SOIL MOISTURE RESPONSES IN TRADITIONAL AND DROUGHT ADAPTED LANDSCAPES IN THE INTERMOUNTAIN WEST

by

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ABSTRACT

Soil Responses in Traditional and Drought Adapted Landscapes in the Intermountain West

by

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Water conservation in the Intermountain West will be an important issue in the future as population and demand for limited water resources increases. In Utah, outdoor water use accounts for up to 60% of total per capita water use with 67% of that outdoor water being used to irrigate non native plant species to maintain a uniform green appearance. The objective of this study was to measure intra landscape changes in soil water potential during a 21.5 day dry down from DOY 215 to 236.5 in the summer of 2005 and 2006. Four, 2 x 2 replicated traditional and drought tolerant landscapes were instrumented with inexpensive resistance blocks at four points and three depths (15, 45, and 90 cm) at the Utah Botanical Center, Kaysville, Utah. Each mixed vegetation landscape consisted of a drainage lysimeter planted with annual and perennial shrubs, bunch grasses, turf grasses, and a 1.5 m coniferous tree. Mean soil water potential varied significantly between landscape treatments (p 0.05).and was most negative at 15 cm at the end of the dry down under Kentucky bluegrass (*Poa pratensis. L*) (-428 ± 50 kPa). In contrast, Buffalograss (*Buchloe dactyloides*) was significantly more negative at 45 cm and 90 cm (-291 ± 50 kPa and -197 ± 50 kPa), respectively, compared to Kentucky bluegrass, suggesting greater soil water extraction by deeper roots. Mean soil water potentials were less negative under the shrub and conifer treatments compared to turfgrasses at the end of the dry down on DOY 236.5, suggesting lower plant water use and/or hydraulic redistribution.

(70 pages)

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James Gregory

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INTRODUCTION

Increasing demand for water resources and recurrent drought in the Intermountain West will require water conservation in urban landscapes. Utah is ranked as the 3rd fastest growing state in the U.S. Utah is one of the five fastest growing states in the nation including: (1) Nevada, (2) Arizona, (3) Utah, (4) Idaho, and (5) Colorado. Currently, population in Utah is estimated at 2.7 million, and is growing at 14.2% a year, over twice the national average of 6.2% (www.census.gov). With the nation's highest birth rate and third highest life expectancy, Utah's population and economic growth rate are projected to continue to out-pace most of the nation through the year 2020. In Utah, average per capita water use of 1215 L per day is second only to Nevada in water consumption with ≥40% of that water being used to irrigate amenity landscapes. By the year 2050, municipal and industrial water diversions in the state of Utah are projected to increase from current levels of 900,000 acre feet per year to 1.9 million acre feet per year. At this rate an estimated 4.16 GL of water per day will be required to provide for an additional 3.4 million people (www.water.utah.gov/WaterPlan). In Utah and other western states where rapid growth is expected, water conservation will be necessary to manage increasingly scarce water resources.

Over drafting of limited surface and groundwater supplies will have negative socioeconomic, environmental, and ecological effects as demand for water increases in the next 20 years (Diaz et al.1985; Kjelgren 2000; Shock et al. 1998). The effects of rapid growth in the western United States will include regional water policy conflicts and land use changes including transfers of water from agricultural land to urban areas to supply rapidly growing cities (Gollehon 1999; Howe et al. 1990). In 1995 Bear Lake, with 1.3 million acre-feet of irrigation water for use in Cache and Box Elder counties ended the irrigation season with virtually no stored irrigation water. This was the first time since 1935 that Bear Lake irrigators had been without irrigation reserves stored in Bear Lake at the start of the new water year on October 1st. In 2004, Bear Lake was 5,903.09 feet above sea level, near the record low of 5,902 feet reported in 1935 (www.bearlakewatch.com). Historical stream flow records from 1999-2004 made it the worst drought in the last 80 years for portions of the upper Colorado River Basin (Piechota et. al. 2004). Snow pack measured at Tony Grove, Bear River Range, Utah in the winter of 2006 was 50% of normal. Numerous record high temperatures were reported in Utah in 2006 and 2007 and temperatures in Utah have averaged 2° F higher than the 100 year average (www.met.utah.edu/news/global_warming_2007_pdf).

The availability of water in the Intermountain West is limited by a semi arid climate where ‘summer rainfall is variable in space and time, evapotranspiration (ET) rates are high, and shallow subsurface water is limited for much of the summer and fall’ (Schwinning 2001). Plant water demand in the Intermountain West is highest between May and September during periods of low rainfall, high temperature, and high vapor pressure deficit. Annual precipitation in semi-arid environments ranges from 150 to 500 mm and is highly variable from year to year (Diaz et al. 1985; Noy-Meir 1973). Precipitation in Utah originates from Pacific frontal systems and low pressure systems (late fall through spring), and monsoonal thunderstorms (summer). During some winters a high pressure ridge is dominant over the Western United States forcing the jet stream north or south of Utah, resulting in winter drought (Wilkowske and Angeroth 2005). The semi arid climate in the summer may be intensified by effects of subtropical high pressure enhancing temperature and lowering humidity (Wright 1993). Precipitation that arrives during the monsoon season in the summer wets only surface soil layers and decreases north of the regional monsoon boundary in central Utah (Williams and Ehleringer 2000). Occasional extension of the subtropical high pressure cell from the tropical circulation, enhances the heat and aridity conditions during summer. Storm type and topography influence the amount of precipitation and availability of water in mountainous regions. Summer precipitation in much of the western United States is characterized by high spatial variability originating from convective thunderstorms that average < 5 mm precipitation (Sala et al. 1992; Schwinning 2001; Singh 1998).

Precipitation in Utah

In the Intermountain West average annual precipitation amounts range from 38.1 mm in the high deserts of Utah to 1778 mm in the mountains at high elevation (Loik et al. 2004). More precipitation falls at higher elevations and is stored as snow where it is released in the spring and summer as runoff in the Bear River, Wasatch, and Uinta mountain ranges. Precipitation at lower elevations is influenced by mountain barriers and rain shadow effects (Figure 1). Cyclical weather patterns that occur at different time scales including the North American Monsoon, El Nino Southern Oscillation, (ENSO), and Pacific Decadal Oscillation, (PDO) contribute to periodic changes in precipitation patterns in the Intermountain West (Loik et al. 2004; Miller 2005). Decadal variations in precipitation over western North America account for 20-50% of variance of annual precipitation (Cayan et al. 1998).

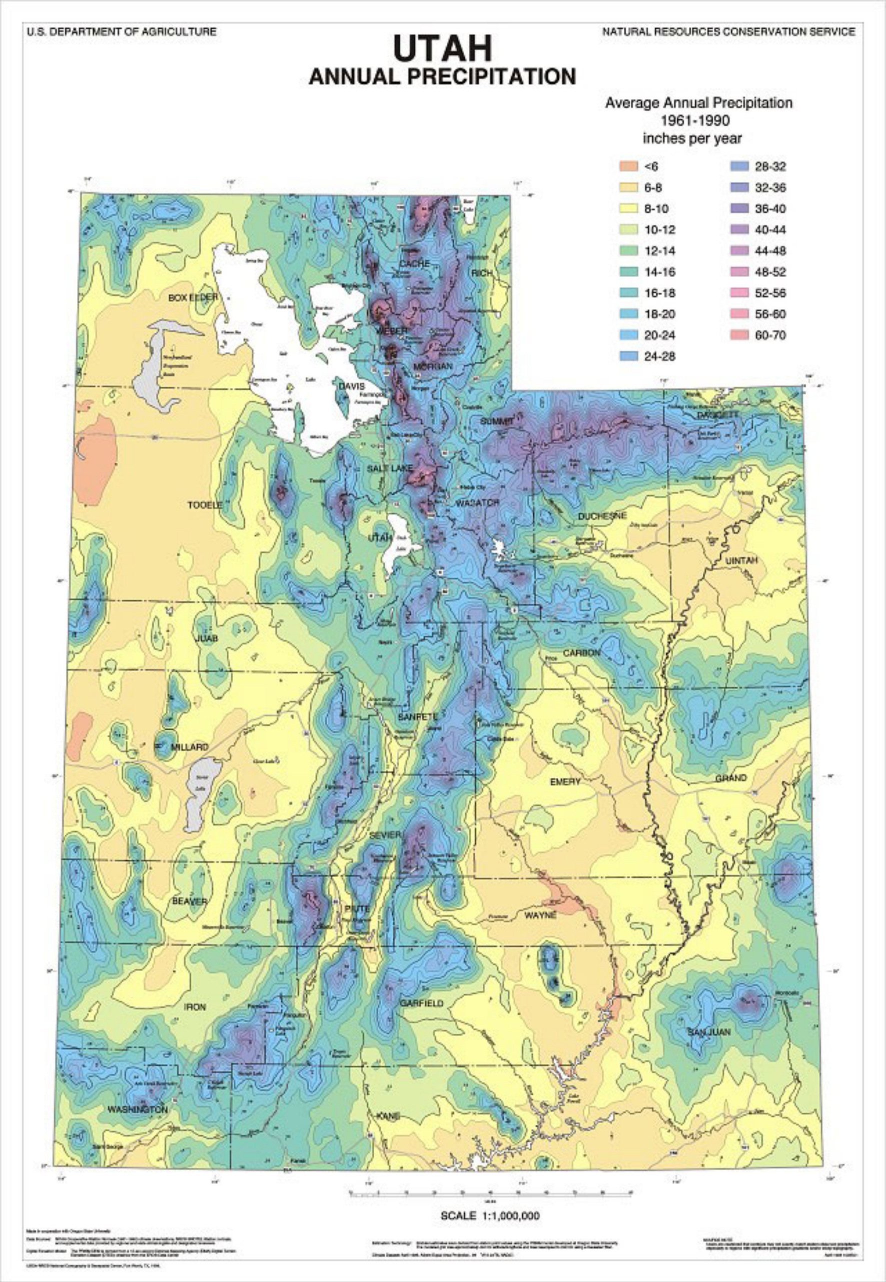


Figure 1 Topographical variations in annual precipitation in the state of Utah from 1961to 1990. Most precipitation is concentrated at higher elevations due to the orographic effect and is stored as snow until it is released as runoff in the spring and summer months. Precipitation at lower elevations is influenced by mountain barriers and rain shadow effects.

Based on estimates of precipitation over the last 750 years, periodic drought appears to occur every 20 to 50 years and may persist for well over 10 years at a time (Gray 2004). In the Uinta Basin of northeastern Utah, significant long term variability in precipitation was demonstrated from tree ring based reconstructions of inter annual and decadal scale precipitation from 1226 to 2001 A.D. (Figure 2). Dry events in the 13th, 16th, and 18th centuries were greater than the magnitude of drought observed in the Uinta Basin after 1900 suggesting that another long cycle of drought may occur in the next 20-100 years (Gray 2004).

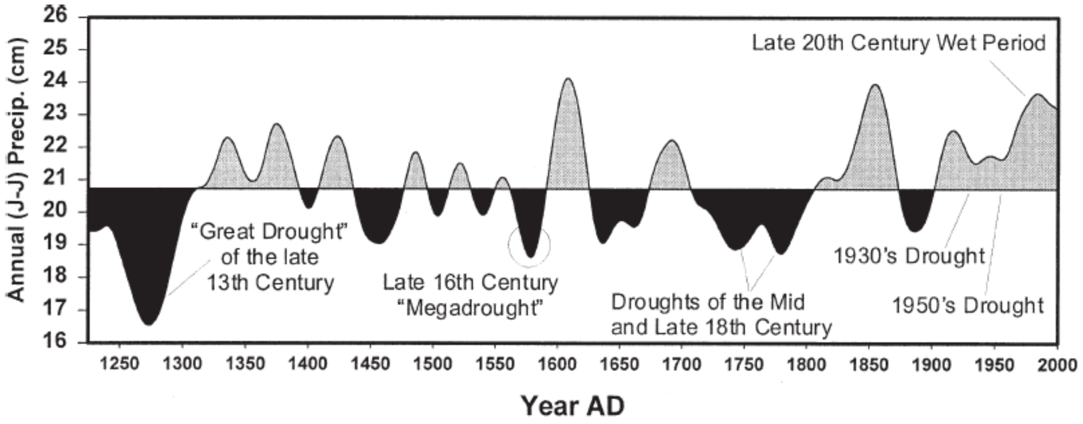


Figure 2 Tree ring based reconstructed precipitation for the Uinta Basin of northeastern Utah (1226-2001 AD). Precipitation is plotted versus the long term mean for annual precipitation (207 mm). Periods of drought are shaded in black and periods above long term mean are grey (Gray 2004).

Global climate models predict an increase in global surface temperatures particularly at northern latitudes by an estimated 1-3.5˚C in response to greenhouse gas emissions causing prolonged drought cycles, changes in hydrologic budgets, and increased scarcity of water resources (Coughenour and Chen 1997; Hanson 2000). Global climate change has important implications for future renewable water supplies, water use, and water resource allocation in arid ecosystems. In the future, water availability may be increasingly limited by periodic droughts and population growth.

Many plant species utilized for amenity landscaping in the U.S. were imported from Europe where they have been in use for over 1,000 years (Beard and Green 1994). In the Intermountain West landscapes are commonly planted with non native species to replicate urban landscapes characteristic of the humid continental climate of the eastern United States. Non native species used for residential and municipal landscape such as C3 turfgrass, are adapted to cool, mesic regions where drought is less frequent and shallow soil water is a more important source of water. Traditional cool season plants used for urban landscapes in semi arid regions are not adapted to high temperatures and extended drought where annual potential evaporation greatly exceeds annual precipitation (Seyfried et al. 2005). Amenity landscapes planted with non native species often require frequent and excessive irrigation during periods of high temperature and vapor pressure deficit to maintain an aesthetically acceptable, green appearance. Kentucky bluegrass, (KBG), a popular high water use, cool season turfgrass uses up to 762 mm of water a year in a semi-arid climate where the precipitation rate averages only 150-570 mm a year (Beard 1973; Noy-Meir 1973). Shallow rooted plant species such as KBG are documented to compete for water with trees and other vegetation that are planted in their root zone (Beard 1973; Stewart et al. 2005).

Traditional non native plants species such as turfgrass typically extract soil water at shallow depths and require frequent irrigation during periods of high temperatures and vapor pressure deficit. In contrast, many drought adapted plants forestall water deficit by extracting soil water from deep soil layers. Although it is assumed that traditional plant species use large amounts of water during the summer, comparison of soil water potential and dry down responses between traditional and drought tolerant, mixed vegetation landscapes is poorly documented. Here it is hypothesized that soil water extraction is different between traditional and drought adapted plant species due to their specific water use characteristics and documented rooting depths. The objective of our study was to measure and compare intra landscape changes in soil water potential in mixed vegetation landscapes during a 3-week dry down in August 2005 and 2006.

The following specific objectives are addressed in this study: 1. Make soil water potential measurements in traditional and drought tolerant mixed vegetation landscapes during a 3- week dry down during the summer at the Utah Botanical Center, Kaysville, Utah. 2. Identify statistically significant intra landscape changes and interactions in soil water potential between traditional and drought tolerant landscapes.

LITERATURE REVIEW

Plant water loss occurs through the exchange of water vapor through stomata (leaf pores) that are embedded in the surfaces of leaves. Plant water use varies during the day depending on meteorological conditions including solar radiation, temperature, relative humidity, wind, and vapor pressure deficit (Kjelgren 2000). Water that is lost both from soil through evaporation and plant transpiration is defined as evapotranspiration (ET) and varies among plant species and cultivars within a species. Variations in ET rates are documented to be related to seasonal growth rate and habit, leaf architecture, stomatal conductivity, and rooting characteristics (Huang and Fry 1999). Soil properties (gravel, sand, silt, loam) affect drainage and the ability of plant roots to extract soil water. Coarse soils with low soil water holding capacity drain faster allowing deep infiltration of soil water minimizing evaporation from shallow soil layers compared to finer textured soil (Singh 1998). Ground covers including mulch or turfgrass intercept solar radiation and reduce soil temperature and loss of shallow soil water from evaporation (Montague and Kjelgren 2003). Different plant species have evolved a number of photosynthetic pathways including C3, C4, or Crassulacean Acid Metabolism (CAM) in response to environmental conditions. For example C3 plants depend completely on open stomata to adsorb carbon dioxide (CO_2) for photosynthesis requiring stomates to remain open for long periods of time to exchange carbon dioxide and oxygen. About 95% of temperate plant species utilize C3 photosynthesis, a more efficient metabolic pathway than C4 or CAM photosynthesis under cool, moist conditions. Under hot, dry conditions C3 plants partially close stomates, reducing the amount of CO_2 that can be fixed from the atmosphere and decreasing water use efficiency (WUE), which may be defined as the dry weight of plant tissue produced over a given time period divided by ET (Ebdon and Kopp 2004; Yordanov et al. 2003; Yu et al. 2005).

Adaptations that allow C3 plant species to maximize shallow subsurface soil moisture in humid regions include shallow root systems and high stomatal sensitivity to plant water status. In contrast, drought tolerant C4 plants utilize an alternative photosynthetic pathway by utilizing PEP carboxylase instead of rubisco in the first step of photosynthesis allowing plants to bind CO_2 faster than C3 species. Plants utilizing C_4 photosynthesis concentrate CO_2 in mesophyll cells and transfer it to bundle sheath cells where rubisco synthesizes oxaloactate, a 4-carbon product via the Calvin-Benson cycle. This strategy reduces the amount of time that stomata need to be open and therefore reduces water lost through ET. The C4 photosynthetic pathway is an important ecophysiological characteristic of plants in arid environments. Yu et al. (2005) found that intrinsic water use efficiency (IWUE) was approximately double for C4 species compared to C3 species and that water loss in terrestrial plants often exceeded carbon gained by photosynthesis by three orders of magnitude. Crassulacean Acid Metabolism plants, native to warm desert regions, are rarely found in the Intermountain West and include cacti and succulents. Ornamental CAM species planted near homes and other structures survive winter by being shielded from desiccating wind and extreme cold temperatures (Cerny et al. 2002). Crassulacean Acid Metabolism photosynthesis prevents water loss by closing stomata during the day and opening them at night when temperature decreases and humidity rises. At night CO_2 is stored as malate in vacuoles and released for photosynthetic reactions during the day. Some plant species such as

Fame flower *(Talinum calycinum),* and Ice plant (*Mesembryanthemum spp*.) have been observed to use both C4 and CAM photosynthesis and shift from C3 to CAM photosynthesis depending on water stress or temperature (Martin and Zee 1983).

Ecosystem structure, function and multi scale interactions are dependent on the amount, location, and duration of water to support biological processes. The availability of water determines the spatial and temporal distribution of plant and animal species in an ecosystem (Loik et al. 2004; Miller 2005; Noy-Meir 1973; Sala 1988; Schwinning 2001; Singh 1998). A conceptual model describing the allocation of above and belowground resources based on leaf area index (LAI) was proposed by Lauenroth and Coffin (1992). This model suggests that the type of competition in plant communities is determined by a hypothetical zone that is limited by soil water defined as "below ground dominance" ecosystems and a zone dominated by light defined as "aboveground dominance" ecosystems. Temperate zone ecosystems dominated by belowground processes were found to occur at precipitation levels below 700 mm yr^{-1} and ecosystems dominated by "aboveground processes" occurred at precipitation levels above 1200 mm yr^{-1}. Zones with precipitation levels between 700 and 1200 mm yr^{-1} were defined as 'indeterminate' ecosystems (Burke 1998; Lauenroth and Coffin 1992). Using these criteria, most semiarid ecosystems are characterized as "belowground" dominated ecosystems where soil water is the most limiting resource. Plant soil and plant-plant interactions in landscapes where light is not a limiting factor for plant growth are controlled by competition for belowground resources such as water and plant nutrients. Plant-soil interactions are determined by a number of factors including plant type, intrinsic plant water use, ground cover, heterogeneity of aboveground biomass, root architecture, soil type, and meteorological conditions (Sperry and Hacke 2002). These dynamics affect soil water potential and water availability between individual plants that compete for available resources including soil nutrients and water.

Many plant species in low rainfall areas have fast root growth and high root to shoot ratios and tend to be spatially distributed in regular patterns in response to overlapping of root systems and competition for water (Barbour 1973; Philips and MacMahon 1981). Morphological and physiological adaptations that allow native plants to survive in semiarid environments are thought to have evolved over long time scales in response to climate change (Jackson and Overpeck 2000). The interglacial period in the late Pleistocene 11,550 years BP (1950) experienced a series of warming and cooling cycles. Global scale climate patterns transitioned to warmer, drier conditions after the Younger Dryas cold spell ended abruptly 10,700 years ago when south Greenland warmed 7 ˚C in 50 years (Dansgaard et al. 1989). After the retreat of the Pleistocene glaciers, archaeological evidence suggests that the landscape in the western United States evolved from cool, mesic woodland vegetation to xeric shrub dominated plant communities (Seyfried et al. 2005). Dry lake beds, a common feature of the Intermountain West are evidence of a cooler, wetter climate before Lake Bonneville began its decline ~14,000 to 8,000 C14 yr. B.P. (Oviatt et al. 2003).

Changes in plant species composition are hypothesized to have occurred over long time scales with interglacial global warming and cooling periods. The “modern semi arid climate of the Inter Mountain West and lack of deep drainage in vegetated inter drainage areas have maintained continuously low soil water potentials of less than -1000 kPa at the base of the root zone 2-3 meters in the soil profile” (Seyfried et al. 2005).

Plants native to the Intermountain West have evolved physiologic and morphologic adaptations to survive extended drought where precipitation typically averages less than 500 mm a year. Plant species native to arid environments where deep soil water is a more important source of water lean toward phenotypes that have large root: shoot ratios low stomatal conductance and sensitivity to conserve water during periods of extended drought, high temperature, and vapor pressure deficit. Plants that are more dependent on shallow soil water in pulse dominated ecosystems have small root:shoot ratios and high stomatal conductance and sensitivity to water status (Schwinning 2001). Plants in arid and semiarid ecosystems conserve water by a number of processes including osmotic regulation and dehydration tolerance during periods of high ET and soil water deficit (Ervin and Koski 1998; J Jiang and Huang 2001; Jones 1981; Morgan 1984). Roots respond to soil drying by synthesizing abscisic acid (ABA) where it is transported to shoots signaling reduction of guard cell turgor and stomatal closure allowing leaves to reduce transpiration of water (Wilkinson and Davies 2002). Many woody shrub species have deep, extensive roots systems that redistribute available soil water to more shallow depths in the soil profile in a process known as hydraulic redistribution (Burgess 1998; Caldwell 1998; Lee and Laurenroth 1994; Leffler 2005; Ryel 2004). Pinyon pine (*Pinus edulis*), a conifer native to the Intermountain West, has adapted to summer precipitation patterns over time by extracting water from inter canopy patches and evolving genetic responses that include changes in stomatal architecture (Mitton and Duran 2004). Physical adaptations that have evolved to conserve water include small leaf area, waxy coatings on leaves and shedding of leaves during drought. Many plants in arid environments have small leaf hairs that deflect solar energy and have the ability to change leaf orientation with respect to the sun in order to deflect and reduce intense solar radiation. Drought tolerant grass species such as buffalograss, a C4 turfgrass species native to the Great Plains, have deep roots to extract soil water from large soil volumes during prolonged drought (Huang 1999). Many traditional amenity plant species in the Intermountain West that have been imported from Europe are selected for their uniform green appearance and require frequent irrigation to maintain an aesthetically acceptable appearance (Aronson 1987). Turfgrass, one of the most commonly used groundcovers for amenity landscaping in xeric regions of the western United States, uses large and often excessive amounts of water (Stewart et al. 2004). Kentucky bluegrass (KBG), one of the most popular turfgrass species in use today, typically has shallow fibrous root systems less than 0.5 m deep and requires frequent recharge of shallow soil water. Deep soil water, an important source of plant available water during extended drought, is unavailable for many turfgrass species that lack deep extensive roots >0.6 m (Da Costa 2004). Physiological responses of turfgrasses to drought stress include closure of stomata, reduced transpiration rates, and dormancy resulting in decreased photosynthesis and WUE. Under conditions of prolonged water deficit, many cool season turfgrasses exhibit reduced turfgrass quality including decreased shoot growth, leaf firing, and chlorosis. Recently, turfgrass cultivars such as KGB have been developed to adapt to drought stress by developing deeper, more extensive roots and maintaining higher concentrations of intracellular ionic solutes and water soluble carbohydrates (Jiang and Huang 2001; Riordan et al. 2000).

The steady increase in demand for water in the next 20 years will require municipalities to implement sustainable water use practices including a transition to more water efficient landscaping (Gleick 1998). One approach to conserve increasingly scarce water resources is to replace non native plants with native, drought tolerant, low water use plants, a practice known as xeriscaping (Carrow 2006; Kjelgren 2000). In Utah and other Western states most of the available water supplied by runoff and groundwater in urban and residential areas is used to maintain amenity landscapes with non native high water use plant species. Outdoor water use in Utah accounts for up to 60% or more of total per capita water consumption with 67 % of that outdoor water being used to irrigate non native plant species to maintain a uniform green appearance (Envision Utah 2000; Utah State Water Plan, 2001). An estimated 129 gallons of water per capita per day is used to irrigate landscapes that are planted mostly with non native plant species such as cool season turfgrass species. Non native high water use plants have negative ecological consequences due to the excessive amounts of water used to irrigate them. Many traditional landscapes frequently waste water from faulty sprinkler heads or irrigation lines that leak allowing excessive water to run off site (Figure 3).

Figure 3 Water is frequently wasted from traditional high water use landscapes due to faulty sprinkler heads or poor irrigation design contributing to excessive water use and runoff.

Inadequate or patchy irrigation from poorly designed irrigation systems increases plant water stress during the hot summer months, reducing the aesthetic appearance of many high water use landscapes (Figure 3). In contrast drought tolerant landscapes known as xeriscapes require infrequent or almost no irrigation during the summer when water demand increases. Although many people prefer turfgrass landscapes, a well designed xeriscape can be a practical and aesthetically acceptable landscape alternative to reduce demand for outdoor water use. Xeriscapes can include practical areas of turfgrass to reduce erosion, contribute to aesthetic appearance, or absorb pollutants. Most plant species that are native to semi arid regions require less water than many traditionally used species that are adapted to cool, mesic regions characteristic of the eastern United States, and Europe. Many colorful and interesting native plant species can be used to replace traditionally used, high water use plant species including shrubs, forbs, or bunchgrasses. A water saving alternative to traditional turfgrass includes buffalograss (*Buchloe dactyloides*), a perennial drought tolerant grass native to the Great Plains. Buffalograss grows from southern Canada to Texas where precipitation averages 381 mm of water per year (www.plants.usda.gov). Deeply rooted buffalograss requires less frequent irrigation to maintain a green appearance during the summer than KBG; however, its aesthetic appearance deteriorates in the spring and fall when temperatures are low and it is coming out of or entering dormancy. Landscapes designed with native, drought adapted plants offer many advantages over traditionally used, cool season turf grasses or other non native high water use plant species. Xeriscapes typically require less maintenance than landscapes dominated by turfgrass and appear more natural, giving the landscape a sense of place and connection to the local natural environment (Cerny et al. 2002). Native plant species that are adapted to xeric environments maintain an aesthetic appearance during extended drought conditions with minimal or no irrigation. Drought-tolerant plants require less water than non native species when used with precision low flow irrigation and do not require weekly mowing or regular application of fertilizer, herbicides, or pesticides that frequently run off landscapes. Many soil amendments that are used to maintain turfgrass quality flow preferentially to groundwater or overland contributing to anthropogenic non point source pollution (Bowman et al. 2002; Erickson et al. 2001; Kung 2000; Williams and Ehleringer 2000). Although turfgrass has a great ability to absorb fertilizers, runoff of excess nutrients can contribute to eutrophication of aquatic ecosystems at levels as low as 0.01 to 0.035 mg L^{-1} (Easton and Petrovic 2004). Recent studies have found that some shallow rooted turfgrass species accounted for leaching of up to 38% of applied nitrogen (Bowman et al. 2002). Non native high water use amenity plant species may contribute to negative ecological consequences including excessive water use and nutrient loading as population increases and water resources grow increasingly scarce. In the future, landscapes planted with native drought resistant plants may be a practical way to reduce non point source pollution and conserve scarce water resources in the Intermountain West.

MATERIALS AND METHODS

In March 2004, nine 6.1 x 9.1 x 1.5 m drainage lysimeters were constructed in a 3 x 3 randomized complete block design at the Utah Botanical Center, Agricultural Experiment Station, Kaysville Utah (41.02259˚ N, -111.93374˚ W; 1337. 1 m. above MSL). The climate of Kaysville is characterized as semi arid with warm summers and cold winters. Mean annual precipitation is approximately 450 mm (National Climatic Data Center 2001). The mean annual temperature ranges from 7.2 to 11.6 degree C. and mean summer temperature ranges from 20 to 22.7 degrees C and the freeze free period from 100 to 140 days. Average temperatures vary from -30 ˚C in January to 41˚ C in July (USDA 1968).

The earth fill used to construct the lysimeters consisted of Kidman sandy loam (fine-coarse-loamy, mixed, super active, mesic, Calcic Haploxeroll). The Kidman soil series is classified as a deep, well drained, soil formed in alluvium or lake sediments from weathered quartzite, sandstone, granite, limestone, and gneiss. Each lysimeter was excavated on site to a depth of 1.5 m and the soil separated into top soil and sub soil layers. The base of each lysimeter was graded to 3% and fitted with 45 mil (1.143 mm) plastic pond liners. A 5.08 cm diameter Schedule 40 polyvinyl (PVC) drain tile was installed at the deepest point in each lysimeter to facilitate drainage into 5.61 m^3 concrete lined wells. The subsoil layers were replaced and compacted to their original bulk density and top soil layers were filled in to ground level and compacted to simulate their original bulk density.

The surface of each 55.51 m² lysimeter was planted with a mixed vegetation landscape and surrounded by a 3.0 m border of coarse wood mulch covered to a depth of ≤5 cm. The central portion of each landscape consisted of turfgrass with mulched ornamental shrubs/forbs and bunchgrasses evenly spaced around the perimeter of the turfgrass. A small coniferous tree less than 1.5 m in height was placed in one corner of each plot 0.75 m from the border of the turfgrass. The traditional landscapes were planted with non native cool season shrubs, forbs, and graminoids, including Kentucky bluegrass. The native/drought adapted landscapes were planted with drought adapted, ornamental shrubs, forbs, and graminoids including buffalograss, a warm season C4 grass species native to the Great Plains. The conifers included non native Bosnian pine (*Pinus heldreichii* 'Leucodermis') and native pinyon pine (*Pinus edulis*).

In June 2005, four of the nine existing lysimeters constructed in March, 2004 at the Utah Botanical Center, Kaysville, UT (UBC) were selected for this study. Two landscapes with traditionally used, high water use landscapes and two native/drought adapted landscapes were chosen for the study to gain the most economical representation of the treatments. The other five landscapes were not studied. Each of the four lysimeters was installed with a total of 12 Irrometer Watermark™ 200 resistance blocks (Irrometer Co. Riverside, CA) at 4 points along a 10.9 m diagonal transect at three different depths 15, 45, and 90 cm. The 4 sensor installation points included three different vegetation treatments including A: ornamental shrubs with shredded bark cover, (3.3 m from turf) B and C: turf grass (0.61 m from the border of mulch, 2.4 m apart) and D: a 1.2 m conifer (1.0 m from turf (Figure 4). Each of the four points along the diagonal transect in each landscape were excavated to 90 cm using a 2.54 cm soil coring auger. At each point three, 2 x 8 cm Watermark resistance blocks were installed with a 2 cm (inner diameter), 2.2 cm (outer diameter) x 1.52 m copper pipe marked to indicate soil depth (Figure 5). A soil and water slurry made from the excavated soil was used as a backfill to bury the sensors and maximize sensor to soil contact. An additional three, type E thermocouple wires were installed near each sensor at 15, 45, and 90 cm at points in each landscape including conifer, turfgrass, and shrub treatments.

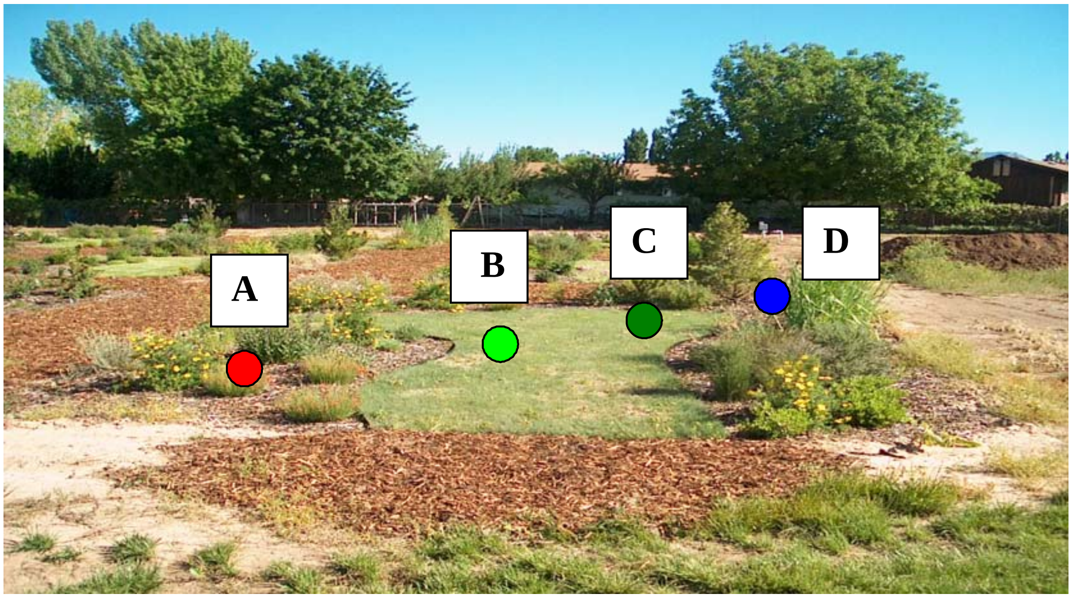


Figure 4 Location of Irrrometer Watermark™ resistance blocks (Riverside, Ca.) at 4 points and 3 depths (15,45, and 90 cm) A. Ornamental shrub/mulch B. and C. turfgrass, and D. conifer.

Figure 5 Inexpensive Irrometer Watermark™ 200 resistance block (Riverside, Ca.) left and Omega Engineering Type E Thermocouple, right. Watermark blocks measured electrical resistance from a 250 mV electrical pulse between double coiled wires imbedded in the granular matrix material.

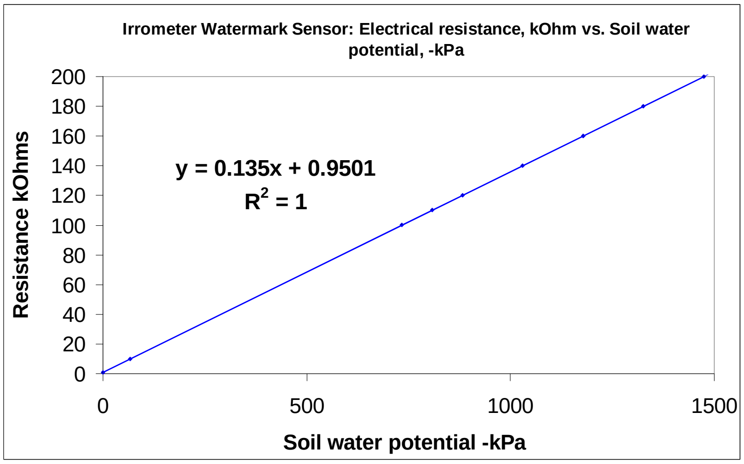
Electrical resistance was measured hourly with 2 CR1000 data loggers in combination with 2 AM/32 Multiplexers, Campbell Scientific Logan, UT (Figure 6) using a 250- mV, 500- msec. electrical pulse and referenced with soil temperature to correct for changes in electrical impedance with changes in soil temperature. Resistance blocks work on the principle that as the surrounding soil and sensor dry out electrical resistance increases. Soil water potential (Ψ), defined in negative units of pressure (-kPa), measures the work needed to extract soil water from soil surfaces. Soil water potential decreases as soil water is depleted requiring plant roots to do more work to extract available water from soil. Plants are often assumed as unable to extract soil water at Ψ more negative than -1500 kPa (15 atm) defined as the permanent wilting point where transpiration ceases and plants lose turgor pressure and wilt (Dingman 2002).

Figure 6 Data was collected with two CR1000 data loggers and AM 16/32 Multiplexers and stored on CFM 100 Compact Flash Memory modules with 1 GB Flash memory drive (Campbell Scientific, Logan, UT).

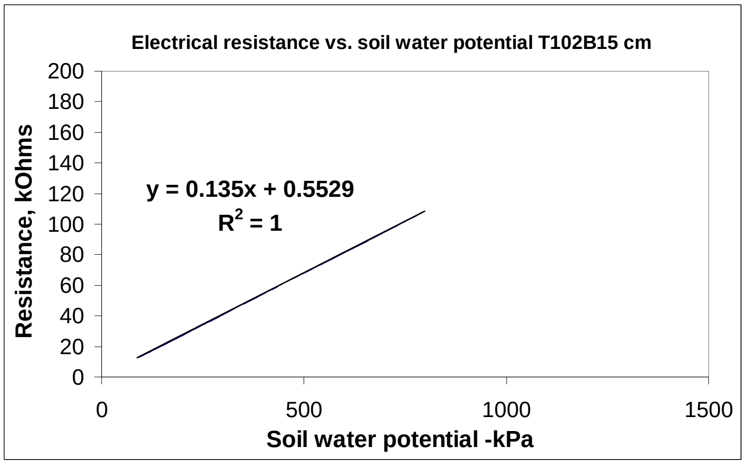
Resistance measurements were automatically converted to soil water potential (-kPa) using empirically derived conversion equations (Allen 2000; Orloff and Hanson 1998). Electrical resistance was corrected with reference temperature measurements using Type E thermocouple to correct for changes in electrical impedance with changes in temperature. Using the equation supplied by Campbell Scientific, Logan, UT, resistance measurements were automatically converted to kilopascals :

$$kPa = \frac{(0.07407 \times (kOhms))}{(1 - (0.018 \times (Tc\,\mathrm{Re}\,f) - 21)} \qquad \textbf{(1)}$$

where:
kPa is equal to soil water potential, electrical resistance is expressed in kilo ohms (kOhms), and 21= 21° C (Figure 7)



A.



B.

Figure 7 A**.** Soil water potential –kPa vs. resistance kOhms from temperature corrected equation supplied by Campbell Scientific, Logan, Utah where y = 0.135x + 0.9501, R^2 = 0.99 and B**.** Actual resistance and soil water potential data from T102B, Kentucky bluegrass at 15 cm (y= 0.136x + 0.6629) R^2=1. Electrical resistance of 200 kOhm was equal to -1500 kPa (permanent wilting point)

Weather data measured at the UBC Meteorological Station, Kaysville, UT including air temperature *(Ta*, ˚C) and dew point temperature (*Td*, ˚C) was measured with a Vaisala HMP45C temperature and relative humidity probe (Helsinki, Finland). Solar radiation ($MJm^{-2}day^{-1}$) was measured with a LI-COR LI200X Silicon Pyranometer (Lincoln, NE) and precipitation (mm) was measured with a Texas Electronics Tipping

Bucket rain gauge (Dallas, TX). Average vapor pressure deficit (kPa) from DOY 215 to 236.5, 2005 and 2006 was calculated from air temperature and dew point temperature data using the numerical expression for the saturation vapor pressure curve (Rosenberg 1983).

$$e_s = 0.6108 \exp\left[\frac{17.27 * T_a}{T_a + 237.3}\right] \text{ kPa} \qquad \textbf{(2)}$$

$$e = 0.6108 \exp\left[\frac{17.27 * T_d}{T_d + 237.3}\right] \text{ kPa} \qquad \textbf{(3)}$$

where:

e equals vapor pressure, e_s equals' saturation vapor pressure Ta equals air temperature and T_d equals dew point temperature.

Soil water potential data from DOY 216-236.5, 2005 and 2006 were combined and log transformed prior to statistical analysis to meet the assumptions for analysis of variance (ANOVA). The experimental results were statistically analyzed using the PROC MIXED repeated measures analysis (SAS Institute Inc., Cary, NC). Landscape position, depth, and day of measurement were fixed variables and replication was a random variable. The analysis was repeated by day of measurement. Pair-wise comparisons of means were made using Saxton's 'pdmix800.sas' macro at a significance level of $p \leq 0.05$ (Saxton 1998).

Table 1 Three landscape treatments were studied including a group of randomly spaced annual and perennial shrubs and forbs, turfgrasses, and a small coniferous tree (1.2 m in height).

Traditional Landscape	**Drought Adapted Landscape**
Conifer	**Conifer**
Bosnian Redcone Pine *Pinus heldreichii* 'Leucodermis' (1.2m)	Pinyon pine *Pinus edulis* (1.2 m)
Forbs, and shrubs (≤ 0.5m)	**Forbs, and shrubs** (≤ 0.5m)
Anthony Waterer Spiraea *Spiraea bumalda* †	Creeping Mahonia *Mahonia repens*
Creeping Phlox *Phlox subulata* 'Emerald Cushion Blue	Goldfinger *Potentilla fruiticosa**
Globe arborvitae *Thuja occidentalis* 'Little Giant'	Lambert's Loco Weed *Oxytropis lambertii*
Paeonia Hybrid *Paeonia lactiflora* 'Nippon Beauty'*	Rocky Mountain Penstemon *Penstemon strictus**
Salvia 'May Nights' *Salvia x superba* *	Wormwood *Artemesia ludovician'Silver King'**
Graminoids (< 5 cm)	**Graminoids** (<5 cm)
Kentucky bluegrass *Poa pratensis*	Buffalograss *Buchloe dactyloides*

Invasive plant species †
Nearest to sensor *

RESULTS AND DISCUSSION

Meteorological data

Average daily air temperature during the 3 week dry down was 23.5 ˚C in 2005 and 24.1 ˚C˚ in 2006 (Figure 8). Total solar radiation averaged 27.02 $MJm^{-2}day^{-1}$ in 2005 and 27.73 $MJm^{-2}day^{-1}$ in 2006. Average saturation vapor pressure deficit (VPD) was 1.86 kPa during the dry down in 2005 and 2.11 kPa in 2006 (Figure 9).

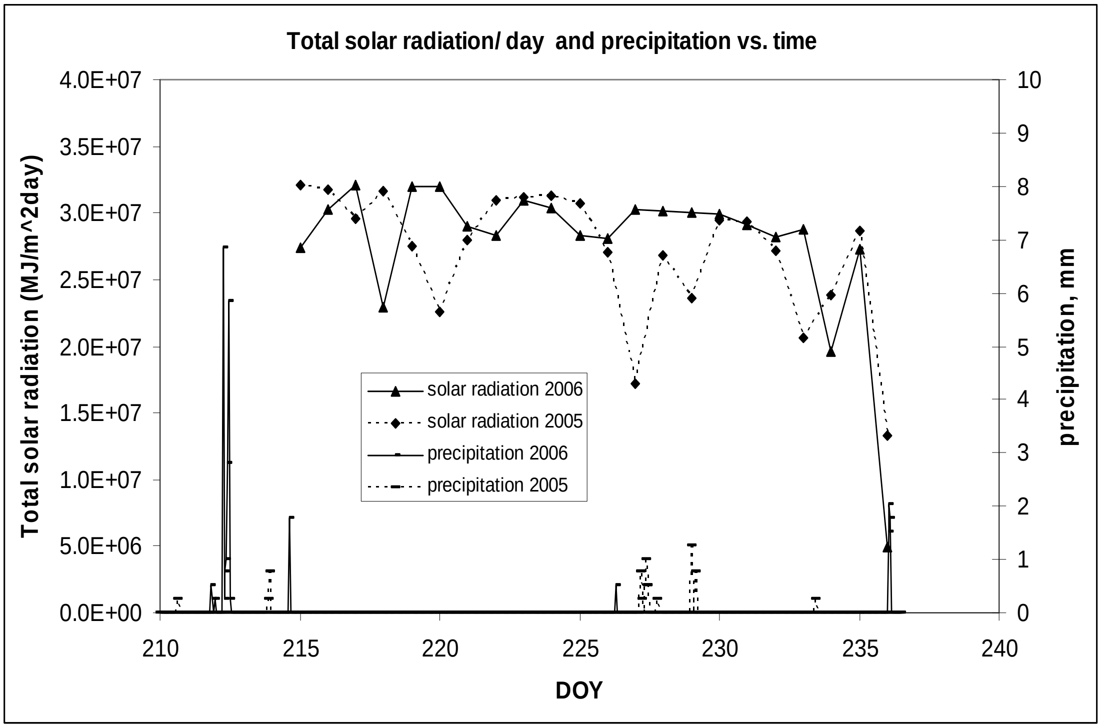


Figure 8 Total solar radiation ($MJm^{-2}day^{-1}$) and precipitation, mm. Precipitation (mm) from DOY 210-240 totaled 6.85 mm. in 2005 and 5.84 mm, 2006. 20.57 mm precipitation fell prior to the dry down, DOY 210 to 215, 2006.

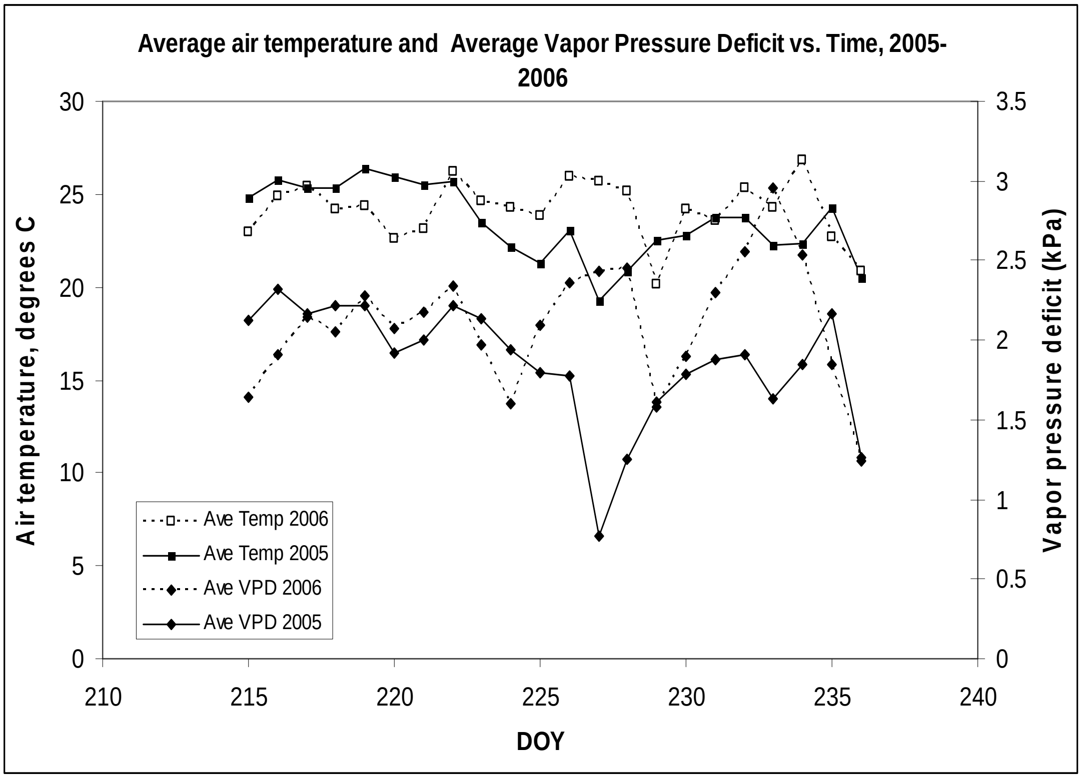


Figure 9 Average air temperature (˚C) and vapor pressure deficit (kPa) DOY 215-236.5, 2005 and 2006. (Utah Botanical Center, Kaysville, UT).

In 2005 and 2006 precipitation at the UBC Meteorological Station, Kaysville, UT totaled 6.85 mm and 26.42 mm, respectively, from DOY 210-236.5 accounting for the initially wetter conditions at the start of the dry down study on DOY 215, 2006 (Figure 8).

Visual appearance of landscapes

At the beginning of the dry down DOY 215, 2006 both turfgrass treatments appeared moderately green with some color patchiness (Figure 12). Visual appearance at the end the dry down deteriorated more in the traditional high water use plots due to increased leaf firing and chlorosis in the Kentucky bluegrass treatment (Figure 13). The conifer and shrub treatments showed minimal deterioration in visual appearance.

Soil dry down responses

Soil water potential responses following water deficit were significantly different ($p \leq 0.05$) on day, day x depth, day x position, and depth x position in 2005 and 2006 (Table 2; 3a. to 10b.). Landscape treatments varied widely in their dry down response between both years. Variables including meteorological conditions, root and shoot growth, differences in rooting mass distribution, leaf area index, intrinsic plant water use and stomatal conductance may have affected dry down response between landscape types. Soil layers dried down gradually and were progressively drier by approximately 100 kPa from 90, 45, and 15 cm respectively (Figure 14). Higher soil water content at depth may be explained by lower root mass density, higher clay content, and lack of vertical drainage below the lysimeter.

The traditional shrub and native conifer treatments dried down less than the other treatments at 15 and 45 cm probably due to lower root mass density and decreased plant water requirements (Figure 17). Soil layers from 15 to 90 cm were driest under the native shrubs, buffalograss and traditional conifers at the beginning and end of the dry down (Figure 10 and 11). Mean soil water potential was most negative at 15 cm under KBG (*Poa pratensis. L*) compared to the other traditional or drought adapted treatments both years (Figure 17, Table 2). Kentucky bluegrass did not dry down extensively at 45 and 90 cm suggesting shallow root architecture. In contrast, soil water potential under

Buffalograss (*Buchloe dactyloides*) was significantly more negative at 45 cm and 90 cm, respectively, suggesting greater soil water extraction by deeper roots (Table 2, Figure 17). In 2006, the drought adapted landscapes were generally drier at 15 and 45 cm at the beginning and end of the dry down compared to the traditional landscapes (Tables 7a to 10b). The conifer treatments varied significantly in their dry down response. Although both confers extracted soil water in a similar pattern at 90 cm, native pinyon pine dried down less at 15 and 45 cm compared to non native Bosnian pine and appeared to and redistribute soil water to more shallow depths (Figure 17).

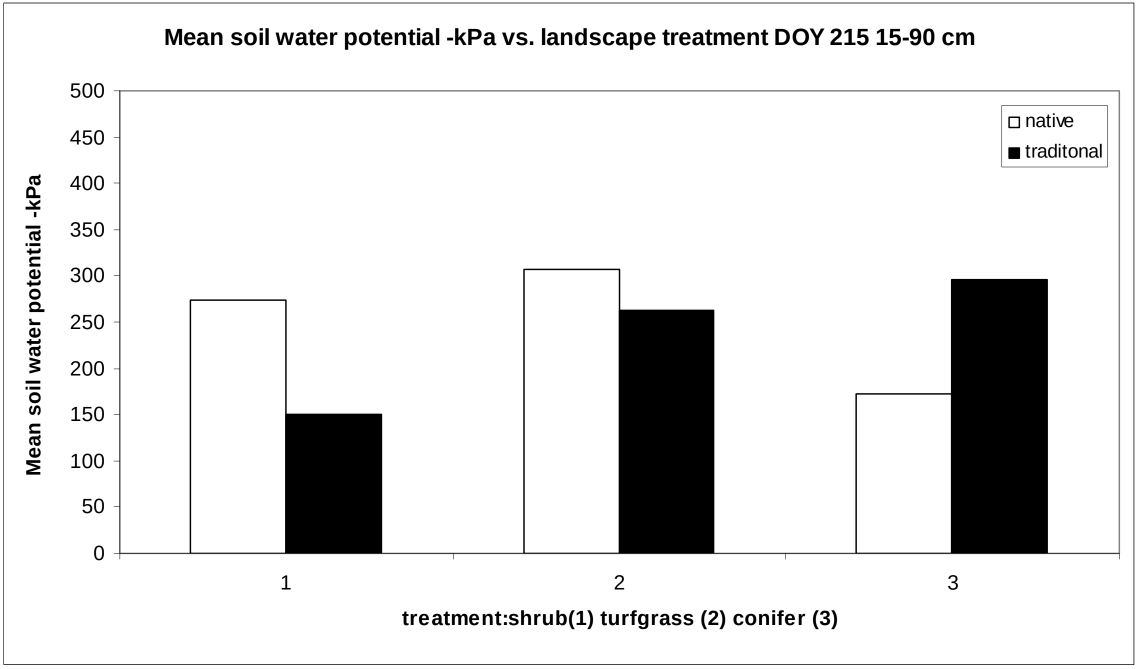


Figure 10 Mean soil water potential (-kPa) at all depths vs. landscape treatment DOY 215, 2005 and 2006 (Utah Botanical Center, Kaysville, UT).

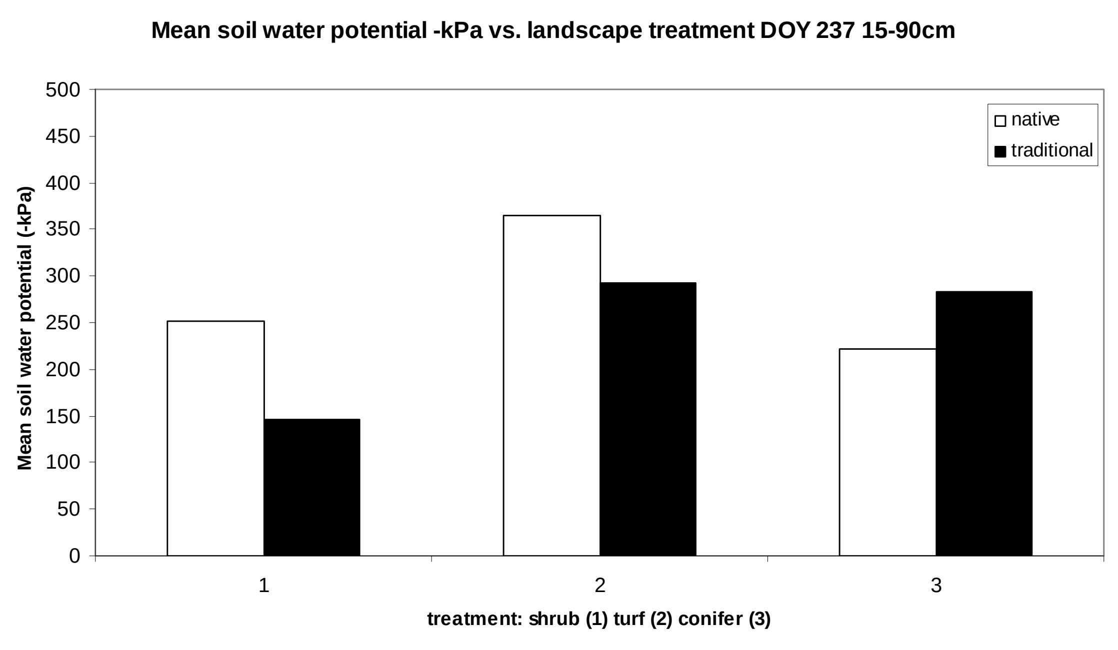


Figure 11 Mean soil water potential (-kPa) at all depths vs. landscape treatment DOY 237, 2005 and 2006 (Utah Botanical Center, Kaysville, UT).

Figure 12 Buffalograss (N101) (left) and Kentucky bluegrass (T202) (right) one day before the beginning of the dry down on DOY 215, 2006.

Figure 13 DOY 237 8-26-2005 at the end of the dry down buffalograss (left) retains a more green appearance under drought conditions compared to Kentucky bluegrass (right).

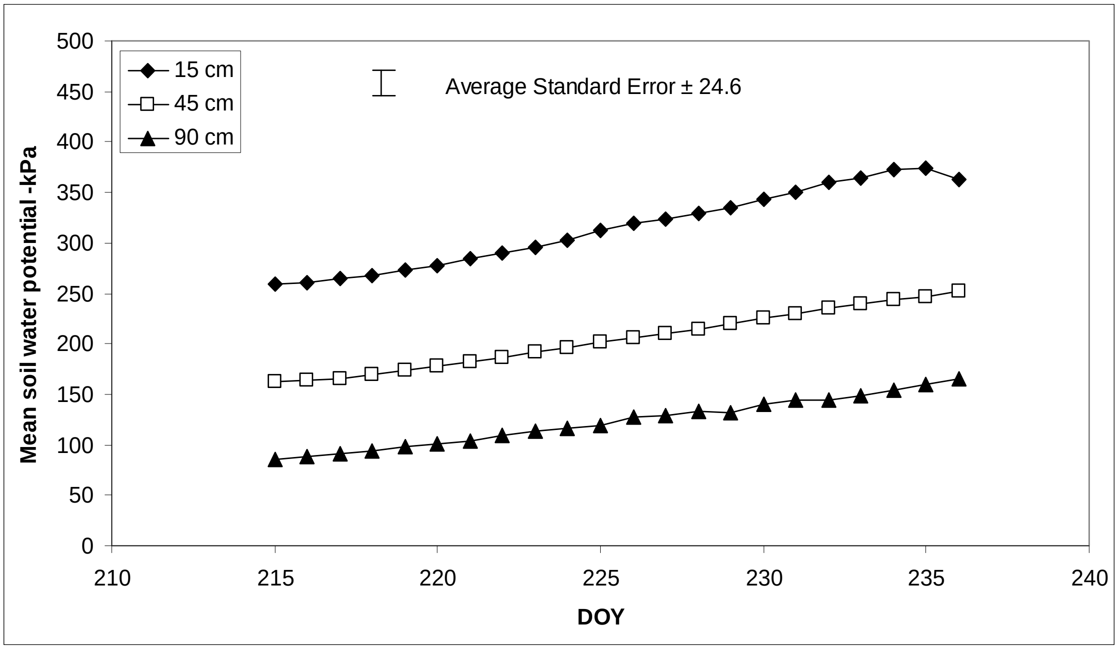


Figure 14 Mean soil water potential, -kPa vs. time for each depth, 15, 45, 90 cm combined from all treatments and landscape types (traditional and drought adapted) DOY 215 to 236.5 (significance level at p 0.05).

The range of soil water potential between all landscape treatments on DOY 216 was 107 kPa and diverged to 218 kPa on DOY 236. The most negative soil water potentials at the end of the dry down were observed under buffalograss and KGB, respectively. In contrast, the least negative values were observed under the traditional shrub and pinyon pine. The drought adapted shrubs and Bosnian pine were intermediate between these values (Figure 15). The range in soil water potential during the dry down were traditional shrub 40.2, drought adapted shrub 41.2, pinyon pine 63.2, and Bosnian pine 80.4. The range in dry down response was greatest under turfgrass: KBG, 120.3 and buffalograss, 198.7 (units in kPa).

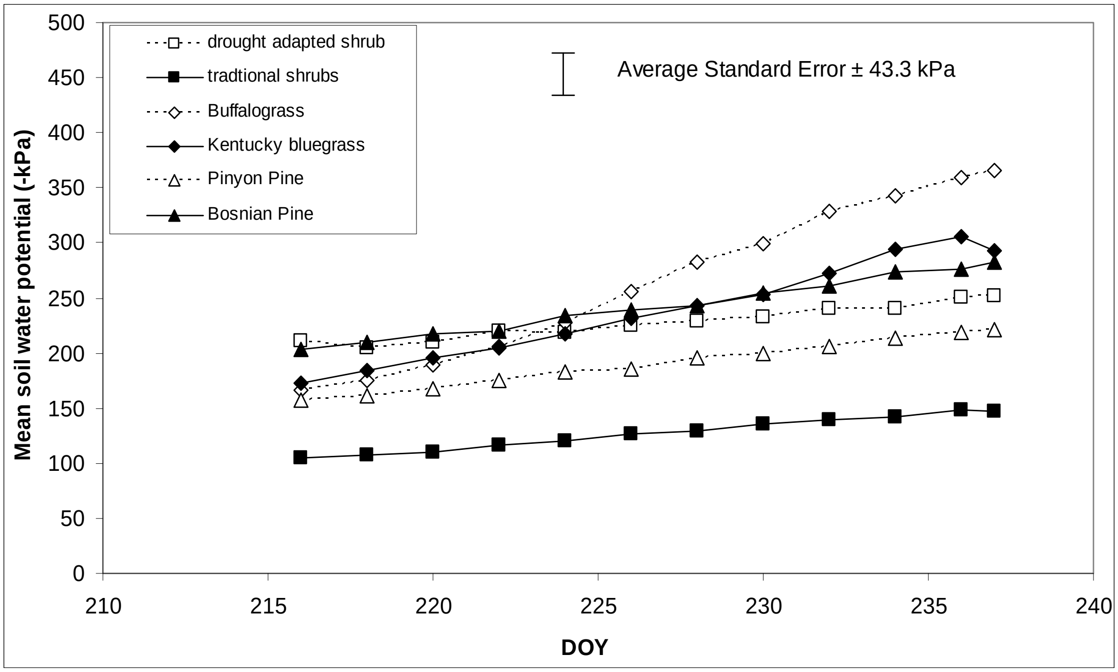


Figure 15 Mean soil water potential, -kPa vs. time for each landscape treatment. Data combined from all depths (15, 45, and 90 cm) DOY 216-237, 2005 and 2006 (significance level at $p \leq 0.05$) of native and non native shrubs buffalograss, Kentucky bluegrass, pinyon pine, and Bosnian pine.

All landscape treatments dried down at a gradual rate with the exception of the turfgrass species. Mean soil water potential decreased rapidly ten days into the dry down on DOY 226 under the buffalograss treatments compared to Kentucky bluegrass, when it dried down more rapidly beginning on DOY 232, 16 days after irrigation was withheld (Figure 15). The different results may be explained by a rapid increase in soil water potential at 15 cm under KBG in response to precipitation events that were recorded from DOY 226 to 229, 2005 that totaled 6.85 mm (Figure 8). Soil water potential increased 100 to 200 kPa for 5 days in both KGB treatments, from DOY 226 to 231 and may be explained by infiltration of precipitation and reduced soil water uptake by shallow roots that may have entered dormancy already 10 days into the dry down. Additionally, a decrease in VPD during this storm interval may have contributed to lower ET and decreased soil water uptake. Soil water potential then rapidly decreased after DOY 231 in 2005. The sudden decrease in soil water potential on DOY 231 is hypothesized to be due to reactivation of shallow roots and increased soil water uptake. In contrast, buffalograss continued to dry down gradually at 15 cm immediately after precipitation probably due to continuous root activity and soil water uptake in the shallow root zone. No precipitation responses were observed at 45 or 90 cm in either landscape type. In 2005, soil water potential decreased more slowly under buffalograss compared to 2006 when the entire soil profile from 15 to 90 cm dried down significantly more than KGB. This was unusual, considering that precipitation totaling 20.57 mm fell prior to the dry down from DOY 210 to 215, 2006 and the soil profile was already considerably dry under the buffalograss treatments. The different response is hypothesized to be due in part to improved turf quality of buffalograss in 2006. In 2005, the sod purchased for the experiment was in sub optimal condition compared to KGB and weeds filled in bare spots in the turf. In addition, the spring of 2005 was reported to be cool and moist when warm season grasses are only coming out of dormancy and cool season grasses are most active, delaying establishment of buffalograss. Additionally, buffalograss canopy temperatures were consistently higher compared to KBG until the end of the dry down on DOY 236, 2005 suggesting lower ET and reduced heat dissipation from transpirational cooling (Kopp 2005). Canopy temperature was not measured in 2006. The differences in dry down response between turfgrasses in 2005 and 2006 may also be due to higher temperatures in the summer of 2006 contributing to increased growth of buffalograss roots and extraction of soil water from deeper soil layers. In 2006 total solar radiation received was 0.71 $MJm^{-2}day^{-1}$ greater than 2005, average air temperature was 0.7 ˚C warmer, and average vapor pressure deficit was 0.25 kPa greater than in 2005 contributing to higher ET.

In 2005, average soil temperature at 15 cm under the traditional mulched groundcover shrubs was 24.7 ˚C, compared to 23.1˚C under KBG at 15 cm and 21.8 ˚C at 45 cm. In contrast, average soil temperature under buffalograss was 24.3˚C at 15 cm and 23.1˚C at 45 cm, and would be expected to be lower than KBG given that soil water potential was less negative at 15 cm (Figure 16). However, spatial variability in soil temperature would not be unexpected in large soil volumes. Soil temperatures were similar in 2006 and deviated ≤ 0.2˚C at all depths compared to 2005. The higher soil temperatures measured under the shrub/mulch treatment may be due to differences in thermal conductivity, (k) of the specific landscape surface. Montague and Kjelgren (2003), found that surfaces mulched to a depth of 10 cm with shredded pine bark (k= 0.12 $Wm^{-1}C^{-1}$) intercepted solar radiation and reduced soil temperature more efficiently than turfgrass surfaces (k=0.85 $Wm^{-1}C^{-1}$) (Kjlegren and Montague 1996). However, the surfaces in this study were covered to a depth of ≤ 3.0 cm and clearly did not block solar radiation and heat transfer as effectively as turfgrass, although they may have affected stomatal conductance, gs.

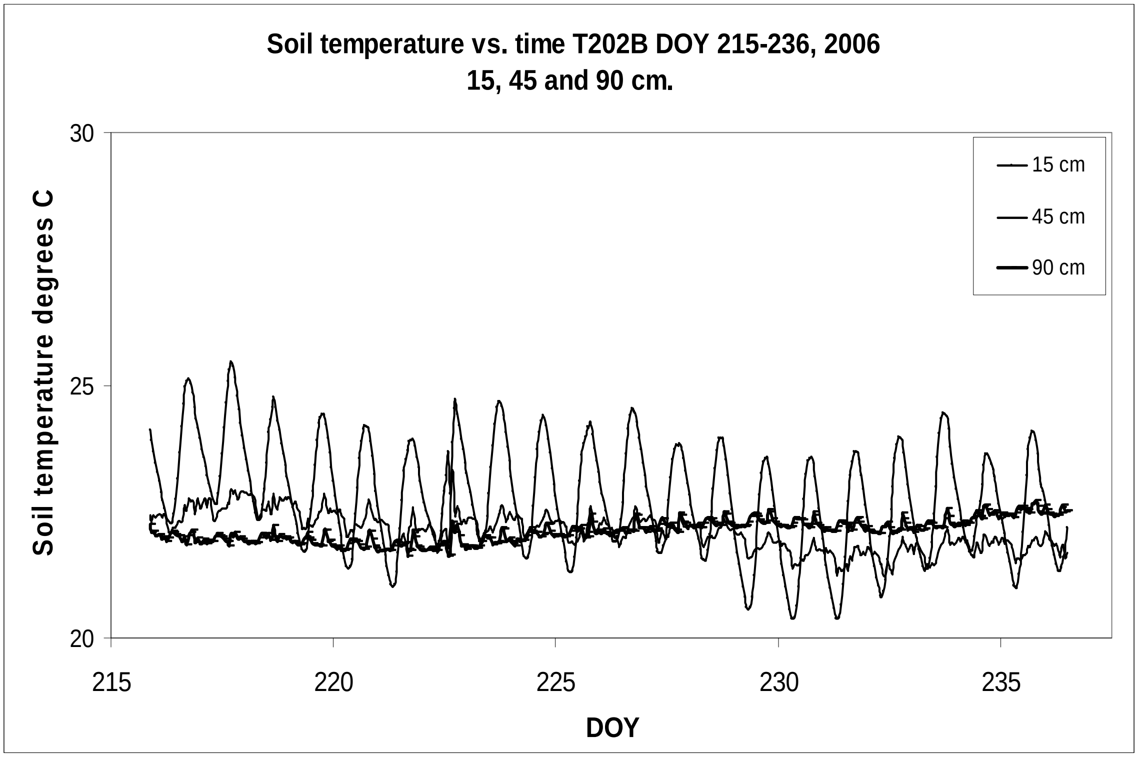


Figure 16 Soil temperature vs. time DOY 215 to 236, 2006 15, 45, and 90 cm. Diurnal changes in soil temperature were more varied at 15 cm.

The traditional and drought adapted herbaceous perennial and deciduous shrub species located nearest the sensors examined in this study exhibited minimal if any visual signs of drought stress at the end of the dry down (Figure 12 and 13). The traditional shrubs appeared to have a somewhat smaller leaf area index (LAI) than the drought adapted shrubs on visual inspection. Stomatal conductance, gs ($mmolm^{-2}s^{-1}$) of Anthony Waterer Spiraea (*Spiraea bumalda)* and Paeonia Hybrid (*Paeonia lactiflora),* 'Nippon Beauty' in 2005 were lower than the drought adapted shrubs including Rocky Mountain Penstemon (*Penstemon strictus),* and Goldfinger (*Potentilla fruiticosa)* (Kopp 2005, personal communication). Mean soil water potentials were less negative under the traditional shrub treatment throughout the 21 day dry down compared to the other landscape treatments. The lower gs and smaller LAI are consistent with these findings. At the end of the dry down, soil water potential was 2.5 times less negative than buffalograss under the traditional shrubs (Figure 15). Stomatal conductance is documented to be lower in plants grown in mulched surfaces during periods of high temperature and vapor pressure deficit and varies from species to species. Additionally, previous studies of the effects of ground mulch type on plant temperature, reported that moderate and high water use plants had similar gs and that low water use plants had a significantly higher gs (Kopp 2005 personal communication; Montague and Kjelgren 2003). In contrast, soil water potential was most negative under the drought adapted shrubs compared to the other landscape treatments at the beginning of the dry down on DOY 215 and ranked as the second driest treatment at 15 cm suggesting increased soil water extraction by shallow roots (Figure 15, Table A-2). Increased gs and LAI measured from the drought adapted shrubs/forbs are consistent with these findings. Soil water potential was less negative for both shrub types at 90 cm compared to the other treatments suggesting shallow rooting depth.

Buffalograss appearance was superior to KBG at the end of the dry down and maintained a more verdant appearance in 2005 and 2006. This is consistent with drought response characteristics of buffalograss in the summer during periods of high temperature and vapor pressure deficit. Buffalograss was the fourth driest treatment at 15 cm and soil water potential was significantly more negative at 45 cm and 90 cm, and at the end of the dry down compared to the other landscape treatments, suggesting deeper rooting depth and higher root activity (Figures 15, 17). These results are consistent with the ecophysiology of buffalograss, a sod forming grass species that is native to upland range sites in the short grass prairie of the Great Plains, where 67% of annual precipitation events average ≤5 mm (Lee and Laurenroth 1994; Sala 1992; Singh 1998). Buffalograss is rated intermediate in rooting depth and is documented to extract available soil water from 30 to 90 cm allowing it to delay drought stress and maintain a more green appearance under hot, dry conditions in the summer compared to other turfgrass species (Huang 1999; Marcum 1995; Riordan et al. 2000; Stewart et al. 2004). Root elongation and root mass distribution at 40 cm under surface drying and well watered conditions were found to be greater for buffalograss than other warm season grasses (Huang 1999). In another study examining drought avoidance, buffalograss was found to extract 66% more water at 90 cm compared to other warm season turfgrasses (Qian 1997).

The more negative soil water potentials measured at 45 and 90 cm under buffalograss suggests extraction of soil water from deeper soil layers, allowing it to remain green and viable until the end of the dry down. Deep rooting in warm season grasses is thought to extract soil water from a larger soil volume and has been correlated with drought resistance among a number of plant species (Bonos 1999; Carrow 2006; Ervin and Koski 1998; Huang and Fry 1999; Marcum 1995; Sheffer 1985). Although buffalograss maintains an aesthetically acceptable appearance in the summer when temperatures are high and shallow soil water is limiting, turfgrass quality decreases when temperatures are lower in the fall and spring even when water is not limiting.

Kentucky bluegrass was visually stressed with patchy leaf firing and chlorosis and was less verdant than buffalograss at the end of the dry down in 2005 and 2006 (Figures 12 and 13). Soil water potential was more negative at 15 cm compared to the other landscape treatments and was the second driest treatment at the end of the dry down

(Figures 15, and 17). The drier shallow soil profile under KBG at the beginning of the dry down in 2005 may be explained by higher root activity and soil water uptake. Mean soil water potentials were significantly less negative at 45 and 90 cm, suggesting shallow root depth (Figure 17). Kentucky bluegrass is adapted to lower temperatures and is documented to have higher root activity and continued water uptake under limited soil water availability during hot, humid summers in the northeastern United States (Bonos 1999). Soil water uptake would be expected to increase under conditions of high temperature and vapor pressure deficit characteristic of semiarid climates. Water use or crop coefficient, Kc values for cool season turfgrass species range from 85% to 100% of reference ET, and may vary by up to 60% between KBG cultivars, while those for warm season turfgrass vary from 80% to 90% of reference ET (Kneebone et al. 1992; Shearman 1986).

Sullivan (2000), found that shallow, dense fibrous roots of KBG contributed to >80% of the total below ground length and approximately 80% of the total fibrous root length with diameters < 0.2 mm. This would explain the higher soil water extraction at 15 cm and negative soil water potential measured under KBG that ranged from -650 to -20 kPa at the end of the dry down (Tables 2, 3a, 4a, 6a, and 7a.) Previous studies have documented that 75% of KBG root mass is located in the upper 12 cm of the soil surface in contrast to tall fescue and perennial ryegrass with only 50% of their roots at this depth (Sheffer 1985). This is consistent with the less negative soil water potentials measured at 45 and 90 cm (Figure 17). In a dry down experiment conducted at the Greenville Research Farm, Logan, UT, Stewart et al. (2004) found that 94% of KBG root mass was located in the upper 30 cm with 80% of its root system in the upper 15 cm. Kentucky bluegrass was documented to extract almost 50% of the available soil water within its root zone to a depth of 0.6 m when it reached incipient water stress on 4, August, 7 days into the dry down. In contrast, buffalograss reached incipient water stress on 20 August when it had extracted 56% of available water within its deeper root zone (90 cm) when compared to bluegrass and 60% by 23 August' (Stewart et al. 2004). These results are consistent with the soil water potential responses and visual appearance of Kentucky bluegrass and buffalograss in 2005 and 2006 (Figures 12, 13, and 17).

Intra landscape gradients in soil water potential across treatments were extremely variable greatest between traditional shrubs and KBG at 15 and 45 cm and buffalograss and pinyon pine at 45 and 90 cm. ranging from 1.9% to 400 % (Table 3b to 10b) Soil water potential gradients between turfgrass-turgrass positions varied from 0.5% to 180% suggesting more uniform dry down between turfgrass sensor locations (Tables 3b to 10b). Large differences in soil water potential between landscape treatments are associated with increased competition for available soil water in mixed vegetation landscapes that have intersecting root zones. Bowman (1998) and others have suggested that fine roots characteristic of shallow rooted turfgrass genotypes produce a larger absorption area per unit weight and are more efficient at absorbing ions and water (Bowman 1998; Sheffer 1985; Smucker 1993; Sullivan 2000). Roots with larger surface area have been documented to be more competitive in single and mixed plant communities and are more advantageous when resources are limiting (Eissenstat and Caldwell 1989; Stewart et al. 2005). Turfgrass species have been documented to compete for available soil water with other landscape plants including newly established trees. Stewart et al. (2005) found that competition for water in precision irrigated landscapes planted with Kentucky bluegrass adversely affected the growth and establishment of newly planted Littleleaf Linden, (*Tilia cordata),* ‘Greenspire’ (Stewart et al. 2005).

At the end of the dry down the conifer treatments did not exhibit any visual signs of drought stress and dried down at a gradual rate unlike the turfgrass treatments. Bosnian pine dried down progressively more at 15 and 45 cm compared to pinyon pine, indicating higher plant water use in the shallow root zone, however, both trees dried down at a similar rate at 90 cm (Figure 17). Mean soil water potential measured under pinyon pine was ≤ -150 kPa at 45 cm suggesting soil water extraction from deep soil layers and redistribution to more shallow depths (Figure 17). This is consistent with findings that many trees and woody shrub species have deep, extensive roots systems that redistribute available soil water to more shallow depths in the soil profile in a process known as hydraulic redistribution (Burgess 1998; Caldwell 1998; Lee and Laurenroth 1994; Leffler 2005; Ryel et al. 2004). Additionally, pinyon pine is thought to utilize shallow water from inter canopy patches in the top 30 cm of the soil profile where root density of under story herbaceous species is greatest (Breshears et al. 1997; Williams and Ehleringer 2000). Although some evidence in the data suggests competition for water with turfgrass, the conifers and shrubs have been established for only 1-2 years and may require more lateral root growth to significantly affect water availability in the turfgrass root zone.

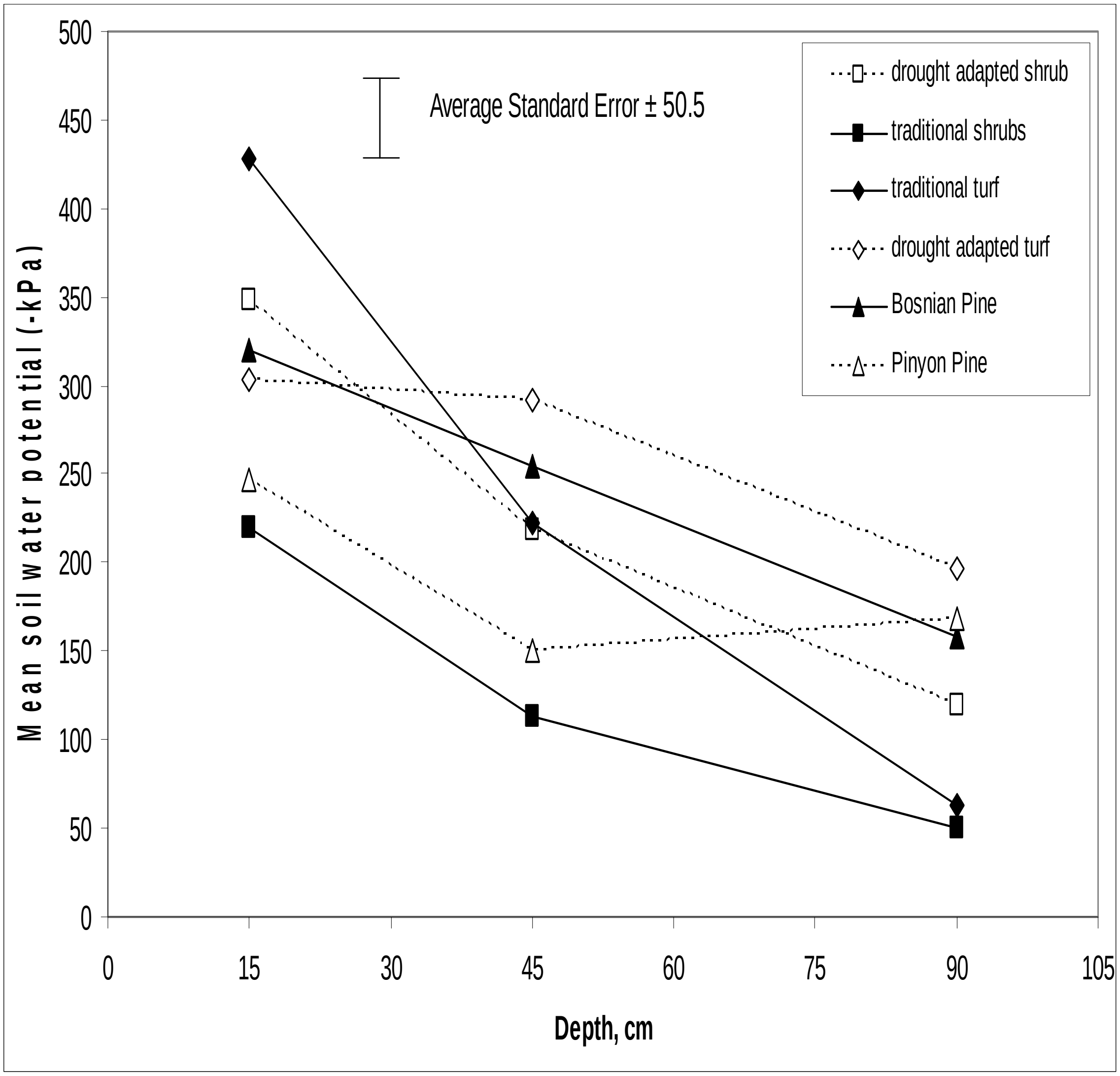


Figure 17 Mean soil water potential vs. depth, cm for each landscape treatment. Data combined from all depths (15, 45, and 90 cm) DOY 216-237, 2005 and 2006 (significance level at $p \leq 0.05$) of native and non native shrubs, buffalograss, Kentucky bluegrass, pinyon pine, and Bosnian pine.

CONCLUSION

Soil moisture responses were consistent with previous studies cited and appeared to be related in part to year to year differences in meteorological conditions, intrinsic plant water use, species-specific stomatal conductance, LAI, and rooting depth. Differences in soil water potential observed between the treatments during the dry down experiment varied widely at each depth. Soil water potentials at 15 cm were driest under KBG suggesting increased shallow root mass density and higher soil water uptake under drought stress compared to the other treatments. Kentucky bluegrass exhibited drought resistance due to physiological dormancy and reduced soil water uptake when temperatures were high and available soil water was most limiting. Although KBG may forestall drought by going into dormancy any drought resistance was offset by decreased turfgrass quality when soil water potentials were less than -400 kPa and offered no aesthetic benefit during the dry down. Limited drought tolerance in KBG has important implications for water conservation in the Intermountain West although development of drought resistant cultivars is a currently being investigated.

Buffalograss dried down more than any of the other treatments at 45 and 90 cm in 2006. Extraction of deep soil water and redistribution at more shallow depths may have allowed it to remain more verdant during the dry down even at soil water potentials less than -500 kPa. Improved drought tolerance and aesthetic appearance of buffalograss are valuable traits that make it a superior amenity turfgrass species compared to KBG under high temperatures and extended drought conditions. Although buffalograss is documented to be more drought resistant than KBG it deteriorated aesthetically in the fall and spring even when available plant water was not limiting. Pinyon pine and traditional shrub treatments dried down less than the other treatments at 15 and 45 and may be accounted for by low intrinsic plant water use and deep root architecture. The more positive soil water potentials measured at 45 cm under pinyon pine suggest hydraulic redistribution, an important drought escape mechanism of deep rooted plants in semi arid environments. Soil moisture responses under the conifer and shrub treatments varied widely however they dried down less in the shallow root zone and appeared to access water deeper in the soil profile compared to the turfgrass species. Unlike KBG the shrub and conifer treatments did not exhibit noticeable decline in aesthetic appearance at the end of the dry down.

The use of mixed vegetation landscapes can potentially use less water than traditional turf dominated landscapes by utilizing deep rooted plants that are adapted to local rainfall conditions (Kjelgren 2000). In the future, more accurate soil moisture sensors such as TDR or TDT probes are recommended to measure soil water potential to provide more accurate measurement of soil water status. Additional information on long term plant growth, rooting depth and root architecture, development of species-specific Kc values, and competition for soil water between plant species in mixed vegetation landscapes will provide more specific information to design more efficient low water use landscapes.

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APPENDIX

Table 2 Mean soil water potential (-kPa) vs. depth DOY 216 to 236.5 2005, 2006

Landscape treatment	Depth, cm	Mean soil water potential (-kPa)	Standard error (±)
Traditional shrub	15	219.7	50.6
	45	112.9	50.6
	90	49.8	50.6
Drought adapted shrub	15	348.1	50.6
	45	218.4	50.6
	90	119.3	50.6
Kentucky bluegrass	15	427.8	50.4
	45	222.7	50.4
	90	63.1	50.4
Buffalograss	15	303.4	50.4
	45	291.2	50.4
	90	197.2	50.4
Bosnian Pine	15	319.5	50.6
	45	254.9	50.6
	90	157.4	50.6
Pinyon Pine	15	246.3	50.6
	45	150.5	50.6
	90	168.6	50.6

Source: SAS Institute Inc. 100 SAS Campus Drive Cary, NC 27513-2414 USA

Table 3a. T102 Soil water potential data for dry down DOY 215.8-236.5, 2005

		DOY 216	DOY 236.5		
Location	Depth, cm	*-kPa*	*-kPa*	Range, *-kPa*	% change
T102A shrubs	15	120.4	239.3	118.9	98.7
	45	71.9	110.7	38.8	53.9
	90	34.1	33.3	-0.8	-2.3
T102B turfgrass	15	689.0	718.2	29.2	4.2
	45	364.1	551.7	187.6	51.5
	90	60.0	93.8	33.8	56.3
T102C turfgrass	15	498.2	563.5	65.3	13.1
	45	217.0	408.0	191.0	88.0
	90	69.9	113.5	43.6	62.4
T102D conifer	15	534.0	435.6	-98.4	-18.4
	45	312.5	308.9	-3.6	-1.1
	90	68.5	111.6	43.1	62.9

Table 3b. T102 Intra landscape differences in soil water potential DOY 215.8-236.5, 2005 A. shrub, B. turfgrass, C. turfgrass, and D. conifer

	DOY 216				DOY 236.5		
Depth, cm	% difference			Depth, cm	% difference		
	A-B	B-C	C-D		A-B	B-C	C-D
15	469.2	38.3	7.2	15	20.1	27.5	29.4
45	406.4	67.8	44.0	45	35.2	35.2	32.0
90	76.0	16.5	2.0	90	181.6	21.0	1.7
	difference -KPa				difference -KPa		
15	568.6	190.8	35.8	15	478.9	154.7	127.9
45	292.2	147.1	95.5	45	441.0	143.7	99.1
90	25.9	9.9	1.4	90	60.5	19.7	1.9

Table 4a. T202 Soil water potential data for dry down DOY 215.8-236.5, 2005

Location	Depth, cm	DOY 216 *-kPa*	DOY 236.5 *-kPa*	Range, *-kPa*	% change
T202A shrubs	15	190.9	349.1	158.2	82.9
	45	73.7	120.8	47.1	63.9
	90	33.3	54.8	21.5	64.6
T202B turfgrass	15	542.7	643.8	92.1	17.0
	45	275.0	377.8	102.8	37.4
	90	38.5	78.6	40.1	104.2
T202C turfgrass	15	612.4	675.5	63.1	10.3
	45	98.8	234.1	135.3	136.9
	90	39.1	74.9	35.8	91.6
T202D conifer	15	231.6	333.2	101.6	43.9
	45	158.2	229.8	71.6	45.3
	90	28.5	60.5	31.9	112.0

Table 4b. T202 Intra landscape differences in soil water potential DOY 215.8-236.5, 2005 A. shrub, B. turfgrass, C. turfgrass, and D. conifer

	DOY 216				DOY 236.5		
Depth, cm	% difference			Depth, cm	% difference		
	A-B	B-C	C-D		A-B	B-C	C-D
15	184.3	12.8	164.4	15	84.4	4.9	102.7
45	273.6	178.3	60.1	45	212.7	61.4	1.9
90	15.6	1.6	37.2	90	43.4	4.9	23.8
	difference -KPa				difference -KPa		
15	351.8	69.7	380.8	15	294.7	31.7	342.3
45	201.3	176.2	59.4	45	257.0	143.7	4.3
90	5.2	0.6	10.6	90	23.8	3.7	14.4

Table 5a. N101 Soil water potential data for dry down DOY 215.8-236.5, 2005

		DOY 216	DOY 236.5		
Location	Depth, cm	*-kPa*	*-kPa*	Range, *-kPa*	% change
N101A shrubs	15	377.6	395.4	17.8	4.7
	45	136.2	230.4	94.2	69.2
	90	55.0	98.8	43.4	78.3
N101B turfgrass	15	263.3	347.0	83.7	31.8
	45	133.5	299.7	166.2	124..5
	90	65.5	111.8	46.3	70.7
N101C turfgrass	15	314.5	310.8	-3.7	1.2
	45	127.9	249.0	121.1	94.7
	90	58.7	110.7	52.0	88.6
N101D conifer	15	389.1	333.3	-55.8	14.3
	45	63.1	90.9	27.8	44.1
	90	33.0	95.8	62.8	190.3

Table 5b. N101 Intra landscape differences in soil water potential DOY 215.8-236.5, 2005 A. shrub, B. turfgras, C. turfgrass, and D. conifer

	DOY 216				DOY 236.5		
Depth, cm	% difference			Depth, cm	% difference		
	A-B	B-C	C-D		A-B	B-C	C-D
15	43.4	19.4	23.7	15	13.9	11.6	7.2
45	2.0	4.4	102.7	45	30.1	20.4	173.9
90	19.0	11.5	77.9	90	13.1	1.0	15.6
	difference -KPa				difference -KPa		
15	114.3	51.2	74.6	15	48.4	36.2	22.5
45	2.7	5.6	64.8	45	69.3	50.7	158.1
90	10.5	6.8	25.7	90	13.0	1.1	14.9

Table 6a. N301 Soil water potential data for dry down DOY 215.8-236.5, 2005

		DOY 216	DOY 236.5		
Location	Depth, cm	*-kPa*	*-kPa*	Range, *-kPa*	% change
N301A shrubs	15	335.0	377.3	42.3	12.6
	45	121.0	192.8	71.8	59.3
	90	29.6	46.7	17.1	57.8
N310B turfgrass	15	457.0	441.8	-15.2	3.3
	45	102.0	220.6	118.6	116.3
	90	43.6	104.8	61.2	140.4
N301C turfgrass	15	332.8	342.1	9.3	2.8
	45	110.4	243.2	132.8	120.3
	90	39.2	96.3	57.1	145.7
N301D conifer	15	104.2	162.3	58.1	55.8
	45	60.6	99.4	38.8	64.0
	90	24.4	47.9	23.5	96.3

Table 6b. N301 Intra landscape differences in soil water potential DOY 215.8-236.5, 2005 A. shrub, B. turfgras, C. turfgrass, and D. conifer

	DOY 216				DOY 236.5		
Depth, cm	% difference			Depth, cm	% difference		
	A-B	B-C	C-D		A-B	B-C	C-D
15	36.4	37.3	219.4	15	17.1	29.1	110.7
45	18.6	8.2	82.2	45	14.4	10.2	144.7
90	47.3	11.2	60.7	90	124.4	8.8	101.0
	difference -KPa				difference -KPa		
15	122.0	124.2	228.6	15	64.5	99.7	179.8
45	19.0	8.4	49.8	45	27.8	22.6	143.8
90	14.0	4.4	14.8	90	58.1	8.5	14.9

Table 7a. T102 Soil water potential data for dry down DOY 215.8-236.5, 2006

		DOY 216	DOY 236.5		
Location	Depth, cm	*-kPa*	*-kPa*	Range, *-kPa*	% change
T102A shrubs	15	168.7	142.8	25.9	16.4
	45	110.9	154.1	43.2	38.9
	90	29.1	75.4	46.3	159.1
T102B turfgrass	15	97.5	649.5	552.0	566.1
	45	47.0	213.7	166.7	354.6
	90	25.0	44.9	19.9	79.9
T102C turfgrass	15	48.9	500.0	452.1	922.4
	45	68.5	128.1	59.6	87.0
	90	53.2	69.0	15.8	29.6
T102D conifer	15	252.0	365.2	113.2	44.9
	45	304.5	305.8	1.3	0.4
	90	374.2	338.5	-35.7	9.5

Table 7b. T102 Intra landscape differences in soil water potential DOY 215.8-236.5, 2006 A. shrub, B. turfgras, C. turfgrass, and D. conifer

	DOY 216				DOY 236.5		
Depth, cm	% difference			Depth, cm	% difference		
	A-B	B-C	C-D		A-B	B-C	C-D
15	73.0	99.4	415.3	15	354.8	29.9	36.9
45	136.0	45.7	344.5	45	38.6	66.8	138.7
90	16.4	112.8	603.4	90	67.9	53.7	390.6
	difference -KPa				difference -KPa		
15	71.2	48.6	203.1	15	506.7	149.5	134.8
45	63.9	21.5	236.0	45	59.6	85.6	177.7
90	4.1	28.2	321.0	90	30.5	24.1	269.5

Table 8a T202 Soil water potential data for dry down DOY 215.8-236.5, 2006

		DOY 216	DOY 236.5		
Location	Depth, cm	*-kPa*	*-kPa*	Range, *-kPa*	% change
T202A shrubs	15	254.1	260.0	5.9	2.3
	45	90.0	140.0	50.0	55.5
	90	27.3	43.4	16.1	58.9
T202B turfgrass	15	130.1	383.9	253.8	195.0
	45	64.0	253.6	189.6	296.2
	90	20.1	35.7	15.6	77.6
T202C turfgrass	15	76.4	405.0	328.6	430.1
	45	49.7	125.6	75.9	152.7
	90	30.8	43.5	12.7	41.2
T202D conifer	15	93.3	210.5	117.2	125.6
	45	159.0	207.0	48.0	30.1
	90	60.6	189.3	128.7	212.3

Table 8b. T202 Intra landscape differences in soil water potential DOY 215.8-236.5, 2006 A. shrub, B. turfgras, C. turfgrass, and D. conifer

	DOY 216				DOY 236.5		
Depth, cm	% difference			Depth, cm	% difference		
	A-B	B-C	C-D		A-B	B-C	C-D
15	95.3	70.3	22.1	15	47.7	5.5	92.4
45	40.6	28.8	219.9	45	81.1	101.9	64.8
90	35.8	53.2	96.8	90	21.5	21.8	77.0
	difference -KPa				difference -KPa		
15	124.0	53.7	16.9	15	123.9	21.1	194.5
45	26.0	14.3	109.3	45	113.6	128.0	81.4
90	7.2	10.7	29.8	90	7.7	7.8	145.8

Table 9a. N101 Soil water potential data for dry down DOY 215.8-236.5, 2006

		DOY 216	DOY 236.5		
Location	Depth, cm	-*kPa*	-*kPa*	Range, -*kPa*	% change
N101A shrubs	15	391.0	378.6	12.4	3.1
	45	285.3	285.0	0.3	0.1
	90	185.4	274.1	88.7	47.8
N101B turfgrass	15	241.9	476.2	234.3	96.8
	45	348.4	649.5	301.1	86.4
	90	132.6	444.3	311.7	235.0
N101C turfgrass	15	90.5	565.2	474.7	524.5
	45	228.8	571.5	342.7	149.7
	90	230.0	536.2	306.2	133.1
N101D conifer	15	345.6	440.4	94.8	27.4
	45	242.2	255.8	13.6	5.6
	90	92.8	329.7	136.9	71.0

Table 9b. N101 Intra landscape differences in soil water potential DOY 215.8-236.5, 2006 A. shrub, B. turfgras, C. turfgrass, and D. conifer

	DOY 216				DOY 236.5		
Depth, cm	% difference			Depth, cm	% difference		
	A-B	B-C	C-D		A-B	B-C	C-D
15	61.6	167.3	281.8	15	25.7	89.0	28.3
45	22.1	52.2	5.8	45	127.9	13.6	123.4
90	115.2	73.4	19.3	90	62.9	26.7	62.6
	difference -KPa				difference -KPa		
15	149.0	151.4	255.1	15	97.6	18.6	124.8
45	63.1	119.6	13.4	45	364.5	78.0	315.7
90	152.8	97.4	37.2	90	170.2	118.9	206.5

Table 10a. N301 Soil water potential data for dry down DOY 215.8-236.5, 2006

		DOY 216	DOY 236.5		
Location	Depth, cm	*-kPa*	*-kPa*	Range, *-kPa*	% change
N301A shrubs	15	296.0	258.1	37.9	12.8
	45	280.1	201.9	78.2	27.9
	90	107.8	193.0	85.2	79.0
N301B turfgrass	15	99.1	417.9	318.8	321.6
	45	250.7	421.7	171.0	68.2
	90	113.2	398.7	285.5	252.2
N301C turfgrass	15	61.1	420.0	318.8	321.6
	45	199.8	556.6	356.8	175.8
	90	161.8	518.0	356.2	225.1
N301D conifer	15	163.8	265.4	101.5	61.9
	45	141.0	183.7	42.7	30.2
	90	179.3	224.9	45.6	25.4

Table 10b. N301 Intra landscape differences in soil water potential DOY 215.8-236.5, 2006 A. shrub, B. turfgras, C. turfgrass, and D. conifer

	DOY 216				DOY 236.5		
Depth, cm	% difference			Depth, cm	% difference		
	A-B	B-C	C-D		A-B	B-C	C-D
15	198.7	62.2	168.2	15	61.9	0.5	58.5
45	11.7	25.4	41.7	45	108.8	31.9	202.9
90	30.3	42.9	10.8	90	106.5	29.9	130.2
	difference -KPa				difference -KPa		
15	197.0	38.0	102.8	15	159.8	2.1	154.6
45	29.4	50.9	58.8	45	219.8	134.9	372.9
90	5.4	48.6	17.5	90	205.7	119.3	293.1