze Little Bluestem), and *Calamgrostis brachytricha* (Korean Feather Reed Grass). Treatments were applied and data was collected in 2014 and 2015 on two separate studies. The first study was in-ground and consisted of four treatments based on ET_o (0%, 25%, 50%, and 100%). The second study was a mini-lysimeter and consisted of three treatments based on ET_o (25%, 50%, and 100%). Only *Schizachyrium scoparium* 'Blaze' (Blaze Little Bluestem) was used in the lysimeter study. Data collected in both studies included plant water potential, biomass accumulation, green up date, flowering date, height, width, circumference, floral impact, landscape impact, overall habit, self-seeding, and color. The in-ground component also measured infrared canopy temperature and soil water content, while the lysimeter study included daily weight measurements which were then transferred to evapotranspiration readings. Plants in the 0% treatment were smaller and not

considered visually suitable for landscape use. All three species in the 25% treatment performed equivalent to the 50% and 100% treatments in all categories. The only exception was plants in the 25% mini-lysimeter study were more stressed than the 50% or 100% treatments during periods of drought. These plants were all considered visually suitable for landscape use based on visual ratings. This suggests that as long as ornamental grasses are kept on a strict weekly regiment of 25% ET_o, and are never exposed to periods of drought, they will be physiologically as well as aesthetically usable in the landscape trade. A weekly amount of 0.25 inches of irrigation on weeks without precipitation was determined to be a usable number for those installing and maintaining ornamental grasses.

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INTRODUCTION

Minimal scientific research has been performed on ornamental grasses, specifically pertaining to the amount of water used. Considering the fact that water-wise gardening is becoming more popular across the United States, it is important to obtain scientific data about landscape plants which can aid this increasing water-wise community. Ornamental grasses are widely used by municipalities, businesses, and homeowners and most ornamental plants are frequently over-irrigated in these situations (GreenCO, 2008). It is a goal of this project to determine the lowest possible irrigation level (relative to bluegrass evapotranspiration) at which common ornamental grasses can be watered while maintaining both beauty and viability. The key aspect of this research is to determine an irrigation level at which the plants are not stressed, and also maintain ornamental quality and health for the future. This is a pioneering study because it couples the idea of survival and stress with visual quality of ornamental grasses as seen by industry personnel and homeowners. A second goal of the study is to quantify the amount of water these ornamental grasses use. Since the industry standard is to assume these grasses are "low water users", it is important to quantify the water use. Coupled with this idea is discovering the critical water potential or critical stress levels these grasses can reach before they are no longer considered viable for sale in the landscape trade. In addition to determine how much water "low water uses" grasses need, the goal of this study is also to determine how long they can go without that water and how stressed they are during that period. Another important aspect is to note what critical stress level these plants reach when they cannot recover from this stress. The critical stress level could have massive implications on how little water these plants actually require. A final element is to determine if these deficit levels of irrigation are feasible during periods of drought. It is great to know that plants can survive using less water, but it is also important to know the consequences of sudden droughts following limited watering. This is an extremely common problem in the nursery industry (Davidson, 2000), and, therefore, prolonged periods of drought are very important to investigate. This study is meant to serve as a launching point for other studies on ornamental grasses and as a general outline for the levels of irrigation, stress, and visual quality these plants are capable of in various generalizable situations.

In addition this study aims to classify the photosynthetic pathway of *Calamgrostis brachytricha* (Korean Feather Reed Grass). Currently the literature is in debate whether this plant is a C_3 or C_4 species (or switches between the two). Since this is a pilot study for common ornamental grasses, determining the photosynthetic pathway of *Calamgrostis brachytricha* is important.

LITERATURE REVIEW

Water is one of the most valuable and limited resources in the world. Water availability in the United States has decreased in the past twenty years as populations steadily increase (Sun et al., 2008). According to the US Census Bureau, the population of Colorado has increased 48% in the past 20 years from 3.496 million to 5.188 million (Endter-Wada, 2008). Further, population growth is expected to increase by a minimum of 50% in the next 20 years (Sun et al., 2008). The United States General Accounting Office states that with increasing population growth and variability in climate change in Colorado, significant water shortages are in store for the future (Costello and Jones, 2000). Diminishing horticultural growing grounds and widely used unsustainable practices also play a large role in reducing water availability (Boyer, 1982). Considering that landscape irrigation can constitute between 40-70% of total household water consumption, finding ways to efficiently use household irrigation should have a significant impact on large scale water savings (Hilaire et al., 2008). Of this 40-70%, it is common for residential landscapes to be supplied with far more water than is needed for healthy growth (Hilaire et al., 2008). With increasing temperatures and decreasing water availability, water use efficiency (defined as desired product produced per unit water used) in residential landscapes is one of the most important aspects of plant development (Qian, 2014). To further compound the problem, between 30-70% of all potable water is used to irrigate these same landscapes (Zollinger et al., 2006). Potable water is extremely valuable and has the potential to be used in other ways that benefit the local community. In Colorado the use of grey water is highly restricted and regulated, forcing most landscapers and municipalities to use water of higher quality (Whiting, 2012: 267).

Landscape irrigation can be defined as the systematic application of water to land areas that supply water needs of ornamental plants (Hilaire et al., 2008). From this definition, it is clear that a highly systematic approach must be taken if this valuable resource is to be used more effectively. One method to conserve water in the horticulture industry is to apply deficit irrigation. Deficit irrigation can be defined as the application of water at a rate of volume lower than that of the evapotranspiration (ET) rate. Aspects such as carbon regulation, and general aesthetic appeal are easy to properly manage at lower levels of irrigation than are currently provided. It has been shown through various research efforts that many ornamental plants perform acceptably when water is applied at significantly lower than general guidelines (20%-50% of ET)(Costello and Jones, 2000; Beeson, 2005). Pittenger and Shaw (2004) were able to show that in a 30 species trial of shrubs 11 species maintained acceptable aesthetic appeal with 0% supplemental irrigation, and another 14 species performed just as well at 18% supplemental irrigation. In this particular study 80% of species performed to proper ornamental standards while being watered at under 20% standard irrigation (below 20% ET) (Schuch and Burger, 1997). This shows that aesthetically pleasing landscapes and water-efficient landscapes are not mutually exclusive concepts (Hilaire et al., 2008). Since quality aesthetics is one of the most important aspect of ornamental production.

To further complicate this issue, much of the information about “standard watering procedures” available to the public is non-research based, and is instead based on general observations and hearsay. One of the many issues with water-efficient landscapes is the way they are portrayed to the public. Many residential landscapers define water-efficient landscapes as unattractive, sparse plantings with large areas of soil and gravel in between. In a public survey conducted by Hurd et al. (2006), one of the highest rated social barriers to installing a water-efficient landscape is aesthetic concerns for the property (Hurd et al., 2006). Only 9% of participants agreed that water-efficient landscapes have the potential to be aesthetically pleasing, whereas 63% disagreed (Hurd et al., 2006). At the same time, 96% of participants agreed that if ornamental grasses proved to maintain visual quality, they would use them in their own garden (Wolfe III, 1998).

These public perceptions are contradicted by frequent legislative practices proposing bills for efficient water use in urban landscapes and municipalities (Hilaire et al., 2008). As more communities begin mandating efficient water use, implementing more water efficient landscapes will be an inevitable and mandatory aspect of future landscapes in Colorado (Hilaire et al., 2008). Clearly, an informational bridge between providing beautiful landscapes for residential landscapers and reducing water inputs to the greatest extent possible needs to be formed. This informational bridge becomes increasingly necessary because the amount of water used in the United States is expected to increase, while precipitation decreases, and ET increases (Hilaire et al., 2008). This implies that more water will be necessary to maintain residential plants while less water will be available for that task.

Drought tolerance is a defining characteristic of many ornamental grass species worldwide (Tucker et al., 2011). There is no single definition, but one definition of drought can be described as a shortage of water, usually associated with a precipitation deficit (McKee et al., 2009). Simply put, drought occurs when the demand for water exceeds the supply of water (McKee et al., 2009). The definition of drought varies depending on the person who supplies the definition. Farmers, hydrologists, and economists all have varying definitions of drought which can include aspects of meteorology, agriculture, hydrology, and socioeconomics (Smith and Klett, 2013), but the common denominator to all definitions is an insufficient supply of water.

Another aspect of drought which most definitions agree upon is that it is episodic in nature (Weaver, 1968). These episodic swings can be seen on multiple levels from decade-long reductions in precipitation, to seasonal fluxes, all the way down to mid-day induction of water stress (Tucker et al., 2011). To this extent, drought is location dependent, as Colorado's wettest year on record (along the Front Range) may still be drier than the driest year on record at locations on the east coast (McKee et al., 2009).

Plants have various strategies to cope with drought stress which can be divided into categories of escape, avoidance, and tolerance (Chaves et al., 2003). Plants can often minimize water loss by closing of stomata, displaying partial dormancy (metabolic inhibition), rolling leaves, and displaying dense trichomes (Chaves et al., 2003). Plants may also maximize water uptake by increased energy investment in roots, increased rooting depth, and the shedding of old leaves (Chaves et al., 2003). While drought is commonly believed to focus on stomatal processes (the opening and closing of pores at a plant's surface) , the various methods by which plants cope with drought show that both stomatal and non-stomatal processes are affected by drought (Zhou et al., 2013). Most plants also have the ability to perceive water deficit and communicate it through signal-transduction to the remaining parts of the plant (Chaves et al., 2003). The extent to which drought reduces productivity is widely debated and is generally thought to be species or genus specific (Smith and Klett, 2013). Critical water potentials (Ψ_{crit}, defined as the minimum water potential a plant can endure and still recover) can range anywhere from -1 MPa to -60 MPa depending on the species (Qian, 2014). Drought resistance is a function of a plant's individual physiology and natural range (Alvarez et al., 2007), and each individual species has a specific range of drought resistance. For this reason it is essential to find species that require minimal irrigation for survival in the hot and dry environment of Colorado.

Evapotranspiration can be described as a combination of the water evaporated from the soil surface and transpired through the plant (Gulik, 2001). ET can be calculated using ET_o (ET of Kentucky Bluegrass at 0.12 meters) as a reference crop (Gulik, 2001). Effective quantification of ET is a key aspect of effective and precise irrigation management (Irmak, 2009). This knowledge will allow users to deliver the proper amount of water to the field at the correct time, in turn conserving water (Irmak, 2009).

Finding ET_c of specific ornamental species would prove to be valuable when it comes to water savings. Instead of optimizing yield, maintaining aesthetic appeal and landscape function are the major concerns of ornamental varieties (Smith and Klett, 2013). For this reason, it is important to find the exact irrigation needs of specific species of ornamental grass, and test the limits to which the plant can survive within those needs. Providing viable irrigation percentages relative to ET_c is of great value and practical importance to industry personnel (Pittenger and Shaw, 2004). Current descriptions such as "high", "medium," and "low" water requirements offered by many nurseries and plant resources are subjective and often not researched. Furthermore, these descriptions do not translate well to Colorado's alkaline soils, intense winds, desiccating sun, and frequent drought regimes. It is very important to acquire ET_c of an ornamental grass crop which can ideally be translated into other related species.

While not as important to the horticulture industry, the concept of critical water potentials (Ψ_{crit}) is important to the field of horticultural research. Ψ_{crit} can be defined as the water potential value (or range) in which a plant will wilt and fail to recover. Ψ_{crit} values of specific species are often difficult to obtain. Not only will an understanding of Ψ_{crit} of ornamental grasses create deeper knowledge within the group, it will promote more research and appreciation for the subject.

Colorado has a semi-arid climate. The annual precipitation in Colorado averages 39.29 centimeters per year (US Department of Interior, 2012). A majority of precipitation is recieved in Colorado's high mountain regions, while the standard rainfall in most of the state ranges from 30.5-38 centimeters (McKee et al., 2009). The driest area of Colorado is the San Luis Valley, averaging 17.78 centimeters per year (McKee et al., 2009). Drought is extremely common in the state of Colorado. Three-month droughts within the state occur in 90 of 100 years at any given location. Ninety three percent of the time, at minimum of 5 percent of the state is experiencing drought between 3-24 months. In the long term, four droughts lasting four or more years have occurred in the past 100 years (McKee et al., 2009). A multi-year drought is standard across the state at increments of about twenty years (Whiting, 2012: 267). As previously mentioned, Colorado's population is steadily on the rise. With these fairly meager precipitation averages and an increasing population, water in Colorado is becoming more valuable and requires more insightful methods of conservation.

In the past 30 years there has been an introduction of new uses of water throughout the state including the support of endangered species, resort snowmaking, reservoir recreational use, and increased hydropower generation (McKee et al., 2009). With all of these new uses coupled with the standard uses (farmers, growing cities, municipalities, and landscaping) the supply of water is being diminished. It can be said that Colorado is far more vulnerable to drought today than under similar precipitation shortages in the past (Pielke et al., 2004).

Colorado receives new water supplies in only one way; precipitation (McKee et al., 2009). In common terms, the way water enters Colorado is from the sky. Colorado feeds various other states from its great river basins, but does not recieve water from any upstream source. Much like drought, precipitation comes in episodes. These episodes vary in both time and space, affecting certain regions more than others. In Colorado, over 50% of the state's water falls within 20% of days when precipitation occurs (McKee et al., 2009). This means that a majority of Colorado's water is dispersed within relatively small periods of time. Of that 50%, much of the rainfall is seasonal, creating even smaller windows of precipitation (McKee et al., 2009). This infrequency of steady precipitation events further compounds issues of drought within the state.

The water in Colorado can be split into five categories: Snowpack, streamflow, reservoir, soil moisture, and groundwater. Snowpack water is used for recreation and is a general "reserve" for water throughout the year. Streamflow and reservoir waters are used for recreation, habitat, irrigation, municipal water, and a majority is sent downstream to other states. This means that a majority of Colorado's water does not belong to Colorado (based on interstate contractual obligations). Soil moisture water is used for vegetation and agriculture, while ground water is used for irrigation and municipal water supplies (McKee et al., 2009). Due to intense regulations and deviation of water resources, these divisions of water further complicate water conservation practices across the state.

Of the many principles of water-wise growing, attention to irrigation efficiency has the greatest potential for water conservation for most residents (Whiting, 2012: 261). Ornamental grasses tend to go hand-in-hand with the principles of water-wise growing. They are generally regarded as "problem-free", an ideal plant for residential consumers (Janik and Whipkey, 2002). Along with this, quality public perception and awareness of the use of the ornamental grasses is beginning to increase. For this reason, the use of these grasses in residential and municipal settings is on the rise. However, our understanding of the water needs of widely planted ornamental grasses is almost nonexistent. Different plants require different amounts of water, and these amounts vary by genus or species. It is easy to say that grasses use less water, but quantifying the actual use of water is more difficult and of much greater importance. Reliable research-based data on ornamental landscape grasses is limited (Pittenger and Shaw, 2004). The most widely referenced publication of water use is the Water Use Classification of Landscape Plants, a publication not based on scientific field research (Pittenger and Shaw, 2004). A majority of research on ornamental grasses has generally focused on biofuel sources, livestock foraging, or grasses in their natural setting. This research lacks information about ornamental and aesthetic quality in the landscape.

As these beautiful plants are becoming more common in the landscape (and nursery production) and water is becoming scarcer, research on water requirements of grass species is necessary in order to get some scientific based data on these important plants. Little Bluestem (*Schizachyrium scoparium*), Switchgrass (*Panicum virgatum*), and Korean Feather Reed Grass (*Calamagrostis brachytricha*) are grasses which are widely planted, fairly vigorous, and adaptable to various conditions including heat and drought (Greenlee, 1992). All three species are notable for their size, beautiful fall color, and addition of year-round movement in the wind. The Encyclopedia of Ornamental Grasses (Greenlee, 1992) lists all three species as “Great grasses for every need”. Little Bluestem and Switchgrass are rated in the top ten “Grasses for hot, dry sites”, “Grass suitable for mass planting”, “Grasses with great movement”, and “Blue/Grey grasses” (Greenlee, 1992). In fact a variety of Switchgrass (*Panicum virgatum ‘Northwind’*) was recently declared the 2014 Perennial Plant of the Year by the National Garden Bureau and Perennial Plant Association (Blazek, 2014).

Previous studies by Sanderson and Reid have shown that Switchgrass is able to maintain quality photosynthetic rates above -3.3 MPa within the plant (Sanderson and Reed, 2000). One of the most important aspects of these three species is that they have the ability to recover and maintain aesthetic quality after being subject to reduced water treatment. Drought reduced photosynthetic rate by 90%, with full recovery upon reintroduction of water (Sanderson and Reed, 2000). In congruence with this, there were negligible differences between the control and water-stressed grasses in terms of dry weight, leaf area, tiller number, and number of buds produced. This highlights the massive extent to which ornamental grass species can recover and maintain ornamental quality even during high levels of stress. Switchgrass under drought treatments of -4.0 MPa (5% field capacity) had equal survival rates and the same proportion of tillers in flower as field capacity treatments (Barney et al., 2009). It was concluded that Switchgrass has the ability to properly grow and flower in low moisture conditions (Barney et al., 2009). Switchgrass has been shown to maintain these properties partially due to the ability to increase solute concentration in cells during periods of drought, but its rigid cell walls may create slightly less drought tolerance than other (more xeric) grasses (Knapp, 1984). Switchgrass is also an extremely vigorous and fast growing plant indicating that there may be a trade-off between drought tolerance and quick plant growth. Both Little Bluestem and Switchgrass are known to extract a majority of their water from the upper .5 meters of the soil profile. However, they adjust rooting and uptake depth during periods of drought (Eggemeyer et al., 2008). It is this type of plasticity that makes popular ornamental grass species crucial for scientific inquiry of water use.

In another study by Thetford et al. (2009), 25 ornamental grass species were evaluated over 3 years for drought tolerance under low-water conditions. Of the 25, six including Switchgrass were rated as excellent with quality aesthetics and limited mortality (Thetford et al., 2009). All three species (Little Bluestem, Switchgrass, and Korean Feather Reed Grass) are becoming more important to the horticultural industry, the limited ornamental research has been focused on Switchgrass. This is likely because it is easy to produce, fast growing, relatively large, long lived, and a common biofuel crop.

Although there is minimal research regarding ornamental plants and their relative response to drought treatments in the field, there are some studies which shed light on the subject. One experiment by Smith and Klett (2013) from Colorado State University assessed the impact of 0%, 25%, 50%, and 100% ET irrigation regimes on four shrub species; Redosier Dogwood (*Cornus sericea*), Smooth Hydrangea (*Hydrangea arborescens*), Diablo Ninebark (*Physocarpus opulifolius*), and Arctic Blue Willow (*Salix purpurea*) for a period of 2 years. It was concluded that survival rate for all species in all irrigation treatments was 100%. All shrub species (excluding Smooth Hydrangea) did thrive in conditions, and were considered acceptable for horticultural sale. Shrubs in the 100% ET were wider than lesser treatments, but it was determined that 25% ET is acceptable for proper aesthetic values of all species listed above (excluding Smooth Hydrangea). At the same time plants receiving 100% ET survived less time when drought was induced. This indicated that lower ET results in a plant adjusting growth characteristics to account for deficit irrigation. (Smith and Klett, 2013)

Another study by Prevete et al. (2000) out of Clemson University assessed the impact of 2, 4, and 6 day droughts to three species; Snowbank Boltonia (*Boltonia asteroids*), Eastern White Snakeroot (*Eupatorium rugosum*), and Three-Lobed Coneflower (*Rudbeckia triloba*). It was concluded that substrate moisture of deficit plants was less than half of the control. *E. rugosum* displayed more stress and experienced reduced spring growth relative to the other taxa. *B. asteroids* maintained comparable photosynthetic rates (and carbohydrate accumulation) throughout the experiment. All plant responses were attributed to differences in water use.

Prevete et al. (2000) concluded that differences in osmotic adjustment during drought stress influence the ability of drought tolerance. This further indicates that drought tolerance needs to be measured on a species-specific level (Prevete et al., 2000).

Another study at Colorado State University performed by Henson et al. evaluated the growth, visual quality, and stress of 17 annual bedding plants. Plants were watered for eight weeks at five levels of irrigation (0%, 25%, 50%, 75%, 100% ET). Certain species such as Merlin White Petunia (*Petunia x hybrida 'Merlin White'*) performed optimally at 0% ET, while other species such as Vodka Begonia (*Begonia carrier Hort 'Vodka'*) grew optimally at a minimum of 50%. It was concluded that 9 of the 17 species in the trial were fit for 25% or less ET (Henson et al., 2006).

Another study of interest was conducted by Yuan et al. (2011) at the Beijing Academy of Agriculture and Forestry Science. Korean Feather Reed Grass (*C. brachytricha*) water use was assessed at four levels of irrigation (25%, 50%, 75%, 100%) using a mini-lysimeter. It was shown that shoot width, tiller number, and dry weight were more affected as irrigation decreased from 75% to 50%. There was no difference between 75% and 100% treatments. Yuan et al. (2011) concluded that 75% ET is sufficient for *C. brachytricha*, and would save 33.1% of annual water use (Yuan et al., 2011). Weighable lysimeters are powerful tests for precisely determining fluctuations in precipitation, actual ET, and seepage (Schelle et al., 2012). They allow researchers to exert maximum physiological limitations on each plant, resulting in more precise drought tolerance effects. This lends some extra validity to the results from the Beijing Academy, a study using a weighing lysimeter methodology.

The research discussed above aids in planning landscapes based on water use requirements. Each study measured responses to drought stress using different methods, and each study used one of the standard methods to induce drought treatments including reduced irrigation, and reduced frequency of irrigation (Prevete et al., 2000; Henson et al., 2006). While these studies are a great start, more research needs to be performed investigating the massive collection of species which are commonly used in landscaping. Specifically, there have been few long term studies on the impact of irrigation on ornamental grasses. As previously discussed, a majority of irrigation requirements were determined in a nonscientific manner, and a great deal of research needs to be conducted to accurately update plant requirement information. This information has a great impact on the horticultural industry as it affects large growers and individual landscapers alike.

CHAPTER 1: WATER USE STUDY

Materials and Methods

The study was conducted at the Colorado State University Plant Environmental Research Center (PERC) located at 630 West Lake St, Fort Collins, CO 80523 (40°34'8" N, 105°5'24" W). The study was initiated by Jane Rozum in June of 2012 and plants were allowed to establish for one year prior to collection of data. Soil samples were collected in May of 2014 and tested at the CSU Soil Water and Plant Testing Laboratory. Soil was a Sandy Clay Loam with a sand:silt:clay ratio of 52%, 18%, 30%. A summarized soil test result can be found (Appendix 12a and 12b).

The study examined three species of ornamental grasses: *Panicum virgatum* 'Rotstrahlbusch' (Rotstrahlbusch Switchgrass) (Southern Weed Science Society, 1998), *Schizachyrium scoparium* 'Blaze' (Blaze Little Bluestem) (USDA NRCS National Plant Materials Center, 2015), and *Calamgrostis brachytricha* (Korean Feather Reed Grass) (Arctos Database, 2014). Plants of uniform size (3.79L, 1 gallon) were purchased at Little Valley Wholesale Nursery in Brighton, CO. A total of 20 individuals of each species were purchased to allow for five replicates to be placed in each of the four irrigation levels (see Appendix 5a) All grasses were planted according to Best Management Practices (GreenCO, 2008) , and no organic matter was amended to the backfill (Rozum). For a full listing of planting techniques and times see Rozum (2014).

The study consisted of four quadrants, each distinguished by the amount of supplemental irrigation relative to the evapotranspiration (ET) for a bluegrass turf reference crop (ET_o). The four treatments were 0%, 25%, 50%, and 100% ET_o. These treatments were based on the

GreenCO reference table which provides general guidelines of appropriate watering amounts based on ET_o (GreenCO, 2008). Each quadrant was of equal size (11m x 19.5m) and were separated by a 2.4 meter mulch path. Mulch was also spread to a depth of 2-3 inches to prevent weeds and more closely represent a residential environment. Quadrants were also separated by a polyethylene barrier buried to a depth of .91 meters to prevent leaching between treatments and from surrounding irrigated areas (Ounsworth, 2007). Diviner (Diviner 2000®, Sentek Environmental Technologies Pty Ltd., Stepney South Australia) access tubes were already in place from a previous shrub study (Smith, 2013), so plant placement was configured according to access tube location. Besides this minor constraint, plant layout was completely randomized, and a full plot design can be seen (Appendix 5a). Plants were spaced a minimum of 1.2 meters apart.

Water used in this experiment was non-potable from College Lake in Fort Collins, CO. Water was supplied to plants using a drip irrigation system (Rainbird ¼” tubing, 3.79 liter per hour emitters). Irrigation was automated by use of a programmable timer (Rainbird, ESP-MC, Azuza, CA). No fertilizer was supplied through the irrigation system.

Weeds were managed in two methods throughout the study; hand removal and backpack spraying. Any weeds within .35 meters of the plant was hand pulled to prevent possible herbicide damage. Weeds located outside of the .35 meter radius were sprayed with Ranger Pro (Glyphosate). Weed management was performed on a bi-weekly basis from May through September of 2014 and 2015.

Each grass received two 3.79L (1 gallon) per hour drip emitters, placed 180° apart to allow for optimal water distribution. Emitters were placed at ground level and were closely positioned to water the majority of plant biomass. In May 2014, ten emitter pairs in each quadrant were tested for flow accuracy. Average emitter efficiency (measured by collecting water over a specified period of time) was 97.8% in the 25% treatment, 97.2% in the 50% treatment, and 98.1% in the 100% treatment. ET_o was recorded using an atmometer (ETGage) with a Kentucky Bluegrass fabric filter, which has been proven to be comparable at estimating Bluegrass ET to Penman Monteith calculation methods. ET readings were taken on a daily basis. Precipitation events were recorded daily with an on-site rain gauge (Productive Alternatives, Fergus Falls, MN).

Irrigation treatments were calculated once a week using the following Irrigations Equation.

$$\text{Area} \times \text{Depth} = \text{Flow Rate} \times \text{Time}$$

(Equation 1)

Area is the area that is to be watered. Depth is the amount of water lost from the soil due to ET, subtracting precipitation. Flow rate is the rate which water is applied to the plants using drip emitters. Time is the amount of time to allow the irrigation system to run. Rearranging Equation 1 to solve for time:

$$Time = \frac{Area \times Depth}{Flow\ Rate}$$

(Equation 2)

This area was based on the estimated rooting area of the grasses. Soil cores at various radii were collected to determine the furthest point where roots were present from the plant. Rooting radii varied by individual plants, and due to limitations with the irrigation system, the value of Area used in Equation 1 was the rooting diameter of the smallest shrub. The smallest diameter was used in order to not over-irrigate the smaller plants. In 2014 the rooting radius was

20.35 cm, while in 2015 it had increased to 26.65 cm. These radii were comparable to canopy radii. Depth was determined by monitoring ET_o and precipitation on a daily basis. The 100% Depth was determined by recording ET_o and subtracting precipitation. The 50% Depth was determined by dividing ET_o by two, and subtracting precipitation. The 25% Depth was determined by dividing ET_o by four and subtracting precipitation. The 0% Depth was always 0, as this plot received no supplemental irrigation. Flow rate was a constant of 7.58L/hr (2gal/hr). ET_o is expressed in units of inches of water, so US volumetric measurements were used to calculate water treatments.

Irrigation events occurred on a weekly basis. Precipitation exceeding ET_o rates were accounted for by assuming the soil moisture deficit as zero, and all excess precipitation was lost due to runoff. Additionally, treatments were not applied for that particular week. Any extraordinary weather events (such a late snow or hail) were also recorded. The mean weekly amount of water applied per quadrant during the 2014 and 2015 seasons can be seen (Appendix 1a). 2014 and 2015 yearly and weekly water budgets and recommendations can be seen alongside this data (Appendix 1b and 1c respectively).

Determining treatment effects was one of the major objectives of this project, so various data parameters were collected. These parameters can be split into two categories; plant water use and stress, and ornamental quality. Plant water use and stress parameters included predawn water potential (Ψ), infrared canopy temperature (IR Temp), and soil moisture using Frequency Domain Reflectometry (FDR). Plant ornamental quality parameters included height, width, circumference, green-up date, flowering date, floral impact, landscape impact, overall habit, color, self-seeding, representative photographs, and dry weight.

Plant water use and stress parameters were collected on a bi-weekly basis. Water Potential (a measure of plant stress) was measured using a Pressure Chamber (PMS Instrument Company, Model 600, Albany, OR). Pressure chambers exert positive pressure on a leaf in order to exude sap from the petiole. The amount of pressure required to exude this sap is proportional to water potential. The more negative a Ψ reading is, the more stressed the plant is (PMS, 2014). Readings were taken between the hours of 11pm to 3am Mountain Standard Time (MST), six days after an irrigation event. A total of 8 data sets were collected in 2014, and 9 data sets in 2015. Two blades from each plant were taken from four plants of each species in each quadrant. Both readings were averaged together to represent a single water potential for each plant.

IR Temperature was another parameter used to measure plant stress. IR Temperature was measured using a handheld infrared thermometer (Omega OS534 Handheld IR Thermometer, Stanford, CT) with a beam diameter of 5 mm which is maintained up to 75 feet from target. Ambient temperature was recorded with an on-site thermometer, and was subtracted from IR Temperature readings to provide a measure of stress compared to ambient temperature. IR Thermometers read the temperature of a plant canopy at midday, where high temperatures are an indicator of plant stress. IR readings were taken at 12 noon, six days after an irrigation event. A total of 8 data sets were collected in 2014, and 9 data sets in 2015. Two temperatures from each plant were taken from every plant in each quadrant. Readings were averaged together to create a composite canopy temperature for each individual.

Soil moisture readings were taken using a Diviner 2000® (Sentek Environmental Technologies Pty, Ltd., Stepney, South Australia). The Diviner 2000® works based on the principles of Frequency Domain Reflectometry, in which sensors on an oscillating circuit detect changes in the dielectric constant of the soil over time. Smaller frequency measurements represent a lower soil volumetric water content within the soil (Sentek, 2009). Plants were located a minimum of 7cm from all Diviner access tubes, so ideally roots were utilizing water located directly next to the tubes. Access tubes reach a depth of 70 cm, and readings are taken at increments of 10 cm starting at 10cm. Measurements were recorded 72 hours after irrigation events.

Plant ornamental quality parameters were based on the National Ornamental Grass Trials criteria as established by Mary Meyer in Minnesota (Meyer, 2015). These measurements were believed to be the best and most representative of accurately determining the ornamental quality of a grass species. Green-up date was taken once at the beginning of the growing season when plants begin to exhibit new growth. Flowering date was monitored throughout the growing season and represents the date a plant first shows a single inflorescence.

Height, width, and circumference measurements were taken on a monthly basis. Five measurements were taken in 2014, and four were taken in 2015. Height was measured from the plant base to the tallest point on the stem, including inflorescences. Grasses were measured at their natural peak, which includes the lodging or “falling over” of any grass blades. Width was measured at the widest point of the grass, and does not include lodging. Circumference was measured 3-5 cm from the base of the plant.

The remainder of the ornamental characteristics were also taken on a monthly basis. Floral impact is a measure of bloom showiness, and is on a scale of 1 to 5. In this scale a measure of 1 shows minimal to no blooms, while 5 shows numerous spectacular and showy blooms. Landscape impact is a measure of the impact/showiness an individual plant could have on a landscape. This is on a scale of 1 to 5 with 1 representing a plant with minimal or no use in a landscape and 5 representing a plant with a remarkable overall presence in the landscape. This measure takes into account color, bloom, showiness, habit, damage, and lodging. Overall habit is a specific measure of the habit of a plant. Since grasses are known to lodge, overall habit is a rating of 1 to 5 with 1 being a completely prostrate plant and 5 being a completely upright plant. Color was determined using a RHS Mobile Colour Chart, which allows for coding and description of the plant color. Self-seeding was rated on a scale of 1-5 and was determined by counting the number of seedlings located around an individual. A representative photograph of each species in each quadrant was taken to provide a visual representation of plant growth. All photographs contain the same measuring device for scale. The visual quality values of each individual scale can be seen (Appendix 5b).

At the end of each growing season, plants were harvested to obtain dry mass measurements. Each plant was uniformly cut 7 cm from the base of the plant. Plant biomass was determined by placing in a drying oven (Despatch V-Series, Model #VRC2-26-1E) set at 70°C (158°F) for 48 hours followed by measuring total dry mass using Ohaus Adventurer Pro model AV2101C scale (Ohaus Corp., Pine Brook, NJ).

Evapotranspiration and the amount of water to apply was determined using an on-site Atmometer and rain gauge to represent bluegrass evapotranspiration. Atmometer readings of ET and rain gauge readings were taken daily. Readings were combined by week, and the inches of ambient rain were subtracted from the inches of ET in order to calculate total water to apply. The experiment applied irrigation by measuring bluegrass ET and applying multiple levels of deficit irrigation relative to that ET. This resulted in each treatment receiving a different amount of water each week. For example, if bluegrass ET was 1.8 inches for a week with no rain, the 100%, 50%, 25%, and 0% plants received 1.8, 0.9, 0.45, and 0.0 inches of additional moisture respectively via the irrigation system.

Data analysis was conducted using the SAS® software with SAS 9.4 for Windows (SAS Institute, Inc., 2014). The Mixed Procedure Package was used on all data to run an analysis of variance (ANOVA) and to compare the least square means. Data were considered statistically significant with a p-value less than or equal to 0.05.

Results and Discussion

The results of the water use study show slight differences between 2014 and 2015, but, on the whole, results from each year exhibit very similar trends. 2014 was characterized as having a moderate amount of rain spread throughout the growing season, while 2015 was characterized as an extremely wet spring with minimal rain during the growing season. Between June 8th and September 14th 2014 the experiment site accumulated 22.17 inches of bluegrass evapotranspiration and 5 inches of rain, while 2015 accumulated 20.56 inches of bluegrass evapotranspiration and 6.13 inches of rain (Appendix 1). The majority of the rain in 2015 occurred before July 15th. Despite the light and frequent rain in 2014 both seasons were well suited for performing experiments on plant water use and water stress. It is important to note that by the end of the experiment 4 of the 60 plants used in the trial had died. This includes one *Schizachyrium scoparium* 'Blaze' and one *Calamagrostis brachytricha* in the 0% treatment; one *Schizachyrium scoparium* 'Blaze' in the 50% treatment; and one *Calamagrostis brachytricha* in the 100% treatment. These deaths appear to be random and are not considered to be an effect of irrigation treatment. It is also important to note that the 2015 season was cut short due to the construction of a new football stadium, and the entire research plot was destroyed by construction activities in early October, 2015. At the end of the 2015 season all remaining plants in the 25%, 50%, and 100% treatments were of high enough quality to be acceptable for ornamental sale.

Water potential is the most important measurement for monitoring plant stress during this study. Since it is a direct and instantaneous measurement, it was used as the platform for plant stress in this study. Since each species has a different capacity to withstand stress, water potential readings were determined separately by species. In 2014, ten measurements of plant water potential were taken, while eight were taken in 2015. In 2014, five of the 10 observations indicated the 0% treatment species to be significantly more stressed while the 25%, 50%, and 100% treatments showed no differences (Figure 1a). It is interesting to note that on nine out of ten dates in 2014, *Panicum virgatum* 'Rotstrahlbusch' was significantly less stressed than both *Schizachyrium scoparium* 'Blaze' and *Calamagrostis brachytricha*. This corroborates the idea that *Panicum virgatum* 'Rotstrahlbusch' is an extremely drought tolerant species capable of maintaining low stress levels with minimal water inputs. In 2015 the same trend from 2014 held true for four of the eight measurement dates (Figure 1b). Of the remaining four dates, three showed no difference in stress between any of the treatments, while one date showed the 0% treatment most stressed, while the 25% treatment was next stressed, and the 50% and 100% were least stressed.

With half of the recorded dates showing the same trend of the 0% treatment being significantly more stressed while the remaining treatments are equally stressed. This indicates that plants grown with minimal irrigation (i.e. 25% ET) are equally unstressed as a plant receiving the full amount of irrigation (100% ET). There were only two out of 18 dates which indicated the 25% treatment being at an equal stress level of the 0%, a number which is feasibly tolerable, especially considering these plants returned to their less stressed levels after water was applied again.

In order to evaluate water potential on a yearly basis, all three species were combined to analyze stress by treatment. When combining all species over all dates, the 0% treatment was significantly more stressed that the other three treatments, while there was no difference between the 25%, 50%, and 100% treatments (Figure 1c). This general trend helps add strength to the argument made when evaluating water potentials on a date by date basis; that the 25% treatment is under the ideal level of stress under these growing conditions.

Allowing for these grasses to be irrigated with 25% bluegrass evapotranspiration allowed for 75% water savings as well as plants that were of equal health and stress levels as those irrigated with 100%. Later the aesthetics of these plants will be discussed, but the broad fact that these 25% ET grasses were equally stressed and of equal aesthetics to their 100% ET counterparts has massive implications of water savings for growers, municipalities, businesses, and homeowners alike (GreenCO, 2008). When comparing water potentials between 2014 and 2015, the average value of each treatment for the entire year was calculated. There was no difference between years for any of the three species.

Infrared canopy temperature (IR Temp) was used as a secondary technique to monitor plant stress. Since higher readings indicate more stressed plants (OmegaScope, 2010), IR Temp is an easy and noninvasive method to corroborate any information obtained from the more invasive water potential method. IR Temp readings were taken nine times in 2014, and eight times in 2015. During each measurement, the statistical trends between species were the same as when species were combined. For this reason, data between species were combined (Figure 1c) to create a more succinct description of the pattern present. This trend shows that the 0% treatment was significantly more stressed than the other three treatments, and there was no difference between the 25%, 50%, and 100% treatments. Of the remaining five dates (not in chronological order), three show the 0% treatment was still more stressed than all three other treatments, however the 25% treatment was more stressed than the 100% treatment. The final two dates showed no differences between groups (Figure 1d). This means that a higher percentage of measurements followed the same trend in 2015. This combined Infrared Thermometer data showed the same trend as 2014, in the 0% treatment being significantly more stressed than the other three treatments, with no difference between the 25%, 50%, and 100% treatments. On two of the three remaining dates the 0% treatment was the same as either the 25% or 50% treatment. The final date showed no differences between treatments (Figure 1e). Charts of individual species were not included, as each species matches Figure 1e precisely in terms of significant differences between treatments.

Two years of data suggests that the 0% supplemental water produced a significantly more stressed plant than all other treatments. More important to note is that on all of the dates tested, the 0% treatment almost always exhibited the highest stress. There were three dates which suggest that the 25% treatment was more stressed than the 50% or 100% treatments. However this was not a significant trend, indicating plants were still healthy. This information suggests that irrigating ornamental grasses to a minimum of 25% can dramatically reduce the stress of these plants while reducing water requirements by a factor of four. Infrared temperature is fairly variable and it can underestimate the intensity of stress if readings were taken on a cooler day with extra cloud cover. While all plants were treated the same, extremely stressed plants were more likely to mask their stress on a cool cloudy day as opposed to a hot sunny day. On the whole, these fluctuations from the general trend (25% treatment being equal to both the 50% and 100% treatment) did not precisely match up with water potentials, and therefore does not have as much scientific validity (Figures 1c-1e).

The year 2014 showed differences between the three species being evaluated for above ground biomass accumulation. *Panicum virgatum* 'Rotstrahlbusch' showed no difference between treatments, while both *Calamagrostis brachytricha* and *Schizachyrium scoparium* 'Blaze' in the 0% treatment accumulated significantly less biomass than all other treatments (Fig 2a). In 2015 all three species showed significantly less biomass accumulation in the 0% treatment compared to the 25%, 50%, and 100% treatments. There were no significant differences between the three higher treatments, except in *Calamagrostis brachytricha* where the 25% plants were significantly larger than their 50% and 100% counterparts (Fig 2b). This trend was likely present as *Calamagrostis brachytricha* is a cool season C_3 grass (discussed in Chapter 3 of this thesis). The smaller plants in the 0% treatment indicated that plants receiving exclusively precipitation will be smaller and accumulate significantly less biomass. These results also indicated that there was no difference between plant weight when they were irrigated at 25%, 50%, or 100%. This suggested that a 25% irrigation regiment could result in 75% water savings with the same, large sized plants. In the case of *Calamagrostis brachytricha,* data indicated it is possible that watering at 25% may actually result in larger plants. Further investigation would be required to validate such a conclusion.

Height, circumference, and width were analyzed in order to compare overall plant size between treatments. Height and circumference were the two most important measurements as they represent the most visually salient growth aspect in the eyes of producers, as well as consumers. In 2014, *Calamagrostis brachytricha* plant height was significantly lower in the 0% treatment, while the 25% and 100% treatment contained the tallest plants. *Panicum virgatum* 'Rotstrahlbusch' plants in the 0% treatment were significantly lower than the 100% treatment, and *Schizachyrium scoparium* 'Blaze' in the 0% treatment had less height than all other treatments (Figure 3a). In 2015 there were more differences between treatments. The one trend which held true in 2015 is the 0% treatment was always lowest in terms of height (Figure 3b). For each species, it is key to note that plants in the 25% treatment were always tallest. This result indicates that grasses receiving the 25% irrigation treatment grow as tall, if not taller, than their 50% and 100% irrigated counterparts.

Circumference is a significant measure of an ornamental grasses spread, as it is typically the first thing an observer notices. In 2014 *Calamagrostis brachytricha* and *Schizachyrium scoparium* ‘Blaze’ plants in the 0% treatment had circumferences which were smaller than 25%, 50%, and 100% treatments. There were no differences among the three larger treatments. *Panicum virgatum* ‘Rotstrahlbusch’ plants in the 0% and 25% treatment were significantly smaller than their 50% and 100% counterparts (Figure 3c). In 2015 all three species in the 0% treatment had significantly reduced circumference than their irrigated counterparts. Again, there were no differences between the 25%, 50%, and 100% treatments (Figure 3d). These results indicate that plants in the 25% treatment grew significantly larger in circumference than their unirrigated counterparts, and were comparable in size to their 50% and 100% counterparts.

While circumference is a more fitting measure of overall plant girth, ornamental grass width is a measure of a plant’s widest point. Since both growing seasons were relatively dry, there was minimal lodging of plant matter allowing for measurements to be true representations of maximum plant spread. In 2014 *Calamagrostis brachytricha* held true to the trend of 0% being significantly smaller than all other treatments. *Panicum virgatum* ‘Rotstrahlbusch’ had 0% plants at the lowest level, while 50% plants were at the highest level. *Schizachyrium scoparium* ‘Blaze’ plants in 0%, 25%, and 50% were all significantly smaller in width than the 100% treatment (Appendix 2a). In 2015 *Calamagrostis brachytricha* and *Panicum virgatum*

‘Rotstrahlbusch’ followed the same trends as 2014. *Schizachyrium scoparium* ‘Blaze’ plants in the 0% and 50% treatments were significantly smaller than those in the 25% and 100% treatments in 2015 (Appendix 2b). These results were not indicative of the 25% treatment being equivalent to the 50% and 100% treatments. However they do highlight the fact that the unirrigated 0% treatment was always in the lowest tier of overall plant growth. In order to get plants with a large breadth in a singular dimension, ornamental grasses must be irrigated to some extent.

When evaluating all growth measurement differences between 2014 and 2015, the average value for the entire season was calculated. In terms of plant height, there were no differences between years for any of the three species. When looking at circumference, there were three significant differences between 2014 and 2015. *Panicum virgatum* ‘Rotstrahlbusch’ plants in the 50% treatment as well as the 100% treatment showed differences in circumference between 2014 and 2015. Plants grown during the 2014 season were smaller than those grown in the 2015 season in both treatments. (Appendix 2c) *Schizachyrium scoparium* ‘Blaze’ plants in the 50% treatment showed differences in circumference between 2014 and 2015. Plants grown during the 2014 season were smaller than those grown in the 2015 season in both treatments (Appendix 2c). With both species, these results were likely due to the increased growth often exhibited after plants have established and adjusted to their environment and have no significant meaning. Since 2015 was the fourth year these grasses were in the ground, a significant increase in circumference is a typical observation amongst most ornamental grass species. Considering all measurements of plant growth, specifically height and circumference, it is clear that ornamental grasses utilizing a 25% irrigation regime resulted in plants that were of comparable size to their 50% and 100% irrigated counterparts. In most cases, plants grown with 25%

irrigation were the same size, and can even be larger than those receiving extra irrigation. It is also important to note that even if a 25% plant fell short of a plant receiving more irrigation, that plant was extremely large and still considered easily salable within the nursery trade. This study has indicated that watering at 25% ET results in equally large and healthy plants while reducing the watering requirements by a factor of four.

Visual rating data was used as an objective way to classify overall plant aesthetics and beauty. Representative treatment photographs of Panicum virgatum ‘Rotstrahlbusch’ can be seen (Figure 4e). The most salient aspect of ornamental grasses to consumers is typically the foliage color, which was coded and described using a Royal Horticultural Society Color Chart (Royal Horticultural Society, 2010). *Calamagrostis brachytricha* is classified as starting the season a standard green color (RHS 144A) and fades to a yellow-green (RHS 145A) in the fall. Plumes were large and extremely showy with a beautiful pink hue (RHS 68C). *Panicum virgatum* ‘Rotstrahlbusch’ begins the season a standard green color (RHS 137A) and deepens to a dark green (RHS 137D) throughout the season. When the cold weather comes in fall, the tips of the foliage turn a deep purple color (RHS 71A). Plumes were light and airy, but add a distinct purple (RHS N79C) “halo” to the grass. *Schizachyrium scoparium* ‘Blaze’ was the most variable in color, as quantified by its striking ‘Blaze’ effect. Plants start a sold blue-green (RHS N134D) and fade to shades of pink-violet (RHS N77D), purple (RHS 71A), and red (RHS 45A) as the season progresses. Plumes were a soft white color (RHS N155D) that stands out against the vibrant purple and blue background. Color and intensity did not vary between irrigation treatments.

In 2014, all *Calamagrostis brachytricha* plants averaged a green-up date of March 26, 2014. *Panicum virgatum* ‘Rotstrahlbusch’ and *Schizachyrium scoparium* ‘Blaze’ averaged April

30, 2014 and April 26, 2014 respectively. In 2015, all *Calamagrostis brachytricha* plants averaged a green-up date of March 24, 2015, while *Panicum virgatum* 'Rotstrahlbusch', and *Schizachyrium scoparium* 'Blaze' averaged May 11, 2015 and May 2, 2015 respectively. There was no difference between treatments for either year.

In 2014, all *Calamagrostis brachytricha* plants averaged a flowering date of August 14, 2014. *Panicum virgatum* 'Rotstrahlbusch' and *Schizachyrium scoparium* 'Blaze' averaged July 12, 2014 and August 11, 2014 for *Panicum virgatum* 'Rotstrahlbusch' and *Schizachyrium scoparium* 'Blaze' respectively. In 2015 all *Calamagrostis brachytricha* plants averaged a flowering date of August 16, 2015, while *Panicum virgatum* 'Rotstrahlbusch' and *Schizachyrium scoparium* 'Blaze' averaged July 16, 2015 and August 13, 2015 respectively. There was no difference between treatments during either year.

Floral impact was evaluated on a monthly basis to ensure a proper mapping of an extremely important ornamental feature to these grasses. In 2014 all three species of grasses in the 0% treatment had a significantly lower floral impact ratings than their 25% irrigated counterparts. The 0% treatment was not different than the 50% for *Panicum virgatum* 'Rotstrahlbusch' and for the 100% *Calamagrostis brachytricha* treatment (Figure 4a). In 2015, the relationships among the groups change, but the trend of all three species of grasses in the 0% treatment being significantly lower continued in floral impact ratings than their 25% irrigated counterparts. During this second year, the 25% treatment had the highest floral impact rating for all three species (Figure 4b).

Landscape impact was evaluated to observe how well a single plant is able to stand out on its own. In 2014 *Panicum virgatum* 'Rotstrahlbusch' and *Schizachyrium scoparium* 'Blaze' plants in the 0% treatment had significantly lower landscape impact ratings than all other treatments. *Calamagrostis brachytricha* showed that 25% irrigation provided a higher landscape impact rating than 0%, 50%, and 100% (Figure 4c). These results further corroborate the fact that this species tends to both perform at a higher level when supplied with smaller amounts of irrigation. In 2015, the 25%, 50%, and 100% treatments were in the top levels of landscape impact for all three species, while the 0% treatment was significantly lower (Figure 4d). These results corroborate the fact that plants receiving no additional irrigation will perform more poorly in terms of aesthetics, while plants receiving as little as 25% irrigation were comparable in aesthetical quality to their 50% and 100% counterparts.

A final important measure of visual impact is the measure of overall habit. As previously mentioned, there was not enough rainfall to produce noticeable lodging on the plants, so conclusions drawn from this information were likely based on the specific species as well as the irrigation treatment. In 2014, there were no differences between treatments, with the exception of the 50% *Panicum virgatum* 'Rotstrahlbusch' having a lower rating than all other treatments (Appendix 3a). In 2015, trends for *Schizachyrium scoparium* 'Blaze' and *Calamagrostis brachytricha* held the same as 2014, while both 25% and 50% *Panicum virgatum* 'Rotstrahlbusch' had lower ratings than their 0% and 100% counterparts (Appendix 3b). Since overall habit is a rating of how upright a plant is, it is easy to see how plants of shorter stature in the 0% treatment would be less likely to lodge. These results indicated that irrigation treatment had little to no effect on overall habit rating, and, in turn, the likelihood of a plant to lodge. It may play a slight factor when dealing with *Panicum virgatum* species. However that relationship is yet undetermined. There were no observed differences in self-seeding between treatments or species. All three species have been bred for minimal self-seeding, and there was little to no evidence of it during this experiment.

The visual rating data suggests that growing ornamental grasses using a 25% irrigation regime relative to bluegrass evapotranspiration is a completely feasible practice. This would result in growers obtaining healthy plants with major aesthetic appeal at a 25% irrigation level. Plants irrigated at 25% obtained high quality color of both foliage and blooms, and put on new season growth as well as floral appendages at equivalent times to their more irrigated counterparts. All plants in the 25% treatment for all three species rated in the highest tiers of floral impact, landscape impact, and overall habit ratings. Aesthetically, there was no difference between plants irrigated at 25%, 50%, and 100% ET. However, ornamental grasses grown in the 0% treatment received significantly lower ratings in terms of visual appearance. This supports the fact that these ornamental grasses do need some irrigation throughout the year. However, the amount of water actually required is significantly less than the current industry standard (Green CO, 2008). It is also important to note that a majority of these visual ratings were very high, further demonstrating that ornamental grasses can also be a beautiful addition to any home landscape.

Frequency Domain Reflectometry (FDR) was used in order to determine the depth at which ornamental grasses were accessing and utilizing the most water. Upon analyzing the information gathered, it was found that there was a difference between species, a difference between measurement dates, and a difference between depths. In order to extract the most detailed information, both year and species were combined in order to analyze by treatment and by depth. Since depth of water access is the most important information to obtain from the FDR research, combining species allows for generalizations about the three species used in this study. Figure 5a is an example in which both species and treatments were combined. Figures of this information, when split up into separate treatments, can be seen in Appendix 4a, 4b, 4c, 4d.

While initial results from Rozum (2014) indicated that ornamental grasses cease accessing significant portions of water at a depth of 40cm, this research indicates a significant drop off between 20cm and 30cm depths. This is extremely important, as this states that these grasses were accessing a majority of their water from the top 20-25cm of soil. This data is corroborated by evidence seen in figure 5b in which all plants in the 25% treatment were analyzed by depth over the course of the entire growing season in 2015. This research indicates that a majority of water was accessed between the 20cm and 30cm depths and maintain relatively constant over the course of the season. It is also noted that there is some access between the 30cm and 40cm depths. However, once roots reach the 40cm depth there is a significant increase in water content over the course of the entire season. Since this is a shallow depth, which is easily dried out by common earth elements (wind, erosion, etc.), it would seem more important to get a widely distributed irrigation pattern around these grasses as opposed to a deeply distributed pattern. This information, coupled with the previous conclusions of 25% ET being a feasible irrigation level, also implies that the grasses themselves may use less than 25% ET if grown in a controlled (greenhouse) setting.

The largest difference when combining (Figure 5a) and separating treatments (Appendix 4a -4d) were differences within the 100% treatment (Appendix 4d), as the 100% treatment appeared to use less water between the depths of 30-40cm, while using more again between the depths of 50-70cm. This is likely attributed to the *Panicum virgatum* ‘Rotstrahlbusch’ in this plot. It has been speculated that *Panicum virgatum* species grown with large amounts of water were able to access extremely deep into the soil in order to access “reserve” water (Barney, 2009). This data seems to support the fact that these *Panicum virgatum* ‘Rotstrahlbusch’ utilized the easy-to-access water at the soil surface, as well as the deep reserve water.

Conclusion

There is a single trend that has persisted through all levels of data analysis of this experiment; 25% deficit irrigation is feasible for ornamental grasses. Physiological measurements, physical plant measurements, and ratings of visual quality support the conclusion that supplying ornamental grasses with no supplemental irrigation will result in more stressed, smaller, and poorer performing plants. A second conclusion is that there were minimal differences between plants receiving 25%, 50%, or 100% ET. Ornamental grasses receiving 25% irrigation were equally stressed, develop an equal amount of above ground biomass, grow the same height and girth, and rate the same in visual/aesthetic quality as those receiving 50% and 100% irrigation. These were arguably the two most important things to consider when looking at plant quality due to a change in plant growth practices. Since all three species of grass were above average in the 25% treatment in nearly every situation, it is safe to recommend that growers, municipalities, homeowners, and anyone who manages ornamental grasses water these plants using a 25% bluegrass evapotranspiration regime.

In order to recommend this practice to growers, landscapers, homeowners, and municipalities, a yearly and weekly water budget was created from 2014 and 2015 Evapotranspiration data (Appendix 1.2, 1.3, 1.4, 1.5). In both seasons a system was created where all weeks which received precipitation were excluded to calculate the amount of water needed for application on weeks without rainfall. Since a week with precipitation typically equaled or slightly exceeded a 25% irrigation regiment, skipping irrigation events on these weeks was a common practice during the study. Visually, these were the data points where the 25% treatment lies below the 0 inch line (Appendix 1.4 and 1.5). Data from both years was added together in order to recommend a set annual amount of water to apply to ornamental grasses in the High Plains and Rocky Mountain Regio. This data was also then broken down on a weekly basis in order to inform growers, nurserypersons, and homeowners the exact amount of water to apply to their ornamental grasses on a weekly basis. The exact amount of water to apply on a weekly basis is 0.23 inches. Since this number is extremely close to a well-rounded number, we were recommending the application of 0.25 inches (a quarter inch) of water to each ornamental grass on weeks when there were no precipitation events (Table 1). It is not recommended that this is the exact amount for every year, as a year with significantly more drought will have higher evapotranspiration demands. That being said, the number of 0.25 is relatively sure to allow ornamental grasses to grow to their full potential while maintaining low levels of stress.

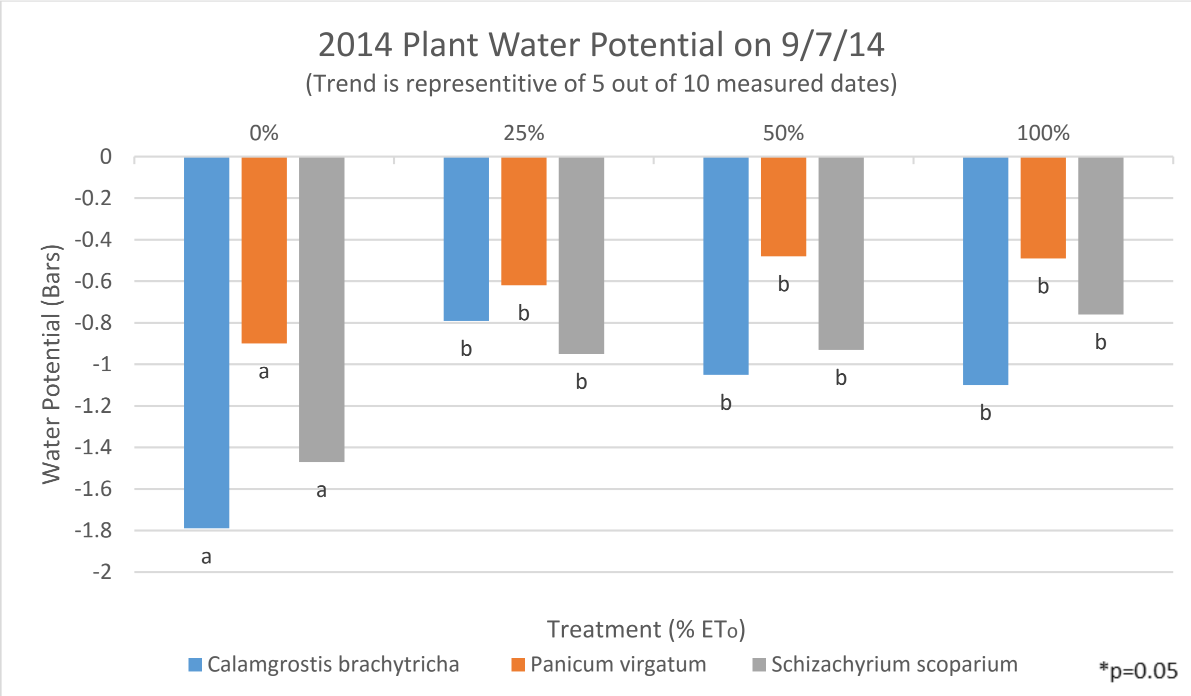


Figure 1a: Representative trend of 2014 water potential by treatment. All species in the 0% treatment were significantly more stressed while the 25%, 50%, and 100% treatments showed no differences. Different letters on bars denote significant differences.

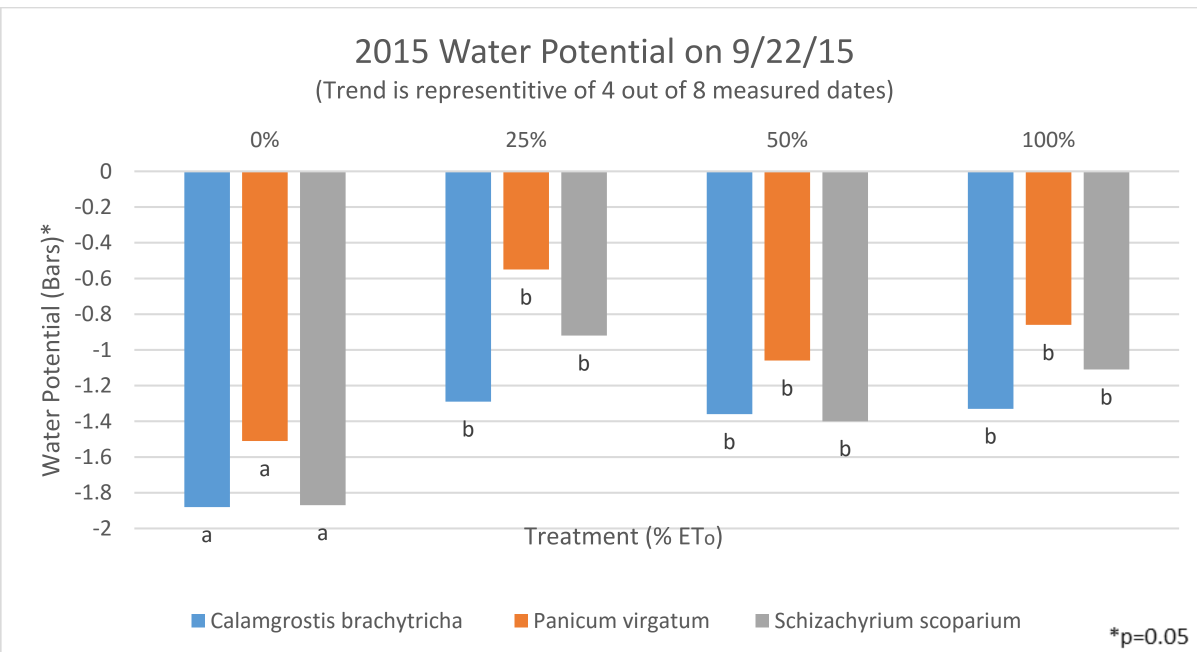


Figure 1b: Representative trend of 2015 water potential by treatment. All species in the 0% treatment were significantly more stressed while the 25%, 50%, and 100% treatments showed no differences. Different letters on bars denote significant differences.

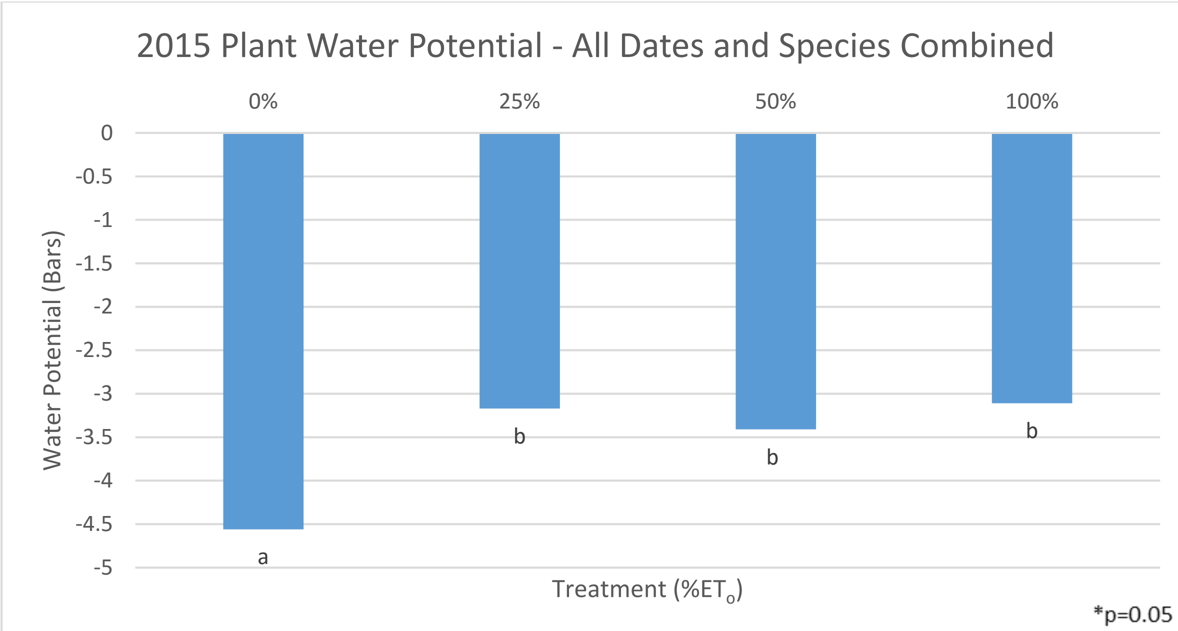


Figure 1c: 2015 water potentials when combining all dates and species to evaluate treatment effects. The 0% treatment was significantly more stressed that the other three treatments, while there was no difference between the 25%, 50%, and 100% treatments. Different letters on bars denote significant differences.

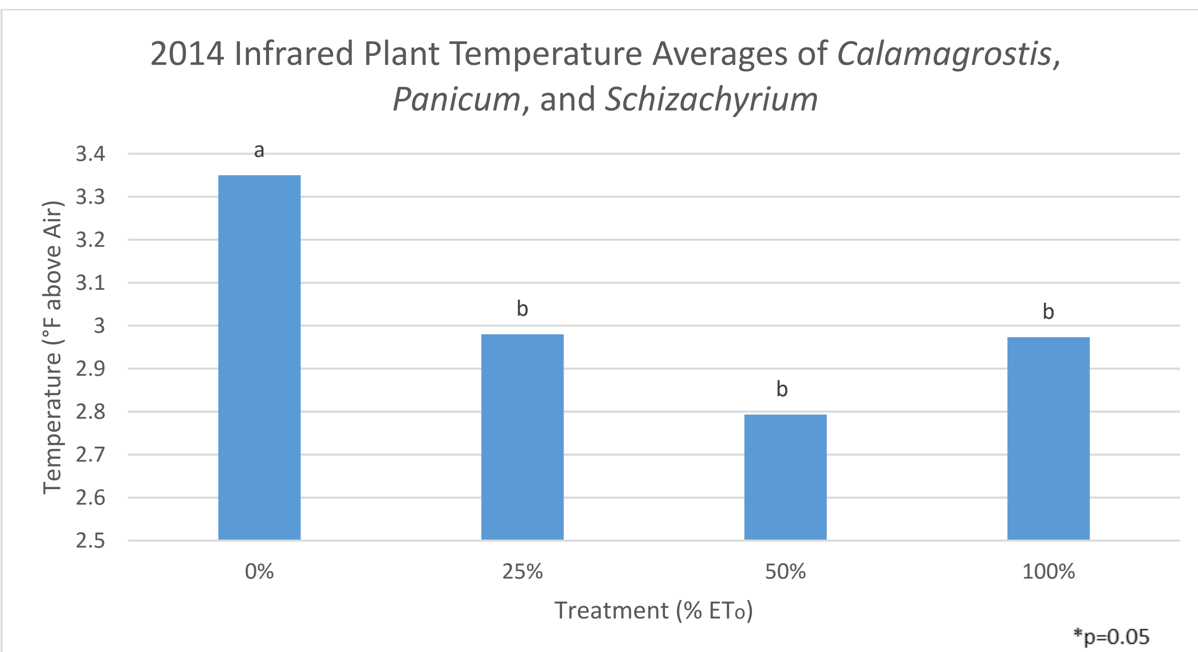


Figure 1d: Representative trend of 2014 Infrared Plant Temperature. The 0% treatment was significantly more stressed than the other three treatments, with no difference between the 25%, 50%, and 100% treatments. Different letters on bars denote significant differences.

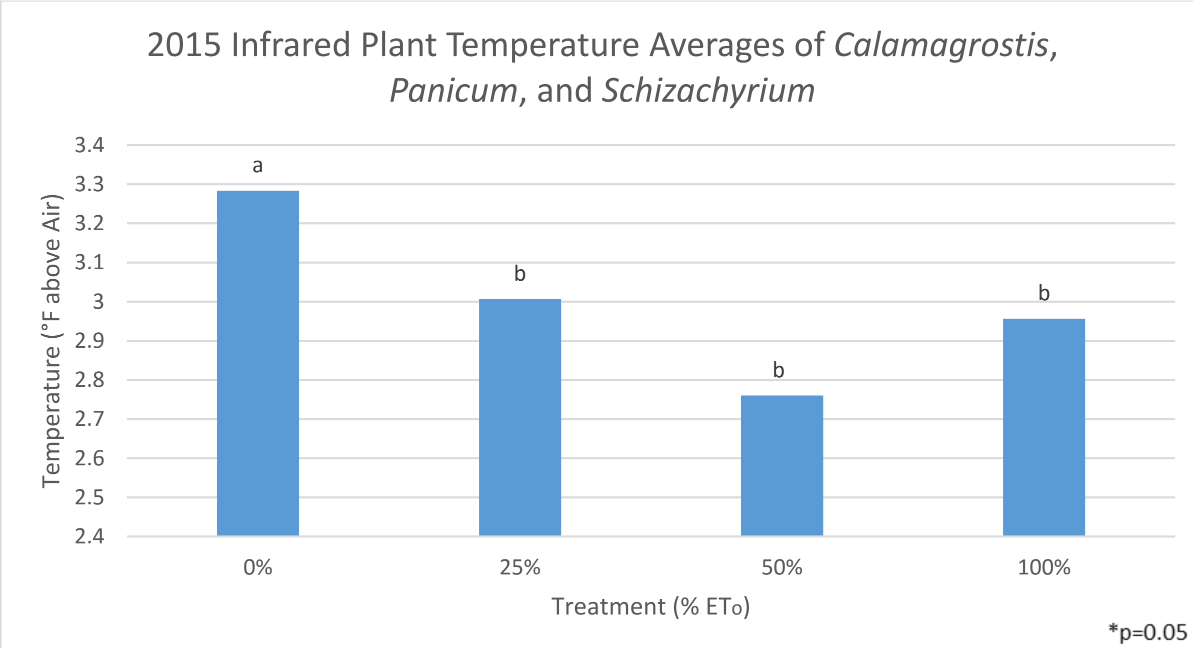


Figure 1e: Representative trend of 2015 Infrared Plant Temperature. The 0% treatment was significantly more stressed than the other three treatments, with no difference between the 25%, 50%, and 100% treatments. Different letters on bars denote significant differences.

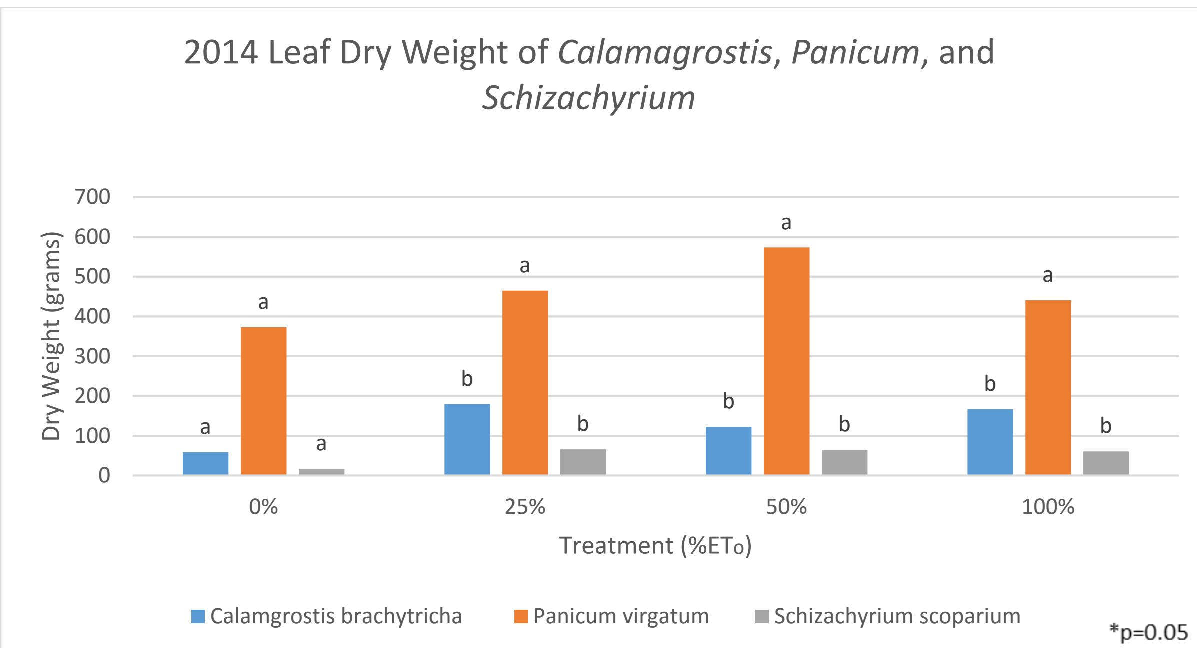


Figure 2a: 2014 leaf dry weight of all three species. *Panicum virgatum* 'Rotstrahlbusch' showed no difference between treatments, while both *Calamagrostis brachytricha* and *Schizachyrium scoparium* 'Blaze' in the 0% treatment accumulated significantly less biomass than all other treatments. Different letters on bars denote significant differences.

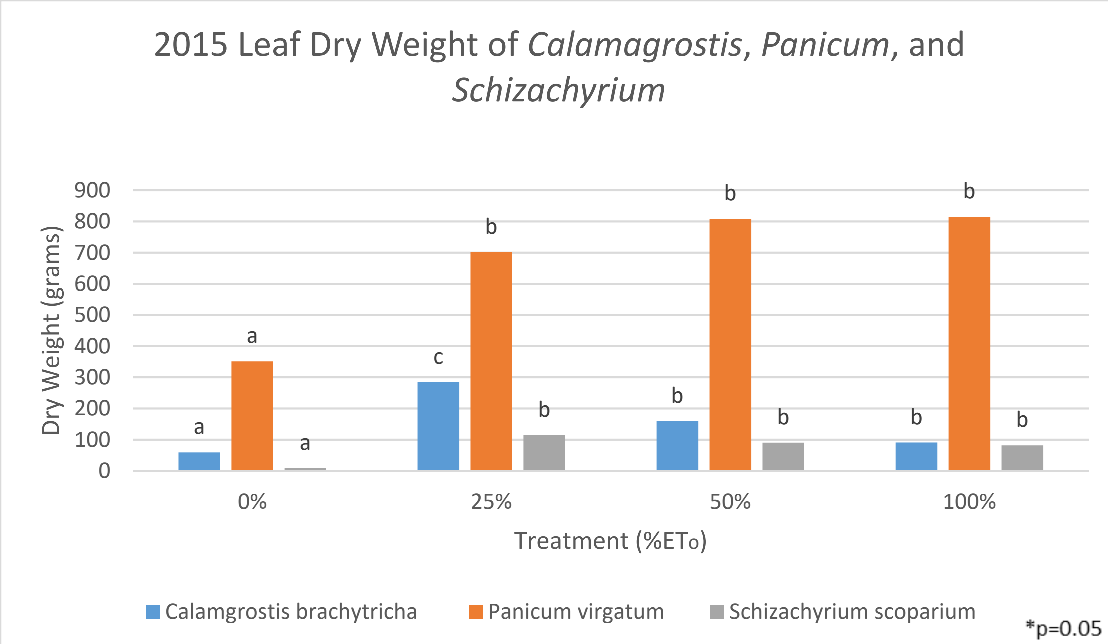


Figure 2b: 2015 leaf dry weight of all three species. All three species showed significantly less biomass accumulation in the 0% treatment compared to the 25%, 50%, and 100% treatments. There were no differences between the three higher treatments, except *Calamagrostis brachytricha* 25% plants were significantly larger than their 50% and 100% counterparts. Different letters on bars denote significant differences.

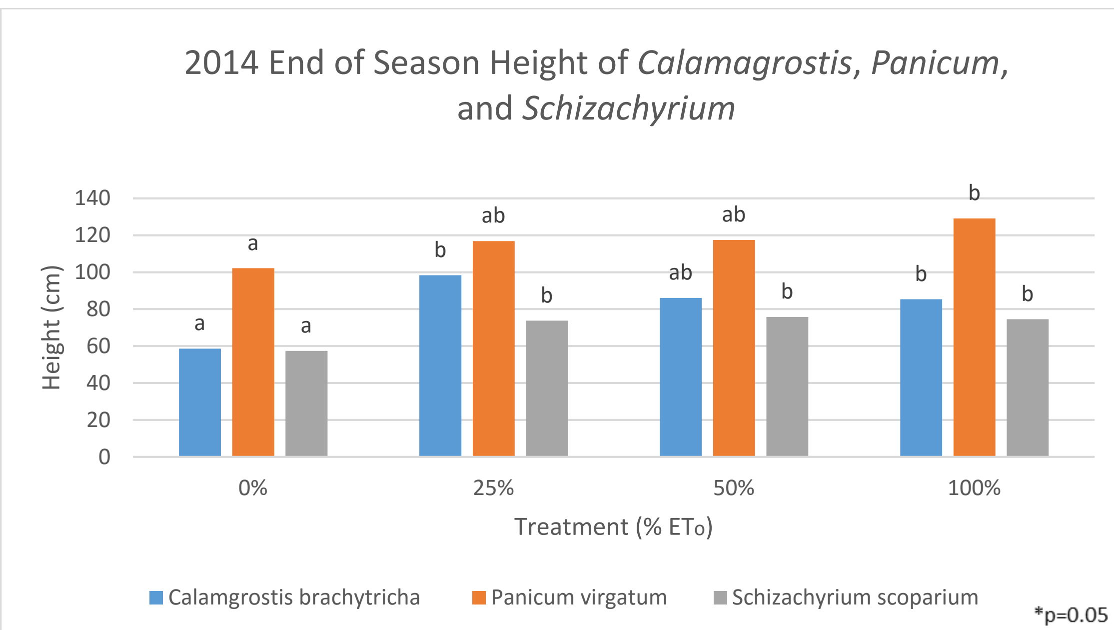


Figure 3a: 2014 end of season height of all three species. There is slight variation, but the 0% treatment was always in the smallest range of plant height. Different letters on bars denote significant differences.

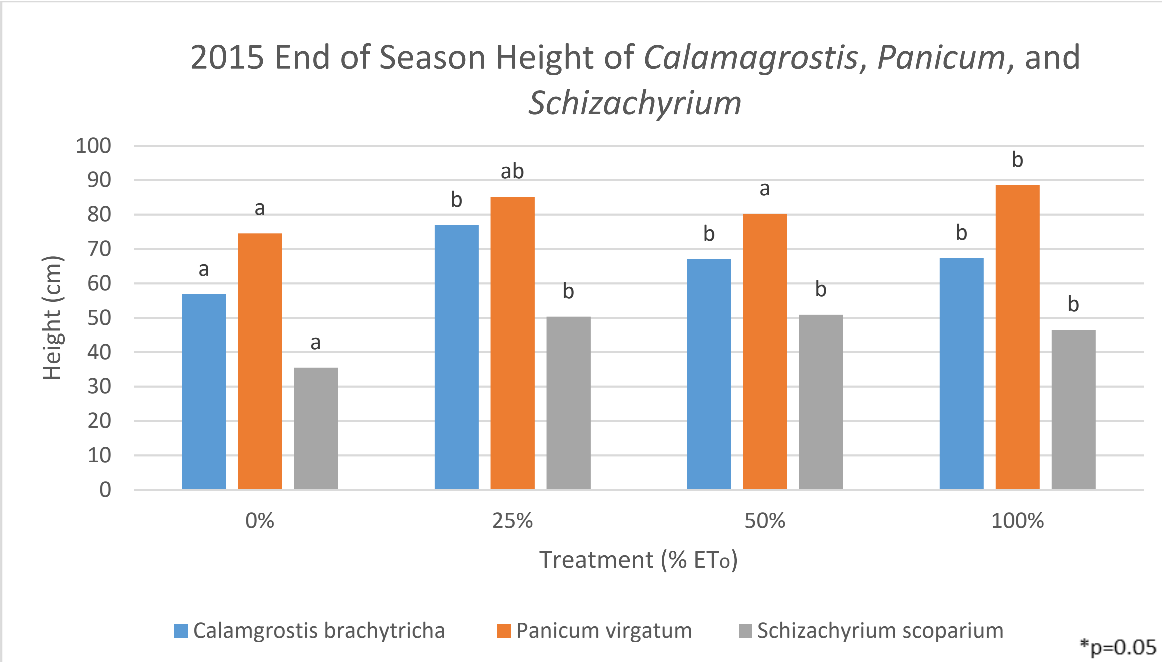


Figure 3b: 2015 end of season height of all three species. The trend still in place was the 0% treatment was shortest, while plants in the 25% treatment were tallest. Different letters on bars denote significant differences.

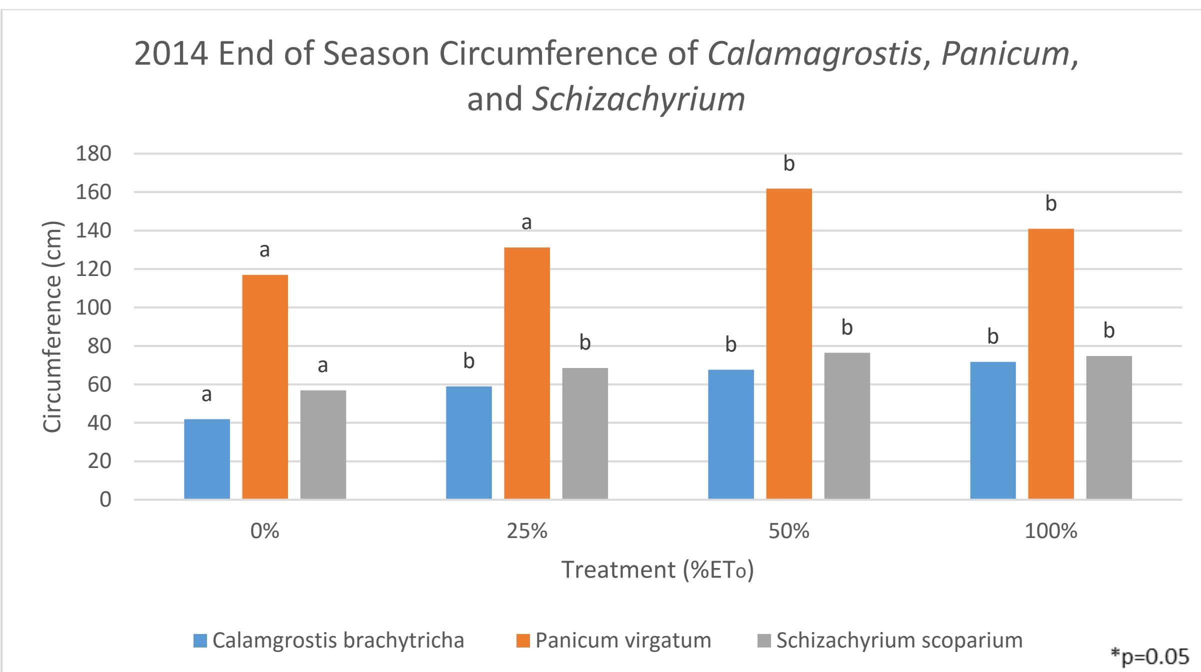


Figure 3c: 2014 end of season circumference of all three species. *Calamagrostis brachytricha* and *Schizachyrium scoparium* 'Blaze' circumferences in the 0% treatment were smaller than 25%, 50%, and 100% treatments. Different letters on bars denote significant differences.

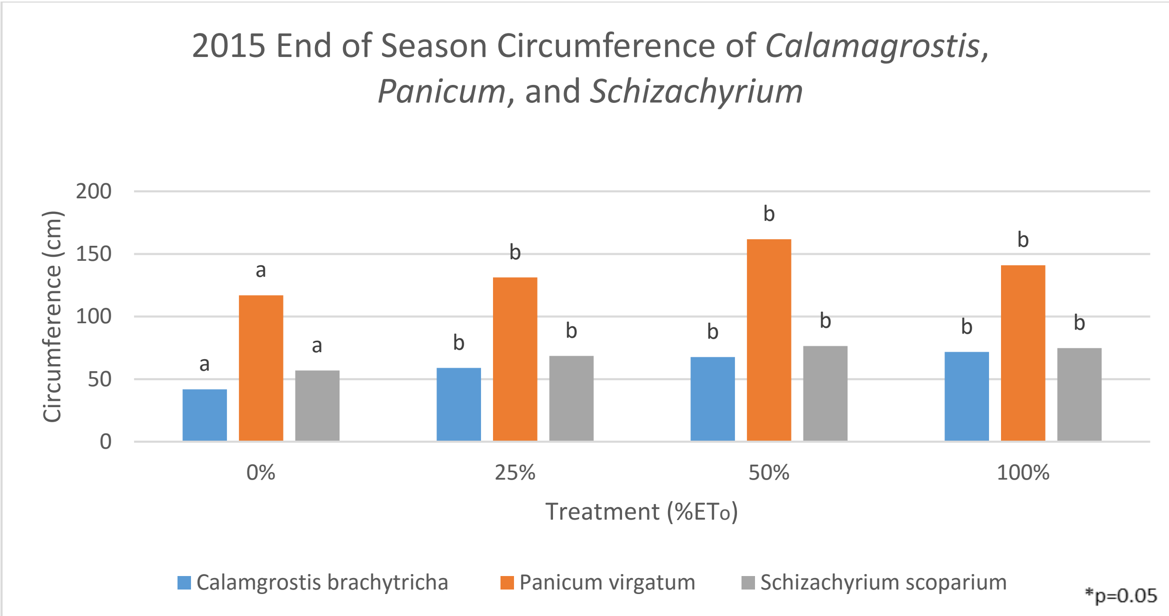


Figure 3d: 2014 end of season circumference of all three species. All three species in the 0% treatment had significantly reduced circumference than their irrigated counterparts, with no differences between the 25%, 50%, and 100% treatments. Different letters on bars denote significant differences.

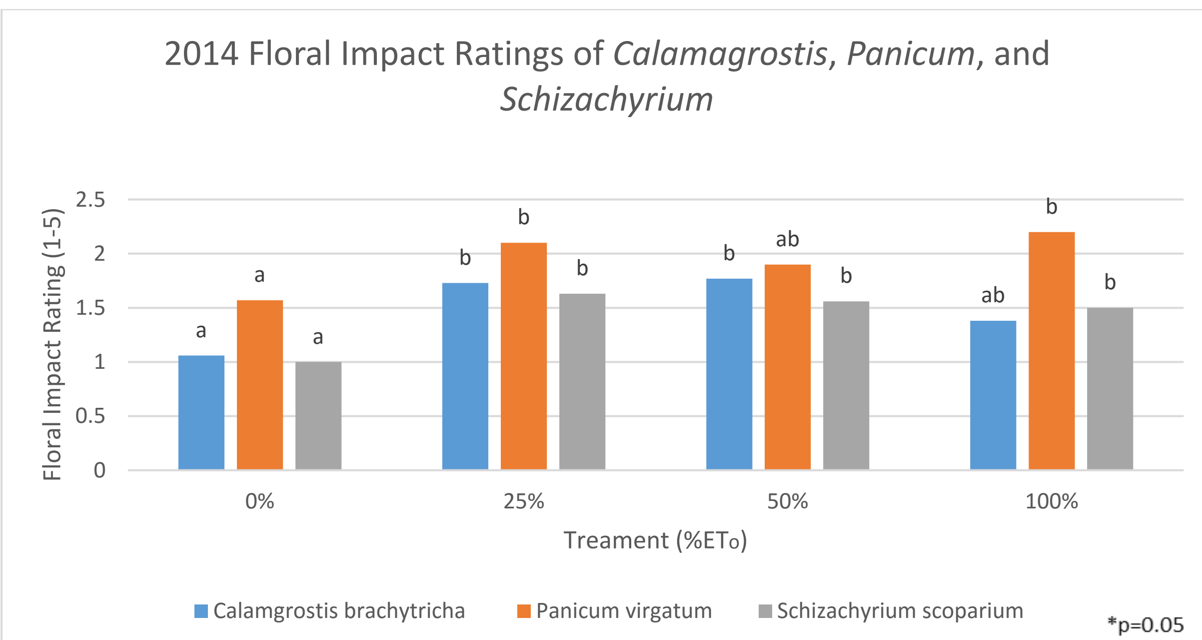


Figure 4a: 2014 floral impact ratings for all three species. All three species of grasses in the 0% treatment had a significantly lower floral impact ratings than their 25% irrigated counterparts. Different letters on bars denote significant differences.

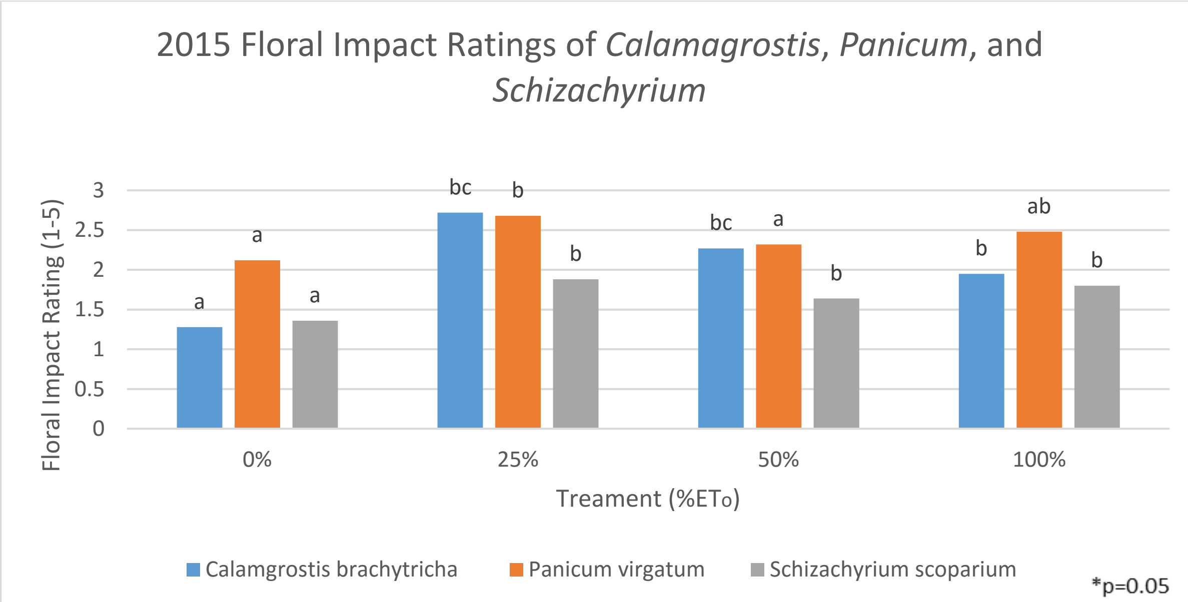


Figure 4b: 2015 floral impact ratings for all three species. The overall relationships between groups changed, but all three species in the 0% treatment had significantly lower ratings than their 25% irrigated counterparts. Different letters on bars denote significant differences.

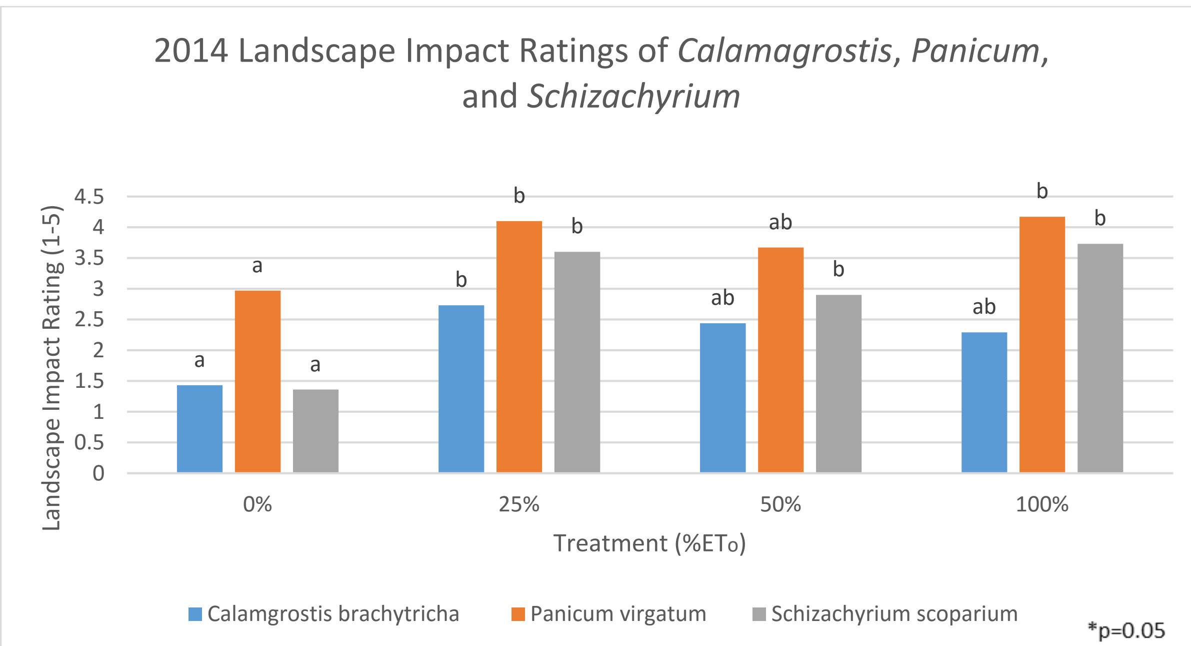


Figure 4c: 2014 landscape impact rating of all three species. *Panicum virgatum* 'Rotstrahlbusch' and *Schizachyrium scoparium* 'Blaze' plants in the 0% treatment had significantly lower landscape impact ratings than all other treatments. *Calamagrostis brachytricha* showed that 25% irrigation provided a higher landscape impact rating than 0%, 50%, and 100%. Different letters on bars denote significant differences.

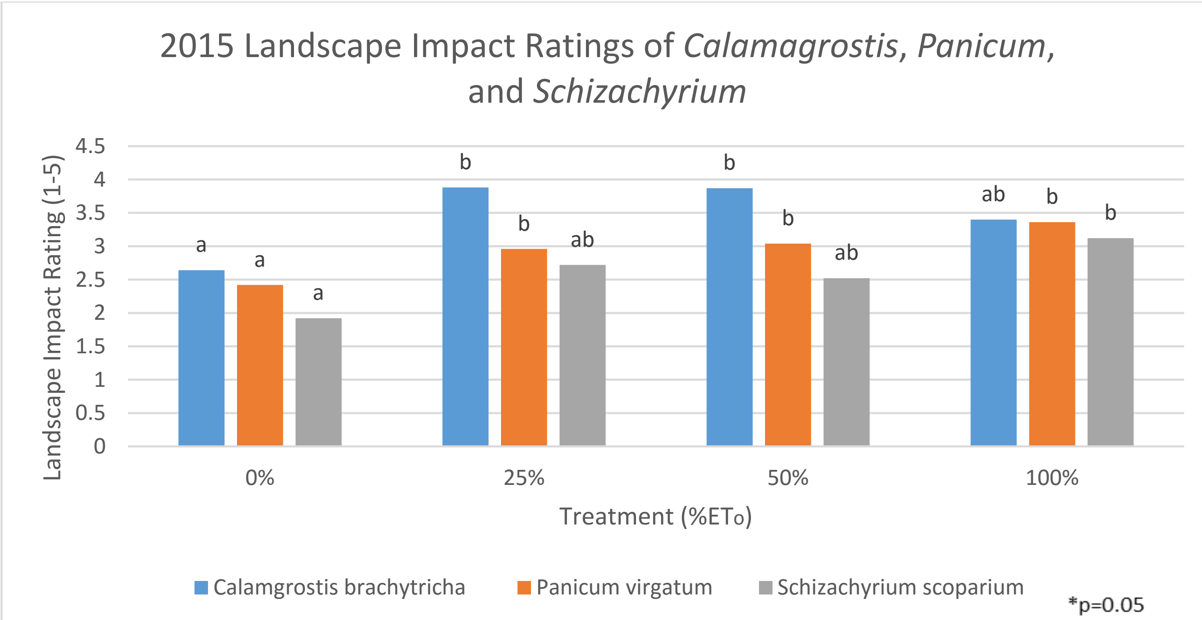


Figure 4d: 2015 landscape impact rating of all three species. 25%, 50%, and 100% treatments were in the top levels of landscape impact for all three species, while the 0% treatment is significantly lower. Different letters on bars denote significant differences.

Figure 4e: Photographs of *Panicum virgatum* 'Rotstrahlbusch' at the beginning of flowering season. Treatments clockwise from Top Left: 1) 0%, 2) 25%, 3) 50%, 4) 100%.

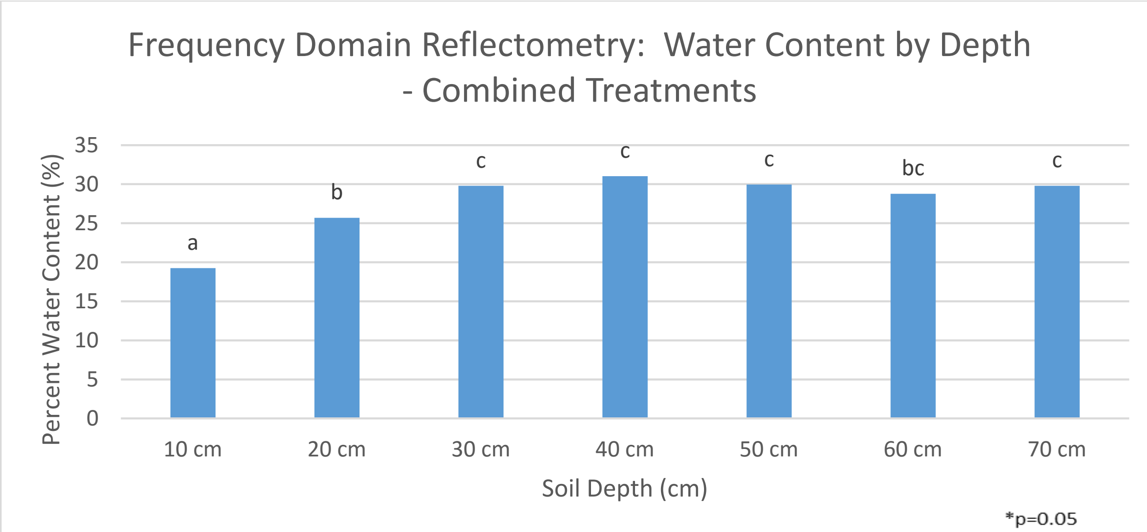


Figure 5a: FDR examining water content by depth within the soil profile. All species and treatments were combined. This research indicates a cessation of accessing significant portions of water between the depths of 20cm and 30cm. Different letters on bars denote significant differences.

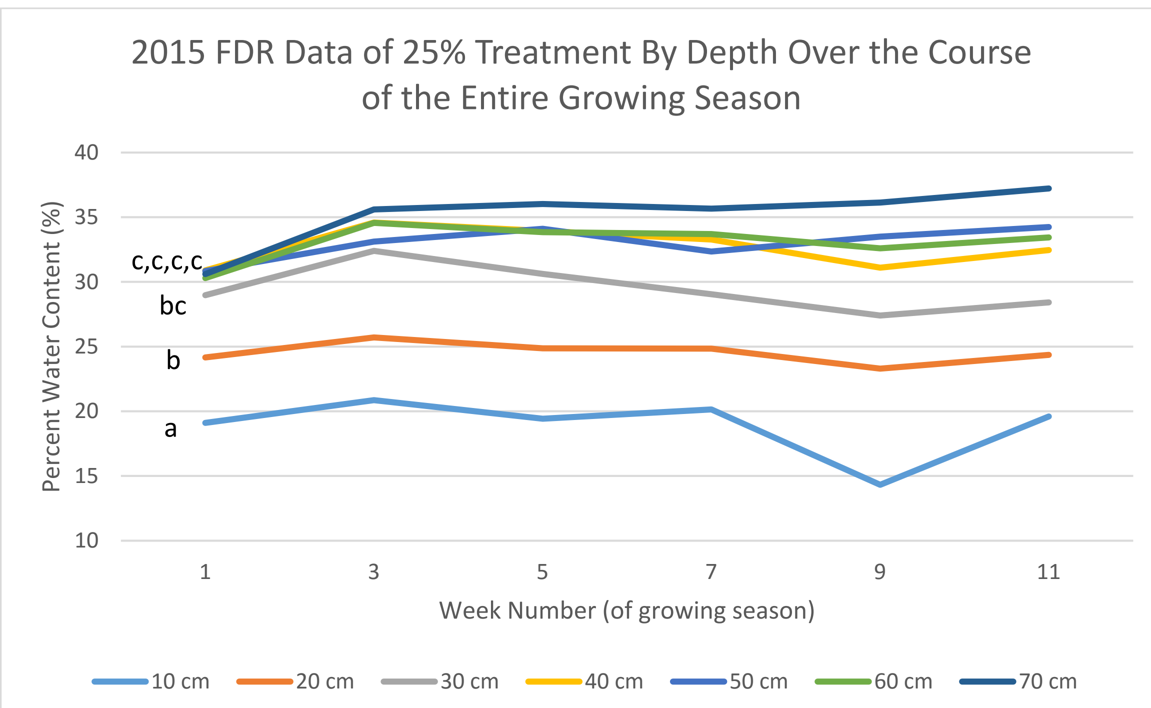


Figure 5b: FDR examining water content by depth over time. All species and treatments were combined. This research indicates a cessation of accessing significant portions of water between the depths of 20cm and 30cm, with some access taking place between 30cm and 40cm. Below 40cm plants cease accessing water. Different letters on lines denote significant differences.

Table 1: Average weekly recommendation when supplying ornamental grasses with a 25% ET_o irrigation regiment. The exact amount is 0.23 inches. However, this number has been rounded to 0.25 inches (one quarter of an inch) for ease of use by members of the horticulture industry. If precipitation exceeds 0.25 inches for the week, no irrigation is necessary. To practice in a practical grower situation, apply the modified Irrigator's Equation (Equation 2) using 0.25 as the value for depth.

2014 Weekly Irrigation Recommendation	0.20545 in.
2015 Weekly Irrigation Recommendation	0.25477 in.
2014/2015 Average Irrigation Recommendation	0.23011 in.
Weekly Irrigation Recommendation: Ornamental Grasses	**0.25 in.**

CHAPTER 2: MINI-LYSIMETER STUDY

Materials and Methods

The study was conducted at the Colorado State University Plant Environmental Research Center (PERC) located at 630 West Lake St, Fort Collins, CO 80523 (40°34’8” N, 105°5’24” W). The study was initiated in April, 2014 when plants were transferred into Greenhouse 4A at the Plant Environmental Research Center. Soil samples were collected in May of 2014 and sent to the CSU Soil Water and Plant Testing Laboratory. Soil was found to be a Sandy Clay Loam with a sand:silt:clay ratio of 57%, 15%, and 28% respectively. A summarized soil test result can be found (Appendix 12a and 12b).

This portion of the study examined a single species of ornamental grass used in the Water Use Study: *Schizachyrium scoparium* ‘Blaze’ (Blaze Little Bluestem) (USDA NRCS National Plant Materials Center, 2015). This variety was selected for its vigorous growth, its lack of extremely deep rooting, and its ornamental popularity. Plants of uniform size (3.79L, 1 gallon) were purchased at Little Valley Wholesale Nursery in Brighton, CO. A total of 25 individual plants were purchased to allow for eight replicates to be placed in each of the three irrigation levels. All grasses were planted into 56.78L (15 gallon) containers according to Best Management Practices. Field soil from a plot adjacent to the Water Use Study was used to fill all containers. Bulk density was determined using a custom Madera Soil Probe from the lab of Dr. Allan Andales, Soil and Crop Sciences, at Colorado State University in order to ensure uniformity (Equation 5). Plants were allowed to establish for 78 Days in in Greenhouse 4A at PERC. During establishment, pots were watered once until saturation was achieved, and allowed to drain to field capacity. After the initial watering, plants were watered as needed.

After establishment, plants were placed in the field in a pot-in-pot system on June 29, 2014. All 56.78L pots in the experiment were the same dimensions. Each plant was provided with 50 grams of Osmocote fertilizer (14-14-14), considered a light amount. There were three treatments in the lysimeter component, which each received supplemental irrigation based on calculated crop coefficient (K_c) and ET_o. The three treatments used were 25%, 50%, and 100% of actual plant ET (ET_s).

There were three treatment rows, each with 8 individuals per row (Appendix 6). There was also a fourth row of six pots filled with only field soil. Two soil pots received 25%, 50%, and 100% ET_s respectively and these pots were used as controls to monitor evaporation during dry down periods. Each plant was placed a minimum of 1.22 m away from any neighboring plant, and all plants were spaced at equal intervals. At the end of the study it was measured that no plant canopies extended beyond the diameter of the container.

In the 2015 growing season measurements were prematurely terminated before the end of the growing season to accommodate construction of a football stadium at CSU.

Water used in this experiment was non-potable from College Lake in Fort Collins, CO. Water was supplied to plants using a drip irrigation system (Rainbird ¼” tubing, 3.79 gallon per hour emitters). Irrigation was automated by use of a programmable timer (Rainbird, ESP-MC, Azuza, CA). No fertilizer was supplied through the irrigation system.

Weeds were managed in two methods throughout the study; hand removal and backpack spraying. Any weeds within pots were hand pulled to prevent possible herbicide damage. Weeds located outside of the pots were sprayed with Ranger Pro (Glyphosate). Weed management was performed on a bi-weekly basis from May-September of 2014 and 2015.

Due to irrigation constraints, grasses in the 100% treatment received four 3.79L (1 gallon) per hour drip emitters, placed 90° apart to allow for optimal water distribution. Grasses in the 50% treatment received two 3.79L (1 gallon) per hour drip emitters, placed 180° apart, and grasses in the 25% treatment received one 3.79L (1 gallon) per hour drip emitter. Emitters were placed at ground level and were closely positioned to the majority of plant biomass. In May 2014, 32 random emitter pairs were tested for flow accuracy. Average emitter efficiency was 98.1%. In May 2015, another 32 random emitter pairs were tested for flow accuracy with an average emitter efficiency of 98.4%. Due to an unusual warming in temperature in March, each plant received one winter watering treatment of 1.5 gallons on March 30, 2015 to ensure plant survival.

ET_o was recorded using an atmometer (ETGage), which has been proven to be comparable at estimating ET to Penman Monteith calculation methods. ET readings were taken on a daily basis. Precipitation events were recorded daily with an on-site rain gauge (Productive Alternatives, Fergus Falls, MN).

ET was quantified in units of mass (grams) of water lost, and these units were converted to inches using the irrigators equation (Equation 3). With a known value of ET (and therefore water) to apply and a known flow rate, irrigation treatments were calculated once a week using a simple and second modified Irrigators Equation.

$$Time = \frac{\text{Volume of Water Lost}}{\text{Flow Rate}}$$

(Equation 3)

Volume of Water Lost is the amount of water lost from the pot throughout the dry down. Flow rate is the rate which water is applied to the plants using drip emitters. Time is the amount of time to allow the irrigation system to run. The time was calculated for the 100% treatment, and all other treatments were applied for identical times with the differences being reduced with emitter numbers. Flow rate varied by treatment, ranging from 3.79L/hr in 25%, 7.58L/hr in 50%, and 15.16L/hr in 100%. For example, all plants in the 100% treatment received the average ET lost among 100% treatments, while the 50% treatment only received half of average ET lost in 50% treatments. ET_o is expressed in units of inches of water, so US volumetric measurements were used to calculate water treatments. Coupling Equation 2 with the Irrigations Equation from the Water Use Study allowed determination of irrigation using Equation 4a:

$$\mathrm{ETs} = \mathrm{Kc} \times \mathrm{ETo}$$

Equation 4a was rearranged to determine a Crop Coefficient (note crop coefficients are determined using the 100% ET rate of unstressed plants) using Equation 4b:

$$\mathrm{Kc} = \frac{\mathrm{ETs}}{\mathrm{ETo}}$$

Irrigation events occurred on a weekly basis. Precipitation exceeding ET_o rates were accounted for. If such an occasion occurred since the last watering event, soil moisture deficit was assumed to be zero, and that all excess precipitation was lost due to flow-through. This means that treatments were not applied for that particular week. Any extraordinary weather events (such a late snow or hail) were recorded. The mean weekly amount of water applied per quadrant during the 2014 and 2015 seasons can be seen in Appendix 7a and 7b.

Bulk Density (BD) of the soil was determined using Equation 5:

$$\mathrm{BD} = \frac{\text{Mass Dry Soil}}{\text{Volume Soil}}$$

Particle Density (PD) of the soil was determined using Equation 6:

$$\mathrm{PD} = \frac{\text{Mass of Solid}}{\text{Volume of Solid}}$$

Gravimetric Water Content (GWC) of the soil was determined using Equation 7:

$$\text{GWC} = \frac{\text{Mass of Water}}{\text{Mass dry soil}}$$

Volumetric Water Content (VWC) of the soil was determined using Equation 8:

$$\text{VWC} = \text{GWC x BD}$$

Determining treatment effects was one of the major objectives of this project, so various data parameters were collected in order to observe the impact of these effects. These parameters can be split into two categories: plant ET and stress, and ornamental quality. Plant ET and stress parameters consisted of predawn water potential (Ψ), plant weight, and daily photographs. Plant ornamental quality parameters included height, width, circumference, green-up date, flowering date, floral impact, landscape impact, overall habit, color, self-seeding, representative photographs, and dry weight (Meyer, 2015).

Four Dry down periods were conducted in both 2014 and 2015. Dry down periods consisted of providing each treatment with its relative level of irrigation, and then allowing plants to dry out to critical stress levels. Plants were provided with their respective level of irrigation, and allowed 24 hours of drainage to remove any deep percolation. Pots were then temporarily sealed with Seal-and-Peel caulking to eliminate drainage. During dry down periods, plants were provided with no supplemental irrigation, and ET and stress parameters were collected on a daily basis. In 2014, stress parameters were also collected daily in between dry downs. Water Potential was measured using a Pressure Chamber (PMS Instrument Company, Model 600, Albany, OR). Readings were taken between the hours of 11pm-3am Mountain Standard Time (MST). Two blades from each plant were taken from five plants in each treatment. Both readings were averaged together to create a single water potential for each individual.

In 2014, entire pot and plant weight was measured for six plants in each treatment including the control on a daily basis. This allowed for a measurement of weight loss, and in turn ET_s. Pots were weighed using a mini-lysimeter A-frame with attached S-beam load cell (Model ZB1-250-000, Sentran, LLC, Ontario, CA) and digital indicator (Model 250, Sentran, LLC, Ontario, CA). The moveable A-frame is shown in Appendix 8. Pots were weighed between the hours of 11pm-3am Mountain Standard Time (MST).

Accompanying Ψ and weight measurements were photographs of each plant. Photographs were taken from above to give an accurate view of canopy density. Photographs were taken on a daily or bi-daily basis between the hours of 12 noon-3pm.

Plant ornamental quality parameter were based on the National Ornamental Grass Trials by Mary Meyer in Minnesota (Meyer, 2015). These measurements were believed to be the best and most representative of accurately determining the ornamental quality of a grass species. Green-up date was taken once at the beginning of the growing season in 2015 when plants begin to exhibit new growth. Green-up date was not recorded in 2014 because plants were grown in a greenhouse prior to being placed at the research site. Flowering date was monitored throughout the growing season and represents the date a plant first shows a single inflorescence.

Height, width, and circumference measurements were taken on a monthly basis. Five measurements were taken in 2014, and four were taken in 2015. Initial measurements were taken immediately when plants were transferred into the field. Height was measured from the plant base to the tallest point on the stem, including inflorescences. Grasses were measured at their natural peak, which includes the lodging or “falling over” of any grass blades. Width was measured at the widest point of the grass, and did not include lodging. Circumference was measured 3-5 cm from the base of the plant.

The remainder of the ornamental characteristics were also taken on a monthly basis. Floral impact is a measure of bloom showiness, and is on a scale of 1 to 5. In this scale a measure of 1 shows minimal to no blooms, while 5 shows numerous spectacular and showy blooms. Landscape impact is a measure of the impact/showiness an individual plant could have on a landscape. This is on a scale of 1 to 5 with 1 representing a plant with minimal or no use in a landscape and 5 representing a plant with a remarkable overall presence in the landscape. This measure takes into account color, bloom, showiness, habit, damage, and lodging. Overall habit is a specific measure of the habit of a plant. Since grasses are known to lodge, overall habit is a rating of 1 to 5 with 5 being a completely prostrate plant and 1 being a completely upright plant. Color was determined using a RHS Mobile Colour Chart (RHS Large Colour Chart, 6th Ed.), which allows for coding and description of the plant color. Self-seeding was rated on a scale of 1 to 5 and was determined by counting the number of seedlings located around an individual. A representative photograph of each species in each quadrant was taken to provide a visual representation of plant growth. All photographs contain the same measuring device for scale. The visual quality values of each individual scale can be seen (Appendix 5b), while photographs of plants by treatment can be seen (Figure 8).

At the end of each growing season, plants were harvested to obtain dry weight measurements. Each plant was uniformly cut 7 cm from the base of the plant. Plant biomass was dried by placing each plant in a drying oven set at 70°C (158°F) for 48 hours and measuring the total dry weight using an Ohaus Adventurer Pro model AV2101C scale (Ohaus Corp., Pine Brook, NJ).

Evapotranspiration and the amount of water to apply was determined by measuring the actual ET used by each treatment. Values for that specific treatment were then divided by the amount of irrigation that treatment was receiving (for example the 50% treatment which used 1.6 inches via ET in a given period was given 0.8 inches when that dry down period was concluded). Since this was a dry down study, irrigation events were applied at the end of each dry down. If there were periods of time when ET was not directly measured using the lysimeter, the on-site atmometer was used as the baseline reading for each treatment. For a full list of the irrigation applied by week, see Appendix 7a and 7b.

One plant in the 100% treatment died over the 2014 to 2015 winter. Due to the death of plant G1, plant G7 was substituted into the G1 position for all 2015 measurements.

Data analysis was conducted using the SAS® software with SAS 9.4 for Windows (SAS Institute, Inc., 2014). The Mixed Procedure was used on all data to run an analysis of variance (ANOVA) and to compare the least square means. Data were considered statistically significant with a p-value less than or equal to 0.05.

Results and Discussion

Evapotranspiration was totaled over the period of a dry down. The amount of water used by each plant in each treatment was used to determine if applying less water to a plant would actually make it use less water in the long run. During the first two dry downs of both 2014 and 2015, there was no difference in evapotranspiration between treatments (Figure 6a-6d). It is important to note for data analysis that each dry down period lasted a different length of time. In 2014, the first two dry downs took place between July 20 to 30, and August 3 to 16. In 2015, the first two dry downs took place between July 12 to 21 and July 29 to August 3. This indicates that as the plants were growing their initial foliage earlier in the season and increasing in both height and width, they used the same amount of water regardless of treatment. The more interesting data comes during the third and fourth dry downs in both seasons. During the third dry down in both 2014 and 2015, the 25% and 50% treatments used less water than the 100% treatment (Figures 6e-6h). It is important to note for data analysis that each dry down period lasted a different length of time. During the fourth dry down in both 2014 and 2015, the 25% treatment used significantly less water than the 50% and 100% treatments. This confirms the hypothesis that during each season, as the plants gain circumference, begin flowering, and acquire fall color, the plants receiving deficit irrigation were using less water. This information coupled with visual rating measurements, which do not differ between treatments, suggests that the plants in the 25% treatment can adapt to use less water while still obtaining their beautiful ornamental characteristics and stature. In 2014, the 25% treatment used 60% of the water used by the 100% treatment, and in 2015, it used 53% of the water used by the 100% treatment. This means that within a few months, *Schizachyrium scoparium* 'Blaze' is capable of adapting to a lower water regiment, and effectively budget the water for proper survival. It is also important to note that during 2015, there were never more than three days between dry downs, indicating that these plants were under slightly more stress than was intended for this study and still performed satisfactory. Since these plants were in pots and likely to dry out slightly faster than those in the ground, it would seem that these results were likely to transfer to other ornamental grass species in a non-potted system.

To compare evapotranspiration from year to year, the total amount of ET used during each dry down was compared between treatments. Since the number of days in each dry down always exceeded seven days, the differences in time periods was not considered significant. All three treatments during each dry down were considered equivalent, exclusive of four situations in which there was a difference in ET between years. During the second dry down of each year, the

25% and 50% treatments each used less water in 2014 (Figure 6e). During the third dry down, the 50% treatment used less water in 2015. In the fourth dry down, the 50% treatment used less water in 2014. In three of these four cases, the plants used less water in 2014. One hypothesis is that as these plants grow larger, they were using more water regardless of treatment. However this is unsubstantiated just based on these four slight deviations. A crop coefficient of 0.69 was determined for the 100% treatment.

Coupled with the concept of different treatments using different amounts of water is the stress that these treatments put on the plant. In the Water Use Study, plants were watered every seven days and never exposed to a period of drought throughout the summer. However, in the Lysimeter Study, these plants were often left for periods up to two weeks without water during the (historically) hottest time of the year (Colorado Climate Center, 2010). For this reason it is extremely important to understand how well these plants perform physiologically under deficit irrigation when they were consistently exposed to prolonged periods of drought. During dry down 1 in 2014, there was no difference between the three treatments from day 1 to 5, and from days 6 to 11, the 25% treatment was more stressed than the other two treatments (Figure 7a). During dry down 2 in 2014, there was no difference between any treatments on any day. During dry down 3 in 2014, the 25% and 50% treatments were more stressed than the 100% treatment for all seven days of the dry down. The final dry down in 2014 resulted in no difference between treatments for the first four days, while on days 5 to 11, the 25% treatment was dramatically more stressed than the other two treatments. The one commonality to each dry down is that the 25% treatment was always significantly more stressed once the plants reached 5 to 7 days without water. This information from 2014 had significant implications as to the health of the plants receiving 25% irrigation, despite their quality visual appearance.

In 2015, there were no differences between any of the treatments during any dates of the first two dry downs (Figure 7b). This could be due to the fact that the extremely heavy clay soil was filled to field capacity by heavy rains in the early summer. During dry down three, when different treatments were beginning to use different amounts of water, the 25% treatment started more stressed than 50%, and the 50% started more stressed than 100%. Day two results in 25% and 50% being more stressed than 100%. For the next six days, the treatments tradeoff between these two trends. The final dry down of 2015 showed the 25% treatment being more stressed than 50% and 100% by the third day. From days 6 to 10 all the treatments were under significantly different levels of stress, with 25% being the most stressed and 100% being the least. The second two dry downs of 2015 supported conclusions of all dry downs from 2014. The final dry down of 2015 begins to suggest that even the plants receiving 50% irrigation were more physiologically stressed than their fully irrigated counterparts. (Two depictions of the differences between treatments on two specific days in both 2014 and 2015 can be seen in Appendix 11a and 11b).

The most important conclusion comes from coupling the concepts of evapotranspiration and water potentials. The evapotranspiration data generated indicates that as the growing season progresses, plants receiving less water were using less water and they were also becoming significantly more stressed. Additionally, the longer a period of drought they experience, the more dramatic these levels of stress can rise. This means that if these plants receive deficit irrigation and were subjected to a period of extreme drought, it is possible they may not be able to survive, while their well-watered counterparts may survive. This information suggests that watering *Schizachyrium scoparium* ‘Blaze’ at 25% irrigation is likely possible. However, irrigation events may need to be more frequent to compensate for the additional stress. When comparing water potentials between 2014 and 2015, the average value of each treatment for each dry down period was calculated. There was no difference between years for any of the three treatments during each of the four dry down periods. Measurement of above ground biomass yielded no statistical difference between treatments for either 2014 or 2015.

Measurements of height, width, and circumference were taken in the same manner as in the Water Use Study. Five readings of each measurement were taken in 2014, and four readings were taken in 2015. For all nine readings there were no differences between treatments for height, circumference, or width (Appendix 9a and 9b). Visually, plants in each treatment looked very similar (Figure 8). There were no significant differences in height, or width between 2014 and 2015. Circumference yielded differences between 2014 and 2015 in all three treatments (Appendix 9c). This effect is likely due to the better establishment of the plants in spring 2015. In 2014, plants were still establishing in their new environment after being transferred from the greenhouse. In 2015 it is likely that plants were established, and therefore were able to increase significantly in girth.

Measurements of floral impact, landscape impact, overall habit, and foliage color were taken in the same manner as in Chapter 1: Water Use Study. Five readings of each measurement were taken in 2014, and four readings in 2015. For all nine readings, there was found to be no difference between treatments for floral impact, landscape impact, and overall habit (Appendix 10a and 10b). The first date of reading in 2014 was the only exception, as the 25% treatment received a lower landscape impact rating than the 100% treatment. This effect was likely due to initial planting size. Visually, plants in each treatment looked very similar (Figure 8). Measurements of foliage color were consistent with that of the Water Use Study for *Schizachyrium scoparium* ‘Blaze’. As a visual observation, plants experiencing higher water potentials in the heat of summer produced larger blooms more frequently and contained a slightly less vibrant foliage color.

Conclusion

The most interesting aspects of the Lysimeter Study are concluded when combined with the Water Use Study. As previously stated, the ET readings state that as the season progresses, plants receiving less water were using less water. However, as these plants were using less water they were becoming significantly more stressed. When exposed to long periods of drought, the plants in the 25% treatment reached extremely low water potentials, even compared to a standard extreme water potential (Kramer and Boyer, 1995). Typically, the longer the drought lasted, the more dramatic these spikes in stress were in the deficit irrigation treatments. The key to understanding how to make the concept of 25% irrigation work comes from the Water Use Study. In this study there were no issues with plant growth, visual appeal, or overall stress when plants were watered on a strict regimen of once a week. This means that as long as these plants were not subjected to periods of drought, a 25% bluegrass evapotranspiration regime is feasible for ornamental grass production and maintenance. The major practical industry implications were that a 75% water savings is possible when growing ornamental grasses. However, if these plants were planted in an area with water restrictions, where it may be impossible to access water during a drought, a 50% or 75% irrigation regime may be a better option. Additional information from the Frequency Domain Reflectometry indicates these grasses tend to access water in the very top 20-25cm of the soil profile. For this reason it may be more practical to water at 25% ET at more frequent intervals in order to ensure the grasses were accessing water from a preferred and shallower location. With the information coupled from these two studies, a

25% bluegrass evapotranspiration regime should be adopted for ornamental grasses, as long as they are not frequently exposed to periods of drought lasting longer than a week.

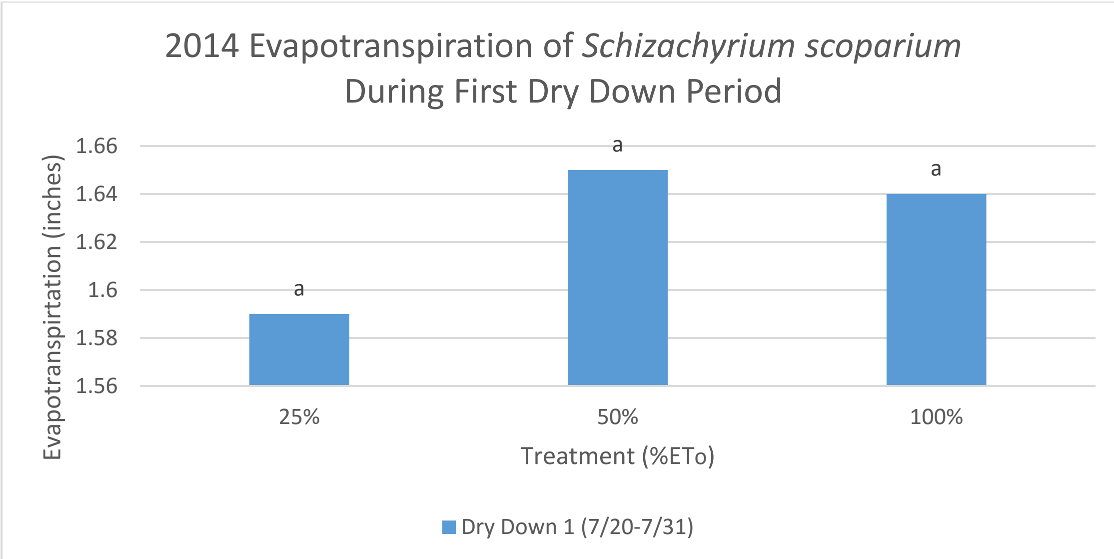


Figure 6a: 2014 evapotranspiration during the first down period. There was no difference in evapotranspiration between treatments. Different letters on bars denote significant differences.

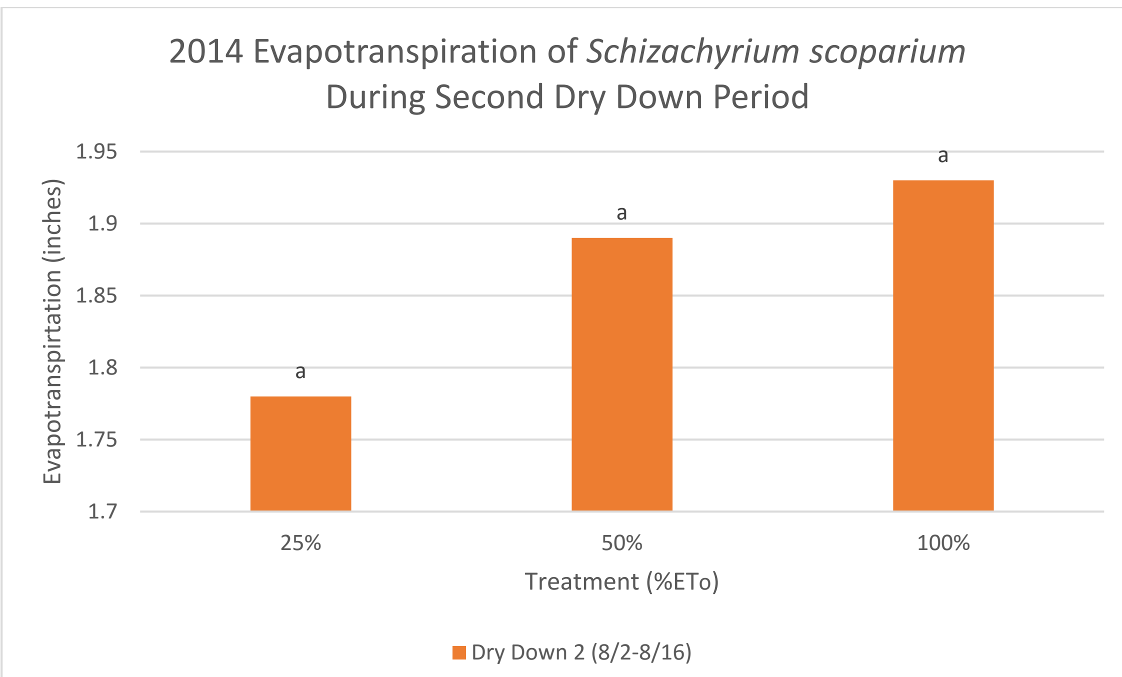


Figure 6b: 2014 evapotranspiration during the second dry down period. There was no difference in evapotranspiration between treatments. Different letters on bars denote significant differences.

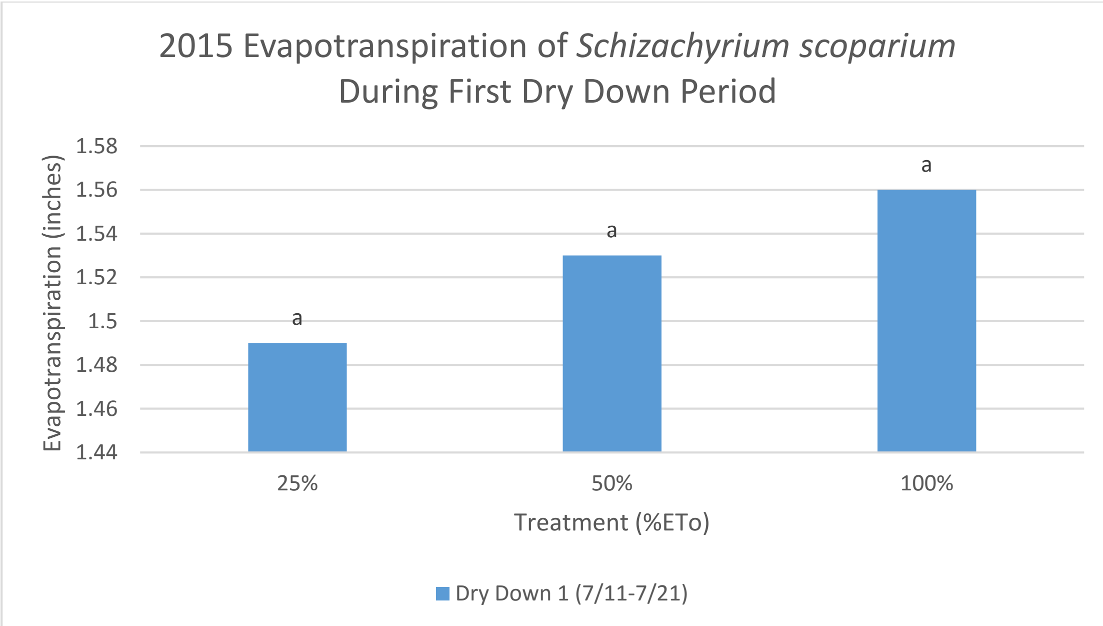


Figure 6c: 2015 evapotranspiration during the first dry down period. There was no difference in evapotranspiration between treatments. Different letters on bars denote significant differences.

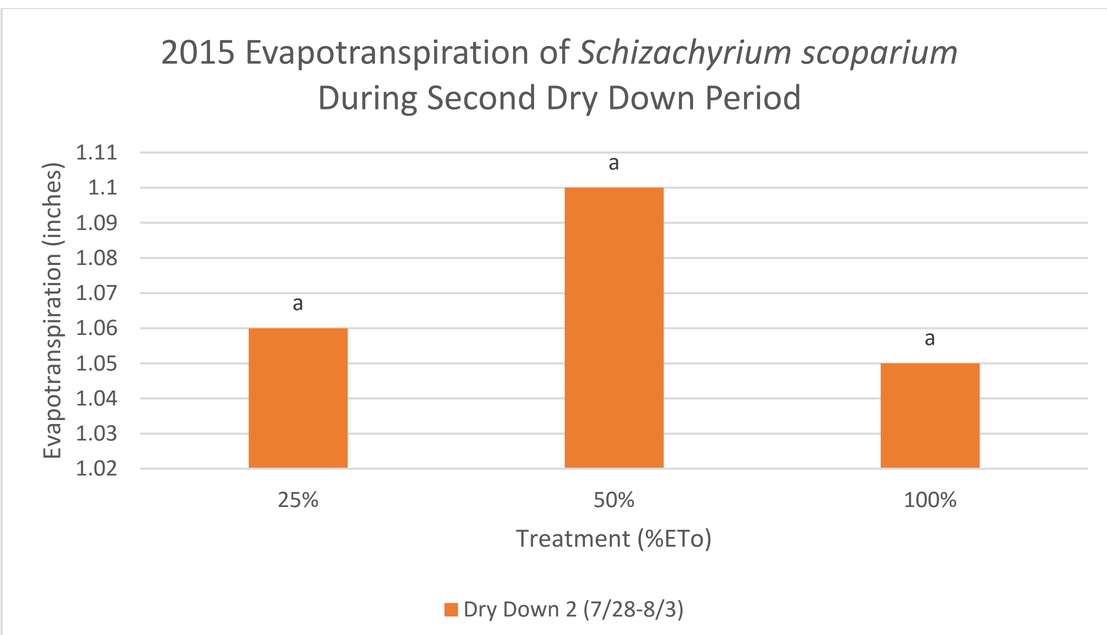


Figure 6d: 2015 evapotranspiration during the second dry down period. There was no difference in evapotranspiration between treatments. Different letters on bars denote significant differences.

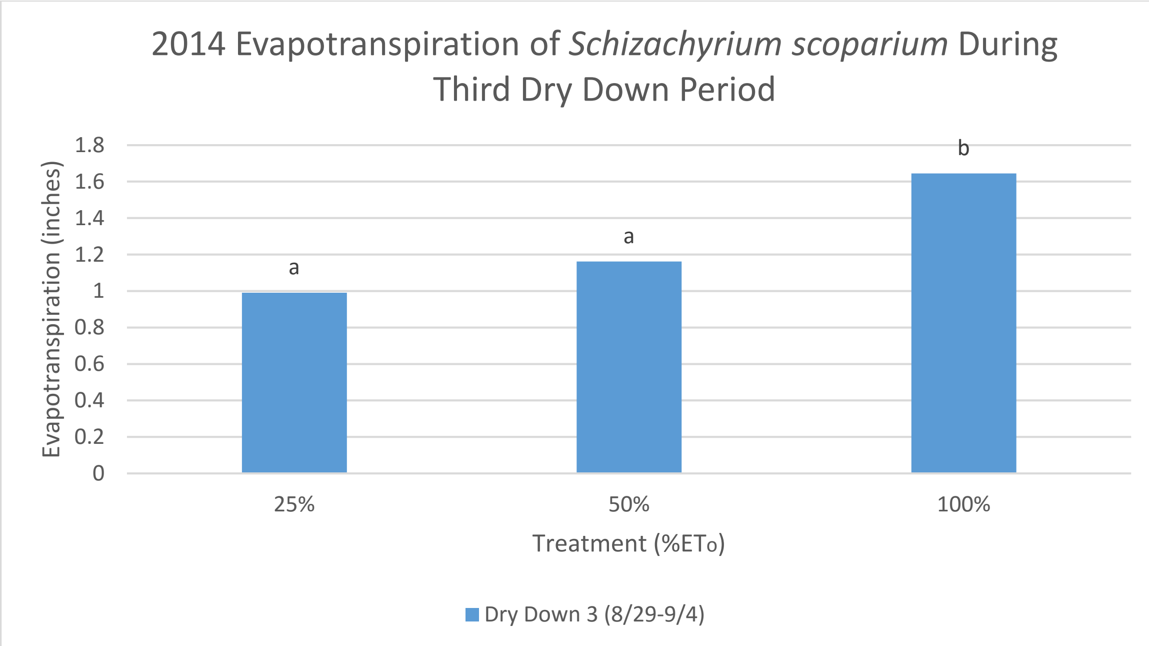


Figure 6e: 2014 evapotranspiration during the third dry down period. The 25% and 50% treatments used less water than the 100% treatment. Different letters on bars denote significant differences.

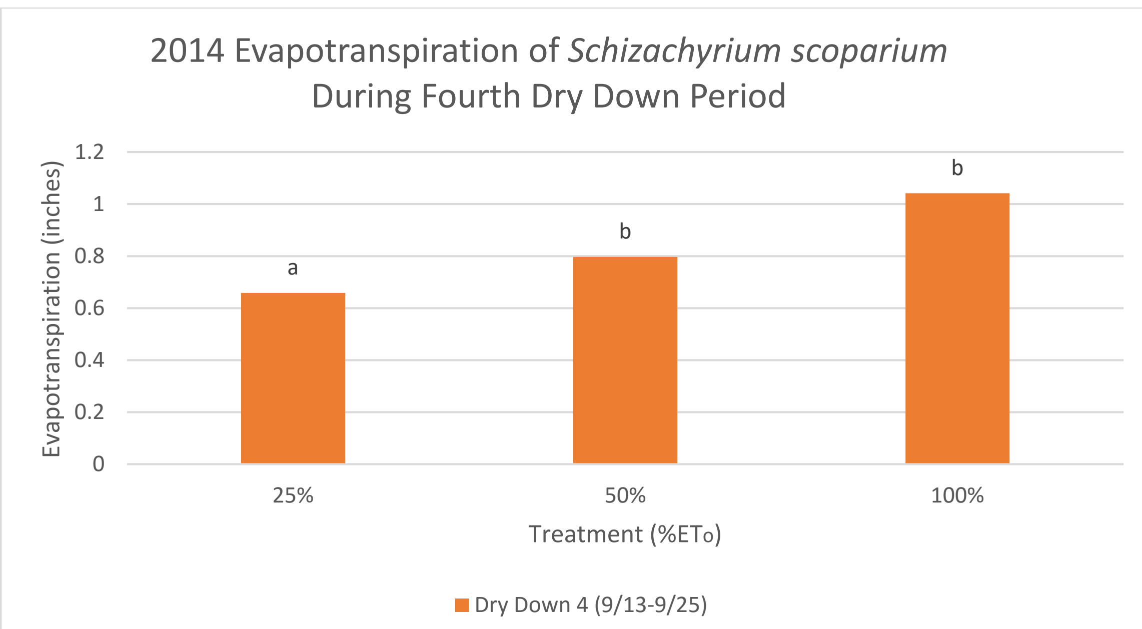


Figure 6f: 2014 evapotranspiration during the fourth dry down period. The 25% treatment used significantly less water than the 50% and 100% treatments. Different letters on bars denote significant differences.

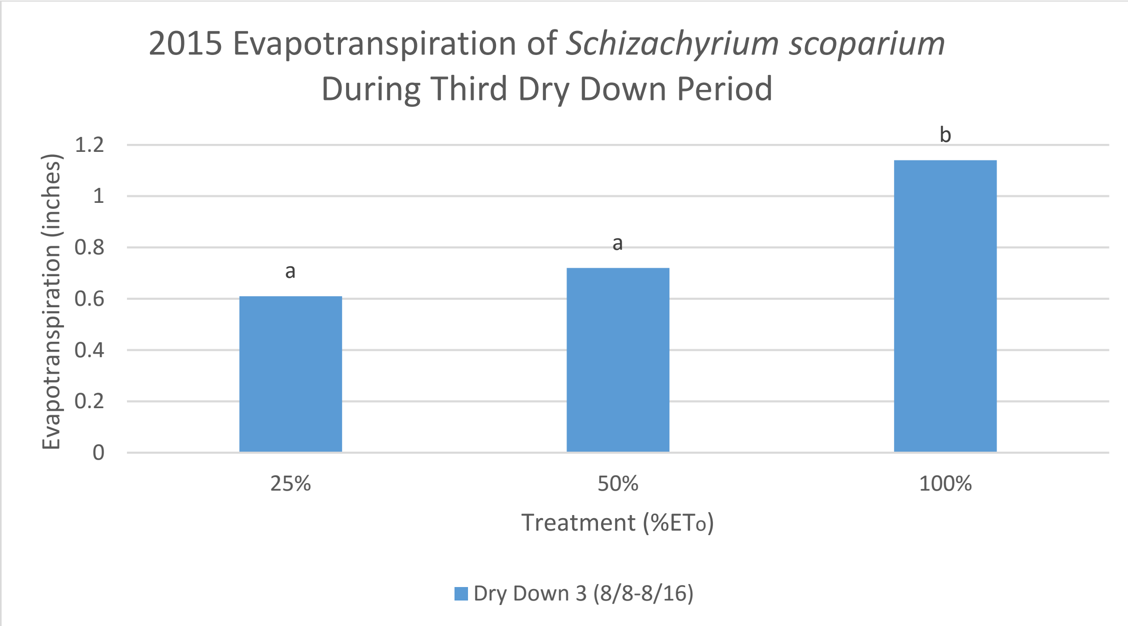


Figure 6g: 2015 evapotranspiration during the third dry down period. The 25% and 50% treatments used less water than the 100% treatment. Different letters on bars denote significant differences.

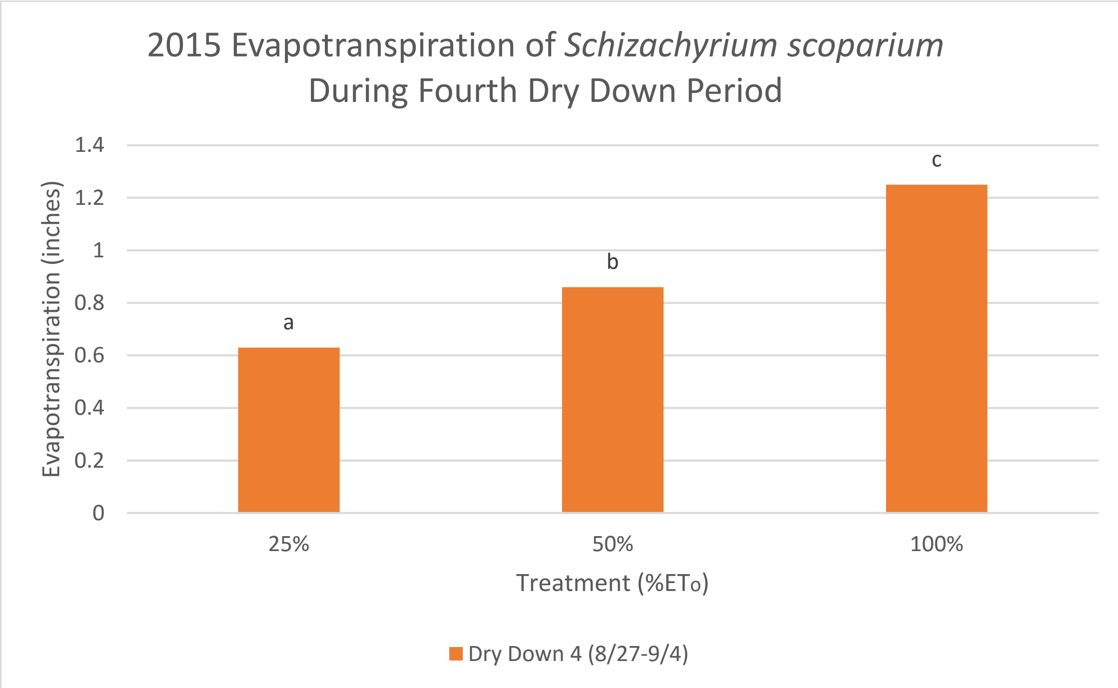


Figure 6h: 2015 evapotranspiration during the fourth dry down period. The 25% treatment used less water than the 50% treatment, and the 50% treatment used less water than the 100% treatment. Different letters on bars denote significant differences.

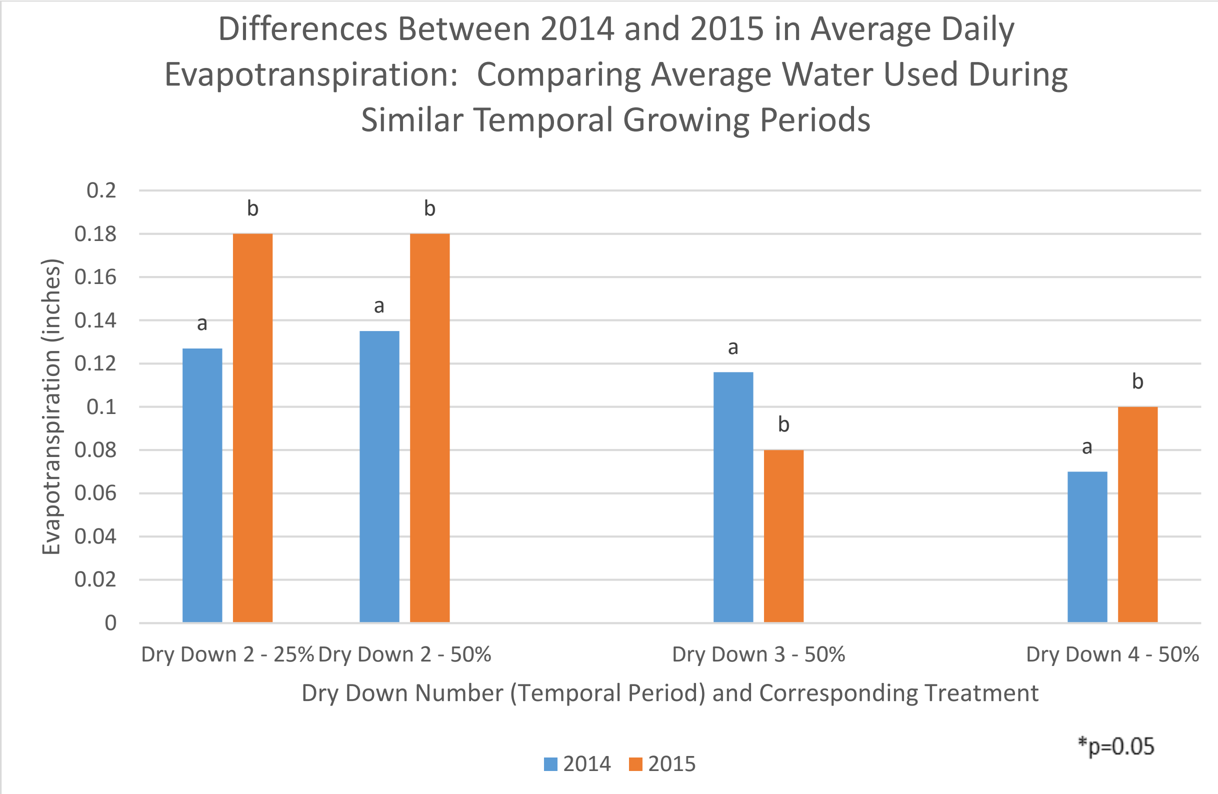


Figure 6i: Differences between 2014 and 2015 in amount of evapotranspiration during similar temporal periods. Only similar treatments were compared. All dry down periods which were not significantly different between years were excluded from graph. In three of the four cases, the plants in 2014 used less water. Different letters on bars denote significant differences.

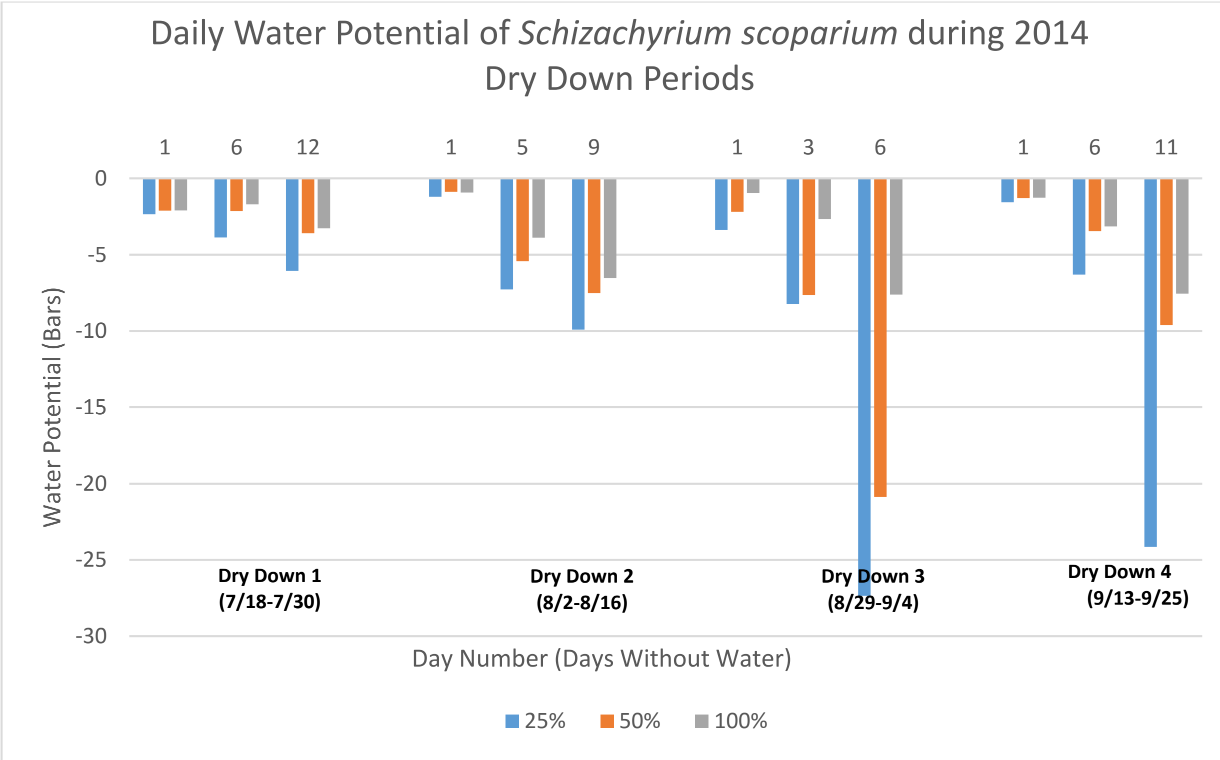


Figure 7a: Daily water potential during all four dry down periods of 2014. The graph emphasizes the lack of stress during early season drought periods, and a large increase in stress during late season drought periods. The significant level of stress (Bars) is also seen. The 25% treatment is always significantly more stressed once the plants reach 5 to 7 days without water. Note, since each dry down period was dictated by outdoor weather, dry down periods lasted a variable number of days. The graph depicts the start and end date, as well as the best representation of the middle date for that dry down period.

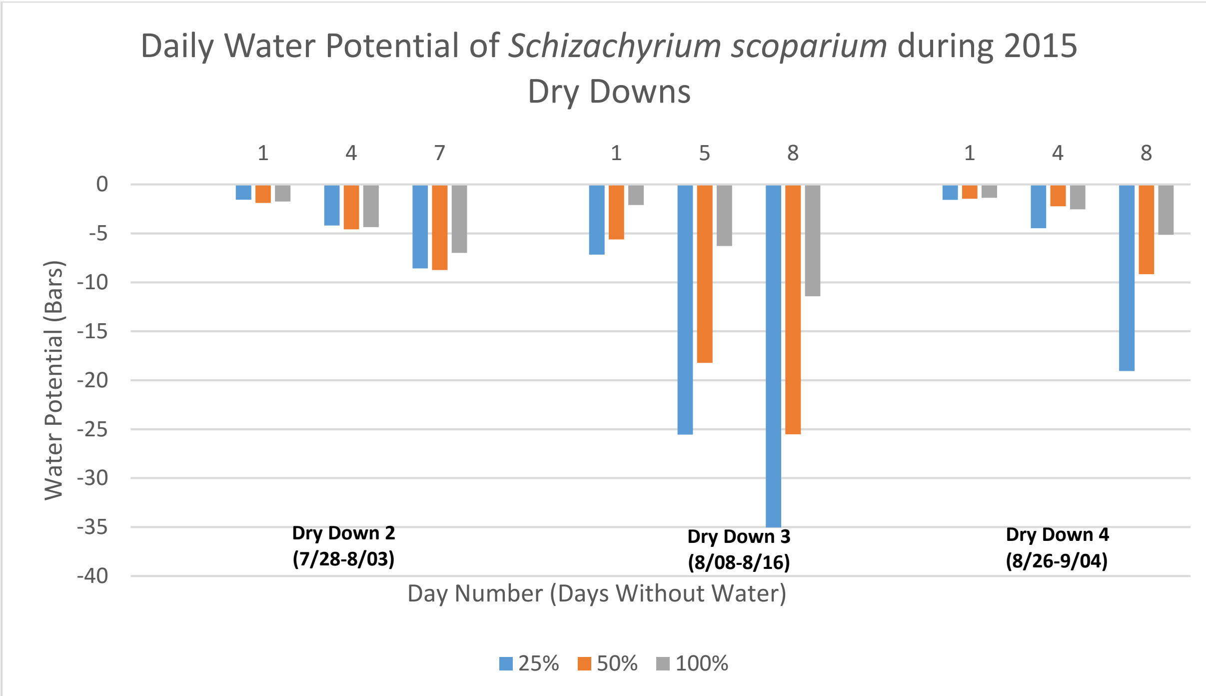


Figure 7b: Daily water potential during three of four dry down periods of 2015. The first dry down period was excluded as a redundant representation of the second dry down period. The graph emphasizes the lack of stress during early season drought periods, and a large increase in stress during late season drought periods. The 25% treatment is always significantly more stressed once the plants reach 5 to 7 days without water. Note, since each dry down period was dictated by outdoor weather, dry down periods lasted a variable number of days. The graph depicts the start and end date, as well as the best representation of the middle date for that dry down period.

Figure 8: From left to right: Representitive photographs of *Schizachyrium scoparium* 'Blaze' 25%, 50%, 100%. Images photographed on July 28, 2015.

CHAPTER 3: PHOTOSYNTHETIC PATHWAY CLASSIFICATION OF *Calamagrostis brachytricha*; KOREAN FEATHER REED GRASS

Introduction

Warm season grasses are classified as having a C_4 photosynthetic system, with carbon assimilation proceeding by a path qualitatively different than many other plants which grow well under high temperature conditions (Moser, 2004). Cool-season, or C_3, grasses dominate areas in which the warm period is short or temperatures are low (Moser, 2004). C_3 grasses are also known to initiate seasonal growth significantly earlier than C_4 species. The most distinct anatomical feature of C_4 grasses is the Kranz Leaf Anatomy, which is represented by the development of large bundle sheath cells (Moser, 2004). Another key feature distinguishing the two photosynthetic pathways is the discrimination of stable isotope 13C compared to 12C. C_4 grasses show improved capabilites at reducing internal CO2 to much lower levels than C_3 grasses. Because of this, C_4 Δ13C ranges from -10 to -14 while C_3 Δ13C ranges from -20 to -35 (Moser, 2004).

Calamagrostis brachytricha is a showy fall blooming reed grass from Eurasia. *Calamagrostis brachytricha* is a clumping grass which grows to about 120 cm in height each season. It is considered one of the most highly desired ornamental grasses in the landscape trade (Grounds, 2003). *Calamagrostis brachytricha* is grown for its changing leaf color, as well as its unusually large and colorful blooms. This species begins the growing season in mid-to-late March with a nice green color (RHS Color Code #137C), and quickly fades to a yellow-green (RHS Color Code #145A) which is unchanging the rest of the season. Occasionally in fall, a purple tinge (RHS Color Code #71A) will be present on some foliage. The flower spikes emerge in early fall, and are both wider, fluffier, and more noticeable than most other feather reed varieties, accounting for its most unique ornamental feature (Greenlee, 1992). The flower plumes fade from green (RHS Color Code #137C) to a spectacular light pink (RHS Color Code #68C) which rises over one foot above the foliage and is visible from a sizeable distance.

The Encyclopedia of Ornamental Grasses (1992) as well as Taylor's Guide to Ornamental Grasses (1997) cites *Calamagrostis brachytricha* as being a warm season grass. Yuan et. al (2011) is one of the few studies to look at water use of *Calamagrostis brachytricha*, and they consider it to be a warm season species when comparing to a cool season species. Warm Season (C_4) Grasses by Moser (2004) focuses on only C_4 species. This book extensively covers all clades of C_4 species, and has a section for both *Panicum virgatum* and *Schizachyrium scoparium*. However there is no mention of any *Calamgrostis* species, implying that *Calamagrostis brachytricha* may not be a C_4 grass. After two seasons of observing this species green up a month earlier and flower at the same time as other warm season grasses, the classification of *Calamagrostis brachytricha* as a warm season grass came into question. For this reason, deeper analysis and further study of this species was needed to classify the photosynthetic pathway.

Materials and Methods

The study was conducted at the National Center for Genomic Research and Preservation (NCGRP) at Colorado State University, Fort Collins, CO 80523. The study examined four samples: *Schizachyrium scoparium* 'Blaze' (Blaze Little Bluestem) (USDA NRCS National Plant Materials Center, 2015), *Calamgrostis brachytricha* (Korean Feather Reed Grass) (Arctos Database, 2014) from the field as well as from the greenhouse, and *Calamagrostis × acutiflora* 'Karl Foerster' (Karl Foerster Reed Grass) (*Ca 'KF'*) (Gilman, Edward, 2014). *Calamagrostis ×*

acutiflora and *Schizachyrium scoparium* were used as references, as *Calamagrostis* × *acutiflora* (Karl Foerster Grass) is a known C_3 grass and *Schizachyrium scoparium* is a known C_4 grass. *Calamagrostis* × *acutiflora*, *Schizachyrium scoparium*, and greenhouse grown *Calamgrostis brachytricha* were considered to be at a mature stage of growth. Field grown *Calamgrostis brachytricha* samples were taken at both initial and mature growth stages. The different growth stages were taken in order to account for any C_3/ C_4 transition periods, if they did occur. A minimum of four leaves were sampled for each species.

The first data set collected for this study involved sectioning on leaf vasculature using a Spurr's Resin Kit for analysis under light microscopy. (The Spurr's Resin full listing of embedding and sectioning protocol and chemical compositions can be seen in Table 2a and 2b). All measurements for the Spurr's kit were made using an Ohaus 1500D scale. Using the Spurr's Kit (Table 2a and 2b) to embed and section, plant material took 9 days to process. Resin blocks were mounted and sectioned using a RMC MTX Rotary Microtome. Glass knives for the microtome were created using a Leica EM KMR2. Sections were then mounted and stained with Stevenel's Stain. Anatomical sections were visually imaged using a Sony Exwave HAD DSP 3CCD Color Model DXC-990 digital camera, which was mounted to an Olympus BH2 Microscope system. Photographs were digitally cataloged and analyzed using Olympus MagnaFIRE version 2.1C software. Sections were compared with known C_3 and C_4 plant vasculature to draw an accurate conclusion.

The second parameter to determine was a Carbon 13 isotope discrimination. Samples of *C. brachytricha* from both the field and greenhouse, as well as *S. scoparium* samples were sent to EcoCore Analytical Services on the Colorado State University campus for a carbon isotope analysis. *Schizachyrium scoparium* was included as a known- C_4 reference plant. Samples were dried, ground, and encapsulated at the EcoCore facility. EcoCore Analytical Servies uses a VG Isochrome continuous flow IRMS (Isoprime Inc., Manchester, UK) Mass spectrometer. Equipment is known to be accurate to within 0.4 per thousand.

The final traits observed to strengthen classification was the date of new growth (green up date), and floral initiation date of *Calamgrostis brachytricha*. C_3, or cool season, species are known to initiate seasonal growth up to a month prior to C_4, or warm season, species (Moser, 2004).

Results and Discussion

Representative examples of vascular anatomy can be seen in Figures 9a-d. All samples of *Calamgrostis brachytricha* show clear vasculature lacking bundle sheath cells. This is confirmation that *Calamgrostis brachytricha* is a C_3 species with a clear C_3 anatomy. Samples were taken at various growth stages to ensure *Calamgrostis brachytricha* was not a transition or obligate C_3 species. Each section taken throughout the various growth stages were congruent with one another, proving that *Calamgrostis brachytricha* is a C_3 species at all developmental stages.

A full Carbon 13 analysis is seen (Table 3). All *Calamgrostis brachytricha* samples analyzed were between the values of -21.6 and -24.1, with an average of -22.87. *Schizachyrium scoparium* was used as a known C_4 reference plant. *Schizachyrium scoparium* sample recorded a value of -12.2897. Typical C_3 δ13C ranges from -20 to -35, while C_4 Δ13C ranges from -10 to -14 (Moser, 2004). The average value of -22.87 is consistent with the information obtained from anatomical characteristics; that *Calamgrostis brachytricha* is a C_3 species. The *Schizachyrium scoparium* value of -12.2897 confirms that the mass spectrometer provided accurate results. The variations in *Calamgrostis brachytricha* δ13C values is likely attributed to environmental conditions. While both field samples were relatively close in δ13C value, the *Calamgrostis brachytricha* sample taken from the greenhouse varies to a larger extent. This can be attributed to the fact that leaf samples taken from this plant had been initiated for months before those taken in the field samples (due to prolonged growing season in the greenhouse setting) (Jones, 2014).

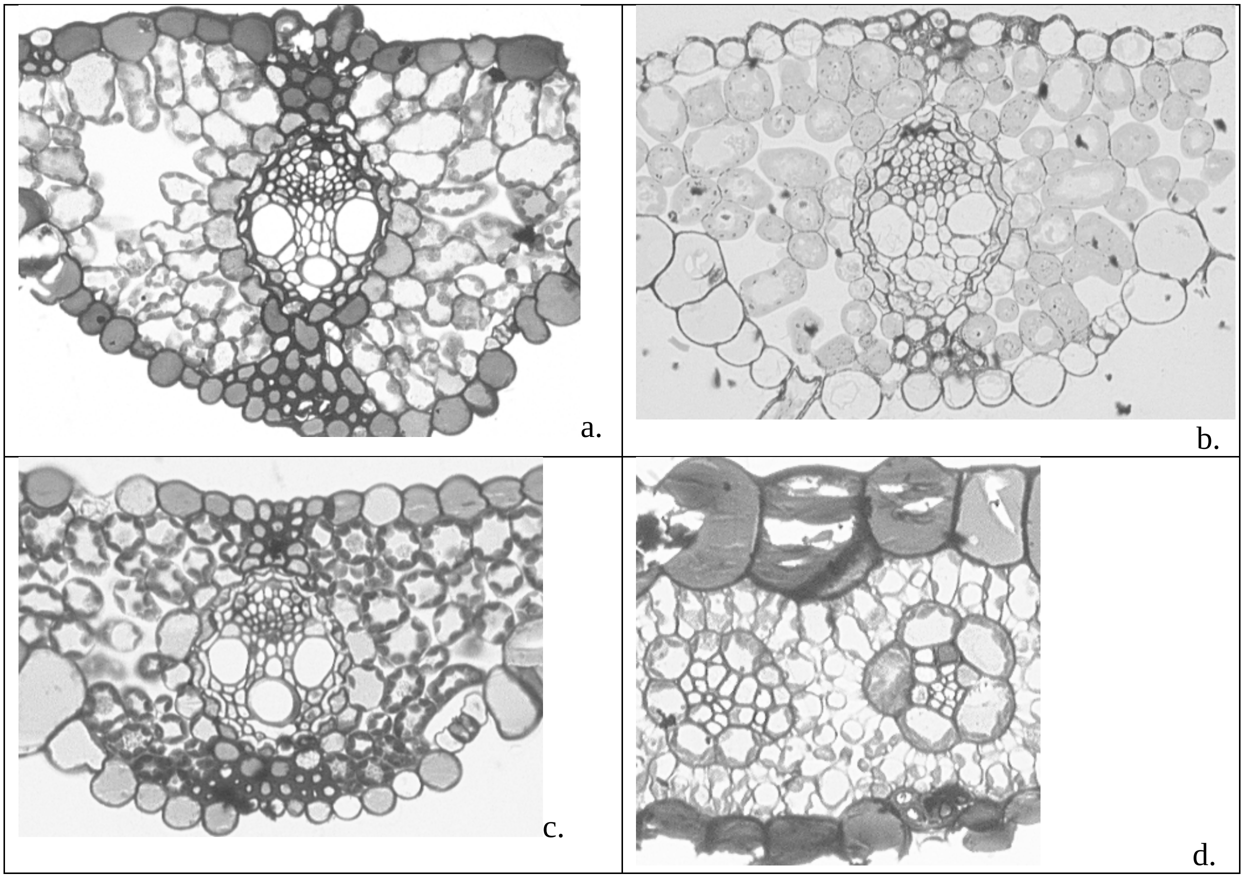
In 2014, all *Calamgrostis brachytricha* plants averaged a green-up date of March 26, 2014. This is compared to an average of April 30, 2014 and April 26, 2014 for *Panicum virgatum* and *Schizachyrium scoparium* respectively. In 2015, all *Calamgrostis brachytricha* Field 2 plants averaged a green-up date of March 24, 2015. This is compared to an average of May 11, 2015 and May 2, 2015 for *Panicum virgatum* and *Schizachyrium scoparium* respectively. From these observations, *Calamgrostis brachytricha* plants began to green up over a month before their well-known warm-season counterparts. This further supports the conclusions presented in the vascular anatomy and carbon isotope analysis results. In conclusion, based on leaf vasculature sectioning, Carbon isotope analysis, and observation of green-up date it is clear that *Calamgrostis brachytricha* is a true C_3 species.

Table 2a: Spurr Resin Kit Embedding Process

DAY	ACTIVITY	TIME FRAME
1	- Cut fresh tissue to 1mm pieces or smaller - Place in fixative	 - Overnight in rotator
2	- Rinse 3x with 50 mM Pipes buffer	- 10 minutes per rinse while rotating
3	- Rinse 3x with 50 mM Pipes buffer <u>BEGIN DEHYDRATION WITH ACETONE</u> - 30% acetone - 50% acetone - 70% acetone - 90% acetone - 100% acetone - 100% acetone - 3:1 acetone:Spurr	- 10 minutes per rinse while rotating - 15 minutes, rotating - 15 minutes, rotating - 15 minutes, rotating - 15 minutes, rotating - 15 minutes, rotating - 15 minutes, rotating - Overnight, rotating
4	- 2:1 acetone:Spurr - 1:1 acetone:Spurr	- 4 hours - 4 hours
5	- 1:2 acetone:Spurr - 1:3 acetone:Spurr	- 4 hours - 4 hours
6	- Pure Resin	- Overnight
7	- Pure Resin	- Overnight
8	- Pure Resin + Accelerator - Polymerize in oven @ 70 degrees	- 6-8 hours - Overnight
9	- Remove from oven	

Table 2b: Spurr Resin Composition Recipe

ITEM	COMPOSITION
Spurr Resin (from Spurr Resin Kit)	- 5g ERL4206, 3g DER736, 13g NSA. - Accelerator (in Spurr Kit) only present in last 100% resin treatment.
Fixative (12ml)	- 1.2ml 500 mM Pipes Buffer - 0.6ml 20% glutaraldehyde - 1.5ml 16% paraformaldehyde - 8.7ml ddH20.
Post-fixation Osmium (5ml)	- 2.5ml Osmium tetroxide - 0.5ml 500 mM Pipes buffer - 2ml ddH20.



Figures 9a-d: Ornamental grass leaf vasculature cross sections.
a) *Calamagrostis* × *acutiflora* 40x cross section; b) *Calamgrostis brachytricha* Field 40x cross section; c) *Calamgrostis brachytricha* Greenhouse 40x cross section; d) *Schizachyrium scoparium* 40x cross section. All samples of *Calamgrostis brachytricha* show clear vasculature lacking bundle sheath cells, confirmation that *Calamgrostis brachytricha* has a clear C_3 anatomy. Samples were taken at various growth stages to ensure *Calamgrostis brachytricha* was not a transition or obligate C_3 species. Figures 9a-d samples represent vasculature at all growth stages for all species.

Table 3: Full Carbon 13 analysis of *Calamgrostis brachytricha* and control species *Schizachyrium scoparium.* All *Calamgrostis brachytricha* samples analyzed were between the values of -21.6 and -24.1, with an average of -22.87; a value consistent with C_3 Δ13C ranges.

SAMPLE I.D.	**DELTA 13 C**	**%C**
Calamgrostis brachytricha Greenhouse	-24.0477	44.41
Calamgrostis brachytricha Field 1	-21.6047	44.79
Calamgrostis brachytricha Field 2	-22.9617	45.66
Schizachyrium scoparium	-12.2897	44.54

REFERENCES

Alvarez E, Schieber SM, Beeson Jr. RC, Sandrock DR. Drought Tolerance Responses of Purple Lovegrass and 'Adagio' Maiden Grass. *HortScience*. 2007; 42(7): p1695-1699.

Arctos Database. Taxonomy Details for *Calamagrostis brachytricha.* 2014. Available at http://arctos.database.museum/taxonomy.cfm?taxon_term==Calamagrostis brachytricha&term_type==species&source=Arctos Plants. Accessed January, 2016.

Barney JN, Mann JJ, Kyser GB, Blumwald E, Deynze AV, DiTomaso JM. Tolerance of switchgrass to extreme soil moisture stress: Ecological implications. *Plant Science*. 2009; doi:10.1016/j.plantsci.2009.09.003.

Beeson RC. Modeling irrigation requirements for landscape ornamentals. *HortTechnology*. 2005; 15: p18-22.

Blazek, D. 2014 Perennial Plant of the Year. Perennial Plant Association. 2014. <http://www.perennialplant.org/index.php/education/plant-of-the-year>. Accesed March 2014.

Boyer JS. Plant Productivity and the Environment. *Science*. 1982; 218: p442-448.

Chavez MM, Maroco JP, Pereira JS. Understanding plant responses to drought – from genes to the whole plant. *Functional Plant Biology*. 2003; 30: p239-264.

Colorado Climate Center. Historical Data Summaries for Selected Sections. 2010. Available at: http://climate.colostate.edu/. Accessed November, 2015.

Costello LR, Jones KS. Water use classification of landscape plants. WUCOLS III. 2000. <http://www.owue.water.ca.gov/docs/wucols00.pdf>. Accessed January 2014.

Davidson H, Mecklenburg R, Peterson, C. *Nursery Management: Administration and Culture*. New Jersey: Prentice Hall; 2000.

Eggemeyer KD, Awada T, Harvey FE, Wedin DA, Zhou X, Zanner CW. Seasonal changes in depth of water uptake for encroaching trees Juniperus virginiana and Pinus ponderosa and two dominant C_4 grasses in a semiarid grassland. *Tree Physiology*. 2008; 29: p157-169.

Endter-Wada J, Kurtzman J, Keenan SP, Kjelgren R, Neale C. Situational Waste in Landscape Watering: Residential and Business Water Use in an Urban Utah Community. *Journal of the American Water Resources Association*. 2008; 44(4): p902-920.

Gilman, Edward. Calamagrostis acutiflora 'Karl Foerster' Feather Reed Grass. UF Fact Sheet. 2014. 1: 1-2.

GreenCO and Wright Water Engineers, Inc. Green Industry Best Management Practices (BMPs) for the Conservation and Protection of Water Resources in Colorado: Moving Toward Sustainability: 3rd Release. 2008: Denver, CO.

Greenlee J. The Encyclopedia of Ornamental Grasses. New York: Michael Friedman Publishing Group; 1992.

Grounds, R. *The Plantfinders Guide to Ornamental Grasses*. Portland, Oregon: Timber Press; 2003.

Gulik TV. Crop Coefficients For Use In Irrigation Scheduling: Water Conservation Factsheet. 577.100-5. British Columbia: Ministry of Agriculture, Food, and Fisheries; 2001.

Henson DY, Newman SE, Hartley DE. Performance of Selected Herbaceous Annual Ornamentals Grown at Decreasing Levels of Irrigation. *HortScience*. 2006; 41(6): p1481-1486.

Hilaire RS, Arnold MA, Wilkerson DC, Devitt CA, Hurd BH, Lesikar BJ, Lohr VI, Martin CA, McDonald GV, Morris RL, Pittenger DR, Shaw DA, Zoldoske DF. Efficient Water Use in Residential Urban Landscapes. *HortScience*. 2008; 43(7): p2081-2092.

Hurd B, Hilaire RS, White J. Residential landscapes, homeowner attitudes and water-wise choices in New Mexico. *HortTechnology*. 2006; 16: p241-246.

Irmak S. Estimating Crop Evapotranspiration from Reference Evapotranspiration and Crop Coefficients. Nebraska. University of Nebraska Extension; 2009.

Janik J, Whipkey A. Trends in New Crops and New Uses. Alexandria, VA: ASHS Press; 2002.

Jones, HG. Plants and Microclimate; *A Quantitative Approach to Environmental Plant Physiology, Edition 3*. United Kingdom: Cambridge University Press; 2014.

Knapp AK. Water Relations and Growth of Three Grasses during Wet and Drought Years in a Tallgrass Prairie. Oecologia. 1984; 65(1): p35-43.

Kramer P, Boyer J. *Water Relations of Plants and Soils*. San Diego, CA: Academic Press; 1995.

McKee TB, Doesken NJ, Kleist J, Shrier CJ, Stanton WP. A History of Drought in Colorado: Lessons Learned and What Lies Ahead. *Colorado Water*. 2000; No 9: 2nd Edition.

Meyer, M. *National Ornamental Grass Trial Blog and Information*. 2015. Available at: http://grasstrials.com. Accessed October, 2015.

Moser LE, Burson BL, Sollenberger LE. *Warm-Season* (C_4) *Grasses*. Madison, WI: American Society of Agronomy; 2004.

OmegaScope. Handheld Infrared Thermometer User's Guide. Connecticut: Omega Products; 2010.

Ounsworth, M. *Water Use and Drought Resistance of Turfgrass and Landscape Shrubs*. Colorado State University Thesis Submission. 2007.

Pielke Sr. RA, Doesken N, Bliss O, Green T, Chaffin C, Salas JD, Woodhouse CA, Lukas JJ, Wolter K. Drought 2002 in Colorado – An UnpredEdented Drought or a Routine Drought?. *Pure and Applied Geophysics*. 2004; 162: p1455-1479.

Pittenger D, Shaw D. What We Know About Landscape Water Requirements. *CO-HORT*. 2004; 6.1: p1-8.

PMS. *Model 600 Pressure Chamber Instrument Instruction Manual*. Oregon: PMS Instrument Company; 2014.

Prevete KJ, Fernandez RT, Miller WB. Drought Response of Three Ornamental Herbaceous Perennials. *Journal of American Society of Horticultural Science*. 2000; 125(3): p310-317.

Qian, Y. Horticulture 571 Class Notes. Colorado State University: Fort Collins, CO. Spring 2014.

Rozum, J. *Irrigation Effects on Growth and Visual Quality of Three Ornamental Grass Species*. Colorado State University Thesis Submission. Spring 2014.

Sanderson MA, Reed RL. Switchgrass Growth and Development: Water, Nitrogen, and Plant Density Effects. *Journal of Range Management*. 2000; 52(2): p221-227.

Schelle H, Idean SC, Fank J, Durner W. Inverse Estimation of Soil Hydraulic and Root Distrobution Parameters from Lysimeter Data. *Vadose Zone Journal*. 2012; doi:10.2136/vzj2011.0169.

Schuch UK, Burger DW. Water use and crop coefficients of woody ornamentals in containers. *Journal of American Society of Horticultural Science*. 1997; 122: p727-734.

Sentek. *Diviner 2000® User Guide Version 1.5*. South Australia: Sentek Pty Ltd; 2009.

Southern Weed Science Society. 1998. *Weeds of the United States and Canada. CD-ROM*. Southern Weed Science Society. Champaign, Illinois.

Smith JF, Klett JE. Responses of Four Common Shrub Species to Different Irrigation Regimes. *Journal of Environmental Horticulture*. 2013; 31(4): p211-220.

Sun G, McNulty SG, Moore Myers JA, Cohen EC. Impacts of Climate Change, Population Growth, Land Use Change, and Groundwater Availability on Water Supply and Demand across the Conterminous US. *AWRA Hydrology & Watershed Management Technical Committee: Watershed Update*. 2008; 6(2): p1-3.

Thetford M, Norcini JG, Ballard B, Aldrich JH. Ornamental Landscape Performance of Native and Nonnative Grasses under Low-input Conditions. *HortTechnology*. 2009; 19(2): p267-285.

Tucker SS, Craine JM, Nippert JB. Physiological drought tolerance and the structuring of tallgrass prairie assemblages. Ecosphere. 2011; 2(4): Article 48.

USDA NRCS National Plant Materials Center. Little Bluestem, Schizachyrium scoparium Plant Fact Sheet. USDA Plant Database. 2015. Available at http://plants.usda.gov/core/profile?symbol=SCSC. Accessed January 29, 2016.

US Department of Interior. Colorado Precipitation Atlas. NationalAtlas.Gov. 2012. <http://www.nationalatlas.gov/printable/images/pdf/precip/pageprecip_co3.pdf>. Accessed March 2014.

Weaver JE. Prairie Plants and the Environment: a fifty year study in the Midwest. Lincoln, Nebraska: University of Nebraska Press. 1968.

Whiting D. Watering Efficiently. *Colorado Master Gardeners Green Notes*. Colorado State University: 2012; 267: p1-7.

Whiting D. Colorado's Water Situation. *Colorado Master Gardeners Green Notes*. Colorado State University: 2012; 261: p1-6.

Wolfe III J, Zajicek JM. Are Ornamental Grasses Acceptable Alternatives For Low Maintenance Landscapes?. *Journal of Environmental Horticulture*. 1998; 16(1): p8-11.

Yuan X, Gu M, Teng W, Yang X, Wu J. Growth of Calamagrostis brachytricha Steud. and Festuca glauca Lam. and estimated water savings under evapotranspiration-based deficit irrigation. *Journal of Horticultural Science & Biotechnology*. 2011; 86(6): p583-588.

Zhou S, Duursma RA, Medlyn BE, Kelly JWG, Prentice IC. How should we model plant responses to drought? An analysis of stomatal and non-stomatal responses to water stress. *Agriculture and Forest Meteorology*. 2013; p182-183 and p204-214.

Zollinger N, Kjelgren R, Cerny-Koenig T, Kopp K, Koenig R. Drought responses of six ornamental herbaceous perennials. *Scientia Horticulturae*. 2006; 109: p267-27

APPENDICES

DATE	ET for week (Inches)	Rainfall for week (Inches)	Total to apply to 100% (inches)	Total to apply to 50% (inches)	Total to apply to 25% (inches)	Total to apply to 0% (inches)
5/26/2014	1.15	0.82	0.33	-0.245	-0.5325	0
6/2/2014	1.45	0.24	1.21	0.485	0.1225	0
6/9/2014	1.35	0.67	0.68	0.005	-0.3325	0
6/16/2014	1.25	0.12	1.13	0.505	0.1925	0
6/23/2014	1.5	0.18	1.32	0.57	0.195	0
6/30/2014	1.25	0.23	1.02	0.395	0.0825	0
7/7/2014	1.8	0	1.8	0.9	0.45	0
7/14/2014	1.35	0.98	0.37	-0.305	-0.6425	0
7/21/2014	1.3	0.615	0.685	0.035	-0.29	0
7/28/2014	1.62	0.41	1.21	0.4	-0.005	0
8/4/2014	1.55	1.4	0.15	-0.625	-1.0125	0
8/11/2014	1.63	0.21	1.42	0.605	0.1975	0
8/18/2014	1.42	0.045	1.375	0.665	0.31	0
8/24/2014	1.41	0.06	1.35	0.645	0.2925	0
8/31/2014	1.17	0.295	0.875	0.29	-0.0025	0
9/7/2014	1.21	0.215	0.995	0.39	0.0875	0
9/14/2014	0.75	0.695	0.055	-0.32	-0.5075	0
9/21/2014	1.27	0	1.27	0.635	0.3175	0
9/28/2014	1.05	0.25	0.8	0.275	0.0125	0
6/8/2015	1.1	0.56	0.54	-0.01	-0.285	0
6/16/2015	1.36	0.69	0.67	-0.01	-0.35	0
6/23/2015	1.53	0.08	1.45	0.685	0.3025	0
6/30/2015	1.62	0.38	1.24	0.43	0.025	0
7/7/2015	1.49	0.7	0.79	0.045	-0.3275	0
7/14/2015	1.23	0.97	0.26	-0.355	-0.6625	0
7/21/2015	1.69	0.02	1.67	0.825	0.4025	0
7/28/2015	1.36	0.05	1.31	0.63	0.29	0
8/4/2015	1.68	0.09	1.59	0.75	0.33	0
8/11/2015	1.63	0.13	1.5	0.685	0.2775	0
8/18/2015	1.39	0.05	1.34	0.645	0.2975	0
8/24/2015	1.53	0.76	0.77	0.005	-0.3775	0
8/31/2015	1.46	0.02	1.44	0.71	0.345	0
9/7/2015	1.84	0.32	1.52	0.6	0.14	0
9/14/2015	1.26	0.18	1.08	0.45	0.135	0

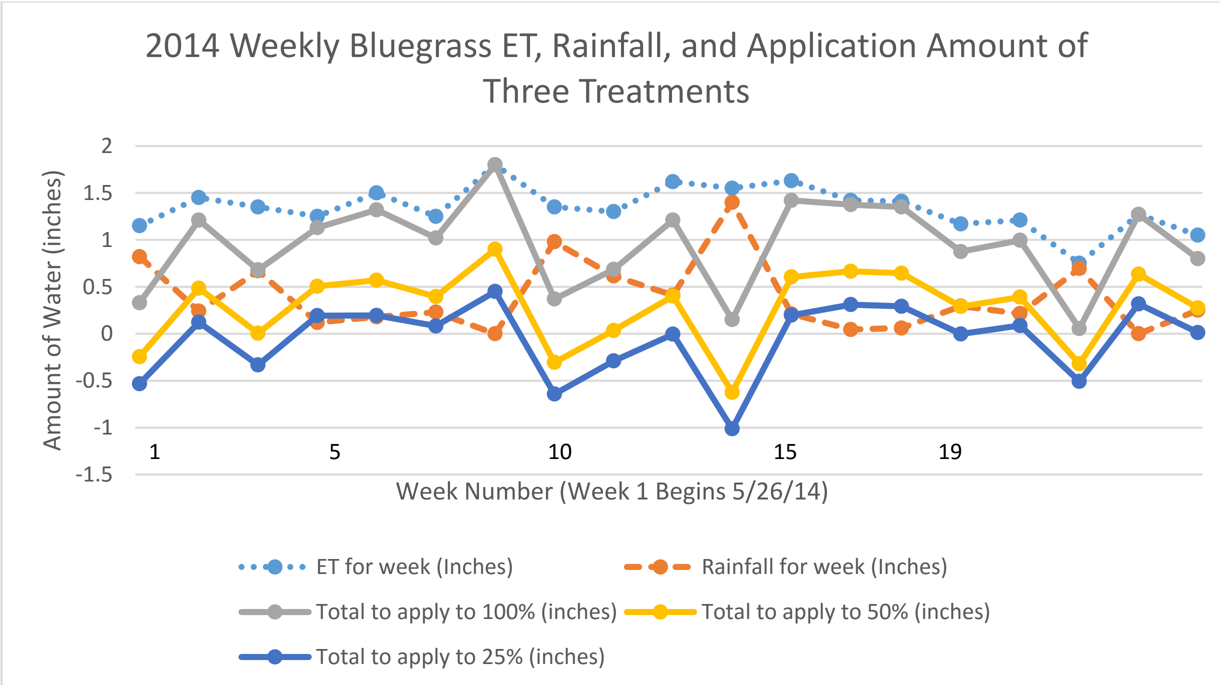
Appendix 1a: Weekly amount of water applied per treatment during the 2014 and 2015 seasons. Bluegrass evapotranspiration (ETo) and Precipitation are included to show calculations. Negative numbers indicate precipitation exceeding irrigation amounts for that week.

DATE	Weekly ET (in)	Weekly Rainfall (in)	Apply to 100%(in)	Apply to 50% (in)	Apply to 25% (in)	Apply to 0% (in)
5/26/2014	1.15	0.82	0.33	-0.245	-0.5325	0
6/2/2014	1.45	0.24	1.21	0.485	0.1225	0
6/9/2014	1.35	0.67	0.68	0.005	-0.3325	0
6/16/2014	1.25	0.12	1.13	0.505	0.1925	0
6/23/2014	1.5	0.18	1.32	0.57	0.195	0
6/30/2014	1.25	0.23	1.02	0.395	0.0825	0
7/7/2014	1.8	0	1.8	0.9	0.45	0
7/14/2014	1.35	0.98	0.37	-0.305	-0.6425	0
7/21/2014	1.3	0.615	0.685	0.035	-0.29	0
7/28/2014	1.62	0.41	1.21	0.4	-0.005	0
8/4/2014	1.55	1.4	0.15	-0.625	-1.0125	0
8/11/2014	1.63	0.21	1.42	0.605	0.1975	0
8/18/2014	1.42	0.045	1.375	0.665	0.31	0
8/24/2014	1.41	0.06	1.35	0.645	0.2925	0
8/31/2014	1.17	0.295	0.875	0.29	-0.0025	0
9/7/2014	1.21	0.215	0.995	0.39	0.0875	0
9/14/2014	0.75	0.695	0.055	-0.32	-0.5075	0
9/21/2014	1.27	0	1.27	0.635	0.3175	0
9/28/2014	1.05	0.25	0.8	0.275	0.0125	0
Yearly (in)	25.48	7.435	18.045	5.305	-1.065	0
Weekly Application Amount (in)			0.949736842	0.279210526	-0.056052632	0
Yearly Application Amount (in): No irrigation on weeks with Precipitation					**2.26**	
Weekly Application Amount (in): No irrigation on weeks with Precipitation					**0.2054545**	

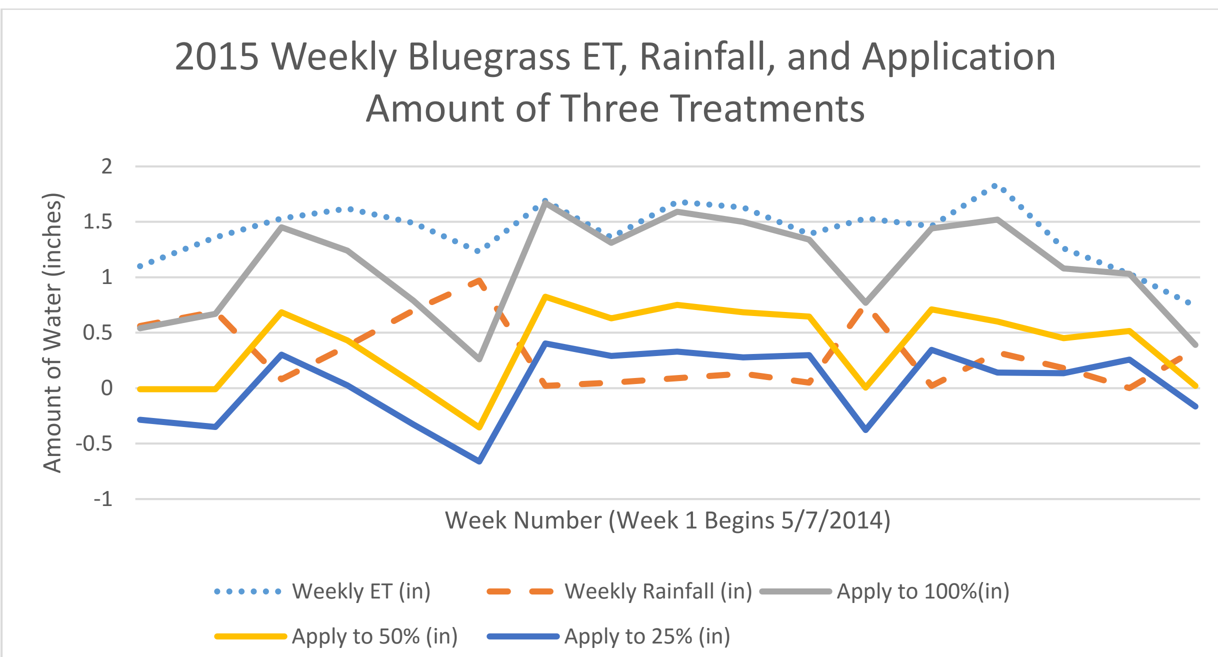
Appendix 1b: 2014 yearly and weekly water budgets and recommendations. Shaded numbers represent adopting the practice of ceasing irrigation on weeks containing precipitation. Negative numbers indicate precipitation exceeding irrigation amounts for that week.

DATE	Weekly ET (in)	Weekly Rainfall (in)	Apply to 100%(in)	Apply to 50% (in)	Apply to 25% (in)	Apply to 0% (in)
6/8/2015	1.1	0.56	0.54	-0.01	-0.285	0
6/16/2015	1.36	0.69	0.67	-0.01	-0.35	0
6/23/2015	1.53	0.08	1.45	0.685	0.3025	0
6/30/2015	1.62	0.38	1.24	0.43	0.025	0
7/7/2015	1.49	0.7	0.79	0.045	-0.3275	0
7/14/2015	1.23	0.97	0.26	-0.355	-0.6625	0
7/21/2015	1.69	0.02	1.67	0.825	0.4025	0
7/28/2015	1.36	0.05	1.31	0.63	0.29	0
8/4/2015	1.68	0.09	1.59	0.75	0.33	0
8/11/2015	1.63	0.13	1.5	0.685	0.2775	0
8/18/2015	1.39	0.05	1.34	0.645	0.2975	0
8/24/2015	1.53	0.76	0.77	0.005	-0.3775	0
8/31/2015	1.46	0.02	1.44	0.71	0.345	0
9/7/2015	1.84	0.32	1.52	0.6	0.14	0
9/14/2015	1.26	0.18	1.08	0.45	0.135	0
9/21/2015	1.03	0	1.03	0.515	0.2575	0
9/28/2015	0.74	0.35	0.39	0.02	-0.165	0
Yearly (in)	23.94	5.35	18.59	6.62	0.635	0
Weekly Application Amount (in)			1.093529412	0.389411765	0.037352941	0
Yearly Application Amont (in): No irrigation on weeks with Precipitation					**2.8025**	
Weekly Application Amont (in): No irrigation on weeks with Precipitation					**0.2547727**	

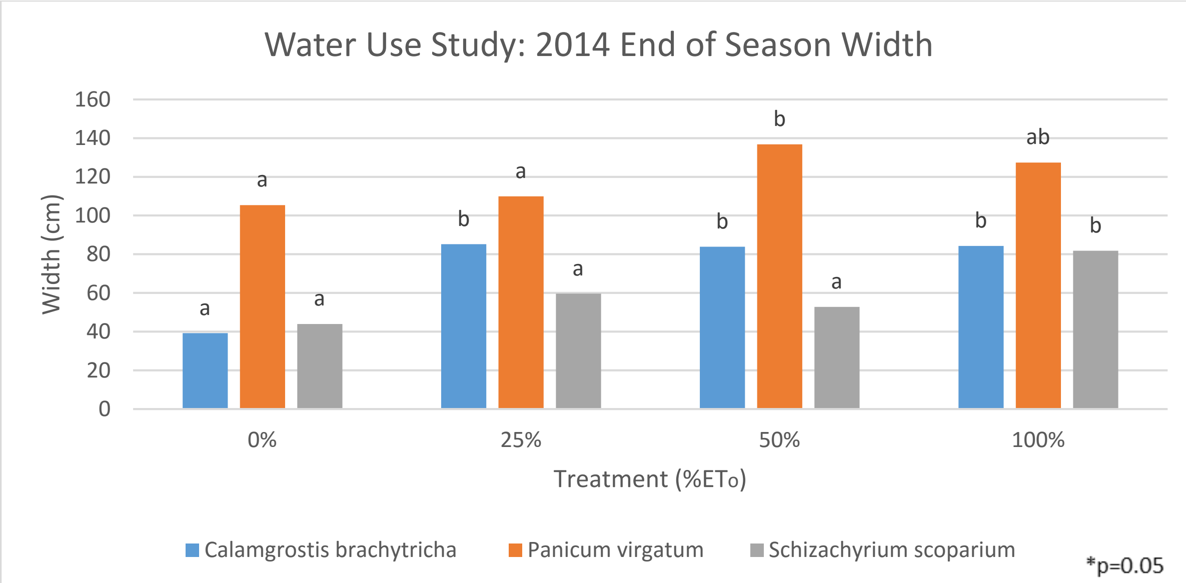
Appendix 1c: 2015 yearly and weekly water budgets and recommendations. Shaded numbers represent adopting the practice of ceasing irrigation on weeks containing precipitation. Negative numbers indicate precipitation exceeding irrigation amounts for that week.



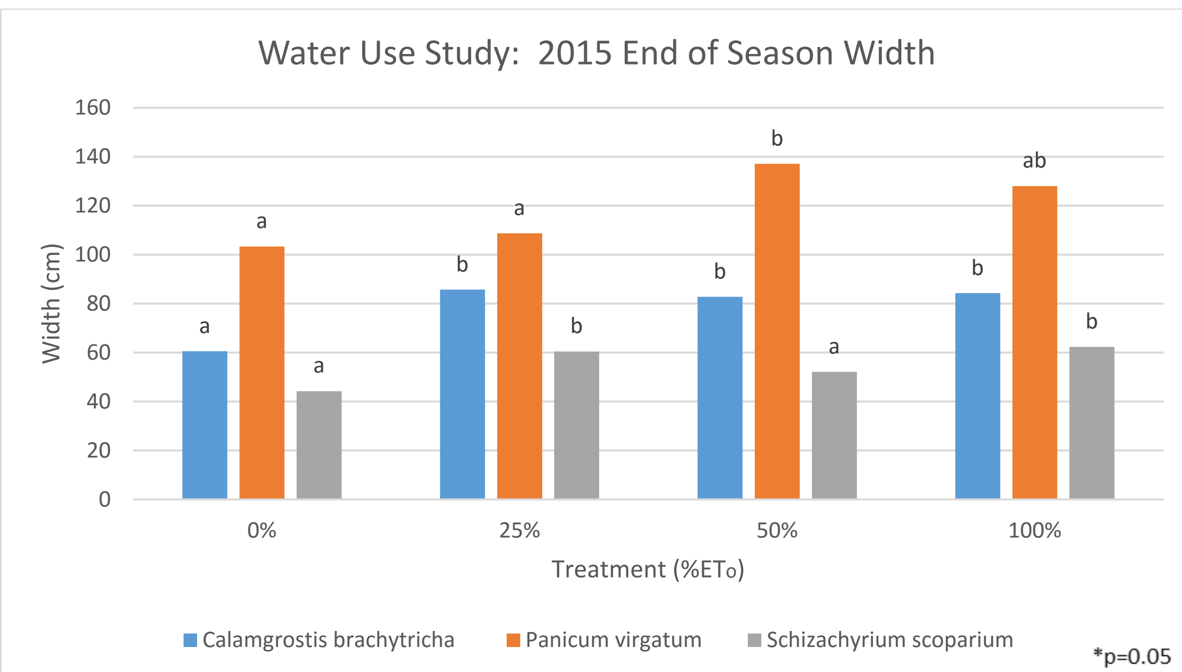
Appendix 1d: 2014 weekly rainfall, bluegrass evapotranspiration, and irrigation application per treatment. Any negative numbers represent weeks without irrigation events.



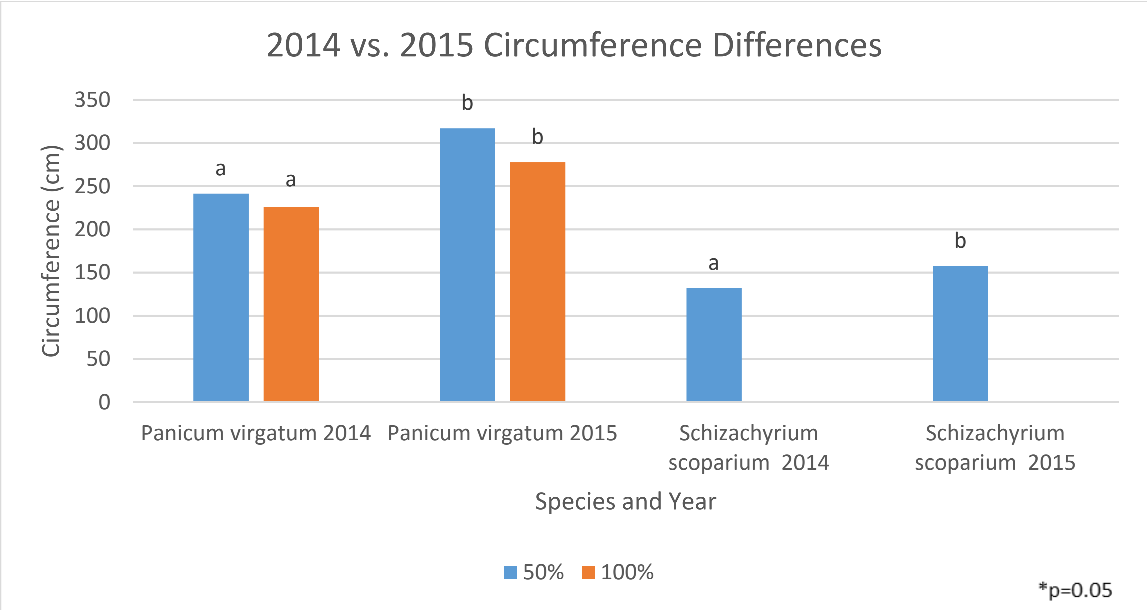
Appendix 1e: 2015 weekly rainfall, bluegrass evapotranspiration, and irrigation application per treatment. Any negative numbers represent weeks without irrigation events.



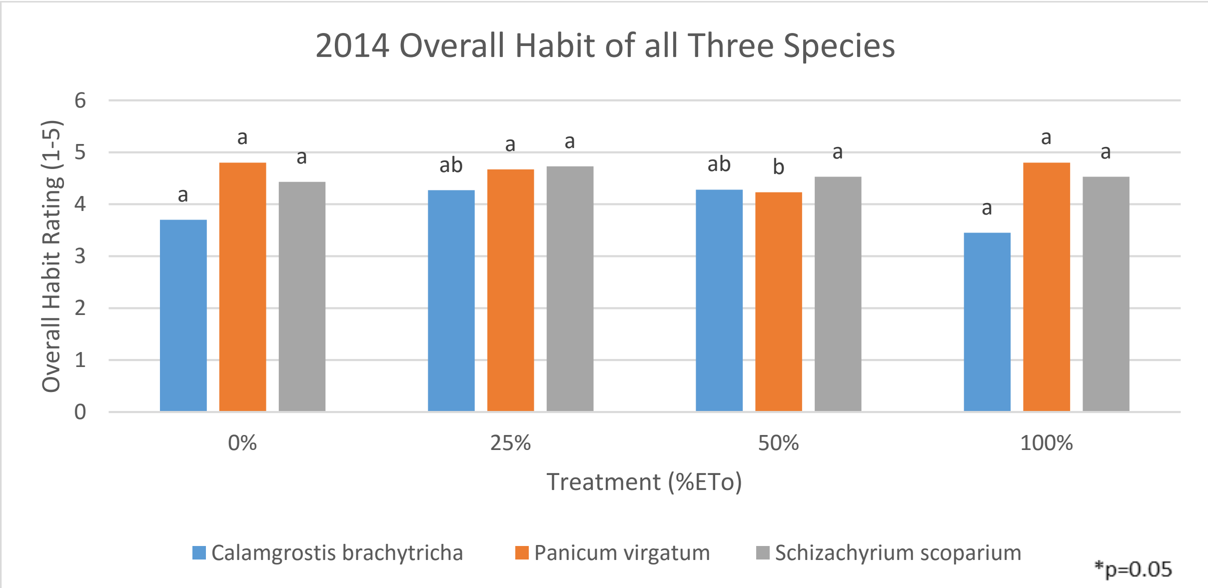
Appendix 2a: 2014 end of season width for all three species. *Calamagrostis brachytricha* in the 0% treatment were significantly smaller than all other treatments. *Panicum virgatum* 'Rotstrahlbusch' 0% plants were at the lowest level, while 50% plants were at the highest level. *Schizachyrium scoparium* 'Blaze' plants in 0%, 25%, and 50% were all significantly smaller in width than the 100% treatment. Different letters on bars denote significant differences.



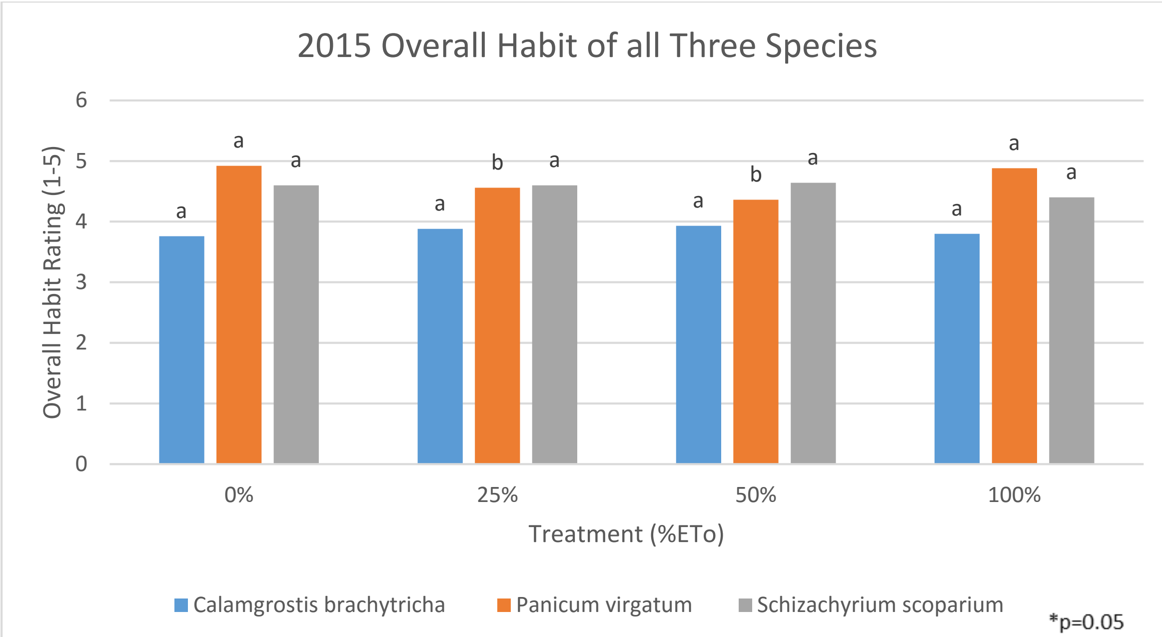
Appendix 2b: 2015 end of season width for all three species. *Calamagrostis brachytricha* and *Panicum virgatum* 'Rotstrahlbusch' followed the same trends as 2014. *Schizachyrium scoparium* 'Blaze' plants in the 0% and 50% treatments were significantly smaller than those in the 25% and 100% treatments. Different letters on bars denote significant differences.



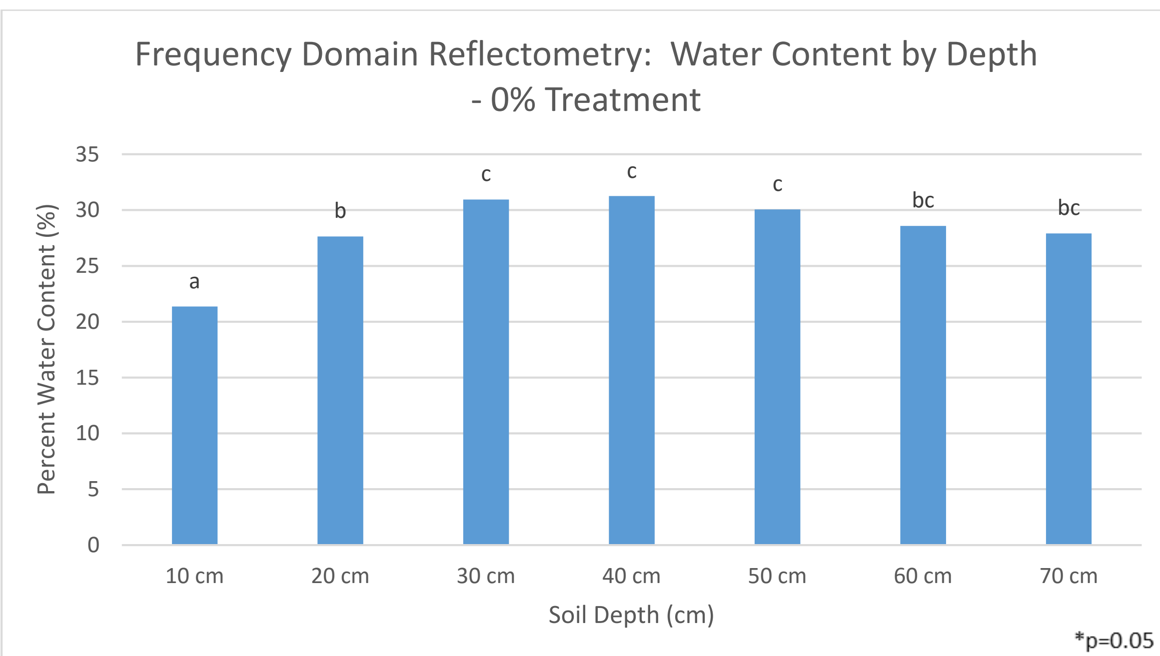
Appendix 2c: *Panicum virgatum* 'Rotstrahlbusch' plants in the 50% and 100% treatment were smaller in circumference in 2014. *Schizachyrium scoparium* 'Blaze' plants in the 50% treatment were smaller than those grown in the 2015 season. These results are likely attributed to the increased growth often exhibited after plants have established and adjusted to their environment. Different letters on bars denote significant differences.



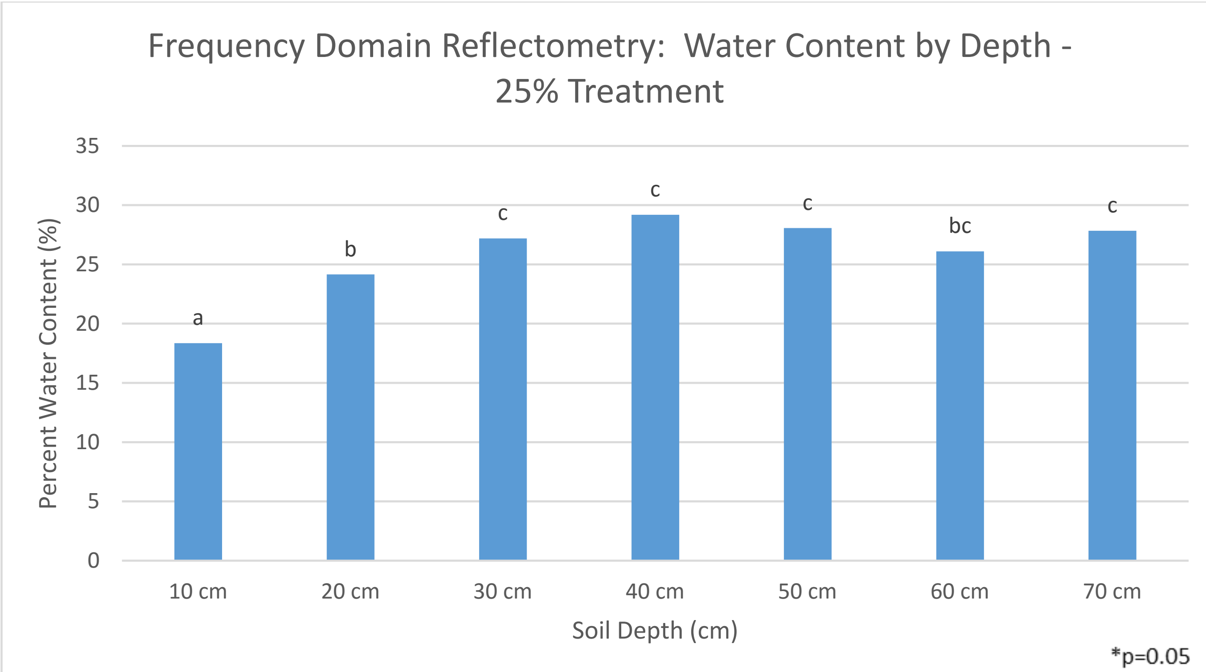
Appendix 3a: 2014 overall habit for all three species. There were no differences between treatments, with the exception of the 50% *Panicum virgatum* 'Rotstrahlbusch' having a lower rating than all other treatments. Different letters on bars denote significant differences.



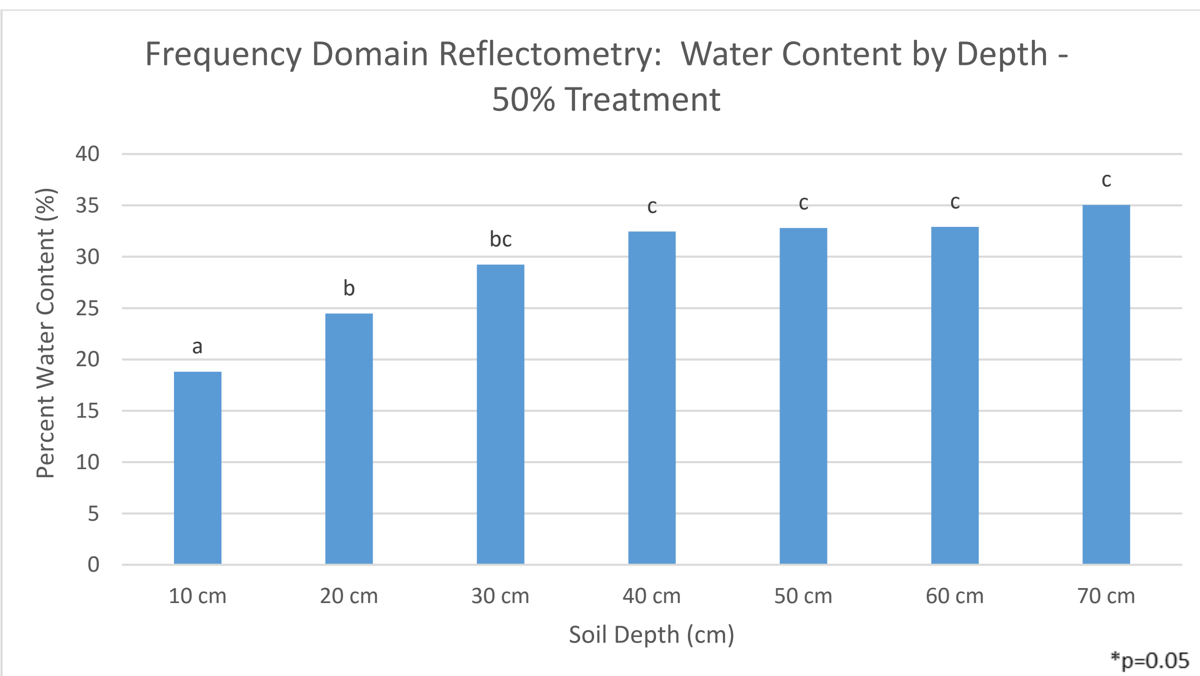
Appendix 3b: 2015 overall habit for all three species. There were no differences between treatments, with the exception of the 25% and 50% *Panicum virgatum* 'Rotstrahlbusch' having lower ratings than their 0% and 100% counterparts. Different letters on bars denote significant differences.



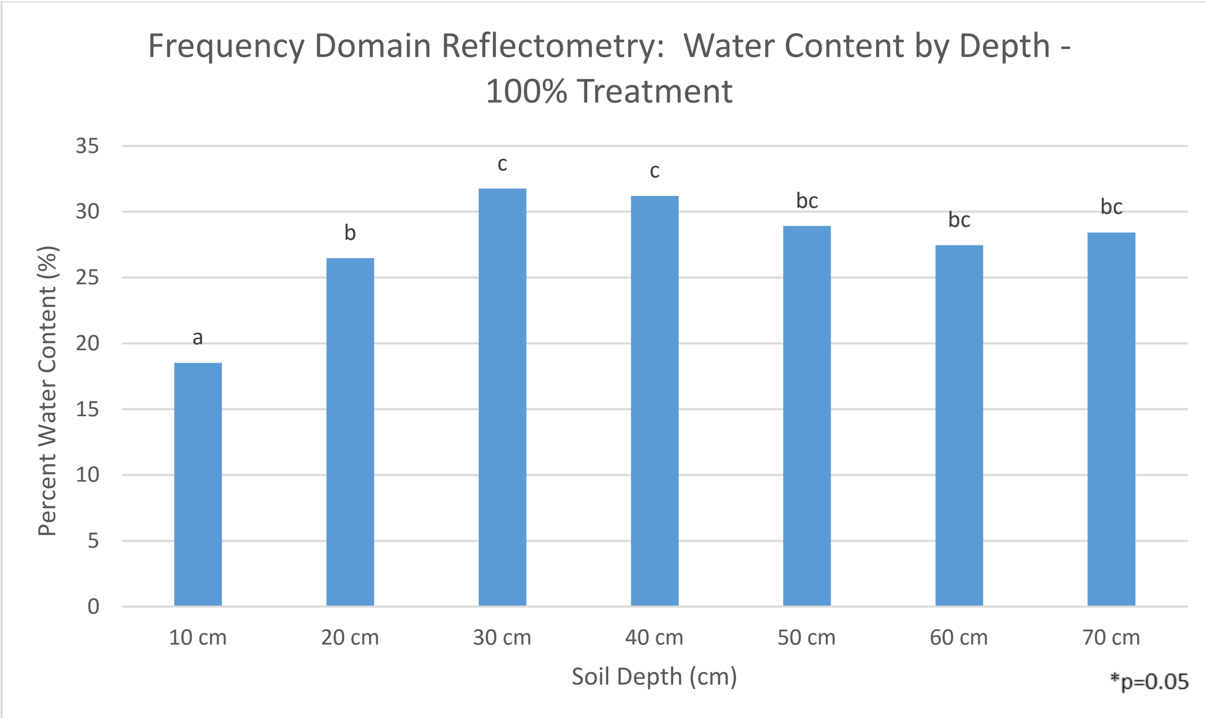
Appendix 4a: FDR examining water content by depth within the soil profile; 0% treatment. This research indicates a cessation of accessing significant portions of water between the depths of 20cm and 30cm. Different letters on bars denote significant differences.



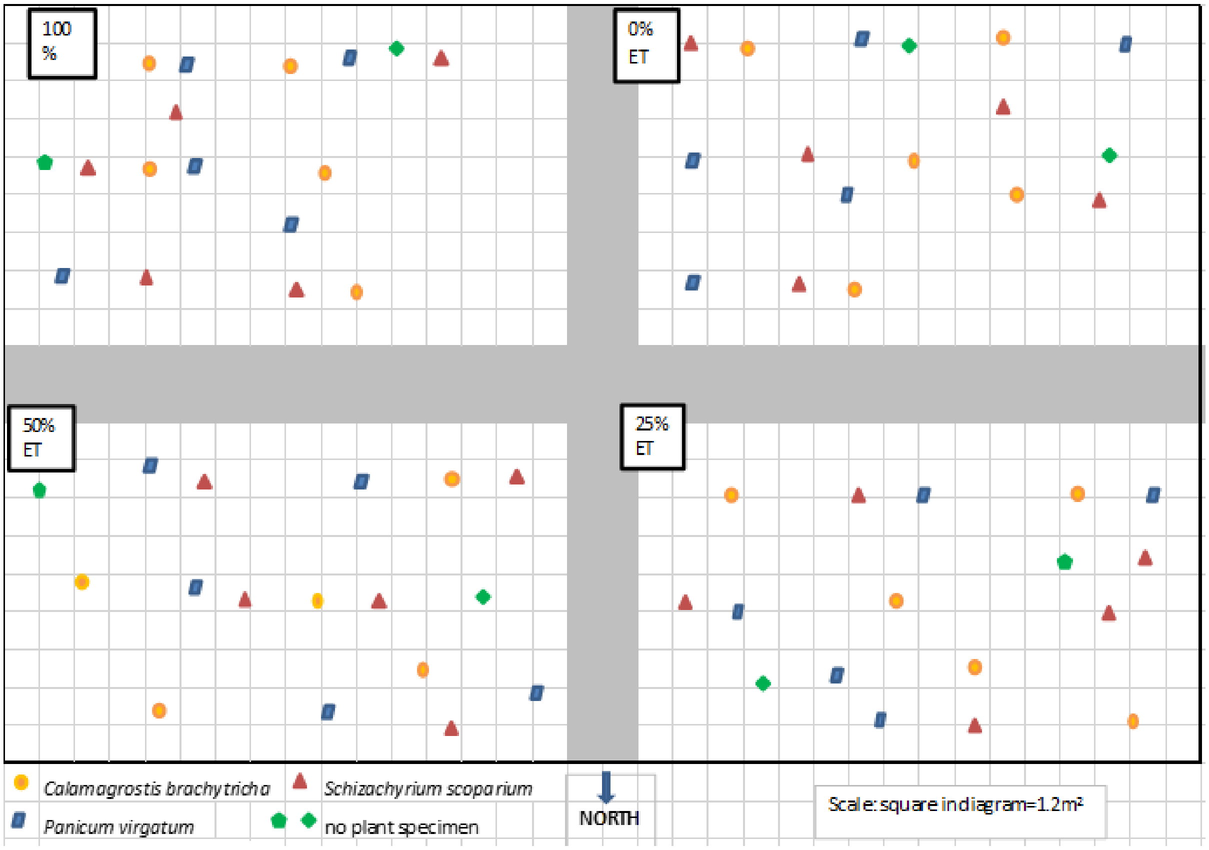
Appendix 4b: FDR examining water content by depth within the soil profile; 25% treatment. This research indicates a cessation of accessing significant portions of water between the depths of 20cm and 30cm. Different letters on bars denote significant differences.



Appendix 4c: FDR examining water content by depth within the soil profile; 50% treatment. This research indicates a cessation of accessing significant portions of water between the depths of 20cm and 40cm. Different letters on bars denote significant differences.



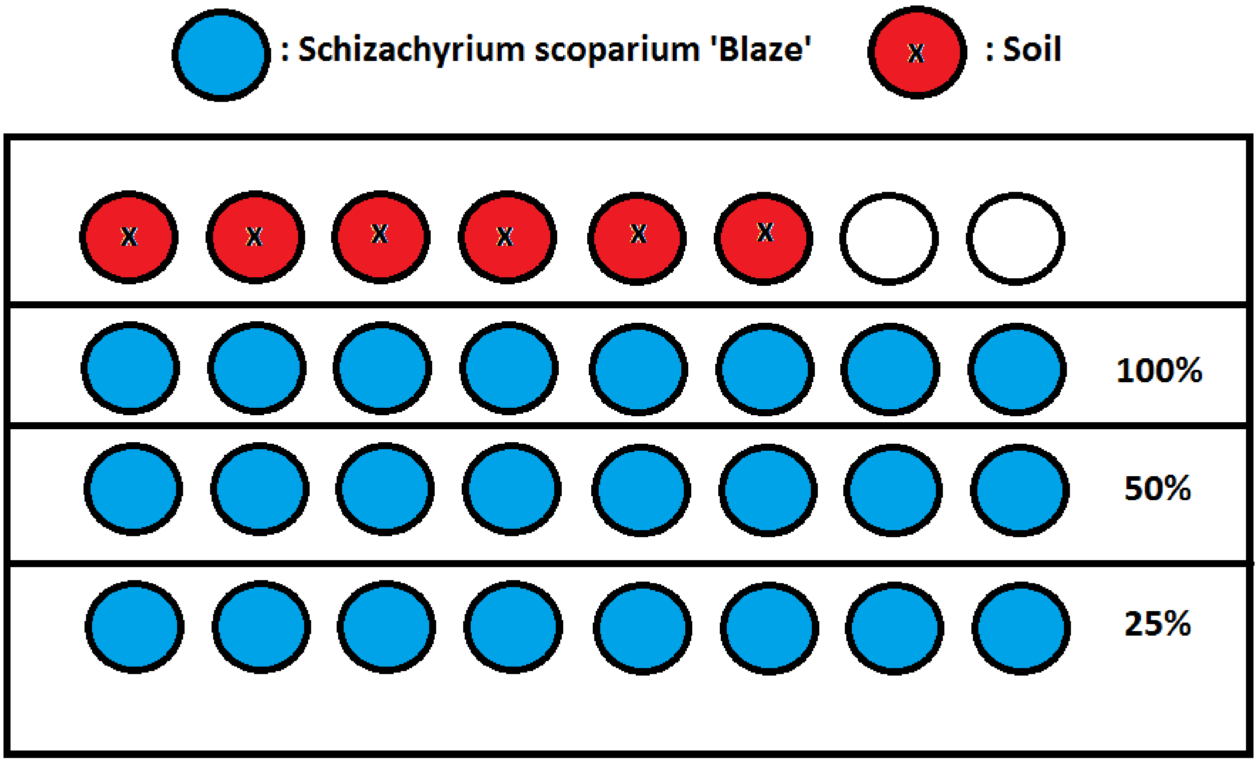
Appendix 4d: FDR examining water content by depth within the soil profile; 100% treatment. This research indicates a cessation of accessing significant portions of water between the depths of 20cm and 30cm, with a slight spike in water usage again between the depths of 50cm and 60cm. Different letters on bars denote significant differences.



Appendix 5a: Plot plan of Water Use Experimentation site. All four treatments are present, and each plot contains five of each species.

ITEM	DESCRIPTION	SCALE
Spring Green Up	When plants start to put out initial foliage growth	date
Height	Height to highest vertical point, including inflorescence	cm
Width	At widest point, does not include lodging parts	cm
Foliage Color	Royal Horticultural Society Color Chart	RHS #
Overall Growth Habit	Uniformity and lodging	1 = 80%+ prostrate 2 = 66% prostrate 3 = 50% lodging/prostrate 4 = 80% of plant upright/uniform/not lodging 5 = 95% of plant upright/attractive
Flowering Date	Initial date of first inflorescence	date
Floral Impact	"Showiness" of inflorescences themselves	1 = no flowers present 2 = 25% impact 3 = 50% impact 4 = 75% impact 5 = 95% impact, very showy
Fall Color	Color of foliage and date of change	RHS #
Self-seeding	Number of seedlings growing near plant	1 = many seedlings near plant 3 = some seedlings 5 = no seedlings
Winter Survival	Winter injury and overall survival	1 = dead 3 = 50% injury 5 = no injury
Pests	Any injury/pests present	1 = pest evident & detracting from appearance 3 = some pest damage, to 50% of plant 5 = no pests
Landscape Impact	Stand-alone ornamental value to the landscape	1 = very little ornamental value in landscape 2 = below average landscape appearance/value. Poor vigor and habit issue 3 = average landscape appearance/value. Good vigor but some habit issues 4 = Above average landscape appearance/value. Only minor problems 5 = Outstanding landscape appearance/value. Good vigor/foliage/flowering. No issues.

Appendix 5b: Visual quality rating values for each individual item. Scale was taken from the National Ornamental Grass Trials from the University of Minnesota (Meyer, 2015)



Appendix 6: Plot plan of Lysimeter Experimentation site. All treatments are present (including the control), and each plot contains eight of each species.

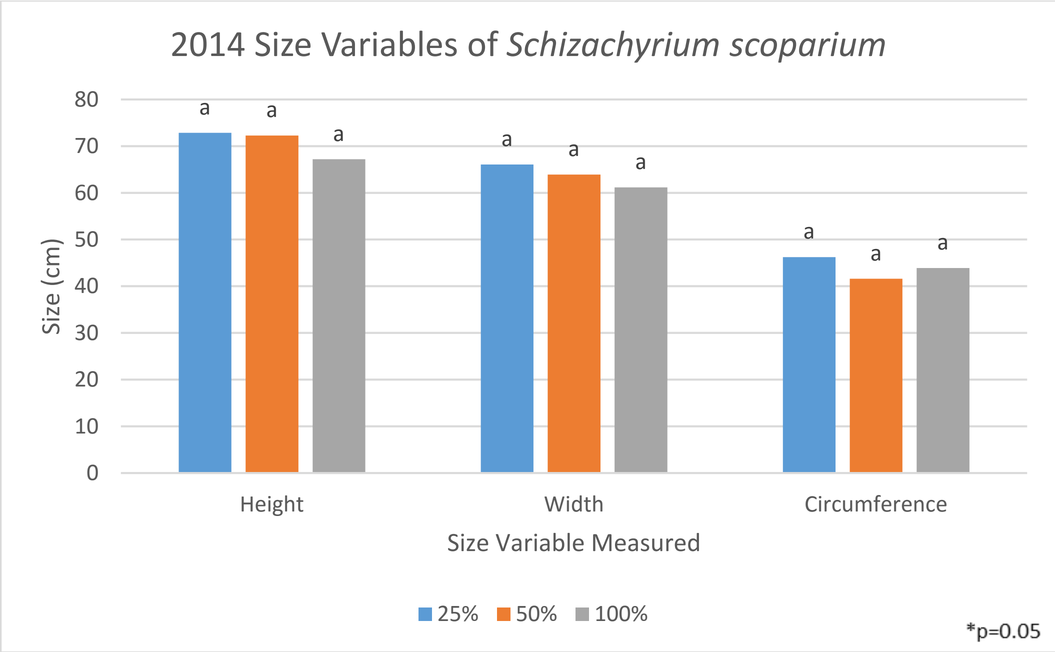
DATE	ET 100%	ET 50%	ET25%	Eto
7/20-7/26 2014	1.11	1.12	1.1	1.74
7/27-8/31 2014	0.525408	0.53353	0.492775	0.77
8/2-8/9 2014	1.068883	1.061376	1.00518	1.46
8/10-8/16 2014	0.856915	0.828499	0.774648	1.29
8/29-9/4 2014	0.987113	0.697022	0.594484	1.24
9/14-9/20 2014	0.872094	0.651626	0.538337	1.27
9/21-9/25 2014	0.378823	0.30327	0.25168	0.8
7/11-7/17 2015	1.15	1.13	1.08	1.7
7/18-7/21 2015	0.42	0.39	0.37	0.7
7/28-8/3 2015	1.05	1.1	1.06	1.49
8/09-8/16 2015	1.14	0.72	0.61	1.61
8/27-9/04 2015	1.25	0.86	0.63	1.9

Appendix 7a: Water use (ET) recorded by *Schizachyrum scoparium 'Blaze'* during each dry down period. The weekly amount of water applied to each treatment during the 2014 and 2015 seasons is seen. ETo represents Kentucky Bluegrass evapotranspiration.

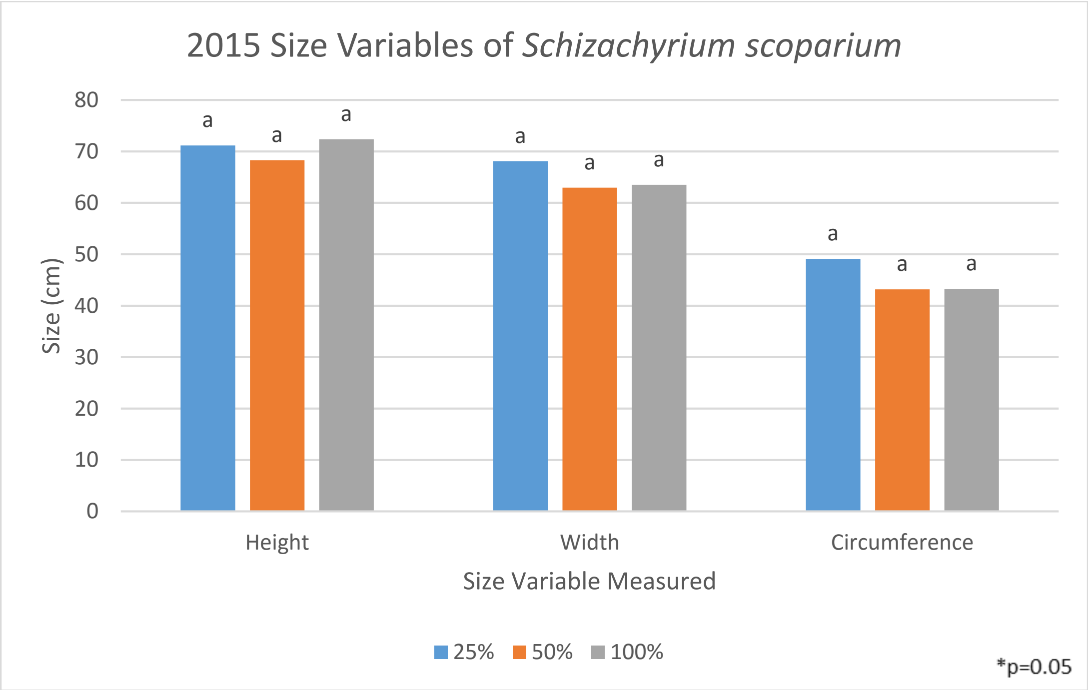
DATE	ET 100%	ET 50%	ET25%
7/20-7/26 2014	1.11	0.56	0.275
7/27-8/31 2014	0.525408	0.266765	0.123194
8/2-8/9 2014	1.068883	0.530688	0.251295
8/10-8/16 2014	0.856915	0.4142495	0.193662
8/29-9/4 2014	0.987113	0.348511	0.148621
9/14-9/20 2014	0.872094	0.325813	0.134584
9/21-9/25 2014	0.378823	0.151635	0.06292
7/11-7/17 2015	1.15	0.565	0.27
7/18-7/21 2015	0.42	0.195	0.0925
7/28-8/3 2015	1.05	0.55	0.265
8/09-8/16 2015	1.14	0.36	0.1525
8/27-9/04 2015	1.25	0.43	0.1575

Appendix 7b: Amount of water applied to each treatment during each dry down period. Information extrapolated from Appendix 7a.

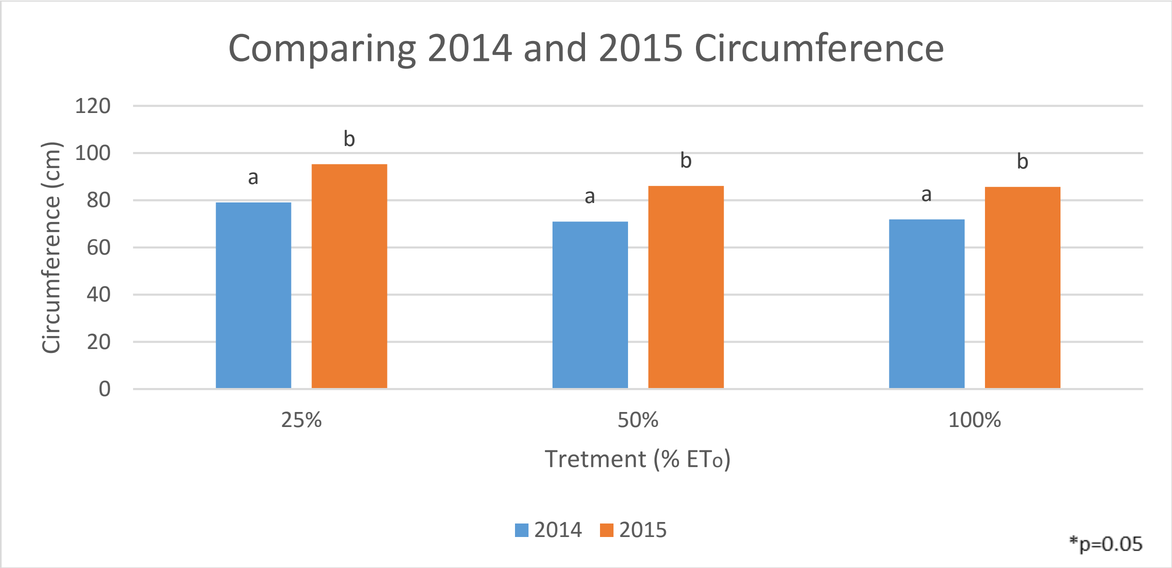
Appendix 8: Moveable A-frame used in the mini lysimeter study.



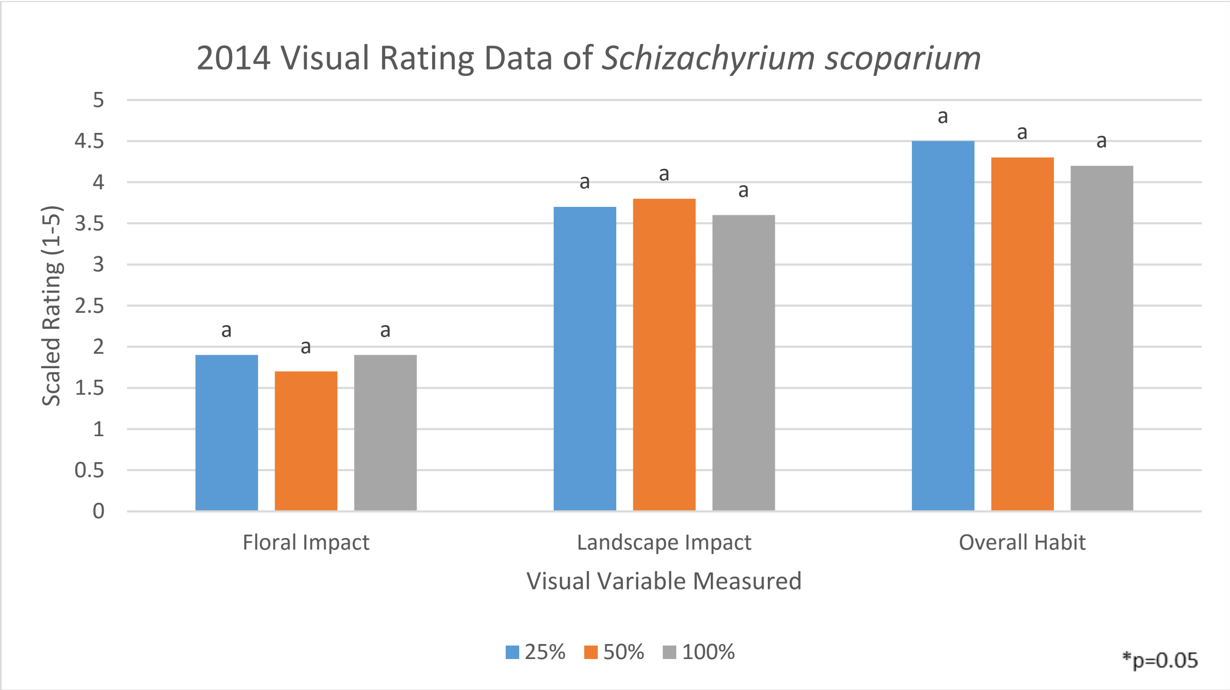
Appendix 9a: 2014 End of season height, width, and circumference of *Schizachyrium scoparium*. There are no differences between treatments. Different letters on bars denote significant differences.



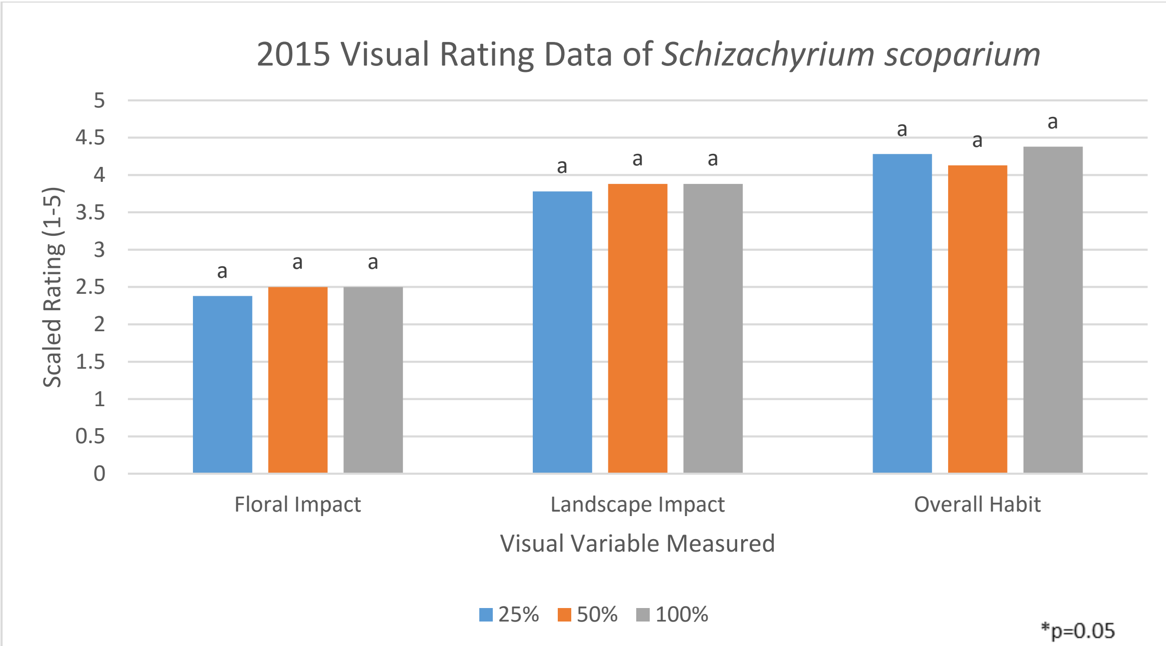
Appendix 9b: 2015 End of season height, width, and circumference of *Schizachyrium scoparium*. There are no differences between treatments. Different letters on bars denote significant differences.



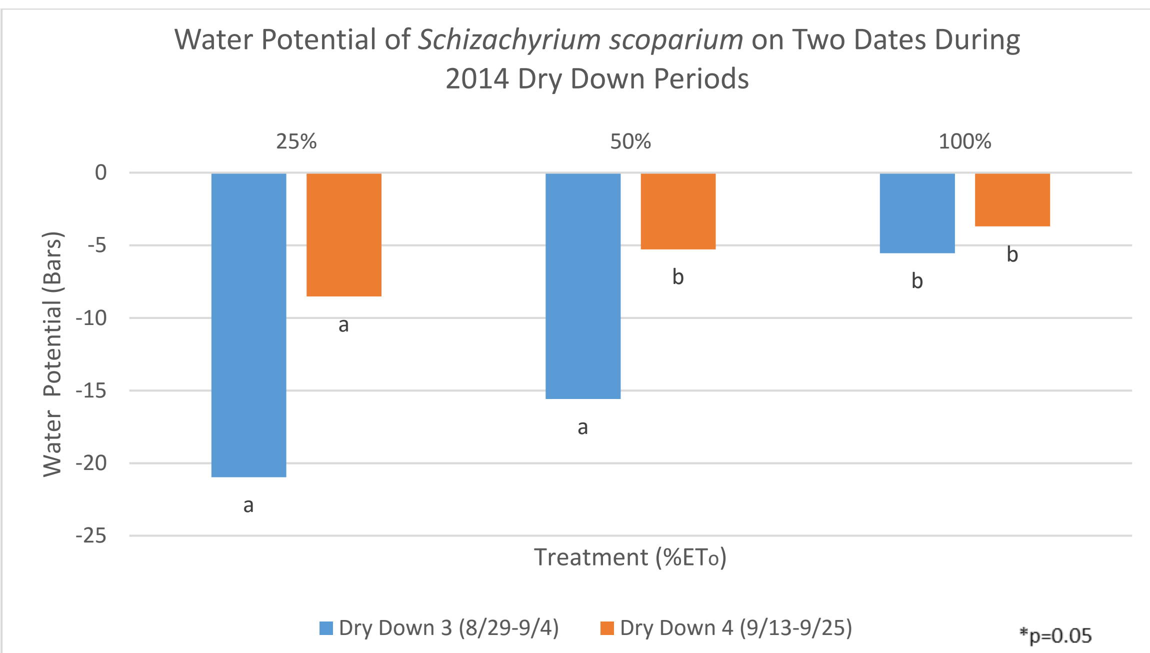
Appendix 9c: Comparing *Schizachyrium scoparium* circumference 2014 to 2015. All three treatments had a larger circumference in 2015. In 2014, plants were still establishing in their new environment after being transferred from the greenhouse. In 2015 it is likely that plants were established, and therefore were able to increase significantly in girth. Different letters on bars denote significant differences.



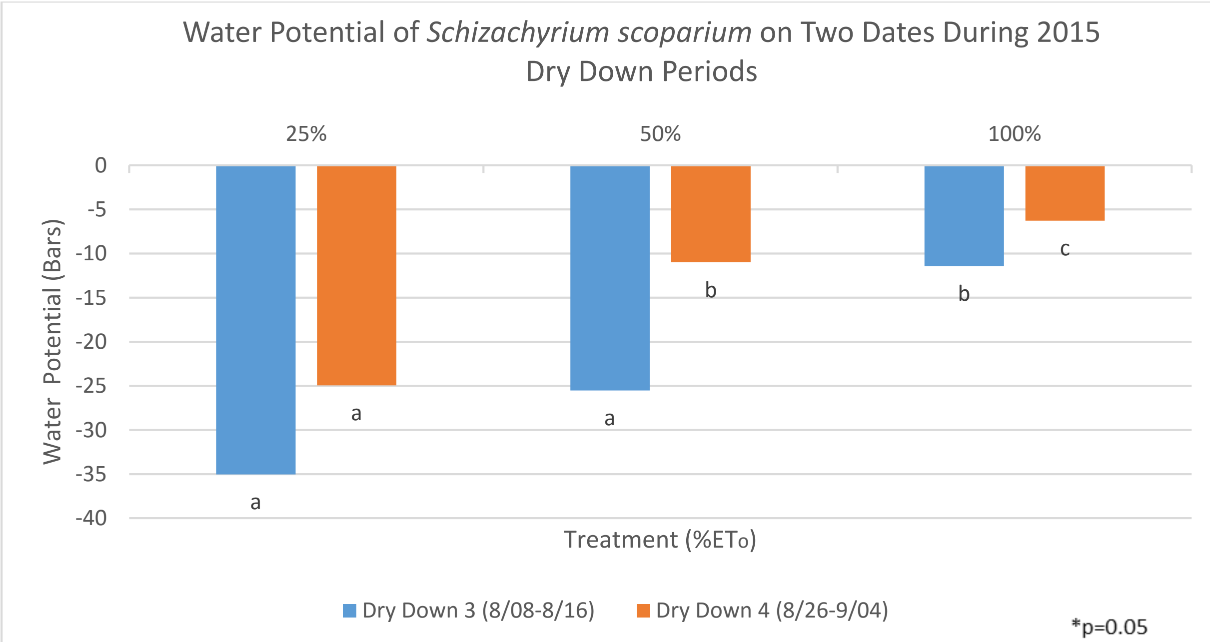
Appendix 10a: 2014 Overall season floral impact, landscape impact, and overall habit of *Schizachyrium scoparium*. There are no differences between treatments. Different letters on bars denote significant differences.



Appendix 10b: 2015 Overall season floral impact, landscape impact, and overall habit of *Schizachyrium scoparium*. There are no differences between treatments. Different letters on bars denote significant differences.



Appendix 11a: Differences between three treatments on two specific dates during the third and fourth dry down periods of 2014. This substantiates that as time passes in the growing season, plants in the 25% are significantly more stressed during drought. Different letters on bars denote significant differences.



Appendix 11b: Differences between three treatments on two specific dates during the third and fourth dry down periods of 2015. This substantiates that as time passes in the growing season, plants in the 25% are significantly more stressed during drought. Different letters on bars denote significant differences.

Report Date: 06/09/2014	
ITEM	**VALUE**
pH	7.6
Electrical Conductivity	0.5 mmhos/cm
Lime	Very High
Texture Estimate	Sandy Clay Loam
Sodium Absorption Ratio	0.1
Organic Material	6.8%
Nitrate	6 ppm

Appendix 12a: Summarized soil test of field soil from Colorado State University Soil, Water and Plant Testing Laboratory.

Report Date: 06/09/2014	
ITEM	**VALUE**
pH	7.5
Electrical Conductivity	0.5 mmhos/cm
Lime	Very High
Texture Estimate	Sandy Clay Loam
Sodium Absorption Ratio	0.1
Organic Material	7.0%
Nitrate	124 ppm
Phosphorus	621.3 ppm

Appendix 12b: Summarized soil test of lysimeter soil from Colorado State University Soil, Water and Plant Testing Laboratory. Lysimeter soil was taken from the field site.