THESIS

IRRIGATION EFFECTS ON GROWTH AND VISUAL QUALITY OF THREE ORNAMENTAL GRASS SPECIES

Submitted by

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ABSTRACT

IRRIGATION EFFECTS ON GROWTH AND VISUAL QUALITY OF THREE ORNAMENTAL GRASS SPECIES

Ornamental grasses have become ubiquitous in the landscape and are popular with consumers and industry professionals because of their favorable low-input cultural characteristics. These characteristics include low water and nutrient requirements, decreased maintenance, fast growth and few disease and insect problems. A study conducted at Colorado State University (Fort Collins, CO) examined the effects of four irrigation levels (0, 25, 50 and 100% of potential evapotranspiration (ET)) on growth and visual quality of three species of ornamental grasses (*Panicum virgatum* 'Rotstrahlbusch' (Rotstrahlbusch Switchgrass), *Schizachyrium scoparium* 'Blaze' (Blaze Little Bluestem) and *Calamagrostis brachytricha* (Korean Feather Reed grass)). Averaged across species, maximum plant height and width was observed at the 25% irrigation level. We found that plant dry weight increased as irrigation level increased from 0 to 50% of ET, but there was a decrease in total plant dry weight at 100% of ET. This indicates that watering these species of ornamental grasses at 100% ET may be detrimental to growth and plant quality. The greatest drought stress, as measured by leaf water potential, was found with the mesic species *C. brachytricha*. Averaged across species, leaf water potential was most negative (greatest drought stress) at 0% of ET and the least amount of stress was observed at 50 and 100% of ET. At the conclusion of the study, visual ratings of plant form, floral impact and landscape impact were highest at the 25% of ET irrigation level. Our research with these three species in Colorado suggests that irrigation at 25% of ET produces the healthiest plants, with

greater height, width, dry weight and visual impact in the landscape. This agrees with anecdotal observations that ornamental grasses will perform better in a landscape with limited irrigation and other inputs.

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CHAPTER 1. Introduction and Literature Review

Ornamental grasses have become ubiquitous in the landscape and are popular landscape plants with consumers and industry professionals because of their favorable low-input cultural characteristics. These characteristics include low water and nutrient requirements, decreased maintenance, fast growth, and few insect and disease problems (Meyer, 2004). Since USDA first defined a separate category for ornamental grasses in the Nursery Crops Summary data in 2003, sales (both retail and wholesale) have increased from $61,213,000 in 2003 to $116,827,000 in 2006, nearly doubling sales in three years (USDA, 2007). This increase in interest in both wholesale and retail sales figures also corresponds with increases in the number of varieties and cultivars. In 1973, 31 taxa of ornamental grasses were identified for landscape use in the United States (Meyer and Mower, 1973). In the 2014-2015 Bluemel Wholesale Nursery catalog, a primary producer of ornamental grasses, 282 cultivars/varieties in 46 genera are listed and available for use in American landscapes (Bluemel, 2014).

Cultivar introductions from native and non-native plant populations have been increasing and the Green Industry is seeking out plants with aesthetic appeal to consumers (Alvarez, 2007). Many cultivars of native and introduced species have been selected for their ornamental characteristics for use in home and commercial landscapes (Dana, 2002; Meyer, 2012). An increasing need for ornamental grass species which respond to desired landscape features are sought after from the nursery industry (Meyer, 2012).

Growing population and agricultural pressures on natural and cultivated plant environments, prediction of increased temperatures, faster evaporation and more sustained droughts in the

Great Plains region of the United States have been forecasted due to climate change (Overbeck, 2010; USGCRP, 2012). Focusing on water use and drought tolerance in native and ornamental grass species seems appropriate and timely. Many native grasses from the Great Plains of the United States have qualities in tune with approaching global climatic change: They have high degree of tolerance to insects, disease and most importantly heat and drought (Thetford, et al. 2009).

Studied Parameters of Native and Ornamental Grasses

Native grasses that thrive in the American tallgrass prairies have been studied for many parameters including carbon sequestration, biofuel sources, livestock forage, water sourcing and drought tolerance(Eggemeyer, et al. 2008, Gibson, 2009, Bolger, 2005, Bacon, 2004, Knapp, 1984). Very few studies examine native grass varieties and cultivars in urban landscape cultural conditions (Wolfe & Zajicek, 1998). Examining studies of native as well as introduced grasses may reveal how the ornamental cultivars respond to differing water and cultural needs.

Ornamental grass studies have evaluated specific varieties and cultivars for cold hardiness and heat zones (Davidson & Gobin, 1998; Meyer & Cunliffe, 2002; Perry, 1992; Wolfe & Zajicek, 1998, Thetford, et al., 2009, 2011) as well as invasive characteristics (Wolfe, et al. 1994), herbicide tolerance (Derr, 2002) and salt-tolerance (Scheiber, et al., 2008). Research on water use and relative drought tolerance in ornamental grass species has not been thoroughly examined, especially for non-native cultivars and under landscape settings (Meyer, 2012). The identification of species whose water requirements correspond to the available water in a landscape would be advantageous to landscape designers and homeowners (Save, 2009). At this time, most of the information on water use in grasses tends to be anecdotal and based on observations rather than research data (Save, 2009; Dana, 2002). For instance, in Colorado, the Green Industries of Colorado (GreenCO) compiled plant water requirement estimates based on surveys of state horticulturalists and industry professionals and rated many landscape plants based on their opinions and observations of water use (GreenCO & Wright, 2008). Since the growth quality of the ornamental plants is important to industry and consumers, studies which incorporate detailed water use and ornamental qualities could provide additional information for industry and consumers to make wise decisions on plant choices. Selection of appropriate cultivars by the nursery industry is important to the survival and growth of ornamental grasses in landscapes (Franco, et al., 2006).

Ornamental Grasses in Irrigation Study

Two species of native grasses have many cultivars available for landscape use. *Panicum virgatum L.* (Common name: Switchgrass) is a perennial native grass found in all regions of the continental US except for California and the Pacific Northwest (USDA, 2011). This warm season, clump-forming rhizomatous spreader reaches to 1.2 to 2.4 meters in height and tolerates a variety of soil types, except heavy clay (Darke, 2007). The USDA lists *P. virgatum* as a moderately drought tolerant grass, or drought tolerant once established, depending on the source (Darke, 2007; Barkworth, et al., 2007). The ability to be drought tolerant varies with variety and may be better in glaucous-leaved forms (Darke, 2007). *P. virgatum* produces numerous panicles in July and August (USDA, 2011).

Schizachyrium scoparium (Michx.)Nash (Common name: Little Bluestem) is a perennial native grass found in all regions of the continental US except Nevada and Oregon. It will grow in a variety of soil types and moisture conditions and has excellent drought tolerance (USDA, 2011; Darke, 2007). This warm season, clump-forming species typically has a mature height ranging from 0.6-1.2 meters.

Both *P. virgatum* and *S. scoparium* are considered warm season C_4 grasses, which characterizes a distinctive photosynthesis mechanism in which they concentrate atmospheric CO_2 using phoshoenopyruvate (PEP) carboxylase to form a four-carbon organic acid. This is in contrast to C_3 grasses such as *Calamagrostis spp.,* which use RuBP carboxylase(Rubisco) to bond CO_2 with Ribulose 1,5 bisphosphate (RuBP) to form two 3-carbon organic acids(Taiz & Zeiger, 2006). C_4 plants have a distinctive Kranz leaf anatomy, where bundle sheath cells take the 4-carbon organic acid product from the mesophyll cells, decarboxylate it where the resulting 3-carbon acid is fixed by Rubisco (Moser, et al., 2004). The difference between the two types of photosynthesis is significant since CO_2 fixation becomes limiting for C_3 plants at high light and temperatures, while C_4 plants are less light sensitive and are less affected by high temperatures (Moser, et al., 2004). When weather is hot, C_3 plants tend to exhibit photorespiration, in which the Rubisco catalyzes a reaction with oxygen instead of CO_2 (which is unavailable due to stomatal closure) causing a reduction of efficiency in the Calvin cycle and decreasing net photosynthesis (Taiz & Zeiger, 2006). On the other hand, in C_4 plants, PEP carboxylase does not bind with oxygen, so high temperatures does not influence respiration; optimal growth temperatures for C_4 photosynthesis ranges from 35-38° C. This gives C_4 grasses an advantage in high temperature and intense light environments, such as those that are present in the Great Plains (Moser, et al., 2004).

Non-native ornamental grass cultural characteristics have been infrequently studied (Meyer, 2012). One such plant, *Calamagrostis brachytricha* Steud. (Korean feather reed grass) is a grass which originates in the moist woodlands of Eastern Asia. It tolerates variable conditions "as long as the moisture levels are sufficient." (RHS, 2014). It grows to 0.61-0.91 meters tall, with flower plumes appearing in early fall. It is sometimes classified as *Calamagrostis arundinacea var. brachytricha* and has been classified as both a warm season (Meyer, 2004; Yuan, 2011) and cool season grass (Darke, 2007), making a definitive classification difficult. According to Sage, *et al*. (2011), many grass genera are difficult to accurately place in a C_4/C_3 lineage due to limited phylogenic information. This may be the case with *C. brachytricha.*

<u>Drought tolerance definitions</u>

The discussion of water use in low precipitation areas such as the high plains of Colorado should also include the adaptive mechanisms plants use to survive low water times during their life cycles. *Drought resistance* is the ability of plants to survive persistent limited soil moisture conditions (Taiz & Zeigler, 2006). This resistance to dry conditions can be divided into 3 categories: escape, avoidance and tolerance. Most plants do not fit just one category of drought resistance, as they may exhibit a range of responses when subject to dry conditions (Chavez, et al., 2003). *Drought escape* defines those plants that complete their lifecycles before low water use conditions effect their metabolic activities (Bacon, 2004). They are able go through an entire life cycle (including seed production) before water becomes scarce.

Avoidance characterizes those plants that can avoid tissue dehydration by either maintaining high water potentials despite low soil moisture conditions or by tolerating low tissue water potentials (Chaves, et al., 2003). These plants utilize deep root systems to maximize water uptake and high shoot to root ratio increasing root area for more water absorption. Other xeromorphic characteristics that can minimize water loss are stomatal control of transpiration, rolling or folding leaves, shedding of older leaves, and leaf hairs (Bolger, et al., 2005; Kadioglu & Terzi, 2007). *Drought tolerance,* on the other hand, includes those plants that can manipulate their own biochemical pathways for osmotic adjustment. They are able to accumulate solutes in cells which lower plant water potential in relation to the soil, which increase the plant's ability to extract water from the soil (Kramer & Boyer, 1995). They also have the ability to withstand low tissue water potentials by decreasing cell size and increasing cell elasticity. *Schizachyrium scoparium, P. virgatum, and C. brachytricha* utilize varying degrees of drought tolerance and avoidance mechanisms to survive periodic drought (Moser, et al. 2004). Recent research on *S. scoparium* has shown that drought causes non-stomatal physiological effects through changes in the C_4 cycle, possibly C_4 enzyme or activation site changes (Maricle & Adler, 2011).

Evapotranspiration

The combined evaporation of water around the plant as well as the transpiration from the leaf tissues is known as evapotranspiration or ET (Hanson, 1991). ET is dependent on many variables including net solar radiation, humidity, wind speed, type of vegetative cover, availability of soil moisture, root depth, land-surface characteristics and time of year (Clifford & Doesken, 2009; Hanson, 1991). Reference ET (ETo) represents the amount of soil water that is vaporized from a specific uniform vegetative cover (Walter, et al., 2005). Reference ET can be calculated in

Colorado with two reference crops; alfalfa and a cool season turfgrass using an ASCE Standardized Penman-Monteith Equation (Walter, et al., 2005). Using ETo is a frequently used method for determining irrigation events for turfgrass landscapes and crops (St.Hilaire, et al., 2008). For the cool season grass reference crop (ETos), this value is measured by the Northern Colorado Water Conservation District in Colorado at many field sites including four Ft. Collins sites (NCWCD, 2014). This reference value (ETos) is then multiplied by the crop coefficient (Kc) which results in the particular crop evapotranspiration (ETc) for a specific crop species (Grant, OM, 2013). Unfortunately, Kc values are unknown for most ornamental plant species (Shaw & Pittenger, 2004). Also, reference crops such as cool season turf grass and corn are usually uniform surfaces; this is not the case for ornamental plantings of varying heights and plant types (St.Hilaire, et al., 2008). Yield is not measured in ornamental plant growth; appearance and proposed function in the landscape are the intended objective (Shaw & Pittenger, 2004). There has been an attempt to calculate individual 'Plant Factor' Kc coefficients in landscape ornamental materials (Shaw & Pittenger, 2004; St.Hilaire, et al., 2008), but these are impractical to calculate for ornamental grasses due to the many cultivars and varieties and the non-uniform growth habit of these plants. Therefore, using an existing reference crop such as a cool-season grass (ETos) could be utilized by using varying percentages of the ETos as watering guidelines to estimate optimal water use needed for plant appearance in ornamental grasses. In GreenCO's Best Management Practices (BMP) (2008), the annual required irrigation application based on ETos was estimated based on survey data collected from regional horticulturalists and industry professionals (GreenCO, 2008). Their list of approximately 1575 plants, including several species of ornamental grasses, gives observed water needs based on experience with the plant material; experimental data was not collected. Therefore, data collected using a percentage of ETos could validate GreenCO's estimated ratings and provide more accurate information on a specific plant's water use. This study's experimentally derived water information would be compared to a plant's appearance and function in the landscape to determine which ornamental grass cultivars/varieties would do well at a specific percentage of ETos.

Research on Ornamental grasses

Studies of water use on selected ornamental grass cultivars plants have been few (Meyer, 2012). Thetford *et al*., (2009) looked at 23 native and nonnative species of grasses in two separate trial sites in Florida. Their 3-year study found that when the species were evaluated for long-term growth, flowering, vigor, quality and survival, differences became apparent not only between species but within the same species planted in the different plots. These plants were grown under low input conditions, and after establishment, the plants were not irrigated or fertilized, however, study sites received approximately 165.1 cm (65 inches) of rainfall/year. When evaluating two cultivars of *P. virgatum* ('Alamo' and 'Heavy Metal') included in the study, it was found that both cultivars survived the duration of the study with a plant mortality rate of 25%. 'Alamo' had good 3-year landscape performance ratings, and 'Heavy Metal' had good marks only during the first year of the study. The author assessed measurable parameters such as plant width and height for the plants in study and used landscape quality ratings and plant survival each year during the study to designate survival in low input conditions.

In a separate study, Thetford, *et al.* (2011) evaluated *S. scoparium* and the *P. virgatum* cultivar 'Prairie Sky' as well as other ornamental species for response to varying degrees of irrigation inputs and fertilization in two North Florida plots. Measured parameters including foliage width and height, basal area and flowering height and appearance were used when evaluating grasses at two irrigations levels. One site had no supplemental irrigation (annual rainfall of 149.9 cm (59 inches) and 119.4 cm (47 inches) at each site), and other site received one gallon (3.79L) of water per plant per week. They found that *S. scoparium* and *P. virgatum* 'Prairie Sky' did not respond in a significant way to irrigation or fertilization during the trial period.

Both of the above studies examined native and non-native ornamentals in field studies, which mimicked a homeowner landscape. Though Thetford, *et al*. (2011) did not find *S. scoparium* responded to irrigation, a greenhouse study by Kochisiek, *et al.* (2006) however, found that native *S. scoparium* did respond to irrigation. In the Kochisiek, *et al.* study (2006), *S. scoparium* had a positive correlation with watering, with an increase in photosynthesis, stomatal conductance and water use efficiency (WUE). This study compared plants which were fertilized and unfertilized, taking time-domain reflectometer soil moisture readings (TDR) and WUE readings (net photosynthesis and stomatal conductance with LICOR 6400) at field capacity and subjecting one group of plants to a dry-down period of 15 days (to 15% of field capacity) before re-watering. Their results show that *S. scoparium* did respond to additional irrigation after the dry-down period. Lower WUE has been shown in the field with studies by Eggemeyer *et al., (*2008) and Awada (2002) which both found that when water was not limiting, *S. scoparium* had lower WUE than *P. virgatum*. When drought stressed, the greater root depth of *P. virgatum* for accessing water in the landscape appears to be an advantage over *S. scoparium*, though this advantage may be reversed when water is present. (Eggemeyer et al., 2008; Kochisiek, 2006).

Alvarez, *et al.* (2007) evaluated two species of ornamental grasses for water stress and growth in a native species of grass (*Eragrostis spectabilis*) from Florida grown for ornamental use and a nonnative species from Asia (*Miscanthus sinensis* 'Adagio'). Plants were subjected to a rain-excluded landscape with irrigation volumes of zero, 0.25L, 0.5L and 0.75L. As irrigation volume increased, it was found that biomass and canopy size increased in both plants, with the native *E. spectabilis* having greater overall growth. They found that *E. spectabilis* water stress integral, (S_Ψ), the cumulative integral of pre-dawn leaf water potential over any chosen period of time, was greater than that of the non-native species *M. sinensis.* This indicates that this native species had greater drought tolerance than the non-native. The author stressed, however, that this finding cannot be applicable in general to all plants placed in drought situations. Evaluations should be done on specific grass species and should also be site specific before plants can be considered low-water use.

Calamagrostis brachytricha was evaluated under four irrigation levels based on crop evapotranspiration (ETc) in Beijing, China. In a mini-lysimeter study, Yuan *et al.* (2011) evaluated the growth responses of *C.brachytricha* and *Festuca glauca* when irrigated at 25%, 50%, 75% and 100% of crop evapotranspiration (ETc). They also calculated the Kc values for these grass species to estimate water savings when deficit irrigation is correlated with ET. Yuan *et al.* (2011), found that both of the ornamental grasses maintained an acceptable appearance in the landscape when 75% ETo (ET reference) was applied to the grasses. They were able to calculate that the grasses needed between 315 to 517 mm (12.4 to 20.35 inches) supplemental water during the growing season. Normal annual rainfall in Beijing is 57.4 cm (22.6 inches). They also noted that shoot height, number of tillers and dry weight were all comparable to the

100% ET plants and concluded that the only irrigation regiment that maintained an acceptable landscape appearance to the 100% ET was the 75% level.

Research on grass response to low water situations

Many papers reference the classical work by Weaver (1958) for root depth of these grass species in their natural habitat. Most grass roots are shallow (>75% in top 0.1 m), but have the ability to penetrate deeper into the soil profile, usually up to 0.91meters (Weaver, 1958). More recent research indicates that 75-80% of the cumulative root biomass and 85-90% of the root length were found in the top 0.3m of the soil (Eggemeyer, et al., 2008). When *S. scoparium* and *P. virgatum* roots were evaluated in soil profile, it was found these species access water (close to 100%) in the top 0.5 meters of soil profile when water was plentiful, but below 0.5 meters during drought (Eggemeyer, et al., 2008). Eggenmeyer, *et al.* (2008) surmise that this primary use of shallow water in semi-arid grasslands may reflect a high threshold of tolerance to relatively low input conditions. Being able to analyze water use depth data on ornamental grasses may confer which cultivars or varieties are able to access water deeper in the soil and therefore show more drought tolerance.

Leaves can respond to low water or drought conditions morphologically as well. Leaf rolling or folding is a drought avoidance mechanism which contributes to the plant's ability to minimize leaf area, which subsequently decreases water loss in the plant (Bolger, et al., 2005). Leaf rolling and/or folding also reduces the surface area of the leaf, limiting the plant's exposure to sunlight as a photo-protective mechanism (Chaves, et al., 2003). Since native and ornamental grasses exhibit rolling or folding of leaves during drought stress, examining these morphological clues to drought stress may also reinforce other data on water stress in plants.

There are few studies of ornamental grasses using amended soils. Since many soils in home landscapes are amended with organic matter, ornamental grass characteristics may change as a response to not only increased nitrogen, but other minerals and micronutrients as well. Studies have shown that a slight increase in nitrogen may confer higher WUE in non-drought stressed landscapes (Ghannoum, 2009). Maricle & Adler (2011) found that decreased nitrogen assimilation did not confer changes to carbon assimilation in drought. When comparing non-native ornamental grass species with more native species (*S. scoparium* and *P. virgatum*) in terms of water use and drought tolerance, the results may give a better indication on which species should be more appropriately marketed and sold in Colorado. Specific species categorized as being more drought tolerant than others will enable the ornamental plant industry to make decisions on the best use of plant material depending on landscape conditions.

Though research has studied switchgrass and little bluestem in regard to their relationship to the tallgrass prairie ecosystem, there have been relatively few studies on the relationship of these grasses and water use to the ornamental landscape. Though ornamental grass use is small in comparison to ecological studies in grasslands, the water use in home landscapes is becoming an increasing concern to municipalities and other government entities which are imposing water use restrictions in response to increasing demand and dwindling supply. Since water use in agronomic crops will most likely continue to take more than 85% of the water in Colorado for future food supply (CAWA, 2008), decreases in water use for home landscapes and the need for low water use plant material will be imperative. Finding plant material, including ornamental grass species that are bred not only for their outstanding ornamental qualities but for their low water use will continue to be important as demands on water increase.

There are many future avenues of study regarding water use for ornamental landscape plants including ornamental grasses. Studies which compare native species with ornamental species which have been bred exclusively for appearance may help determine characteristics that also confer some measure of drought tolerance. When dealing with ornamentals, however, visual appearance will continue to be an important variable in selection of plants for marketing and sale.

Colorado and other semi-arid regions of the country need to be the site of future studies. Our low relative humidity and low rainfall (less than 38.3 cm per year) and focus on plants with low-water or xeric characteristics make this an ideal area to study water use in ornamentals. Contrasting studies done in Colorado with the results already reported in Florida, China and elsewhere could give some indication which cultivars should be grown for their distinct climates.

Study Objectives

For this study, the following objectives were explored. First, the ornamental grass species will differ in their water use rates. Second, *P. virgatum* will provide higher quality ornamental characteristics than *S. scoparium* and *C. brachytricha* in low water situations. Third, none of the grasses studied will exhibit acceptable visual qualities without supplemental irrigation.

CHAPTER 2: Materials and Methods

This study was conducted at Colorado State University Plant Environmental Research Center (PERC) which is located at 630 W. Lake Street, Ft. Collins, CO (40° 34' 8" N, 105° 5' 24" W) on an Altvan-Satanta loam. Soil samples were collected prior to planting and sent to the CSU Soil, Water and Plant Testing Laboratory. The complete soil test results can be found in Appendix A.

This study examined three ornamental grass species: *Calamagrostis brachytricha* (Korean Feather Reed grass), *Panicum virgatum* 'Rotstrahlbusch' (Rotstrahlbusch Switchgrass), and *Schizachyrium scoparium* 'Blaze' (Blaze Little Bluestem). Plants of uniform size (3.79L; 1 gallon) were purchased at a local nursery. A total of 20 plants per species were selected, so that five replicates could be placed in each of the four irrigation levels (Fig. 2.1).

Each of the four quadrants in the study were assigned a water treatment of 0%, 25%, 50% and 100% of ET for a bluegrass turf reference crop (ETos). These treatments were based on the GreenCO reference table which provides anecdotal guidelines from industry professionals on approximate watering for plants based on evapotranspiration percentages (Table 2.1).

Table 2.1: Estimated Annual Required Irrigation Application, GreenCo

Water Use Category	**Percentage of Reference ET (ET_o = cool season turfgrass)**
High	75 – 100%
Medium	50 – 75%
Low	25-50%
Very Low	0-25%

Each irrigation treatment quadrant was rectangular with dimensions approximately 11 meters by 19.5 meters and were separated by a 2.4 meter mulch path. The 5 plants of each species for each quadrant were situated according to the location of the diviner access tubes (Diviner 2000®; Sentek Environmental Technologies Pty Ltd., Stepney South Australia) which were placed from a previous shrub study. The layout of the individual plants in the plot plan can be viewed in (Figure2.2). Other than the need to place the plants near diviner access tubes, the layout was a complete randomized design. Plants were spaced at least 1.2 m apart.

Figure 2.1 Photograph of Ornamental Grass irrigation study at the Plant Environmental Research Center, 630 W. Lake St., Ft. Collins, Colorado in July, 2012.

The grasses were planted on June 10, 2012. As per current BMP (Best Management Practice) guidelines (CNGA, 2011), planting holes were dug with an auger and shovel approximately 2 ½ times the diameter of the root ball, the root ball was loosened, and planted at soil grade. There was no organic amendment added to backfill. After planting, the plants were watered twice a week, and given 3.79L (one gallon) per irrigation event until August, when the plants were given 100% of ETos until October. Plants were not watered over the winter.

In early spring 2013, it was determined that the plants had not sufficiently grown around the diviner access tubes so that soil moisture measurements could be accurately assessed for the 2013 growing season. On April 12, 2013, all the plants were moved closer to the diviner access tubes (to within approximately 7 cm) so that diviner measurements taken during the growing season could accurately access the soil water moisture in the plant's root system. The dried plant material was then removed from approximately 7 cm (2.8 inches) from the base of plant (CNGA, 2011). All plants were watered 3.79L (one gallon) of water each week with hand-watering wand equipped with water meter until snow and or rain prevented necessity of additional watering. When the irrigation system was activated on the site on May 23, 2013, the plants were given 100% of ETos of water per week for further establishment. Water treatments were started on June 17, 2013.

Site specifications and maintenance

Water used in this experiment was non-potable from College Lake in Ft. Collins, CO. To prevent leaching of surrounding irrigated areas and between plots, former study site participants surrounded the experimental plot area with a polyethylene plastic barrier buried to a depth of 0.91meters (3 ft.). Water was supplied by a drip irrigation system with programmable timing. (Rainbird, ESP-MC, Azuza, CA) and drip irrigation heads (Rainbird ¼ inch tubing; 1.0 gph emitters).

During the establishment year (2012), the quadrants were hand-weeded. In spring of 2013, approximately 5.08-7.62 cm (2-3 inches) of wood-chip mulch was spread across the entire surface of the four quadrants and within 2 cm of each plant. This was done to minimize weeds and to mimic homeowner growing conditions. Weeds were managed in 2013 by hand-pulling around the immediate plant area within 0.35 m (1 foot) of each study plant as well as spraying weeds in the remainder of each plot with a non-specific herbicide. Glyphosate (Ranger Pro, Monsanto) in a 2% concentration was used outside of the hand-pulling radius of the plant on three occasions during the growing season, to control both perennial and annual weeds.

Each grass received 2 x 3.79L (1 gal) per hour drip emitters, placed 180° apart, at ground level and closely positioned near each plant. In July 2013, the emitters were tested for flow accuracy. The water from five emitters from each quadrant was collected and measured to determine emitter efficiency. The average emitter efficiency was 97.1% efficient in the25% treatment, in 97.6% efficient in the 50% treatment and 96.3% efficient in the 100% treatment.

Precipitation events were noted and recorded with a rain gauge (Productive Alternatives, Fergus Falls, MN) on the plot and readings were collected daily. Exceptions were on July 27 and 28 and August 2 and 3, 2013, when two days of readings were recorded together. Values for bluegrass reference Evapotranspiration (ETos) were collected through the Northern Colorado Water Conservation District (NCWCD) data collection site located approximately 1.5 kilometers (0.93 miles) away from the study site. NCWCD calculates ETos values using the ASCE Standardized Reference Evapotranspiration Equation (NCWCD, 2013).

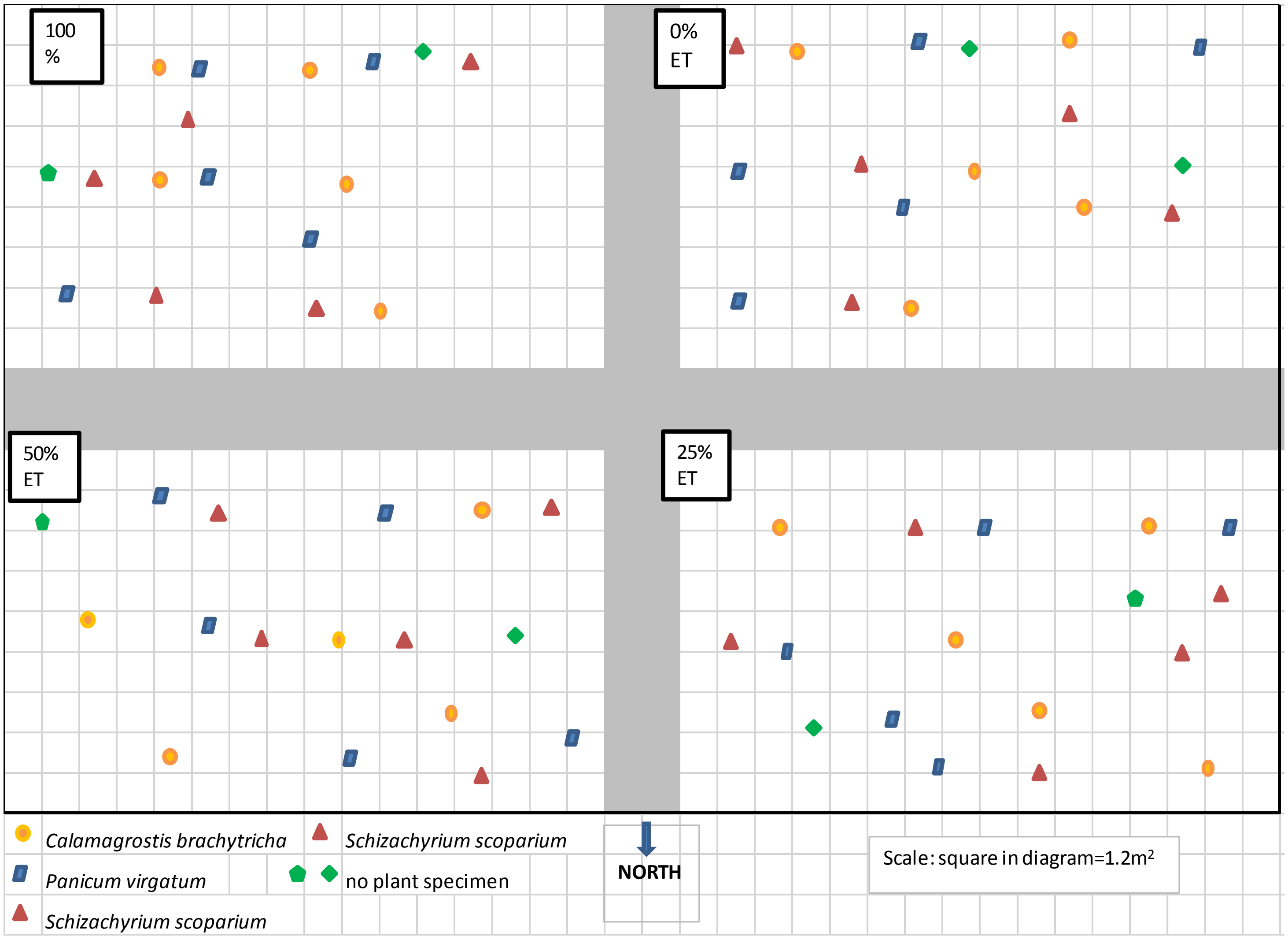


Figure 2.2: Ornamental Grass Irrigation Study Plot Plan, Plant Environmental Research Center, Ft. Collins, Colorado

During 2013 growing season, water treatments were calculated once a week using a modified Irrigator's Equation:

Flow rate * Time = Depth * Area

Area is the area (in square inches) that is watered; Depth is the amount of water applied, by irrigation or by precipitation (in inches). Flow Rate is the rate at which water was applied (volume/hour). Time is equivalent to the time the irrigation system runs. The time calculated in this manner would be the amount of water in minutes that the 100% treatment would receive; the 50% treatment would receive half of that amount and the 25% treatment would receive half of the 50% treatment. The 0% treatment did not receive any supplemental water. Since ETos is expressed in inches of water, US volumetric measurements were used to calculate water treatments. If precipitation during a particular week exceeded ETos rates, treatments were not applied for that particular week and the excess soil moisture was assumed to be lost. Table 2.2 shows the amount of water given in inches for a particular week.

Table 2.2. ETos, precipitation and watering amounts for Ornamental Grass Irrigation Study, 2013

	Jun 26-Jul 3	Jul 4-Jul 9	Jul 10-Jul 16	Jul 17-Jul 23	Jul 24-Jul 30	Jul 31-Aug 6	Aug 7-Aug 13	Aug 14-Aug 20	Aug 21-Aug 27	Aug 28-Sep 3	Sep 4-Sep 10	Sep 11-Sep 17	Sep 18-Sep 24	Sep 25-Oct 1
ETos (inches)	1.61	1.48	1.41	1.41	0.99	1.21	0.98	1.31	1.18	1.02	0.89	0.065	0.93	0.68
Precipitation (inches)	0.55	0.52	0.15	0.38	0.74	0.7	0.03	0	0.01	0.01	3.18	2.67	0.38	0.25
Added Water for 100% treatment (in.)	1.06	0.96	1.26	1.03	0.25	0.51	0.95	1.31	1.17	1.01	-2.29	-2.67	0.55	0.43

Data Collection

Treatment effect was examined by measuring plant growth, evaluating plant water use parameters and visual and quality ratings. Plant growth measurements included plant height and width, which were collected at pre-planting (June 2012) and again in the field on October 2012 and October 2013 (Appendix B). Height was measured from plant base to tallest stem height, including inflorescence if present. In measurements for height, the plants are measured at their natural peak, which includes the natural arc of the top end the grass blade or inflorescence. Tiller height data was taken at the end of the growing season in October, 2013 to assess additional information on plant height. A tiller is defined as the grass shoots which develop from the crown of the plant. Three tillers were selected at random from each plant and were harvested as close to the base of the plant as possible. These were measured from cut end to tip, extending the tiller to its full length when measured. Due to the different measuring techniques, the tiller and height measurements may be related, but not directly correlated. Width was measured by compass orientation from north to south as well as east to west. These two width measurements were then averaged together for the average plant width. Circumference data was collected on all plants in October, 2013. The circumference was measured approximately 3 cm up from the base of the plant.

At the end of the 2013 growing season, and after the first frost (October 10, 2013), study plants were harvested to obtain dry weight measurements. Each plant was cut as uniformly as possible approximately 7 cm (2.8 inches) from the base of the plant. This above ground biomass, as well as tillers samples, were placed in drying oven set at 70°C (158°F) for 48 hours and their weights combined for the total dry weight measurement.

Water use data was collect by several methods. Water potential was measured using a pressure chamber (PMS Instrument Company, Model 600, Albany, OR). Readings were taken starting at approximately 11 pm, MST (Mountain Standard Time) two weeks apart. A total of six data sets were taken starting on July 3, July 17, July 30, August 13, August 28 and September 20. Because of inclement weather and wet leaves, no readings were taken from August 28 to September 20. Two leaves from each plant were taken from three plants of each species on each plot. These two readings were averaged and the mean was used for statistical analysis.

An additional measurement which indicates plant stress was canopy temperature. Higher canopy temperatures indicate stressed plants. Stressed plants transpire less than their well-watered counterparts which causes latent heat flux at the leaf surface (Fuchs, 1990). These data were taken before watering between noon and 1pm on the same days as the pressure chamber readings. An Omega OS534 Handheld Infra-Red Thermometer (Stamford, CT) was used to record canopy temperature in degrees Celsius; two readings of each plant were collected and their temperatures were averaged. Following manual guidelines, adjustments to the settings were not needed since the emissivity of the most organic materials is 0.95 and this was the manufacturer's preset value. With the laser sighting, all measurements were taken within 45.7 cm (18 inches) of each plant.

Soil moisture readings were taken using the Diviner 2000® (Sentek Environmental Technologies Pty Ltd., Stepney, South Australia). This instrument measures volumetric soil moisture (in relative percent) in 10 cm increments to 70 cm depth in the soil profile; therefore the Diviner 2000 gives a snapshot of the soil moisture content at a specific depth in the soil profile. The Diviner 2000® uses Frequency Domain Reflectometry (FDR) principles to determine the volumetric soil moisture. The basis of this technique is that capacitance sensors detect changes in the dielectric permittivity (dielectric constant) of the soil over time. The frequency reading is affected by water molecules since water has a greater dielectric constant than air. The smaller the frequency measurement between the brass rings in the sensor and access tube, the greater amount of water in the soil. (Sentek, 2008) The plants in the study were placed within seven cm of the diviner access tubes, therefore all five replicates of the three species were growing close to the access tubes so theoretically, the plant roots utilized the soil water next to the diviner access tube and would influence soil moisture readings. Measurements were taken 24 hours after watering treatments.

Visual and quality ratings were also taken in October 2012 and 2013. Measurements included floral impact, plant form, and landscape impact and were taken using a scaled rating system. The visual quality values of each of the scales are included in Appendix C. The plant form rating indicates the overall growth habit of each plant, including uniformity, and lodging (M. Meyer, personal communication January 18, 2012). Floral impact rating is determined by how the inflorescence on the plant enhances the plant's appearance. This rating is on a scale of 1-5; a value of one indicates no flowering, a value of 5 indicates inflorescence is very showy (M. Meyer, personal communication January 18, 2012). Landscape impact rating indicates the total impact of a plant on the landscape from growth habit and appearance as well as disease or insect problems. A low rating would indicate that the plant has no value in the landscape or weak growth and sparse flowering; a high value indicates outstanding landscape appearance (B. Pemberton, personal communication June 10, 2012). In addition, a leaf rolling scale was included for one species, *Calamagrostis brachytricha*, since it exhibited various degrees of leaf rolling over the various treatments and data collection dates. Leaf rolling can indicate water stress and is a response which contributes to drought avoidance since it minimizes effective leaf area, which lead to decreasing water loss in the plant. *Panicum virgatum* and *S. scoparium* did not exhibit this characteristic.

Data Analysis

SAS/STAT® software with SAS 9.4 for Windows (SAS Institute Inc., Cary, NC) was used to conduct data analysis. Mixed Procedure was used on all data and ANOVA (analysis of variance) was used to compare the least square means. Fixed effects were species and treatment effects; the random effects were the measured parameters such as height, width, circumference, dry weight, FDR depth, leaf rolling of *C.brachytricha*, and visual characteristics. ANCOVA (analysis of co-variance) was used to compare dry weight and circumference measurements; using mixed procedure to compare least square means. The CORR Procedure in SAS was utilized to examine Pearson Correlation Coefficients for plant height and tiller height. Significant differences were observed at the $p \leq 0.05$ level.

Since water treatments were not randomized, treatment effect due to irrigation and spatial variability was shown by the homogenous growth pattern of the ornamental grasses grown on each quadrant which received the same water treatments (50% ET) each week during the experiment. Variability due to spatial effects were not observed.

CHAPTER 3: Results and Discussion

Table 3.1 shows the weather conditions for the 2013 growing season. Water potential, canopy temperature and volumetric soil moisture were taken every 2 weeks, commencing on July 3, 2013 to Sept. 20, except for a three week hiatus due to September rain events. Growth data was taken in September and early October, soon after the rain events and at the end of the season.

Table 3.1. Mean monthly weather data for the 2013 season[a]

	Max Air Temp °C	Max Air Temp °F	Min Air Temp °C	Min Air Temp °F	Ave Air Temp °C	Ave Air Temp °F	Precip. (cm)[b]	Precip. (in)[b]	Ave Precip. (cm)[d]	Ave Precip. (in)[d]	Etos (cm)[c]	Etos (in)[c]
April	25.7	78.2	-13.4	7.9	5.3	41.5	4.37	1.72	5.00	1.97	8.61	3.39
May	30.6	87.0	-8.8	16.2	14.1	57.3	5.84	2.30	6.96	2.74	14.00	5.51
June	35.8	96.4	3.1	37.5	20.6	69.1	1.54	0.61	4.65	1.83	17.27	6.80
July	36.6	97.9	10.7	51.2	21.6	70.9	5.33	2.10	4.11	1.62	14.91	5.87
August	35.8	96.4	8.4	47.1	21.4	70.5	1.90	0.75	3.61	1.42	12.88	5.07
September	35.4	95.8	0.1	32.2	16.9	62.5	16.48	6.49	3.23	1.27	8.89	3.50
October	25.8	78.4	-4.6	23.7	7.23	45.0	4.37	1.72	2.87	1.13	5.99	2.36

[a] Northern Colorado Water Conservation District weather station at Rolland Moore Park, Ft. Collins, CO, 1.2km away from treatment quadrants.

[b] Productive Alternatives Rain gauge located on 100% treatment quadrant, Colorado State University Plant Environmental Research Center, Ft. Collins, CO

[c] ETos: Evapotranspiration for bluegrass short reference crop

[d] Colorado Climate Center, Average Precipitation data (1988-2013)

Growth Measurements

Data were collected in various ways to demonstrate seasonal growth of the plants. Plants were measured at the start of the study, in June 2012, before planting. Season-ending height and width measurements in 2012 and 2013 were averaged for each quadrant (Appendix B). In 2012, plants were watered for establishment, so total water given to each plant was the same and differed from the water treatments in 2013. The difference in growth between treatments is evident in the measurements across treatment levels between the two seasons. Circumference, taken at approximately three centimeters above the ground, as well as dry weight of the harvested grasses were taken at the end of the 2013.

Plant Height and Tiller Height

Height for 2013, differed not only between species but by treatment (Figure 3.1); treatment x species effect were not significant.   The three species have a genetically regulated predisposition for height (Taiz & Zeiger, 2006) and differ from each other regardless of treatment. Treatment effects in height were noted; not all treatments had significant effects across species. The 0% plants were as a group the shortest. Interestingly, the 25% treatment height across species were not significantly different from the 100% treatment. Heights across all species was significantly different between the 0% treatment and the 25% and 100%, and between 25% and 50% treatments. This suggests that the 25% irrigation treatment may be adequate for maximum height.

Panicum virgatum demonstrated little variation in height between treatments (Figure 3.2b). This corroborates with the findings of Thetford, *et al*. (2011), which found that this species did not show an increase in foliage height with increased irrigation. *Schizachyrium scoparium* (Figure 3.2c) was significantly taller in the 25% treatment when compared to the 0%, but not significantly different from the 50% and 100%. This may indicate that this was the optimal watering treatment for height may be at the 25% for this species. Thetford, et al., (2011) found that S. scoparium height did not differ with irrigation treatments. *Calamagrostis brachytricha* (Figure 3.2a) was tallest in the 25% treatment. This differential in height between treatments in this species may be due to the fact that only 47% of the plants had inflorescent spikes during the last measurement date, influencing the overall height measurement across treatments. It is possible that the fall-flowering nature of this species occurs relatively close to the first frost, and cold weather on the treatment quadrants inhibited inflorescence development. First frost date in Ft. Collins was Oct. 4, 2013 (NCWCD, 2013).

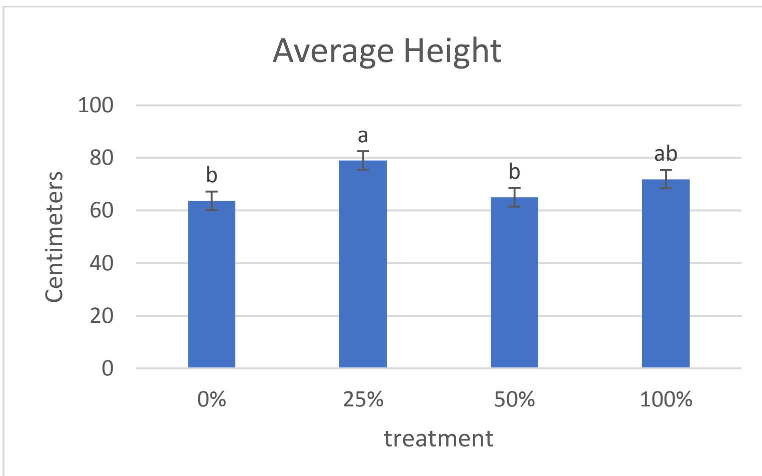
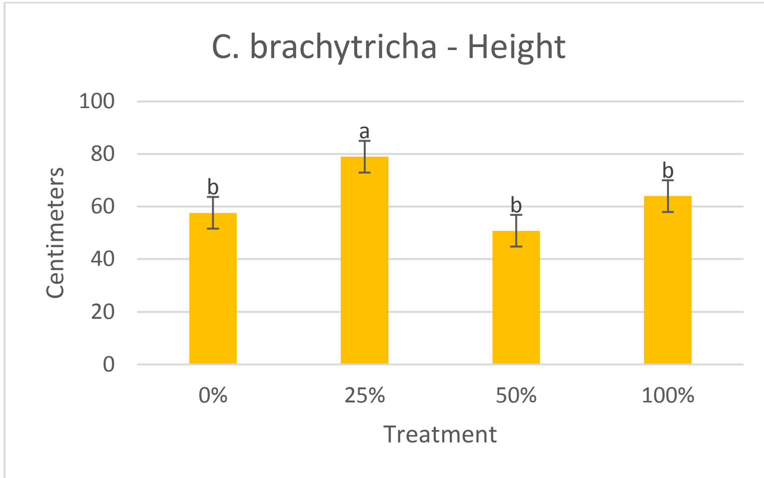
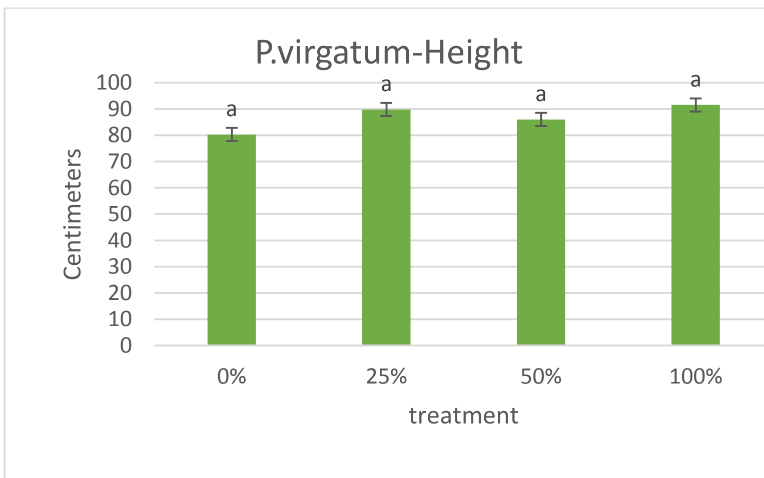


Figure 3.1. Average Height of 3 ornamental grass species (*C. brachytricha, P.virgatum, S.scoparium)* by treatment (0%, 25%, 50%, 100% of ETos) at end of 2013 season. Treatments with different letters are significantly different at $p \leq 0.05$

(a)


C. brachytricha - Height
Centimeters
100
80
60
40
20
0
b
a
b
b
0%
25%
50%
100%
Treatment

(b)


P.virgatum-Height
Centimeters
100
90
80
70
60
50
40
30
20
10
0
a
a
a
a
0%
25%
50%
100%
treatment

(c)

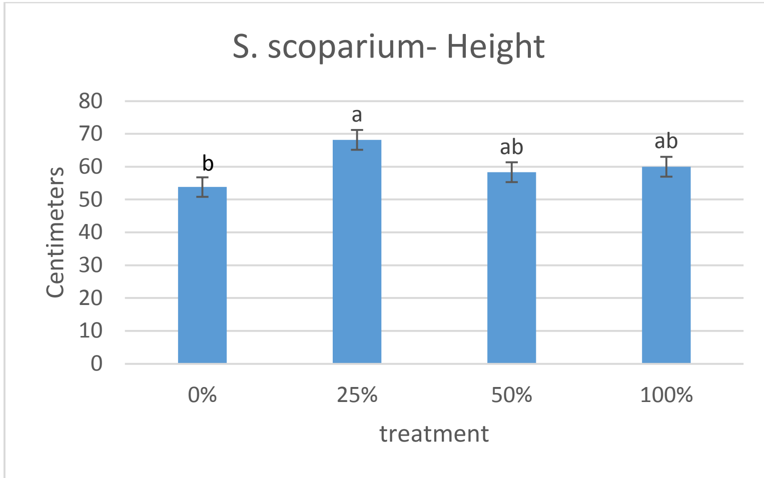


Figure 3.2 a-c. Average height of *C. brachytricha (a), P. virgatum (b), S. scoparium(c)* by treatment (0%, 25%, 50%, 100% of reference ET) at end of 2013 season. Treatments with different letters are significantly different at $p \leq 0.05$.

Tiller height was measured at the end of the 2013 season (Figure 3.3). The three randomly selected tillers were measured and their values averaged for this analysis. Significant differences existed between the 0% treatment and all other treatments; the 0% treatment had lower average tiller heights across all species and water treatments. There was a significant difference between the 50% treatment and the 25% treatment and suggests that the 25% treatment allows for taller tiller growth than the 50%. There was no statistical difference between the 25% treatment and the 100% treatment. These results corroborate the total average height results and similar conclusions can be drawn for tiller height.

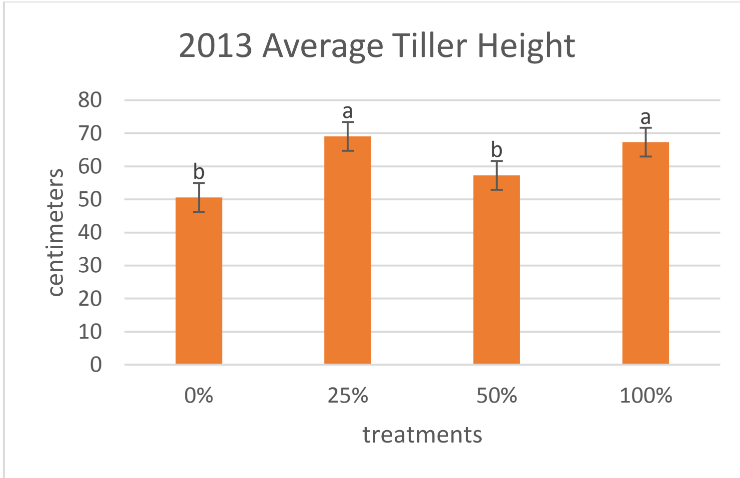


Figure 3.3. Average tiller height of 3 ornamental grass species by treatment (0%, 25%, 50%, 100% of reference ET) at end of 2013 season. Treatments with different letters are significantly different at $p \leq 0.05$.

Pearson's correlation coefficient analysis was calculated with the CORR procedure to ascertain whether there was a linear relationship between tiller height and total height in 2013 (SAS, 2014). This estimate showed that there was a strong overall positive correlation between height and tiller height ($r=0.87$). Graphs of the regression are in Appendix D.

Width

Width was also measured at the end of the 2013 growing season. These results also showed differences in both species and treatment effects (Figure 3.4). Significant differences existed between the 0% treatments and the other treatments, but treatment differences were not significant between the 25%, 50% and 100% treatments. Species differences existed between the 0% and other treatments in all three species. *P. virgatum* exhibited some variation between treatments, with 50% treatment exhibiting the largest width (Figure 3.5b). This result suggests for *C. brachytricha* (Figure 3.5a) and *S. scoparium* (Figure 3.5c), the 25% irrigation treatment may be adequate for maximum width; though for *P. virgatum*, the 50% treatment conferred the largest width, though not significantly so. This result seems to contradict Thetford, et al (2011) study which found there was no difference in width of *P. virgatum* and *S. scoparium* with additional water. The Thetford, *et al.* study was also in areas of Florida that receive approximately 165 cm (65 inches) of rain per year; Ft. Collins, Colorado receives an average of 38.3 cm (15.08 inches) of precipitation per year (CCC, 2014). Even with the additional 34.5 cm (13.6 inches) of water provided by the 100% irrigation treatment over the course of the 2013 season, this experiment provided a substantially lower amount of water to plants.

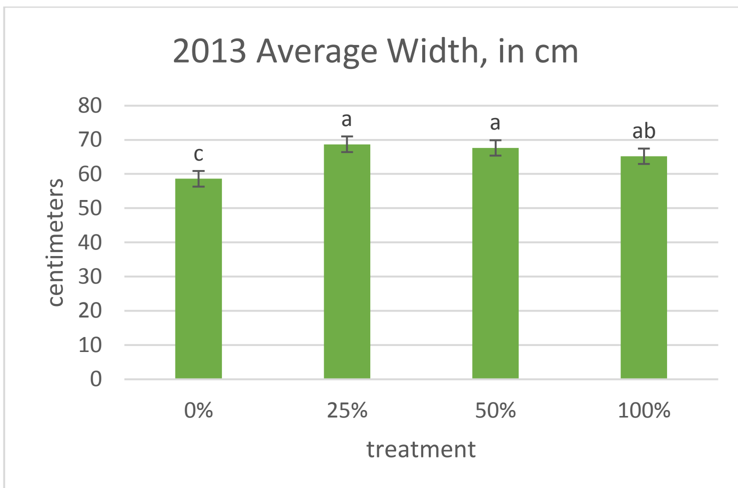
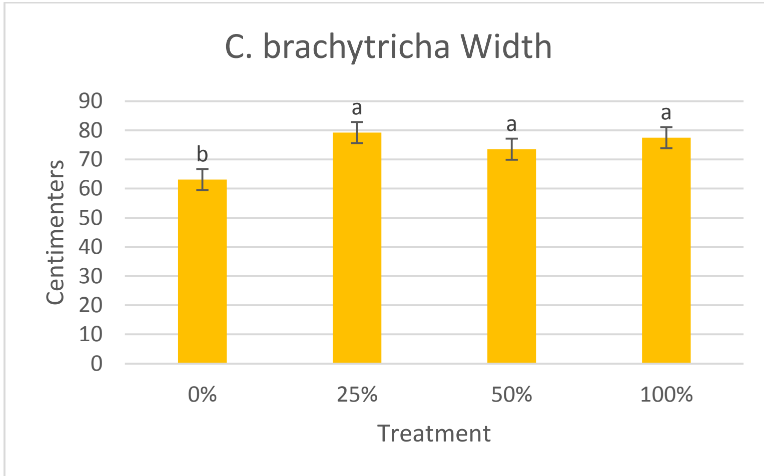
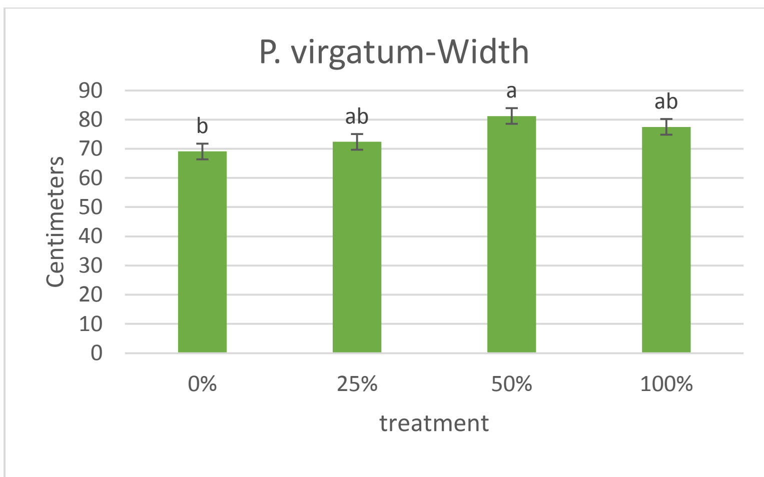


Figure 3.4. Average width of three ornamental grass species by treatment (0%, 25%, 50%, 100% of ref ETos) at end of 2013 season. Treatments with different letters are significantly different at $p \leq 0.05$.

(a)


C. brachytricha Width
90
80
70
60
50
40
30
20
10
0
Centimenters
b
a
a
a
0%
25%
50%
100%
Treatment

(b)


P. virgatum-Width
90
80
70
60
50
40
30
20
10
0
Centimeters
b
ab
a
ab
0%
25%
50%
100%
treatment

(c)

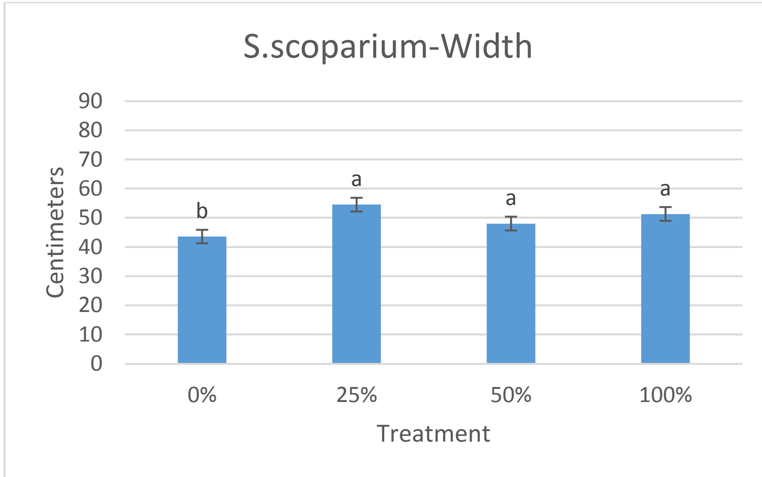


Figure 3.5 a-c. Average width of (a) *C. brachytricha,* (b) *P. virgatum,* (c) *S. scoparium* by treatment (0%, 25%, 50%, 100% of reference ET) at end of 2013 season. Treatments with different letters are significantly different at p≤0.05.

Circumference

Differences in circumference were also evident between species and treatments (Figure 3.6). Treatment effects varied. There was no statistical difference in circumference between the 100% and 25% treatments, since those both had the largest circumferences. This may also demonstrate that the 25% treatment confers the same growth as the 100%, though this is not as clear as in the height and width measurements. The 50% treatment had the smallest average circumference, though it was not significantly different from the 0% treatment. In the 50% treatment, the *C. brachytricha* and the *S. scoparium* both had the smallest average circumference size, while *P. virgatum* only had significant differences at the smaller 0% treatment (Figures 3.7a-c). Though references to circumference measurements in the literature were not found, Thetford, *et al.* (2011) states that *S. scoparium's* basal area did not change with irrigation, though *P.virgatum*'s basal width area increased.

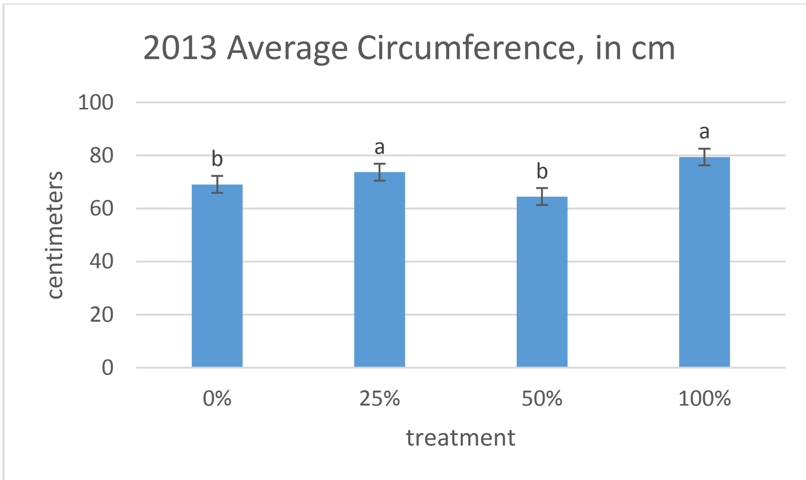
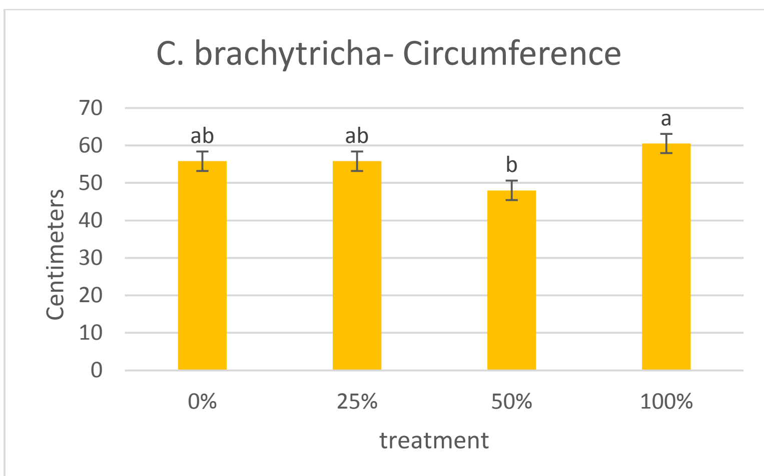
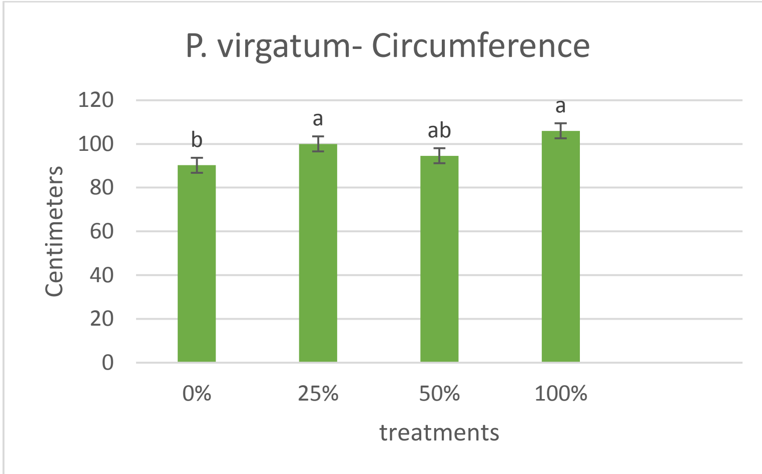


Figure 3.6. Average circumference of 3 ornamental grass species by treatment (0%, 25%, 50%, 100% of reference ET) at end of 2013 season. Treatments with different letters are significantly different at P≤0.05.

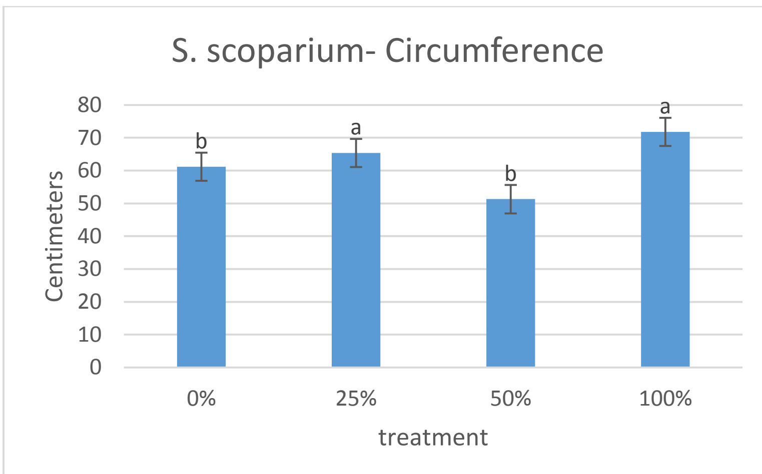
(a)



(b)



(c)



Figures 3.7 a-c. Average circumference of *C. brachytricha, P. virgatum, S. scoparium* by treatment (0%, 25%, 50%, 100% of reference ET) at end of 2013 season. Treatments with different letters are significantly different at $p \leq 0.05$.

Dry weight

No significant treatment differences were noted between the 25% and 50% water treatments and indicates that these two treatments confer the same dry weight (Figure 3.8). The 25% and 50% water treatments had significantly more mass when compared to the 0%. Across all species, there was an approximate 32% increase in mean dry weight between 25%/50% and the

0% treatment. When comparing the 25%/50% water treatment dry weight means to the 100% treatment, there was an 11% decrease in dry weight. There was a significant difference in the dry weight measurements between the 0% and 100% treatments across species. This may indicate that irrigating some of the species at 100% of ET actually decreases plant mass or inhibits the plant's ability to increase plant biomass in some species. *Schizachyrium scoparium* demonstrated the largest dry weights in the 25% and 50% treatments and the smallest at the 0% and 100%, though these results were not significant at the $p \leq 0.05$ level (Figure 3.9c). The lack of significance is likely due the intra-treatment variation in the sample measurements and small sample size. If these values had been significant, there are two possible reasons *S. scoparium* would have would have a smaller dry weight at the 0% treatment. Volder, et al (2013) indicates that *S. scoparium* may be less resistant to chronic drought, so at low water treatments, it does not add biomass. Other research mentions *S. scoparium's* shallow roots in comparison to *P. virgatum*, which may makes it less likely to access water deeper in the soil profile (Eggemeyer, et al 2008). The 100% treatment may represent a more mesic year, and Knapp (1984) observed that in wetter years, *S. scoparium* lacks a production response possibly due to their internal drought avoidance mechanisms, which can inhibit increases in production.

Calamagrostis brachytricha dry weights also showed no significant differences between treatments (Figure 3.9a). *P. virgatum* showed significant differences between the 0% and 50% treatment which contradicts the findings of Thetford, *et al*. (2011), which found that this species did not show an increase in foliage height with increased irrigation(Figure 3.9b).

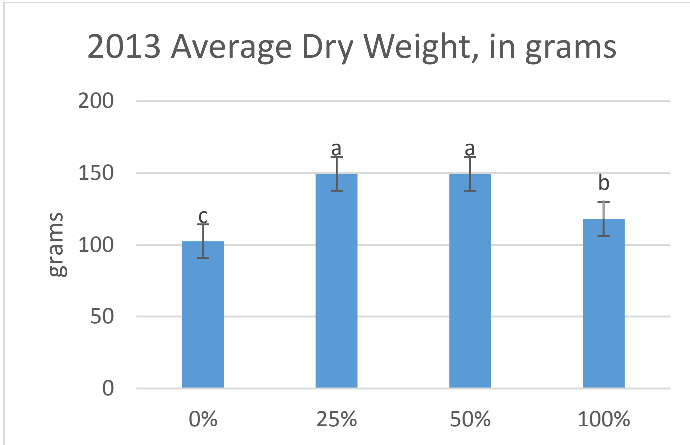
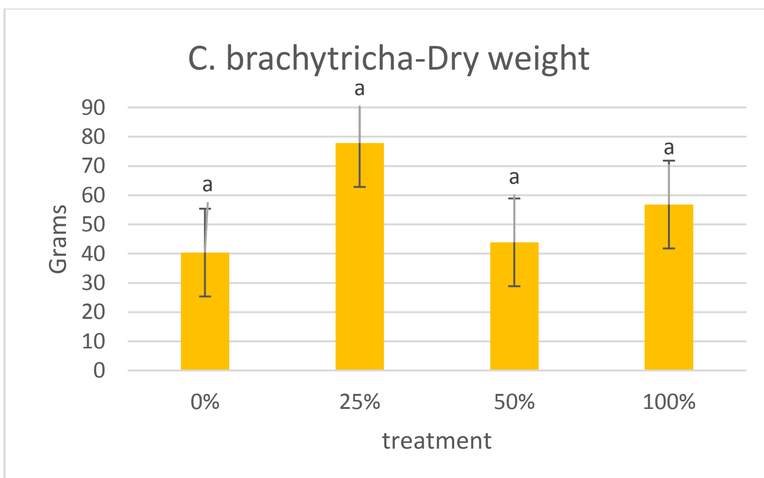
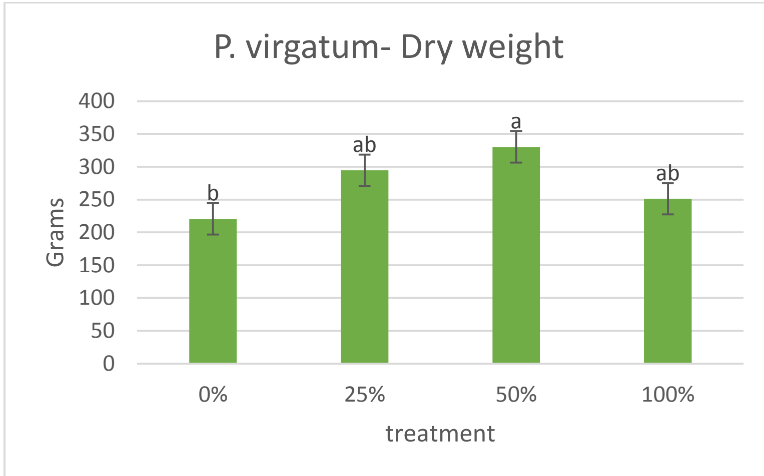


Figure 3.8. Average dry weight of 3 ornamental grass species by treatment (0%, 25%, 50%, 100% of reference ET) at end of 2013 season. Treatments with different letters are significantly different at p≤0.05.

(a)



(b)



(c)

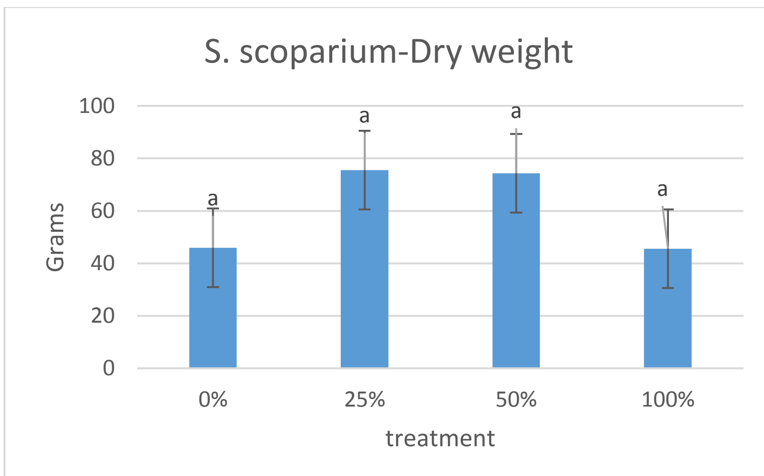


Figure 3.9 a-c. Average dry weight of (a) *C. brachytricha,* (b) *P. virgatum,* (c) *S. scoparium* by treatment (0%, 25%, 50%, 100% of reference ET) at end of 2013 season. Treatments with different letters are significantly different at p≤0.05.

Analysis of Covariance between circumference and dry weight

Comparing circumference and dry weight statistically helps visualize and compare the data that were taken across species. By analyzing these two parameters by ANCOVA (SAS Institute, 2013), we can measure how much dry weight (dependent variable) and circumference (covariate) change together and how strong the relationship is between them. So, it essentially adjusts the dry weight in each species to what it would be if all the species had the same circumference, so between species comparisons can be made. For this comparison, the ANCOVA analysis indicates that the mean dry weight increases by 1.87 grams for every one centimeter of circumference. Therefore, the slope assumed no irrigation effect; deviation from the slope would indicated a significant change of a specific irrigation treatment. Figure 3.10 shows the values for dry weight for species when circumference is factored in as a co-variable. It indicated that *P. virgatum* has the largest dry weight at any given fixed circumference. Figure 3.11 shows that there is no significant treatment effect between the 25% and 50% treatments, but these treatments are significantly different from the 0% and 100% treatments. This again shows that the 25% treatment is adequate for irrigation and confers a growth advantage to these grasses across species.

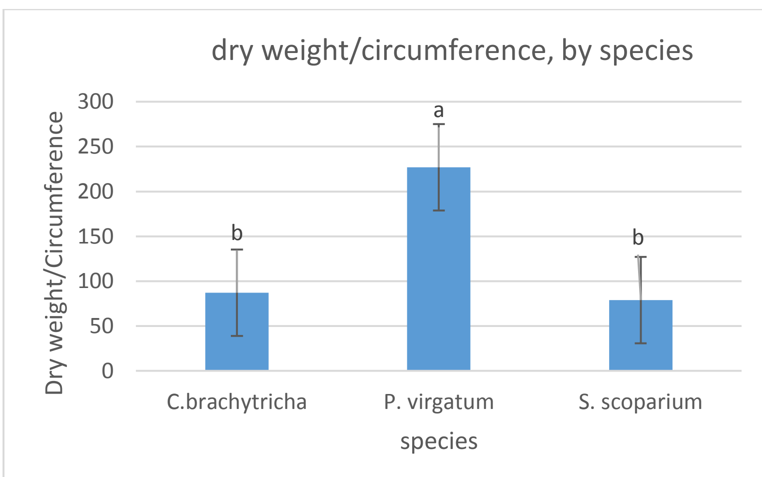


Figure 3.10. Average dry weight with fixed circumference of *C. brachytricha, P. virgatum, S. scoparium* at end of 2013 season. Treatments with different letters are significantly different at p≤0.05.

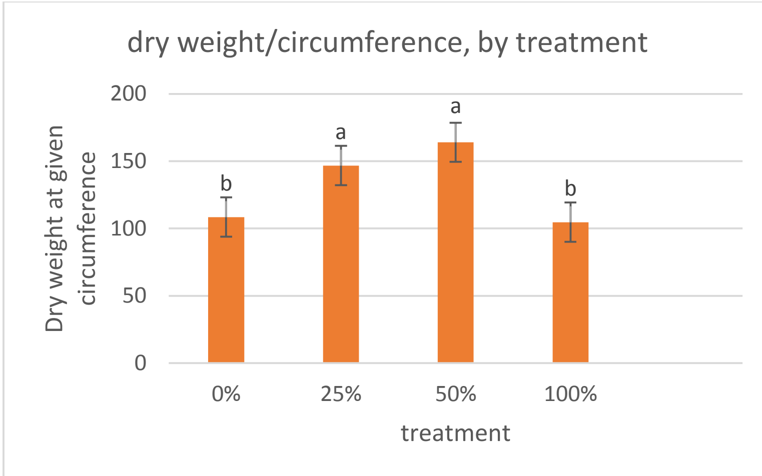


Figure 3.11. Average dry weight with circumference as a fixed variable for 3 ornamental grass species by treatment (0%, 25%, 50%, 100% of reference ET) at end of 2013 season. Treatments with different letters are significantly different at P≤0.05.

Water Use and Plant Stress Measurements

Leaf Water Potential

Pre-dawn leaf water potential (mean species effect) varied and were significantly different across all data collection dates. *Panicum virgatum* had the highest water potentials (less negative). *Schizachyrium scoparium and C. brachytricha* had lower water potential (more negative) and were significantly different from *P.virgatum*, but not from each other. This indicates that *P. virgatum* were less stressed and *S. scoparium* and *C. brachytricha* were more stressed (Figure 3.12). These data follows other sources (Knapp, 1984; Barney, et al., 2009, Eggemeyer, 2008) which state that *P. virgatum* and *S. scoparium* are drought tolerant species, and therefore would have lower water potentials than the more mesic species, *C. brachytricha*. Research indicates that *C. brachytricha* optimally grows at water treatments at 75% ETo or above, though this study calculated the crop coefficient (ETc) and cannot be directly compare to bluegrass ETos in this study (Yuan, 2011). Table 3.2 shows the leaf water potential averages across all species and treatments. The 0% treatment showed the largest differences between species, especially in the drier and warmer months of August. Significant treatment effects across all species were only noted on August 27, 2013 data (Figures 3.13 a-c). It can be reasoned that this was because it was the only timeframe that showed a sustained period without rainfall (from August 10 to August 29). Therefore, the water treatments show the largest change from the 0% treatment. The previous treatment intervals all received rainfall between watering treatments (Appendix E). On August 27, there were significant differences between the 0% treatments and all other treatments, indicating that the 0% treatment plants were more stressed than their watered treatment counterparts. No significant differences occurred across treatments at the 25%, 50% and 100% levels. This indicates that the plants were approximately equal in their water stress response at these levels.

Table 3.2: Average water potentials for C. brachytricha, P.virgatum and S. scoparium for 2013.

	Calamagrostis brachytricha				**Panicum virgatum**				**Schizachyrium scoparium**			
	0%	**25%**	**50%**	**100%**	**0%**	**25%**	**50%**	**100%**	**0%**	**25%**	**50%**	**100%**
7/3/2013	7.2	7.8	4.8	12.2	5	3.9	5.1	3.8	5.7	9.7	7.7	6.3
7/16/2013	10.3	8.7	6.8	7.7	5.2	4.5	4.4	3.3	8.8	8.3	7.3	5.7
7/30/2013	4.5	4.3	4.3	4	3.7	3.4	4.1	3.5	5.8	4.8	4.8	4.9
8/13/2013	7.8	6.4	10.4	7.7	4.3	3.7	3.9	3.4	5.8	5.1	6.3	5.3
8/27/2013	17.4	14.5	6.5	7.6	8.3	6.1	4.6	11.3	16.8	7.6	7.8	5.3
9/19/2013	4.4	3.3	4.4	3.5	4.5	3.6	4.1	3.6	5.2	4.6	5.2	5.2

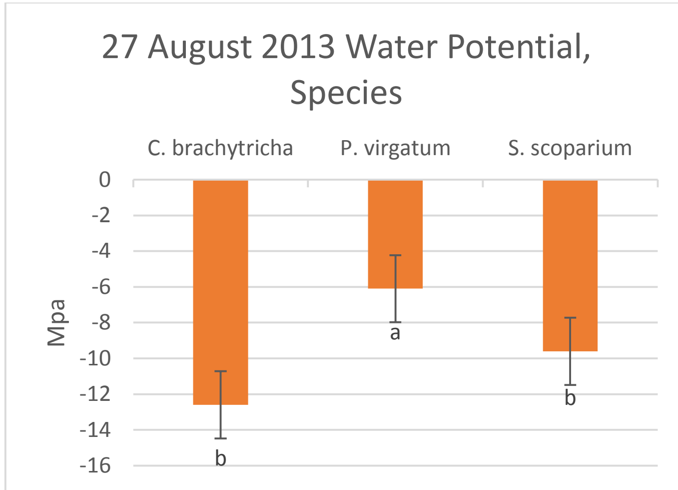
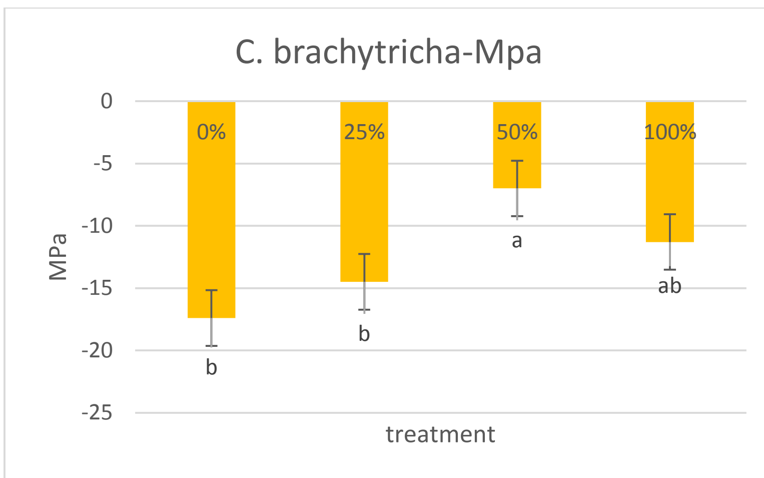
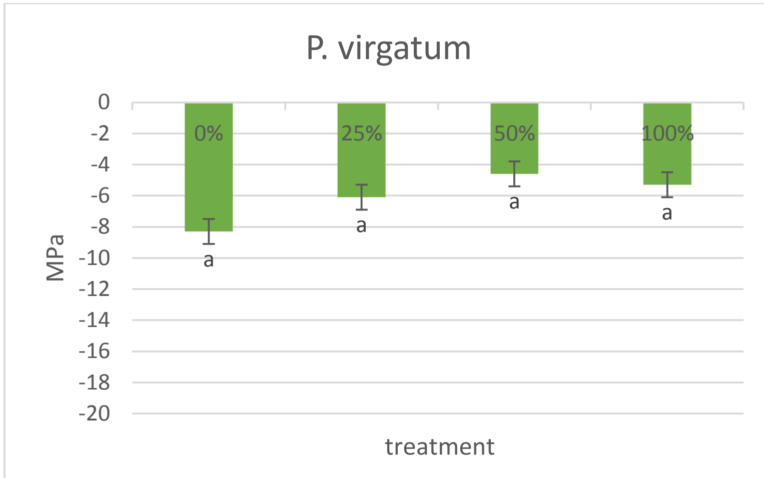


Figure 3.12. Average leaf water potential of *C. brachytricha, P. virgatum* and *S. scoparium* at end of 2013 season. Treatments with different letters are significantly different at P≤0.05.

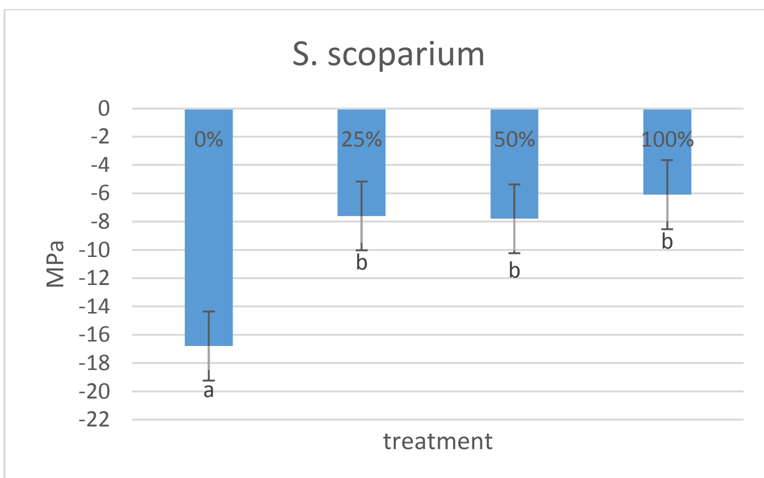
(a)



(b)



(c)



Figures 3.13 a-c. Water potential of (a) *C. brachytricha,* (b) *P. virgatum,* (c) *S. scoparium* across treatments (0%, 25%, 50%, 100% of ETos) on August 27, 2013. Treatments with different letters are significantly different at $p \leq 0.05$.

Canopy temperature

Infrared temperatures across all dates had both species and treatment effects. *Calamagrostis brachytricha* had the highest canopy temperatures across all species, followed by *S. scoparium* and finally *P. virgatum* (Figure 3.14)*.* The lower canopy temperatures are an indication of lower plant stress in *P. virgatum* in relation to the other species. Lower canopy temperature's inverse relationship to water potential has been well documented (Turner, et al., 1986) and this relationship was observed in this study as well. *Panicum virgatum* had the highest water potentials (less stress) and corresponding lowest canopy temperatures across all treatments indicating that this species was less stressed than either *S. scoparium* or *C. brachytricha*. All of the readings showed significant differences between the 0% and 100% treatments, with the lowest canopy temperatures in the 100% treatment, and the highest at the 0% treatment. This result seems sound since the 100% treatment amount provided the most water to the plants and therefore they were less stressed and had lower canopy temperatures. On August 27, the date with the greatest differentiation between treatment water potentials, the 25% and 50% canopy temperatures were not significantly different from each other, and were significantly higher than the 100% treatment (Figure 3.15). This correlates well with the leaf water potential data with the three species, showing that in most instances, the 25% and 50% treatments showed more plant stress than the 100% (Figure 3.16 a-c). However, the differences between the 0%, 25 and 50% treatments indicates that the plants were less stressed as the water treatments increased. One interesting observation from this data was that the 0% treatment had a significantly lower canopy temperatures than the 25%/50% treatments. This could be due to the ability of some species, to osmotically adjust to the lower water conditions in the 0% treatment (Chen, 2010).

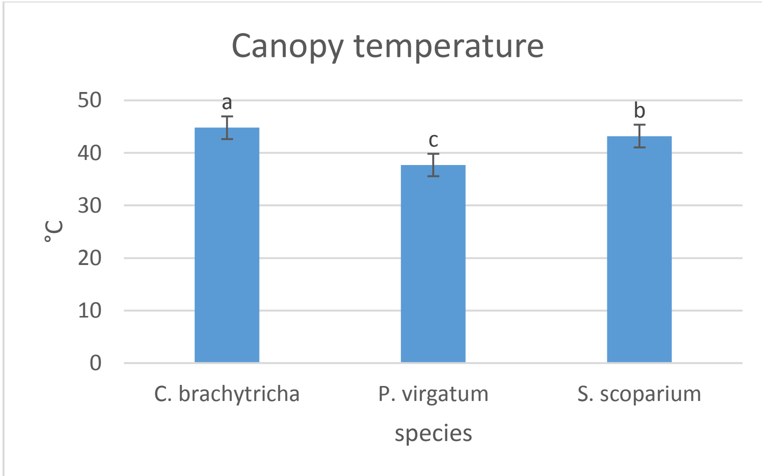


Figure 3.14. Average canopy temperature of *C. brachytricha, P. virgatum, S. scoparium* at end of 2013 season. Treatments with different letters are significantly different at p≤0.05.

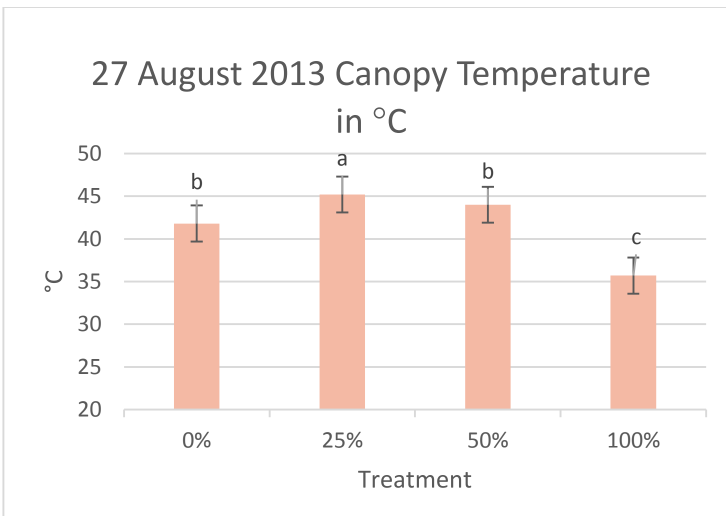
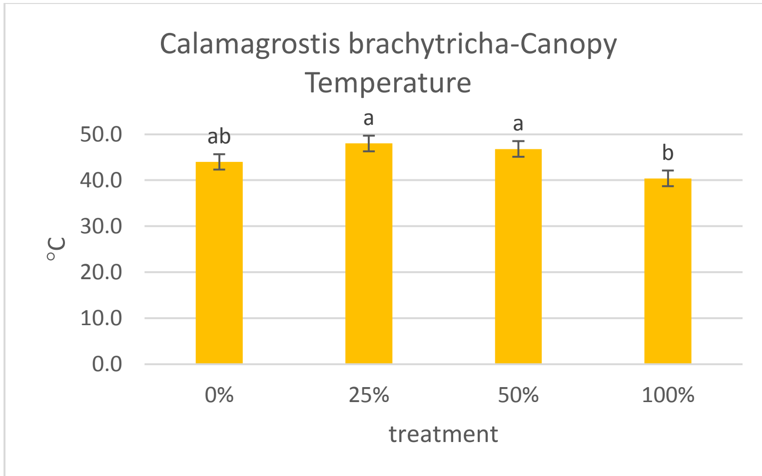


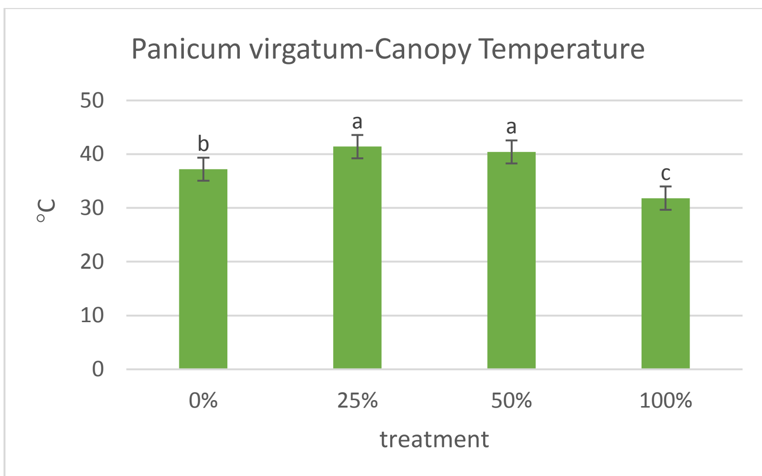
Figure 3.15. Canopy temperature of 3 ornamental grass species by treatment (0%, 25%, 50%, 100% of reference ET) on August 27, 2013. Treatments with different letters are significantly different at p≤0.05.

(a)



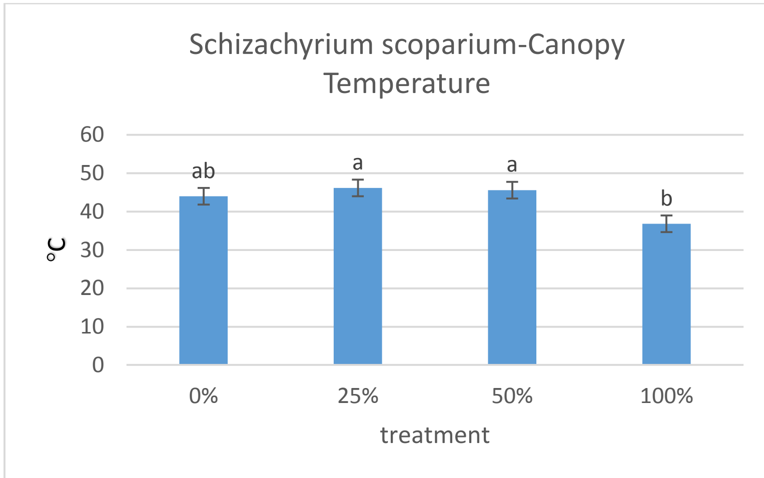
Calamagrostis brachytricha-Canopy Temperature
°C
50.0
40.0
30.0
20.0
10.0
0.0
ab
a
a
b
0%
25%
50%
100%
treatment

(b)



Panicum virgatum-Canopy Temperature
°C
50
40
30
20
10
0
b
a
a
c
0%
25%
50%
100%
treatment

(c)



Figures 3.16 a-c. Canopy temperature of (a) *C. brachytricha,* (b) *P. virgatum,* (c) *S. scoparium* across treatments (0%, 25%, 50%, 100% of reference ET) on August 27, 2013. Treatments with different letters are significantly different at p≤0.05.

Volumetric Soil Moisture (VSM)

Soil moisture data were collected using the Diviner 2000® during the 2013 season. Species and/or treatment differences were noted at all depths (10-70 centimeters). (Figure 3.17). All species data at each depth is located in Appendix. In evaluating the data, it was found that statistically significant species differences were observed only at the 10 cm depth. Large fluctuations in volumetric soil moisture (VSM) at the 10 cm depth were found with species and treatments, due to the placement of the diviner access tubes in the soil. Some of the access tubes had been placed 2-6 cm above soil level, which produced soil moisture readings at a shallower depth than 10 cm and therefore lower VSM readings closer to the soil surface.

Across species, *P. virgatum* (Figure 3.18b) had the lowest VSM for all treatments. *Schizachyrium scoparium* (Figure 3.18c) and *Calamagrostis brachytricha* (Figure 3.18a) did not have statistically significant differences in VSM between the water treatments within a soil depth increment. This result was similar over all treatments and across all data collection dates. It can be surmised that the *P. virgatum* was able to access more water in the soil around the diviner access tubes because they were larger plants and therefore have a larger rooting system than the other species, so had an increased root structure to pull water from the soil. Irrigation treatment effects were observed at the 60 and 70 cm depths, likely due to the lack of roots that reached that depth in the soil around the diviner access tubes. Without roots to access soil moisture at a specific depth, the only effect noted would be from the individual water treatments. This would correspond to other research (Eggemeyer, et al.) which found that in field studies, both *P. virgatum* and *S. scoparium* extract most of their water from the upper soil profile (5-50 cm). Nippert and Knapp (2007) found that in their natural habitats, *S. scoparium* and other C_4 grasses take up most of their water from the top 30 cm of soil.

In the initial statistical analysis of the data, it was noted that the treatment effects on VSM on July 17, July 30, August 13 and August 30 did not vary significantly across dates, so the data were combined for statistical analysis. Across all treatments, 25% treatment was one of the lowest, if not the lowest, VSM between 20-50 cm. Since the 25% treatment also contains the plants that have the greatest height, width and dry weight, these statistically significant observations may be correlated. One possible hypothesis for this result could be that a larger root mass would be found on larger plants, therefore they would extract more water around the roots and near the access diviner tubes. Since plants in the 100% treatment also had large height and weight, but had higher VSM near the plant roots and diviner tubes, this may indicate that the plants did not need to access all the water needed in the root zone and around the diviner access tubes.

The 40 cm depth was the only depth that had a combined treatment and species effect (Figure 3.19). Figures at other depths are included in Appendix F. At this depth, *C. brachytricha* had a lower VSM at the 25% treatment, *P. virgatum* was lower at 25% and 50% treatment levels and *S. scoparium* had a lower VSM at the 25% treatment level. One hypothesis for the interaction of species and treatment effects occurring at this depth could be because this is where optimal root growth may be found and that there was possibly more root tissue at this depth, so those root withdrew more water from the soil at 40 cm. The ornamental grass species differed in their water uptake according the water treatment. *Calamagrostis brachytricha* at 40 cm showed varying results by treatment. This could be related to plant size at each quadrant; there appears an inverse relationship between VSM and dry weight. VSM at this depth is lower under *C. brachytricha* with a higher dry weight. *Panicum virgatum* demonstrated a similar correlation to dry weight and VSM. *Schizachyrium scoparium* did not show this correlation. This may be due to its more shallow root system which was not accessing water at 40 cm (Nippert and Knapp, 2007), or that the plants at the 100% and 0% treatment levels were smaller and therefore utilizing less water around the diviner access tubes. For *S. scoparium*, the 50% treatment level appears to have the highest VSM even though these plants had close to the highest average dry weight measurement. Therefore, the possible shallow root system of *S. scoparium* may be the best possible explanation of this finding.

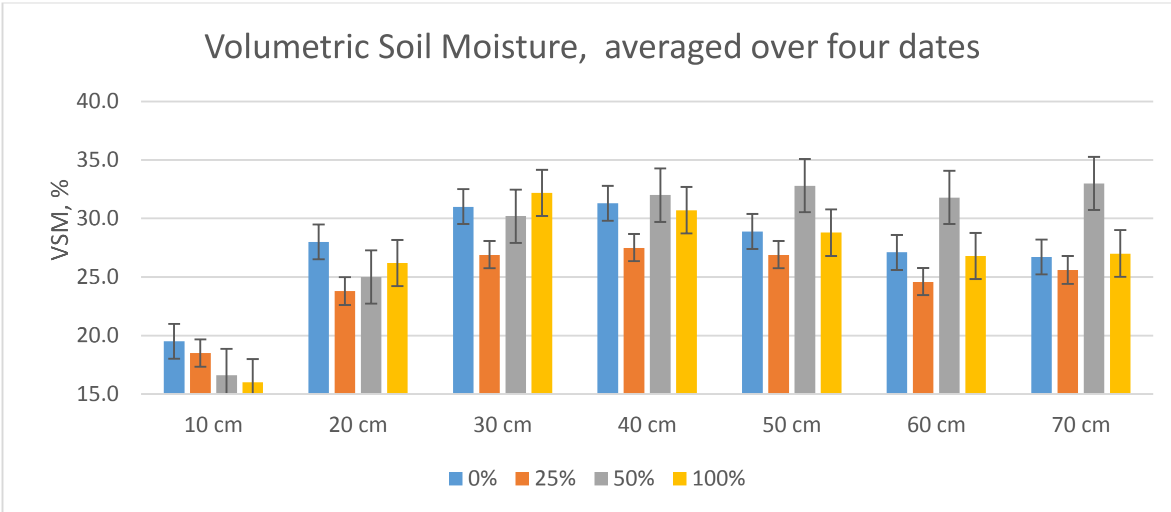
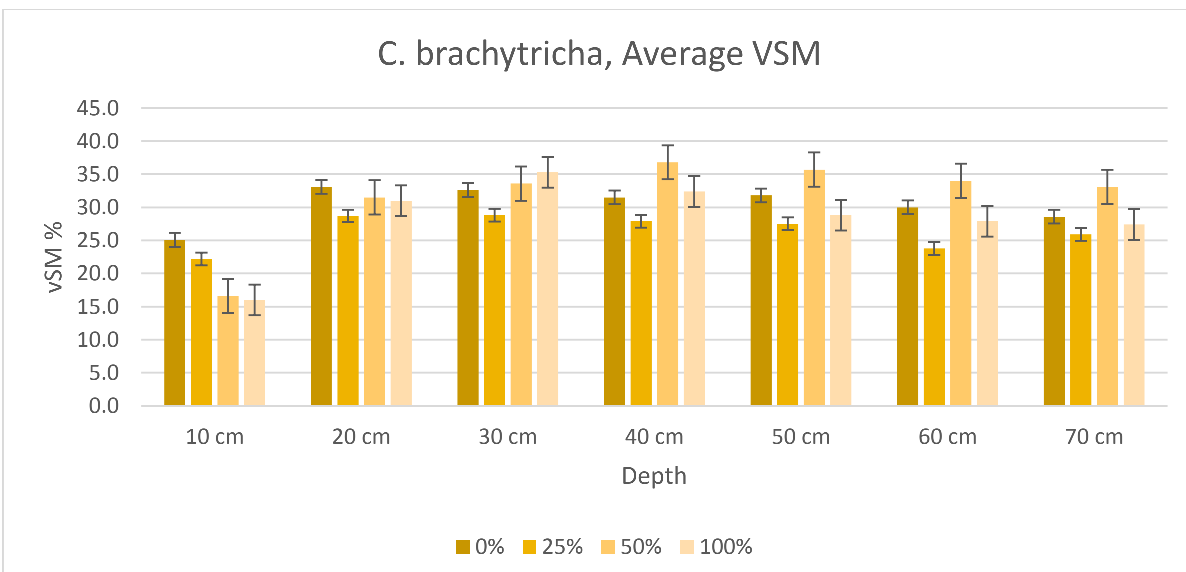
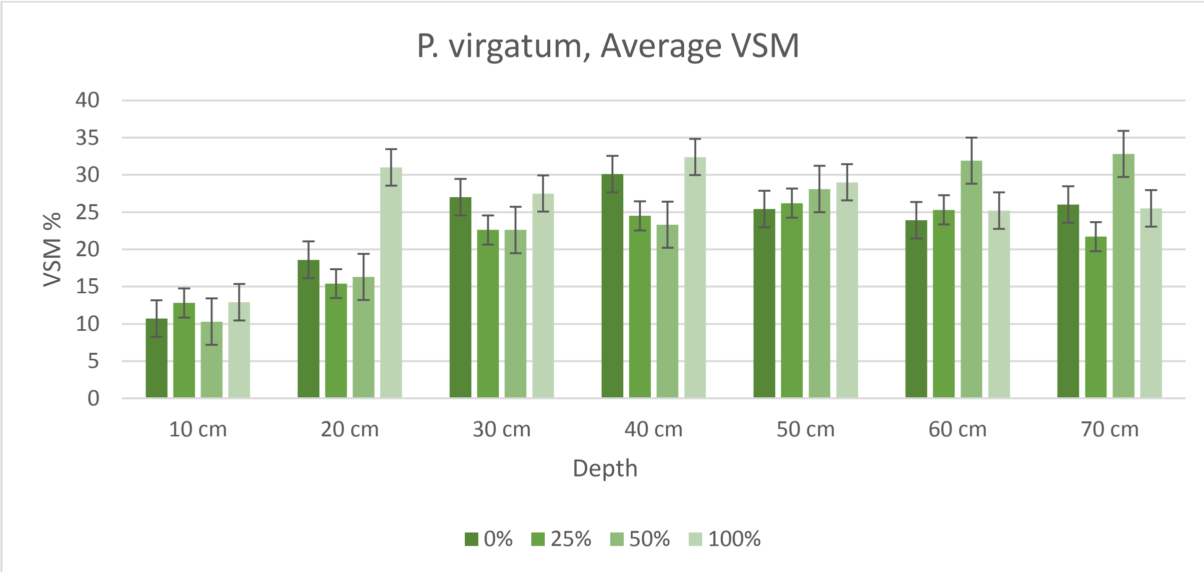


Figure 3.17. Volumetric soil moisture, averaged over 4 dates in 2013 (July 17, July 30, August 13, August 27) and 4 treatment levels (0%, 25%, 50%, 100%) at each depth (10-70 cm). Error bars indicate standard errors (±1)at p≤0.05.

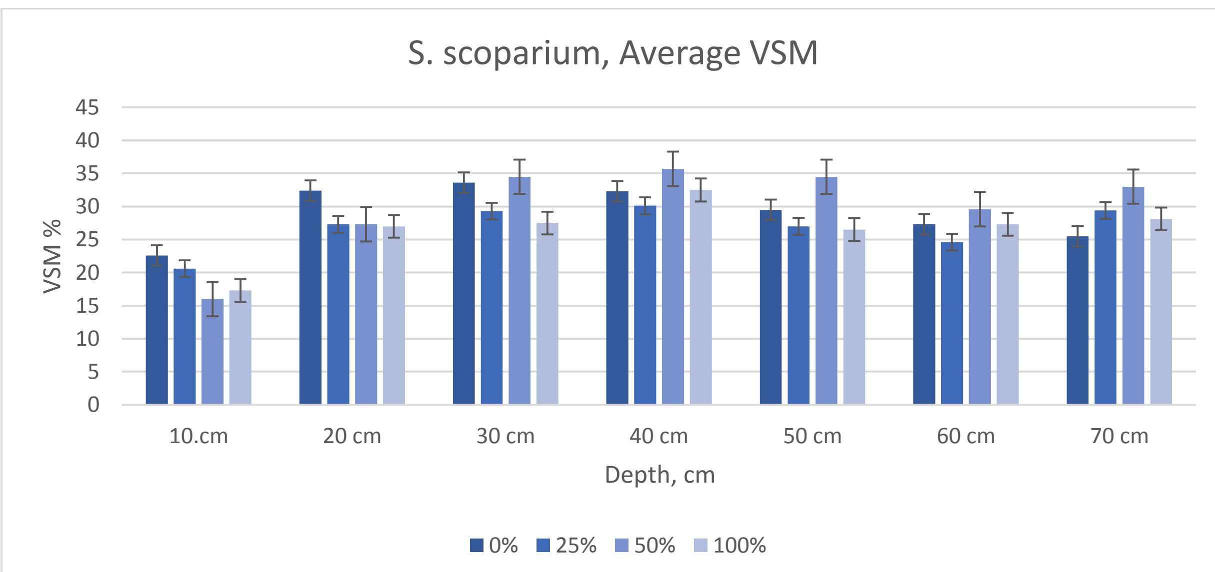
(a)



(b)



(c)



Figures 3.18 a-c. Volumetric soil moisture (VSM) of (a) *C. brachytricha,* (b) *P. virgatum,* (c) *S. scoparium* across treatments (0%, 25%, 50%, 100% of reference ET) at 4 soil depths. Error bars indicate standard errors (±1) at p≤0.05.

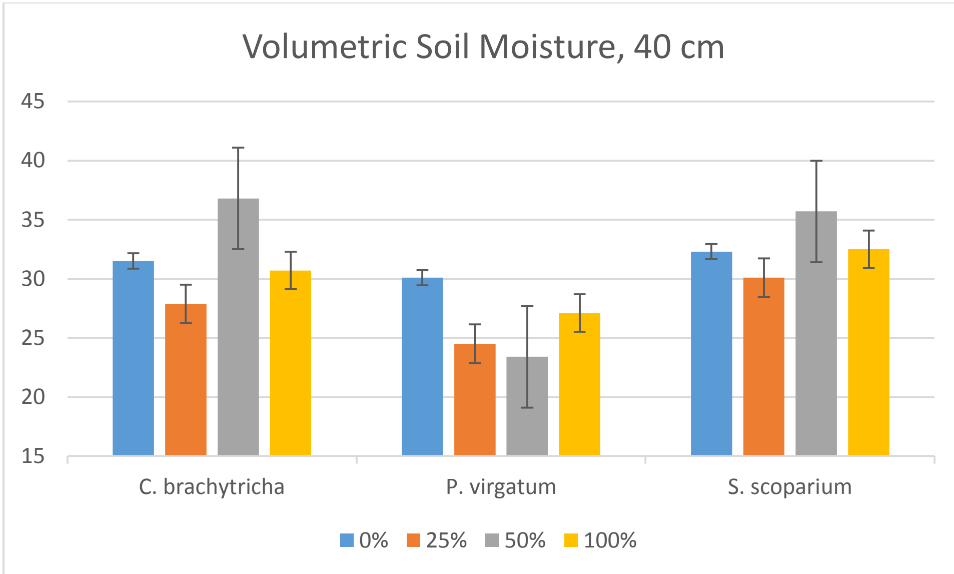


Figure 3.19. Volumetric soil moisture (VSM) of (a) *C. brachytricha,* (b) *P. virgatum,* (c) *S. scoparium* across treatments (0%, 25%, 50%, 100% of reference ET) at 40 cm depth. Error bars indicate standard errors (±1) at p≤0.05.

Visual Ratings

All three ornamental grasses are possible landscape selections by homeowners. Watering regimes should be applied so plants have an aesthetically pleasing appearance at reduced watering levels. Three separate subjective ratings were used to reflect the appearance of the grasses in the study quadrants: Plant Form, Floral Impact and Landscape Impact, as well as photos of the three species at each treatment level (Figure 3.20). The rating scale definitions are in Appendix C. In addition, a leaf curling scale was added to visually determine the stress level in *Calamagrostis brachytricha*. As stated previously, *S. scoparium* folds it leaves and it was determined that this characteristic applied to all the plants in the study and across all water treatments, so data were not taken on this characteristic. Leaf curling in *P. virgatum* was not noted in the study quadrants. Leaf curling on *C. brachytricha* was noted monthly in July, August and September, 2013 prior to a water treatments on each quadrant.

Photographs of each plant were taken at the end of the season. A representative photograph of each species in each watering treatment in September, 2013 is shown in Appendix G a-c. With *C. brachytricha*, it is clearly demonstrated that the 0% plants do not have a high landscape appearance as the other treatments. In *S. scoparium*, the 0% and 100% treatments resulted in plants which were not as visually appealing as the 25% and 50% treatments. It was difficult to assess the differences in quality of P. virgatum between water treatments by the photographs. As the water increased, the P. virgatum was noticeably larger and contained an increased amount of flowering tillers, though this observation was not quantified.

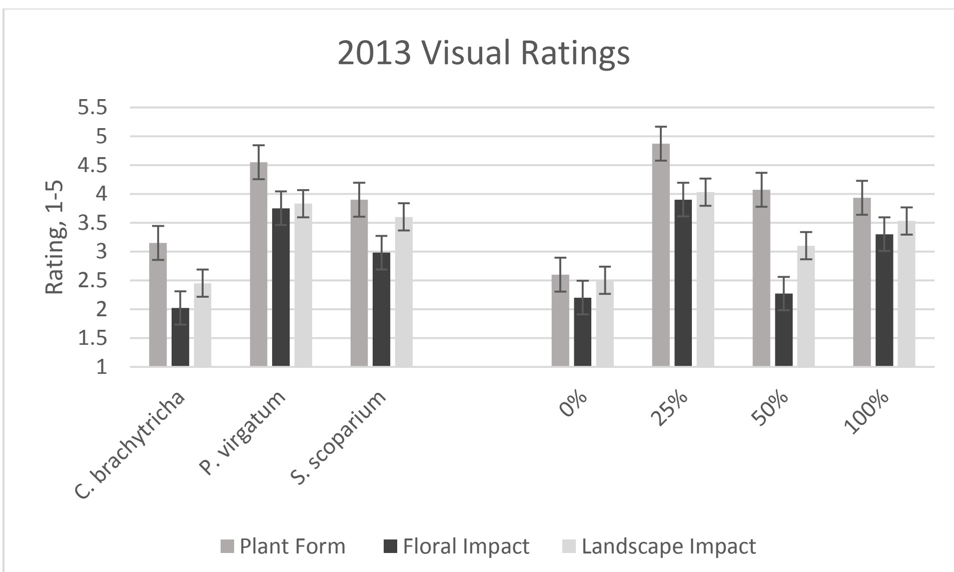


Figure 3.20. Visual ratings (Plant Form, Floral Impact, Landscape Impact) of species C. brachytricha, P. virgatum, S. scoparium and treatment levels (0%, 25%, 50%, 100%) compiled in September, 2013. Error bars indicate standard errors (±1) at p≤0.05.

Plant Form

Plant form was significantly different at the species, treatment and species/treatment levels. (Figure 3.21). *Panicum virgatum* scored the highest across all treatments. Significant differences between treatments were noted across all treatment levels except between the 100% and 50% levels. The highest rating was given to plants in the 25% treatment quadrant, the lowest to plants in the 0% treatment level. The highest ratings for species within a treatment level for *C. brachytricha* was in the 25% water treatment level. For *P. virgatum*, the highest values were observed at the 25% and 50% treatment levels. For *S. scoparium*, the highest values were also found in the 25% and 50% quadrants. These findings indicate that across all treatments, plant form was maintained at the 25% treatment level, and little to no improvement in plant form was noticed above this treatment level.

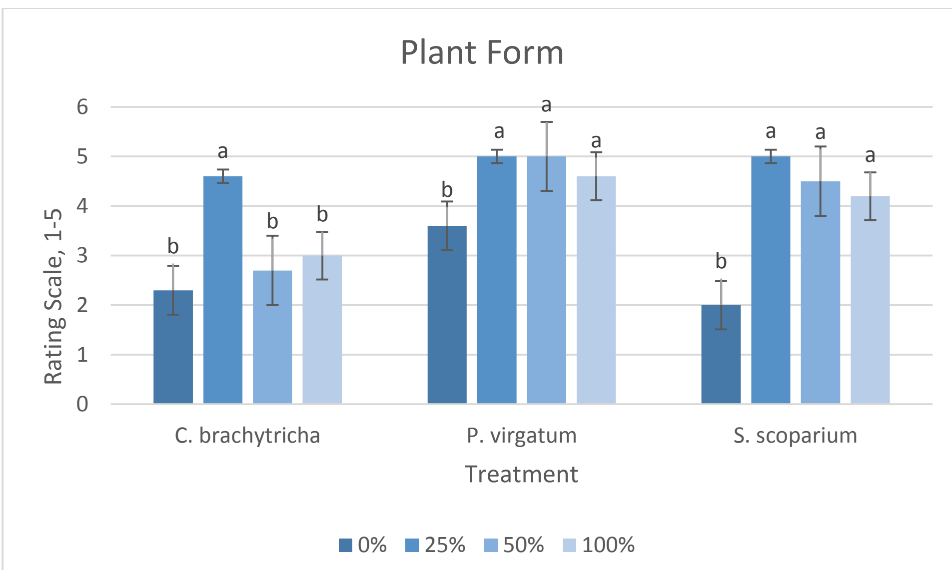


Figure 3.21. Plant Form Rating of species C. brachytricha, P. virgatum, S. scoparium and treatment levels (0%, 25%, 50%, 100%) in September, 2013. Error bars indicate standard error at P≤0.05.

Floral Impact

Species and treatment effects were noted for floral impact (Figure 3.22). Species effects varied, since these species have different flowering types and time of maximum bloom. When this characteristic was evaluated in late September, 2013, *P. virgatum* had the highest floral impact with *C. brachytricha* having the lowest. This due to the fact that many of the *C. brachytricha* plants did not yet have any inflorescence present in the four quadrants. Treatment differences were also noted. Across all species, the highest floral impact rating was in the 25% treatment quadrant; it was significantly higher than both the 0% and 50% treatments, though it was not significantly different from the 100% treatment. This indicated that floral impact does not change considerably between the 25% and the 100% treatment, though there was a significant change between the 25% and 50% treatments. With *C. brachytricha*, this may be due to the low floral impact ratings on the 50% treatment plot, where none of this species developed inflorescence over the course of the season. Overall, the addition of water between the 25% treatment and the 100% treatment does not appear to affect the impact of the inflorescence.

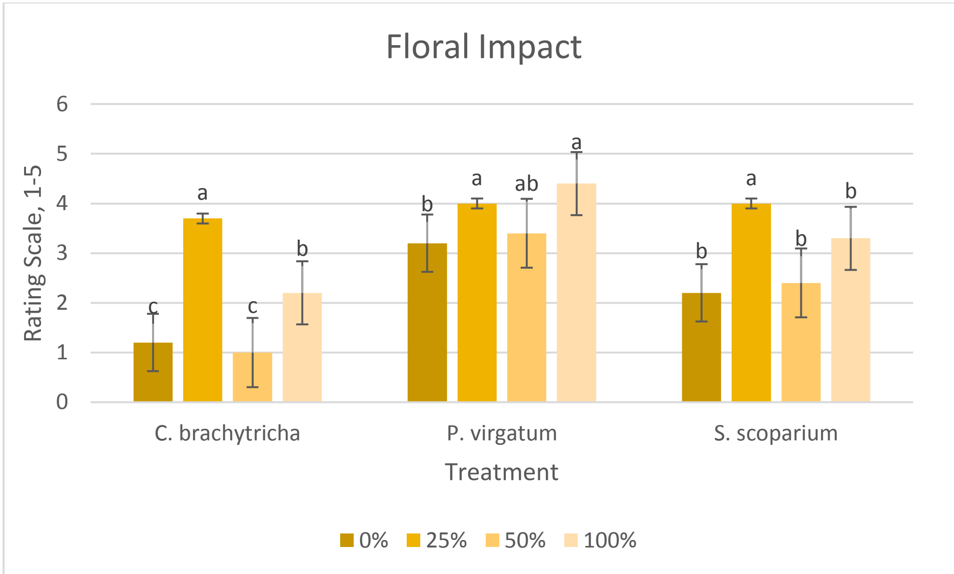


Figure 3.22. Floral Impact Rating of species *C. brachytricha, P. virgatum, S. scoparium* at treatment levels (0%, 25%, 50%, 100%) in September, 2013. Error bars indicate standard error at $p \leq 0.05$.

Landscape Impact

This scale indicated the overall form and flowering of the plant, also taking into consideration disease and pest problems. Plants were evaluated over the entire season for disease and pest problems as well as leaf scorch or other unsightly leaf changes. The final evaluation occurred at the end of September. Both species and treatment effects were noted (Figure 3.23). *P. virgatum* had the highest landscape impact rating, followed by *S. scoparium* and lastly *C. brachytricha*. The 0% treatment level had significantly lower ratings than all other treatment levels. The 25% treatment level had the highest impact ratings, with significant differences between the 100% and the 25% ratings in *C.brachytricha*. This indicates that the increased watering at the 100% level did not increase the landscape impact of these plants.

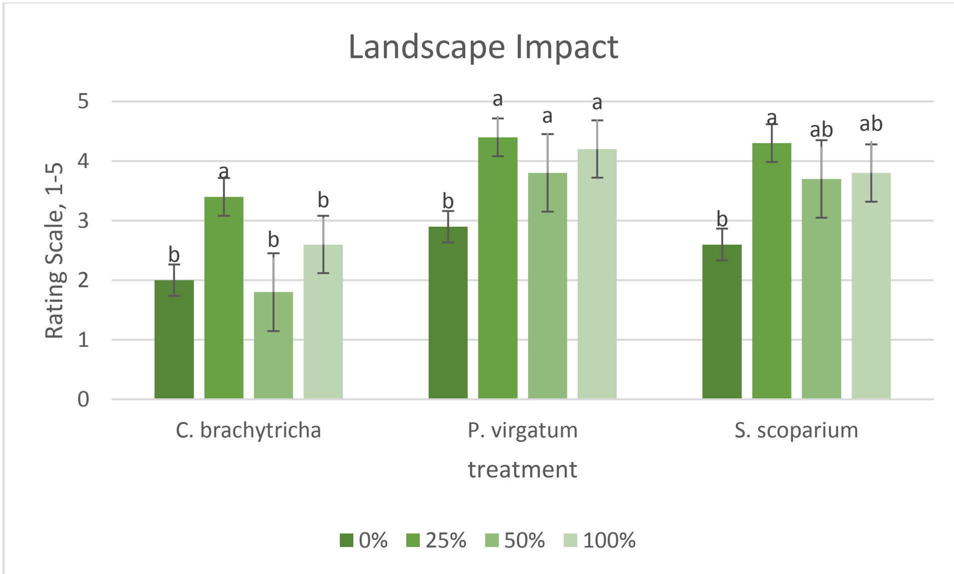


Figure 3.23 Landscape Impact Rating of species *C. brachytricha, P. virgatum, S. scoparium* at treatment levels (0%, 25%, 50%, 100%) in September, 2013. Error bars indicate standard error at $p \leq 0.05$.

Leaf Rolling

Calamagrostis brachytricha was the only species which exhibited this water-stress reaction across water treatments (Figure 3.24). Data were not taken on other species, since *S. scoparium* folded its leaves across all treatments and leaf rolling was not noted in *P. virgatum*. Leaf rolling in this species was most pronounced, and statistically greater in the 0% treatment plot. Since this treatment received the lowest amount of supplemental water, *C. brachytricha* exhibited more signs of stress when the plants were under-watered. Both the 25% and the 50% water treatments had similar ratings for leaf rolling, but both were significantly higher than the 100% water treatment. This indicates that this water stress indicator increased from the 100% treatment to the 0%.

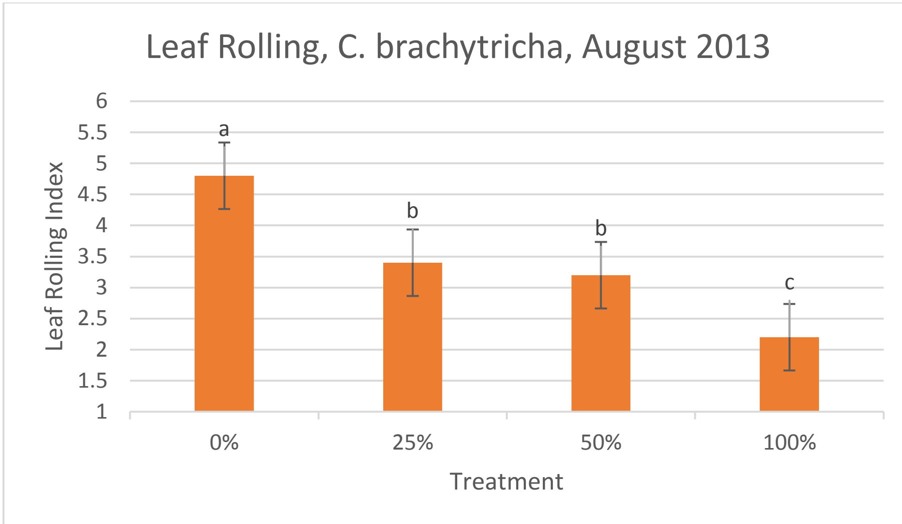


Figure 3.24. Leaf rolling index of C. brachytricha for irrigation treatments (0%, 25%, 50%, 100%) averaged across 3 measurements in 2013 (July 30, August 13, August 30). Treatments with different letters are significantly different at P≤0.05.

CHAPTER 4: Conclusion

Weather played a major factor in the collection of usable data in the 2013 growing season. Unseasonably cold temperatures in April 2013 delayed the establishment of the grasses early in the season and unusually heavy rain amounts in September 2013 limited the data collection later in the season.

Visual ratings of plant form, floral impact and landscape impact were highest at the 25% of ET irrigation level. Photographs confirm this across all species and treatments. The pre-study objective which stated that acceptable visual qualities would not be apparent without supplemental irrigation was only partially correct. *Panicum virgatum* at the 0% treatment had acceptable to good visual quality ratings (above a rating of 3) in plant form and floral impact ratings, but below this threshold in landscape impact rating. Both *C. brachytricha* and *S. scoparium* exhibited less than acceptable ratings in all visual rating scales when supplemental irrigation was not provided. *Panicum virgatum,* due to its ability to adequately grow at all treatment levels, provided higher quality ornamental characteristics than *S. scoparium* and *C. brachytricha* in low water situations. This pre-study objective was met in this study.

Calamagrostis brachytricha, the more mesic species, grew well early and late in the season, but water stress measurements indicated that during dry, hot times during the season and at 0% irrigation, it was more stressed. Ornamental features such as increased inflorescence confer that the 25% treatment showed optimal visual quality. *Panicum virgatum* on the other hand, seemed to be visually acceptable at all irrigation levels, though visual quality was optimal at the

25% treatment or above. This confers with other studies where *P. virgatum* responds to increased water treatments by increased plant size and inflorescence. *Schizachyrium scoparium* did not have acceptable visual ratings at the 0% treatment, and had lower visual quality ratings at the 100% treatment. This may indicate that for highest visual ratings, the 25% treatment gives adequate moisture for optimal plant form, floral impact and landscape impact ratings.

Averaged across all three species, maximum plant height, tiller height, width and circumference were observed at the 25% irrigation level and similar to the same plant characteristics observed at the 100% irrigation level. This finding was different from the first study objective which stated that the three species would have different optimal irrigation rates. We found that plant dry weight increased as irrigation level increased from 0 to 50% of ET, however, there was a decrease in total plant dry weight at 100% of ET, across species and specifically with *C. brachytricha* and *S. scoparium*. This indicates that watering these species of ornamental grasses at 100% ET may decrease growth. *Panicum virgatum's* growth at 100% of ET was not significantly different between 25% and 100%. Covariate analysis of dry weight and circumference show that the 25% irrigation treatment confer optimal growth across all species. Therefore, the 25% treatment gave the highest, or one of the highest measurements in all of the growth categories. It appears that optimal growth from measured parameters for all of the species was at the 25% treatment level. The growth at water treatments above 25% ET may have been stimulated by excessive water and did not add to the visual quality of this species. Water savings could be realized by only watering these plants at 25% ET.

The greatest drought stress, as measured by leaf water potential, was found with the mesic species *C. brachytricha*, which has been previously studied in its native range and in irrigated landscapes (Yuan, et al., 2011). Leaf rolling data collected on *C. brachytricha* seems to confirm this finding, with the highest leaf rolling index found with the 0% treatment. *Panicum virgatum* displayed the least negative leaf water potential and across all species was the least stressed. Averaged across all plant species, leaf water potential was most negative (greatest drought stress) at 0% ET and the least amount of stress was observed at 50 and 100% of ET. Highest canopy temperatures were seen with those treatments that experienced the most negative leaf water potentials. The differences between the 0% to 100% treatments indicated that the plants were less stressed as the water treatment amounts increased. It should be noted that the 0% reading in canopy temperature did not always confer the lowest canopy temperatures and may be due to the ability of some of the species (*S. scoparium* and *P. virgatum*) to osmotically adjust to this lower irrigation treatment (Barney, et al., 2009, Knapp, 1984). These data seem to confer with the growth measurements that for the drought-tolerant species *S. scoparium* and *P. virgatum*, 25% ET treatments does not cause plant stress which could inhibit adequate growth. Volumetric soil moisture (VSM) measurements indicate that plants accessed water to approximately 50 cm soil depth, but not below this point. *Panicum virgatum* demonstrated the lowest VSM across all treatments, which parallels this species large size and therefore larger root system to access soil moisture.

Our research with these three species in Colorado showed that irrigation at 25% ET irrigation produced plants with greater height, width, dry weight and visual impact in the landscape. GreenCO rated *C. brachytricha, P. virgatum* and *S. scoparium* in the 'Low' category (25-50% ET) in plant water requirement estimates for the Front Range of Colorado, and this study has validated their recommendations (GreenCO, 2008). The three ornamental grasses in this study will perform well in landscape situations with limited irrigation and other inputs.

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Appendix I

Table A1.1. Soil Test Result, Ornamental Grass Irrigation Study, 2012. Testing by CSU Soil, Water and Plant Testing Laboratory.

Year/Zone	pH	EC (mmhos.com)	Lime, %	Texture	Organic matter, %	N (nitrate) ppm	P ppm	K ppm	Zn ppm	Fe ppm	Mn ppm	Cu ppm	B ppm
2012/A	7.3	0.5	>5	sandy/clay	6.7	37	80	957	11.6	33.2	7.7	4	0.6
2012/B	7.5	0.5	>5	sandy/clay	5.5	33	84	844	10	33	9.7	4.3	0.5
2012/C	7.5	0.5	>5	sandy/clay	5.5	27	100	966	10.8	33.2	9.5	4.3	0.53
2012/D	7.5	0.4	>5	sandy/clay	6.2	26	75	924	9	28.1	8.7	3.6	0.54

Table A1.2: Average Height and (width) of Ornamental grasses – pre-plant, October 2012 and October 2013; in centimeters

		Calamagrostis brachytricha				Panicum virgatum				Schizachyrium scoparium			
		Zone A	Zone B	Zone C	Zone D	Zone A	Zone B	Zone C	Zone D	Zone A	Zone B	Zone C	Zone D
Pre-plant - June 2012		30.4 (23.4)	31.5 (24.3)	30.9 (23.7)	30.4 (23.6)	43.2 (25.0)	43.6 (25.8)	43.3 (25.6)	44 (24)	30.2 (23)	31.4 (23.7)	30.8 (24.7)	28.4 (24)
Oct-12		37.3 (48.8)	43 (49.6)	39.2 (52)	44.8 (53.3)	95 (79.6	91.8 (65.6)	89.8 (85)	95.6 (84.8)	76.8 (45.5)	76.4 (45.6)	83.4 (59)	45.8 (51.4)
Oct-13		50.8 (73.5)	79 (79.2)	57.6 (63.1)	64 (77.5)	86 (81.2)	89.8 (72.4)	80.3 (69.1)	91.6 (66.8)	58.3 (48)	68.2 (54.5)	53.8 (43.6)	60 (51.3)

Table A1.3: Plant Form, Floral Impact, Leaf Rolling and Landscape Impact rating scales used for Ornamental grass irrigation study, 2013.

	Plant Form	Floral Impact	Landscape Impact	Leaf Rolling
1	80% or more of the plant is prostrate	no impact (no inflorescence present);	Very little or no ornamental value in the landscape. Growth weak with poor foliage color, high rate of lodging, little flowering (if flowers should be present) and/or high rate of disease or insect damage.	no rolling
2	approximately 66% of the plant is prostrate, or is lodged or is in any way 'non-uniform'	25% impact	Below average landscape appearance and value. Vigor poor with significant problems with plant habit and/or disease or insect damage.	up to 25% rolling
3	50% lodging or prostrate	50% impact	Average landscape appearance and value. Vigor good, but with some problems with plant habit, and/or disease or insect damage.	up to 50% rolling
4	80% or more of the plant is upright, uniform, very little lodging	75% impact	Above average landscape appearance and value with only minor problems with plant growth habit and disease or insect damage.	up to 75% rolling
5	95% or more of the plant is upright, uniform, attractive, very ornamental, no lodging	95% impact, very showy	Outstanding landscape appearance and value. Good vigor, foliage color, and flowering (if flowers should be present), with little or no disease or insect damage.	rolling, 100%

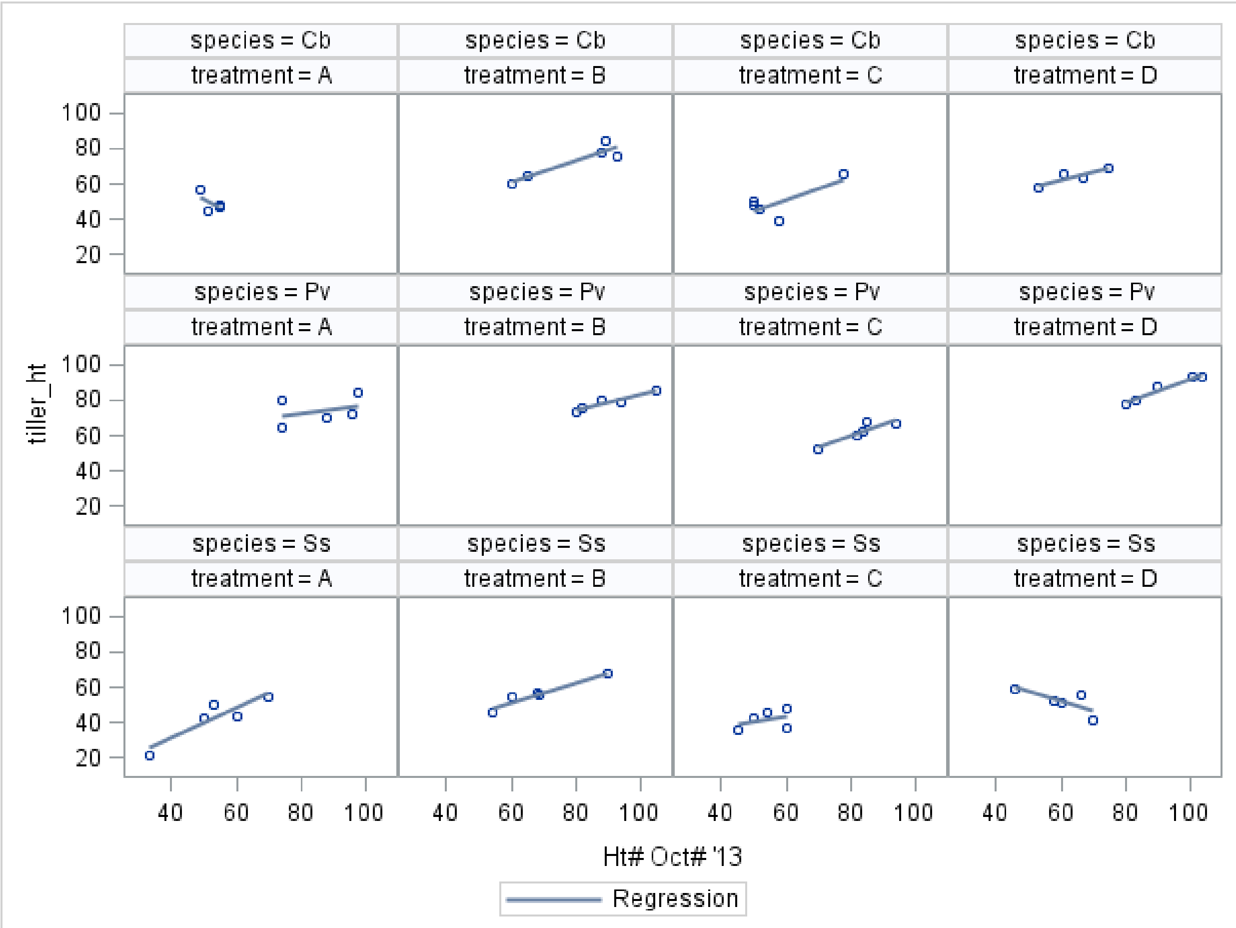


Figure A1.1. Pearson Correlation Coefficient regressions of end of season 2013, comparisons of height and tiller height measurements. Cb=Calamagrostis brachytricha, Pv=Panicum virgatum, Ss=Schizachyrium scoparium. Irrigation treatments: A=50%; B=25%; C=0%; D=100%. Statistical significance at the p≤ 0.05.

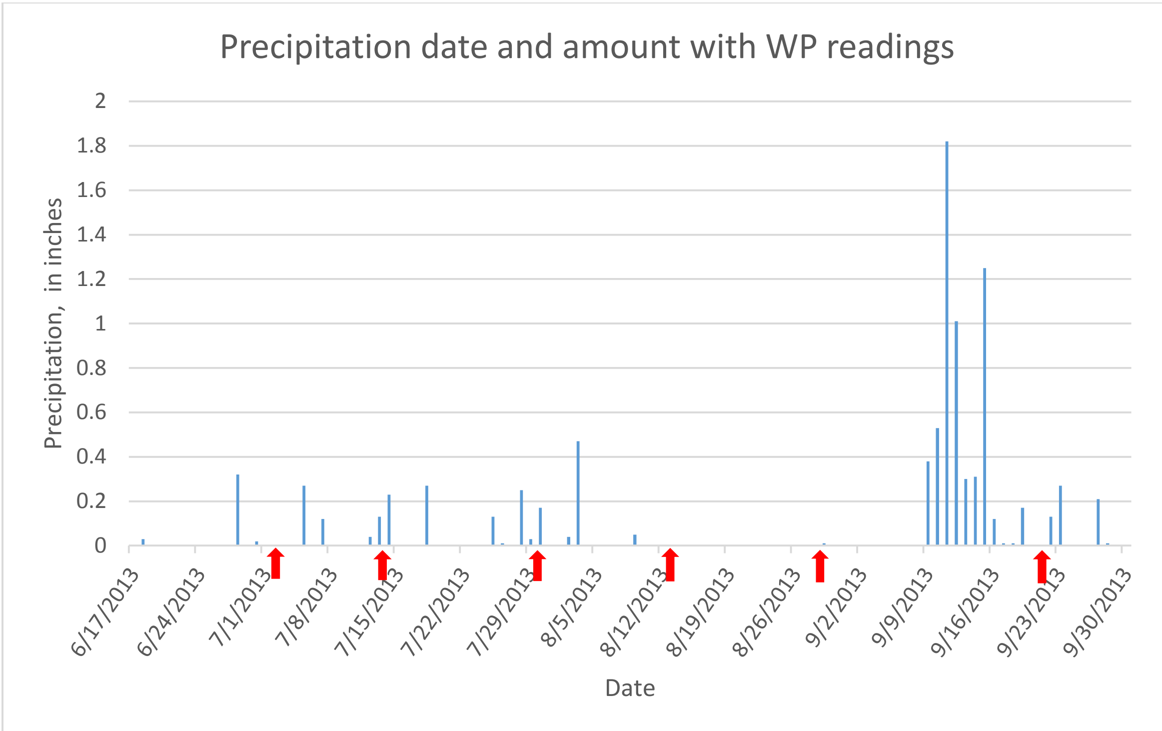
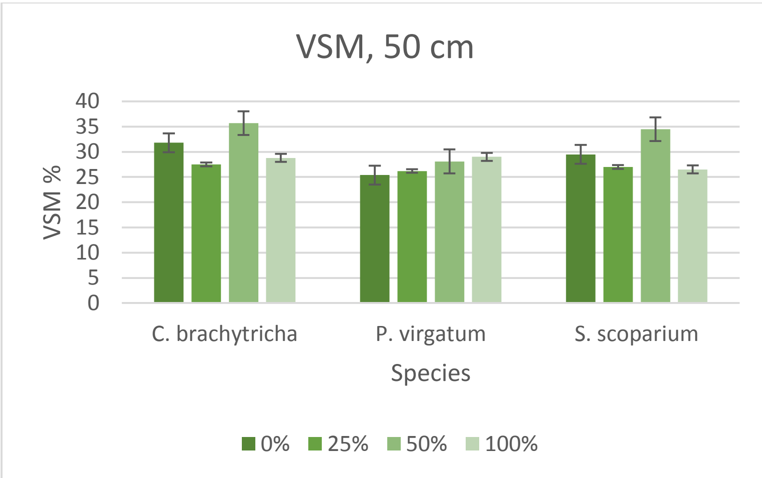
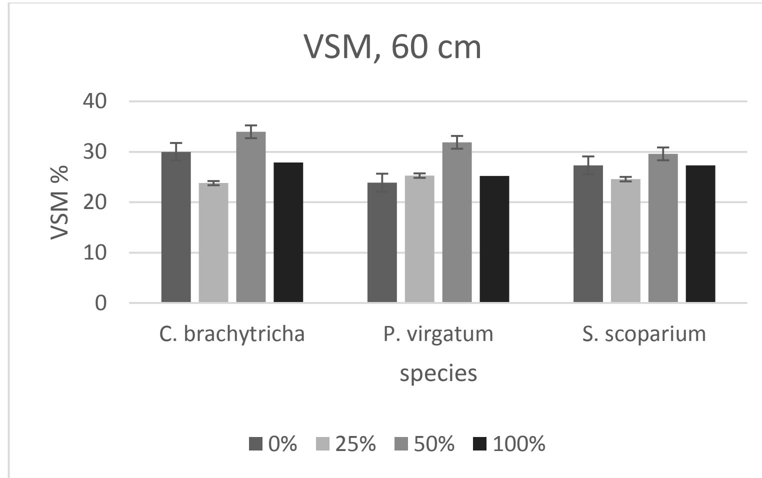


Figure A1.2. Precipitation amounts (in inches) during 2013 Ornamental grass Irrigation Study with dates of water potential measurements indicated by arrow

Figure A1.3 (a-g). Volumetric Soil Moisture (VSM) of C. brachytricha, P. virgatum and S.scoparium at each soil moisture depth (10-70 cm) Error bars indicate ±1 standard error. p≤0.05.



e.



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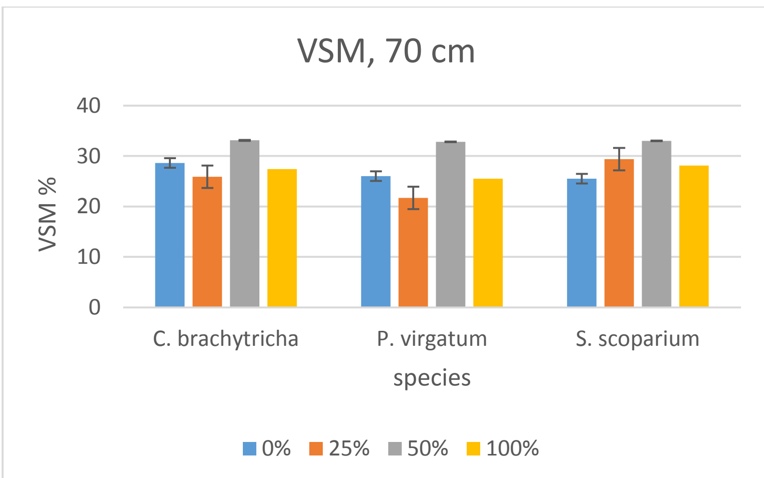

g.

Figure A1.3 (a-g). Volumetric Soil Moisture (VSM) of C. brachytricha, P. virgatum and S.scoparium at each soil moisture depth (10-70 cm) Error bars indicate ±1 standard error. p≤0.05.

:

(a)

(b)

(c)

(d)

Figure A1.4. Photos of *Calamagrostis brachytricha* on September 30, 2013 at (a) 0%, (b) 25%, (c) 50% and (d) 100% water treatment.

(a)

(b)

(c

(d)

Figure A1.5. Photos of *Panicum virgatum* on September 30, 2013 at (a) 0%, (b) 25%, (c) 50% and (d) 100% water treatment.

(a) (b) (c) (d)

Figure A1.6. Photos of *Schizachyrium scoparium* on September 30, 2013 at (a) 0%, (b) 25%, (c) 50% and (d) 100% water treatment.